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BUILDING DYNAMICS AND INDOOR AIR QUALITY

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The question may be asked—Why are building characteristics important to the understanding of indoor air quality? The answer is that indoor air quality is determined by the way a building is constructed and the materials used, and by the way the building is operated (Fanger 1987; American Society of Heating, Refrigerating, and Air-Conditioning Engineers [ASHRAE] 1989). Building characteristics are a major influence on indoor air quality in even the smallest house and in the largest commercial building.

The minimum ventilation necessary to maintain reasonable indoor air quality is treated in ASHRAE *Standard 62, Ventilation for Acceptable Indoor Air Quality* (ASHRAE 1989). *Standard 62* points out the need for concern not only for occupant factors, but also for factors related to building materials and the mechanical systems. Fanger emphasizes this point in two recent papers (Fanger 1987); (Fanger et al. 1988) based on an investigation of twenty Danish buildings. Fanger found the polluting effect of mechanical systems to cause 38 percent of the building indoor air quality problem: material outgasing, 36 percent; people, 7 percent; and smoking, 19 percent. From these and other studies it is evident that in any building the approach to maintaining indoor air quality must be first to limit the source of pollution (source control) or to control the pollution with local exhaust from the area, and only if these measures fail should ventilation be used to dilute the pollutants to acceptable concentration levels. These principles apply to all buildings, and the building dynamics can interact directly with both the spread and the control of pollutants. Inside-outside pressure differences caused by temperature and wind effects, air systems operation, the use of equipment in the building, and the activities of the occupants also influence indoor air quality. This chapter reviews the critical factors that determine the presence or absence of problems in indoor air quality, with a focus on building features and dynamics and the movement of air into and within buildings.

CHARACTERISTICS OF THE BUILDING AND ASSOCIATED AIRFLOWS

The building envelope, that part of the building which separates the inside environment from the vagaries of the weather outside, is an important determinant of air infiltration (ASHRAE 1985a; Harrje, Dutt, and Beyea 1979) which has been defined as inward air leakage through cracks and interstices and through ceilings, floors, and walls (ASHRAE 1989). Air infiltration supplies most of the required ventilation in dwellings and, even in more sophisticated buildings, a substantial amount of the outside air that reaches the building occupants (Harrje 1985; Grot and Persily 1986). The location of the openings in the building envelope directly affects how much air can enter and the timing of air entry (Blomsterberg and Harrje 1979a, 1979b; ASHRAE 1985a).

The contribution of leakage sites to air infiltration and energy consumption has prompted studies of how leakage is distributed in residential structures. In most of the homes surveyed, the windows and doors accounted for 20–25 percent of the leakage (Figure 3.1), with four to five times as much leakage occurring through other sites (Harrje and Born 1982; Reinhold and Sonderegger 1983). Many of the other leakage sites were in the lower portion of the house, where soil gas and other pollutants can easily enter. Air inversion layers near buildings (Geiger 1965) can cause pollutants to collect from the soil or from nearby vehicular traffic and can funnel the pollutants to the building air inlet.

The degree of structural tightness between floors directly influences vertical airflow in a building. This vertical airflow is stack driven; that is, temperature-related density differences provide pressure that causes vertical air movement, with warmer air rising and cooler air falling. If the floors are structurally well separated, these vertical air movements will be impeded (ASHRAE 1985a). Open staircases and other easy airflow paths facilitate a free exchange of air between floors. Mechanically driven air movement in a building may suppress or enhance these natural air flows (Elmroth and Levin 1983).

Natural vertical air movement can be maximized with openings at the top of the building to allow warm building air to exfiltrate during the heating season and with openings at the lowest building level for air infiltration. Window openings in a high-low pattern can also be used to ventilate the building, utilizing the stack effect. Window openings also involve cross-ventilation, which changes with wind direction and pressures caused by the wind. Opening windows to allow air to enter on the windward (higher pressure) side and exit on the leeward (lower pressure) side of the building can optimize airing of the interior space (Blomsterberg and Harrje 1979a, 1979b; Persily 1982). Unintentional building openings function in the same manner to produce ventilation, although in an uncontrolled and often undesirable fashion.

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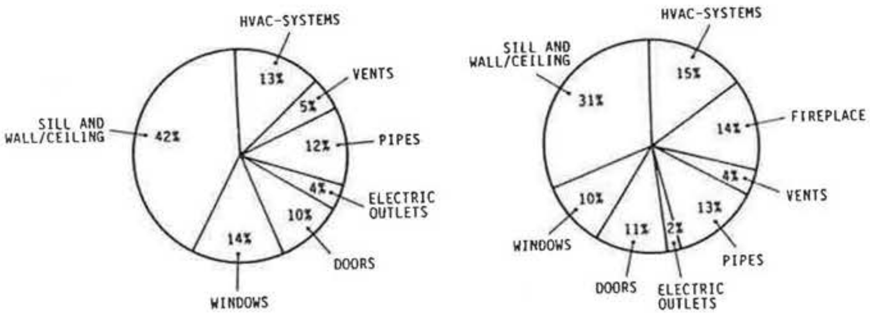

Figure 3.1. Typical air leakage distributions are shown for components in residential buildings. Eleven houses without fireplaces and nineteen houses with fireplaces were used as the data base. *Source:* Reinhold and Sonderegger (1983), reprinted with permission.

