EPA/600/R-18/121F
July 2018

Update for Chapter 19 of the Exposure Factors Handbook

Building Characteristics

National Center for Environmental Assessment
Office of Research and Development
U.S. Environmental Protection Agency
Washington, DC 20460

DISCLAIMER

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

19. BUILDING CHARACTERISTICS

19.1. INTRODUCTION

This document is an update to Chapter 19 (Building Characteristics) of the *Exposure Factors Handbook; 2011 Edition*. New information that has become available since 2011 has been added, and the recommended values have been revised, as needed to reflect the additional information. The chapter includes a comprehensive review of the scientific literature through 2017. The new literature was identified via formal literature searches conducted by EPA library services as well as targeted internet searches conducted by the authors of this chapter. Appendix A provides a list of the key terms that were used in the literature searches. Revisions to this chapter have been made in accordance with the approved quality assurance plan for the *Exposure Factors Handbook*.

As described in Chapter 1 of the *Exposure Factors Handbook: 2011 Edition* (U.S. EPA, 2011), key studies represent the most up-to-date and scientifically sound for deriving recommendations for exposure factors, whereas other studies are designated “relevant,” meaning applicable or pertinent, but not necessarily the most important. For example, studies that provide supporting data or information related to the factor of interest (e.g., building materials, building foundation types), or have study designs or approaches that make the data less applicable to the population of interest (e.g., studies not conducted in the United States) have been designated as relevant rather than key. Key studies were selected based on the general assessment factors described in Chapter 1 of the Handbook.

Unlike previous chapters in this handbook, which focus on human behavior or characteristics that affect exposure, this chapter focuses on building characteristics. Assessment of exposure in indoor settings requires information on the availability of the chemical(s) of concern at the point of exposure, characteristics of the structure and microenvironment that affect exposure, and human presence within the building. The purpose of this chapter is to provide data that are available on building characteristics that affect exposure in an indoor environment. This chapter addresses residential and nonresidential building characteristics (volumes, surface areas, mechanical systems, and types of foundations), transport phenomena that affect chemical transport within a building (airflow, chemical-specific deposition and filtration, and soil tracking), information on indoor water uses, and on various types of indoor building-related sources associated with airborne exposure and soil/house dust sources. Source-receptor relationships in indoor exposure scenarios can be complex due to interactions among sources, and transport/transformation processes that result from chemical-specific and building-specific factors.

There are many factors that affect indoor air exposures. Indoor air models generally require data on several parameters. This chapter provides recommendations on two parameters, volume and air exchange rates. Other factors that affect indoor air quality are furnishings, siting, weather, ventilation and infiltration, environmental control systems, material durability, operation and maintenance, occupants and their activities, and building structure. Available relevant information on some of these other factors is provided in this chapter, but specific recommendations are not provided, as site-specific parameters are preferred.

Figure 19-1 illustrates the complex factors that must be considered when conducting exposure assessments in an indoor setting. The primary cause of indoor pollution is the release of gases or particles into the air from indoor and outdoor sources. In addition to sources within the building, chemicals of concern may enter the indoor environment from outdoor air, soil, gas, water supply, tracked-in soil, and industrial work clothes worn by the residents. Indoor concentrations are affected by loss mechanisms, also illustrated in Figure 19-1, involving chemical reactions, deposition to and re-emission from surfaces, and transport out of the building. Particle-bound chemicals can enter indoor air through resuspension. Indoor air concentrations of gas-phase organic chemicals are affected by the presence of reversible sinks formed by a wide range of indoor materials. In addition, the activity of human receptors greatly affects their exposure as they move from room to room, entering and leaving areas with different levels and types of chemicals. Data on human activities, such as time spent at various rooms in the house, can be found in Chapter 16 of this handbook.

Inhalation of airborne chemicals in indoor settings are typically modeled by considering the building as an assemblage of one or more well-mixed zones. A zone is defined as one room, a group of interconnected rooms, or an entire building. At this macroscopic level, well-mixed assumptions form the basis for interpretation of measurement data as well as simulation of hypothetical scenarios. Exposure assessment models on a macroscopic level incorporate important physical factors and processes. These well-mixed, macroscopic models have been used to perform indoor air quality simulations (Axley, 1989), as well as indoor air exposure assessments (McKone, 1989; Ryan, 1991). Nazaroff and Cass (1986) and Wilkes et al. (1992) have used computer programs featuring finite difference or finite element numerical techniques to model mass balance. A simplified approach using desktop spreadsheet programs has been used by Jennings et al. (1987a). U.S. Environmental Protection Agency (EPA) has created two useful indoor air quality models: the (I-BEAM) (https://www.epa.gov/indoor-air-quality-iaq/indoor-air-quality-building-education-and-assessment-model), which estimates indoor air quality in commercial buildings and the *Multi-Chamber Concentration and Exposure Model* (MCCEM) (https://www.epa.gov/tsca-screening-tools/multi-chamber-concentration-and-exposure-model-mccem-version-12), which estimates average and peak indoor air concentrations of chemicals released from residences.

Major air transport pathways for airborne substances in buildings include the following:

- Air exchange across the building envelope—Air leakage through windows, doorways, intakes and exhausts, and "adventitious openings" (i.e., cracks and seams) that combine to form the leakage configuration of the building envelope plus natural and mechanical ventilation;
- Interzonal airflows—Transport through doorways, ductwork, and service chaseways that interconnect rooms or zones within a building; and
- Local circulation—Convective and advective air circulation and mixing within a room or within a zone.

The air exchange rate is generally expressed in terms of air changes per hour (ACH), with units of (hour^{-1}). It is defined as the ratio of the airflow (m^3 hour^{-1}) to the volume (m^3). The distribution of airflows across the building envelope that contributes to air exchange and the interzonal airflows along interior flowpaths is determined by the interior pressure distribution. The forces causing the airflows are temperature differences, the actions of wind, and natural and mechanical ventilation systems. Basic concepts on distributions and airflows have been reviewed by the American Society of Heating Refrigerating & Air Conditioning Engineers (ASHRAE, 2013). Indoor-outdoor and room-to-room temperature differences create density differences that help determine basic patterns of air motion. During the heating season, warmer indoor air tends to rise to exit the building at upper levels by stack action. Exiting air is replaced at lower levels by an influx of colder outdoor air. During the cooling season, this pattern is reversed: stack forces during the cooling season are generally not as strong as in the heating season because the indoor-outdoor temperature differences are not as pronounced.

The position of the neutral pressure level (i.e., the point where indoor-outdoor pressures are equal) depends on the leakage configuration of the building envelope. The stack effect arising from indoor-outdoor temperature differences is also influenced by the partitioning of the building interior. When there is free communication between floors or stories, the building behaves as a single volume affected by a generally rising current during the heating season and a generally falling current during the cooling season. When vertical communication is restricted, each level essentially becomes an independent zone. As the wind flows past a building, regions of positive and negative pressure (relative to indoors) are created within the building; positive pressures induce an influx of air, whereas negative pressures induce an outflow. Wind effects and stack effects combine to determine a net inflow or outflow.

The final element of indoor transport involves the actions of natural and mechanical ventilation systems. Natural ventilation uses pressure differences indoors and outdoors that arise from natural forces through openings such as windows, while mechanical systems circulate indoor air through the use of fans. There are generally three air distribution methods used for room ventilation: mixed ventilation, displacement ventilation, and stratum ventilation (Cheng and Lin, 2015). A mixed ventilation results in a uniform environment since air is supplied by jets. Displacement ventilation uses gravity to form a stratified environment. In stratum ventilation, the air is directly delivered to occupants' head level.

Mechanical ventilation systems may be connected to heating/cooling systems that, depending on the type of building, recirculate thermally treated indoor air or a mixture of fresh air and recirculated air. Mechanical systems also may be solely dedicated to exhausting air from a designated area, as with some kitchen range hoods and bath exhausts, or to recirculating air in designated areas as with a room fan. Local air circulation also is influenced by the movement of people and the operation of local heat sources.

19.2. RECOMMENDATIONS

Table 19-1 presents the recommendations for residential building volumes and air exchange rates. Table 19-2 presents the confidence ratings for the recommended residential building volumes. The 2009 Residential Energy Consumption Survey (RECS) data indicates a 446 m^3 average living space (approximately 2000 ft^2 area, assuming an 8 ft ceiling height) (U.S. DOE, 2013). However, these values vary depending on the type of housing (see Section 19.3.1.1). The recommended lower end of housing volume is 154 m^3 (approximately 675 ft^2 area assuming ceiling height of 8 ft). The 10th percentile is based on EPA's analysis of the data from the 2005 RECS survey. Other percentiles are available in Section 19.3.1.1.

Residential air exchange rates vary by region of the country and seasonally. The recommended median air exchange rate for all regions combined is 0.45 ACH. The arithmetic mean is not preferred because it is influenced fairly heavily by extreme values at the upper tail of the distribution. This value was derived by Koontz and Rector (1995) using the perflourocarbon tracer (PFT) database and is supported by Persily et al. (2010). Although Persily et al. (2010) provides more recent information on air exchange rates, the data were based on modeling data from two databases including the RECS database and the U.S. Census Bureau American Housing Survey (AHS) database. Koontz and Rector (1995) also has an advantage over Persily et al. (2010) in that it provides data for the various regions of the country. Section 19.5.1.1.1 presents distributions for the various regions of the country. For a conservative value, the 10th percentile for the PFT database (0.18 ACH) is recommended (see Section 19.5.1.1.1).

Table 19-3 presents the recommended values for nonresidential building volumes and air exchange rates. Volumes of nonresidential buildings vary with type of building (e.g., office space, malls). They range from 1,889 m^3 for food services to 287,978 m^3 for enclosed malls. The mean for all buildings combined is 5,575 m^3. These data come from the Commercial Buildings Energy Consumption Survey (CBECS) (U.S. DOE, 2008b). The last CBECS for which data are publicly available was conducted in 2012. However, microdata from this survey year have not been analyzed by EPA. Instead, analyses of the 2003 data were conducted by EPA to derive recommendations for nonresidential building volume and air exchange rates. Table 19-4 presents the confidence ratings for the nonresidential building volume recommendations. The mean air exchange rate for all nonresidential buildings combined is 1.5 ACH. The 10th percentile air exchange rate for all buildings combined is 0.60 ACH. These data come from Turk et al. (1987).

Table 19-5 presents the confidence ratings for the air exchange rate recommendations for both residential and nonresidential buildings. Air exchange rate data presented in the studies are extremely limited. Therefore, the recommended values have been assigned a "low" overall confidence rating, and these values should be used with caution.

Volume and air exchange rates can be used by exposure assessors in modeling indoor-air concentrations as one of the inputs to exposure estimation. Other inputs to the modeling effort include rates of indoor pollutant generation and losses to (and, in some cases, re-emissions from) indoor sinks. Other things being equal (i.e., holding constant the pollutant generation rate and effect of indoor sinks), lower values for either the indoor volume or the air exchange rate will result in higher indoor-air concentrations. Thus, values near the lower end of the distribution (e.g., 10th percentile) for either parameter are appropriate in developing conservative estimates of exposure.

There are some uncertainties in, or limitations on, the distribution for volumes and air exchange rates that are presented in this chapter. In addition, there are no systematic survey studies of air exchange rate. For example, the RECS contains information on floor area rather than total volume. The PFT database did not base its measurements on a sample that was statistically representative of the national housing stock or balanced by time of the year. PFT has been found to underpredict seasonal average air exchange by 15 to 35% Sherman (1989). Using PFT to determine air exchange can produce significant errors when conditions during the measurements greatly deviate from idealizations calling for constant, well-mixed conditions. Principal concerns focus on the effects of naturally varying air exchange and the effects of temperature in the permeation source. Some researchers have found that failing to use a time-weighted average temperature can greatly affect air exchange rate estimates (Leaderer et al., 1985). A final difficulty in estimating air exchange rates for any particular zone results from interconnectedness of multizone models and the effect of neighboring zones as demonstrated by Sinden (1978) and Sandberg (1984).

Table 19-1. Summary of Recommended Values for Residential Building Parameters

	Mean	10th Percentile	Source
Volume of residence[a]	446 m^3 (central estimate)[b]	154 m^3 (lower percentile)[c]	EPA analysis of U.S. DOE, (2013, 2008a)
Air exchange rate	0.45 ACH (central estimate)[d]	0.18 ACH (lower percentile)[e]	Koontz and Rector (1995); Persily et al. (2010)

[a] Volumes vary with type of housing. For specific housing type volumes, see Tables 19-6 and 19-7.

[b] Mean value presented in Table 19-6 recommended for use as a central estimate for all single family homes, including mobile homes and multifamily units.

[c] 10th percentile value from Table 19-9 recommended to be used as a lower percentile estimate.

[d] Median value recommended to be used as a central estimate based across all U.S. census regions and various housing types (see Tables 19-25 and 19-26).

[e] 10th percentile value across all U.S. census regions recommended to be used as a lower percentile value (see Table 19-25).

ACH = Air changes per hour.

Table 19-2. Confidence in Residential Volume Recommendations[a]

General Assessment Factors	Rationale	Rating
Soundness		Medium
Adequacy of Approach	The study was based on primary data. Volumes were estimated assuming an 8-foot ceiling height. The effect of this assumption has been tested by Murray (1997) and found to be insignificant.	
Minimal (or defined) bias	Selection of residences was random.	
Applicability and utility		Medium
Exposure factor of interest	The focus of the studies was on estimating house volume as well as other factors.	
Representativeness	Residences in the United States were the focus of the study. The sample size was fairly large and representative of the entire United States. Samples were selected at random.	
Currency	The most recent RECS surveys for which volume data are available were conducted in 2005 and 2009.	
Data collection period	Data were collected in 2005 and 2009.	
Clarity and completeness		High
Accessibility	The RECS database is publicly available.	
Reproducibility	Direct measurements were made.	
Quality assurance	Not applicable.	
Variability and uncertainty		Medium
Variability in population	Distributions are presented by housing type and regions, but some subcategory sample sizes were small.	
Uncertainty	Although residence volumes were estimated using the assumption of 8-foot ceiling height, Murray (1997) found this assumption to have minimal impact.	
Evaluation and review		Medium
Peer review	The RECS database is publicly available. Some data analysis was conducted by EPA.	
Number and agreement of studies	Only one study was used to derive recommendations. Other relevant studies provide supporting evidence.	
Overall Rating		**Medium**

[a] See Section 1.5.2 in Chapter 1 of the *Exposure Factors Handbook: 2011 Edition* (U.S. EPA, 2011) for a detailed description of the evaluation criteria used in this table.

Table 19-3. Summary of Recommended Values for Nonresidential Building Parameters

	Mean[a]	10th Percentile[b]	Source
Volume of building (m^3)[c]			
Vacant	4,789	408	EPA analysis of U.S. DOE (2008b)
Office	5,036	510	
Laboratory	24,681	2,039	
Nonrefrigerated warehouse	9,298	1,019	
Food sales	1,889	476	
Public order and safety	5,253	816	
Outpatient healthcare	3,537	680	
Refrigerated warehouse	19,716	1,133	
Religious worship	3,443	612	
Public assembly	4,839	595	
Education	8,694	527	
Food service	1,889	442	
Inpatient healthcare	82,034	17,330	
Nursing	15,522	1,546	
Lodging	11,559	527	
Strip shopping mall	7,891	1,359	
Enclosed mall	287,978	35,679	
Retail other than mall	3,310	510	
Service	2,213	459	
Other	5,236	425	
All buildings[d]	5,575	527	
Air Exchange Rate[e]	Mean (SD)1.5 (0.87) ACH Range 0.3−4.1 ACH	0.60 ACH	Turk et al. (1987)

[a] Mean values are recommended as central estimates for nonresidential buildings (see Table 19-21).
[b] 10th percentile values are recommended as lower estimates for nonresidential buildings (see Table 19-21).
[c] Volumes were calculated assuming a ceiling height of 20 feet for warehouses and enclosed malls and 12 feet for other structures (see Table 19-21).
[d] Weighted average assuming a ceiling height of 20 feet for warehouses and enclosed malls and 12 feet for other structures (see Table 19-21).
[e] Air exchange rates for commercial buildings (see Table 19-30).
SD = Standard deviation.
ACH = Air changes per hour.

Table 19-4. Confidence in Nonresidential Volume Recommendations[a]

General Assessment Factors	Rationale	Rating
Soundness		Medium
Adequacy of approach	All nonresidential data were based on one study: CBECS (U.S. DOE, 2008b). Volumes were estimated assuming a 20-foot ceiling height assumption for warehouses and a 12-foot height assumption for all other nonresidential buildings based on scant anecdotal information. Although Murray (1997) found that the impact of an 8-foot ceiling assumption was insignificant for residential structures, the impact of these ceiling height assumptions for nonresidential buildings is unknown.	
Minimal (or defined) bias	Selection of residences was random for CBECS.	
Applicability and utility		High
Exposure factor of interest	CBECS (U.S. DOE, 2008b) contained ample building size data, which were used as the basis provided for volume estimates.	
Representativeness	CBECS (U.S. DOE, 2008b) was a nationwide study that generated weighted nationwide data based upon a large random sample.	
Currency, data collection period	The data were collected in 2003.	
Clarity and completeness		High
Accessibility	The data are available online in both summary tables and raw data. http://www.eia.doe.gov/emeu/cbecs/contents.html.	
Reproducibility	Direct measurements were made.	
Quality assurance	Not applicable.	
Variability and uncertainty		Medium
Variability in population	Distributions are presented by building type, heating and cooling system type, and employment, but a few subcategory sample sizes were small.	
Uncertainty	Volumes were calculated using speculative assumptions for building height. The impact of such assumptions may or may not be significant.	
Evaluation and review		Low
Peer review	There are no studies from the peer-reviewed literature.	
Number and agreement of studies	All data are based upon one study: CBECS (U.S. DOE, 2008b).	
Overall Rating		**Medium**

[a] See Section 1.5.2 in Chapter 1 of the *Exposure Factors Handbook: 2011 Edition* (U.S. EPA, 2011) for a detailed description of the evaluation criteria used in this table.

Table 19-5. Confidence in Air Exchange Rate Recommendations for Residential and Nonresidential Buildings[a]

General Assessment Factors	Rationale	Rating
Soundness		Low
Adequacy of approach	The studies were based on primary data; however, most approaches contained major limitations, such as assuming uniform mixing, and residences were typically not selected at random.	
Minimal (or defined) bias	Bias may result because the selection of residences and buildings was not random or balanced by time of the year. The commercial building study (Turk et al., 1987) was conducted only on buildings in the northwest United States.	
Applicability and utility		Low
Exposure factor of interest	The focus of the studies was on estimating air exchange rates as well as other factors.	
Representativeness	Study residences were typically in the United States, but only RECS (U.S. DOE, 2008a and 2013) and the AHS selected residences randomly. PFT residences were not representative of the United States. Distributions are presented by housing type and regions; although some of the sample sizes for the subcategories were small. The commercial building study (Turk et al., 1987) was conducted only on buildings in the northwest United States.	
Currency	Measurements in the PFT database were taken between 1982−1987. The Turk et al. (1987) study was conducted in the mid-1980s.	
Data Collection Period	Only short-term data were collected; some residences were measured during different seasons; however, long-term air exchange rates are not well characterized. Individual commercial buildings were measured during one season.	
Clarity and completeness		Medium
Accessibility	Papers are widely available from government reports and peer-reviewed journals.	
Reproducibility	Precision across repeat analyses has been documented to be acceptable.	
Quality assurance	Not applicable.	

Table 19-5. Confidence in Air Exchange Rate Recommendations for Residential and Nonresidential Buildings[a] (Continued)

General Assessment Factors	Rationale	Rating
Variability and uncertainty		Medium
Variability in population	For the residential estimates, distributions are presented by U.S. regions, seasons, and climatic regions, but some of the sample sizes for the subcategories were small. The commercial estimate comes from buildings in the northwest United States representing two climate zones, and measurements were taken in three seasons (spring, summer, and winter).	
Uncertainty	Some measurement error may exist. Additionally, PFT has been found to underpredict seasonal average air exchange by 15−35% (Sherman, 1989). Turk et al. (1987) estimates a 10−20% measurement error for the technique used to measure ventilation in commercial buildings.	
Evaluation and review		Low
Peer review	The studies appear in peer-reviewed literature.	
Number and agreement of studies	Three residential studies are based on the same PFT database. The database contains results of 20 projects of varying scope. The commercial building rate is based on one study.	
Overall rating		**Low**

[a] See Section 1.5.2 in Chapter 1 of the *Exposure Factors Handbook: 2011 Edition* (U.S. EPA, 2011) for a detailed description of the evaluation criteria used in this table.

19.3. RESIDENTIAL BUILDING CHARACTERISTICS STUDIES

19.3.1. Key Study of Volumes of Residences

19.3.1.1. *U.S. DOE (2017, 2013, 2008a)—Residential Energy Consumption Survey (RECS)*

Measurement surveys have not been conducted to directly characterize the range and distribution of volumes for a random sample of U.S. residences. Related data, however, are regularly collected through the U.S. Department of Energy's (DOE) RECS. In addition to collecting information on energy use, this survey collects data on housing characteristics including direct measurements of total and heated floor space for buildings visited by survey specialists. The last three surveys were conducted in 2005, 2009, and 2015. Data from these survey years were made available in 2008, 2013, and 2017, respectively. For the most recent survey conducted in 2015, a multistage probability sample of more than 5,600 residences was surveyed, representing 118.2 million housing units nationwide (www.eia.gov/consumption/residential/about.php). However, not all of the data from the 2015 survey were available in time for the revisions to this chapter. For example, the floor space area from the residences surveyed in 2015 is not available yet. In 2009, the survey consisted of a multistage probability sample of 12,083 residences, representing 113.6 million housing units nationwide. The 2009 survey response rate was 79% (U.S. DOE, 2013). Housing volumes were estimated using the RECS 2009 data since the data from the 2015 were not available. These were estimated by multiplying the heated floor space area by an assumed ceiling height of 8 feet. The data and data tables were released to the public in 2013 and are available from https://www.eia.gov/consumption/residential/data/2009/index.php?view=characteristics.

Table 19-6 presents results for average residential volume by type of residence, census region, and urbanicity (i.e., urban vs. rural). The predominant housing type—single-family detached homes—also had the largest average volume. Multifamily units and mobile homes had volumes averaging about half that of single-family detached homes, with single-family attached homes about halfway between these extremes. The average house volume for all types of units for all years was estimated to be 446 m^3. Table 19-7 presents the average residential volume for single family homes, multifamily homes, and mobile homes by housing unit type, census region, and urbanicity. Data on the relationship of residential volume to year of construction are provided in Table 19-8 and indicate a slight decrease in residential volumes between 1950 and 1979, followed by an increasing trend. A ceiling height of 8 feet was assumed in estimating the average volumes, whereas there may have been some time-related trends in ceiling height. It is important to note that the available data used to derived volumes included all basements, finished or conditioned (heated or cooled) areas of attics, and conditioned garage space that is attached to the home. Unconditioned and unfinished areas in attics and attached garages are excluded.

In 2010, the EPA conducted an analysis of the RECS 2005 survey microdata files. The RECS 2005 survey consisted of a sample of 4,382 residences representing 111 million housing units nationwide. The response rate in the 2005 RECS survey was 71% (U.S. DOE 2008a). Table 19-9 presents distributions of residential volumes for all house types and all units estimated by the EPA using the 2005 microdata. Similar analysis has not been conducted with the more recent data sets from 2009 and 2015.

The advantages of this study were that the sample size was large, and it was representative of houses in the United States. Also, it included various housing types. A limitation of this analysis is that volumes were estimated assuming a ceiling height of 8 feet. Volumes of individual rooms in the house cannot be estimated. In addition, not all the data from the most recent survey years have been released.

19.3.2. Relevant Studies of Volumes of Residences

19.3.2.1. *Versar (1990)—Database on Perfluorocarbon Tracer (PFT) Ventilation Measurements*

Versar (1990) compiled a database of time-averaged air exchange and interzonal airflow measurements in more than 4,000 residences. These data were collected between 1982 and 1987. The residences that appear in this database are not a random sample of U.S. homes. However, they represent a compilation of homes visited in about 100 different field studies, some of which involved random sampling. In each study, the house volumes were directly measured or estimated. The collective homes visited in these field projects are not geographically balanced. A large fraction of these homes are located in southern California. Statistical weighting techniques were applied in developing estimates of nationwide distributions to compensate for the geographic imbalance. The Versar (1990) PFT database found a mean value of 369 m^3 (see Table 19-10).

The advantage of this study is that it provides a distribution of house volumes. However, more up-to-date data are available from RECS 2009 (U.S. DOE, 2013).

