17. RESIDENTIAL BUILDING CHARACTERISTICS

17.1. INTRODUCTION

Unlike previous chapters in this handbook which focus on human behavior or characteristics that affect exposure, this chapter focuses on residence characteristics. Assessment of exposure in residential 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 residence. The purpose of this chapter is to provide data that are available on residence characteristics that affect exposure in an indoor environment. Source-receptor relationships in residential exposure scenarios can be complex due to interactions among sources, and transport/transformation processes that result from chemical-specific and building-specific factors. Figure 17-1 illustrates the complex factors that must be considered when conducting exposure assessments in a residential setting. 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 17-1, 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 the exposure scene.

Inhalation exposure assessments in residential and other indoor settings are 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. This macroscopic level, well-mixed perspective forms 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). Nazzaroff and Cass (1986) and Wilkes et al. (1992) have used code-intensive computer programs featuring finite difference or finite element numerical techniques to model mass balance. A simplified approach using desk top spreadsheet programs has been used by Jennings et al. (1985).

In order to model mass balance of indoor contaminants, the indoor air volume is represented as a network of interconnected zones. Because conditions in a given zone are determined by interactions with other connecting zones, the multizone model is stated as a system of simultaneous equations. The mathematical framework for modeling indoor air has been reviewed by Sinden (1978) and Sandberg (1984).

Indoor air quality models typically 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 -- developed at the National Institute of Standards and Technology (NIST) with support from U.S. EPA and the U.S. Department of Energy (DOE) (Axley, 1988; Grot, 1991; Walton, 1993);

- EXPOSURE -- developed at the Indoor Air Branch of U.S. EPA Air and Energy Engineering Research Laboratory (EPA/AEERL) (Sparks, 1988, 1991);

- MCCEM -- the Multi-Chamber Consumer Exposure Model developed for U.S EPA Office of Pollution Prevention and Toxics (EPA/OPPT) (GEOMET, 1989; Koontz and Nagda, 1991); and

- THERdbASE -- the Total Human Exposure Relational Data Base and Advanced Simulation Environment software developed by researchers at the Harry Reid Center for Environmental Studies at University Nevada, Las Vegas (UNLV) (Pandian et al., 1993).

Section 17.2 of this chapter summarizes existing data on building characteristics (volumes, surface areas, mechanical systems, and types of foundations). Section 17.3 summarizes transport phenomena that affect chemical transport (airflow, chemical-specific deposition and filtration, and effects of water supply and soil tracking). Section 17.4 provides information on various types of indoor sources associated with airborne exposure, waterborne sources, and soil/house dust sources. Section 17.5 summarizes advanced concepts.

17.2. BUILDING CHARACTERISTICS

17.2.1. Key Volumes of Residence Studies

Versar (1990) - Database on Perfluorocarbon Tracer (PFT) Ventilation Measurements - A database of time-averaged air exchange and interzonal airflow measurements in more than 4,000 residences has been compiled by Versar (1990) to allow researchers to access these data (see Section 17.3.2). 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 do 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 (see Section 17.3.2) to compensate for the geographic imbalance.

U.S. DOE (1995) - Housing Characteristics 1993, 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. DOE's RECS (U.S. DOE, 1995). In addition to collecting information on energy use, this triennial survey collects data on housing characteristics including direct measurements of total and heated floor space for buildings visited by survey specialists. For the most recent survey (1993), a multistage probability sample of over 7,000 residences was surveyed, representing 96 million residences nationwide. The survey response rate was 81.2 percent. Volumes were estimated from the RECS measurements by multiplying the heated floor space area by an assumed ceiling height of 8 feet, recognizing that this assumed height may not apply universally to all homes.

Results for residential volume distributions from the RECS (Thompson, 1995) are presented in Table 17-1. Estimated parameters of residential volume distributions (in cubic meters) from the PFT database (Versar, 1990) are also summarized in Table 17-1, for comparison to the RECS data. The arithmetic means from the two sources are identical (369 cubic meters). The medians (50th percentiles) are very similar: 310 cubic meters for the RECS data, and 321 cubic meters for the PFT database. Cumulative frequency distributions from the two sources (Figure 17-2) also are quite similar, especially between the 50th and 75th percentiles.

The RECS also provides relationships between average residential floor areas and factors such as housing type, ownership, household size and structure age. The predominant housing type--single-family detached homes--also has the largest average volume (Table 17-2). Multifamily units and mobile homes have volumes averaging about half that of single-family detached homes, with single-family attached homes about halfway between these extremes. Within each category of housing type, owner-occupied residences average about 50 percent greater volume than rental units. The relationship of residential volume to household size (Table 17-3) is of particular interest for purposes of exposure assessment. For example, one-person households would not include children, and the data in the table indicate that multi-person households occupy residences averaging about 50 percent greater volume than residences occupied by one-person households.

Data on year of construction indicate a slight decrease in residential volumes between 1950 and 1984, followed by an increasing trend over the next decade. 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.

Murray (1996) - Analysis of RECS and PFT Databases. Using a database from the 1993 RECS and an assumed ceiling height of 8 feet, Murray (1996) 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 17-1. Murray's (1996) 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 measure-ments, Murray (1996) estimated an average volume of 369 m^3, the same as previously given in Table 17-1. 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.

17.2.2. Volumes and Surface Areas of Rooms

Room Volumes - 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 cubic meters per hour and, correspondingly, express volumes in cubic meters. A measurement in cubic feet can be converted to cubic meters by multiplying the value in cubic feet 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 cubic feet or 24.5 cubic meters. Similarly, a living room with dimensions of 12 feet wide by 20 feet long by 8 feet high has a volume of 1920 cubic feet or 54.3 cubic meters, and a bathroom with dimensions of 5 feet by 12 feet by 8 feet has a volume of 480 cubic feet or 13.6 cubic meters.

Murray (1996) 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 (1996) 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.

Surface Areas - 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 17-4 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 12 feet (typical for commercial buildings). The loading ratios for the 8-foot ceiling height range from 0.98 m^2m^{-3} to 2.18 m^2m^{-3} for wall area and from 0.36 m^2m^{-3} to 0.44 m^2m^{-3} for floor area. In comparison, ASTM Standard E 1333 (ASTM, 1990), for large-chamber testing of formaldehyde levels from wood products, specifies the following loading ratios: (1) 0.95 m^2m^{-3} for testing plywood (assumes plywood or paneling on all four walls of a typical size room); and (2) 0.43 m^2m^{-3} for testing particleboard (assumes that particleboard decking or underlayment would be used as a substrate for the entire floor of a structure).

Products and Materials - Table 17-5 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 Table 17-5 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 Table 17-5 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 carpeting, either as an indoor source or as an indoor sink, then the ASTM loading ratio of 0.43 m^2m^{-3} for floor materials could 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 0.43 m^2m^{-3} and coverage of 80% would have 103 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.

Furnishings - Information on the relative abundance of specific types of indoor furnishings, such as draperies or upholstered furniture, was not readily available. The exposure assessor is advised to rely on common sense and professional judgment. For example, the number of beds in a residence is usually related to household size, and information has been provided (Table 17-3) on average house volume in relation to household size.

17.2.3. 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 and air conditioning (HAC); (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 will not disperse to floors below.

Central forced-air HAC 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 17-3) that can remove particle-phase contaminants. Further removal of particles, via deposition on various room surfaces (see Section 17.3.2), is accomplished through increased air movement when the air handler is operating.