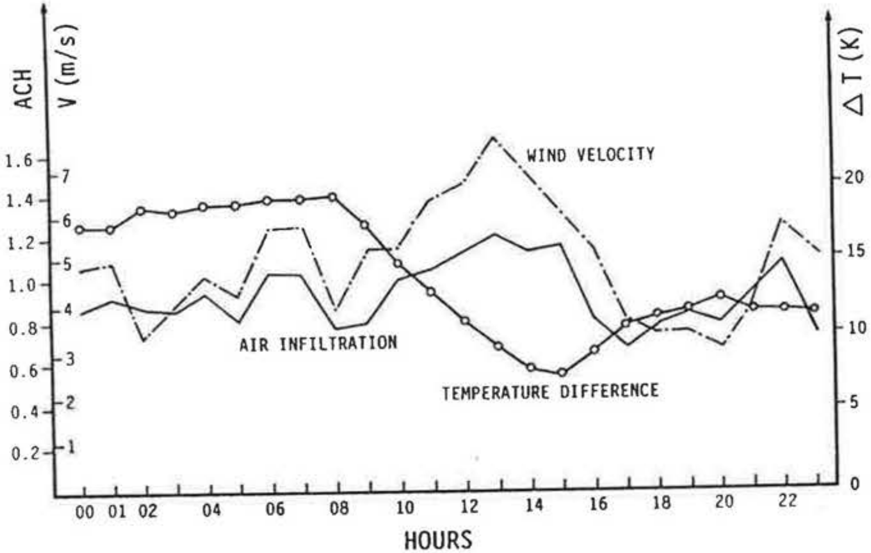

Figure 3.2. Air infiltration rates change rapidly due to stack, wind, and occupant effects. Ventilation levels may be excessive one minute and too low the next, as the wind changes direction or windows are closed. Minute-by-minute monitoring reveals the dynamic behavior.

Unfortunately, the effects due to wind and stack-induced pressures that cause air infiltration are not necessarily additive (Sinden 1978) and may actually oppose each other (Sinden 1978; Blomsterberg and Harrje 1979a, 1979b). Figure 3.2 illustrates how complex these combinations of effects may be as the variation of air infiltration is recorded over a period of time in a simple house.

A number of methods have been developed to identify sites of air infiltration and to describe the extent of the openings. These methods range from simple smoke tracers to indicate airflow to infrared scanning devices that rapidly determine details of the actual air leakage sites (Harrje, Dutt, and Beyea 1979; American Society for Testing Materials [ASTM] 1988c). Other methods such as fan pressurization (ASTM 1988b) and gas tracer techniques (ASTM 1988a) are used to determine the extent of the resultant air infiltration. These methods are used when air infiltration is likely to be a major factor in an indoor air quality problem and enable building diagnosticians to determine whether air exchange rates are acceptable, below standards, or excessive. The methods can also be used to find solutions to ventilation or infiltration problems.

METHODS OF CHECKING FOR VENTILATION/AIR INFILTRATION

FAN PRESSURIZATION

The simplest test for assessing the tightness of the building envelope is fan pressurization (Blomsterberg and Harrje 1979a, 1979b; Harrje and Born 1982; Persily 1982; Reinhold and Sonderegger 1983; ASTM 1988b). When applied to houses, this technique may use a blower door; that is, a flow-calibrated fan or blower is adjusted to fit an exterior doorway. Blower doors change the pressure difference between inside and outside by varying the airflow rate and flow direction. This procedure, detailed in ASTM *Standard Procedure E779–87*, provides a pressure versus flow profile for the house (Figure 3.3), indicating whether the house is too leaky, reasonably tight, or too tightly constructed. Too leaky implies unnecessary air infiltration, with energy waste and discomfort from drafts; too tight means that mechanical ventilation may be required to maintain air quality.

The fan pressurization/depressurization technique is not a precise measure of the amount of ventilation needed to achieve acceptable air quality but rather provides a gauge of the building envelope tightness. For an average house with 1,600 ft^2 of floor area, seven house volume air changes per hour at a pressure difference of 0.02 inches of water (50 Pascal) is calculated to be a desired goal. Using a rule of thumb translation to air changes per hour (ACH), under average outside heating season conditions, the 7 ACH is divided by twenty, giving 0.35 ACH as an average air infiltration rate (Kronvall 1980; Reinhold and Sonderegger 1983; Brunsell 1987). The value of 0.35 ACH is the prescribed air exchange rate for residential buildings in the latest draft version of ASHRAE *Standard 62–1989* (ASHRAE 1989). This version of ASHRAE *Standard 62* also states that smaller houses and a higher density of occupancy both require 15 cfm per person, minimum. In this case, for a 1,000 ft^2 home with four to five occupants, the blower door target becomes 10 ACH at 50 Pa, and the ventilation rate will equal 0.5 ACH under average conditions.