19.3.2.2. *Murray (1997)—Analysis of RECS and PFT Databases*

Using a database from the 1993 RECS and an assumed ceiling height of 8 feet, Murray (1997) estimated a mean residential volume of 382 m^3 using RECS estimates of heated floor space. This estimate is slightly different from the mean of 369 m^3 given in Table 19-10. Murray's (1997) sensitivity analysis indicated that when a fixed ceiling height of 8 feet was replaced with a randomly varying height with a mean of 8 feet, there was little effect on the standard deviation of the estimated distribution. From a separate analysis of the PFT database, based on 1,751 individual household measurements, Murray (1997) estimated an average volume of 369 m^3, the same as previously given in Table 19-10. In performing this analysis, the author carefully reviewed the PFT database in an effort to use each residence only once, for those residences thought to have multiple PFT measurements.

Murray (1997) analyzed the distribution of selected residential zones (i.e., a series of connected rooms) using the PFT database. The author analyzed the "kitchen zone" and the "bedroom zone" for houses in the Los Angeles area that were labeled in this manner by field researchers, and "basement," "first floor," and "second floor" zones for houses outside of Los Angeles for which the researchers labeled individual floors as zones. The kitchen zone contained the kitchen in addition to any of the following associated spaces: utility room, dining room, living room, and family room. The bedroom zone contained all the bedrooms plus any bathrooms and hallways associated with the bedrooms. The following summary statistics (mean ± standard deviation) were reported by Murray (1997) for the volumes of the zones described above: 199 ± 115 m^3 for the kitchen zone, 128 ± 67 m^3 for the bedroom zone, 205 ± 64 m^3 for the basement, 233 ± 72 m^3 for the first floor, and 233 ± 111 m^3 for the second floor.

The advantage of this study is that the data are representative of homes in the United States. However, more up-to-date data are available from the RECS 2009 (U.S. DOE, 2013).

19.3.2.3. *U.S. Census Bureau (2017)—American Housing Survey for the United States: 2015*

The American Housing Survey (AHS) is conducted by the Census Bureau for the Department of Housing and Urban Development. It collects data on the Nation's housing, including apartments, single-family homes, mobile homes, vacant housing units, household characteristics, housing quality, foundation type, drinking water source, equipment and fuels, and housing unit size. National data are collected biennially between May and September in odd-numbered years. The 2015 survey was comprised of a national sample of 5,686 housing units representing 118.2 million occupied primary households in the United States. The U.S. Census Bureau (2017) lists the number of residential single detached and manufactured/mobile homes in the United States within the owner or renter categories, based on the AHS (see Table 19-11). Assuming an 8-foot ceiling, these units have a median size of 340 m^3; however, these values do not include multifamily units, but include single detached and manufactured/mobile homes. It should be mentioned that 8 feet is the most common assumed ceiling height, and Murray (1997) has shown that the effect of the 8-foot ceiling height assumption is not significant.

The advantage of this study is that it was a large national sample and, therefore, representative of the United States. The limitations of these data are that distributions were not provided by the authors, and the analysis did not include multifamily units.

19.3.3. Other Factors

19.3.3.1. *Surface Area and Room Volumes*

The surface areas of floors are commonly considered in relation to the room or house volume, and their relative loadings are expressed as a surface area-to-volume, or loading ratio. Table 19-12 provides the basis for calculating loading ratios for typical-sized rooms. Constant features in the examples are a room width of 12 feet and a ceiling height of 8 feet (typical for residential buildings), or a ceiling height of 12 feet (typical for some types of commercial buildings).

Volumes of individual rooms are dependent on the building size and configuration, but summary data are not readily available. The exposure assessor is advised to define specific rooms, or assemblies of rooms, that best fit the scenario of interest. Most models for predicting indoor air concentrations specify airflows in m^3 per hour and, correspondingly, express volumes in m^3. A measurement in ft^3 can be converted to m^3 by multiplying the value in ft^3 by

0.0283 m^3/ft^3. For example, a bedroom that is 9 feet wide by 12 feet long by 8 feet high has a volume of 864 ft^3 or 24.5 m^3. Similarly, a living room with dimensions of 12 feet wide by 20 feet long by 8 feet high has a volume of 1,920 ft^3 or 54.3 m^3, and a bathroom with dimensions of 5 feet by 12 feet by 8 feet has a volume of 480 ft^3 or 13.6 m^3.

19.3.3.2. *Products and Materials*

Table 19-13 presents examples of assumed amounts of selected products and materials used in constructing or finishing residential surfaces (Tucker, 1991). Products used for floor surfaces include adhesive, varnish, and wood stain; and materials used for walls include paneling, painted gypsum board, and wallpaper. Particleboard and chipboard are commonly used for interior furnishings such as shelves or cabinets but could also be used for decking or underlayment. It should be noted that numbers presented in the table for surface area are based on typical values for residences, and they are presented as examples. In contrast to the concept of loading ratios presented above (as a surface area), the numbers in the table also are not scaled to any particular residential volume. In some cases, it may be preferable for the exposure assessor to use professional judgment in combination with the loading ratios given above. For example, if the exposure scenario involves residential wall to wall carpeting in a room of 3 × 4 m with a ceiling height of 2.5 m (approximately 8 feet), it will have a loading ratio of 0.4 m^2m^{-3} (Tichenor, 2006). This can be multiplied by an assumed residential volume and assumed fractional coverage of carpeting to derive an estimate of the surface area. More specifically, a residence with a volume of 300 m^3, a loading ratio of 0.4 m^2m^{-3}, and coverage of 80%, would have 96 m^2 of carpeting. The estimates discussed here relate to macroscopic surfaces; the true surface area for carpeting, for example, would be considerably larger because of the nature of its fibrous material.

19.3.3.3. *Mechanical System Configurations*

Mechanical systems for air movement in residences can affect the migration and mixing of pollutants released indoors and the rate of pollutant removal. Three types of mechanical systems are (1) systems associated with heating, ventilating, and air conditioning (HVAC); (2) systems whose primary function is providing localized exhaust; and (3) systems intended to increase the overall air exchange rate of the residence.

Portable space heaters intended to serve a single room, or a series of adjacent rooms, may or may not be equipped with blowers that promote air movement and mixing. Without a blower, these heaters still have the ability to induce mixing through convective heat transfer. If the heater is a source of combustion pollutants, as with unvented gas or kerosene space heaters, then the combination of convective heat transfer and thermal buoyancy of combustion products will result in fairly rapid dispersal of such pollutants. The pollutants will disperse throughout the floor where the heater is located and to floors above the heater, but may not disperse to floors below.

Central forced-air HVAC systems are common in many residences. Such systems, through a network of supply/return ducts and registers, can achieve fairly complete mixing within 20 to 30 minutes (Koontz et al., 1988). The air handler for such systems is commonly equipped with a filter (see Figure 19-2) that can remove particle-phase contaminants. Further removal of particles, via deposition on various room surfaces (see Section 19.5.5), is accomplished through increased air movement when the air handler is operating.

Figure 19-2 also distinguishes forced-air HVAC systems by the return layout in relation to supply registers. The return layout shown in the upper portion of the figure is the type most commonly found in residential settings. On any floor of the residence, it is typical to find one or more supply registers to individual rooms, with one or two centralized return registers. With this layout, supply/return imbalances can often occur in individual rooms, particularly if the interior doors to rooms are closed. In comparison, the supply/return layout shown in the lower portion of the figure by design tends to achieve a balance in individual rooms or zones. Airflow imbalances can also be caused by inadvertent duct leakage to unconditioned spaces such as attics, basements, and crawl spaces. Such imbalances usually depressurize the house, thereby increasing the likelihood of contaminant entry via soil-gas transport or through spillage of combustion products from vented fossil-fuel appliances such as fireplaces and gas/oil furnaces.

Mechanical devices such as kitchen fans, bathroom fans, and clothes dryers are intended primarily to provide localized removal of unwanted heat, moisture, or odors. Operation of these devices tends to increase the air exchange rate between the indoors and outdoors. Because local exhaust devices are designed to be near certain indoor sources, their effective removal rate for locally generated pollutants is greater than would be expected from the dilution effect of increased air exchange. Operation of these devices also tends to depressurize the house, because replacement air usually is not provided to balance the exhausted air.

An alternative approach to pollutant removal is one which relies on an increase in air exchange to dilute pollutants generated indoors. This approach can be accomplished using heat recovery ventilators (HRVs) or energy recovery ventilators (ERVs). Both types of ventilators are designed to provide balanced supply and exhaust airflows and are intended to recover most of the energy that normally is lost when additional outdoor air is introduced. Although ventilators can provide for more rapid dilution of internally generated pollutants, they also increase the rate at which outdoor pollutants are brought into the house. A distinguishing feature of the two types is that ERVs provide for recovery of latent heat (moisture) in addition to sensible heat. Moreover, ERVs typically recover latent heat using a moisture-transfer device such as a desiccant wheel. It has been observed in some studies that the transfer of moisture between outbound and inbound air streams can result in some re-entrainment of indoor pollutants that otherwise would have been exhausted from the house (Andersson et al., 1993). Inadvertent air communication between the supply and exhaust air streams can have a similar effect.

Studies quantifying the effect of mechanical devices on air exchange using tracer-gas measurements are uncommon and typically provide only anecdotal data. The common approach is for the expected increment in the air exchange rate to be estimated from the rated airflow capacity of the device(s). For example, if a device with a rated capacity of 100 ft^3 per minute, or 170 m^3 per hour, is operated continuously in a house with a volume of 400 m^3, then the expected increment in the air exchange rate of the house would be 170 m^3 $hour^{-1}$/400 m^3, or approximately 0.4 ACH.

U.S. DOE RECS contains data on residential heating characteristics. The data show that most homes in the United States have some kind of heating and air conditioning system (U.S. DOE, 2017). The types of system vary regionally within the United States. Table 19-14 shows the type of primary and secondary heating systems found in U.S. residences. The predominant primary heating system in the Midwest is natural gas (used by 67.0% of homes there) while most homes in the South (60.1%) primarily heat with electricity. Nationwide, 36.6% of residences have a secondary heating source, typically an electric source.

Table 19-15 shows the type of heating systems found in the United States by climate region. It is noteworthy that 51.4% of residences in very cold/cold climate use central heating compared to 19.7% in hot humid climate.

Table 19-16 shows that 87.2% of U.S. residences have some type of cooling system: 65.2% have central air while 26.7% use individual air conditioning units. Like heating systems, cooling system type varies regionally as well. In the South, 95.3% of residences have either central or room air conditioning units whereas only 54.9% of residences in the Western United States have air conditioning.

19.3.3.4. *Type of Foundation*

The type of foundation of a residence is of interest in residential exposure assessment. It provides some indication of the number of stories and house configuration, as well as an indication of the relative potential for soil−gas transport. For example, such transport can occur readily in homes with enclosed crawl spaces. Homes with basements provide some resistance, but still have numerous pathways for soil−gas entry. By comparison, homes with crawl spaces open to the outside have significant opportunities for dilution of soil gases prior to transport into the house. Using data from the 2015 AHS, of total housing units in the United States, 31% have a basement under the entire building, 11% have a basement under part of the building, 22% have a crawl space, and 36% are on a concrete slab (U.S. Census Bureau, 2017).

19.3.3.4.1. Lucas et al. (1992)—National Residential Radon Survey

The estimated percentage of homes with a full or partial basement according to the National Residential Radon Survey of 5,700 households nationwide was 44% (see Table 19-17) (Lucas et al., 1992). The National Residential Radon Survey provides data for more refined geographical areas, with a breakdown by the 10 EPA Regions. The New England region (i.e., EPA Region 1), which includes Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont, had the highest prevalence of basements (93%). The lowest prevalence (4%) was for the South Central region (i.e., EPA Region 6), which includes Arkansas, Louisiana, New Mexico, Oklahoma, and Texas. Section 19.3.3.4.2 presents the states associated with each census region and EPA region.

19.3.3.4.2. U.S. DOE (2008a, 2013, 2017)—Residential Energy Consumption Survey (RECS)

The three most recent RECS (described in Section 19.3.1.1) were administered in 2005, 2009, and 2015 (U.S. DOE, 2008a, 2013, 2017). The type of information requested by the survey questionnaire included the type of foundation for the residence (i.e., basement, enclosed crawl space, crawl space open to outside, or concrete slab). This information was not obtained for multifamily structures with five or more dwelling units or for mobile homes. EPA analyzed the RECS 2015 data (U.S. DOE, 2017) to estimate the percentage of residences with basements by census region. Table 19-18 indicates that 43.5% of residences have basements nationwide. Table 19-19 shows the states associated with each EPA region and census region. Table 19-20 presents the percentage of residences with each foundation type, by census region, and for the entire United States. The foundation type data (other than basements) were not included in the RECS 2015 survey. Therefore, the values presented in Table 19-20 are based on data from the RECS 2009 survey (U.S. DOE, 2013). The percentages can add up to more than 100% because some residences have more than one type of foundation; for example, many split-level structures have a partial basement combined with some crawlspace that typically is enclosed. The data in Table 19-20 indicate that 39.9% of residences nationwide have a basement. It also shows that a large fraction of homes have concrete slabs (46.5%). There are also variations by census region. For example, around 74.7 and 72.5% of the residences in the Northeast and Midwest regions, respectively, have basements. In the South and West regions, the predominant foundation type is concrete slab.

The advantage of this study is that it had a large sample size, and it was representative of houses in the United States. Also, it included various housing types. A limitation of this analysis is that homes have multiple foundation types, and the analysis does not provide estimates of square footage for each type of foundation. Also, the information collected varied slightly across survey years and the data from the most recent survey were not available to be analyzed.

19.4. NONRESIDENTIAL BUILDING CHARACTERISTICS STUDIES

19.4.1. U.S. DOE (2008b, 2016)—Nonresidential Building Characteristics—Commercial Buildings Energy Consumption Survey (CBECS)

The U.S. Department of Energy conducts the CBECS to collect data on the characteristics and energy use of commercial buildings. CBECS is a national survey of U.S. buildings that DOE first conducted in 1979. The survey is conducted every 4 years. In 2010, EPA conducted an analysis of the U.S. DOE CBECS 2003 data, released in 2008. CBECS defines "Commercial" buildings as all buildings in which at least half of the floorspace is used for a purpose that is not residential, industrial, or agricultural, so they include building types that might not traditionally be considered commercial, such as schools, correctional institutions, and buildings used for religious worship.

The 2003 CBECS provided nationwide estimates for the United States based upon a weighted statistical sample of 5,215 buildings. DOE releases a data set about the sample buildings for public use. The 2003 CBECS Public Use Microdata set includes data for 4,820 nonmall commercial buildings (U.S. DOE, 2008b). A second data set is available that includes information on malls, lacks building characteristics data. Building characteristics data provided by CBECS includes floor area, number of floors, census division, heating and cooling design, principal building activity, number of employees, and weighting factors. Although DOE released the Microdata from the 2012 survey in 2016, EPA did not analyze these data to estimate volumes of commercial buildings, the number of hours per week they are open, and the number of employees during the main shift because of the amount of effort involved and the likelihood that values have not changed considerably.

Table 19-21 shows that nonresidential buildings vary greatly in volumes. The table shows average volume for a numbers of structures including offices (5,036 m^3), restaurants (food services) (1,889 m^3), schools (education) (8,694 m^3), hotels (lodging) (11,559 m^3), and enclosed shopping malls (287,978 m^3). Each of these structures varies considerably in size as well. The large shopping malls are over 500,000 m^3 (90th percentile). The most numerous of the nonresidential buildings are office buildings (17%), nonfood service buildings (13%), and warehouses (12%).

Table 19-22 presents data on the number of hours various types of nonresidential buildings are open for business and the number of employees that work in such buildings. In general, places of worship have the most limited hours. The average place of worship is open 32 hours per week. On the other extreme are healthcare facilities, which are open 168 hours a week (24 hours per day, 7 days per week). The average restaurant is open 86 hours per week. Hours vary considerably by building type. Some offices, labs, warehouses, restaurants, police stations, and hotels are also open 24 hours per day, 7 days per week, as reflected by the 90th percentiles. Table 19-22 also presents the number of employees typically employed in such buildings during the main shift. Overall, the average building houses 16 workers during its primary shift, but some facilities employ many more. The average hospital employs 471 workers during its main shift, although those in the 10th percentile employ only 175, and those in the 90th employ 2,250.

EPA used the 2012 CBECS, however, to update the information on the heating and cooling sources using the summary tables tabulated by the U.S. Energy Information Administration of the U.S. DOE and released to the public in 2016 (U.S. DOE, 2016). Tables 19-23 and 19-24 present these data. Table 19-23 indicates that electricity and natural gas are the heating sources used by a majority of nonresidential buildings. Of those buildings heated by fuel oil, most are older buildings.

Table 19-24 describes nonresidential building cooling characteristics. About 80% (i.e., 4,461/5,557 × 100) of nonresidential buildings have air conditioning, but this varies regionally from 14% in the Northeast to 40% in the South. Nationwide, 79% (i.e., 4,413/5,557 × 100) of nonresidential buildings use electricity for air conditioning. The remaining fraction use natural gas or chilled water.

It should be noted, however, that there are many critical exposure assessment elements not addressed by CBECS. These include a number of elements discussed in more detail in the Residential Building Characteristics Studies section (i.e., Section 19.3). Data to characterize the room volume, products and materials, and foundation type for nonresidential buildings were not available in CBECS.

Another characteristic of nonresidential buildings needed in ventilation and air exchange calculations is ceiling height. Unseen spaces (e.g. above ceiling tiles) complicate the volume and mixing assumptions by creating rather large separate compartments. In the residential section of this chapter, ceiling height was assumed to be 8 feet, a figure often assumed for residential buildings. For nonresidential buildings, EPA has assumed a 20-foot ceiling height for warehouses and enclosed shopping malls and a 12-foot average ceiling height for other structures. These assumptions are based on EPA's professional judgment. Murray (1997) found that the impact of assuming an 8-foot ceiling height for residences was insignificant, but nonresidential ceiling height varies more greatly and may or may not have a significant impact on calculations.

19.5. TRANSPORT RATE STUDIES

19.5.1. Air Exchange Rates

Air exchange is the balanced flow into and out of a building and is composed of three processes: (1) infiltration—air leakage through random cracks, interstices, and other unintentional openings in the building envelope; (2) natural ventilation—airflows through open windows, doors, and other designed openings in the building envelope; and (3) forced or mechanical ventilation—controlled air movement driven by fans (Breen et al., 2014).

For nearly all indoor exposure scenarios, air exchange is treated as the principal means of diluting indoor concentrations. The air exchange rate is generally expressed in terms of ACH (with units of hours^{-1}). It is defined as the ratio of the airflow ($\text{m}^3\ \text{hours}^{-1}$) to the volume ($\text{m}^3$). Thus, ACH and building size and volume are negatively correlated. Air exchange rates can affect the dynamic and the steady state behavior of indoor air pollutants (Breen et al., 2014).

Air exchange rates are influenced by many factors including building characteristics, type of ventilation system affecting air flow patterns (includes natural and mechanical), temperature differentials between rooms and floors and between indoors and outdoors, seasonality, occupant behavior (e.g., walking from room to room, opening of windows) and measurement techniques (Lee et al., 2016; Wu and Lin, 2015; Breen et al., 2014). Higher air exchange rates have been observed in the summer and during occupied daytime periods (Bekö et al., 2016; Lee et al., 2016; Wu and Lin, 2015; Breen et al., 2014; Kearney et al 2014; Zhao and Zeng, 2009).

The primary method for measuring air exchange rates in a building consist of releasing a nonreactive gas tracer into the building and allowing it to mix with the indoor air. The tracer gas can be injected into the building using an emitter device (e.g., SF_6) or released from the exhaled breath of building occupants in the form of CO_2. These tracer concentrations are monitored to estimate the air exchange rates. The gas tracer methods are based on a mass balance approach assuming that the gas tracer is well mixed, the tracer concentration outdoor is zero, and accounting for air leakage (Breen et al., 2014).

No measurement surveys have been conducted to directly evaluate the range and distribution of building air exchange rates. In addition, there is almost no information on the use of natural ventilation (e.g., how much or often windows are kept open). Although a significant number of air exchange measurements have been carried out over the years, there has been a diversity of protocols and study objectives. Since the early 1980s, however, an inexpensive PFT technique has been used to measure time-averaged air exchange and interzonal airflows in thousands of occupied residences using essentially similar protocols (Dietz et al., 1986). The PFT technique utilizes miniature permeation tubes as tracer emitters and passive samplers to collect the tracers. Sampling periods (e.g., days, weeks, months) vary depending on the study design. The passive samplers are returned to the laboratory for analysis by gas chromatography. These measurement results have been compiled to allow various researchers to access the data (Versar, 1989).

19.5.1.1. *Key Study of Residential Air Exchange Rates*

19.5.1.1.1. Koontz and Rector (1995)—Estimation of distributions for residential air exchange rates

In analyzing the composite data from various projects (2,971 measurements), Koontz and Rector (1995) assigned weights to the results from each state to compensate for the geographic imbalance in locations where PFT measurements were taken. The results were weighted in such a way that the resultant number of cases would represent each state in proportion to its share of occupied housing units, as determined from the 1990 U.S. Census of Population and Housing.

Table 19-25 shows summary statistics from the Koontz and Rector (1995) analysis, for the country as a whole and by census regions. Based on the statistics for all regions combined, the authors suggested that a 10th percentile value of 0.18 ACH would be appropriate as a conservative estimator for air exchange in residential settings, and that the 50th percentile value of 0.45 ACH would be appropriate as a typical air exchange rate. In applying conservative or typical values of air exchange rates, it is important to realize the limitations of the underlying database. Although the estimates are based on thousands of measurements, the residences represented in the database are not a random sample of the U.S. housing stock. Also, the sample population is not balanced in terms of geography or time of year, although statistical techniques were applied to compensate for some of these imbalances. In addition, PFT measurements of air exchange rates assume uniform mixing of the tracer within the building. This is not always so easily achieved. Furthermore, the degree of mixing can vary from day to day and house to house because of the nature of the factors controlling mixing (e.g., convective air monitoring driven by weather, and type and operation of the heating system). The relative placement of the PFT source and the sampler can also cause variability and uncertainty. It should be noted that sampling is typically done in a single location in a house that may not represent the average from that house. In addition, very high and very low values of air exchange rates based on PFT measurements have greater uncertainties than those in the middle of the distribution. Despite such limitations, the estimates in Table 19-25 are believed to represent the best available information on the distribution of air exchange rates across U.S. residences throughout the year.

19.5.1.1.2. Persily et al. (2010)—Modeled infiltration rate distributions for U.S. housing

Persily et al. (2010) generated frequency distributions of residential infiltration rates using CONTAM, a multizone airflow model. A collection of 209 residences was selected to be representative of 80% of the U.S. housing stock. The residences were taken from a database resulting from two residential housing surveys: the U.S. Department of Energy Residential Energy Consumptions Survey (RECS) and the U.S. Census Bureau American Housing Survey (AHS). Together, these data sets included over 60,000 U.S. residences. The RECS 1997 was conducted between mid-April to the middle of June 1997 (U.S. DOE, 1997). The residences were grouped into four categories: detached, attached, manufactured homes, and apartments, and include key characteristics such as age, floor area, number of floors, foundation type, and garage. Representations of these residences were created in the airflow model CONTAM, and were used in this study to provide distributions for infiltration rates. The simulations were conducted for 19 cities representing U.S. climates and accounted for the impacts of ventilation system operation on infiltration rates.

Distributions of air change rates for various house categories are presented in Table 19-26. The 10th and 50th percentiles national average air change rate for single family homes were 0.16 and 0.44 ACH, respectively. For all house categories, the 50th percentile air change rate ranged from 0.09 to 0.58 ACH. In general, houses built after 1970 are tighter and show lower air exchange rates than those built before 1970.

The advantages of this study are that it is based on a relatively large number of homes and that the residences are representative of homes across the United States. However, the results of the study are based on modeling and the data used to generate the simulations were collected in 1997.

19.5.1.2. *Relevant Studies of Residential Air Exchange Rates*

19.5.1.2.1. Nazaroff et al. (1988)—Radon entry via potable water

Nazaroff et al. (1988) aggregated the data from two studies conducted earlier using tracer-gas decay.

At the time these studies were conducted, they were the largest U.S. studies to include air exchange measurements. The first (Grot and Clark, 1981) was conducted in 266 dwellings occupied by low-income families in 14 different cities. The geometric mean ± standard deviation for the air exchange measurements in these homes, with a median house age of 45 years, was 0.90 ± 2.13 ACH. The second study (Grimsrud et al., 1983) involved 312 newer residences, with a median age of less than 10 years. Most of the houses were located in Washington, California, Colorado, New York and Ontario, Canada. Based on measurements taken during the heating season, the geometric mean ± standard deviation for these homes was 0.53 ± 1.71 ACH. Based on an aggregation of the two distributions with proportional weighting by the respective number of houses studied, Nazaroff et al. (1988) developed an overall distribution with a geometric mean of 0.68 ACH and a geometric standard deviation of 2.01.