Figure 17-3 also distinguishes forced-air HAC 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 cubic feet per minute (cfm), or 170 cubic meters per hour, is operated continuously in a house with a volume of 400 cubic meters, then the expected increment in the air exchange rate of the house would be 170 $m^3 h^{-1}$ / 400 m^3, or approximately 0.4 air changes per hour.

17.2.4. 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, and provides 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.

Lucas et al. (1992) - National Residential Radon Survey - The National Resdental Radon Survey, sponsored by the U.S. EPA, was conducted by Lucas et al. (1992) in about 5,700 households nationwide. In addition to radon measurements, information on a number of housing characteristics was collected, including whether each house had a basement. The estimated percentage (45.2 percent) of homes in the U.S. having basements (Table 17-6) from this survey is the same as found by the RECS (Table 17-7).

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 percent). The lowest prevalence (4 percent) was for the South Central region (i.e., EPA Region 6), which includes Arkansas, Louisiana, New Mexico, Oklahoma, and Texas. Table 17-8 presents the States associated with each Census Region and EPA Region.

U.S. DOE (1995) - Housing Characteristics 1993 - Residential Energy Consumption Survey (RECS) - The most recent RECS (described in Section 17.2.1) was administered in 1993 to over 7,000 households (U.S. DOE, 1995). 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. Table 17-7 presents estimates from the survey of the percentage of residences with each foundation type, by census region, and for the entire U.S. The percentages can add to more than 100 percent because some residences have more than one type of foundation; for example, most split-level structures have a partial basement combined with some crawlspace that typically is enclosed.

The data in Table 17-7 indicate that close to half (45 percent) of residences nationwide have a basement, and that fewer than 10 percent have a crawl space that is open to outside. It also shows that a large fraction of homes have concrete slabs (31 percent). There are also variations by census region. For example, nearly 80 percent of the residences in the Northeast and Midwest regions have basements. In the South and West regions, the predominant foundation types are concrete slabs and enclosed crawl spaces. Table 17-8 illustrates the four Census Regions.

17.3. TRANSPORT RATES

17.3.1. Background

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

- Air exchange - 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 distribution of airflows across the building envelope that contribute 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 mechanical ventilation systems. Basic concepts have been reviewed by ASHRAE (1993). 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 pronounced.

In examining a data base of air leakage measurements, Sherman and Dickerhoff (1996) observed that houses built prior to 1980 showed a clear increase in leakage with increasing age and were leakier, on average, than newer houses. They further observed that the post-1980 houses did not show any trend in leakiness with age.

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 mechanical ventilation systems that circulate indoor air through the use of fans. 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.

17.3.2. 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. 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 air changes per hour (ACH, with units of h^{-1}), the ratio of the airflow (m^3 h^{-1}) to the volume (m^3).

No measurement surveys have been conducted to directly evaluate the range and distribution of residential air exchange rates. 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 perfluorocarbon tracer (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. 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, 1990).

Nazaroff et al. (1988) - Prior to the Koontz and Rector (1995) study, 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 255 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. 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.

Versar (1990) - 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. The larger projects in the PFT database are summarized in Table 17-9, in terms of the number of measurements (samples), states where, and months when, samples were taken, and summary statistics for their respective distributions of measured air exchange rates. For selected projects (LBL, RTI, 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.

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.

Summary statistics from the Koontz and Rector (1995) analysis are shown in Table 17-10, 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 data base. Although the estimates are based on thousands of measurements, the residences represented in the database are not a random sample of the United States housing stock. The sample population is not balanced in terms of geography or time of year. 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 which 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 17-10 are believed to represent the best available information on the distribution of air exchange rates across United States residences throughout the year.

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 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. The months of December, January and February were defined as winter, March, April and May were defined as spring, and so on. The results of Murray and Burmaster (1995) are summarized in Table 17-11. 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 (Section 17.3.2), 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 this region in particular should be used with caution since 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 (Table 17-11).

17.3.3. 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

Liddament and Allen (1983), and by Persily and Linteris (1984). Basic principles are concisely summarized in the ASHRAE Handbook of Fundamentals (ASHRAE, 1993). 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 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:

$$A = a + b\,|T_i - T_o| + cU^n \qquad \text{(Eqn. 17-1)}$$

where:

- A = air infiltration rate (h^{-1})
- T_i = indoor temperature (°C)
- T_o = outdoor temperature (°C)
- U = windspeed (ms^{-1})
- n is an exponent with a value typically between 1 and 2
- 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:

$$A = L\left(0.006\Delta T + \frac{0.03}{C}\,U^{1.5}\right) \qquad \text{(Eqn. 17-2)}$$

where:

- A = average air changes per hour or infiltration rate, h^{-1}
- L = generalized house leakiness factor ($1 < L < 5$)
- C = terrain sheltering factor ($1 < C < 10$)
- ΔT = indoor-outdoor temperature difference (C°)
- U = windspeed (ms^{-1})

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 ms^{-1}, the predicted infiltration rate for that house would be 3 (0.006 x 20 + 0.03/5 x 51.5), or 0.56 air changes per hour. 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 17.2.3). Occupant behavior, such as opening windows, can, of course, overwhelm the idealized effects of temperature and wind speed.

17.3.4. 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.

17.3.4.1. Deposition

The deposition of particulate matter and reactive gas-phase pollutants to indoor surfaces is often stated in terms of a characteristic deposition velocity ($m\ h^{-1}$) allied to the surface-to-volume ratio ($m^2\ m^{-3}$) of the building or room interior, forming a first order loss rate (h^{-1}) similar to that of air exchange. Theoretical considerations specific to indoor environments have been summarized in comprehensive reviews by Nazaroff and Cass (1989) 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 17-4 illustrates the general trend for particle deposition across the size range of general concern for inhalation exposure (<10 μm). 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).

Wallace (1996) - Indoor Particles: A Review - In a major review of indoor particles, Wallace (1996) cited overall particle deposition rates for respirable ($PM_{2.5}$), inhalable (PM_{10}), and coarse (difference between PM_{10} and $PM_{2.5}$) size fractions determined from EPA's PTEAM study. These values, listed in Table 17-12, were derived from measurements conducted in nearly 200 residences.

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. These values are listed in Table 17-13. In a subsequent evaluation of data collected in 100 Dutch residences, Layton and Thatcher (1995) estimated settling velocities of 2.7 m h^{-1} for lead-bearing particles captured in total suspended particulate matter (TSP) samples.

17.3.4.2. Filtration

A variety of air cleaning techniques have been applied to residential settings. Basic principles related to residential-scale air cleaning technologies have been summarized in conjunction with reporting early test results (Offerman et al., 1984). General engineering principles are summarized in ASHRAE (1988). In addition to fibrous filters integrated into central heating and air conditioning systems, extended surface filters and High Efficiency Particle Arrest (HEPA) filters as well as electrostatic systems are available to increase removal efficiency. Free-standing air cleaners (portable and/or console) are also being used. 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.

17.3.5. Interzonal Airflows

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 17-5, 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, six airflows are needed to accommodate interzonal airflows plus air exchange; with three zones, twelve 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.

17.3.6. Water Uses

Among indoor water uses, showering, bathing and handwashing of dishes or clothes provide the primary opportunities for dermal exposure. Virtually all indoor water uses will result in some volatilization of chemicals, leading to inhalation exposure.

