16

CONTROL STRATEGIES

Jerry F. Ludwig, Ph.D.
William Turner, M.S.

For centuries, air quality and thermal conditions in buildings have been recognized as important determinants of health and comfort. Unfortunately, in times of escalating fuel costs, energy is often saved by reducing ventilation to inadequate levels, and air quality and thermal comfort may become conflicting goals. This chapter addresses thermal comfort and indoor air quality in the context of relevant aspects of building design and construction, the consequences for air quality of changing use and operation of a building, and methods for air cleaning.

HISTORY OF VENTILATION AND THERMAL COMFORT CONTROL

The art and industry of comfort conditioning (heating, ventilating, and air conditioning) have evolved falteringly and gradually over hundreds of years. Its history includes such illustrious names as Leonardo da Vinci (Ingles 1952), Galileo (Ingles 1952), Benjamin Franklin (Franklin 1906), Florence Nightingale, Dr. John Billings (Billings 1893), Thomas Tredgold (Woolrich 1947), Dr. John Gorre, and the man often referred to as *the father of air conditioning*, Willis H. Carrier (Ingles 1952). Comfort conditioning first became widely used in the United States during the early 1920s in motion picture theaters. Several hundred theaters were comfort conditioned by the end of that decade (Ingles 1952), and since then, comfort conditioning and ventilation have become a major consideration in many countries, usually as a building code or lease requirement, for all buildings designed for human occupancy.

Presently, systems for comfort conditioning typically represent about 10 percent of the first cost of the average commercial-institutional building built in the United States (verbal communication). Commercial-institutional buildings represented 7 percent of the total energy consumption in the United States in 1986 (U.S. Department of Energy 1988), of which the majority was used for comfort conditioning. These figures indicate the substantial cost of comfort conditioning and the potential interactions between the design and operation of heating, ventilating, and air conditioning (HVAC) systems and energy costs.

In the years that immediately followed the oil embargo of 1973, public concerns about the cost of energy resources increased greatly, and attempts were made to reduce the energy cost of comfort conditioning. One approach was to identify and plug energy leaks in building HVAC systems. Since the energy cost of heating the outdoor air brought into a building for ventilation is a significant operating expense and is readily identifiable in budgets, it was often intensely scrutinized. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) specified the use of minimum permissible ventilation rates in buildings in its publication *Energy Conservation in Buildings* (ASHRAE *Standard 90-75*) (Janssen 1987). However, in many documented cases, a building operator compromised the quality of air provided to the building occupants (and the energy efficiency of the HVAC system) by reducing significantly the amount of outdoor air brought into the building via the building's HVAC system. For a time, thermal comfort in some commercial and institutional buildings was compromised by a thermostat set-back program mandated by the U.S. government.

To estimate energy cost savings by such practices, the effect of increasing the ventilation rate from 5 to 20 cfm per person on the annual energy consumption and construction costs of a building was modeled for a prototype 600,000-square foot, thirty-eight-story office building (Eto and Meyer 1988). Using DOE–2.1C, a computer model, the effect of the change was simulated from climate and energy cost data for ten cities in the United States and three in Canada. The modeling showed that the annual energy operating costs of the buildings were increased less than 5 percent with the higher ventilation rate. However, this increment was expressed as a percentage of total costs, which included energy used for many purposes other than comfort conditioning. Construction costs for the HVAC system to handle the higher minimum outside ventilation rates were estimated to increase total building construction costs by less than 0.5 percent.

Before the oil embargo of 1973, energy was inexpensive and often regarded by the general public as having negligible cost. Consequently, HVAC systems were designed for low construction costs, with little or no consideration given to energy consumption. In the 1980s, greater consideration was given to both the initial capital outlay and the operating expenses. However, even at the greater energy costs of the present, the expense of providing comfortable indoor air quality in an office building is still a minor proportion of the total operating expenses, which include salaries, health care, and other costs of maintaining a business (Woods and Crawford 1989).

The problems caused by reducing the amount of outdoor air brought indoors have been worsened by modern construction practices. To control thermal heat loss through the building envelope, air leakage (infiltration) was often decreased. The practice of controlling infiltration by construction methods, widespread in residential construction, has now become increasingly common in commercial construction. New construction materials, which tend to increase the concentrations of a variety of organic chemicals, may be used to reduce infiltration. These chemicals are present in products used as mastics, adhesives, and sealers. The use of composite materials, which also contain volatile compounds, has become increasingly common in the interior of buildings. Thus, indoor air quality problems have been worsened by the contemporary combination of more pollution sources and less dilution of air.

EVOLUTION OF CONTROL STRATEGIES FOR INDOOR AIR QUALITY AND THERMAL COMFORT

Building designs are diverse, and buildings often serve purposes unanticipated in the original design. Some buildings are constructed under restrictions of government bidding procedures or are developed to meet a functional demand of local economics (e.g., offices and apartments). In addition, building designs tend to reflect the availability of local construction materials, labor resources, and energy costs. Often, considerations related to the HVAC system which extend beyond the required minimal codes are subjugated to concerns other than air quality.

As building design and construction techniques have changed to conform with available resources and style, building HVAC systems have also evolved. This section describes some of the types of HVAC systems which have been used typically in commercial-institutional buildings in the United States since the beginning of the twentieth century (Haines 1987; ASHRAE 1987). Emphasis is placed on changes that were made in HVAC system designs consequent to the 1973 oil embargo and the effects that these changes have had on indoor air quality and thermal comfort.

The HVAC system in a commercial-institutional building is usually the primary means for meeting thermal comfort requirements. It is also relied upon to dilute the concentrations of occupant-generated bioeffluents and other pollutants. Conventional design has resulted in several types of HVAC systems. Once the amount of outdoor air required for the building has been determined, usually by local or state building codes, a system for supplying this air to the occupied space is designed. For residential structures, natural infiltration of air has generally been the source of outdoor air, although newer homes may have specific systems. In general, for commercial, industrial, and institutional buildings, outdoor air is deliberately drawn into the HVAC system in a manner similar to the system schematically illustrated in Figure 16.1.

The requirements for ventilation air vary with the intended use of the space. Certain types of areas, such as laboratories, animal care facilities, hospital operating rooms, and special manufacturing areas, may require the use of 100 percent outdoor air, which must be conditioned for comfort. However, in most commercial buildings, for saving energy and reducing capital costs of HVAC equipment, the supply air from the HVAC units has proportionally more recirculated air than

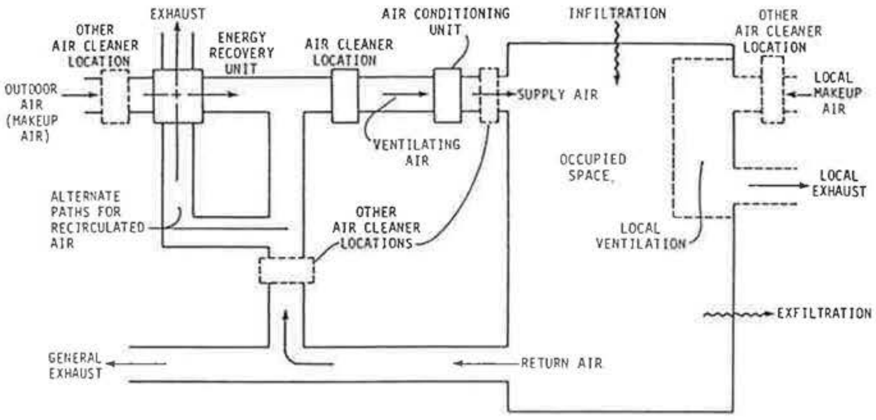

Figure 16.1. General ventilation system. *Source:* ASHRAE Standard 62-1989. By permission.

ventilation (outside) air. Typically, only a minimal amount of outdoor air is introduced into the space to dilute internally generated contaminants.

The simplest method of controlling the volume of outdoor air supplied to the space is to open a "minimum outside air" damper whenever the HVAC system is operated in a "building-occupied" mode. This type of outdoor air control is simple to understand, maintain, and operate (Figure 16.1) (ASHRAE 1989b), and the thermal conditions of the outdoor air in many climates are such that less heating or cooling of the incoming air is required than for the recirculated air from the space. Two types of outdoor air volume control strategies which minimize heating or cooling requirements are currently used. These two strategies are commonly referred to as *economizer cycles*. One strategy controls the proportion of outdoor air and return air to achieve the desired supply air condition based solely on temperature conditions of the two airstreams whereas the second bases the proportions of outdoor air and return air on the "enthalpy" conditions of the two airstreams. These control strategies operate identically, with the exception that the enthalpy control strategy considers the total heat value (i.e., temperature and humidity) of both the return air and outdoor air whereas the sensible control strategy considers only the dry-bulb temperature of the two airstreams.

To minimize capital cost, HVAC systems are often designed with one unit to control the thermal comfort conditions in many spaces in the building, even though requirements may vary among the spaces. Other HVAC systems employ control strategies to achieve thermal comfort conditions in all zones simultaneously. The following paragraphs describe some of the more widely used of these HVAC design strategies, with emphasis on the advantages and disadvantages of each.