The limitation of this study is that houses did not represent all climatic regions of the United States and the number of houses included in the studies was small.

19.5.1.2.2. Versar (1989)—Database of PFT ventilation measurements

The residences included in the PFT database do not constitute a random sample across the United States. They represent a compilation of homes visited in the course of about 100 separate field-research projects by various organizations, some of which involved random sampling, and some of which involved judgmental or fortuitous sampling. Table 19-27 summarizes the larger projects in the PFT database, in terms of the number of measurements (samples), states where samples were taken, months when samples were taken, and summary statistics for their respective distributions of measured air exchange rates. For selected projects (Lawrence Berkeley Laboratory, Research Triangle Institute, Southern California—SOCAL), multiple measurements were taken for the same house, usually during different seasons. A large majority of the measurements are from the SOCAL project that was conducted in Southern California. The means of the respective studies generally range from 0.2 to 1.0 ACH, with the exception of two California projects—RTI2 and SOCAL2. Both projects involved measurements in Southern California during a time of year (July) when windows would likely be opened by many occupants.

The limitation of this study is that the PFT database did not base its measurements on a sample that was statistically representative of the national housing stock. PFT has been found to underpredict seasonal average air exchange by 15 to 35% (Sherman, 1989). Using PFT to determine air exchange can produce significant errors when conditions in the measurement scene greatly deviate from idealizations calling for constant, well-mixed conditions.

19.5.1.2.3. Murray and Burmaster (1995)—Residential air exchange rates in the United States: empirical and estimated parametric distributions by season and climatic region

Murray and Burmaster (1995) analyzed the PFT database using 2,844 measurements (essentially the same cases as analyzed by Koontz and Rector (1995), but without the compensating weights). These authors summarized distributions for subsets of the data defined by climate region and season. The months of December, January, and February were defined as winter; March, April, and May were defined as spring; and so on. Table 19-28 summarizes the results of Murray and Burmaster (1995) Neglecting the summer results in the colder regions, which have only a few observations, the results indicate that the highest air exchange rates occur in the warmest climate region during the summer. As noted earlier, many of the measurements in the warmer climate region were from field studies conducted in Southern California during a time of year (July) when windows would tend to be open in that area. Data for warmer climate region in particular should be used with caution because other areas within this region tend to have very hot summers, and residences use air conditioners, resulting in lower air exchange rates. The lowest rates generally occur in the colder regions during the fall.

19.5.1.2.4. Diamond et al. (1996)—Ventilation and infiltration in high-rise apartment buildings

Diamond et al. (1996) studied air flow in a 13-story apartment building and concluded that "the ventilation to the individual units varies considerably." With the ventilation system disabled, units at the lower level of the building had adequate ventilation only on days with high temperature differences, while units on higher floors had no ventilation at all. At times, units facing the windward side were over-ventilated. With the mechanical ventilation system operating, they found wide variation in the air flows to individual apartments. Diamond et al. (1996) also conducted a literature review and concluded there were little published data on air exchange in multifamily buildings, and that there was a general problem measuring, modeling, and designing ventilation systems for high-rise multifamily buildings. Air flow was dependent upon building type, occupants' behavior, unit location, and meteorological conditions.

19.5.1.2.5. Graham et al. (2004)—Contribution of vehicle emissions from an attached garage to residential indoor air pollution levels

There have been several studies of vehicle emission seepage into homes from attached garages, which examined a single home. Graham et al. (2004) conducted a study of vehicle emission seepage of 16 homes with attached garages. On average, 11% of total house leakage was attributed to the house/garage interface (equivalent to an opening of 124 cm^2), but this varied from 0.6 to 29.6%. The amount of in-house chemical concentrations attributed to vehicle emissions from the garage varied widely between homes from 9 to 85%. Greater leakage tended to occur in houses where the garage attached to the house on more than one side. The home's age was not an important factor. Whether the engine was warm or cold when it was started was important because cold-start emissions are dominated by the by-products of incomplete combustion. Cold-start tail pipe emissions were 32 times greater for carbon monoxide (CO), 10 times greater for nitrogen oxide ($NO_{x)}$), and 18 times greater for total hydrocarbon emissions than hot-start tailpipe emissions.

19.5.1.2.6. Price et al. (2006)—Indoor-outdoor air leakage of apartments and commercial buildings

Price et al. (2006) compiled air exchange rate data from 14 different studies on apartment buildings in the United States and Canada. The authors found that indoor-outdoor air exchange rates seem to be twice as high for apartments as for single-family houses. The observed apartment air exchange rates ranged from 0.5 to 2 ACH.

19.5.1.2.7. Breen et al. (2010)—Residential air exchange rates from questionnaires and meteorology: model evaluation in central North Carolina

Breen et al. (2010) conducted a study comparing air exchange rate predictions from two mechanistic models with measurements from 31 detached homes in central North Carolina. Air monitoring was performed for 7 consecutive days in each of four consecutive seasons from summer 2000 to spring 2001. The study included two cohorts. The Raleigh cohort consisted of low to moderate socioeconomic status neighborhoods and the Chapel Hill cohort include moderate socioeconomic status neighborhoods (Breen et al., 2010). Daily 24-hour air exchange rates were measured using the PFT method. Distributions of air exchange rate for each season and number of days that windows were opened are presented in Table 19-29. It is important to note that information about amount of time that windows were open during the day is lacking.

19.5.1.2.8. Yamamoto et al. (2010)—Residential air exchange rates in three U.S. metropolitan areas: results from the relationship among indoor, outdoor, and personal air study 1999—2001

Between 1999 and 2001, Yamamoto et al. (2010) conducted approximately 500 indoor-outdoor air exchange rate calculations based on residences in metropolitan Elizabeth, NJ; Houston, TX; and Los Angeles, CA. The median air exchange rate across these urban areas was 0.71 ACH; 0.87 in California, 0.88 in New Jersey, and 0.47 in Texas. In Texas, the measured air exchange rates were lower in the summer cooling season (median = 0.37 ACH) than in the winter heating season (median = 0.63 ACH), likely because of the reported use of room air conditioners. The measured air exchange rates in California were higher in summer (median = 1.13 ACH) than in winter (median = 0.61 ACH) because summers in Los Angeles County are less humid than New Jersey or Texas, and residents are more likely to utilize natural ventilation through open windows and screened doors. In New Jersey, air exchange rates in the heating and cooling seasons were similar.

19.5.1.3. *Key Study of Nonresidential Air Exchange Rates*

19.5.1.3.1. Turk et al. (1987)—Commercial building ventilation rates and particle concentrations

Few air exchange rates for commercial buildings are provided in the literature. Turk et al. (1987) conducted indoor air quality measurements, including air exchange rates, in 38 commercial buildings. The buildings ranged in age from 0.5 to 90 years old. One test was conducted in 36 buildings, and two tests were conducted in 2 buildings. Each building was monitored for 10 working days over a 2-week period yielding a minimum sampling time of 75 hours per building. Researchers found an average ventilation measurement of 1.5 ACH, which ranged from 0.3 to 4.1 ACH with a standard deviation of 0.87. Table 19-30 presents the results by building type.

19.5.1.3.2. Bennett et al. (2012)—Ventilation, temperature, and HVAC characteristics in small and medium commercial buildings in California

HVAC system characteristics and ventilation rates of commercial buildings in California were evaluated by Bennett et al. (2012). A total of 37 small and medium commercial buildings (SMCBs) were selected for study and were classified into small (24 buildings, 90–1,100 m^2), medium (7 buildings, 1,100–2,300 m^2), and medium/large (6 buildings, 2,300–4,600 m^2). The majority of the SMCBs were selected to be representative of retail establishments, offices and restaurants, the most frequent building types in California. Other building types, selected for their potential for indoor pollutant sources, included beauty salons, dental offices, gas stations and gyms. For each building, the heating, ventilating, and air conditioning (HVAC) systems were inspected and measurements of air exchange and indoor environmental quality parameters, such as CO_2 levels, temperature and relative humidity were taken. In addition, whole building ventilation rates were determined using a tracer decay method.

Ventilation measurements for the buildings are presented in Table 19-31. The mean air exchange rate was 1.6 ± 1.7 exchanges per hour, and was similar between buildings with or without outdoor air provided.

This study provides useful information on the HVAC system characteristics and ventilation rates of SMCBs. However, the sample size was relatively small and all of the SMCBs were located in California which may not be representative of SMCBs located in other areas of the United States.

19.5.2. Indoor Air Models

Achieving adequate indoor air quality in a nonresidential building can be challenging. There are many factors that affect indoor air quality in buildings (e.g., building materials, building configuration, outdoor environment, ventilation systems, operation and maintenance, occupants and their activities). Indoor air models are typically used to study, identify, and solve problems involving indoor air quality in buildings, as well as to assess efficiency of energy use. The emphasis of most models is on the physical processes, but for some chemical reactions indoor which may be an important, but variable sink. Models generally assume a known and constant rate of reaction.

Indoor air quality models generally are not software products that can be purchased as “off-the-shelf” items. Most existing software models are research tools that have been developed for specific purposes and are being continuously refined by researchers. Leading examples of indoor air models implemented as software products are as follows:

- CONTAM 3.2—CONTAM was developed at the National Institute of Standards and Technology (NIST) with support from EPA and the U.S. DOE. (Dols and Polidoro, 2016; Wang et al., 2010; Axley, 1988). CONTAM has been used by others to study the effects of model parameters (e.g., wind speed, presence of natural and mechanical ventilation) and the presence of an attached garage on the infiltration of contaminants indoors (Nirvan et al., 2012).
- IAQX—The Indoor Air Quality and Inhalation Exposure model is a Windows-based simulation software package developed by EPA (Guo, 2000).
- CPIEM 2.0—The California Population Indoor Exposure Model was developed for the California Air Resources Board (Rosenbaum et al., 2002).
- TEM—The Total Exposure Model was developed with support from EPA and the U.S. Air Force (Wilkes, 1998; Wilkes and Nuckols, 2000).
- RISK—RISK was developed by the Indoor Environment Management Branch of the EPA National Risk Management Research Laboratory (Sparks, 1997).
- TRIM—The Total Risk Integrated Methodology is an ongoing modeling project of EPA’s Office of Air Quality Planning and Standards (Efroymson and Murphy, 2001; Palma et al., 1999).
- TOXLT/TOXST—The Toxic Modeling System Long-Term was developed along with the release of the new version of the EPA’s Industrial Source Complex Dispersion Models (U.S. EPA, 1995).
- MIAQ—The Multi-Chamber Indoor Air Quality Model was developed for the California Institute of Technology and Lawrence Berkeley National Laboratory. Documentation last updated in 2002. (Nazaroff and Cass, 1986; Nazzaroff and Cass, 1989a).
- MCCEM 1.2—the Multi-Chamber Consumer Exposure Model was developed for EPA Office of Pollution Prevention and Toxics (EPA/OPPT) (GEOMET, 1989; Koontz and Nagda, 1991).
- ART—Advanced Regulation, Evaluation, Authorization and restriction of Chemicals

(REACH) Tool was designed to model inhalation exposures in the occupational setting for a defined group of workers sharing specific operational conditions (Tielemans et al., 2011, 2008; Cherrie et al., 2011)

Price (2001) evaluated the use of many of the above products (TOXLT/TOXST, MCCEM, IAQX, CONTAM, CPIEM, TEM, TRIM, and RISK) in a tiered approach to assessing exposures and risks to children. The information provided is also applicable to adults.

19.5.3. Air Infiltration Models

A variety of mathematical models exist for prediction of air infiltration rates in individual buildings. A number of these models have been reviewed, for example, by Breen et al., (2014), Liddament and Allen (1983), and by Persily and Linteris (1984). Basic principles are concisely summarized in the ASHRAE Handbook of Fundamentals (ASHRAE, 2013). These models have a similar theoretical basis; all address indoor-outdoor pressure differences that are maintained by the actions of wind and stack (temperature difference) effects. The models generally incorporate a network of airflows where nodes representing regions of different pressure are interconnected by leakage paths. Individual models differ in details such as the number of nodes they can treat or the specifics of leakage paths (e.g., individual components such as cracks around doors or windows versus a combination of components such as an entire section of a building). Such models are not easily applied by exposure assessors, however, because the required inputs (e.g., inferred leakage areas, crack lengths) for the model are not easy to gather.

Another approach for estimating air infiltration rates is developing empirical models. Such models generally rely on the collection of infiltration measurements in a specific building under a variety of weather conditions. The relationship between the infiltration rate and weather conditions can then be estimated through regression analysis and is usually stated in the following form:

$$A = a + b\left|T_i - T_0\right| + cU^n \qquad \text{(Eqn. 19-1)}$$

where:

A = air exchange rate (hours^{-1}),
T_i = indoor temperature (°C),
T_o = outdoor temperature (°C),
U = windspeed (m/second),
n is an exponent with a value typically between 1 and 2, and
a, b and c are parameters to be estimated.

Relatively good predictive accuracy usually can be obtained for individual buildings through this approach. However, exposure assessors often do not have the information resources required to develop parameter estimates for making such predictions.

A reasonable compromise between the theoretical and empirical approaches has been developed in the model specified by Dietz et al. (1986). The model, drawn from correlation analysis of environmental measurements and air infiltration data, is formulated as follows:

$$A = L\left(0.006\Delta T \frac{0.03}{C} U^{1.5}\right) \qquad \text{(Eqn. 19-2)}$$

where:

A = average ACH or infiltration rate, hours^{-1},
L = generalized house leakiness factor ($1 < L < 5$),
C = terrain sheltering factor ($1 < C < 10$),
ΔT = indoor-outdoor temperature difference (°C), and
U = windspeed (m/second).

The value of L is greater as house leakiness increases, and the value of C is greater as terrain sheltering (reflects shielding of nearby wind barrier) increases. Although the above model has not been extensively validated, it has intuitive appeal, and it is possible for the user to develop reasonable estimates for L and C with limited guidance. Historical data from various U.S. airports are available for estimation of the temperature and windspeed parameters. As an example application, consider a house that has central values of 3 and 5 for L and C, respectively. Under conditions where the indoor temperature is 20°C (68°F), the outdoor temperature is 0°C (32°F), and the windspeed is 5 m/second, the predicted infiltration rate for that house would be

3 (0.006 × 20 + 0.03/5 × 51.5), or 0.56 ACH. This prediction applies under the condition that exterior doors and windows are closed and does not include the contributions, if any, from mechanical systems (see Section 19.3.3.3). Occupant behavior, such as opening windows, can, of course, overwhelm the idealized effects of temperature and wind speed.

Chan et al. (2005) analyzed the U.S. Residential Air Leakage database at Lawrence Berkley National Laboratory (LBNL) containing approximately 70,000 air leakage measurements from 30 states (predominantly Ohio, Alaska, and Wisconsin). They present the following equation for estimating ACH:

$$ACH = 48\left(\frac{2.5}{H}\right)^{0.3} \frac{NL}{HF}\left[h^{-1}\right] \qquad \text{(Eqn. 19-3)}$$

where:

ACH = air changes per hour,
H = building height (meters),
NL = normalized leakage (unitless),
F = scaling factor (unitless), and
h = hours.

Chan et al. (2005) found that “older and smaller homes are more likely to have higher normalized leakage areas than newer and larger ones.” Table 19-32 summarizes the normalized leakage distributions in the United States.

It should be noted that newer homes were generally built tighter until about 1997 when the construction trend leveled off. Sherman and Matson (2002) also examined LBNL’s U.S. Residential Air Leakage database and found that average normalized leakage for 22,000 houses already in the database was 1.18 *NL* (total leakage cm^2 normalized for dwelling size m^2), but leakage among the 8,300 newer homes averaged 0.30 *NL*.

19.5.4. Vapor Intrusion

Vapor intrusion is the process by which contaminants present in the subsurface (both soil and groundwater) migrate through the soil via diffusion and advection and can enter building structures through the foundation cracks (U.S. EPA 2015, 2012; Murphy and Chan, 2011; Yao et al., 2011). In 1998, concerns about subsurface contamination of soil or ground water impacting indoor air quality led the EPA to develop a series of models for estimating health risks from subsurface vapor intrusion into buildings based on the analytical solutions of Johnson and Ettinger (1991). Models describing the vapor entry into buildings generally consist of two main parts. One part describes the vapor transport in the soil and the other its entry into the building (Yao and Suuberg, 2013). Models can vary from simple 1-dimentional screening tools to more complex 3-dimentional models requiring numerical solutions (Yao and Suuberg, 2013). Since 1991, the models have been revised, and new models have been added. The 3-phase soil contamination models theoretically partition the contamination into three discrete phases: (1) in solution with water, (2) sorbed to the soil organic carbon, and (3) in vapor phase within the air-filled pores of the soil. Two new models have been added, allowing the user to estimate vapor intrusion into buildings from measured soil gas data (U.S. EPA 2000a). When Non-Aqueous Phase Liquid (NAPL) is present in soils, the contamination includes a fourth or residual phase. In such cases, the new NAPL models can be used to estimate the rate of vapor intrusion into buildings and the associated health risks. The new NAPL models use a numerical approach for simultaneously solving the time-averaged soil and building vapor concentration for each of up to 10 soil contaminants (U.S. EPA 2000a). This involves a series of iterative calculations for each contaminant. A spreadsheet with these models is available online from EPA at https://www.epa.gov/vaporintrusion/epa-spreadsheet-modeling-subsurface-vapor-intrusion. Technical information and resources pertaining to vapor intrusion can be found in https://www.epa.gov/vaporintrusion/vapor-intrusion-resources.

Although mathematical models such as the Johnson and Ettinger (1991) have been widely used, vapor intrusion modeling has been the focus of more recent studies (Yao and Suuberg, 2013). Other analytical approximations have been applied to estimate contaminant subslab concentrations and study the effects of foundation features and source location on vapor intrusion (Yao et al., 2012, Yao et al., 2011). Other researchers have developed a systematic approach to model steady state advective and diffusive fluxes between multimedia compartments including ground water, soil, and air with applications to vapor intrusion calculations (Murphy and Chan, 2011). They determined that the presence of a basement significantly reduces first floor exposures. In addition, they concluded that the resistance associated with diffusion in ground water and water table fluctuations cannot be neglected (Murphy and Chan, 2011.) In addition to foundation characteristics, Yao and Suuberg (2013) observed that biodegradation plays a significant role in subslab concentration attenuation. However, other processes, like reaction mechanisms and kinetics, are not well understood. The lack of formal vapor intrusion model validation continues to be a challenge (Yao and Suuberg, 2013).

19.5.5. Deposition and Filtration

Deposition refers to the removal of airborne substances to available surfaces that occurs as a result of gravitational settling and diffusion, as well as electrophoresis and thermophoresis. Filtration is driven by similar processes, but is confined to material through which air passes. Filtration is usually a matter of design, whereas deposition is a matter of fact.

Outdoor particles can penetrate (infiltrate) building structures and become a source of indoor particle exposure (Gao and Zhang et al., 2009). Infiltration factors are affected by numerous elements including: air exchange rates, forced air heating, exhaust fan operation, air conditioning use, the use of filtration devices, meteorological parameters such as wind speed, indoor-outdoor temperature differentials, particle size, and composition of particulate matter (e.g., volatile chemicals) (Kearney et al., 2014). Air exchange rates can have a significant effect on particle number concentrations indoor under stable outdoor particle number concentrations. Generally, a higher ACH results in lower particulate number concentrations indoors (Guo et al., 2008). Models have been developed that help predict indoor concentrations of outdoor particles in residences (El Orch et al., 2014).

Semivolatile organic compounds (SVOC) are also present in indoor air environments. Sources of these compounds include for example: indoor materials, consumer products (e.g., personal care products, household cleaning products), combustion products, environmental tobacco smoke, and intrusion from outdoor air (Singer et al., 2003; Weschler and Nazaroff 2008). The formation of organic films on indoor surfaces have been confirmed by both direct and indirect measurements (Weschler and Nazaroff, 2017). Weschler and Nazaroff (2017) developed a simple model of organic film growth to improve estimates of human exposure to SVOCs.

Gases can also penetrate the building envelope from attached garages. In addition to automobile exhaust, people often store gasoline, oil, paints, lacquers, and yard and garden supplies in garages. Appliances such as furnaces, heaters, hot water heaters, dryers, gasoline-powered appliances, and wood stoves may also impact indoor air quality. Garages can be a source of volatile organic compounds (VOCs) such as benzene, toluene, ethylbenzene, *m*,*p*-xylene, and *o*-xylene. Emmerich et al. (2003) conducted a literature review on indoor air quality and the transport of pollutants from attached garages to residential living spaces. The authors found the body of literature on the subject was limited and contained little data with regard to airtightness and geometry of the house-garage interface, and the impact of heating and cooling equipment. They concluded, however, that there is substantial evidence that the transport of contaminants from garages has the potential to negatively impact residences.

19.5.5.1. *Deposition*

The deposition of particulate matter and reactive gas-phase pollutants to indoor surfaces is often stated in terms of a characteristic deposition velocity (m hour^{-1}) allied to the surface-to-volume ratio ($m^2\ m^{-3}$) of the building or room interior, forming a first order loss rate (hour^{-1}). Theoretical considerations specific to indoor environments have been summarized in comprehensive reviews by Nazaroff and Cass (1989b) and Nazaroff et al. (1993).

For airborne particles, deposition rates depend on aerosol properties (size, shape, density) as well as room factors (thermal gradients, turbulence, surface geometry). The motions of larger particles are dominated by gravitational settling; the motions of smaller particles are subject to convection and diffusion. Consequently, larger particles tend to accumulate more rapidly on floors and up-facing surfaces while smaller particles may accumulate on surfaces facing in any direction. Figure 19-3 illustrates the general trend for particle deposition across the size range of general concern for inhalation exposure (<10 μm). Nano-particles have been demonstrated to have higher deposition rates and lower penetration efficiencies (Guo et al., 2008). Penetration refers to the infiltration of particles in the air that passes through the building shell (Chen and Zhao, 2011) (See also Section 19.5.7). The current thought is that theoretical calculations of deposition rates are likely to provide unsatisfactory results due to knowledge gaps relating to near-surface air motions and other sources of inhomogeneity (Nazaroff et al., 1993).

19.5.5.1.1. Thatcher and Layton (1995)—Deposition, resuspension, and penetration of particles within a residence

Thatcher and Layton (1995) evaluated removal rates for indoor particles in four size ranges (1−5, 5—10, 10−25, and >25 μm) in a study of one house occupied by a family of four. Table 19-33 lists these values. In a subsequent evaluation of data collected in

100 Dutch residences, Layton and Thatcher (1995) estimated settling velocities of 2.7 m $hour^{-1}$ for lead-bearing particles captured in total suspended particulate matter samples.

19.5.5.1.2. Wallace (1996)—Indoor particles: a review

In a major review of indoor particles, Wallace (1996) cited overall particle deposition per hour ($hour^{-1}$) for respirable ($PM_{2.5}$), inhalable (PM_{10}), and coarse (difference between PM_{10} and $PM_{2.5}$) size fractions determined from EPA's Particle Total Exposure Assessment Methodological Study (PTEAM) study. These values, listed in Table 19-34, were derived from measurements conducted in nearly 200 residences.

19.5.5.1.3. Thatcher et al. (2002)—Effects of room furnishings and air speed on particle deposition rates indoors

Thatcher et al. (2002) measured deposition loss rate coefficients for particles of different median diameters (0.55 to 8.66 mm) with fans off and on at various airspeeds in three types of experimental rooms: (1) bare (unfurnished with metal floor), (2) carpeted and unfurnished, and (3) fully furnished. Table 19-35 summarizes the results.

19.5.5.1.4. He et al. (2005)—Particle deposition rates in residential houses

He et al. (2005) investigated particle deposition rates for particles ranging in size from 0.015 to 6 µm. The lowest deposition rates were found for particles between 0.2 and 0.3 µm for both minimum (air exchange rate: 0.61 ± 0.45 $hour^{-1}$) and normal (air exchange rate: 3.00 ± 1.23 $hour^{-1}$) conditions. Thus, air exchange rate was an important factor affecting deposition rates for particles between 0.08 and 1.0 µm, but not for particles smaller than 0.08 µm or larger than 1.0 µm.

19.5.5.2. *Filtration*

A variety of air cleaning techniques have been applied to residential settings. EPA (2009) summarizes available information on residential air cleaners. Basic principles related to residential-scale air cleaning technologies have also been summarized in conjunction with reporting early test results (Offerman et al., 1984). General engineering principles are summarized in ASHRAE (2016). In addition to fibrous filters integrated into central heating and air conditioning systems, extended surface filters and High Efficiency Particle Arrest filters, as well as electrostatic systems, are available to increase removal efficiency. Free-standing air cleaners (portable and/or console) are also being used. Shaughnessy and Sextro (2007) discuss the testing process to evaluate the efficacy of portable air cleaners. Product-by-product test results reported by Hanley et al. (1994); Shaughnessy et al. (1994); and Offerman et al. (1984) exhibit considerable variability across systems, ranging from ineffectual (<1% efficiency) to nearly complete removal.