The exposure potential for a given situation will depend on the source of water, the types and extents of water uses, and the extent of volatilization of specific chemicals. According to the results of the 1987 Annual Housing Survey (U.S. Bureau of the Census, 1992), 84.7 percent of all U.S. housing units receive water from a public system or private company (as opposed to a well). Across the four major regions defined by the U.S. Census Bureau (Northeast, South, Midwest, and West), the percentage varies from 82.5 in the Midwest region to 93.2 in the West region (the Northeast and South regions both are very close to the national percentage).

The primary types of water use indoors can be classified as showering/bathing, toilet use, clothes washing, dishwashing, and faucet use (e.g., for drinking, cooking, general cleaning, or washing hands). Substantial information on water use has been collected in California households by the Metropolitan Water District of Southern California (MWD, 1991) and by the East Bay Municipal Utility District (EBMUD, 1992). An earlier study by the U.S. Department of Housing and Urban Development (U.S. DHUD, 1984) monitored water use in 200 households over a 20-month period. The household selection process for this study was not random; it involved volunteers from water companies and engineering organizations, most of which were located in large metropolitan areas. Nazaroff et al. (1988) also assembled the results of several smaller surveys, typically involving between 5 and 50 households each.

A common feature of the various studies cited above is that the results were all reported in gallons per capita per day (gcd), or in units that could be easily converted to gcd. Most studies also provided estimates by type of use--shower/bath, toilet, laundry, dishwashing, and other (e.g., faucets). A summary of the various study results is provided in Table 17-14. There is generally about a threefold variation across studies for total in-house water use as well as each type of use. Central values for total use, were obtained by taking the mean and median across the studies for each type of water use and then summing these means/medians across uses. These central values are shown at the bottom of the table. The means and medians were summed across types of uses to obtain the mean for all uses combined because only a subset of the studies reported values for other uses.

The following sections provide a summary of the water use characteristics for the primary types of water uses indoors. To the extent found in the literature, each water use is described in terms of the frequency of use; flowrate during the use; quantity of water used during each occurrence of the water use; and quantity used by an average person. Table 17-15 summarizes the studies of U.S. DHUD and the Power Authorities by locations and number of households.

Caution should be exercised when using the data collected in these studies and shown here. The participants in these studies are not a representative sample of the general population. The participants consisted of volunteers, mostly from large metropolitan areas.

Showering and Bathing Water Use Characteristics - The HUD study (U.S. DHUD, 1984) monitored 162 households for shower duration. The individuals were also subdivided by people who only shower or only bath. The results are given in Table 17-16. The flowrates of various types of shower heads were also evaluated in the study (Table 17-17).

Toilet Water Use Characteristics - The HUD study (U.S. DHUD, 1984) reported water volume per flush for various types of toilets and monitored 162 households for shower duration. The results of this study are shown in Table 17-18. Since the HUD study was conducted prior to 1984, the newer (post 1984) conserving toilets that are designed to use approximately 1.6 gallons per flush were not tested.

The frequency of use for toilets in households was examined in several studies (U.S. DHUD, 1984; Ligman, et al., 1974; Siegrist, 1976). The observed mean frequencies in these studies are given in Table 17-19. Tables 17-20 through 17-24 present indoor water use frequencies for dishwashers and clothes washers.

17.3.7. House Dust and Soil

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 (see, for example, Wolkoff and Wilkins, 1994; Hirvonen et al., 1995), pesticides from imported soil particles as well as from direct applications indoors (see, for example, Roberts et al., 1991), and trace metals derived from outdoor sources (see, for example, 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. More recent data, however, have shown that deposition (incompletely addressed in earlier studies) accounts for the indoor-outdoor contrast, and outdoor particles smaller than 10 μm aerodynamic diameter penetrate the building envelope as completely as nonreactive gases (Wallace, 1996).

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 also measured in conjunction with the Non-Occupational Pesticide Exposure Study (NOPES). In this study house dust was sampled from a representative grid using a specially constructed high-volume surface sampler (HVS2). The surface sampler collection efficiency was verified in conformance with ASTM F608 (ASTM, 1989). The data summarized in Table 17-25 were 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.

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 (Table 17-26). 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.

Mass loading of floor surfaces (Table 17-27) was measured in the study of Thatcher and Layton (1995) by thoroughly cleaning the house and sampling accumulated dust, after one week of normal habitation. Methodology, validated under ASTM F608 (ASTM, 1989), showed fine dust recovery efficiencies of 50 percent with new carpet and 72 percent 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.

17.4. 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., 1987; 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.

17.4.1. Source Descriptions for Airborne Contaminants

Table 17-28 summarizes simplified indoor source descriptions for airborne chemicals for direct discharge 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-discharge 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-discharge sources would include volatiles released from water use and from pressurized consumer products. Resuspension of house dust (see Section 17.3.7) 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 non-emitting 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 17-28 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:

$$\frac{E_c}{E_o} = e^{-k_s t_c} \quad \text{or} \quad \frac{M_c}{M} = 1 - e^{-k_s t_c} \qquad \text{(Eqn. 17-3)}$$

The critical time period can be derived from product-specific considerations (e.g., equating drying time for a paint to 90 percent 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:

$$M = \int_0^\infty E_o e^{-k_s t} dt = \frac{E_o}{k_s} \qquad \text{(Eqn. 17-4)}$$

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 (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 the multiple-zone model.

17.4.2. Source Descriptions for Waterborne Contaminants

Residential water supplies may convey chemicals to which occupants can be exposed through ingestion, dermal contact, or inhalation. These chemicals may appear in the form of contaminants (e.g., trichloroethylene) as well as naturally-occurring byproducts of water system history (e.g., chloroform, radon). Among indoor water uses, showering, bathing and handwashing 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 situation 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 (summarized in Section 17.3) include showering/bathing, toilet use, clothes washing, dishwashing, and faucet use (e.g., for drinking, cooking, general cleaning, or washing hands).

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 h^{-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, Little, 1992; Andelman, 1990; McKone, 1987).

Release rates are formulated as:

$$S = K_m F_W \left[C_w - \frac{C_a}{H} \right] \qquad \text{(Eqn. 17-5)}$$

where:

S	=	chemical release rate (g h^{-1})
K_m	=	dimensionless mass-transfer coefficient
F_w	=	water flow rate (m^3 h^{-1})
C_w	=	concentration in feed water (g m^{-3})
C_a	=	concentration in air (g m^{-3})
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):

$$\frac{1}{K}\left(\frac{D_{Li}}{D_{Lr}}\right)^{1/2} = \frac{1}{K_{Lr}} = \frac{1}{K_{Gr}} - \frac{1}{H}\left(\frac{D_{Gr}}{D_{Gi}}\right)^{2/3}\left(\frac{D_{Li}}{D_{Lr}}\right)^{1/2} \qquad \text{(Eqn. 17-6)}$$

where:

D_L	=	liquid diffusivity (m^2 s^{-1})
D_G	=	gas diffusivity (m^2 s^{-1})
K_L	=	liquid-phase mass transfer coefficient
K_G	=	gas-phase mass transfer coefficient
H	=	dimensionless Henry's Law constant

17.4.3. Soil and House Dust Sources

The rate process descriptions compiled for soil and house dust in Section 17.3 provide inputs for estimating indoor emission rates (S_d, g h^{-1}) in terms of dust mass loading (M_d, g m^{-2}) combined with resuspension rates (R_d, h^{-1}) and floor area (A_f, m^2):

$$S_d = M_d \, R_d \, A_f \qquad \text{(Eqn. 17-7)}$$

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).