Dual-duct HVAC systems, as the name implies, are multizone systems with two ducts (one hot, the other cold) and with mixing dampers (boxes) located near the zone. This type of system is generally used for smaller zones and responds to load

perturbations faster than other types of systems. These systems also ensure that a consistent amount of supply air is delivered at all times.

Single-duct variable-volume systems provide control with only a single duct. The supply air in many of these systems is maintained at a temperature that varies according to the season. The individual zone thermostats vary the quantity of air supplied to the zone to maintain the desired temperature conditions. Change from *cooling* to *heating* alters the set point of the supply air thermostat and reverses the action of the zone thermostat. For example, on *cooling*, the zone thermostat modulates the open air damper toward minimum closure as the zone temperature decreases; the change to *heating* causes the opposite sequence to take place. With this system, however, it is not possible to heat some zones and simultaneously cool others, and overcooling or not cooling sufficiently can be a problem with heterogeneous areas. Single-duct variable-volume systems may be a problem in buildings with differential radiant heating loads. If minimum damper position detents (stops) are not installed on the zone damper to prevent complete closing, air quality may be compromised in zones with low cooling loads.

Dual-duct variable-volume systems, as the name implies, are multizone systems with two ducts (one hot, the other cold) that have mixing dampers (boxes) located near each zone. To maintain the desired temperature conditions, the individual zone thermostats vary the quantity of air supplied to the zone by changing the position of a supply air damper near the zone supply diffuser(s). Unlike the single-duct variable-volume system, this system is capable of heating some zones while simultaneously cooling others. Because of the capital cost of this system, it is seldom designed as part of new construction and is usually introduced as a conversion of a simple dual-duct system to a variable-volume system for the purpose of lowering operating costs in perimeter areas of a building.

Terminal reheat systems provide control with a single duct. The air supply temperature is essentially constant, or reset slightly, at a value suitable for comfort all year round. Reheat coils for each zone are controlled by zone thermostats to satisfy zone temperature requirements, thus providing more flexibility than variable-volume systems. The terminal reheat system can provide simultaneous heating of some zones and cooling of other zones. Terminal reheat systems cost somewhat more to install than variable-volume systems, and depending upon the design, they consume more energy. Some of the operating cost disadvantages of the terminal reheat systems may be overcome by combining terminal reheat with variable-volume systems.

Fan-coil systems are essentially small single-zone air-handling units with a fan, filter, and an oversized coil that may be used for both hot and chilled water. Some more sophisticated but more expensive units are divided into heating and cooling sections. If outside air is not ducted to the fan-coil unit, it must be provided to the occupants through some other means.

Induction-coil systems depend upon a central source of temperature-controlled high-pressure air which induces a secondary flow of air across the unit coil. The induction coil is supplied with hot or chilled water through a two-, three-, or fourpipe system. Thus, it is necessary to control the primary air supply temperature furnished by the central air unit and control the flow of hot or chilled water to the coil according to the heating or cooling demand in the induction-coil zone.

"STATE OF THE ART" CONTROL STRATEGIES FOR INDOOR AIR QUALITY AND THERMAL COMFORT

The usual approach in designing for acceptable indoor air quality within a conditioned space has been based on the mass balance technique. Assuming that the ventilation air and the air of a conditioned space are completely and instantaneously mixed, a general equation for the concentration of an indoor air pollutant (Constance 1970; Drivas, Simmonds, and Shair 1972; Esman 1978; Ishizu 1980; Maldonado 1982; Maldonado and Woods 1983; Offerman et al. 1983; Sandburg 1981, 1983; Skaret 1982; Skaret and Mathisen 1983; Turk 1963, 1968; Woods and Crawford 1989) can be expressed as

$$V\frac{dC}{dt} = G + Q_sC_s - Q_eC - Q_rE_rC \qquad (1)$$

where

- C represents the contaminant concentration;
- $V\frac{dC}{dt}$ represents the change in the mass of a contaminant in a volume with respect to time (g/s);
- G represents the generation rate of the contaminant (g/s);
- Q_sC_s represents the rate at which a contaminant is entering into a space in the supply air (g/s). Q_s is the volume flow rate in volumes per time, and C_s is the external concentration in mass per volume;
- Q_eC represents the rate at which a contaminant is removed from a space by the exhaust air (g/s). Q_e is the exhaust air volume flow rate in volumes per time. C is concentration in mass per volume;
- Q_rE_rC represents the removal rate of a contaminant from a space by filtration techniques (or other loss mechanisms) (g/s). E_r is the filter removal efficiency (unitless). Q_r is the volume flow rate through a filter, device, or ductwork that removes some mass (volume per time). C is defined above.

In this equation, four key parameters control the concentration of indoor air pollutants: source strength, air entering, air exhausting, and removal in the space. Thus, four approaches are evident for reducing concentrations of indoor pollutants: (*a*) source control (reduce G, the contaminant generation rate); (*b*) dilution ventilation (reduce Q_sC_s, dilute the polluted air with cleaner air); (*c*) local exhaust (increase Q_eC, i.e., exhaust the polluted air); and (*d*) air cleaning (increase Q_rE_rC, i.e., remove the pollutants from the air in the space using contaminant filtration techniques). Each control technique is discussed in the following sections.

SOURCE CONTROL

Solving Equation 1 for steady-state conditions (i.e., $V\cdot dC/dt = 0$) and assuming that G, Q_s, Q_e, E_r, and C_s are constant gives the following result (Woods and Crawford 1989):

$$C = \frac{G + Q_sC_s}{Q_e + Q_rE_r} = \frac{A}{B} \qquad (2)$$

where

- $A = G + Q_sC_s$ the combination of air contaminants entering the control volume by internal generation and from outside;
- $B = Q_e + Q_rE_r$ the combination of contaminant removal by exhausting and filtration.

Examination of this expression shows that once a contaminant enters the control volume either by internal generation or by being brought in with air from outside the control volume (i.e., A, the source term, is greater than zero), complete elimination of occupant exposure to the contaminant requires that B, the removal term, increase to infinity (Figure 16.2).

Although this expression points to the obvious solution of removing the pollution source as the best way to reduce pollution concentration within a confined environment, removal may not always be practical or possible.

Pollution sources in buildings may be the building materials, the furnishings or decorating materials, consumer products used within the building, and various processes such as photocopying. Achievement of a source-free environment is impossible. Some pollution sources can be used at the discretion of building occupants; however, the occupants have no control over the building materials specified by the designer or builder. Only recently have manufacturers begun producing low-emission materials, such as adhesives and paints, for finishing or decorating the interiors (Harriman Associates staff, personal communication 1989).

Some home builders now attempt to reduce the amount of toxic or hazardous materials used in construction (Small 1983; Bierman-Little, personal communication 1988). These builders have focused on the use of building materials known to contain fewer potentially irritating compounds, such as paints and interior finishes not emitting volatile organic compounds and insulation materials that do not contain irritating fibers. This approach incurs additional construction costs. Unfortunately, only limited information is available concerning the pollutant source strengths of building materials. However, guidelines for building products and consumer product substitution have been published recently (Fossel 1987; Natural Resource Council of Maine 1987).

Some large companies have limited the type of finish materials used when remodeling inhabited commercial buildings, avoiding the use of solvent-based paints, adhesives, or epoxy finishes (verbal communication). A few companies also have attempted to limit the use of materials emitting toxic compounds in new

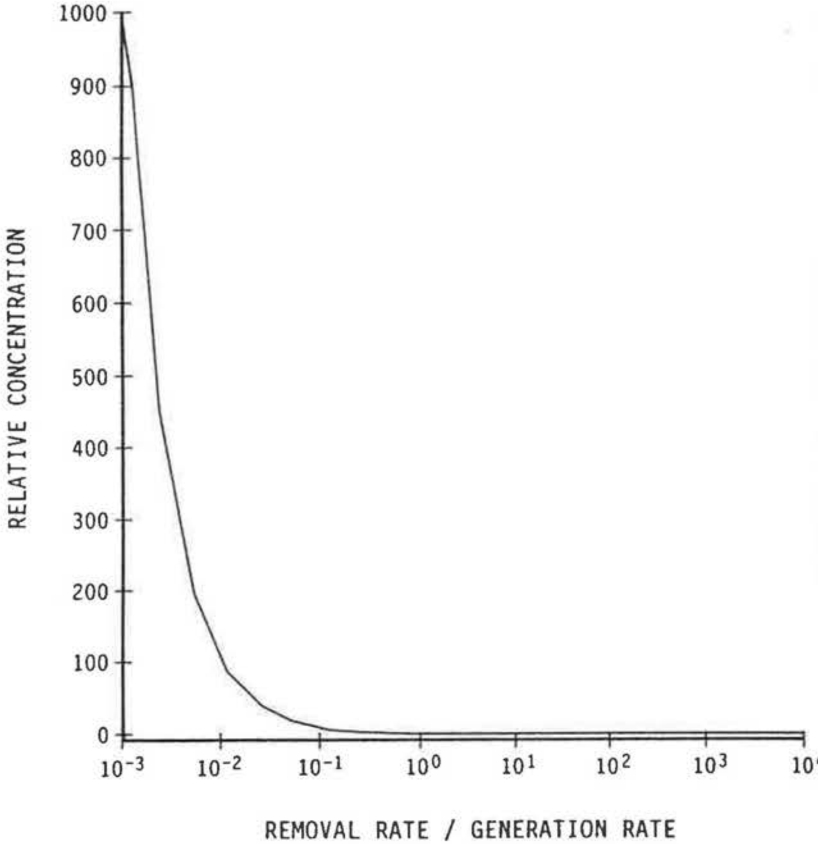

Figure 16.2. Concentration versus removal rate/generation rate for a ventilation system operating in steady-state conditions.

commercial office buildings (Wetherall, personal communication 1988). This approach to source control has not been used widely in commercial buildings because information on pollutant source strengths of building materials is limited and because commercial office buildings are typically ventilated at higher rates than residences.