19.5.6. Interzonal Airflows

Exposure assessments for indoor air pollutants generally assume a well-mixed environment. However, pollutant concentrations vary with distance from the source, ventilation rate, and relative height of the source (Acevedo-Bolton et al., 2012).

Residential structures consist of a number of rooms that may be connected horizontally, vertically, or both horizontally and vertically. Before considering residential structures as a detailed network of rooms, it is convenient to divide them into one or more zones. At a minimum, each floor is typically defined as a separate zone. For indoor air exposure assessments, further divisions are sometimes made within a floor, depending on (1) locations of specific contaminant sources and (2) the presumed degree of air communication among areas with and without sources.

Defining the airflow balance for a multiple-zone exposure scenario rapidly increases the information requirements as rooms or zones are added. As shown in Figure 19-4, a single-zone system (considering the entire building as a single well-mixed volume) requires only two airflows to define air exchange. Further, because air exchange is balanced flow (air does not "pile up" in the building, nor is a vacuum formed), only one number (the air exchange rate) is needed. With two zones, 6 airflows are needed to accommodate interzonal airflows plus air exchange; with three zones, 12 airflows are required. In some cases, the complexity can be reduced using judicious (if not convenient) assumptions. Interzonal airflows connecting nonadjacent rooms can be set to zero, for example, if flow pathways do not exist. Symmetry also can be applied to the system by assuming that each flow pair is balanced.

Axley (2007) discusses the history and theory of multizonal airflow models. Examples of interzonal airflow models include CONTAM (developed by NIST) and COMIS (Haas et al., 2002; Feustel, 1999; Feustel and Raynor-Hoosen, 1990).

19.5.7. House Dust and Soil Loadings

House dust is a complex mixture of biologically derived material (animal dander, fungal spores, etc.), particulate matter deposited from the indoor aerosol, and soil particles brought in by foot traffic. House dust may contain VOCs (Wolkoff and Wilkins, 1994; Hirvonen et al., 1995), pesticides from imported soil particles as well as from direct applications indoors (Roberts et al., 1991), and trace metals derived from outdoor sources (Layton and Thatcher, 1995). The indoor abundance of house dust depends on the interplay of deposition from the airborne state, resuspension due to various activities, direct accumulation, and infiltration.

In the absence of indoor sources, indoor concentrations of particulate matter are significantly lower than outdoor levels. For some time, this observation supported the idea that a significant fraction of the outdoor aerosol is filtered out by the building envelope. The ratios of indoor to outdoor particle concentrations vary depending on factors such as: the difference in size-dependent indoor particle emission rates, the geometry of the cracks in building envelopes, and the air exchange rates (Chen and Zhao, 2011).

It should be noted that carpet dust loadings may be higher than previously believed. This is important because embedded dust is a reservoir for organic compounds. Fortune et al. (2000) compared the mass of dust in carpets removed using conventional vacuuming to that removed by vacuuming with a beater-bar to remove deeply embedded dust. The amount removed was 10 times that removed by conventional vacuuming.

19.5.7.1. *Roberts et al. (1991)—Development and Field Testing of a High-Volume Sampler for Pesticides and Toxics in Dust*

Dust loadings, reported by Roberts et al. (1991), were measured in conjunction with the Nonoccupational Pesticide Exposure Study (NOPES). In this study, house dust was sampled from a representative grid using a specially constructed high-volume surface sampler. The surface sampler collection efficiency was verified in conformance with ASTM F608 (ASTM, 1989). Table 19-36 summarizes data collected from carpeted areas in volunteer households in Florida encountered during the course of NOPES. Seven of the nine sites were single-family detached homes, and two were mobile homes. The authors noted that the two houses exhibiting the highest dust loadings were only those homes where a vacuum cleaner was not used for housekeeping.

19.5.7.2. *Thatcher and Layton (1995)—Deposition, Resuspension, and Penetration of Particles within a Residence*

Relatively few studies have been conducted at the level of detail needed to clarify the dynamics of indoor aerosols. One intensive study of a California residence (Thatcher and Layton, 1995), however, provides instructive results. Using a model-based analysis for data collected under controlled circumstances, the investigators verified penetration of the outdoor aerosol and estimated rates for particle deposition and resuspension (see Table 19-37). The investigators stressed that normal household activities are a significant source of airborne particles larger than 5 μm. During the study, they observed that just walking into and out of a room could momentarily double the concentration. The airborne abundance of submicrometer particles, on the other hand, was unaffected by either cleaning or walking. They also concluded that large particles (over 25 μm) settle eight times faster than small particles (1−5 μm).

Mass loading of floor surfaces (see Table 19-38) was measured in the study of Thatcher and Layton (1995) by thoroughly cleaning the house and sampling accumulated dust, after 1 week of normal habitation and no vacuuming. The methodology, validated under ASTM F608 (ASTM, 1989), showed fine dust recovery efficiencies of 50% with new carpet and 72% for linoleum. Tracked areas showed consistently higher accumulations than untracked areas, confirming the importance of tracked-in material. Differences between tracked areas upstairs and downstairs show that tracked-in material is not readily transported upstairs. The consistency of untracked carpeted areas throughout the house, suggests that, in the absence of tracking, particle transport processes are similar on both floors.

19.6. CHARACTERIZING INDOOR SOURCES

Product- and chemical-specific mechanisms for indoor sources can be described using simple emission factors to represent instantaneous releases, as well as constant releases over defined time periods; more complex formulations may be required for time-varying sources. Guidance documents for characterizing indoor sources within the context of the exposure assessment process are limited (see, for example, Jennings et al., 1987b; Wolkoff, 1995). Fairly extensive guidance exists in the technical literature, however, provided that the exposure assessor has the means to define (or estimate) key mechanisms and chemical-specific parameters. Basic concepts are summarized below for the broad source categories that relate to airborne contaminants, waterborne contaminants, and for soil/house dust indoor sources.

19.6.1. Source Descriptions for Airborne Contaminants

Table 19-39 summarizes simplified indoor source descriptions for airborne chemicals for direct emission sources (e.g., combustion, pressurized propellant products), as well as emanation sources (e.g., evaporation from “wet” films, diffusion from porous media), and transport-related sources (e.g., infiltration of outdoor air contaminants, soil gas entry).

Direct-emission sources can be approximated using simple formulas that relate pollutant mass released to characteristic process rates. Combustion sources, for example, may be stated in terms of an emission factor, fuel content (or heating value), and fuel consumption (or carrier delivery) rate. Emission factors for combustion products of general concern (e.g., CO, NO_x) have been measured for a number of combustion appliances using room-sized chambers (see, for example, Relwani et al., 1986). Other direct-emission sources would include volatiles released from water use and from pressurized consumer products. Resuspension of house dust (see Section 19.5.5.1) would take on a similar form by combining an activity-specific rate constant with an applicable dust mass.

Diffusion-limited sources (e.g., carpet backing, furniture, flooring, dried paint) represent probably the greatest challenge in source characterization for indoor air quality. Vapor-phase organics dominate this group, offering great complexity because (1) there is a fairly long list of chemicals that could be of concern, (2) ubiquitous consumer products, building materials, coatings, and furnishings contain varying amounts of different chemicals, (3) source dynamics may include nonlinear mechanisms, and (4) for many of the chemicals, emitting as well as nonemitting materials evident in realistic settings may promote reversible and irreversible sink effects. Very detailed descriptions for diffusion-limited sources can be constructed to link specific properties of the chemical, the source material, and the receiving environment to calculate expected behavior (see, for example, Schwope et al., 1992; Cussler, 1984). Validation to actual circumstances, however, suffers practical shortfalls because many parameters simply cannot be measured directly.

The exponential formulation listed in Table 19-39 was derived based on a series of papers generated during the development of chamber testing methodology by EPA (Dunn, 1987; Dunn and Tichenor, 1988; Dunn and Chen, 1993). This framework represents an empirical alternative that works best when the results of chamber tests are available. Estimates for the initial emission rate (E_o) and decay factor (k_s) can be developed for hypothetical sources from information on pollutant mass available for release (M) and supporting assumptions.

Assuming that a critical time period (t_c) coincides with reduction of the emission rate to a critical level (E_c) or with the release of a critical fraction of the total mass (M_c), the decay factor can be estimated by solving either of these relationships:

$$\frac{E_c}{E_0} = e^{-k_s t_c} \qquad \text{(Eqn. 19-4)}$$

where:

E_c = emission rate to a critical level (µg hour^{-1}),
E_0 = initial emission rate (µg hour^{-1}),
k_s = decay factor (µg hour^{-1}), and
t_c = critical time period (hours),

or

$$\frac{M_c}{M} = 1 - e^{-k_s t_c} \qquad \text{(Eqn. 19-5)}$$

where:

M_c = critical mass (µg), and
M = total mass (µg).

The critical time period can be derived from product-specific considerations (e.g., equating drying time for paint to 90% emissions reduction). Given such an estimate for k_s, the initial emission rate can be estimated by integrating the emission formula to infinite time under the assumption that all chemical mass is released:

$$M = \int_0^\infty E_0\, e - k_s t\, dt = \frac{E_0}{k_s} \qquad \text{(Eqn. 19-6)}$$

The basis for the exponential source algorithm has also been extended to the description of more complex diffusion-limited sources. With these sources, diffusive or evaporative transport at the interface may be much more rapid than diffusive transport from within the source material, so that the abundance at the source/air interface becomes depleted, limiting the transfer rate to the air. Such effects can prevail with skin formation in "wet" sources like stains and paints (see, for example, Chang and Guo, 1992). Similar emission profiles have been observed with the emanation of formaldehyde from particleboard with "rapid" decline as formaldehyde evaporates from surface sites of the particleboard over the first few weeks. It is then followed by a much slower decline over ensuing years as formaldehyde diffuses from within the matrix to reach the surface (see, for example, Zinn et al., 1990).

Transport-based sources bring contaminated air from other areas into the airspace of concern. Examples include infiltration of outdoor contaminants, and soil gas entry. Soil gas entry is a particularly complex phenomenon and is frequently treated as a separate modeling issue (Provoost et al., 2010; Little et al., 1992; Sextro, 1994). Room-to-room migration of indoor contaminants would also fall under this category, but this concept is best considered using multizone models.

19.6.2. Source Descriptions for Waterborne Contaminants

Residential water supplies may be a route for exposure to chemicals through ingestion, dermal contact, or inhalation. These chemicals may appear in the form of contaminants (e.g., trichloroethylene) as well as naturally occurring by-products of water system history (e.g., chloroform, radon). Among indoor water uses, showering, bathing, and hand-washing of dishes or clothes provide the primary opportunities for dermal exposure. The escape of volatile chemicals to the gas phase associates water use with inhalation exposure. The exposure potential for a given chemical will depend on the source of water, the types and extents of water uses, and the extent of volatilization of specific chemicals. Primary types of residential water use include showering/bathing, toilet use, clothes washing, dishwashing, and faucet use (e.g., for drinking, cooking, general cleaning, or washing hands). Information about household water use has been investigated by the Water Research Foundation and published in the Residential End Use of Water (REU) (DeOreo et al., 2016). The survey collected data from 2010 through 2013 from randomly selected single-family houses in the United States and Canada. The average per capita indoor water use was 58.6 gal/day. Figure 19-5 shows the relative percentage of indoor per capita water use across all uses. Toilet flushing was the largest indoor water use in gallons per capita per day (14.2 gpcd, 24%). Other relevant information on activity patterns (e.g., time showering, time indoors, etc.) can be bound in Chapter 16 of the *Exposure Factors Handbook* (U.S. EPA 2011).

Upper-bounding estimates of chemical release rates from water use can be formulated as simple emission factors by combining the concentration in the feed water (g m^{-3}) with the flow rate for the water use (m^3 hour^{-1}), and assuming that the chemical escapes to the gas phase. For some chemicals, however, not all of the chemical escapes in realistic situations due to diffusion-limited transport and solubility factors. For inhalation exposure estimates, this may not pose a problem because the bounding estimate would overestimate emissions by no more than approximately a factor of two. For multiple exposure pathways, the chemical mass remaining in the water may be of importance. Refined estimates of volatile emissions are usually considered under two-resistance theory to accommodate mass transport aspects of the water-air system (see, for example, U.S. EPA, 2000b; Howard-Reed et al., 1999; Moya et al., 1999; Little, 1992; Andelman, 1990; McKone, 1987). More detailed descriptions of models used to estimate emissions from indoor water sources including showers, bathtubs, dishwashers, and washing machines are included in EPA, (2000b). Release rates (*S*) are formulated as

$$S = K_m F_w \left[C_w - \frac{C_a}{H} \right] \qquad \text{(Eqn. 19-7)}$$

where:

S = chemical release rate (g hour^{-1}),
K_m = dimensionless mass-transfer coefficient,
F_w = water flow rate (m^3 hour^{-1}),
C_w = concentration in feed water (g m^{-3}),
C_a = concentration in air (g m^{-3}), and
H = dimensionless Henry's Law constant.

Because the emission rate is dependent on the air concentration, recursive techniques are required. The mass-transfer coefficient is a function of water use characteristics (e.g., water droplet size spectrum, fall distance, water film) and chemical properties (diffusion in gas and liquid phases). Estimates of practical value are based on empirical tests to incorporate system characteristics into a single parameter (see, for example, Giardino et al., 1990). Once characteristics of one chemical-water use system are known (reference chemical, subscript *r*), the mass-transfer coefficient for another chemical (index chemical, subscript *i*) delivered by the same system can be estimated using formulations identified in the review by Little (1992):

$$\frac{1}{K}\left(\frac{D_{Li}}{D_{Lr}}\right)^{1/2} = \frac{1}{K_{Lr}} = \frac{1}{K_{Gr}} - \frac{1}{H}\left(\frac{D_{Gr}}{D_{Gi}}\right)^{2/3}\left(\frac{D_{Li}}{D_{Lr}}\right)^{1/2} \qquad \text{(Eqn. 19-8)}$$

where:

D_L = liquid diffusivity (m^2 $second^{-1}$),
DG = gas diffusivity (m^2 $second^{-1}$),
KL = liquid-phase mass-transfer coefficient,
KG = gas-phase mass transfer coefficient, and
H = dimensionless Henry's Law constant.

19.6.3. Soil and House Dust Sources

The rate process descriptions compiled for soil and house dust provide inputs for estimating indoor emission rates:

$$S_d = M_d R_d A_f \qquad \text{(Eqn. 19-9)}$$

where:

S_d = dust emission (g $hour^{-1}$),
M_d = dust mass loading (g m^{-2}),
R_d = resuspension rates ($hour^{-1}$), and
A_f = floor area (m^2).

Because house dust is a complex mixture, transfer of particle-bound constituents to the gas phase may be of concern for some exposure assessments. For emission estimates, one would then need to consider particle mass residing in each reservoir (dust deposit, airborne).

19.7. ADVANCED CONCEPTS

19.7.1. Uniform Mixing Assumption

Many exposure measurements are predicated on the assumption of uniform mixing within a room or zone of a house. Mage and Ott (1994) offer an extensive review of the history of use and misuse of the concept. Experimental work by Baughman et al. (1994) and Drescher et al. (1995) indicates that, for an instantaneous release from a point source in a room, fairly complete mixing is achieved within 10 minutes when convective flow is induced by solar radiation. Another study by Gadgil et al. (2003) showed that mixing time depended on the room airflow the source location. However, up to 100 minutes may be required for complete mixing under quiescent (nearly isothermal) conditions. While these experiments were conducted at extremely low air exchange rates (<0.1 ACH), based on the results, attention is focused on mixing within a room.

The situation changes if a human invokes a point source for a longer period and remains in the immediate vicinity of that source. Personal exposure in the near vicinity of a source can be much higher than the well-mixed assumption would suggest. A series of experiments conducted by GEOMET (1989) for the EPA involved controlled point-source releases of carbon monoxide tracer (CO), each for 30 minutes. Breathing-zone measurements located within 0.4 m of the release point were 10 times higher than for other locations in the room during early stages of mixing and transport.

Similar investigations by Acevedo-Bolton et al. (2012) studied the proximity of source effects in two naturally ventilated homes in Northern California. They found high variability of CO concentrations measured within 1 m from the source with 5 minute averages varying more than 100 fold. Other research conducted by Furtaw et al. (1996) involved a series of experiments in a controlled-environment, room-sized chamber. Furtaw et al. (1996) studied spatial concentration gradients around a continuous point source simulated by sulfur hexafluoride (SF_6) tracer with a human moving about the room. Average breathing-zone concentrations when the subject was near the source exceeded those several meters away by a factor that varied inversely with the ventilation intensity in the room. At typical room ventilation rates, the ratio of source-proximate to slightly-removed concentration was on the order of 2:1.

19.7.2. Reversible Sinks

The sorption of SVOCs onto indoor surfaces are referred to as the "sink effect." Different building materials sorb different compounds based on polarity, indoor humidity, and temperature (Won et al., 2001). Surface roughness also plays a role in the absorption of chemicals onto surfaces (Wu et al., 2017). The subsequent re-emission of these compounds into indoor air is referred to as a "reversible sink." The reversible sink effect can significantly affect the fate and transport of indoor SVOCs (Wu et al., 2017). For some chemicals, the actions of reversible sinks are of concern. For an initially "clean" condition in the sink material, sorption effects can greatly deplete indoor concentrations. However, once enough of the chemical has been adsorbed, the diffusion gradient will reverse, allowing the chemical to escape. For persistent indoor sources, such effects can serve to reduce indoor levels initially, but once the system equilibrates, the net effect on the average concentration of the reversible sink is negligible. Over suitably short time frames, this can also affect integrated exposure. For indoor sources whose emission profile declines with time (or ends abruptly), reversible sinks can serve to extend the emissions period as the chemical desorbs long after direct emissions are finished. Reversible sink effects have been observed for a number of chemicals in the presence of carpeting, wall coverings, and other materials commonly found in residential environments. As an example, in the case of environmental tobacco smoke, clothing and human skin have been found to serve as a reversible sink. The lingering residues of tobacco products are referred to as third-hand smoke (Sleiman et al., 2010).

Interactive sinks (and models of the processes) are of special importance; while sink effects can greatly reduce indoor air concentrations, re-emission at lower rates over longer time periods could greatly extend the exposure period of concern. For completely reversible sinks, the extended time could bring the cumulative exposure to levels approaching the sink-free case. Publications (Axley and Lorenzetti, 1993; Tichenor et al., 1991) show that first principles provide useful guidance in postulating models and setting assumptions for reversible-irreversible sink models. Sorption/desorption can be described in terms of Langmuir (monolayer) as well as Brunauer-Emmet-Teller (BET, multilayer) adsorption.

19.8. REFERENCES FOR CHAPTER 19

Acevedo–Bolton, V; Cheng, K–C; Jiang, R–T; Ott, WR; Klepeis, NE; Hildemann, LM. (2012) Measurement of the proximity effect for indoor air pollutant sources in two homes. J Environ Monit 14(1):94–104.

Andelman, JB. (1990) Total exposure to volatile organic compounds in potable water. In: Ram, NM; Christman, RF; Cantor, KP; eds. Significance and treatment of volatile organic compounds in water supplies. Chelsea, MI: Lewis Publishers; pp 485–504.

Andersson, B; Andersson, K; Sundell, J; Zingmark, P–A. (1993) Mass transfer of contaminants in rotary enthalpy heat exchangers. Indoor Air 3(2):143–148.

ASHRAE (American Society of Heating Refrigerating & AC Engineers). (2016) ASHRAE handbook: HVAC systems and equipment. Atlanta, GA: ASHRAE.

ASHRAE. (American Society of Heating Refrigerating & AC Engineers). (2013) ASHRAE handbook: fundamentals. Atlanta, GA: ASHRAE.

ASTM (American Society for Testing and Materials). (1989) Standard laboratory test method for evaluation of carpet–embedded dirt removal effectiveness of household vacuum cleaners. Standard F 608–89. Philadelphia, PA: ASTM.

Axley, JW. (1988) Progress toward a general analytical method for predicting indoor air pollution in buildings: indoor air quality modeling phase III report. NBSIR 88–3814. National Bureau of Standards, Gaithersberg, MD. Available online at https://archive.org/details/progresstowardge8838axle.

Axley, JW. (1989) Multi–zone dispersal analysis by element assembly. Build Environ 24(2):113–130.

Axley, JW; Lorenzetti, D. (1993) Sorption transport models for indoor air quality analysis. In: Nagda, NL; ed. Modeling of indoor air quality and exposure. ASTM STP 1205. Philadelphia, PA: ASTM; pp. 105–127.

Axley, J. 2007. Multizone airflow modeling in buildings: history and theory. HVAC&R Res 13(6):907–928.

Baughman, AV; Gadgil, AJ; Nazaroff, WW. (1994) Mixing of a point source pollutant by natural convection flow within a room. Indoor Air 4(2):114–122.

Bekö, G; Gustavsen, S; Frederiksen, M; Bergsøe, NC; Kolarik, B; Gunnarsen, L; Toftum, J; Clausen, G. (2016) Diurnal and seasonal variation in air exchange rates and interzonal airflows measured by active and passive tracer gas in homes. Build Environ 104:178–187.

Bennett, DH; Fisk, W; Apte, MG; Wu, X; Trout, A; Faulkner, D; Sullivan, D. (2012) Ventilation, temperature, and HVAC characteristics in small and medium commercial buildings in California. Indoor Air 22:309–320.

Breen, MS; Breen, M; Williams, RW; Schultz, BD. (2010) Predicting residential air exchange rates from questionnaires and meterology: Model evaluation in central North Carolina. Environ Sci Technol 44:9349–9356.

Breen, MS; Schultz, BD; Sohn, MD; Long, T; Langstaff, J; Williams, R; Isaacs, K; Qing, YM; Stallings, C; Smith, L (2014) A review of air exchange rate models for air pollution exposure assessments. J Expo Sci Environ Epidemiol 24:555–563.

Chan, WR; Nazaroff, WW; Price, PN; Sohn, MD; Gadgil, AJ. (2005) Analyzing a database of residential air leakage in the United States. Atmos Environ 39(19):3445–3455.

Chang, JCS; Guo, Z. (1992) Characterization of organic emissions from a wood finishing product - wood stain. Indoor Air 2(3):146−53.

Chen, C; Zhao, B. (2011). Review of relationship between indoor and outdoor particles: I/O ratio, infiltration factor and penetration factor. Atmos Environ 45:275–288.

Cheng, Y; Lin, Z. (2015) Experimental study of airflow characteristics of stratum ventilation and multi-occupant room with comparison to mixing ventilation and displacement ventilation. Indoor Air 25(6):662−671.

Cherrie, JW; MacCalman, L; Fransman, W; Tielemans, E; Tischer, M; Van Tongeren, M. (2011) Revisiting the effect of room size and general ventilation on the relationship between near- and far-field air concentrations. Ann Occup Hyg 55(9):1006−1015.

Cussler, EL. (1984) Diffusion: mass transfer in fluid systems. New York, NY: Cambridge University Press.

DeOreo, WB; Mayer, P; Water Research Foundation; Dziegielewski, B. (2016). Residential end uses of water: version 2. Water Research Foundation, Denver, CO. Available online at http://www.waterrf.org/Pages/Projects.aspx?PID=4309

Diamond, RC; Feustel, HE; Dickerhoff, DJ. (1996) Ventilation and infiltration in high-rise apartment buildings. Berkeley, CA: Lawrence Berkeley Laboratory. LBL–38103.

Dietz, RN; Goodrich, RW; Cote, EA; Wieser, RF. (1986) Detailed description and performance of a passive perfluorocarbon tracer system for building ventilation and air exchange measurements. In: Trechsel, HR; Lagus, PL; eds. Measured air leakage of buildings. ASTM STP 904. Philadelphia, PA: ASTM Intl; pp. 203–264.

Dols, WS; Polidoro, BJ. (2016) NIST Technical note 1887 CONTAM user guide and program documentation ersion 3.2. National Institute of Standards and Technology, U.S. Department of Commerce. Available online at: http://dx.doi.org/10.6028/NIST.TN.1887.

Drescher, AC; Lobascio, C; Gadgil, AJ; Nazaroff, WW. (1995) Mixing of a point-source indoor pollutant by forced convection. Indoor Air 5(3):204–214.

Dunn, JE. (1987) Models and statistical methods for gaseous emission testing of finite sources in well–mixed chambers. Atmos Environ 21(2):425–430.

Dunn, JE; Chen, T. (1993) Critical evaluation of the diffusion hypothesis in the theory of porous media volatile organic compounds (VOC) sources and sinks. In: Nagda, NL; ed. Modeling of indoor air quality and exposure. STM STP 1205. Philadelphia, PA: ASTM; pp. 64–80.