17.5. ADVANCED CONCEPTS

17.5.1. 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) offers 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. 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 U.S. 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 ten times higher than for other locations in the room during early stages of mixing and transport.

Similar investigations conducted by Furtaw et al. (1995) involved a series of experiments in a controlled-environment room-sized chamber. Furtaw et al. (1995) 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.

17.5.2. Reversible Sinks

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.

Interactive sinks (and models of the processes) are of a 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. Recent publications (Axley et al., 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.

17.6 RECOMMENDATIONS

Table 17-29 presents a summary of volume of residence surveys and Table 17-30 presents a summary of air exchange rates surveys. Table 17-31 presents the recommended values. Tables 17-32 and 17-33 provide the confidence in recommendations for house volume and air exchange rates, respectively. Key studies or analyses described in this chapter were used in selecting recommended values for residential volume. The air exchange rate data presented in the studies are extremely limited. Therefore, studies have not been classified as key or relevant studies. However, recommendations have been provided for air exchange rates and the confidence recommendation has been assigned a "low" overall rating. Therefore, these values should be used with caution. Both central and conservative values are provided. These two parameters -- volume and air exchange rate -- 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.

For the volume of a residence, both key studies (U.S. DOE (1995) and Versar (1990) PFT database) have the same mean value -- 369 m^3 (see Table 17-1). This mean value is recommended as a central estimate residential volume. Intuitively, the 10th percentile of the distribution from either study -- 147 m^3 for RECS survey or 167 m^3 for the PFT database -- is too conservative a value, as both these values are lower than the mean volume for multifamily dwelling units (see Table 17-2). Instead, the 25th percentile -- 209 m^3 for RECS survey or 225 m^3 for PFT database, averaging 217 m^3 across the two key studies -- is recommended (Table 17-1).

For the residential air exchange rate, the median value of 0.45 air changes per hour (ACH) from the PFT database (see Table 17-9) is recommended as a typical value (Koontz and Rector, 1995). This median value is very close to the geometric mean of the measurements in the PFT database analyzed by Koontz and Rector (1995). The arithmetic mean is not preferred because it is influenced fairly heavily by extreme values at the upper tail of the distribution. For a conservative value, the 10th percentile for the PFT database -- 0.18 ACH -- is recommended (Table 17-10).

There are some uncertainties in, or limitations on, the distribution for volumes and air exchange rates that are presented in this chapter. For example, the RECS used to infer volume distributions used a nationwide probability sample, but measured floor area rather than total volume. By comparison, field studies contributing to the PFT data base measured house volumes directly, but the aggregate sampling frame for these studies is not statistically representative of the national housing stock.

Although the PFT methodology is relatively simple to implement, it is subject to errors and uncertainties. The general performance of the sampling and analytical aspects of the system are quite good. That is, laboratory analysis will measure the correct time-weighted-average tracer concentration to within a few percent (Dietz et al., 1986). Nonetheless, significant errors can arise when conditions in the measurement scene 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.

Sherman (1989) carried out an error analysis of the PFT methodology using mathematical models combined with typical weather data to calculate how an ideal sampling system would perform in a time-varying environment. He found that for simple single-story (ranch) and two-story plus basement (colonial) layouts, seasonal measurements would underpredict seasonal average air exchange by 20 to 30 percent. Underprediction can occur because the PFT methodology is measuring the effective ventilation (the product of ventilation efficiency and air exchange), and the temporal efficiency will generally be less than unity over averaging periods of this length. Sherman

(1989) also noted, however, that while the bias could have an impact on determining air exchange (absent knowledge of ventilation efficiency) for calculating energy loads, the effective air exchange term is directly relevant to determining average indoor concentrations resulting from constant sources.

Leaderer et al. (1985) conducted a series of experiments in a room-sized-environmental chamber to evaluate the practical impacts of varying air exchange and the temperature response of the permeation sources. The negative bias anticipated in the measured (effective) versus actual air exchange as conditions varied diurnally between 0.4 and 1.5. ACH was evident but minor (3 to 6 percent), most likely due to the mechanical mixing in the chamber and the relatively short integration time (72 h). Similarly, cycling temperature diurnally over an 8°C range (holding air exchange steady at 0.6 ACH) would cause concentrations changes of about 20 percent as emissions fluctuated. The investigators found, however, that using a time-weighted average temperature to define the emission rate reduced the temperature bias to essentially zero.

Table 17-1. Summary of Residential Volume Distributions in Cubic Meters[a]

Parameter	RECS Data (1)	PFT Database (2)
Arithmetic Mean	369	369
Standard Deviation	258	209
10th Percentile	147	167
25th Percentile	209	225
50th Percentile	310	321
75th Percentile	476	473
90th Percentile	672	575

[a] In cubic meters

Sources: (1) Thompson, 1995; (2) Versar, 1990

Table 17-2. Average Estimated Volumes of U.S. Residences, by Housing Type and Ownership						
	Ownership					
	Owner-Occupied		Rental		All Units	
Housing Type	Volume[a] (m^3)	Percent of Total	Volume[a] (m^3)	Percent of Total	Volume[a] (m^3)	Percent of Total
Single-Family (Detached)	471	53.1	323	8.5	451	61.7
Single-Family (Attached)	406	4.6	291	2.9	362	7.5
Multifamily (2-4 units)	362	1.6	216	6.7	243	8.3
Multifamily (5+ Units)	241	1.7	183	15.2	190	16.8
Mobile Home	221	4.6	170	1.2	210	5.8
All Types	441	65.4	233	34.6	369	100.0

[a] Volumes calculated from floor areas assuming a ceiling height of 8 feet.
Source: Adapted from U.S. DOE, 1995.

Table 17-3. Residential Volumes in Relation to Household Size and Year of Construction

	Volume[a] (m^3)	Percent of Total
Household Size		
1 Person	269	24.3
2 Persons	386	32.8
3 Persons	387	17.2
4 Persons	431	15.1
5 Persons	433	7.0
6 or More Persons	408	3.6
All Sizes	369	100.0
Year of Construction		
1939 or before	385	21.1
1940 to 1949	338	7.1
1950 to 1959	365	13.5
1960 to 1969	358	15.5
1970 to 1979	350	18.7
1980 to 1984	344	8.8
1985 to 1987	387	5.7
1988 to 1990	419	4.9
1991 to 1993	438	4.7
All Years	369	100.0

[a] Volumes calculated from floor areas assuming a ceiling height of 8 feet.

Source: U.S. DOE, 1995.

Table 17-4. Dimensional Quantities for Residential Rooms							
Nominal Dimensions	Length (m)	Width (m)	Height (m)	Volume (m^3)	Wall Area (m^2)	Floor Area (m^2)	Total Area (m^2)
Eight Foot Ceiling							
12'x15'	4.6	3.7	2.4	41	40	17	74
12'x12'	3.7	3.7	2.4	33	36	13	62
10'x12'	3.0	3.7	2.4	27	33	11	55
9'x12'	2.7	3.7	2.4	24	31	10	51
6'x12'	1.8	3.7	2.4	16	27	7	40
4'x12'	1.2	3.7	2.4	11	24	4	32
Twelve Foot Ceiling							
12'x15'	4.6	3.7	3.7	61	60	17	94
12'x12'	3.7	3.7	3.7	49	54	13	80
10'x12'	3.0	3.7	3.7	41	49	11	71
9'x12'	2.7	3.7	3.7	37	47	10	67
6'x12'	1.8	3.7	3.7	24	40	7	54
4'x12'	1.2	3.7	3.7	16	36	4	44

Table 17-5. Examples of Products and Materials Associated with Floor and Wall Surfaces in Residences

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

[a] Based on typical values for a residence.
Source: Adapted from Tucker, 1991.