TRACER GAS TECHNIQUES

Tracer gas techniques offer another approach to evaluation of air infiltration/ventilation rates (Harrje, Grot, and Grimsrud 1981). Standards have been established for tracer gas use; ASTM *Standard Practice E741–83* (ASTM 1988a)

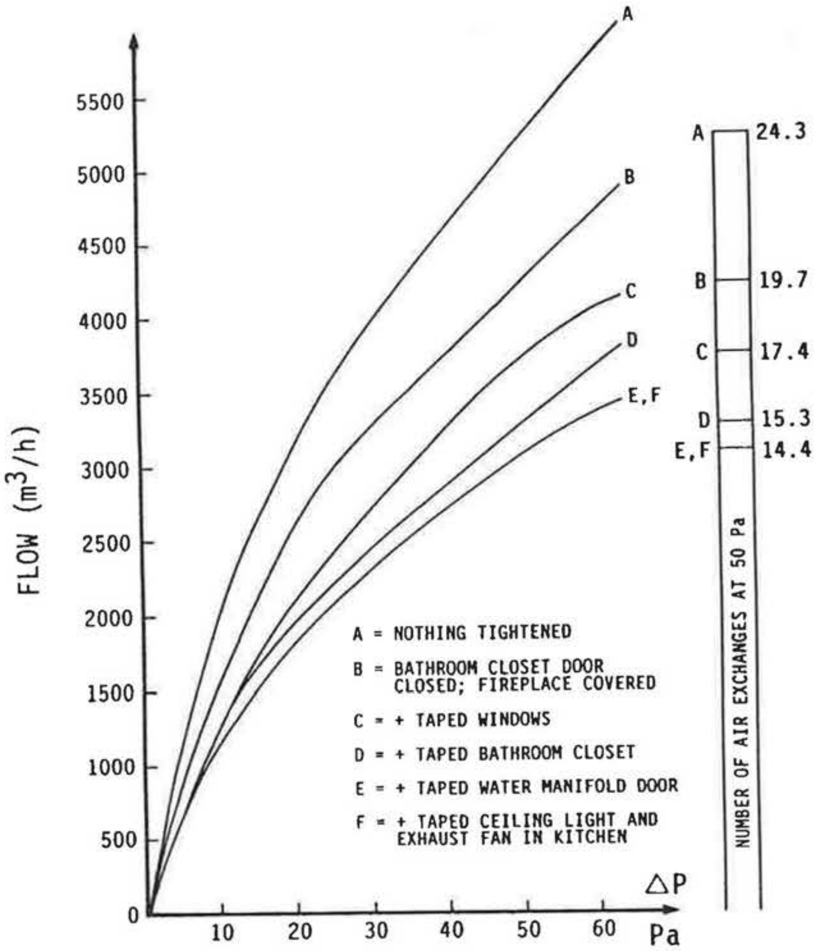

Figure 3.3. Fan pressurization produces flow profiles indicating the tightness of the structure. Evaluated at 50 Pa, curve A shows a very leaky structure. Even profile E,F predicts a 14.5 ACH. If we divide by twenty, a value of 0.73 ACH air infiltration seasonal rate is indicated, which is twice the required ventilation value.

discusses the different techniques, which include tracer gas dilution (decay of tracer concentration over time), constant injection of tracer into the spaces evaluated, and constant concentration of tracer gas maintained in each zone of the building (tracer gas sent to each zone is then directly proportional to the air infiltrating into the zone) (Harrje, Grot, and Grimsrud 1981).

Tracer Gas Dilution The space to be evaluated is "seeded" with tracer gas by mixing the tracer in the space to a uniform concentration and then measuring the concentration of tracer gas over time. The rate of decay is directly related to the air

exchange rate in the space being measured. An average air infiltration rate in the period of decay can be calculated from repeated measurements during the period.

The application of the dilution (or decay) technique can be simplified and made less costly by periodically capturing air samples in special bags or plastic bottles for later analysis rather than using on-site measuring equipment. This method has been used in relatively large field studies (Grot and Clark 1981; Harrje, Gadsby, and Linteris 1982). For example, in a study by Grot and Clark (1981), more than two hundred houses were measured using the bag sampling and tracer dilution technique. The purpose of the project was to evaluate the potential for weatherization of the homes of lower-income people. The tracer gas was dispersed with syringes so that each zone in the house could receive a roughly proportionate amount of tracer.

Constant Injection of Tracer Gas In this method of evaluating air exchange rates, the tracer is injected at a constant rate, and the concentration is generally measured continuously (Harrje, Grot, and Grimsrud 1981; ASTM 1988a).