Dunn, JE; Tichenor, BA. (1988) Compensating for sink effects in emissions test chambers by mathematical modeling. Atmos Environ 22(5)885–894.

Efroymson, RE; Murphy DL. (2001) Ecological risk assessment of multimedia hazardous air pollutants: estimating exposure and effects. Sci Total Environ 274 (1–3):219–230.

El Orch, Z; Stephens, B; Waring, MS. (2014) Predictions and determinants of size–resolved particle infiltration factors in single–family homes in the U.S. Build Environ 74:106–118.

Emmerich, S; Gorfain, J; Howard-Reed, C. (2003) Air and pollutant transport from attached garages to residential living spaces – literature review and field tests. Int J Vent 2(3):265–276.

Feustel, HE; Raynor-Hoosen, A; eds. (1990) Fundamentals of the multizone airflow model COMIS. Technical note AIVC 29. Air Infiltration and Ventilation Centre, Coventry, UK; 115 p. Available online at

Feustel, HE. (1999) COMIS—an international multizone air-flow and contaminant transport model. Energy Build 30:3–18.

Fortune, CR; Blanchard, FT; Elleson, WD; Lewis, RG. (2000) Analysis of aged in–home carpeting to determine the distribution of pesticide residues between dust, carpet, and pad compartments. U.S. Environmental Protection Agency, Research Triangle Park, NC; EPA/600/R–00/030.

Furtaw, EJ; Pandian, MD; Nelson, DR; Behar, JV. (1996) Modeling indoor air concentrations near emission sources in perfectly mixed rooms. Engineering solutions to indoor air quality problems. J Air Waste Manag Assoc 46(9):861–868.

Gadgil, AJ; Lobscheid, C; Abadie, MO; Finlayson, EU. (2003) Indoor pollutant mixing time in an isothermal closed room: an investigation using CFD. Atmos Environ 37(39):5577–5586.

Gao, Z; Zhang, JS. (2009) Numerical simulation of particle penetration through the building envelope. Proceedings EERB-BEPH 2009:193–201.

GEOMET. (1989) Assessment of indoor air pollutant exposure within building zones. Report Number IE-2149, prepared for U.S. EPA Office of Health and Environmental Assessment under Contract No. 68-02-4254, Task No. 235. Germantown, MD: GEOMET Technologies, Inc.

Giardino, NJ; Gummerman, E; Esmen, NA; Andelman, JB; Wilkes, CR; Small, MJ. (1990) Real-time air measurements of trichloroethylene in domestic bathrooms using contaminated water. Proceedings of the 5th International Conference on Indoor Air Quality and Climate, Toronto, 2:707–712.

Graham, LA; Noseworthy, L; Fugler, D; O'Leary, K; Karman, D; Grande, C. (2004) Contribution of vehicle emissions from an attached garage to residential indoor air pollution levels. J Air Waste Manage Assoc 54(5):563–584. Available online at https://homes.lbl.gov/sites/default/files/max_sherman_-_9416.pdf.

Grimsrud, DT; Sherman, MH; Sondereggen, RC. (1983) Calculating infiltration: implications for a construction quality standard. In: Proceedings of the American Society of Heating, Refrigerating and Air-Conditioning Engineers Conference. Thermal performance of exterior envelopes of buildings II. ASHRAE SP38, Atlanta, GA, pp. 422–449. Available online at https://homes.lbl.gov/sites/default/files/max_sherman_-_9416.pdf.

Grot, RA; Clark, RE. (1981) Air leakage characteristics and weatherization techniques for low-income housing. In: Proceedings of the American Society of Heating, Refrigerating and Air–Conditioning Engineers Conference. Thermal performance of exterior envelopes of buildings. ASHRAE SP28, Atlanta, GA, pp. 178–194. Available online at https://www.researchgate.net/publication/255551463_Air_leakage_characteristics_and_weatherization_techniques_for_low-income_housing_Final_report.

Guo, Z. (2000) Simulation tool kit for indoor air quality and inhalation exposure (IAQX) version 1.0 user's guide. U.S. Environmental Protection Agency, Office of Research and Development, National Risk Management Research Laboratory, Research Triangle Park, NC; EPA-600/R-00/094. Available online at http://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P1000A0G.txt.

Guo, H; Morawska, L; He, C; Gilbert, D. (2008) Impact of ventilation scenario on air exchange rates and on indoor particle number concentrations in an air-conditioned classroom. Atmos Environ 42:757–768.

Hanley, JT; Ensor, DS; Smith, DD; Sparks, LE. (1994) Fractional aerosol filtration efficiency of in-duct ventilation air cleaners. Indoor Air 4(3):169–178.

Haas, A; Weber, A; Dorer, V; Keilholz, W; Pelletret, R. (2002) COMIS v3.1 simulation environment for multizone air flow and pollutant transport modelling. Energy Build 34(9):873–882.

He, C; Morawska, L; Gilbert, D. (2005) Particle deposition rates in residential houses. Atmos Environ 39(21):3891–3899.

Hirvonen, A; Pasanen, P; Tarhanen, J; Ruuskanen, J. (1995) Thermal desorption of organic compounds associated with settled household dust. Indoor Air 4(4):255–264.

Howard-Reed, C; Corsi, R; Moya, J. (1999) Mass transfer of volatile organic compounds from drinking water to indoor air: the role of residential dishwashers. Environ Sci Technol 33(13):2266–2272.

Jennings, PD; Carpenter, CE; Krishnan, MS. (1987a) Methods for assessing exposure to chemical substances volume 12: methods for estimating the concentration of chemical substances in indoor air. U.S. Environmental Protection Agency, Office of Pesticides and Toxic Substances, Washington, DC; EPA 560/5-85/016.

Jennings, PD; Hammerstrom, KA; Adkins, LC; Chambers, T; Dixon, DA. (1987b) Methods for assessing exposure to chemical substances volume 7: methods for assessing consumer exposure to chemical substances. U.S. Environmental Protection Agency, Office of Pesticides and Toxic Substances, Washington, DC; EPA/560/5-85/007. Available online at http://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P1007I8Y.txt.

Johnson, PC; Ettinger, RA. (1991) Heuristic model for predicting the intrusion rate of contaminant vapors into buildings. Environ Sci Technol 25:1445–1452.

Kearney, J; Wallace, L; MacNeill, M; Héroux, M-E; Kindzierski, W; Wheeler, A. (2014) Residential infiltration of fine and ultrafine particles in Edmonton. Atmos Environ 94:793–805.

Koontz, MD; Nagda, NL. (1991) A multichamber model for assessing consumer inhalation exposure. Indoor Air 1(4):593–605.

Koontz, MD; Rector, HE; Fortmann, RC; Nagda, NL. (1988) Preliminary experiments in a research house to investigate contaminant migration in indoor air. Prepared for the U.S. Environmental Protection Agency, Office of Pesticides and Toxic Substances, Washington , DC; by GOMET Technologies, Inc, Germantown, Inc. EPA 560/5–88/004. Available online at http://nepis.epa.gov/Adobe/PDF/P1003BBS.PDF.

Layton, DW; Thatcher, TL. (1995) Movement of outdoor particles to the indoor environment: An analysis of the Arnhem Lead Study. Paper No. 95–MP4.02. Presented at the Air & Waste Management Association's 88th Annual Meeting, June 18–23, 1995, San Francisco, CA. Available online at https://e-reports-ext.llnl.gov/pdf/229906.pdf.

Leaderer, BP; Schaap, L; Dietz, RN. (1985) Evaluation of perfluorocarbon tracer technique for determining infiltration rates in residences. Environ Sci Technol 19(12):1225–1232.

Lee, S; Park, B; Kurabuchi, T. (2016). Numerical evaluation of influence of door opening on interzonal air exchange. Build Environ 102:230–42.

Liddament, M; Allen, C. (1983) Validation and comparison of mathematical models of air infiltration. Technical Note AIC 11. Air Infiltration Centre, Great Britain.

Little, JC. (1992) Applying the two-resistance theory to contaminant volatilization in showers. Environ Sci Technol 26(7):1341–1349.

Little, JC; Daisey, JM; Nazaroff, WW. (1992) Transport of subsurface contaminants into buildings – an exposure pathway for volatile organics. Environ Sci Technol 26(11):2058−2066.

Lucas, RM; Grillo, RB; Perez-Michael, A; Kemp, S. (1992) National residential radon survey statistical analysis – volume 2: Summary of the questionnaire data. RTI/5158/49–2F. Research Triangle Institute, Research Triangle Park, NC.

Mage, DT; Ott, WR. (1994) The correction for nonuniform mixing in indoor microenvironments. Conference paper in the ASTM Symposium on Methods for Characterizing Indoor Sources and Sinks, September 25-28, 1994, Washington, DC; EPA/600/A-94/196.

McKone, TE. (1987) Human exposure to volatile organic compounds in household tap water: the inhalation pathway. Environ Sci Technol 21(12):1194–1201.

McKone, TE. (1989) Household exposure models. Toxicol Lett 49(2–3):321–339.

Moya, J; Howard–Reed, C; Corsi, R. (1999) Volatilization of chemicals from tap water to indoor air from contaminated water used for showering. Environ Sci Technol 33(14):2321–2327.

Murphy, B.L. and Chan, W.R. (2011) A multi–compartment mass transfer model applied to building vapor intrusion. Atmos Environ 45:6650–6657.

Murray, DM. (1997) Residential house and zone volumes in the United States: empirical and estimated parametric distributions. Risk Anal 17(4):439–446.

Murray, DM; Burmaster, DE. (1995) Residential air exchange rates in the United States: empirical and estimated parametric distribution by season and climatic region. Risk Anal 15(4):459–465

Nazaroff, WW; Cass, GR. (1986) Mathematical modeling of chemically reactive pollutants in indoor air. Environ Sci Technol 20(9):924–934.

Nazaroff, WW; Cass, GR. (1989a) Mathematical modeling of indoor aerosol dynamics. Environ Sci Technol 23(2):157–166.

Nazaroff, WW; Cass, GR. (1989b) Mass-transport aspects of pollutant removal at indoor surfaces. Environ Int 15(1–6):567–584.

Nazaroff, WW; Doyle, SM; Nero, AV; Sextro, RG. (1988) Radon entry via potable water. In: Nazaroff, WW; Nero, AV; eds. Radon and its decay products in indoor air. New York, NY: Wiley–Interscience; pp. 131–157.

Nazaroff, WW; Gadgil, AJ; Weschler, CJ. (1993) Critique of the use of deposition velocity in modeling indoor air quality. In: Nagda, NL; ed. Modeling of indoor air quality and exposure. ASTM STP 1205 Philadelphia, PA: ASTM; pp. 81–104.

Nirvan, G; Haghighat, F; Wang, LL; Akbari, H. (2012) Contaminant transport through the garage – House interface leakage. Build Environ 56:176–183.

Offerman, FJ; Sextro, RG; Fisk, W; Nazaroff, WW; Nero, AV; Revzan, KL; Yater, J. (1984) Control of respirable particles and radon progeny with portable air cleaners. Report No. LBL–16659. Berkley, CA: Lawrence Berkley Laboratory. Aailable online at http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/16/010/16010207.pdf.

Palma, T; Vasu, AB; Hetes, RG. (1999). Total risk integrated methodology (TRIM). Air and Waste Management Association - EM Magazine. March pp 30–34

Persily, AK; Linteris, GT. (1984) A comparison of measured and predicted infiltration rates. ASHRAE Trans 89(2):183–199.

Persily, A; Musser, A; Emmerich, SJ. (2010) Modeled infiltration rate distributions for U.S. housing. Indoor Air 20:473–485.

Price, S. (2001) An evaluation of the potential for use of existing exposure software (or software currently under development) in a tiered approach to the assessment of exposures and risks to children. Prepared for the American Chemistry Council. Available online at http://www.epa.gov/opptintr/vccep/pubs/revmodlr.pdf.

Price, PN; Shehabi, A; Chan, R. (2006) Indoor-outdoor air leakage of apartments and commercial buildings. Prepared for California Energy Commission by Lawrence Berkeley National Laboratory, Berkeley, CA. Dec 2006 CEC-500-2006-111. Available online at http://www.energy.ca.gov/2006publications/CEC-500-2006-111/CEC-500-2006-111.PDF.

Provoost, J; Bosman, A; Reijnders, L; Bronders, J; Touchant, K; Swartjes, F. (2010) Vapour intrusion from the vadose zone—seven algorithms compared. J Soils Sed 10(3):473–483 DOI 10.1007/s11368-009-0127-4.

Relwani, SM; Moschandreas, DJ; Billick, IH. (1986) Effects of operational factors on pollutant emission rates from residential gas appliances. J Air Poll Control Assoc 36(11):1233–1237.

Roberts, JW; Budd, WT; Ruby, MG; Bond, AE; Lewis, RG; Wiener, RW; Camann, DE. (1991) Development and field testing of a high volume sampler for pesticides and toxics in dust. J Expo Anal Environ Epidemiol 1(2):143–155

Rosenbaum, AS; Cohen, JP; Kavoosi, F. (2002) Update and refinement of an indoor exposure assessment methodology. Final report. Prepared for California Air Resources Board, Research Division. Contract 98-327. Available online at http://www.arb.ca.gov/research/apr/past/98−327.pdf.

Ryan, PB. (1991) An overview of human exposure modeling. J Expo Anal Environ Epidemiol 1(4):453–474.

Sandberg, M. (1984) The multi–chamber theory reconsidered from the viewpoint of air quality studies. Build Environ 19(4):221−233.

Schwope, AD; Goydan, R; Little, AD; Reid, RC. (1992) Methods for assessing exposure to chemical substances. Volume 11: Methodology for estimating the migration of additives and impurities from polymeric substances., U.S. Environmental Protection Agency, Office of Pollution Prevention, Pesticides, and Toxic Substances, Washington, DC; EPA 560/5 85/015. Available online at http://www.epa.gov/oppt/exposure/pubs/amemuserguide.pdf.

Sextro, RG. (1994) Radon and the natural environment. In: Nagda, NL; ed. Radon — prevalence, measurements, health risks and control, ASTM MNL 15. Philadelphia, PA: ASTM; pp. 9–32.

Shaughnessy, RJ; Sextro, RG (2007) What is an effective portable air cleaning device? A review, J Occup Environ Hyg 3(4):169–181, DOI: 10.1080/15459620600580129

Shaughnessy, RJ; Levetin, E; Blocker, J; Sublette, KL. (1994) Effectiveness of portable indoor air cleaners: sensory testing results. Indoor Air 4(3):179–188.

Sherman, MH. (1989) Analysis of errors associated with passive ventilation measurement techniques. Build Environ 24(2):131–139.

Sherman, MH; Matson, NE. (2002) Air tightness of new U.S. housing: a preliminary report. Report LBNL–48671. Berkeley, CA: Lawrence Berekeley National Laboratory. Available online at http://eetd.lbl.gov/ie/pdf/LBNL–48671.pdf.

Sinden, FW. (1978) Multi-chamber theory of air infiltration. Build Environ 13:21–28.

Singer, BC; Hodgson, AT; Nazaroff, WW. (2003) Gas–phase organics in environmental tobacco smoke: 2. Exposure–relevant emission factors and indirect exposures from habitual smoking. Atmos Environ 37(39):5551–5561.

Sleiman, M; Gundel, LA; Pankow, JF; Jacob, P 3rd; Singer, BC; Destaillats, H. (2010) Formation of carcinogens indoors by surface-mediated reactions of nicotine with nitrous acid, leading to potential thirdhand smoke hazards. Proc Nat Acad Sci 107(15):6576–6581.

Sparks, LE. (1997) RISK version 1.7. Multiple pollutant IAQ model. Draft. Indoor Environment Management Branch, National Risk Management Research Laboratory. Air Pollution Prevention and Control Division. Office of Research and Development, Environmental Protection Agency, Washington, DC.

Thatcher, TL; Layton, DW. (1995) Deposition, resuspension, and penetration of particles within a residence. Atmos Environ 29(13):1487–1497.

Thatcher, TL; Lai, ACK; Moreno-Jackson, R; Sextro, RG; Nazaroff, WW. (2002) Effects of room furnishings and air speed on particle deposition rates indoors. Atmos Environ. 36(11):1811–1819.

Tichenor, BA; Guo, Z; Dunn, JE; Sparks, LE; Mason, MA. (1991) The interaction of vapor phase organic compounds with indoor sinks. Indoor Air 1:23–35.

Tichenor, BA. (2006). Criteria for evaluating programs that assess materials/products to determine impacts on indoor air quality. Contractor final report to EPA's Office of Radiation and Indoor Air Indoor Environments Division EPA Order No. EP 05WO00995. Available online at https://www.epa.gov/indoor-air-quality-iaq/criteria-evaluating-programs-assess-materialsproducts-determine-impacts.

Tielemans, E; Schneider, T; Goede, H; Tischer, M; Warren, N; Kromhout, H; Van Tongeren, M; Van Hemmen, J; Cherrie, JW. (2008) Conceptual model for assessment of inhalationexposure: defining modifying factors. Ann Occup Hyg 52(7):577–586.

Tielemans, E; Warren, N; Fransman, W; Van Tongeren, M; McNally, K; Tischer, M; Ritchie, P; Kromhout, H; Schinkel, J; Schneider, T; Cherrie, JW. (2011) Advanced REACH Tool (ART): Overview of version 1.0 and research needs. Ann Occup Hyg 55(9):949–956.

Tucker, WG. (1991) Emission of organic substances from indoor surface materials. Environ Int 17:357–363.

Turk, BH; Brown, JT; Geisling-Sobotka, K; Froehlich, DA; Grimsrud, DT; Harrison, J; Koonce, JF; Prill, RJ; Revzan, KL. (1987) Indoor air quality and ventilation measurements in 38 Pacific Northwest commercial buildings. Volume 1: measurement results and interpretation. Final report. Prepared for U.S. DOE. DE–AC03–76SF00098 by Lawrence Berkeley Laboratory, University of California, Berkeley CA. Available online at https://pubarchive.lbl.gov/islandora/object/ir%3A89218.

U.S. Census Bureau. (2017) American housing survey for the United States: 2015. Washington, DC: Available online at https://www.census.gov/programs-surveys/ahs.html.

U.S. DOE (Department of Energy). (1997) Residential energy consumption survey (RECS) Methodology. U.S. Department of Energy, Energy Information Administration, Washington, DC. Available online at https://www.eia.gov/consumption/residential/data/1997/index.php?view=methodology#methodology_jump.

U.S. DOE (Department of Energy). (2008a) U.S. EPA analysis of survey data. Residential energy consumption survey (RECS) Report No. DOE/EIA–0314 (93). U.S. Department of Energy, Energy Information Administration, Washington, DC. Available online at http://www.eia.gov/consumption/residential/data/2005/microdata.cfm.

U.S. DOE (Department of Energy). (2008b). U.S. EPA analysis of survey data. Commercial buildings energy consumption survey (CBECS). Form EIA–871A. U.S. Department of Energy, Energy Information Administration, Washington, DC. Available online at http://www.eia.gov/emeu/cbecs/cbecs2003/detailed_tables_2003/detailed_tables_2003.html.

U.S. DOE (Department of Energy). (2013) Residential energy consumption survey (RECS). Technical documentation summary. U.S. Department of Energy, Energy Information Administration, Washington, DC. Available online at https://www.eia.gov/consumption/residential/methodology/2009/pdf/techdoc–summary010413.pdf.

U.S. DOE (Department of Energy). (2015) Residential energy consumption survey (RECS). 2009 survey data. U.S. Department of Energy, Energy Information Administration, Washington, DC. Available online at https://www.eia.gov/consumption/residential/data/2009/.

U.S. DOE (Department of Energy). (2016) Commercial building energy consumption survey. 2012 Survey Data. U.S. Department of Energy, Energy Information Administration, Washington, DC. Available online at https://www.eia.gov/consumption/commercial/.

U.S. DOE (Department of Energy). (2017) Residential energy consumption survey (RECS). 2015 Survey Data. U.S. Department of Energy, Energy Information Administration, Washington, DC. Available online at https://www.eia.gov/consumption/residential/data/2015/.

U.S. EPA (Environmental Protection Agency). (1995) Estimation of distributions for residential air exchange rates. Prepared for U.S. Environmental Protection Agency, Office of Pollution Prevention and Toxics, Washington, DC. EPA Contract No. 68-D9-0166, Work Assignment No. 3-19 by GOMET Technologies, Inc, Germantown, Inc. Available online at http://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=910063GS.txt.

U.S. EPA (Environmental Protection Agency). (1995) User's guide for the industrial source complex (ISC3) dispersion models. Volume 1: User instructions. Research Triangle Park, NC; EPA-454/B-95-003a. Available online at https://www3.epa.gov/scram001/userg/regmod/isc3v1.pdf.

U.S. EPA (Environmental Protection Agency) (2000a) User's guide for the NAPL screen and NAPL ADV models for subsurface vapor intrusion into buildings. Office of Emergency and Remedial Response, Washington DC. Available online at https://www.epa.gov/sites/production/files/2015-09/documents/naplguide.pdf.

U.S. EPA (Environmental Protection Agency). (2000b) Volatilization rates from water to indoor air—phase II. Office of Research and Development, Washington, DC; EPA/600/R-00/096. Available online at http://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=30002F5O.txt.

U.S. EPA (Environmental Protection Agency). (2009). Residential air cleaners: (second edition): A summary of available information. Office of Air and Radiation, Washington DC; Available online at: https://www.epa.gov/indoor-air-quality-iaq/residential-air-cleaners-second-edition-summary-available-information.

U.S. EPA (Environmental Protection Agency) (2011). Exposure factors handbook 2011 edition. Final report. Office of Research and Development, Washington DC; EPA/600/R-09/52F. Available online at https://cfpub.epa.gov/ncea/risk/recordisplay.cfm?deid=236252.

US EPA (Environmental Protection Agency) (2012). Conceptual model scenarios for the vapor intrusion pathway. Office of Solid Waste and Emergency Response; Washington DC; EPA 530-R-10-003. Available online at https://www.epa.gov/vaporintrusion/conceptual-model-scenarios-vapor-intrusion-pathway.

US EPA (Environmental Protection Agency). (2015). OSWER technical guide for assessing and mitigating the vapor intrusion pathway from subsurface vapor sources to indoor air. Office of Solid Waste and Emergency Response, Washington DC; OSWER Publication 9200.2-154. Available online at https://www.epa.gov/sites/production/files/2015-09/documents/oswer-vapor-intrusion-technical-guide-final.pdf.

Versar. (1990) Database of perfluorocarbon tracer (PFT) ventilation measurements: description and user's manual. U.S. EPA Contract No. 68-02-4254, Task No. 39. Agency, Office of Toxic Substances, Washington, DC.

Wallace, LA. (1996) Indoor particles: A review. J Air Waste Manag Assoc 46(2):98–126.

Wang, L; Dols, WS; Chen, Q. (2010) Using CFD capabilities of CONTAM 3.0 for simulating airflow and contaminant transport in and around buildings. HVAC&R Res 16(6):49–763.

Weschler, CJ; Nazaroff, WW. (2008). Semivolatile organic compounds in indoor environments. Atmos Environ 42(40):9018–9040.

Weschler, CJ; Nazaroff, WW. (2017) Growth of organic films on indoor surfaces. Indoor Air. DOI: 10.1111/ina.12396.

Wilkes, CR. (1998) Case studies. In: Exposure to contaminants in drinking water: Estimating uptake through the skin and by inhalation. Prepared by ILSI working group. Bocan Raton: CRC Press.

Wilkes, C; Nuckols, JR. (2000) Comparing exposure classification by three alternative methods: measured blood levels, questionnaire results, and model predictions (abstract). In: Proceedings of the international society of exposure analysis 2000 Conference. Monterey Peninsula, California October 24−27, 2000.

Wilkes, CR; Small, MJ; Andelman, JB; Giardino, NJ; Marshall, J. (1992) Inhalation exposure model for volatile chemicals from indoor uses of water. Atmos Environ 26(12):2227−2236.

Wolkoff, P. (1995) Volatile organic compounds: sources, measurements, emissions, and the impact on indoor air quality. Indoor Air 5(Suppl3):1–73.

Wolkoff, P; Wilkins, CK. (1994) Indoor VOCs from household floor dust: Comparison of headspace with desorbed VOCs; method for VOC release determination. Indoor Air 4(4):248–254.

Won, D; Corsi, RL; Rynes, M. (2001) Sorptive interactions between VOCs and indoor materials. Indoor Air 11(4):246–256.

Wu, W, Lin, Z. (2015) An experimental study of the influence of a walking occupant on three air distribution methods. Build Environ 85:211–219.

Wu, Y; Eichler, CM; Leng, W; Cox, SS; Marr, LC; Little, JC. (2017) Adsorption of phthalates on impervious indoor surfaces. Environ Sci Technol 51(5):2907–2913.