SOURCE MODIFICATION

Some exposures can be reduced through source modification when the source cannot be totally eliminated. The source strength can be changed chemically or physically by using sealers, reducing the frequency of use, or altering other characteristics of the space, for example, moisture. Also, the exposure can be reduced by relocation or redistribution of the source.

For example, restricting smoking to specific locations reduces the number of areas directly impacted by environmental tobacco smoke (ETS). The approach of concentrating smokers in fewer locations may change the magnitude of personal exposures to ETS but does not produce a smoke-free environment. If the designated smoking area is served by an HVAC system that recirculates the return air to other locations in the building, areas that are intended to be smoke free, ETS exposures still occur. Many modern buildings may recirculate 50–85 percent of the air; the newer commercial aircraft (Boeing 757 and 767 models) recirculate up to 50 percent of the cabin air (National Research Council [NRC] 1986). Simply separating smokers and nonsmokers within the same air space may reduce, but does not eliminate, exposure of nonsmokers to ETS (U.S. Department of Health and Human Services [DHHS] 1986; Bearg and Turner 1987).

DILUTION BY GENERAL VENTILATION

Dilution ventilation refers to ventilation with uncontaminated air to reduce the concentration of contaminants in a room or building for the purpose of health hazard or nuisance control (American Conference of Governmental Industrial Hygienists [ACGIH] 1984). This method of control continues to be used widely in commercial office buildings, schools, institutions, multifamily housing, and modern homes. Dilution provides a comfortable environment with lower levels of potentially odoriferous and irritating compounds. General ventilation is often supplemented with local exhaust.

Historically, ASHRAE ventilation guidelines have been based on the dilution approach, with "clean" outdoor air used to dilute stale indoor air to acceptable odor levels. The work by Yaglou was particularly prominent (Yaglou, Ripley, and Coggins 1936; Yaglou and Witheridge 1937). More recently, the minimum ventilation recommendations for outside air supply set out in ASHRAE *Standard 62-1989* (ASHRAE 1989b) were based on several criteria, including odors, in addition to expected pollutant source strengths and occupant comfort requirements.

Researchers have sought recently to use a mass balance approach to specify the amount of ventilation air needed to provide acceptable pollutant concentrations for pollutants of known source emission rates. One problem with this approach is the actuality of the assumption of perfect mixing.

The mass balance equation (Equation 1) for predicting pollutant concentration in the space as a function of time is solved for the non-steady-state case (i.e., $V \cdot dC/dt \neq 0$) by integration. Assuming that G, Q_s, Q_e, Q_r; E_r, and C_s are all constant over these integration limits, the following result is obtained.

$$C = \frac{G + Q_s C_s}{Q_e + Q_r E_r} = \frac{A}{B}\left[1 - e^{[(-(Q_e + Q_r E_r)/V) \cdot t]}\right] + \left[1 - e^{(-(Q_e + Q_r E_r)/V)}\right] \qquad (3)$$

Although this analytical model accounts for all sources and sinks within the control volume, it has been shown that in many cases this model either underpredicts or overpredicts the actual concentration of pollutants. The poor fit of the model can usually be attributed to imperfect mixing. Figure 16.3 illustrates qualitatively the design techniques that should be either employed or avoided to facilitate "good mixing" of dilution air in a ventilated space. The quantitative differences between measurements and modeled results are reflected in a "mixing" or "ventilation efficiency" factor.

At least two different mixing factors (Drivas, Simmonds, and Shair 1972; Ishizu 1980) and nine different ventilation efficiency factors (Skaret and Mathisen 1983; Maldonado and Woods 1983; Offerman et al. 1983; Sandburg 1981, 1983) have been proposed and applied. All of these parameters emphasize that mixing and ventilation efficiencies are important with respect to controlling indoor air pollutants. These parameters represent a complex process and vary with geometry, thermal parameters, and meteorologic conditions at the time of measurement.

One long-used approach for determining required amounts of outside air for dilution ventilation has been based upon "acceptable" odor levels. This approach involves determining what ventilation rates would be required for visitors entering an area not to object to the odor. This approach was first used in a test chamber by Yaglou and developed further by Cain and Leaderer.

Cain and co-workers (1983) evaluated odors associated with ETS (see Chapter 6). They reported that ventilation rates up to 30 cfm outside air per smoking occupant were not sufficient to achieve a 75–80 percent acceptance of the odor by visitors to the space, which was the criterion for adequacy of ventilation. They concluded that a ventilation rate as high as 100 cfm per smoking occupant might be necessary to meet the criterion of acceptability in situations in which smoking takes place more or less continuously. Cain and co-workers also reported that surfaces in an enclosed room seem to be important sinks for tobacco smoke indoors and that absorbed particles may carry condensed volatiles that could evaporate gradually, thereby imparting a lingering odor. To prevent this contamination of surfaces in a smoking area, Bearg and Turner (1987) recommended local exhaust ventilation as the preferred method of control.

The concept of odor acceptance has been used to evaluate the air quality of buildings. Using an odor panel as a subjective instrument, Fanger (1987) defined the olf (abbreviation for olfaction unit) as the emission rate of bioeffluents from a standard sedentary person in thermal comfort. The curve shown in Figure 16.4 was based on comprehensive studies of more than one thousand sedentary male and female occupants judged by approximately two hundred male and female judges.

Fanger used this subjective instrument to quantify pollution sources in twenty offices and assembly halls in Copenhagen. Each space was visited three times; (*a*) when the space was unoccupied and unventilated, to quantify pollution sources from materials in the space; (*b*) when the space was unoccupied and ventilated, to quantify the combined pollution sources in the space and ventilation system; and (*c*) when the space was normally occupied and ventilated, to quantify the combined effects of the occupants and pollution sources in the space and ventilation system. Each judge was asked to determine whether the air quality was acceptable or not and to evaluate odor intensity. Figure 16.5 illustrates the results obtained

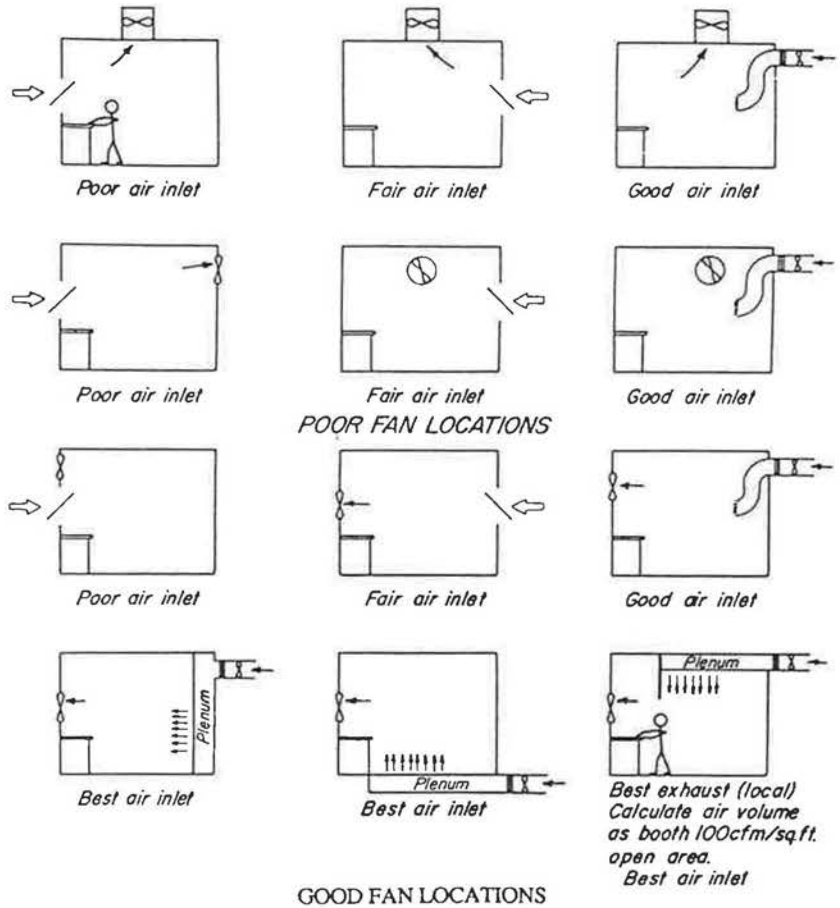

Figure 16.3. General techniques to avoid or employ to facilitate good mixing of dilution air in a ventilated space. Some general rules of dilution ventilation should be followed in order to facilitate good mixing of dilution air in the ventilated zone. The top six designs are examples of poor exhaust air duct placement. The exhaust port is above or behind the work surface (which is the point of contaminant release), causing smoke, fumes, or gases emitted at the workbench to be drawn into the worker's breathing zone. The bottom six diagrams all have the exhaust ports located in the work area. In this location, the exhaust port will provide local exhaust for the work bench in addition to the general room air exhaust. Also demonstrated by this figure are correct and incorrect inlet air locations. Poor inlet air locations either short-circuit directly to the exhaust or push the contaminants from the bench (source) into the room; fair inlet locations do not mix the workbench emissions with room supply air; the best air inlet uses a plenum to distribute makeup air over a large area. *Source:* ACGIH (1984).