Table 17-6. Percent of Residences with Basement, by Census Region and EPA Region

Census Region	EPA Region	Percent of Residences with Basements
Northeast	1	93.4
Northeast	2	55.9
Northeast	3	67.9
South	4	19.3
Midwest	5	73.5
South	6	4.1
Midwest	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 17-7. Percent of Residences with Certain Foundation Types by Census Region

Census Region	Percent of Residences[a]			
	With Basement	With Enclosed Crawlspace	With Crawlspace Open to Outside	With Concrete Slab
Northeast	78.0	12.6	2.8	15.8
Midwest	78.1	19.5	5.6	14.7
South	18.6	31.8	11.0	44.6
West	19.4	36.7	8.1	43.5
All Regions	45.2	26.0	7.5	31.3

[a] Percentage may add to more than 100 percent because more than one foundation type may apply to a given residence.
Source: U.S. DOE, 1995.

Table 17-8. States Associated with EPA Regions and Census Regions

US EPA Regions

Region 1	Region 4	Region 6	Region 9
Connecticut	Alabama	Arkansas	Arizona
Maine	Florida	Louisiana	California
Massachusetts	Georgia	New Mexico	Hawaii
New Hampshire	Kentucky	Oklahoma	Nevada
Rhode Island	Mississippi	Texas	
Vermont	North Carolina		Region 10
	South Carolina	Region 7	Alaska
Region 2	Tennessee	Iowa	Idaho
New Jersey		Kansas	Oregon
New York	Region 5	Missouri	Washington
	Illinois	Nebraska	
Region 3	Indiana		
Delaware	Michigan	Region 8	
District of Columbia	Minnesota	Colorado	
Maryland	Ohio	Montana	
Pennsylvania	Wisconsin	North Dakota	
Virginia		South Dakota	
West Virginia		Utah	
		Wyoming	

US Bureau of Census Regions

Northeast Region	Midwest Region	South Region	West Region
Connecticut	Illinois	Alabama	Alaska
Maine	Indiana	Arkansas	Arizona
Massachusetts	Iowa	Delaware	California
New Hampshire	Kansas	District of Columbia	Colorado
New Jersey	Michigan	Florida	Hawaii
New York	Minnesota	Georgia	Idaho
Pennsylvania	Missouri	Kentucky	Montana
Rhode island	Nebraska	Louisiana	Nevada
Vermont	North Dakota	Maryland	New Mexico
	Ohio	Mississippi	Oregon
	South Dakota	North Carolina	Utah
	Wisconsin	Oklahoma	Washington
		South Carolina	Wyoming
		Tennessee	
		Texas	
		Virginia	
		West Virginia	

Table 17-9. 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	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] Standard deviation
Source: Adapted from Versar, 1990.

Table 17-10. Summary Statistics for Air Exchange Rates (air changes per hour-ACH), 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

Source: Koontz and Rector, 1995.

Table 17-11. Distributions of Residential Air Exchange Rates[a] by Climate Region and Season									
					Percentiles				
Climate Region	Season	Sample Size	Arithmetic Mean	Standard Deviation	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] In air changes per hour

Source: Murray and Burmaster, 1995.

Table 17-12. Deposition Rates for Indoor Particles	
Size Fraction	Deposition Rate
$PM_{2.5}$	0.39 h^{-1}
PM_{10}	0.65 h^{-1}
Coarse	1.0 h^{-1}

Source: Adapted from Wallace, 1996.

Table 17-13. Particle Deposition During Normal Activities	
Particle Size Range	Particle Removal Rate (h^{-1})
1-5	0.5
5-10	1.4
10-25	2.4
>25	4.1

Source: Adapted from Thatcher and Layton, 1995.

Table 17-14. In-house Water Use Rates (gcd), by Study and Type of Use						
Study	Total, All Uses	Shower or Bath	Toilet	Laundry	Dishwashing	Other
MWD[1]	93	26	30	20	5	12
EBMUD[2]	67	20	28	9	4	6
U.S. DHUD[3]	40	15	10	13	2	--
Nazaroff et al., 1988	52	6	17	11	18	--
Study 1						
Study 2						
- Rural	46	11	18	14	3	--
- Urban	43	10	18	11	4	--
Study 3	42	9	20	7	4	2
Study 4	45	9	15	11	4	6
Study 5	70	21	32	7	7	3
Study 6	59	20	24	8	4	3
Study 7	40	10	9	11	5	5
Study 8	52-86	20-40	4-6	20-30	8-10	--
Mean Across Studies[5]	59	17	18	13	6	5
Median Across Studies[5]	53	15	18	11	4	5

[1] Metropolitan Water District of Southern California, 1991.

[2] East Bay Municipal Utility District, 1992.

[3] U.S. Department of Housing and Urban Development, 1984.

[4] Results of eight separate studies.

[5] The average value from each range reported in Study No. 8 was used to calculate the median across studies. The mean and median for the "Total, all Uses" column were obtained by summing across the means and medians for individual types of water use.

Table 17-15. Summary of Selected HUD and Power Authority Water Use Studies			
	Number of Households	Location	Reference
U.S. DHUD Studies			
Study 1	37	Los Angeles, CA	a,b
Study 2	7	Sacramento, CA	a,c
Study 3	40	Walnut Creek, CA	a,c
Study 4	7	Washington, DC	a
Study 5	21	Sacramento, CA	a
Study 6	19	Los Angeles, CA	a
Power Authority Studies			
Study 1	32	Seattle, WA	a
Study 2	23	Denver, CO	a
Study 3	15	Aurora, CO	a
Study 4	10	Fairfax, VA	a
TOTAL	211		

Sources:

[a] U.S. Department of Housing and Urban Development, 1984.

[b] Metropolitan Water District of Southern California, 1991.

[c] East Bay Municipal Utility District, 1992.

Table 17-16. Showering and Bathing Water Use Characteristics

Characteristic	Mean Duration	Mean Frequency
Individuals who Shower only	10.4 minutes/shower	0.74 showers/day/person
Individuals who Bath only	NA	0.41 baths/day/person
Individuals who Shower and Bath	NA	NA

Source: Adapted from U. S. DHUD, 1984.

Table 17-17. Showering Characteristics for Various Types of Shower Heads	
Shower Head Type	Mean Flow Rate (gpm)
Non-Conserving (> 3 gpm)	3.4
Low Flow (≤ 3 gpm)	1.9
Restrictor (≤ 3 gpm)	2.1
Zinplas[a]	1.8
Turbojector[a]	1.3

[a] Types of low flow water fixtures.

Source: Adapted from U.S. DHUD, 1984.

Table 17-18. Toilet Water Use Characteristics

Toilet Type	Average Water Use (gallons/flush)
Non-Conserving	5.5
Bottles	5.0
Bags	4.8
Dams	4.5
Low-flush	3.5

Source: Adapted from U.S. DHUD, 1984.