A simple passive version of the constant injection method uses perfluorocarbon tracers (Grot and Clark 1981; Dietz and Cote 1982; Dietz et al. 1986). The perfluorocarbon tracer technique uses capillary adsorption tube samplers (CATS), which are small glass tubes half the length of a cigarette and holding a charcoal-like material. The tracer gas is released at a controlled rate from even smaller containers. The tracer gas adsorbed in the CATS is recovered by heating the tube to 750–850°F and analyzing the gases with a gas chromatograph. By using the tracer diffusion rate and exposure time of the CATS, the tracer gas volume can be converted to an average concentration and the ventilation/air infiltration rate estimated. Using different tracers in various rooms allows interzone estimates of flow rates in addition to the primary measurements.

Constant Concentration of Tracer Gas This third measurement method has gained considerable favor in the last few years (Harrje, Grot, and Grimsrud 1981; Harrje, Bohac, and Nagda 1985; Harrje et al. 1985; Liddament 1986; Bohac and Harrje 1987; Harrje, Bohac, and Fortmann 1987; ASTM 1988a). Although the measurement system requires the use of a computer, it can monitor ten (or even more) zones simultaneously. The rate of gas injection into each zone to maintain constant tracer gas concentration is used to calculate the air exchange rate.

The constant concentration measurement approach eliminates the influences of flow between zones and supplies individual air infiltration/ventilation values for each zone. By stopping tracer injection in one or more of the zones, information on interzone effects can also be obtained (Bohac and Harrje 1987). Another more commonly used approach is to employ multiple tracer gases so that individual tracers may reveal the interzone flows (I'Anson, Irwin, and Howarth 1982; Dietz, D'Ottavio, and Goodrich 1985).

Residential buildings, when studied using the techniques described above, show a log normal distribution of air infiltration (Figure 3.4) (Grot and Clark 1981). This distribution implies that many homes are much too leaky and require excessive heating and cooling to maintain comfort conditions. The homes with less than the one-third to one-half air change per hour are at risk for indoor air quality problems. Although Figure 3.4 places relatively few houses in that category, these data (Grot and Clark 1981) were taken in older homes of lower-income people. Data on newer housing indicate a greater proportion of homes in the "too tight" category and a lesser proportion in the "tail" of houses that are overventilated. To guide home builders in targeting the appropriate range of tightness, a proposed standard, SPC 119, has been written by an ASHRAE special committee. Titled "Air Leakage Performance for Detached Single-Family Residential Buildings," the proposed standard concentrates on weather influences in North America and provides guidelines for air infiltration and building tightness control to achieve a balance between energy needs and indoor air quality.

INSIDE-OUTSIDE TEMPERATURE DIFFERENCES: THE STACK EFFECT

The stack effect is an important but often overlooked factor that influences airflow in buildings. Nearby buildings or surrounding vegetation tend to shield the majority of buildings from much of the effect of the wind. In contrast, the stack effect reflects the inside-outside temperature difference, and from an air infiltration standpoint, it often becomes nature's dominant force (Blomsterberg and Harrje 1979a, 1979b; ASHRAE 1985a; Harrje 1985).

The stack effect increases air infiltration on the lowest floors of the building and maximizes air exfiltration at the highest floor level. This pressure-driven flow causes soil gases to enter buildings, producing a variety of pollutant problems including the entry of radon gas (Highland et al. 1985; Nazaroff et al. 1985; Harrje 1986; Harrje and Gadsby 1986; Harrje, Hubbard, and Sanchez 1987, 1988; Erickson 1988). The height at which interior and exterior pressures are equal is termed the *neutral pressure level* (NPL), that is, the height at which building envelope air leakage would have the least effect.

Even in a single-story building the influence of stack effect can be evident (ASHRAE 1985a; Harrje 1986; Harrje and Gadsby 1986). In multistory buildings, the effect can become much more pronounced as the number of floors increases unless the floors are isolated from each other. Even if the floors communicate, however, the vertical flow may not provide effective mixing of the air on each floor (Jun and Sheng 1987), and air moving up staircases may prove ineffective in removing pollutants from the floors it passes. Because of the stack effect, upper floors may receive little air directly from the outside and instead get "used air" from the lower floors.

The stack effect is usually conceptualized as most prominent during the heating season when the air within a building becomes increasingly more buoyant as the