Yamamoto, N; Shendell, DG; Winter, AM; Zhang, J. (2010) Residential air exchange rates in three U.S. metropolitan areas: results from the relationship among Indoor, outdoor, and personal air study 1999–2001. Indoor Air 20:85–90.

Yao, Y; Pennell, KG; Suuberg, E. (2011) Vapor intrusion in urban settings: Effect of foundation features and source location. Proc Environ Sci 4:245–250.

Yao, Y; Pennell, KG; Suuberg, EM. (2012) Estimation of contaminant subslab concentration in vapor intrusion. J Haz Mat 231–232:10–17.

Yao, Y; Suuberg, EM. (2013) A review of vapor intrusion models. Environ Sci Technol; 47(6):2457–2470. doi:10.1021/es302714g.

Zhao, B; Zeng J. (2009) A simple model to study the influence of fluctuating airflow on the effective air exchange rate when using natural ventilation. Build Simul 2: 63–66. DOI 10.1007/S12273-009-9304-z

Zinn, TW; Cline, D; Lehmann, WF. (1990) Long-term study of formaldehyde emission decay from particleboard. Forest Prod J 40(6):15−18.

Table 19-6. Average Estimated Volumes of U.S. Residences, by Housing Type, Census Region, and Urbanicity

	Volume (m^3)[a]	% of Total
Housing Type		
Single-family detached	562	63.3
Single-family attached	401	5.9
Apartments in 2−4 unit buildings	249	7.9
Apartments in 5 or more unit buildings	192	16.8
Mobile homes	246	6.1
Census Region		
Northeast	480	18.3
Midwest	515	22.8
South	423	37.1
West	387	21.8
Urban and Rural[b]		
Urban	421	77.6
Rural	536	22.4
All housing types	446	NA

[a] Volumes calculated from floor areas assuming a ceiling height of 8 feet. Includes all basements, finished or conditioned (heated or cooled) areas of attics, and conditioned garage space that is attached to the home. Unconditioned and unfinished areas in attics and attached garages are excluded.

[b] Housing units are classified as urban or rural using definitions created by the U.S. census bureau.

Source: U.S. DOE (2013).

Table 19-7. Average Volume of Single Family, Multifamily and Mobile Homes by Type[a]

Number of Stories or Levels in Housing Unit	Single Family		Multifamily		Mobile Homes	
	Volume (m^3)	% of Total	Volume (m^3)	% of Total	Volume (m^3)	% of Total
1 story	438	58.8	199	90.8	NA	NA
2 stories	705	37.7	321	8.5	NA	NA
3 or more stories	777	2.0	494	0.7	NA	NA
Split level	635	1.5	NA	NA	NA	NA
Census region						
Northeast	644	16.2	224	27.0	233	7.2
Midwest	616	24.5	217	19.9	247	15.9
South	506	37.8	209	29.9	256	56.5
West	476	21.5	191	23.1	225	20.3
Urbanicity[b]						
Urban	531	73.4	210	95.7	227	50
Rural	598	26.6	225	4.3	266	50

[a] Volumes calculated from floor areas assuming a ceiling height of 8 feet. Includes all basements, finished or conditioned (heated or cooled) areas of attics, and conditioned garage space that is attached to the home. Unconditioned and unfinished areas in attics and attached garages are excluded.

[b] Housing units are classified as urban or rural using definitions created by the U.S. Census Bureau.

Source: U.S. DOE (2013).

Table 19-8. Residential Volumes in Relation to Year of Construction

Year of Construction	Volume[a] (m^3)	% of Total
Before 1940	483	12.7
1940−1949	421	4.6
1950−1959	419	11.9
1960−1969	397	11.7
1970−1979	382	16.1
1980−1989	401	15.0
1990−1999	498	14.4
2000−2009	558	13.7
All years	447	100

[a] Volumes calculated from floor areas assuming a ceiling height of 8 feet. Includes all basements, finished or conditioned (heated or cooled) areas of attics, and conditioned garage space that is attached to the home. Unconditioned and unfinished areas in attics and attached garages are excluded.

Source: U.S. DOE (2013).

Table 19-9. Summary of Residential Volume Distributions Based on U.S. DOE (2008a)[a] (m^3)

Parameter	Volume
Arithmetic mean	492
Standard deviation	349
10th percentile	154
25th percentile	231
50th percentile	395
75th percentile	648
90th percentile	971

[a] All housing types, all units.

Source: EPA's Analysis of U.S. DOE (2008a).

Table 19-10. Summary of Residential Volume Distributions Based on Versar (1989) (m^3)

Parameter	Volume
Arithmetic mean	369
Standard deviation	209
10th percentile	167
25th percentile	225
50th percentile	321
75th percentile	473
90th percentile	575

Source: Versar (1989); based on PFT database.

Table 19-11. Number of Residential Single Detached and Mobile Homes by Volume[a] (m^3) and Median Volumes by Housing Type

Volume (m^3)[a]	Total Housing Units	Occupied	Seasonal	Vacant
Less than 113.3	2,738	2,218	133	388
113.3−169.7	7,940	6,368	339	1,233
169.9−226.3	13,805	11,409	383	2,012
226.5−339.6	27,098	23,563	664	2,871
339.8−452.8	21,635	19,657	356	1,621
453.1−566.1	14,007	13,028	167	813
566.3−679.4	7,290	6,817	83	390
679.6−905.9	7,075	6,593	93	389
906 or more	3,313	3,024	66	223
Not reported/don't know	29,889	25,614	638	3,637
Median volume (m^3)[b]	340	340	261	NA

[a] Includes single detached and manufactured/mobile homes.
[b] Converted from ft^2. Assumes 8-foot ceiling.

Source: U.S. Census Bureau (2015).

Table 19-12. Dimensional Quantities for Residential Rooms

Nominal Dimensions	Length (meters)	Width (meters)	Height (meters)	Volume (m^3)	Wall Area (m^2)	Floor Area (m^2)	Total Area (m^2)
8-foot ceiling							
12’ × 15’	4.6	3.7	2.4	41	40	17	74
12’ × 12’	3.7	3.7	2.4	33	36	13	62
10’ × 12’	3.0	3.7	2.4	27	33	11	55
9’ × 12’	2.7	3.7	2.4	24	31	10	51
6’ × 12’	1.8	3.7	2.4	16	27	7	40
4’ × 12’	1.2	3.7	2.4	11	24	4	32
12-foot ceiling							
12’ × 15’	4.6	3.7	3.7	61	60	17	94
12’ × 12’	3.7	3.7	3.7	49	54	13	80
10’ × 12’	3.0	3.7	3.7	41	49	11	71
9’ × 12’	2.7	3.7	3.7	37	47	10	67
6’ × 12’	1.8	3.7	3.7	24	40	7	54
4’ × 12’	1.2	3.7	3.7	16	36	4	44

Table 19-13. Examples of Products and Materials Associated with Floor and Wall Surfaces in Residences

Material Sources	Assumed Amount of Surface Covered[a] (m^2)
Silicone caulk	0.2
Floor adhesive	10.0
Floor wax	50.0
Wood stain	10.0
Polyurethane wood finish	10.0
Floor varnish or lacquer	50.0
Plywood paneling	100.0
Chipboard	100.0
Gypsum board	100.0
Wallpaper	100.0

[a] Based on typical values for a residence.

Source: Adapted from Tucker (1991).

Table 19-14. Residential Heating Characteristics by U.S. Census (%)

Space Heating Characteristics	Housing Units %[a]	U.S. Census Region Northeast	Midwest	South	West
Total homes	100.0	100.0	100.0	100.0	100.0
Space heating equipment					
Use space heating equipment	96.0	100.0	100.0	95.9	89.4
Have space heating equipment but do not use it	2.8	Q	N	3.6	6.4
Do not have space heating equipment	1.2	N	N	0.7	4.2
Main heating fuel and equipment[b]					
Natural gas	47.3	53.8	67.0	28.8	53.4
Central warm-air furnace	38.1	31.9	59.8	24.1	44.7
Steam or hot water system	5.5	19.0	5.7	1.1	1.9
Built-in room heater	1.8	1.9	Q	1.6	3.4
Other equipment	1.9	Q	0.8	2.0	3.4
Electricity	36.3	14.8	20.8	60.1	29.2
Central warm-air furnace	15.1	3.3	9.1	26.6	11.4
Heat pump	10.2	3.3	2.7	20.0	6.8
Built-in electric units	7.6	6.2	7.2	8.3	8.0
Portable electric heater	2.5	Q	Q	4.5	2.3
Other equipment	0.8	N	Q	0.7	0.8
Fuel oil/kerosene	5.0	22.4	Q	2.0	Q
Central warm-air furnace	3.1	13.3	Q	1.4	Q
Steam or hot water system	1.4	7.1	Q	Q	Q
Other equipment	0.6	1.9	Q	Q	Q
Propane	4.7	3.3	8.7	3.8	3.4
Central warm-air furnace	3.6	2.4	7.6	2.3	2.3
Other equipment	1.2	Q	1.1	1.4	0.8
Wood	1.9	2.9	2.3	1.1	2.7
Heating stove	1.5	1.9	1.5	0.9	1.9
Other equipment	0.4	0.5	Q	Q	0.8
Some other fuel[c]	Q	Q	Q	N	Q
Do not have or use heating equipment	4.0	Q	N	4.3	10.6
Main heating equipment (including all fuels)					
Central warm-air furnace	60.1	51.4	77.3	54.5	59.1
Heat pump	11.6	3.8	3.4	22.1	8.3
Steam or hot water system	7.9	28.1	7.6	1.4	3.0
Built-in electric units	7.6	6.2	7.2	8.3	8.0
Built-in oil or gas room heater	2.6	3.3	1.1	2.5	3.8

Table 19-14. Residential Heating Characteristics by U.S. Census (%) (Continued)

Space Heating Characteristics	Housing Units %[a]	U.S. Census Region			
		Northeast	Midwest	South	West
Portable electric heater	2.5	Q	Q	4.5	2.3
Heating stove burning wood	1.5	1.9	1.5	0.9	1.9
Built-in pipeless furnace	1.0	Q	Q	0.7	1.9
Fireplace	0.6	Q	Q	0.5	1.1
Some other equipment	0.8	Q	Q	0.7	Q
Do not use heating equipment	4.0	Q	N	4.3	10.6
Secondary heating fuel and equipment					
Secondary heating equipment used	36.6	41.0	39.8	35.4	32.2
Natural gas	6.3	6.7	7.6	5.6	6.4
Fireplace	5.5	5.7	6.4	4.7	6.1
Some other equipment	0.8	Q	1.1	0.9	0.4
Electricity	19.4	21.9	22.0	18.0	16.7
Portable electric heaters	17.0	18.6	19.7	16.4	14.0
Some other equipment	2.4	3.3	2.3	1.6	2.7
Wood	7.9	7.6	7.6	8.1	7.6
Heating stove	3.1	4.8	3.0	2.5	3.0
Fireplace	4.7	2.9	4.2	5.6	4.5
Some other equipment	Q	N	Q	N	N
Some other fuel	3.0	4.3	2.3	3.6	1.5
Do not use secondary heating equipment	59.4	59.0	60.2	60.6	57.2

[a] Total United States includes all primary occupied housing units in the 50 states and the District of Columbia. Vacant housing units, seasonal units, second homes, military housing, and group quarters are excluded. Housing characteristics data were collected between August 2015 and April 2016.

[b] Use of heating equipment for another housing unit also includes the use of the heating equipment for a business or farm building as well as another housing unit.

[c] Some other fuel includes coal and district steam.

Q = Data withheld either because the Relative Standard Error (RSE) was greater than 50% or fewer than 10 households were sampled

N = No cases in reporting sample.

Notes: Because of rounding, data may not sum to totals.

Source: EPA Analysis of U.S. DOE (2015).

Table 19-15. Residential Heating Characteristics by Climate Region (%)

		Climate Region[b]				
Space Heating	Housing Units %[a]	Very Cold/ Cold	Mixed-Humid	Mixed-Dry/ Hot-Dry	Hot-Humid	Marine
Total homes	100.0	100.0	100.0	100.0	100.0	100.0
Space heating equipment						
Use space heating equipment	96.0	99.8	100.0	84.5	89.9	93.9
Have space heating equipment but do not use it	2.8	Q	Q	10.9	7.0	4.5
Do not have space heating equipment	1.2	Q	Q	4.7	3.1	Q
Main heating fuel and equipment[c]						
Natural gas	47.3	61.6	42.9	54.3	22.8	48.5
Central warm-air furnace	38.1	51.4	31.0	44.2	19.7	40.9
Steam or hot water system	5.5	7.8	8.3	2.3	Q	Q
Built-in room heater	1.8	1.2	1.2	4.7	2.2	3.0
Other equipment	1.9	1.2	2.7	3.9	0.9	3.0
Electricity	36.3	19.3	41.7	27.9	64.5	36.4
Central warm-air furnace	15.1	7.1	16.1	13.2	31.6	9.1
Heat pump	10.2	3.1	15.2	7.0	18.4	10.6
Built-in electric units	7.6	7.3	7.1	5.4	8.3	13.6
Portable electric heater	2.5	0.9	3.0	2.3	5.3	3.0
Other equipment	0.8	1.2	Q	Q	Q	Q
Fuel oil	5.0	8.3	6.8	N	Q	Q
Central warm-air furnace	3.1	5.7	3.6	N	Q	Q
Steam or hot water system	1.4	2.1	2.1	N	N	N
Other equipment	0.6	0.7	1.2	N	N	N
Propane	4.7	6.4	6.3	1.6	1.8	3.0
Central warm-air furnace	3.6	5.2	4.5	Q	0.9	Q
Other equipment	1.2	1.2	1.5	Q	0.9	Q
Wood	1.9	2.8	1.8	Q	0.4	4.5
Heating stove	1.5	2.1	1.5	Q	Q	3.0
Other equipment	0.4	0.7	Q	Q	Q	Q
Some other fuel[d]	Q	Q	Q	N	N	N
Do not have or use heating equipment	4.0	Q	Q	15.5	10.1	6.1
Main heating equipment (including all fuels)						
Central warm-air furnace	60.1	69.6	55.1	58.1	52.6	51.5
Heat pump	11.6	3.3	17.9	8.5	18.9	10.6
Steam or hot water system	7.9	11.6	11.6	2.3	Q	Q

Table 19-15. Residential Heating Characteristics by Climate Region (%) (Continued)

		Climate Region[b]				
Space Heating	Housing Units %[a]	Very Cold/ Cold	Mixed-Humid	Mixed-Dry/ Hot-Dry	Hot-Humid	Marine
Built-in electric units	7.6	7.3	7.1	5.4	8.3	13.6
Built-in oil or gas room heater	2.6	2.1	2.1	4.7	2.6	4.5
Portable electric heater	2.5	0.9	3.0	2.3	5.3	3.0
Heating stove burning wood	1.5	2.1	1.5	Q	Q	3.0
Built-in pipeless furnace	1.0	0.7	0.9	2.3	Q	Q
Fireplace	0.6	0.5	Q	Q	Q	Q
Some other equipment	0.8	1.7	Q	N	Q	Q
Do not have or use heating equipment	4.0	Q	Q	15.5	10.1	6.1
Secondary heating fuel and equipment						
Secondary heating equipment used	36.6	41.5	41.1	23.3	25.4	45.5
Natural gas	6.3	7.8	6.8	6.2	3.5	4.5
Fireplace	5.5	6.6	6.0	6.2	2.6	4.5
Some other equipment	0.8	1.2	0.9	Q	Q	Q
Electricity	19.4	21.9	21.4	10.9	14.5	25.8
Portable electric heaters	17.0	18.6	19.6	10.9	13.2	19.7
Some other equipment	2.4	3.3	1.8	Q	1.3	6.1
Wood	7.9	8.0	8.6	5.4	6.6	12.1
Heating stove	3.1	4.5	3.9	Q	Q	6.1
Fireplace	4.7	3.5	4.8	4.7	6.1	6.1
Some other equipment	Q	Q	Q	N	N	N
Some other fuel	3.0	4.0	4.2	Q	1.3	3.0
Do not use secondary heating equipment	59.4	58.3	58.9	61.2	64.5	48.5
Do not use any heating equipment	4.0	Q	Q	15.5	10.1	6.1

[a] Total United States includes all primary occupied housing units in the 50 states and the District of Columbia. Vacant housing units, seasonal units, second homes, military housing, and group quarters are excluded. Housing characteristics data were collected between August 2015 and April 2016.

[b] These climate regions were created by the Building America program, sponsored by the U.S. Department of Energy's Office of Energy and Efficiency and Renewable Energy (EERE).

[c] Use of heating equipment for another housing unit also includes the use of the heating equipment for a business or farm building as well as another housing unit.

[d] Some other fuel includes coal and district steam.

Q = Data withheld either because the Relative Standard Error (RSE) was greater than 50% or fewer than 10 households were sampled.

N = No cases in reporting sample.

Notes: Because of rounding, data may not sum to totals.

Source: EPA Analysis of U.S. DOE (2015).

Table 19-16. Residential Air Conditioning Characteristics by U.S. Census Region (%)

	Housing Units %[a]	Northeast	Midwest	South	West
All homes	100.0	100.0	100.0	100.0	100.0
Air-conditioning equipment					
Use air-conditioning equipment	87.2	85.7	92.0	95.3	70.1
Do not use air-conditioning equipment	12.8	14.3	7.6	5.0	29.9
Type of air-conditioning equipment used (more than one may apply)					
Use central air-conditioning equipment	65.2	36.2	70.8	81.5	54.9
Do not use central air-conditioning equipment	34.8	63.8	29.2	18.5	45.1
Use individual air-conditioning units	26.7	53.3	26.1	19.6	18.2
With 1 unit	13.3	21.9	15.2	9.0	11.7
With 2 units	8.0	17.6	8.0	5.4	4.5
With 3 or more units	5.5	13.8	2.7	5.2	1.9
Do not use individual air-conditioning units	73.3	46.7	73.9	80.6	81.8
Air-conditioned basement					
Yes	11.9	10.0	30.3	6.1	4.9
No	15.0	34.3	24.2	6.1	4.9
Not asked (air-conditioned homes with no basement)	33.8	8.6	14.4	54.7	38.3
Not asked (unair-conditioned homes, apartments, and mobile homes)	39.3	47.1	30.7	33.3	51.9
Air-conditioned attic					
Yes	1.4	2.9	1.9	0.9	0.8
No	33.8	29.0	36.4	41.4	22.3
Not asked (air-conditioned homes with no attic)	25.5	21.4	31.1	24.3	25.0
Not asked (unair-conditioned homes, apartments, and mobile homes)	39.3	47.1	30.7	33.3	51.9
Air-conditioned, attached garage					
Yes	0.8	Q	0.8	1.1	0.8
No	35.0	27.1	41.3	34.9	35.2
Not asked (air-conditioned homes with no attached garage)	24.8	25.2	26.9	30.6	12.5
Not asked (unair-conditioned homes, apartments, and mobile homes)	39.3	47.1	30.7	33.3	51.9
Dehumidifier usage					
Use a dehumidifier	14.0	25.2	26.5	7.7	3.4
Less than 4 months	4.9	10.0	9.1	2.0	1.5
4 to 6 months	5.5	8.1	12.1	3.2	0.8

Table 19-16. Residential Air Conditioning Characteristics by U.S. Census Region (%) (Continued)

	Housing Units %[a]	Northeast	Midwest	South	West
7 to 9 months	1.7	3.3	2.7	1.1	Q
10 to 11 months	Q	Q	Q	Q	N
Turned on all 12 months	1.8	3.3	2.7	1.4	Q
Do not use a dehumidifier	86.0	74.8	73.5	92.3	96.6
Use an evaporative or swamp cooler (asked only in arid areas)					
Yes	2.4	N	N	1.1	8.7
No	46.4	N	N	71.8	86.7
Not asked	51.3	100.0	100.0	27.0	4.5
Fan types used (more than one may apply)					
Ceiling fans	72.3	58.6	75.4	81.5	64.4
Floor, window, or table fans	45.9	51.9	52.7	38.7	46.6
Whole house fans	5.2	4.3	5.7	4.3	6.8
Attic fans	7.4	8.6	8.0	7.7	5.3
Number of ceiling fans used					
0	27.7	41.4	24.6	18.7	35.6
1	17.9	18.1	20.5	13.5	23.1
2	16.0	14.8	17.4	17.1	13.6
3	12.8	11.4	13.6	14.6	9.5
4 or more	25.5	14.8	23.5	36.3	18.2

[a] Total United States includes all primary occupied housing units in the 50 states and the District of Columbia. Vacant housing units, seasonal units, second homes, military housing, and group quarters are excluded. Housing characteristics data were collected between August 2015 and April 2016.

Q = Data withheld either because the Relative Standard Error (RSE) was greater than 50% or fewer than 10 households were sampled.

N = No cases in reporting sample.

Notes: Because of rounding, data may not sum to totals.

Source: EPA Analysis of U.S. DOE (2015).

Table 19-17. Percentage of Residences with Basement, by Census Region and EPA Region

Census Region	EPA Regions	% of Residences With Basements
Northeast	1	93.4
Northeast	2	55.9
Midwest	3	67.9
Midwest	4	19.3
South	5	73.5
South	6	4.1
South	7	75.3
West	8	68.5
West	9	10.3
West	10	11.5
	All Regions	45.2

Source: Lucas et al. (1992).

Table 19-18. Percentage of Residences with Basement, by Census Region[a]

Census Region[b]	Census Divisions	% of Residences with Basements[c]
Northeast	New England	82.9
Northeast	Mid Atlantic	84.8
Midwest	East North Central	75.8
Midwest	West North Central	84.1
South	South Atlantic	26.5
South	East South Central	23.1
South	West South Central	Q
West	Mountain	31.7
West	Mountain North	65.5
West	Mountain South	Q
West	Pacific	14.5
	All Divisions	43.5

[a] Housing characteristics data were collected between August 2015 and April 2016.

[b] Housing units are classified using criteria created by the U.S. Census Bureau based on 2010 Census data. Urbanized areas are densely settled groupings of blocks or tracts with 50,000 or more people, while urban clusters have at least 2,500 but less than 50,000 people. All other areas are rural.

[c] Total United States includes all primary occupied housing units in the 50 states and the District of Columbia. Vacant housing units, seasonal units, second homes, military houses, and group quarters are excluded. Includes single family detached and attached homes.

Q = Data withheld either because the Relative Standard Error (RSE) was greater than 50% or fewer than 10 households were sampled.

Source: EPA Analysis of U.S. DOE (2017).

Table 19-19. States Associated with EPA Regions and Census Regions

EPA Regions

Region 1
Connecticut
Maine
Massachusetts
New Hampshire
Rhode Island
Vermont

Region 2
New Jersey
New York

Region 3
Delaware
District of Columbia
Maryland
Pennsylvania
Virginia
West Virginia

Region 4
Alabama
Florida
Georgia
Kentucky
Mississippi
North Carolina
South Carolina
Tennessee

Region 5
Illinois
Indiana
Michigan
Minnesota
Ohio
Wisconsin

Region 6
Arkansas
Louisiana
New Mexico
Oklahoma
Texas

Region 7
Iowa
Kansas
Missouri
Nebraska

Region 8
Colorado
Montana
North Dakota
South Dakota
Utah
Wyoming

Region 9
Arizona
California
Hawaii
Nevada

Region 10
Alaska
Idaho
Oregon
Washington

U.S. Census Bureau Regions

Northeast region
Connecticut
Maine
Massachusetts
New Hampshire
New Jersey
New York
Pennsylvania
Rhode Island
Vermont

Midwest region
Illinois
Indiana
Iowa
Kansas
Michigan
Minnesota
Missouri
Nebraska
North Dakota
Ohio
South Dakota
Wisconsin

South region
Alabama
Arkansas
Delaware
District of Columbia
Florida
Georgia
Kentucky
Louisiana
Maryland
Mississippi
North Carolina
Oklahoma
South Carolina
Tennessee
Texas
Virginia
West Virginia

West region
Alaska
Arizona
California
Colorado
Hawaii
Idaho
Montana
Nevada
New Mexico
Oregon
Utah
Washington
Wyoming

Source: RECS Terminology available on line at: https://www.eia.gov/consumption/residential/terminology.php#c

Table 19-20. Percentage of Residences with Certain Foundation Types by Census Region

Census Region	% of Residences[a, b] With Basement	 With Crawlspace	 With Concrete Slab
Northeast	74.7	18.4	27.8
Midwest	72.5	26.1	28.9
South	14.7	32.6	59.6
West	16.7	39.2	60.2
All Regions	39.9	29.8	46.5

[a] Percentage may add to more than 100 because more than one foundation type may apply to a given residence.

[b] Included single family attached and detached homes and apartments in buildings of 2−4 units.

Source: EPA Analysis of U.S. DOE, 2013.