Table 17-19. Toilet Frequency Use Characteristics

Study	Flush Frequency (flushes/person/day)
U.S. DHUD, 1984[a]	4.2 flushes/household/day
Ligman, et al., 1974 Rural, M-F	3.6 flushes/person/day
Ligman, et al., 1974 Rural, Sat-Sun	3.8 flushes/person/day
Ligman, et al., 1974 Urban, M-F	3.6 flushes/person/day
Ligman, et al., 1974 Urban, Sat-Sun	3.1 flushes/person/day
Siegrist, 1976	2.3 flushes/person/day
Unweighted Mean	3.43 flushes/person/day

[a] The HUD value may in fact be flushes/household/day

Table 17-20. Dishwasher Frequency Use Characteristics	
Study	Use Frequency
U.S. DHUD, 1984	0.47 loads/person/day
Ligman, et al., 1974 Rural	1.3 loads/day
Siegrist, 1976	0.39 loads/person/day
Unweighted Mean	0.92 loads/day

Table 17-21. Dishwasher Water Use Characteristics			
Brand	Average Water Use (gallons/regular cycle)	Cycle Duration (minutes)	
		140°F	120°F
Maytag	11.5	75	--
Frigidaire	12	75	75
General Electric	10.5	80	95
Sears	10	75	95
Whirlpool	9.5	60	110
White/Westinghouse	12	75	75
Waste King	11.5	65	85
Kitchen Aid	9.5	80	80
Magic Chef	11.5	70	--
Unweighted Mean	10.9	72.8	87.9

Source: Adapted from Consumer Reports, 1987.

Table 17-22. Clothes Washer Frequency Use Characteristics	
Study	Use Frequency
U.S. DHUD, 1984	0.3 loads/person/day
Ligman, et al., 1974 Rural	0.34 loads/person/day
Ligman, et al., 1974 Urban	0.27 loads/person/day
Siegrist, 1976	0.31 loads/day

Table 17-23. Clothes Washer Water Use Characteristics		
Brand	Average Water Use (gallons/regular cycle)	Cycle Duration (minutes)
Maytag	41	32
Frigidaire	48	40
General Electric	51	48
Hotpoint	51	48
Sears	49	40
Whirlpool	53	44
White/Westinghouse	54	47
Kelvinator	46	52
Norge	55	49

Source: Adapted from Consumer Reports, 1982.

Table 17-24. Range of Water Uses for Clothes Washers

Type of Clothes Washer	Range of Water Use
Conventional	27-59 gallons/load
Low Water	16-19 gallons/load
All Clothes Washers	16-59 gallons/load

Source: Adapted from Consumer Reports, 1982.

Table 17-25. Total Dust Loading for Carpeted Areas		
Household	Total Dust Load ($g\text{-}m^{-2}$)	Fine Dust (<150 μm) Load ($g\text{-}m^{-2}$)
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 17-26. Particle Deposition and Resuspension During Normal Activities		
Particle Size Range (μm)	Particle Deposition Rate (h^{-1})	Particle Resuspension Rate (h^{-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 17-27. Dust Mass Loading After One Week Without Vacuum Cleaning	
Location in Test House	Dust Loading ($g\text{-}m^{-2}$)
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	43.34
Source: Adapted from Thatcher and Layton, 1995.	

Table 17-28. Simplified Source Descriptions for Airborne Contaminants		
Description	Components	Dimensions
Direct Discharge		
Combustion	$E_f H_f M_f$	$g\ h^{-1}$
	E_f = emission factor	$g\ J^{-1}$
	H_f = fuel content	$J\ mol^{-1}$
	M_f = fuel consumption rate	$mol\ h^{-1}$
Volume Discharge	$Q_p C_p \epsilon$	$g\ h^{-1}$
	Q_p = volume delivery rate	$m^3\ h^{-1}$
	C_p = concentration in carrier	$g\ m^{-3}$
	ϵ = transfer efficiency	$g\ g^{-1}$
Mass Discharge		
	$M_p w_e \epsilon$	$g\ h^{-1}$
	M_p = mass delivery rate	$g\ h^{-1}$
	w_e = weight fraction	$g\ g^{-1}$
	ϵ = transfer efficiency	$g\ g^{-1}$
Diffusion Limited		
	$(D_f \delta^{-1})(C_s - C_i)A_i$	$g\ h^{-1}$
	D_f = diffusivity	$m^2\ h^{-1}$
	δ^{-1} = boundary layer thickness	m
	C_s = vapor pressure of surface	$g\ m^{-3}$
	C_i = room concentration	$g\ m^{-3}$
	A_i = area	m^2
Exponential		
	$A_i E_o e^{-k t}$	$g\ h^{-1}$
	A_i = area	m^2
	E_o = initial unit emission rate	$g\ h^{-1} m^{-2}$
	k = emission decay factor	h^{-1}
	t = time	h
Transport		
Infiltration	$Q_{ji} C_j$	$g\ h^{-1}$
Interzonal	Q_{ji} = air flow from zone j	$m^3\ h^{-1}$
Soil Gas	C_j = air concentration in zone j	$g\ m^{-3}$

Table 17-29. Volume of Residence Surveys				
Study	Number of Residences	Survey Type	Areas Surveyed	Comments
Key Studies				
U.S. DOE, 1995 (RECS)	Over 7,000	Direct measurement of floor area; estimation of volume	Nationwide (random sample)	Volumes were estimated assuming 8 ft. ceiling height. Provides relationships between average residential volumes and facilities such as housing type, ownership, household size, and structure age.
Versar, 1990 (PFT database)	Over 2,000	Direct measurement and estimated	Nationwide (not random sample); a large fraction located in CA	Sample was not geographically balanced; statistical weighting was applied to develop nationwide distributions
Murray, 1996	7,041 (RECS) 1,751 (PFT)	Direct measurements and estimated	RECS-Nationwide (random sample); PFT - Nationwide (not random sample); a large fraction located in CA	Duplicate measurement were eliminated; tested the effects of using 8 ft. assumption on ceiling height to calculate volume; data from both databases were analyzed.

Table 17-30. Air Exchange Rates Surveys				
Study	Number of Residences/Measurements	Survey Type	Areas Surveyed	Comments
Versar, 1990 (PFT database)	Over 2,000 residences	Measurements using PFT technique	Nationwide (not random sample); a large fraction located in CA	Multiple measurements on the same home were included.
Koontz & Rector, 1995 (PFT database)	2,971 measurements	Measurements using PFT technique	Nationwide (not random sample); a large fraction located in CA	Multiple measurements on the same home were included. Compensated for geographic imbalances. Data are presented by region of the country and season.
Murray and Burmaster, 1995 (PFT database)	2,844 measurements	Measurements using PFT technique	Nationwide (not random sample); a large fraction located in CA	Multiple measurements on the same home were included. Did not compensate for geographical imbalances. Data are presented by climate region and season.
Nazaroff et al., 1988	255 (Grot and Clark, 1981)	Direct measurement	255, low-income families in 14 cities	Sample size was small and not representative of the U.S.
	312 (Grimsrud, 1983)	Direct measurement	321, newer residences, median age <10 years	Sample size was small and not representative of the U.S.

Table 17-31. Recommendations - Residential Parameters		
Volume of Residence	369 m^3 (central estimate)[a]	217 m^3 (mean)[b]
Air Exchange Rate	0.45 ACH (median)[c]	0.18 ACH (10th percentile)[d]

a Same mean value presented in two studies (Table 17-1) - recommended to be used as the central estimate.

b Mean of two 25th percentile values (Table 17-1) - recommended to be used as the mean value.

c Recommended to be used as a typical value (Table 17-10).

d Recommended to be used as a conservative value (Table 17-10).