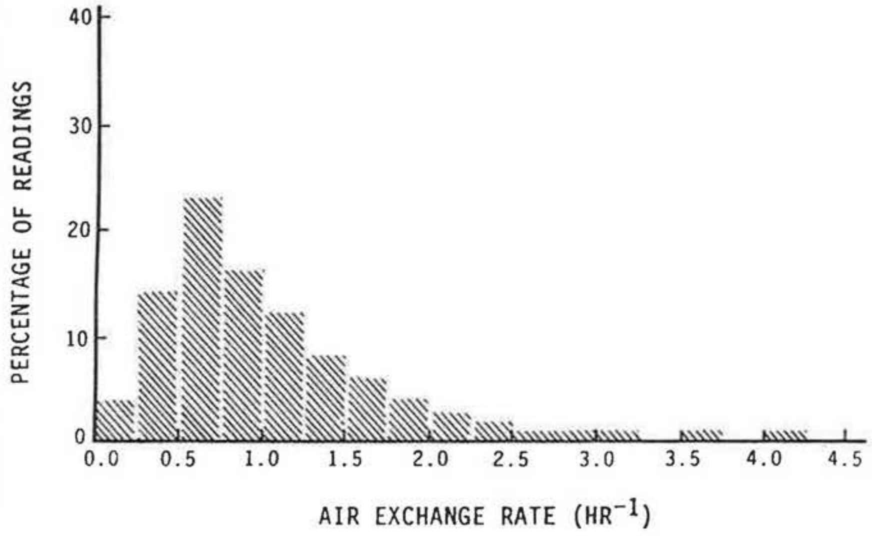

Figure 3.4. The typical histogram of measured air infiltration versus percent of readings follows a log normal distribution. The data shown are for 14 cities, 266 houses, and 1,048 readings with an average air infiltration of 1.12 ACH. Many of the houses exceed the 0.35–0.50 ACH goal, indicating energy waste, but there are also a number of houses with marginal air exchange rates, pointing to possible indoor air quality problems. *Source:* Grot and Clark (1981), reprinted with permission.

outside temperature drops. During the cooling season, reversal of the stack effect, with air entering upper stories and flowing to the lower stories and basement, might be anticipated. However, the temperature difference across a building in the cooling season is not so great as in the heating seasons in most areas of the United States. Furthermore, extremely high attic temperatures, 120°F or more, produce upward flow from the attic to outdoors in the summer. To make up for that flow, air may be drawn from the living space and thereby counteract the downward flow from the reversed stack effect. Because of such counteracting flows, the consequences of the stack effect cannot be readily predicted during the cooling season. Summer weather conditions have been shown repeatedly to produce the least air infiltration and to lead to major indoor air quality problems in houses (Harrje, Bohac, and Nagda 1985; Harrje, Bohac, and Fortmann 1987) when open windows are not used for cooling.

The stack effect and other pressure-driven flows cause soil gases to enter buildings (Nazaroff et al. 1985; Harrje 1986; Harrje and Gadsby 1986; Harrje, Hubbard, and Sanchez 1987, 1988). Although the problem of radon gas has received the most publicity, other undesirable pollutants emanate from in and around the building foundation or are constituents of soil gases. The pollutants of concern include pesticides, especially termicides, and constituents in ground water (Highland et al. 1985; Harrje 1986). The movement of soil gas has not yet been well characterized (Nazaroff et al. 1985; Harrje, Hubbard, and Sanchez 1987; 1988). The quantity of soil gas measured experimentally indicates that the gas may travel many feet through the soil.

EFFECT OF THE WIND

Prevailing wind conditions also produce pressure-driven flows (Blomsterberg and Harrje 1979a, 1979b; ASHRAE 1985a). Wind effects can be very complex and have both static and dynamic features. For the unprotected building, wind can be the dominant effect, and if wind speeds are high, for example, greater than 20 mph, even the wind-protected building will sustain pressure effects.

The wind speed affecting the building generally correlates with the wind speed recorded at the local weather station. Wind speed has a profile from zero speed at the ground to a maximum value at a point above the terrain effects. Even the 10-m-high standard wind measurement sensor is placed in a changing wind speed regime within the boundary layer (Blomsterberg and Harrje 1979a, 1979b; ASHRAE 1985a). Wind effects are made complex by the nature of the terrain that surrounds the building and the shape of the building itself. Changes in the wind direction may establish entirely different wind paths, which may be further affected by trees or other buildings standing in the path of the wind (Buckley et al. 1978; Harrje, Mattingly, and Heisler 1979).

Because of openings in the building envelope and the profiles of pressure on the building surfaces, various levels of local pressurization or depressurization may take place at any opening. Thus, opening a window may allow air to enter or exit the building just as flow over the chimney may force the chimney to backflow or at the other extreme, may cause a higher exhaust flow. Zones of high and low pressure on the building surface vary in position with wind direction and speed and with stack effects. Similar pressure increases and decreases occur on the surrounding ground surface and can influence the flow of soil gases into the building (Harrje, Hubbard, and Sanchez 1987).

EQUIPMENT AND APPLIANCES FOR VENTILATION

Although most prevalent in larger buildings, mechanical ventilation is becoming more common in the advanced design homes of the past few years such as the R–2000 homes in Canada. A heat recovery ventilator (HRV, air-to-air heat exchanger) is central to the ventilation design of these homes and provides controlled ventilation during all seasons (Riley 1985). By generating its own pressure and flow conditions, mechanical ventilation systems can overwhelm the pressures developed by stack and wind effects.