from this investigation. Surprisingly, Fanger found that people were the source for only about 25 percent of the odor generation. The materials and ducting (HVAC) system were very important odor sources, each contributing about 40 percent of the perceived odor strength. Generalizing from Fanger's studies, it should not be

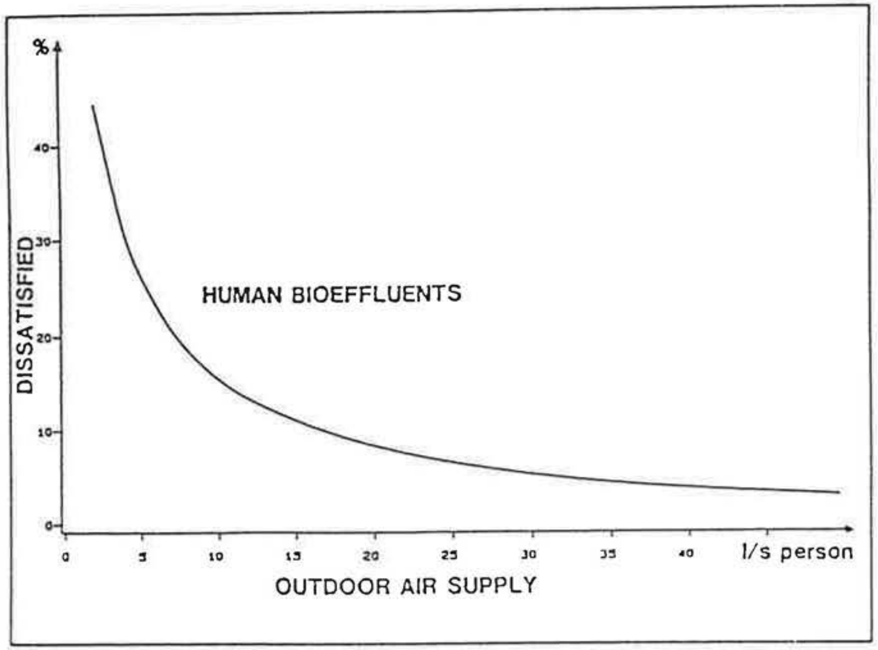

Figure 16.4. The percentage of persons finding the air quality unacceptable when entering a space with a given ventilation rate. *Source:* Fanger (1987), reprinted with permission.

surprising that ventilation standards designed to dilute "people odors" are, in many cases, found to be insufficient.

LOCAL EXHAUST VENTILATION

An advantage of local exhaust ventilation over dilution ventilation is that proper placement of exhaust registers and supply grilles can achieve plug-flow (one directional airflow) through the space. This type of air movement provides the maximum air contaminant removal for a given airflow and is effective in energy conservation and in meeting the requirements of multiple-use spaces. For example, the most efficient way to ventilate a space in which pollutants are emitted in thermally buoyant plumes (i.e., cigarette smoke) is to locate the supply air diffusers in the lower regions of the space and the exhaust registers near the ceiling. This type of exhaust situation has been described in detail by the Norwegian Technical Institute (Skaret 1982) and recently recommended in ASHRAE *Standard 62-1989* (ASHRAE 1989b) as "increasing ventilation efficiency." Exhaust strategies based on the natural tendencies of some air pollutants to stratify vertically in the space have yielded successful results in smoking lounges, print rooms, computer rooms, and industrial facilities. It is also an appropriate strategy for kitchens, where combustion emissions and/or cooking-generated odors rise in buoyant air.

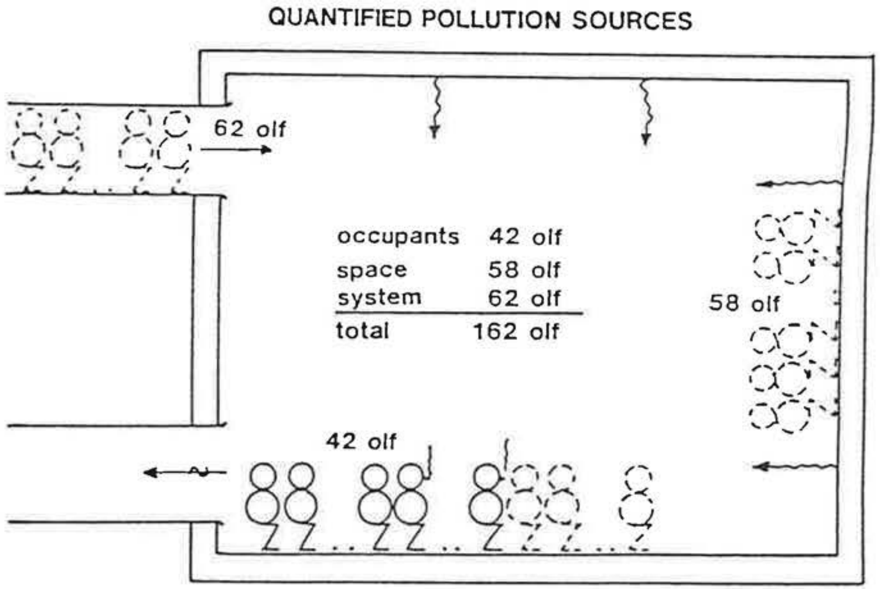

Figure 16.5. Mean values of pollution sources quantified in twenty offices and assembly halls in Copenhagen. The spaces had a mean size of 2,210 m² and an average of seventeen occupants. As an average, five of the occupants were smokers, each polluting six olf. This makes the seventeen occupants pollute forty-two olf. There were large differences in the pollution sources from space to space. *Source:* Fanger (1987), reprinted with permission.

Local exhaust is frequently utilized in residences and commercial buildings and in industrial applications. The goal of good local exhaust ventilation design is to minimize the air volume required and to maximize the collection efficiency. The exhausting of air also requires that quantities of makeup air (approximately equal in volume to that exhausted) be supplied to the room or zone from which the contaminants are being exhausted. Aside from the complete elimination of activities causing emissions, this approach has the greatest potential for achieving environments with low concentrations of contaminants. Certain principles should be followed in using local exhaust (verbal communication with IBM corporate safety officer and with mechanics staff at Harriman Associates):

1. The area should be properly designed to isolate the contaminant to be exhausted.
2. The area also needs to be isolated from the rest of the recirculating air-handling system to prevent the transport of the air contaminants to other locations in the building.
3. The location of both the exhaust register and the makeup supply air and the adjoining rooms' pressure relationships are also important for the correct operation of an exhaust system. It is important that the supply and exhaust be

Table 16.1 Portable Air Cleaner Descriptions and Results

Device Type	Device Number	Device Description	Retail Costs[a] ($) Device	Retail Costs[a] ($) Filter	Speed	Power (watts)	Flow Rate (m^3 h^{-1})	Ratio (m^3 h^{-1}/watt)	Efficiency[b] (%)	ECR[c] (m^3 h^{-1})
Panel filters	PF1	Foam filter	30	4	High	20	17	0.9	0 ± 1	0 ± 2
	PF2	Electret filter	40	5	High	27	49	1.8	11 ± 1	5 ± 2
	PF3	Electret filter	35	6	High	18	36	2.0	16 ± 3	5 ± 2
	PF4	Negative corona	150	12	Medium	28	29	1.0	39 ± 11	12 ± 3
Extended surface filters	ES1	Electret filter and negative ion generator	295	16	High	32	112	3.5	86 ± 9	97 ± 3
	ES2	HEPA filter	395	77	Medium	67	267	4.0	115 ± 17	306 ± 14
Electrostatic	EP1	Two-stage flat plate, positive corona	370	15 (carbon)	Medium	109	366	3.4	57 ± 11	207 ± 32
	EP2	Two-stage flat plate, positive corona	395	15 (carbon)	Medium	77	340	4.4	58 ± 6	197 ± 9
Ion generators	IG1	Residential model, negative corona, positive collector	80	None		2	0			2 ± 2
	IG2	Commercial model, negative corona, no collector	120	None		3	0			51 ± 2
Circulating fan	CF1	Oscillating fan, two units	52 each	None	High	44 each	3,060[d] each	69.6	0 ± 1	2 ± 2

Source: Offerman et al. (1985), reprinted with permission.
[a]Retail costs obtained from manufacturers or local distributors (prices as of mid-1983).
[b]Efficiency calculated as the observed effective cleaning rate divided by the measured airflow rate (±90% confidence limits).
[c]Effective cleaning rate calculated as the flow rate of particle-free air required to produce the observed decay rate in cigarette smoke.
[d]Flow rate as reported by the manufacturer.

located so as to minimize any short-circuiting of the supply air directly to the exhaust air (Turner and Bearg 1987).