Table 17-32. Confidence in House Volume Recommendations		
Considerations	Rationale	Rating
Study Elements		
• Level of peer review	All key studies are from peer reviewed literature.	High
• Accessibility	Papers are widely available from peer review journals.	High
• Reproducibility	Direct measurements were made.	High
• Focus on factor of interest	The focus of the studies was on estimating house volume as well as other factors.	High
• Data pertinent to U.S.	Residences in the U.S. was the focus of the key studies.	High
• Primary data	All the studies were based on primary data.	High
• Currency	Measurements in the PFT database were taken between 1982-1987. The RECS survey was conducted in 1993.	Medium
• Adequacy of data collection period	Not applicable	
• Validity of approach	For the RECS survey, volumes were estimated assuming an 8 ft. ceiling height. The effect of this assumption has been tested by Murray (1996) and found to be insignificant.	Medium
• Study size	The sample sizes used in the key studies were fairly large, although only 1 study (RECS) was representative of the whole U.S. Not all samples were selected at random; however, RECS samples were selected at random.	Medium
• Representativeness of the population	RECS sample is representative of the U.S.	Medium
• Characterization of variability	Distributions are presented by housing type and regions; although some of the sample sizes for the subcategories were small.	Medium
• Lack of bias in study design (high rating is desirable)	Selection of residences was random for RECS.	Medium
• Measurement error	Some measurement error may exist since surface areas were estimated using the assumption of 8 ft. ceiling height.	Medium
Other Elements		
• Number of studies	There are 3 key studies; however there are only 2 data sets.	Low
• Agreement between researchers	There is good agreement among researchers.	High
Overall Rating	Results were consistent; 1 study (RECS) was representative of residences in the whole U.S.; volumes were estimated rather than measured in some cases.	Medium

Table 17-33. Confidence in Air Exchange Rate Recommendations		
Considerations	Rationale	Rating
Study Elements		
• Level of peer review	The studies appear in peer reviewed literature. Although there are 3 studies, they are all based on the same database (PFT database).	High
• Accessibility	Papers are widely available from government reports and peer review journals.	High
• Reproducibility	Precision across repeat analyses has been documented to be acceptable.	Medium
• Focus on factor of interest	The focus of the studies was on estimating air exchange rates as well as other factors.	High
• Data pertinent to U.S.	Residences in the U.S. was the focus of the PFT database.	High
• Primary data	All the studies were based on primary data.	High
• Currency	Measurements in the PFT database were taken between 1982-1987.	Medium
• Adequacy of 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.	Medium
• Validity of approach	Although the PFT technology is an EPA standard method (Method IP-4A), it has some major limitations (e.g., uniform mixing assumption).	Low
• Study size	The sample sizes used in the key studies were fairly large, although not representative of the whole U.S. Not all samples were selected at random.	Medium
• Representativeness of the population	Sample is not representative of the U.S..	Low
• Characterization of variability	Distributions are presented by U.S. regions, seasons, and climatic regions; although some of the sample sizes for the subcategories were small and not representative of U.S. The utility is limited..	Low
• Lack of bias in study design (high rating is desirable)	Bias may result since the selection of residences was not random.	Low
• Measurement error	Some measurement error may exist.	Medium
Other Elements		
• Number of studies	There are 3 key studies; however there are only 1 data set. However, the database contains results of 20 projects of varying scope.	Medium
• Agreement between researchers	Not applicable	
Overall Rating	Sample was not representative of residences in the whole U.S., but covered the range of occurrence. PFT methodology has limitations. Uniform mixing assumption may not be adequate. Results will vary depending on placement of samples and on whether windows and doors are closed or opened.	Low

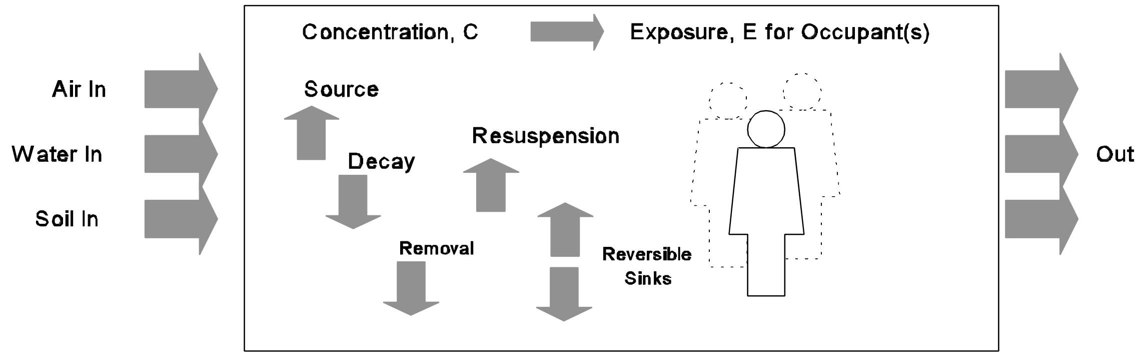

Figure 17-1. Elements of Residential Exposure

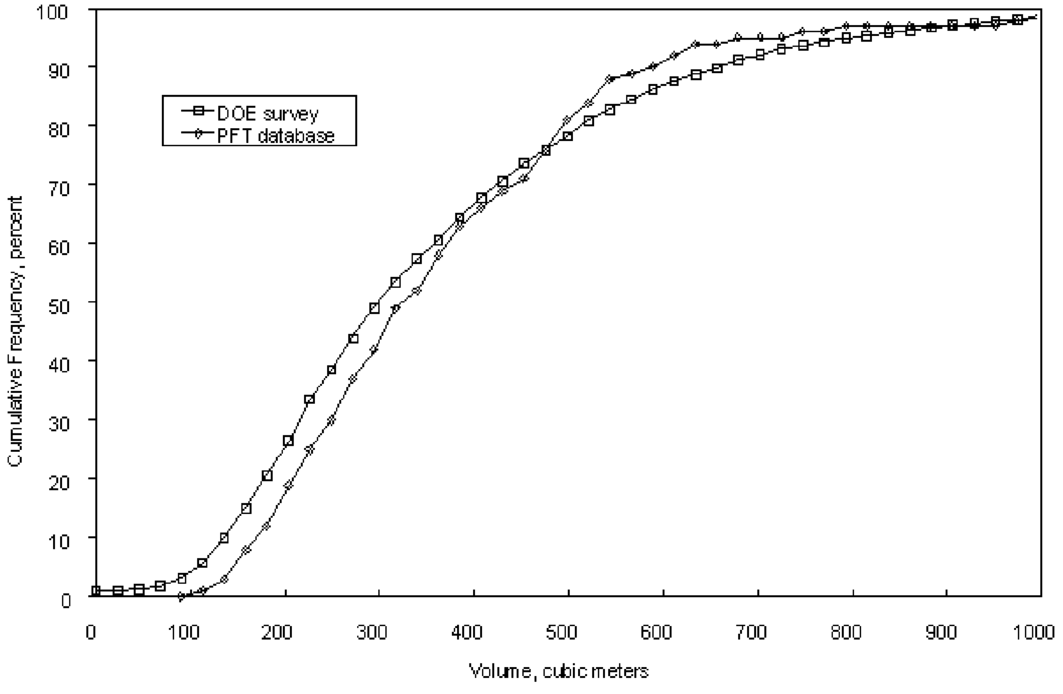

Figure 17-2. Cumulative Frequency Distributions for Residential Volumes
from the PFT Data Base and the U.S. DOE's RECs.