Many of the ventilation-related components in buildings use balanced flow operation: Supply air and return air are equal or have a known relationship to each other to maintain a desired pressure condition and flow distribution. Turning on an exhaust fan, however, produces local depressurization in a large office building or in a home kitchen or bathroom. The depressurization can draw air from other spaces in the building to the exhausted room or zone or suck air and soil gas in from

the outside. The depressurization can also cause backdrafting of combustion exhaust systems (ASHRAE 1985a; Harrje, Hubbard, and Sanchez 1987, 1988).

Heating, ventilating, and air-conditioning (HVAC) equipment commonly leads to locally pressurized and depressurized zones, particularly if the system is not balanced. The system may be balanced initially, but changes over time and "adjustments" by operations personnel or occupants may greatly alter it. System designs that provide adequate air supplies but insufficient air returns may also produce localized inhomogeneity of pressure in all types of buildings (Harrje, Gadsby, and Comer 1986). The home with conditioned air supplies in every room but only one (or at the most two) return grills is a simple but common example. Each time the furnace, air conditioner, or heat pump operates, certain rooms are pressurized, causing higher than normal air exfiltration, while others are depressurized, increasing air infiltration locally. Thus, operation of the HVAC system increases air infiltration to sometimes more than double the rate observed with the system off or adequately balanced. In the basement, where the HVAC equipment is located, basement air is sucked into leaks in the return ducts and air handler fan housing because of inadequate returns. A depressurized basement can suck in soil gas (Harrje 1986; Harrje and Gadsby 1986; Harrje, Hubbard, and Sanchez 1987, 1988) and cause backdrafting from combustion devices into the home (Harrje, Hubbard, and Sanchez 1987, 1988).

Throughout the house, dryer vent fans, kitchen fans, bathroom fans, and even attic fans can cause negative pressures to exist for short or long periods of time and increase entry of unwanted soil gas or exhaust products into living areas.

THE ROLE OF THE OCCUPANTS

Although the building characteristics, ventilation equipment, and meteorology all affect building dynamics, the most important factor influencing air movements is often the actions of the occupants themselves. The occupants may directly influence ventilation through use of doors, vents, and windows. This effect on ventilation may be manifest in energy use. For example, studies of energy use typically show a twofold variation in energy use for identical homes (Fracastoro and Lyberg 1983).

Although the importance of occupant behavior has been mostly studied in single-family housing, larger buildings may also be affected by it. Studies in multifamily homes have pointed to ten-fold variations in window ventilation levels for interior temperature control—residents open windows to lower temperatures in overheated rooms (Harrje and Kempton 1986; Bohac, Dutt, and Feuermann 1987).

MODELING POLLUTANT FLOWS

Modeling of pollutant flows within buildings, taking into account pressure differences from exterior and interior sources, building geometry, and interior events, has been achieved with equations based on the work of Walton (ASHRAE 1985b; Walton 1985; Grot and Axley 1987). The building airflow patterns are described by the program AIRMOV, using PC-sized computers. The measurement techniques discussed previously in this chapter are useful in providing a data base for validating the computer program solutions.

Two classes of flow elements have been developed in models from the National Institute of Standards and Technology: flow-resistant elements and fan/pump elements. The flow resistant element may be used to model a large variety of flow paths, from ducting to envelope or interior surface openings. The fan/pump elements model the HVAC system where appropriate. Currently, detailed time histories of airborne contaminants are being modeled using these procedures (Grot and Axley 1987).

SUMMARY

In all buildings, from the most sophisticated to the simple one-family home, understanding the dynamics of air entry into the building and air flow within the building is vitally important if acceptable air quality is to be maintained. To this end, the education of building occupants, builders, and maintenance staff is highly important. Monitoring, which is more than a research tool, plays a key role in maintaining indoor air quality and can allow near-optimum building function, with individual building dynamics and occupancy factors as part of the total equation.

REFERENCES

American Society of Heating, Refrigerating, and Air-Conditioning Engineers. 1985a. Natural ventilation. In *ASHRAE Handbook of Fundamentals;* 22.1–51. Atlanta, Ga.: ASHRAE.

American Society of Heating, Refrigerating, and Air-Conditioning Engineers. 1985b. Duct design. In *ASHRAE Handbook of Fundamentals,* Atlanta, Ga.: ASHRAE.

American Society of Heating, Refrigerating, and Air-Conditioning Engineers. 1989. *ASHRAE Standard 62-1989. Ventilation for acceptable indoor air quality.* Atlanta, Ga.: ASHRAE.

ASTM. 1988a. *Standard E741-82.* Standard test method for determining air leakage rate by tracer dilution. *Annual Book of ASTM Standards,* 568–75. Philadelphia: ASTM.

ASTM. 1988b. *Standard E779-87.* Standard test method for determining air leakage rate by fan pressurization. *Annual Book of ASTM Standards,* 603–6. Philadelphia: ASTM.

ASTM. 1988c. *Standard E11-86.* Standard practice for air leakage site detection in building envelopes. *Annual Book of ASTM Standards,* 885–89. Philadelphia: ASTM.

Blomsterberg, A. K., and Harrje, D. T. 1979a. Approaches to evaluation of air infiltration energy losses in buildings. *ASHRAE Trans.* 85:797–815.