4. The exhaust fan for the system should also be located outside or as close to the outside as possible so that the ductwork transporting the air contaminants is under negative pressure in the building. If the ductwork is not leak tight and is under positive pressure, leakage of air contaminants may occur.
5. The exhaust discharge must be designed to avoid reentrainment of the exhausted material. Guidelines for the correct design of exhaust systems are presented in the ACGIH *Industrial Ventilation Handbook* (ACGIH 1988; ASHRAE 1989a).

AIR CLEANING

Air cleaning refers to the use of equipment to remove undesirable contaminants from air. The air cleaning device may be designed as part of the HVAC system or as an isolated installation near the site of contaminant generation. Air cleaning equipment designed to remove particles from the air stream typically includes a medium efficiency filter to remove larger particles and either a final filter (high efficiency particulate air [HEPA] filter) or electrostatic precipitators, which can remove the smaller respirable particles. Most particle removal systems have not been designed to also remove the volatile, semivolatile, or gaseous components of an airstream (Bearg and Turner 1987).

Air cleaners for control of particulate matter are available as both in-duct devices and as portable unducted devices (Offerman et al. 1985; Consumer Reports 1985; Godish 1989). In-duct devices are designed to be integrated with the forced-air HVAC system, whereas portable air cleaners are designed primarily for cleaning the air in one room. In-duct devices have been available for the past thirty years. During that time, their performance has been assessed (Silverman and Dennis 1956, 1959), and performance evaluation standards have been devised (ASHRAE 1976). Since about 1982, a variety of portable air cleaners has appeared on the market. Prices of these portable devices range from $10 to $500 (Godish 1989). Little information on performance, other than general claims by the manufacturer, is available. The results of published studies of portable air cleaners indicate a wide range of performance (Whitby, Anderson, and Rubow 1983; New Shelter 1982; Offerman et al. 1985); Table 16.1 shows the results of one such study (Offerman et al. 1985).

Removal of particles from air by mechanical filtration is accomplished by passing air through a fibrous medium. The deposition mechanisms of impaction, interception, and diffusion predominate for different conditions of particle size and air velocity. Figure 16.6 illustrates the relationship between filter efficiency and particle size for a typical fibrous filter. Three basic kinds of fibrous media filters are available for indoor air cleaning: dry, viscous impingement, and charged-media filters.

Dry-type panel filters have high porosities and low efficiencies. Their typical application is as a dust stop or coarse roughing filter to protect mechanical equip-

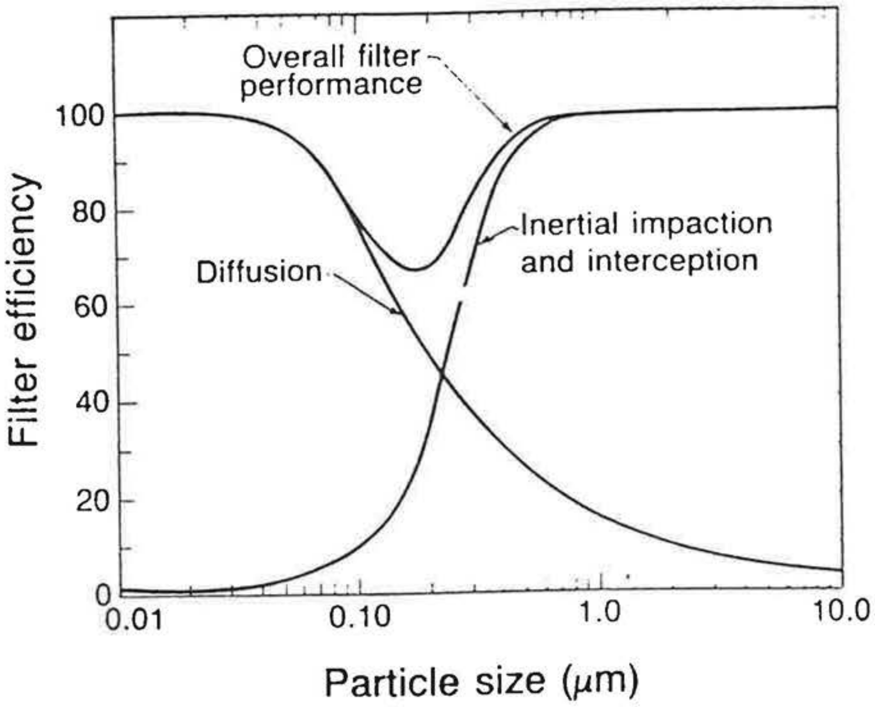

Figure 16.6. Particle removal efficiency as a function of particle size for a typical fibrous filter. *Source:* Reprinted with permission from *Atmospheric Environment* 19, Offerman F. J. et al., Control of respirable particles in indoor air with portable air cleaners. Copyright 1985, Pergamon Press PLC.

ment in HVAC systems and home furnaces or as prefilters for higher efficiency filters. Dry-type panel filters collect large particles by impaction and interception. The media of dry panel filters are commonly open-cell foams, nonwoven textile cloth, or paperlike mats of glass or cellulose fibers.

Viscous media panel filters are comprised of coarse fibers coated by a viscous, oily material to which particles adhere as they impact or impinge on the filter media. Like dry-type panel filters, these filters have low efficiencies for the particle range common to indoor air but are very efficient in collecting fabric dust or lint.

Extended surface dry-type filters are those in which the fiber thickness or density is increased to increase collection efficiency. To offset the resulting increased resistance to airflow, the surface area of the filter is increased, principally by pleating the filter medium. Extended surface filters are available in a variety of designs and performance levels. They vary in media thickness and density, fiber size, media materials, number of pleats per unit area, and filter depth. The filter medium typically is in the form of a random fiber orientation mat or blanket. Common media fibers include cellulose, bonded glass, wool felt, and synthetics.

The most efficient of the extended media filters commonly available is the HEPA

filter. HEPA filters are characterized by efficiencies in excess of 99.97 percent at a minimum particle diameter of 0.3 μm. HEPA filters, originally designed for the nuclear power industry, are widely used in industrial and military clean rooms and have been incorporated recently into portable room air cleaners (Offerman et al. 1985; Godish 1989, Jorgensen, 1983).

Electrostatic precipitators remove particles from the air by electrostatic forces. Three basic designs are available: low-voltage, two-stage, charged-media non-ionizing, and charged-media ionizing precipitators.

The two-stage low-voltage electrostatic precipitators (often referred to as electronic air cleaners) are used widely in residential, commercial, and office buildings. The units are packaged either as freestanding modular units that are suspended from the ceiling or mounted on the wall or as in-duct units installed in residential heating/cooling systems or, in large buildings, placed in the HVAC system. Electronic air cleaner operation is based on the principle that particles moving in an airstream can be electrically charged and subsequently collected on plates of opposite charge. The electronic air cleaner draws particle-laden air past a series of ionizing wires that produce positive ions. The ions attach to the particles and make them positively charged. The air then passes through channels that consist of a series of alternate positively and negatively charged collection plates. The negatively charged plates attract and hold the positively charged particles which lose their positive charge and take on the negative charge of the plate.

Typical ionization potentials are 12 kV whereas the collection plates commonly carry a 6-kV potential difference between plates. During the ionization process, the corona discharge near the ionizing wire produces ozone. To minimize ozone production, most ionizing plate devices use positive coronas since this polarity produces less ozone. The efficiency of the collection plates gradually decreases as the plates become coated with particles, and the accumulated particles reduce the strength of the electrostatic forces. Plates must then be cleaned to remove their accumulated particle load, typically by washing with hot water. Electronic air cleaners installed in large HVAC systems often are equipped with cleaning subsystems for this purpose.

Charged media nonionizing air cleaners combine characteristics of both electronic air cleaners and dry filters. These units consist of a dielectric filtering medium made of a mat of glass fiber, cellulose, or some similar material supported on a grid of alternatively charged or grounded members. A strong electrostatic field is formed through the dielectric filter medium. As particles approach the charged filter medium, they are polarized and drawn to it. Since this filter is a media filter, resistance to airflow increases as the filter becomes soiled. The filter therefore has a limited life before it must be replaced.