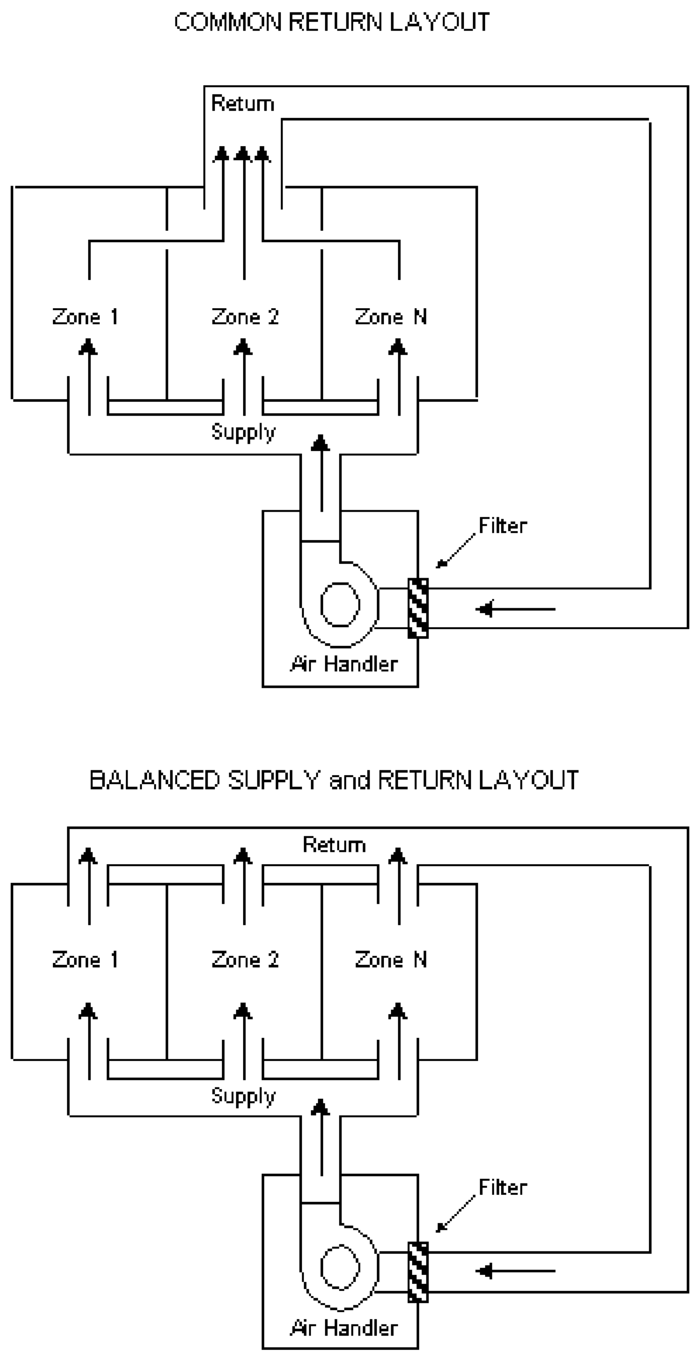

Figure 17-3. Configuration for Residential Forced-air Systems

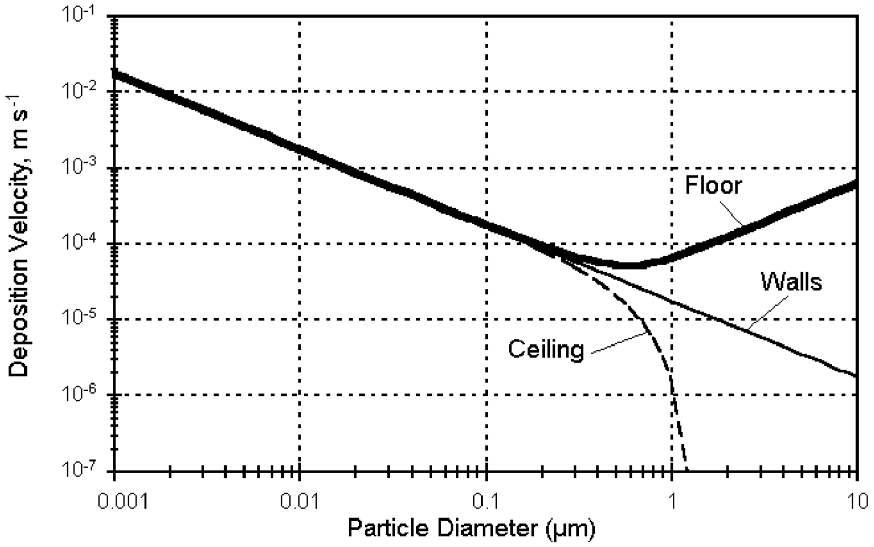

Figure 17-4. Idealized Patterns of Particle Deposition Indoors

Source: Adapted from Nazaroff and Cass, 1989.

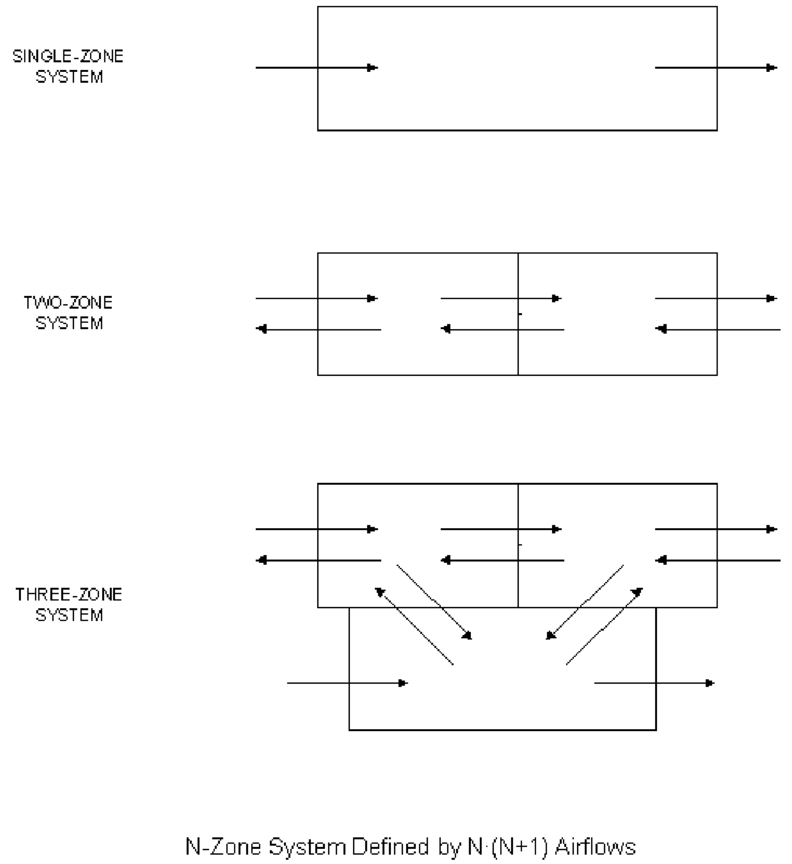

Figure 17-5. Air Flows for Multiple-zone Systems

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DOWNLOADABLE TABLES FOR CHAPTER 17

The following selected tables are available for download as Lotus 1-2-3 worksheets.

Table 17-1. Summary of Residential Volume Distributions [WK1, 1 kb]

Table 17-9. Summary of Major Projects Providing Air Exchange Measurements in the PFT Database [WK1, 6 kb]

Table 17-11. Distributions of Residential Air Exchange Rates by Climate Region and Season [WK1, 3 kb]