Blomsterberg, A. G., and Harrje, D. T. 1979b. Evaluating air infiltration energy losses. *ASHRAE J.* 21:25–32.

Bohac, D. L., and Harrje, D. T. 1987. The use of modified constant concentration techniques to measure infiltration and interzone air flow rates. *Proceedings of the eighth AIVC conference: Ventilation technology, research and application,* 129–52. Coventry, Great Britain: AIVC. Publication no. AIC-PROC-8-5-87.

Bohac, D. L.; Dutt, G. S.; and Feuermann, D. 1987. Approaches to estimating air flows in a large multifamily building. *ASHRAE Trans.* 93:1335–58.

Brunsell, J. T. 1987. The effect of vapor barrier thickness on air tightness. *Proceedings of the eighth AIVC conference: Ventilation technology, research and application,* 63–73. Coventry, Great Britain: AIVC. Publication no. AIC-PROC-8-5-87.

Buckley, C. E., et al. 1978. *The optimum use of coniferous trees in reducing home energy consumption.* Princeton, N.J.: Princeton University Center for Environmental Studies. Report no. 71.

Dietz, R. N., and Cote, E. A. 1982. Air infiltration measurements in a home using a convenient perfluorocarbon tracer technique? *Environ. Int.* 8:419–33.

Dietz, R. N.; D'Ottavio, T. W.; and Goodrich, R. W. 1985. Multizone infiltration measurements in homes and buildings using a passive perfluorocarbon tracer method. *ASHRAE Trans.* 91:1761–75.

Dietz, R. N., et al. 1986. Detailed description and performance of a passive perfluorocarbon tracer system for building ventilation and air exchange measurements. In *Measured air leakage of buildings.* Ed. H. R. Trechsel and P. L. Lagus, 203–64. Philadelphia: ASTM. Publication no. ASTM-STP/904.

Elmroth, A., and Levin, P., eds. 1983. *Air infiltration control in housing: A guide to international practice.* Stockholm, Sweden: Swedish Council for Building Research. Publication no. D2 1983.

Erickson, B. E. 1988. *Radon in housing.* Gavle, Sweden: Swedish National Institute for Building Research.

Fanger, P. O. 1987. A solution to the sick building mystery. In *Indoor air '87: Proceedings of the fourth international conference on indoor air quality and climate.* Ed. B. Seifert et al., Vol. 4, 49–55. Berlin: Institute for Water, Soil, and Air Hygiene.

Fanger, P. O., et al. 1988. Air pollution sources in offices and assembly halls quantified by the Olf unit. *Energy and buildings,* Vol. 12, 7–19. Lausanne, Switzerland: Elsevier Sequoia.

Fracastoro, G. V., and Lyberg, M. D., eds. 1983. *Guiding principles concerning design of experiments, instrumentation and measuring techniques.* Stockholm, Sweden: Swedish Council for Building Research. Publication no. D11.

Geiger, R. 1965. *The climate near the ground.* Cambridge, Mass.: Harvard University Press.

Grot, R. A., and Axley, R. 1987. The development of models for the prediction of indoor air quality in buildings. *Supplement to Proceedings of the eighth AIVC conference: Ventilation Technology and Application,* 171–97. Coventry, Great Britain: AIVC. Publication no. AIC-PROC-8-5-87.

Grot, R. A., and Clark, R. E. 1981. Air leakage characteristics and weatherization techniques for low-income housing. *Proceedings of the ASHRAE/DOE-ORNL conference: Thermal performance of the exterior envelopes of buildings,* 178–94. Atlanta, Ga.: ASHRAE.

Grot, R. A., and Persily, A. K. 1986. Measured air infiltration and ventilation rates in eight large office buildings. In *Measured air infiltration in buildings.* Ed. H. R. Trechsel and P. L. Lagus, 151–83. Philadelphia, Pa.: ASTM. Publication no. ASTM STP-904.

Harrje, D. T. 1985. Air exchange in buildings. *Proceedings of the indoor air quality seminar: Implications for electric utility conservation programs,*`3:1–10. Palo Alto,