Charged media ionizing air cleaners pass the particle-laden airstream through a corona discharge ionizer that charges the particles. Particles are then collected on a charged-media filter.

The removal of gaseous contaminants from air can be achieved by the application of a variety of well-known principles, including adsorption, chemisorption, catalytic oxidation or reduction, and absorption. Adsorption is a chemical/physical phenomenon in which gases, vapors, or liquids coming into contact with a surface adhere to it. This adherence results from the same physical forces that hold atoms, ions, and molecules together in a solid state. Although adsorption is a chemical/physical phenomenon, no chemical reaction takes place. Heat is released and is approximately equal to that liberated when the adsorbed gas or vapor undergoes condensation.

Although adsorption occurs on a variety of solid surfaces, only a few materials have properties suitable for air cleaning: activated carbons, molecular sieves, zeolites, porous clay minerals, silica gel, and activated alumina. These materials have high surface area to volume ratios and surfaces typically comprised of vast labyrinths of submicroscopic pores and channels.

Chemisorption refers to chemical reactions taking place on the large internal surface area of sorbents. These surfaces are often coated or impregnated with chemicals that will selectively react with or chemisorb molecules from a gas stream.

Some adsorption materials remove gases/vapors by catalyzing their conversion to other less objectionable forms. For instance, activated carbon catalyzes ozone to oxygen. Activated carbon has also been shown to speed other reactions. The activated carbon is frequently impregnated with catalysts for specific applications.

Absorption refers to a chemical reaction that occurs between an absorbing medium and contaminant gases in air. In industrial applications, a variety of contaminant gases (including sulfur dioxide and hydrochloride) are removed from waste gas streams by absorbing them in water or in a reactive liquid reagent or slurry.

Because of the complex nature of indoor air pollutant mixtures and the selectivity of gaseous filtration techniques, filtration for removal of gaseous contaminants has been used less widely than particulate filtration. Studies of the air cleaning effectiveness of adsorption/chemisorption systems have been very limited and often based on subjective criteria (Jorgensen 1983; Godish 1989).

The performance of air cleaning equipment in a space can be predicted relatively easily with information to characterize the pollutant and its source strength. For example, consider a home of 270 m^3 (9,600 ft^3) in which ETS is controlled to acceptable levels by natural infiltration at 2.0 air changes per hour (ACH). If the homeowner weatherizes the home, reducing the infiltration rate to 0.5 ACH, and smoking habits do not change, the level of ETS is increased fourfold. If the homeowner purchases a device of 85 percent efficiency to remove the ETS, the device needs to be capable of cleaning 1.75 ACH or 475 m^3/hour (280 cfm). In order for this air cleaner to be most effective, it should be positioned in the room in which the most smoking activity occurs. Likewise, to control air pollution within a single room, the appropriate air cleaner can be chosen using the guidance given by the mass balance equation shown in Equation 2. Assuming that the amount of pollutant removed by exhausting air (Q_e) from the space is reduced, an air cleaner with the appropriate flow (Q_r) and (E_r) quotient can be used to compensate for the reduction of air exchange.

RADON AND OTHER SOIL GASES

The control of radon in indoor environments poses unique problems. The major cause of elevated levels of radon in homes, schools, and commercial buildings is the transport of soil gases from the earth under or around a building into the structure through pressure-driven flow (Figure 16.7). Consequently, the most effective control strategy in residences for radon gas (and other soil gases) originating from the soil is to combine sealing with active reduction of the pressure outside the foundation walls or under the floor. This approach actively prevents the flow of the gas into the structure (Nazaroff and Nero 1984; Nazaroff et al. 1987; D'Ottavio and Dietz 1987; Ericson and Schmied 1984; Brennan and Turner 1986; Turner and Brennan 1985; Turner et al. 1988; Piersol and Fugler 1987). The same principle has been applied in residences for control of volatile organic compounds, termiticides, and gases from landfill decomposition (Jurinski 1984; van de Wiel and Bloemen 1987; Lillie and Barnes 1987; Qazi 1987; Jaquith, McDavit, and Reinert 1987). Other techniques that have been utilized in homes include building pressur-

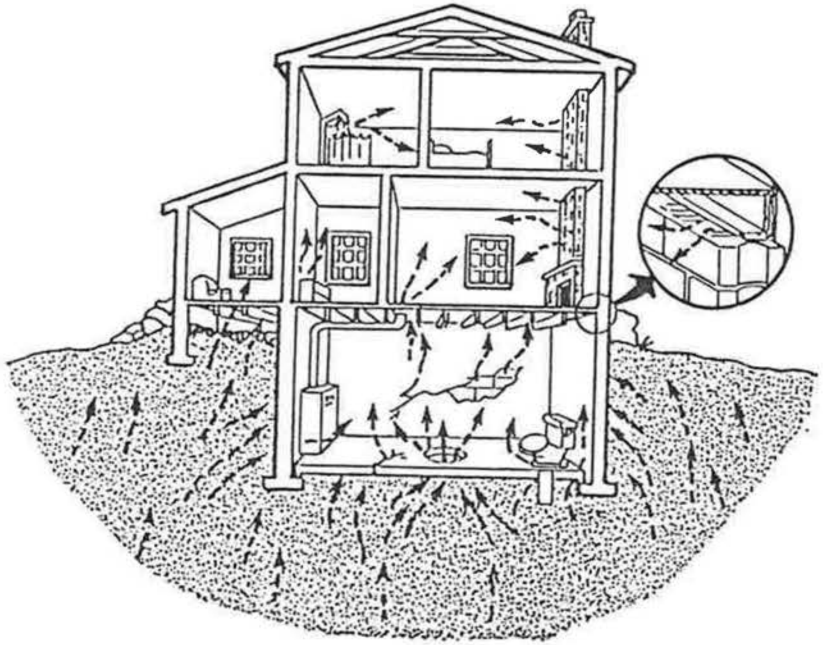

Figure 16.7. Radon entry routes into homes. *Source:* U.S. EPA (1988).

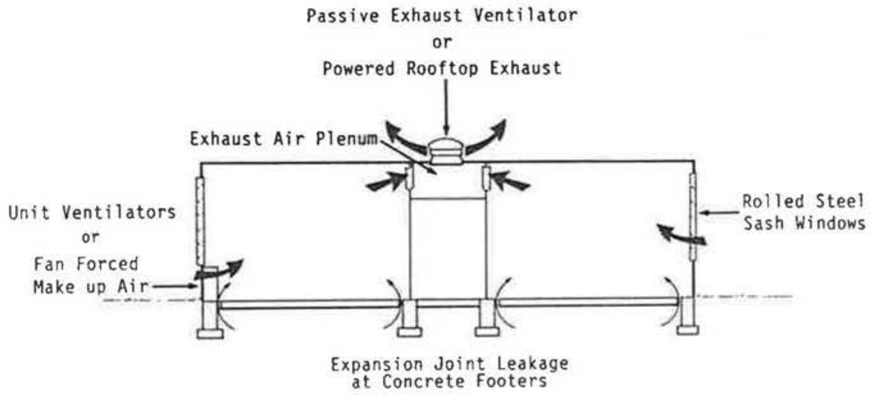

Figure 16.8. Radon entry into buildings under negative pressure.

ization, soil pressurization, specialized building ventilation (i.e., basement exhaust and first floor supply), and air cleaning devices.

Recent data collected for schools and commercial buildings suggest that in many cases, proper design and operation of the ventilation system will prevent soil gases from entering a building. However, this control strategy will only work when the ventilation system is in operation and the building is occupied (Turner and co-workers, personal communication 1990). One of the major causes of negative pressure in a structure is exhaust-only ventilation or a ventilation system that is not supplied with sufficient makeup air (Figure 16.8).

Techniques for constructing radon-resistant residences have been researched and published by the Environmental Protection Agency (EPA) (U.S. EPA 1987, 1988). Techniques for constructing radon-resistant schools and commercial buildings have been suggested, and draft guidelines for this type of building are expected to be available from the EPA by the end of 1990. Engineering firms and designers are now reported to be incorporating features into building designs to reduce the likelihood of soil gas problems (personal communication).

STRATEGIES FOR POLLUTANT CONTROL

Strategies for pollution control are numerous and depend upon the pollutant present. Table 16.2 lists the more common pollutants by source and presents a summary of the control options that are available for each source.