Table 19-21. Average Estimated Volumes[a] of U.S. Commercial Buildings, by Primary Activity

Primary Building Activity	*N*	Mean	SE of Mean	Percentiles					% of Total
				10th	25th	50th	75th	90th	
Vacant	134	4,789	581	408	612	1,257	3,823	11,213	3.7
Office	976	5,036	397	510	714	1,359	3,398	8,155	17.0
Laboratory	43	24,681	1,114	2,039	5,437	10,534	40,776	61,164	0.2
Nonrefrigerated warehouse	473	9,298	992	1,019	1,812	2,945	7,504	16,990	12.0
Food sales	125	1,889	106	476	680	951	2,039	3,398	4.6
Public order and safety	85	5,253	482	816	1,019	1,699	3,398	8,495	1.5
Outpatient healthcare	144	3,537	251	680	1,019	2,039	3,398	6,966	2.5
Refrigerated warehouse	20	19,716	3,377	1,133	1,699	3,398	8,212	38,511	0.3
Religious worship	311	3,443	186	612	917	2,039	4,163	8,325	7.6
Public assembly	279	4,839	394	595	1,019	2,277	4,417	7,136	5.7
Education	649	8,694	513	527	867	2,379	10,194	23,786	7.9
Food service	242	1,889	112	442	680	1,189	2,039	3,568	6.1
Inpatient healthcare	217	82,034	5,541	17,330	25,485	36,019	95,145	203,881	0.2
Nursing	73	15,522	559	1,546	5,097	10,534	17,330	38,737	0.4
Lodging	260	11,559	1,257	527	1,376	4,078	10,194	27,184	2.5
Strip shopping mall	349	7,891	610	1,359	2,277	4,078	6,966	19,709	4.3
Enclosed mall	46	287,978	14,780	35,679	35,679	113,268	453,070	849,505	0.1
Retail other than mall	355	3,310	218	510	680	1,631	3,398	6,116	9.1
Service	370	2,213	182	459	629	934	2,039	4,587	12.8
Other	64	5,236	984	425	544	1,427	3,398	9,175	1.4
All buildings[b]	5,215	5,575	256	527	816	1,699	4,248	10,194	100

[a] Volumes calculated from floor areas assuming a ceiling height of 12 feet for other structures and 20 feet for warehouses.

[b] Weighted average calculated from floor areas assuming a ceiling height of 12 feet for all buildings except warehouses and enclosed malls, which assumed 20-foot ceilings.

N = Number of observations.
SE = Standard error.

Source: EPA Analysis of U.S. DOE (2008b).

Table 19-22. Nonresidential Buildings: Hours per Week Open and Number of Employees

Primary Building Activity	*N*	%	Number of Hours/Week Open							Number of Employees During Main Shift						
					Percentiles							Percentiles				
			Mean	SE of Mean	10th	25th	50th	75th	90th	Mean	SE of Mean	10th	25th	50th	75th	90th
Vacant	134	2.8	6.7	1.2	0	0	0	0	40	0.35	0.08	0	0	0	0	0
Office	976	20.2	54.7	1.6	40	45	54	65	168	34.2	2.8	4	11	57	300	886
Laboratory	43	0.9	103.5	0.8	50	58	98	168	168	105.6	4.5	20	55	156	300	435
Nonrefrigerated warehouse	473	9.8	66.2	4.8	20	40	55	80	168	7.0	0.9	0	1	8	25	64
Food sales	125	2.6	107.3	2.5	60	80	109	127	168	6.3	0.5	1	2	4	15	50
Public order and safety	85	1.8	103.0	7.6	10	40	168	168	168	19.1	2.2	1	4	15	60	200
Outpatient healthcare	144	3.0	52.0	2.8	40	45	54	70	168	21.5	1.9	5	8	40	125	200
Refrigerated warehouse	20	0.4	61.3	0.7	44	53	102	126	168	18.2	2.4	4	8	38	61	165
Religious worship	311	6.5	32.0	2.4	5	13	40	60	79	4.6	0.5	1	1	3	10	19
Public assembly	279	5.8	50.3	3.8	12	40	63	96	125	8.7	1.5	0	2	5	22	80
Education	649	13.5	49.6	1.0	38	42	54	70	85	32.4	8.8	3	14	38	75	133
Food service	242	5.0	85.8	2.6	40	66	84	105	130	10.5	0.9	2	4	8	15	33
Inpatient healthcare	217	4.5	168.0	*	168	168	168	168	168	471.0	40.4	175	315	785	1,300	2,250
Nursing	73	1.5	168.0	*	168	168	168	168	168	44.8	2.5	15	25	50	80	170
Lodging	260	5.4	166.6	0.8	168	168	168	168	168	12.3	2.0	1	3	10	25	80
Retail other than mall	355	7.4	59.1	1.5	42	50	62	80	105	7.8	0.7	2	3	6	22	72
Service	370	7.7	55.0	2.1	40	40	50	68	105	5.9	0.6	1	2	4	10	35
Other	64	1.3	57.8	7.1	12	40	51	90	168	12.3	1.7	1	2	10	44	150
All Activities	4,820	100.0	61.2	1.2	30	45	60	98	168	15.7	1.2	1	3	14	66	300

* All sampled inpatient healthcare and nursing buildings reported being open 24 hours a day, 7 days a week.
N = Number of observations.
SE = Standard error.

Source: EPA Analysis of U.S. DOE (2008b).

Table 19-23. Nonresidential Heating Energy Sources for Commercial Buildings

			Primary Space-Heating Energy Source Used[a]			
	All Buildings	Buildings with Space Heating	Electricity	Natural Gas	Fuel Oil	District Heat
All buildings	5,557	4,722	1,819	2,322	205	47
Building floorspace (square feet)						
1,001 to 5,000	50	48	51	44	58	Q
5,001 to 10,000	22	22	22	22	18	Q
10,001 to 25,000	16	17	15	19	16	Q
25,001 to 50,000	6	6	6	7	Q	13
50,001 to 100,000	4	4	4	4	3	21
100,001 to 200,000	2	2	1	2	1	19
200,001 to 500,000	1	1	0	1	Q	11
Over 500,000	0	0	0	0	Q	4
Principal building activity						
Education	7	8	8	8	8	26
Food sales	3	3	5	2	Q	N
Food service	7	8	8	8	Q	Q
Health care	3	3	3	4	2	4
Inpatient	0	0	Q	0	Q	2
Outpatient	3	3	3	3	Q	Q
Lodging	3	3	5	2	Q	9
Mercantile	11	12	13	12	Q	Q
Retail (other than mall)	8	9	9	8	Q	Q
Enclosed and strip malls	3	3	4	4	Q	Q
Office	18	21	23	21	16	26
Public assembly	6	7	5	7	Q	15
Public order and safety	2	2	Q	2	Q	Q
Religious worship	7	9	7	9	Q	N
Service	11	11	7	12	23	Q
Warehouse and storage	14	9	10	9	Q	Q
Other	2	2	2	2	Q	Q
Vacant	5	2	2	2	Q	Q

Table 19-23. Nonresidential Heating Energy Sources for Commercial Buildings (Continued)

			Primary Space-Heating Energy Source Used[a]			
	All Buildings	Buildings with Space Heating	Electricity	Natural Gas	Fuel Oil	District Heat
Year constructed						
Before 1920	7	7	4	8	20	11
1920 to 1945	9	9	6	11	12	15
1946 to 1959	11	11	10	11	14	11
1960 to 1969	11	12	9	14	18	19
1970 to 1979	12	13	12	13	Q	21
1980 to 1989	16	16	20	14	Q	4
1990 to 1999	15	14	15	14	10	4
2000 to 2003	7	7	8	6	Q	9
2004 to 2007	6	6	9	5	Q	4
2008 to 2012	5	6	7	4	Q	Q
Census region and division						
Northeast	14	15	8	16	69	32
New England	5	6	2	3	45	Q
Middle Atlantic	9	10	5	12	23	19
Midwest	22	23	11	33	Q	13
East North Central	13	14	5	23	Q	6
West North Central	9	9	6	10	Q	9
South	40	39	57	28	16	38
South Atlantic	20	18	31	10	10	17
East South Central	7	7	8	6	Q	Q
West South Central	14	13	18	12	Q	11
West	23	22	24	24	Q	15
Mountain	6	6	4	8	Q	Q
Pacific	17	16	20	16	Q	11
Climate region[b]						
Very cold/cold	37	38	19	47	76	36
Mixed-humid	31	33	36	31	25	43
Mixed-dry/hot-dry	15	14	18	14	N	9
Hot-humid	14	13	26	5	N	Q
Marine	3	2	Q	4	N	Q
Ownership and occupancy						
Nongovernment owned	86	85	88	84	86	45
Owner occupied	44	47	46	44	53	28

Table 19-23. Nonresidential Heating Energy Sources for Commercial Buildings (Continued)

			Primary Space-Heating Energy Source Used[a]			
	All Buildings	Buildings with Space Heating	Electricity	Natural Gas	Fuel Oil	District Heat
Leased to tenant(s)	31	31	34	32	25	Q
Owner occupied and leased	6	7	7	7	Q	4
Unoccupied	4	1	Q	1	Q	Q
Government owned	14	15	12	16	14	55
Federal	1	1	Q	1	Q	2
State	3	4	3	3	Q	38
Local	10	10	8	12	13	15
Energy sources (more than one may apply)						
Electricity	94	100	100	100	100	100
Natural gas	53	61	28	100	7	36
Fuel oil	8	10	5	5	100	21
District heat	1	1	Q	Q	Q	100
District chilled water	1	1	1	0	N	55
Propane	9	10	7	2	23	Q
Other	3	4	2	2	Q	2
Energy end uses (more than one may apply)						
Buildings with space heating	85	100	100	100	100	100
Buildings with cooling	80	90	95	92	66	91
Buildings with water heating	80	90	88	93	82	94
Buildings with cooking	29	32	31	33	28	28
Buildings with manufacturing	5	5	5	5	Q	Q
Buildings with electricity generation	7	8	7	9	12	32
Percentage of floorspace heated						
Not heated	15	N	N	N	N	N
1 to 50	13	15	20	11	15	Q
51 to 99	13	15	15	16	14	15
100	59	70	65	74	71	85

Table 19-23. Nonresidential Heating Energy Sources for Commercial Buildings (Continued)

			Primary Space-Heating Energy Source Used[a]			
	All Buildings	Buildings with Space Heating	Electricity	Natural Gas	Fuel Oil	District Heat
Heating equipment (more than one may apply)						
Heat pumps	11	13	27	5	Q	4
Furnaces	14	16	11	21	Q	Q
Individual space heaters	22	26	22	27	40	17
District heat	1	1	Q	Q	Q	100
Boilers	10	12	5	15	35	Q
Packaged heating units	50	59	58	65	41	6
Other	1	1	1	1	Q	Q

[a] Additionally, 261,000 buildings used propane and 67,000 buildings used wood, coal, or some other energy source for primary space heating.

[b] These climate regions were created by the Building America program, sponsored by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE).

Q = Data withheld either because the Relative Standard Error (RSE) was greater than 50% or fewer than 20 buildings were sampled.

N = No cases in reporting sample.

Source: EPA Analysis of U.S. DOE (2016).

Table 19-24. Air Conditioning Energy Sources for Nonresidential (%)

	Cooling Energy Sources Used (More Than One May Apply)					Floor Space by Cooling Energy Sources Used (More Than One May Apply) (million ft^2)				
	All Buildings	Buildings with Cooling	Elect-ricity	Natural Gas	District Chilled Water	All Buildings	Buildings with Cooling	Electricity	Natural Gas	District Chilled Water
All buildings (N)	5,557	4,461	4,413	12	54	87,093	79,294	76,034	732	4,608
Building floorspace (ft^2)										
1,001 to 5,000	50	46	47	Q	Q	8,041	6,124	6,107	Q	Q
5,001 to 10,000	22	23	23	Q	Q	8,900	7,304	7,252	Q	Q
10,001 to 25,000	16	17	17	Q	17	14,105	12,357	12,211	Q	145
25,001 to 50,000	6	7	7	Q	Q	11,917	10,813	10,615	Q	Q
50,001 to 100,000	4	4	4	Q	19	13,918	13,069	12,618	Q	567
100,001 to 200,000	2	2	2	Q	17	12,415	12,152	11,034	Q	1,273
200,001 to 500,000	1	1	1	Q	7	10,724	10,518	9,887	Q	1,064
Over 500,000	0	0	0	(*)	2	7,074	6,958	6,310	167	1,306
Principal building activity										
Education	7	8	8	Q	46	12,239	11,811	10,673	Q	1,292
Food sales	3	4	4	N	N	1,252	1,190	1,190	N	N
Food service	7	8	8	N	Q	1,819	1,712	1,668	N	Q
Health care	3	3	3	(*)	Q	4,155	4,148	3,966	200	523
Inpatient	0	0	0	(*)	2	2,374	2,374	2,227	176	477
Outpatient	3	3	3	Q	Q	1,781	1,774	1,739	Q	Q
Lodging	3	3	3	Q	Q	5,826	5,700	5,308	Q	Q
Mercantile	11	13	13	Q	N	11,330	11,121	11,121	Q	N
Retail (other than mall)	8	9	9	N	N	5,439	5,230	5,230	N	N
Enclosed and strip malls	3	4	4	Q	N	5,890	5,890	5,890	Q	N

Table 19-24. Air Conditioning Energy Sources for Nonresidential (%) (Continued)

	Cooling Energy Sources Used (More Than One May Apply)					Floor Space by Cooling Energy Sources Used (More Than One May Apply) (million ft^2)				
	All Buildings	Buildings with Cooling	Elect-ricity	Natural Gas	District Chilled Water	All Buildings	Buildings with Cooling	Electricity	Natural Gas	District Chilled Water
Office	18	22	22	Q	19	15,952	15,882	15,179	Q	1,096
Public assembly	6	7	7	N	9	5,559	5,235	4,629	N	880
Public order and safety	2	2	2	Q	Q	1,440	1,384	1,358	Q	Q
Religious worship	7	8	8	N	Q	4,557	4,271	4,271	N	Q
Service	11	10	10	N	N	4,630	3,773	3,758	N	N
Warehouse and storage	14	9	9	Q	N	13,077	10,120	10,059	Q	N
Other	2	2	2	Q	Q	2,002	1,820	1,806	Q	Q
Vacant	5	1	1	N	Q	3,256	1,125	1,048	N	Q
Year constructed										
Before 1920	7	6	6	N	Q	3,983	3,087	2,908	N	Q
1920 to 1945	9	8	8	Q	Q	6,025	5,215	5,081	Q	Q
1946 to 1959	11	11	11	Q	Q	7,381	6,679	6,569	Q	203
1960 to 1969	11	12	12	Q	20	10,362	9,634	8,962	Q	923
1970 to 1979	12	13	13	Q	17	10,846	10,031	9,440	Q	811
1980 to 1989	16	16	16	Q	6	15,230	14,011	13,830	Q	310
1990 to 1999	15	15	15	Q	19	13,803	12,402	11,924	Q	664
2000 to 2003	7	7	7	Q	9	7,215	6,939	6,463	Q	Q
2004 to 2007	6	7	7	Q	11	6,524	6,071	5,722	Q	418
2008 to 2012	5	5	5	Q	Q	5,723	5,225	5,135	Q	Q
Census region and division										
Northeast	14	13	13	50	13	15,534	13,949	13,303	305	794
New England	5	4	4	Q	Q	4,302	3,482	3,317	Q	Q

Table 19-24. Air Conditioning Energy Sources for Nonresidential (%) (Continued)

	Cooling Energy Sources Used (More Than One May Apply)					Floor Space by Cooling Energy Sources Used (More Than One May Apply) (million ft^2)				
	All Buildings	Buildings with Cooling	Elect-ricity	Natural Gas	District Chilled Water	All Buildings	Buildings with Cooling	Electricity	Natural Gas	District Chilled Water
Middle Atlantic	9	9	9	25	Q	11,232	10,467	9,986	216	656
Midwest	22	22	22	Q	4	18,919	17,144	16,826	Q	585
East North Central	13	13	14	Q	4	12,742	11,675	11,474	Q	420
West North Central	9	8	8	Q	Q	6,178	5,469	5,352	Q	Q
South	40	42	42	Q	65	34,279	31,734	29,950	Q	2,479
South Atlantic	20	21	21	Q	41	17,981	17,094	16,368	Q	1,202
East South Central	7	8	7	Q	Q	4,904	4,710	4,307	Q	Q
West South Central	14	14	14	Q	11	11,394	9,931	9,275	Q	773
West	23	23	23	Q	17	18,360	16,467	15,955	Q	749
Mountain	6	6	6	Q	2	4,981	4,489	4,205	Q	Q
Pacific	17	17	17	Q	15	13,379	11,978	11,749	Q	329
Climate region[a]										
Very cold/cold	37	34	34	67	13	31,898	28,228	27,377	403	1,227
Mixed-humid	31	33	33	25	33	27,873	26,365	24,968	272	2,027
Mixed-dry/hot-dry	15	15	15	Q	13	12,037	10,887	10,490	Q	Q
Hot-humid	14	16	15	Q	39	12,831	11,624	11,043	Q	752
Marine	3	2	2	Q	Q	2,454	2,190	2,157	Q	Q
Ownership and occupancy										
Nongovernment owned	86	86	86	92	31	67,550	60,960	59,329	542	2,104
Owner occupied	44	46	46	Q	26	30,637	28,174	26,984	147	1,478
Leased to tenant(s)	31	32	32	Q	4	26,115	23,907	23,688	Q	297
Owner occupied and leased	6	7	7	Q	2	8,873	8,602	8,379	Q	329

Table 19-24. Air Conditioning Energy Sources for Nonresidential (%) (Continued)

	Cooling Energy Sources Used (More Than One May Apply)					Floor Space by Cooling Energy Sources Used (More Than One May Apply) (million ft^2)				
	All Buildings	Buildings with Cooling	Elect-ricity	Natural Gas	District Chilled Water	All Buildings	Buildings with Cooling	Electricity	Natural Gas	District Chilled Water
Unoccupied	4	1	1	N	N	1,925	278	278	N	N
Government owned	14	14	14	Q	69	19,543	18,334	16,705	Q	2,504
Federal	1	1	1	Q	Q	1,573	1,573	1,403	Q	Q
State	3	4	3	Q	37	5,539	5,252	4,086	Q	1,448
Local	10	10	10	Q	30	12,431	11,508	11,217	Q	612

[a] These climate regions were created by the Building America program, sponsored by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE).

Q = Data withheld either because the Relative Standard Error (RSE) was greater than 50% or fewer than 20 buildings were sampled.

N = No cases in reporting sample.

(*) = Value rounds to zero in the units displayed.

Notes: Because of rounding, data may not sum to totals.

Source: EPA Analysis of U.S. DOE (2016).

Table 19-25. Summary Statistics for Residential Air Exchange Rates (in ACH),[a] by Region

	West Region	North Central Region	Northeast Region	South Region	All Regions
Arithmetic mean	0.66	0.57	0.71	0.61	0.63
Arithmetic standard deviation	0.87	0.63	0.60	0.51	0.65
Geometric mean	0.47	0.39	0.54	0.46	0.46
Geometric standard deviation	2.11	2.36	2.14	2.28	2.25
10th percentile	0.20	0.16	0.23	0.16	0.18
50th percentile	0.43	0.35	0.49	0.49	0.45
90th percentile	1.25	1.49	1.33	1.21	1.26
Maximum	23.32	4.52	5.49	3.44	23.32

[a] ACH = Air changes per hour.

Source: Koontz and Rector (1995).

Table 19-26. Distribution of Air Exchange Rates in (ACH)[a] by House Category

House Category	5%	10%	25%	50%	75%	90%	95%
Single family—national average	0.10	0.16	0.27	0.44	0.70	1.00	1.21
Single family—built before 1940	0.17	0.25	0.39	0.58	0.92	1.33	1.57
Single family—built 1941-1969	0.14	0.21	0.34	0.54	0.81	1.10	1.28
Single family—built 1970-1989	0.09	0.14	0.22	0.36	0.55	0.76	0.89
Single family—built 1990 or newer	0.05	0.09	0.15	0.26	0.43	0.60	0.70
Detached—East North Central	0.11	0.17	0.28	0.42	0.75	1.10	1.31
Detached—East South Central	0.08	0.13	0.24	0.48	0.67	0.95	1.12
Detached—Middle Atlantic	0.14	0.20	0.30	0.41	0.76	1.09	1.29
Detached—Mountain	0.09	0.14	0.24	0.50	0.63	0.84	0.98
Detached—New England	0.15	0.22	0.32	0.44	0.82	1.18	1.39
Detached—Pacific	0.15	0.20	0.29	0.40	0.61	0.83	0.97
Detached—South Atlantic	0.07	0.12	0.22	0.48	0.63	0.88	1.04
Detached—West North Central	0.11	0.18	0.29	0.45	0.79	1.16	1.39
Detached—West South Central	0.09	0.15	0.28	0.42	0.67	0.90	1.06
Apartments built before 1940	0.11	0.16	0.21	0.31	0.46	0.61	0.72
Apartments built 1941−1969	0.09	0.13	0.18	0.29	0.42	0.56	0.65
Apartments built 1970−1989	0.06	0.10	0.15	0.23	0.39	0.49	0.55
Apartments built 1990 or newer	0.05	0.07	0.08	0.14	0.18	0.31	0.39

[a] ACH = Air changes per hour.

Source: Persily et al. (2010).

Table 19-27. Summary of Major Projects Providing Air Exchange Measurements in the PFT Database

Project Code	State	Month(s)[a]	Number of Measurements	Mean Air Exchange Rate (ACH)	SD[b]	Percentiles				
						10th	25th	50th	75th	90th
ADM	CA	5−7	29	0.70	0.52	0.29	0.36	0.48	0.81	1.75
BSG	CA	1, 8−12	40	0.53	0.30	0.21	0.30	0.40	0.70	0.90
GSS	AZ	1–3, 8−9	25	0.39	0.21	0.16	0.23	0.33	0.49	0.77
FLEMING	NY	1–6, 8−12	56	0.24	0.28	0.05	0.12	0.22	0.29	0.37
GEOMET1	FL	1,6−8, 10−12	18	0.31	0.16	0.15	0.18	0.25	0.48	0.60
GEOMET2	MD	1−6	23	0.59	0.34	0.12	0.29	0.65	0.83	0.92
GEOMET3	TX	1−3	42	0.87	0.59	0.33	0.51	0.71	1.09	1.58
LAMBERT1	ID	2−3, 10−11	36	0.25	0.13	0.10	0.17	0.23	0.33	0.49
LAMBERT2	MT	1−3, 11	51	0.23	0.15	0.10	0.14	0.19	0.26	0.38
LAMBERT3	OR	1−3, 10−12	83	0.46	0.40	0.19	0.26	0.38	0.56	0.80
LAMBERT4	WA	1−3, 10−12	114	0.30	0.15	0.14	0.20	0.30	0.39	0.50
LBL1	OR	1−4, 10−12	126	0.56	0.37	0.28	0.35	0.45	0.60	1.02
LBL2	WA	1−4, 10−12	71	0.36	0.19	0.18	0.25	0.32	0.42	0.52
LBL3	ID	1−5, 11−12	23	1.03	0.47	0.37	0.73	0.99	1.34	1.76
LBL4	WA	1−4, 11−12	29	0.39	0.27	0.14	0.18	0.36	0.47	0.63
LBL5	WA	2−4	21	0.36	0.21	0.13	0.19	0.30	0.47	0.62
LBL6	ID	3−4	19	0.28	0.14	0.11	0.17	0.26	0.38	0.55
NAHB	MN	1−5, 9−12	28	0.22	0.11	0.11	0.16	0.20	0.24	0.38
NYSDH	NY	1−2, 4, 12	74	0.59	0.37	0.28	0.37	0.50	0.68	1.07
PEI	MD	3−4	140	0.59	0.45	0.15	0.26	0.49	0.83	1.20
PIERCE	CT	1−3	25	0.80	1.14	0.20	0.22	0.38	0.77	2.35
RTI1	CA	2	45	0.90	0.73	0.38	0.48	0.78	1.08	1.52
RTI2	CA	7	41	2.77	2.12	0.79	1.18	2.31	3.59	5.89
RTI3	NY	1–4	397	0.55	0.37	0.26	0.33	0.44	0.63	0.94
SOCAL1	CA	3	551	0.81	0.66	0.29	0.44	0.66	0.94	1.43
SOCAL2	CA	7	408	1.51	1.48	0.35	0.59	1.08	1.90	3.11
SOCAL3	CA	1	330	0.76	1.76	0.26	0.37	0.48	0.75	1.11
UMINN	MN	1–4	35	0.36	0.32	0.17	0.20	0.28	0.40	0.56
UWISC	WI	2–5	57	0.82	0.76	0.22	0.33	0.55	1.04	1.87

[a] 1 = January, 2 = February, etc.