Calif.: Electric Power Research Institute. Publication no. EPRI-EA/EM/3824.
Harrje, D. T. 1986. Clean and economical air in houses. *Architect. Technol.* July/August: 33–36.
Harrje, D. T., and Born, G. J. 1982. Cataloguing air leakage components in houses. *Proceedings of the ACEEE 1982 summer study: Existing residences*. Washington, D.C.: American Council for an Energy Efficient Economy.
Harrje, D. T., and Gadsby, K. J. 1986. Practical engineering solutions for optimizing energy conservation and indoor air quality in residential buildings. *Proceedings of the international conference on indoor air quality and climate*, IAQ 1986. Atlanta, Ga.: ASHRAE.
Harrje, D. T., and Kempton, W. M. 1986. Ventilation, air infiltration and building occupant behavior. *Proceedings of the seventh AIC conference: Occupant interaction with ventilation systems* 2.1–16. Coventry, Great Britain: AIVC. Publication no. AIC-PROC-7-86.
Harrje, D. T.; Bohac, D. L.; and Fortmann, R. C. 1987. Measurement of seasonal air flow rates in an unoccupied single-family house. *Proceedings of the eighth AIC Conference: Ventilation Technology. Research and Application*, 15.1–15. Coventry, Great Britain: AIVC. Publication no. AIC-PROC-8-87.
Harrje, D. T.; Bohac, D. L.; and Nagda, N. L. 1985. Air exchange rates based upon individual room and single cell measurements. *Proceedings of the sixth AIC conference: Ventilation strategies and measurement techniques*, 7.1–14. Coventry, Great Britain: AIVC. Publication no. AIC-PROC-6-85;
Harrje, D. T.; Dutt, G. S.; and Beyea, J. 1979. Locating and eliminating obscure but major energy losses in residential housing. *ASHRAE Trans.* 85:521–34.
Harrje, D. T.; Gadsby, K. J.; and Comer, C. J. 1986. Transients and physics of return air. In *Proceedings of the air movement and distribution conference*. Ed. C. G. Marsh and V. W. Goldschmidt, Vol. 2, 10–16. Lafayette, Ind.: Purdue University.
Harrje, D. T.; Gadsby, K. J.; and Linteris, G. T. 1982. Sampling for air exchange rates in a variety of buildings. *ASHRAE Trans.* 88:1373–84.
Harrje, D. T.; Grot, R. A.; and Grimsrud, D. T. 1981. Air infiltration—site measurement techniques. *Proceedings of the 2nd AIC conference: Building design for minimum air infiltration*, 113–33. Coventry, Great Britain: AIVC. Publication no. AIC-PROC-2-81.
Harrje, D. T.; Hubbard, L. M.; and Sanchez, D. C. 1987. *Proceedings of the radon diagnostics workshop*. Princeton, N.J.: Princeton University Center for Energy and Environmental Studies. Report no. 233.
Harrje, D. T.; Hubbard, L. M.; and Sanchez, D. C. 1988. Diagnostic approaches to better solutions of radon IAQ problems. *Proceedings of healthy buildings*. Stockholm, Sweden: Swedish Council of Building Research.
Harrje, D. T.; Mattingly, G.; and Heisler, G. 1979. The effectiveness of an evergreen windbreak for reducing residential energy consumption. *ASHRAE Trans.* 85:428–44.
Harrje, D. T., et al. 1985. Documenting air movements and air infiltration in multicell buildings using various tracer techniques. *ASHRAE Trans.* 91:2012–26.
Highland, J. H., et al. 1985. The impact of groundwater contaminants on indoor air quality. *Proceedings of the twelfth energy technology conference*, 728–40. Rockville, Md.: Government Institutes.
I'Anson, S. J.; Irwin, C.; and Howarth, A. T. 1982. Air flow measurement using three tracer gases. *Building Environ.* 17:245–52.
Jun, G., and Sheng, L. M. 1987. The effective and ineffective heat loss by infiltration: Field measurement in a dormitory. *Proceedings of the third international congress on building energy management, Vol. 3: Ventilation air movement and air quality*, 52–57. Lausanne, Switzerland: École Polytechnique Federale de Lausanne.
Kronvall, J. 1980. *Airtightness: Measurements and measurement methods*. Stockholm, Sweden: Swedish Council of Building Research. Report D8.
Liddament, M. W. 1986. A review of European research into airtightness and air infiltration measurement techniques. In *Measured air leakage of buildings*. Ed. H. R. Trechsel and P. L. Lagus, 407–15. Philadelphia: ASTM. Publication no. ASTM-STP/904.
Nazaroff, W. W., et al. 1985. Radon transport into a detached one-story house with a basement. *Atmos. Environ.* 19:31–46.
Persily, A. K. 1982. Understanding air infiltration in homes. Ph.D. diss., Princeton University Center for Energy and Environmental Studies, Princeton, N.J. Report 129.
Reinhold, C., and Sonderegger, R. 1983. Component leakage areas in residential buildings. *Proceedings of the fourth AIC conference: Air infiltration reduction in existing buildings*, 16.1–30. Bracknell, Berkshire, Great Britain: AIVC. Publication no. AIC-PROC-11-83.
Riley, M. 1985. Mechanical ventilation system requirements and measured results for homes constructed under the R-2000 Super Energy-Efficient Home Program. *Proceedings of the sixth AIC conference: Ventilation strategies and measurement techniques*, 16.1–21. Coventry, Great Britain: AIVC. Publication no. AIC-PROC-6-85.
Sinden, F. W. 1978. Multi-chamber theory of air infiltration. *Building Environ.* 13:21–28.
Walton, G. 1985. *Estimating interroom contaminant movements*. Washington, D.C.: U.S. Department of Commerce, National Bureau of Standards. Publication no. NBSIR 85-3229.