OPPORTUNITIES FOR IMPROVING BUILDING CONTROL SYSTEMS

Avoidance of contaminants that may be generated or emitted in the occupied space is the most effective method of control. Architects and interior designers are only now becoming aware of the impact on indoor air quality of their choices of

Table 16.2 Strategies for Pollutant Control

Typical Source	Pollutant	Equipment and Material Selection	Ventilation Design	Occupant Involvement
Earth and rock beneath home (entering through cracks and holes in the foundation)	Radon and daughters; organic vapors from contaminated ground water	Vapor barrier around foundation; good dampproofing; seal cracks and holes, traps in floor drains, 100% basement seal, and subslab ventilation	Vent crawlspace, vent sumphole to exterior, vent under slab, vent basement, or whole house vent	Vent as near to source as possible (subslab, basement, or whole house); seal cracks and holes; maintain seals and fans; move building; replace backfill
Well water	Radon	Install suitable charcoal scrubber aerator system	Vent bath and laundry	Maintain scrubber or aerator
Insulation in building and on pipes	Asbestos	Do not use; coat existing asbestos with a sealant; enclose and isolate area	Not applicable	Do not disturb, unless a professional; educate service and maintenance personnel; respiratory protection for some activities
Urea-formaldehyde foam insulation, glues, particleboard, fiberglass insulation; furniture, paneling, masking, plywood	Formaldehyde	Use low-emission materials; seal source materials from living space	Vent house, particularly when new or when work has recently been done	Maintain covering or fan equipment
Dust mites, molds, fungus, bacteria, virus, animal dander	Biologic microorganisms	Moisture control with good insulation in building shell, good foundation, dampproofing, proper intake duct design (no condensation)	Provide adequate ventilation to bath and kitchen crawlspaces to maintain inside relative humidity of 35–50%	Clean filters in air handlers, exhaust excess moisture, maintainence and cleaning of potential sources such as humidifiers, drain pans in HVAC and refrigerators

(continued)

Table 16.2 (*Continued*)

Typical Source	Pollutant	Equipment and Material Selection	Ventilation Design	Occupant Involvement
Hairsprays, paints, cleansers, glues, fabric softeners, pesticides, perfumes, deodorizers, carpet cleaners, art and hobby supplies	Organic vapors	Substitute waterbase or nonvolatile substances; label instructions and contents clearly	Ventilate specific source areas (e.g., laundry, shop) (cross-ventilation)	Read labels, use safest products and follow directions; substitute products with less volatile solvents
Unvented heaters, kerosene or gas	NO_2, SO_2, CO, particles	Do not use in inhabited space; provide outside combustion air		Consider vented units; added insulation as replacement; keep units tuned and maintained
Wood stoves, fireplaces	Particles, aldehydes, aromatics	Proper chimney and combustion air; airtight design catalyst	Supply correct combustion	Wood stoves with an updraft
Cigarettes, cigars	Particles, nicotine, gases	Not applicable	Exhaust smoke	Provide separate zones; develop no-smoking policies; provide incentives for cessation
Gas stoves, pilots, burners	CO, NO_2	Pilotless ignition; "tune" appliance	Ventilating hood, room exhaust fan	Use range fan or room fan; do not use range for space heating
Outside air: loading docks, attached or underground garages, reentrained exhaust, neighboring sources	Particles, gases, odors	Proper separation and design of exhaust and intake vents; maintain positive pressure in building; provide separation of zones within structure	Separate zone ventilation of source areas	Maintain equipment in good working condition; do not permit trucks to idle at loading docks

building materials, furnishings, and wall and floor coverings. Whenever possible, low-emission materials should always be specified for use within the interior envelope of a building. Manufacturers of building materials, furnishings, and surface treatments also need to realize that they should be concerned with emissions from their materials and products. These emissions should be identified and quantified. Studies should also be conducted to quantify the emissions of materials as they age and to learn whether products can be cured so that most of the pollutant has been emitted by the time the product is installed in a building.

Buildings currently incapable of meeting the increased minimum ventilation rates should be modified to meet these requirements. In some cases in which the current HVAC system is already operating at heating or cooling capacity, the installation of heat recovery ventilation systems may be an attractive way to minimize the capital cost of the system retrofit.

Systems exist currently for filtering recirculated and contaminated outdoor air. As filtration is practiced more widely, the experience gained and the economy of scale may make these systems more appealing to building owners.

Some HVAC control manufacturers are pursuing sensor technology to measure surrogate indoor air contaminants such as carbon dioxide. Using a monitoring technique, the outdoor air dampers might be modulated to control the level of the surrogate contaminant. These devices may provide opportunities to make the building somewhat more responsive to changing occupancy conditions and yet conserve energy used to condition ventilation air from outdoors.

Architects and engineers need to inform building owners and managers of the design assumptions of building control strategies. The architect or engineer should provide guidance to the building owner concerning the consequences of building remodeling and/or system changes on the functioning of control strategies. ASHRAE *Public Review Draft GPC 1P: Guideline for Commissioning of HVAC Systems* (ASHRAE 1988) has been written to address these concerns.

Better communications between the building owner and the architect/engineer would also be helpful for purposes of planning the occupancy patterns of the building. Building occupants may unknowingly violate the control strategies developed by the architect/engineer when remodeling the space.

SUMMARY

Much research is currently directed toward the subject of indoor air quality and its control, and new information is being published constantly. In this chapter we have attempted to present some of the problems of air pollution control and control systems and the state of the art equipment and strategies available to deal with those problems.

Present public awareness of the possible hazards of poor indoor air quality, coupled with the high cost of the energy required to maintain acceptable air quality and comfort levels in buildings, make it incumbent upon everyone concerned with building construction, maintenance, management, or ownership to study the subject of indoor air pollution and its control. The quality of indoor air can be monitored; polluting substances can be avoided; and air-conditioning systems can be updated or converted if they become inefficient or inadequate. The price of failure to do any one of these things can be high in terms of money or of health.

REFERENCES

American Conference of Governmental Industrial Hygienists (committee on industrial ventilation). 1984. *Industrial ventilation: A manual of recommended practice*. 18th ed. Lansing, Mich.: ACGIH.

American Conference of Governmental Industrial Hygienists (committee on industrial ventilation). 1988. *Industrial ventilation: A manual of recommended practice*. 19th ed. Lansing, Mich.: ACGIH.

American Society of Heating, Refrigerating, and Air-Conditioning Engineers. 1976. *Standard 52-76: Method of testing air-cleaning devices used in general ventilation for removing particulate matter*. Atlanta, Ga.: ASHRAE.

American Society of Heating, Refrigerating, and Air-Conditioning Engineers. 1987. Automatic control. In *ASHRAE Handbook*. Atlanta, Ga.: HVAC systems and applications, ASHRAE.

American Society of Heating, Refrigerating, and Air-Conditioning Engineers. 1988. *Public Review Draft GPC 1P. Guideline for commissioning of HVAC systems*. Atlanta, Ga.: ASHRAE.

American Society of Heating, Refrigerating, and Air-Conditioning Engineers. 1989a. Air flow around buildings. In *ASHRAE Handbook*. Atlanta, Ga.: ASHRAE.

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

Bearg, D. W. 1987. *Achieving tobacco smoke-free environments: The problems and some solutions*. Atlanta, Ga.: ASHRAE.

Bearg, D. W., and Turner, W. A. 1985. Building assessment techniques for indoor air quality evaluations. In *Proceedings of the APCA international speciality conference on indoor air quality in cold climates: Hazards and Abatement Measures*, 29 April–1 May, Ottawa, Canada.

Bearg, D. W., and Turner, W. A. 1987. Achieving tobacco smoke-free environments: The problem and some solutions. Paper presented at ASHRAE IAQ '87, May, Washington, D.C.

Billings, J. S. 1893. *Ventilation and heating*. New York: The Engineering Record.

Brennan, T., and Turner, W. A. 1986. Defeating radon. *Solar Age Mag.* 11:33–37.

Cain, W. S., et al. 1983. Ventilation requirements in buildings: Control of occupancy odor and tobacco smoke odor. *Atmos. Environ.* 17:1183–97.

Constance, J. D. 1970. Mixing factor is guide to ventilation. *Power* 114(2):56–57.

Consumer Reports. 1985. Air cleaners. *Consumer Rep.* 50:7–11.

D'Ottavio, T. W., and Dietz, R. N. 1987. Radon source rate measurements using multiple perfluorocarbon tracers. In *Indoor air '87: Proceedings of the fourth international conference on indoor air quality and climate*. Ed. B. Seifert et al., Vol. 2, 388–92. Berlin: Institute for Water, Soil, and Air Hygiene.

Drivas, P. J.; Simmonds, P. G.; and Shair, F. H. 1972. Experimental characterization of ventilation systems in buildings. *Environ. Sci. Technol.* 6:609–14.

Ericson, S., and Schmied, H. 1984. Modified technology in new constructions, and cost effective remedial action in existing structures, to prevent infiltration of soil gas carrying radon. In *Proceedings of the third international conference on indoor air quality and climate*. Ed. B. Berglund, T. Lindvall, and J. Sundell, Vol. 2. Stockholm: Swedish Council for Building Research.

Esman, N. A. 1978. Characterization of contaminant concentrations in enclosed spaces. *Environ. Sci. Technol.* 12:337–39.

Eto, J. H., and Meyer, C. 1988. The HVAC costs of increased fresh air ventilation rates in office buildings. *ASHRAE Trans.* 94, Part 2:331–45.