[b] SD = Standard deviation.

Source: Adapted from Versar (1990).

Table 19-28. Distributions of Residential Air Exchange Rates (in ACH)[a] by Climate Region and Season

Climate Region[b]	Season	Sample Size	Arithmetic Mean	Standard Deviation	Percentiles				
					10th	25th	50th	75th	90th
Coldest	Winter	161	0.36	0.28	0.11	0.18	0.27	0.48	0.71
	Spring	254	0.44	0.31	0.18	0.24	0.36	0.53	0.80
	Summer	5	0.82	0.69	0.27	0.41	0.57	1.08	2.01
	Fall	47	0.25	0.12	0.10	0.15	0.22	0.34	0.42
Colder	Winter	428	0.57	0.43	0.21	0.30	0.42	0.69	1.18
	Spring	43	0.52	0.91	0.13	0.21	0.24	0.39	0.83
	Summer	2	1.31	—	—	—	—	—	—
	Fall	23	0.35	0.18	0.15	0.22	0.33	0.41	0.59
Warmer	Winter	96	0.47	0.40	0.19	0.26	0.39	0.58	0.78
	Spring	165	0.59	0.43	0.18	0.28	0.48	0.82	1.11
	Summer	34	0.68	0.50	0.27	0.36	0.51	0.83	1.30
	Fall	37	0.51	0.25	0.30	0.30	0.44	0.60	0.82
Warmest	Winter	454	0.63	0.52	0.24	0.34	0.48	0.78	1.13
	Spring	589	0.77	0.62	0.28	0.42	0.63	0.92	1.42
	Summer	488	1.57	1.56	0.33	0.58	1.10	1.98	3.28
	Fall	18	0.72	1.43	0.22	0.25	0.42	0.46	0.74

[a] ACH = air changes per hour.

[b] The coldest region was defined as having 7,000 or more heating degree days, the colder region as 5,500−6,999 degree days, the warmer region as 2,500−5,499 degree days, and the warmest region as fewer than 2,500 degree days.

— Few observations for summer results in colder regions. Data not available.

Source: Murray and Burmaster (1995).

Table 19-29. Distribution of Measured 24-hour Average Air Exchange Rates in 31 Detached Homes in North Carolina

Season: Year[a] or Cohort	Number of Detached Homes	Number of days Windows Opened[b]	Air Exchange Rates (h^{-1})											
			Sample Size	Mean	SD	Min	P5	P10	P25	P50	P75	P90	P95	Max
Summer: 2000	29	90(44%)	203	0.50	0.58	0.05	0.16	0.21	0.26	0.36	0.50	0.70	1.53	4.83
Fall: 2000	27	63(38%)	167	0.60	0.37	0.09	0.21	0.24	0.35	0.51	0.77	1.03	1.29	2.24
Winter: 2000−01	23	29(22%)	129	1.11	0.88	0.23	0.34	0.40	0.56	0.81	1.25	2.53	3.34	4.87
Spring: 2001	23	71(50%)	143	0.64	0.48	0.15	0.20	0.22	0.34	0.53	0.72	1.16	1.76	3.17
Raleigh cohort[c]	27	215(39%)	555	0.70	0.66	0.05	0.21	0.24	0.32	0.51	0.77	1.29	2.00	4.87
Chapell Hill cohort[d]	4	38(44%)	87	0.56	0.44	0.06	0.12	0.16	0.26	0.45	0.70	1.25	1.43	2.58
All	31	253(39%)	642	0.68	0.63	0.05	0.20	0.23	0.32	0.50	0.76	1.27	1.85	4.87

[a] Summer: June, July, and August; fall: September, October, and November; winter: December, January, and February; spring: March, April, and May.
[b] Percentage of days windows are opened in parenthesis relative to corresponding sample size.
[c] Low to moderate socioeconomic status neighborhoods.
[d] Moderate socioeconomic status neighborhoods.
SD = Standard deviation.

Source: Breen et al. (2010).

Table 19-30. Air Exchange Rates in Commercial Buildings by Building Type

Building Type	*N*	Mean (ACH[a])	SD	10th Percentile	Range (ACH)
Educational	7	1.9			0.8 to 3.0
Office (<100,000 ft^2)	8	1.5			0.3 to 4.1
Office (>100,000 ft^2)	14	1.8			0.7 to 3.6
Libraries	3	0.6			0.3 to 1.0
Multiuse	5	1.4			0.6 to 1.9
Naturally ventilated	3	0.8			0.6 to 0.9
Total (all commercial)	40	1.5	0.87	0.60[b]	0.3 to 4.1

[a] ACH = air changes per hour.
[b] Calculated from data presented in Turk et al. (1987), Table IV.C.1.
N = Number of observations.
SD = Standard deviation.

Source: Turk et al. (1987).

Table 19-31. Summary Statistics of Ventilation Rates

Measurement	*n*	Mean	SD	Min	25th %	Median	75th %	95th %	Max
Whole building ventilation rate									
Ventilation rate per area (L/s per m^2)	40	1.4	1.4	0.1	0.6	1.0	1.5	3.9	7.7
Ventilation rate per person (L/s per person)	40	61	71	7	17	36	72	261	321
Air exchange rate (per hour)	40	1.6	1.7	0.3	0.7	1.0	1.9	4.7	9.1
Air exchange rate, doors open (per hour)	7	3.1	2.9	0.6	1.0	2.3	4.0	9.1	9.1
Air exchange rate, doors shut (per hour)	33	1.3	1.1	0.3	0.7	1.0	1.5	4.3	5.1
HVAC ventilation[a]									
Outdoor air delivery rate by HVAC units per Unit floor area (L/s per m^2)	23	1.2	1.4	0.1	0.3	0.6	1.3	3.4	5.4
Outdoor air delivery rate by HVAC units per person (L/s per person)	23	35	30	2	10	26	69	83	95
Percentage of total ventilation supplied through HVAC units[b] (%)	14	39	25	8	14	35	63	78	78
Additional ventilation rate (per hour) [c]									
In buildings with doors kept open	7	2.9	3.0	0.4	1.2	1.8	4.0	9.1	9.1
In buildings with doors shut	29	0.5	0.6	0.0	0.0	0.4	0.7	1.9	1.9

[a] Fourteen buildings had HVAC units that did not provide outdoor air. Complete measurements could not be made on three buildings.

[b] Fourteen buildings had 0% of outdoor air provided through the HVAC units, and nine buildings were estimated to have 100% of outdoor air provided through HVAC units.

[c] One of the 14 buildings that did not provide HVAC ventilation had leakage into the system, and thus, is not included in the calculation for additional ventilation.

Source: Bennett et al. (2012).

Table 19-32. Statistics of Estimated Normalized Leakage Distribution Weighted for all Dwellings in the United States

House Code	Estimated Normalized Leakage Percentiles							Estimated	
	5th	10th	25th	50th	75th	90th	95th	GM	GSD
Low income	0.30	0.39	0.62	0.98	1.5	2.2	2.7	0.92	1.9
Conventional	0.17	0.21	0.31	0.48	0.75	1.1	1.4	0.49	1.9
Whole United States	0.17	0.22	0.33	0.52	0.84	1.3	1.7	0.54	2.0

GM = Geometric mean.
GSD = Geometric standard deviation.

Source: Chan et al. (2005).

Table 19-33. Particle Deposition During Normal Activities

Particle Size Range	Particle Removal Rate (hour^{-1})
1−5	0.5
5−10	1.4
10−25	2.4
>25	4.1

Source: Adapted from Thatcher and Layton (1995).

Table 19-34. Deposition Rates for Indoor Particles

Size Fraction	Deposition Rate (hour^{-1})
$PM_{2.5}$	0.39
PM_{10}	0.65
Coarse	1.01

Source: Adapted from Wallace (1996).

Table 19-35. Measured Deposition Loss Rate Coefficients (hour^{-1})

Median particle diameter (µm)	Fans Off			Room Core Airspeed 5.4 cm/second			Room Core Airspeed 14.2 cm/second 14.2 cm/s			Room Core Airspeed 19.1 cm/second		
	Bare room surfaces	Carpeted room	Fully furnished	Bare room surfaces	Carpeted room	Fully furnished	Bare room surfaces	Carpeted room	Fully furnished	Bare room surfaces	Carpeted room	Fully furnished
0.55	1.10	0.12	0.20	0.10	0.13	0.23	0.09	0.18	0.23	0.14	0.16	0.27
0.65	0.10	0.12	0.20	0.10	0.13	0.23	0.10	0.19	0.24	0.14	0.17	0.28
0.81	0.10	0.11	0.19	0.10	0.15	0.24	0.11	0.19	0.27	0.15	0.19	0.30
1.00	0.13	0.12	0.21	0.12	0.20	0.28	0.15	0.23	0.33	0.20	0.25	0.38
1.24	0.20	0.18	0.29	0.18	0.28	0.38	0.25	0.34	0.47	0.33	0.38	0.53
1.54	0.32	0.28	0.42	0.27	0.39	0.54	0.39	0.51	0.67	0.51	0.59	0.77
1.91	0.49	0.44	0.61	0.42	0.58	0.75	0.61	0.78	0.93	0.80	0.89	1.11
2.37	0.78	0.70	0.93	0.64	0.84	1.07	0.92	1.17	1.32	1.27	1.45	1.60
2.94	1.24	1.02	1.30	0.92	1.17	1.46	1.45	1.78	1.93	2.12	2.27	2.89
3.65	1.81	1.37	1.93	1.28	1.58	1.93	2.54	2.64	3.39	3.28	3.13	3.88
4.53	2.83	2.13	2.64	1.95	2.41	2.95	3.79	4.11	4.71	4.55	4.60	5.46
5.62	4.41	2.92	3.43	3.01	3.17	3.51	4.88	5.19	5.73	6.65	5.79	6.59
6.98	5.33	3.97	4.12	4.29	4.06	4.47	6.48	6.73	7.78	10.6	8.33	8.89
8.66	6.79	4.92	5.45	6.72	5.55	5.77	8.84	8.83	10.5	12.6	11.6	11.6

Source: Thatcher et al. (2002).

Table 19-36. Total Dust Loading for Carpeted Areas

Household	Total Dust Load (g/m^2)	Fine Dust (<150 µm) Load (g/m^2)
1	10.8	6.6
2	4.2	3.0
3	0.3	0.1
4	2.2; 0.8	1.2; 0.3
5	1.4; 4.3	1.0; 1.1
6	0.8	0.3
7	6.6	4.7
8	33.7	23.3
9	812.7	168.9

Source: Adapted from Roberts et al. (1991).

Table 19-37. Particle Deposition and Resuspension During Normal Activities

Particle Size Range (µm)	Particle Deposition Rate (hour^{-1})	Particle Resuspension Rate (hour^{-1})
0.3−0.5	(Not measured)	9.9×10^{-7}
0.6−1	(Not measured)	4.4×10^{-7}
1−5	0.5	1.8×10^{-5}
5−10	1.4	8.3×10^{-5}
10−25	2.4	3.8×10^{-4}
>25	4.1	3.4×10^{-5}

Source: Adapted from Thatcher and Layton (1995).

Table 19-38. Dust Mass Loading after 1 Week without Vacuum Cleaning

Location in Test House	Dust Loading (g/m^2)
Tracked area of downstairs carpet	2.20
Untracked area of downstairs carpet	0.58
Tracked area of linoleum	0.08
Untracked area of linoleum	0.06
Tracked area of upstairs carpet	1.08
Untracked area of upstairs carpet	0.60
Front doormat	43.4

Source: Adapted from Thatcher and Layton (1995).

Table 19-39. Simplified Source Descriptions for Airborne Contaminants

Description	Components	Dimensions
Direct emission rate		
Combustion emission rate	$E_f H_f M_f$	g hour^{-1}
	E_f = emission factor	g J^{-1}
	H_f = fuel content	J mol^{-1}
	M_f = fuel consumption rate	mol hour^{-1}
Volume emission rate	$Q_p C_p\_\varepsilon$	g hour^{-1}
	Q_p = volume delivery rate	m^3 hour^{-1}
	C_p = concentration in carrier	g m^{-3}
	ε = transfer efficiency	g g^{-1}
Mass emission rate	$M_p w_e \varepsilon$	g hour^{-1}
	M_p = mass delivery rate	g hour^{-1}
	w_e = weight fraction	g g^{-1}
	ε = transfer efficiency	g g^{-1}
Diffusion limited emission rate	$(D_f \delta^{-1})(C_s - C_i)A_i$	g hour^{-1}
	D_f = diffusivity	m^2 hour^{-1}
	δ^{-1} = boundary layer thickness	meters
	C_s = vapor pressure of surface	g m^{-3}
	C_i = room concentration	g m^{-3}
	A_i = area	m^2
Exponential emission rate	$A_i E_o e^{-k t}$	g hour^{-1}
	A_i = area	m^2
	E_o = initial unit emission rate	g hour^{-1} m^{-2}
	k = emission decay factor	hour^{-1}
	t = time	hours
Transport		
Infiltration	$Q_{ji} C_j$	g hour^{-1}
Interzonal	Q_{ji} = air flow from zone j	m^3 hour^{-1}
Soil gas	C_j = air concentration in zone j	g m^{-3}

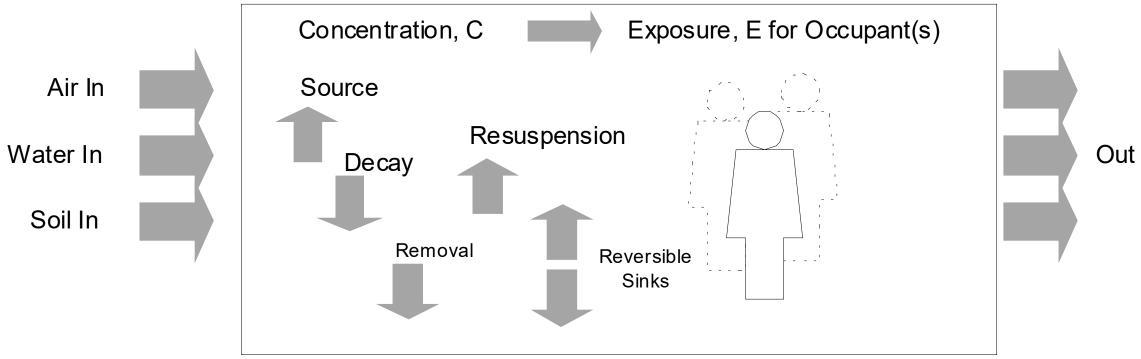

Figure 19-1. Elements of residential exposure.

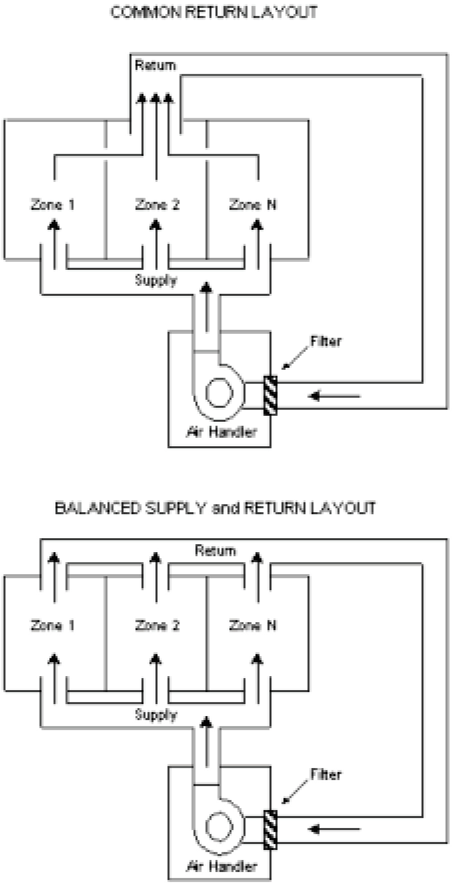

Figure 19-2. Configuration for residential forced-air systems.

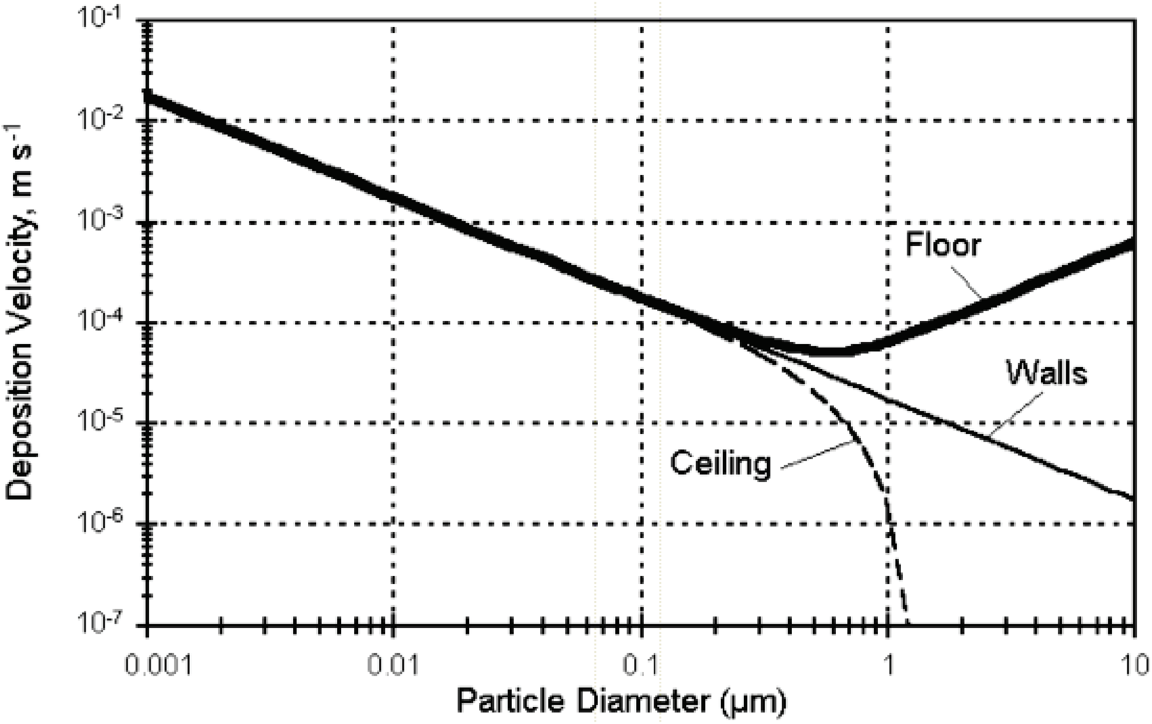

Figure 19-3. Idealized patterns of particle deposition indoors.

Source: Adapted from Nazaroff and Cass (1989a).

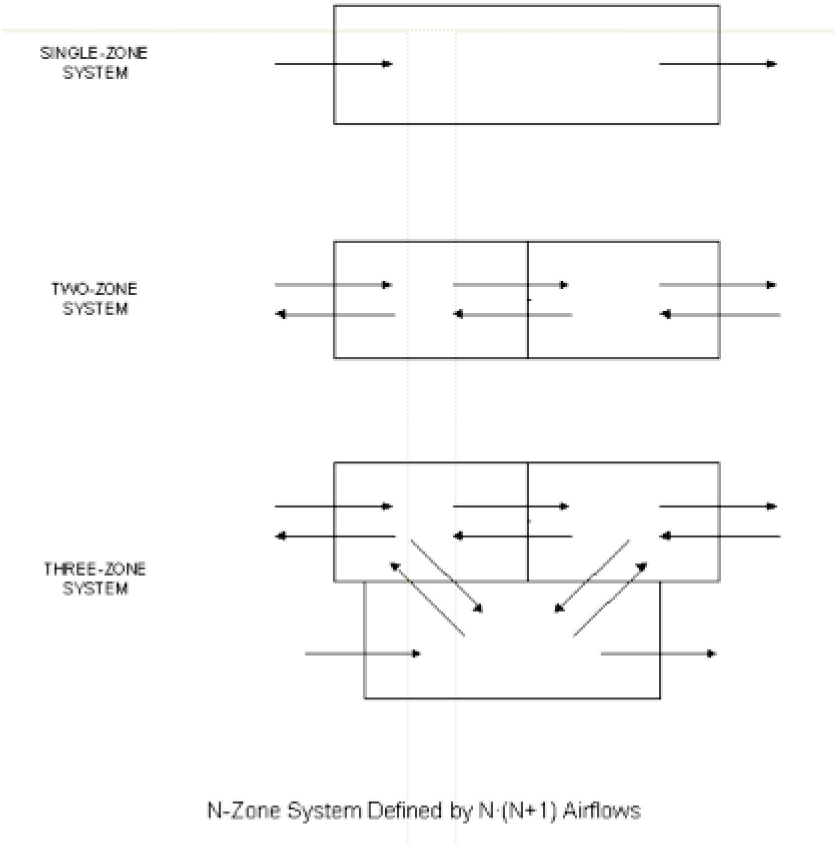

Figure 19-4. Air flows for multiple-zone systems.

Source: Koontz and Rector (1995).

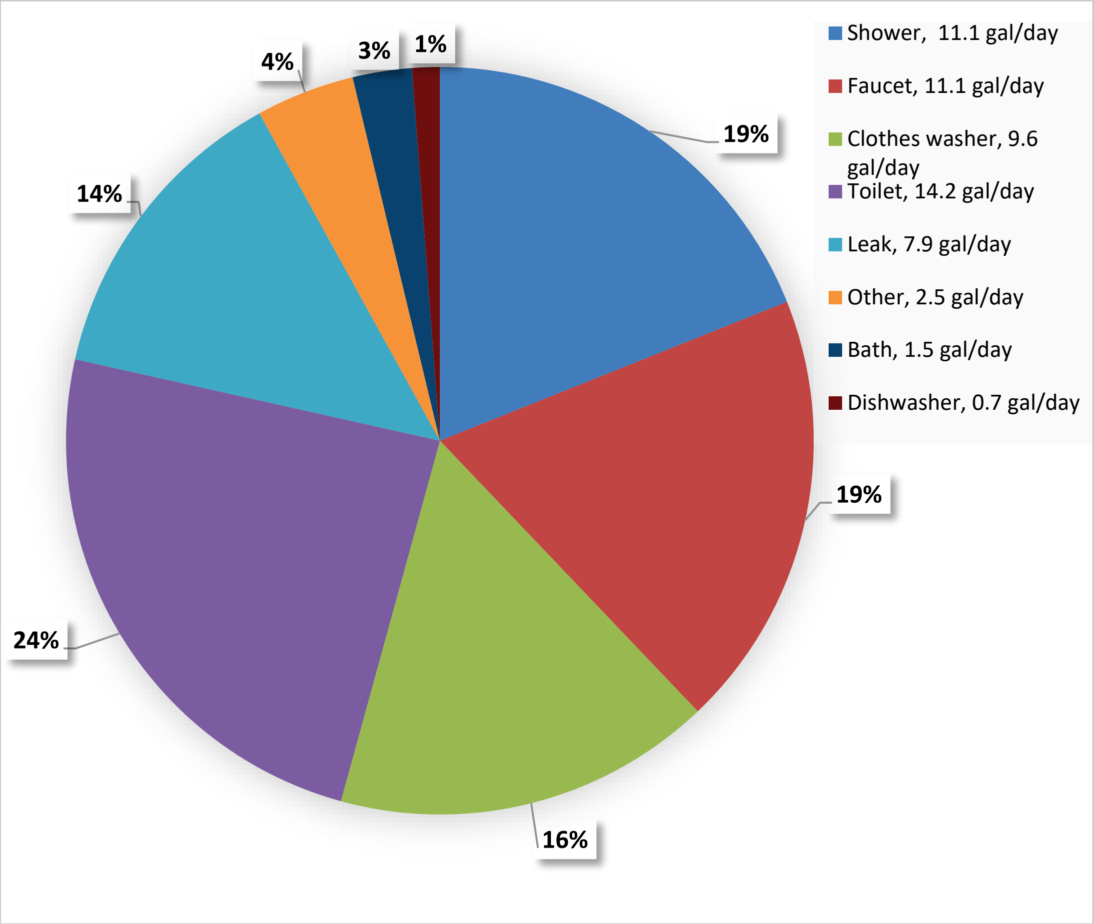

Figure 19-5. Average percentage per capita indoor water use across all uses.

Source: DeOreo et al. (2016). Reprinted with permission. © Water Research Foundation.

APPENDIX A

Table A-1. Terms Used in Literature Searches
Indoor air and pollutant
Indoor air and mixing
Indoor air and exposure
Indoor air and quality
Indoor air and sinks
Indoor air and exchange
Infiltration rates
Vapor intrusion
House volume
Room volumes
Dunn JE
Axley JW
Koontz MD
Nazaroff WW
Targeted search terms
Uniform mixing
Vapor intrusion
Soil gas entry indoors
Residential air leakage models
Indoor particles
Interzonal airflow models
House dust and soil loadings