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, 49–56. Berlin: Institute for Water, Soil, and Air Hygiene.

Fossel, P. 1987. Sick home blues. *Harrowsmith* 11:46–55.

Franklin, B. 1906. Pennsylvania fireplaces. Reprinted in *Am. Soc. Heat. Vent. Eng. Trans.* 12.

Godish, T. 1989. *Indoor air pollution control*. Chelsea, Mich.: Lewis Publishers.

Haines, R. 1987. *Control systems for heating, ventilating, and air conditioning*. New York: Van Nostrand Reinhold Company.

Ingles, M. 1952. *Willis Haviland Carrier: Father of air conditioning*. Garden City, N.Y.: Country Life Press.

Ishizu, Y. 1980. General equation for the estimation of indoor pollution. *Am. Chem. Soc. Environ. Sci. Technol.* 14(10):1254–57.

Janssen, J. E. 1987. Ventilation for acceptable indoor air quality. In *Proceedings from IFMA '87, eighth annual international facility management conference and exposition*, 1–4 November. Dallas, Tex.

Jaquith, D. A.; McDavit, W. M.; and Reinert, J. C. 1987. Monitoring of air levels of termiticides in homes in the United States. In *Indoor air '87: Proceedings of the fourth international conference on indoor air quality and climate*. Ed. B. Seifert et al., Vol. 1, 230–34. Berlin: Institute for Water, Soil, and Air Hygiene.

Jorgensen, R., ed. 1983. *Air cleaning from fan engineering: An engineer's handbook on fans and their application*, 29.1–46. Buffalo, N.Y.: Buffalo Forge Company.

Jurinski, N. B. 1984. The evaluation of chlordane and heptachlor vapor concentrations within buildings treated for insect pest control. In *Proceedings of the third international conference on indoor air quality and climate*. Ed. B. Berglund, T. Lindvall, and J. Sundell, Vol. 4, 51–56. Stockholm, Sweden: Swedish Council for Building Research.

Lillie, T. H., and Barnes, E. S. 1987. Airborne termiticide levels in houses on United States Air Force installations. In *Indoor air '87: Proceedings of the fourth international conference on indoor air quality and climate*. Ed. B. Seifert et al., Vol. 1, 200–204. Berlin: Institute for Water, Soil, and Air Hygiene.

Maldonado, E. A. B. 1982. A method to characterize air exchange in residences for evaluation of indoor air quality. Ph.D. dissertation. Ames: Iowa State University.

Maldonado, E. A. B., and Woods, J. E. 1983. Ventilation efficiency as a means of characterizing air distribution in a building for indoor air quality evaluation. *ASHRAE Trans.* 89, Part 2b:496–506.

National Research Council. 1986. *The airline cabin environment: Air quality and safety*. Washington, D.C.: National Academy Press.

National Resource Council of Maine. 1987. *Tips on toxics: Suggested safe substitutes.* Augusta, Maine: NRC.

Nazaroff, W. W., and Nero, A. V. 1984. Transport of radon from soil into residences. In *Proceedings of the third international conference on indoor air quality and climate.* Ed. B. Berglund, T. Lindvall, and J. Sundell, Vol. 2, 15–20. Stockholm, Sweden: Swedish Council for Building Research.

Nazaroff, W. W., et al. 1987. Experiments on pollutant transport from soil into residential basements by pressure-driven airflow. *Environ. Sci. Technol.* 21(5):459–66.

New Shelter. 1982. *A test of small air cleaners.* Rodale Press, New Shelter, July/August: 49–57.

Offerman, F. J., et al. 1983. Ventilation efficiencies of wall-or-window-mounted residential air-to-air heat exchangers. *ASHRAE Trans.* 89, Part 2b:507–29.

Offerman, F. J., et al. 1985. Control of respirable particles in indoor air with portable air cleaners. *Atmos. Environ.* 19:1761–71.

Piersol, P., and Fugler, D. 1987. *Development and evaluation of soil gas sampling techniques for the research division, policy development and research sector. Final Report, P-5340/FG.* Ontario, Canada: Ontario Research Foundation, Canada Mortgage and Housing Corporation, and Gratner Lee Associates.

Qazi, A. H. 1987. Termiticides in indoor environments. In *Indoor air '87: Proceedings of the fourth international conference on indoor air quality and climate.* Ed. B. Seifert et al., Vol. 1. Berlin: Institute for Water, Soil, and Air Hygiene.

Sandburg, M. 1981. What is ventilation efficiency? *Build. Environ.* 16:123–35.

Sandburg, M. 1983. Ventilation efficiency as a guide to design. *ASHRAE Trans.* 89, Part 2:455–79.

Silverman, L., and Dennis, R. 1956. Removal of air-borne particulates and allergens by a portable electrostatic precipitator. *Air Cond. Heat. Ventil.* 53:75–80.

Silverman, L., and Dennis, R. 1959. Pollen removal by air filters. *Air Cond. Heat. Ventil.* 56:61–66.

Skaret, E. 1982. *Ventilation by stratification and displacement.* Trondheim, Norway: Norwegian Institute of Technology, Division of Heating and Ventilating. Publication no. N-7034.

Skaret, E., and Mathisen, H. M. 1983. Ventilation efficiency: A guide to efficient ventilation. *ASHRAE Trans.* 89, Part 2:480–95.

Small, B. 1983. *Indoor air pollution and housing: Technology.* Bookwood, Ontario, Canada: Loc IAO, Technology and Health Foundation.

Turk, A. 1963. Measurement of odorous vapors in test chambers: Theoretical considerations. *ASHRAE J.* October: 55–58.

Turk, A. 1968. *Concentrations of odorous vapors in test chambers: Basic principles of sensory evaluation;* 79–83. Philadelphia: American Society for Testing and Materials, Publication no. ASTM STP 433.

Turner, W. A., and Brennan, T. 1985. Radon's threat can be subdued. *Solar Age Mag.* 19–22.

Turner, W. A., and Bearg, D. W. 1987. Delivering "designed" cfm of outside air to the occupants, problems and solutions. Paper presented at ASHRAE IAQ '87, May, Washington, D.C.

Turner, W. A.; Bearg, D. W.; and Spengler, J. D. 1986. Indoor air quality evaluations, procedures and results. Presented at ASHRAE, IAQ-86: Managing Indoor Air for Health and Energy Conservation, 20–23 April, Atlanta, Ga.

Turner, W. A.; Bearg, D. W.; and Spengler, J. D. 1989. Diagnostic aspects of sick building syndrome: Comprehensive IAQ/HVAC system diagnostics for buildings with elevated IAQ complaint levels. Measurements of toxic and related air pollutants. In *Proceedings of the U.S. EPA/AWMA international symposium,* May, Raleigh, N.C.

Turner, W. A., et al. 1988. Defeating soil gas transport into residential and commercial structures. In *Proceedings of the EEBA, Energy Efficient Building Conference and Exposition,* 28–29 April, Portland, Maine.

U.S. Department of Energy. 1988. *Annual energy review.* Washington, D.C.: Energy Information Administration. Publication no. 0384(88).

U.S. Department of Health and Human Services. 1986. *The health consequences of involuntary smoking: A report of the surgeon general.* Washington, D.C.: Government Printing Office. DHHS Publication no. (CDC) 87/8398.

U.S. Environmental Protection Agency. 1987. *Radon reduction in new construction: An interim guide.* Washington, D.C.: Government Printing Office. Publication no. OPA/87/009.

U.S. Environmental Protection Agency. 1988. *Radon reduction techniques for detached houses: Technical guidance.* Research Triangle Park, N.C., Government Printing Office. Publication no. EPA/625/5-87/019.

van de Wiel, H., and Bloemen, H. 1987. The relation between soil pollution and indoor air pollution with volatile organic compounds. In *Indoor air '87: Proceedings of the fourth international conference on indoor air quality and climate.* Ed. B. Seifert et al., Vol. 1, 122–25. Berlin: Institute for Water, Soil, and Air Hygiene.

Whitby, K. T.; Anderson, G. R.; and Rubow, K. L. 1983. Dynamic method for evaluating room size air purifiers. *ASHRAE Trans.* 89:172–82.

Wilson, D. J. 1983. A design procedure for estimated air intake contamination from nearby exhaust events. *ASHRAE Trans.* 89:683–90.

Woods, J. E., and Crawford, R. R. 1989. Cost avoidance and productivity in owning and operating buildings. *Occupational Medicine: State of the Art Reviews,* Vol. 4, No. 4, 753–70. Philadelphia: Hanley & Belfus.

Woolrich, W. R. 1947. Mechanical refrigeration: It's America's birthright. Part II: *Refrig. Eng.* March/April:305–8.

Yaglou, C. P., and Witheridge, W. N. 1937. Ventilation requirements, part 2: *ASHVE Trans.* 43:423–36.

Yaglou, C. P.; Riley, E. C.; and Coggins, D. I. 1936. Ventilation requirements. *ASHVE Trans.* 42:133–62.