AIR POLLUTION AND CONTROL, INDOOR

1. Introduction

Indoor air quality (IAQ) has become a growing environmental issue over the past 20 years. An increasing number of health and comfort problems have been reported in office buildings, schools, residences, and similar nonindustrial settings. Many books and scientific articles have dealt with the nature of IAQ problems. The first comprehensive review of indoor air was published in 1981 (1). Compilations of more recent research articles can be found in scientific and technical journals and in proceedings of the recent triennial international conferences on IAQ and climate (see General References section).

Because the human body processes far more air than other environmental media, relatively small concentrations of contaminants can be of concern. (A typical adult breathes 15–20 m^3/day or about 20–25 kg of air; total intake of food and water is about 3–4 kg/day.) Whereas we often think of water and food contamination in parts per million (ppm), many air contaminants are of concern at concentrations in micrograms per cubic meter ($\mu g/m^3$), which is roughly equivalent to parts per billion. The quality of the air we breathe while indoors is especially important, since on average we spend $\sim$90% of our time inside buildings, not including industrial workplaces (2). Unfortunately, studies have shown that indoor concentrations of many contaminants are higher than outdoor concentrations (3,4).

This article deals with air quality inside residential, commercial, and institutional buildings, which are the spaces normally associated with "indoor air" in the literature. Industrial workplaces present quite different exposures (typically, 40 h/week) and populations (typically, healthy workers). Principles of industrial hygiene address quite different sources, exposures, and protective options than those that are dealt with in most residential, commercial, or institutional situations. Therefore, while many aspects of industrial hygiene practice are applicable, requirements for providing good indoor air quality for the general population are generally stricter.

2. Concerns

2.1. Historical Concerns. Bad odors, smoke, dampness, and infectious diseases have been indicators of poor indoor air quality for centuries (5). Controlling body odors (bioeffluents) has been the basis of ventilation standards since the eighteenth century (6). While these contaminants continue to be problems, the range of concerns broadened considerably in the 1970s—first in Europe, then in North America—as buildings were made tighter and operated with less ventilation to conserve energy. Air quality complaints became more focused on synthetic chemicals and microbial organisms such as molds and mildews (7). Specific contaminants that drew attention to indoor air quality in the 1960s and 1970s included asbestos (from various insulation and building materials), formaldehyde (from faulty foam insulation and pressed-wood products such as particleboard), carbon monoxide (from unvented or leaking vented combustion appliances) and radon (from soil gas infiltrated into homes).

2.2. Current Concerns. As more sophisticated measurements were made in the 1980s and 1990s, it became apparent that there are hundreds of measurable organic compounds in indoor air, present either as gases or associated with particles. See, eg, ref. 3 for a typical listing. Microbial contaminants and their associated gas-phase organic products of respiration and decomposition have also been investigated increasingly in recent years, but sampling and analytical methods are more cumbersome, so data are less complete. See ref. 7 for more detailed discussion of microbial contaminants.

Field investigations of residences, office buildings, and schools show that these contaminants come predominantly from indoor sources such as new materials, cleaning materials, office machines and appliances, and moist areas with favorable conditions for microbial growth. Furthermore, indoor concentrations are highly variable with time and place within a building. Any of hundreds of substances can be the most important with respect to concentration or potential health impact in a given space, at a given time.

The health concerns themselves are numerous. They range from vague dissatisfaction to frank irritation to chronic disease. Common terms found in the literature to classify the health and comfort effects or symptoms are (8):

- **Odor**.
- **Irritation** of eyes, nose, upper airways, throat, and skin.
- **Respiratory function decreases** in nonasthmatics including wheezing, cough, chest tightness, and shortness of breath.
- **Neurological symptoms** including nausea, dizziness, headache, loss of coordination, tiredness, and loss of concentration.
- **Immunological reactions** including inflammatory reactions, delayed hypersensitivity, and immediate hypersensitivity (allergic) reactions.
- Aggravation of **asthma**.
- **Cancer**.
- **Respiratory infections**.
- **Increased susceptibility** to infections or adverse responses to chemical substances.

See references 9–11 for current discussions of the health effects associated with indoor air quality.

Many of the effects or symptoms listed above are included in terms like "sick building syndrome" or "multiple chemical sensitivity (or intolerance)" that are commonly used to describe reactions to or perceptions of the indoor environment. These terms have evolved from complaints of various odors and forms of sensory irritation (especially of mucous membranes in the eyes, nose, throat) by occupants of residences, schools and office buildings. See ref. 12 for a review of sick building syndrome studies and ref. 13 for a discussion of multiple chemical sensitivity/intolerance. Cullen (14) has coined the generally accepted definition of multiple chemical sensitivity.

In addition to frank and perceived health effects, there has recently been increasing concern about monetary impacts of poor indoor air quality: Worker productivity in non-industrial workplaces has been shown in some studies to be measurably affected (15–17). However, more study is needed to separate the effects of air contaminants from the effects of other indoor environmental conditions such as lighting levels, temperature, and relative humidity. The literature (eg, ref. 18) shows a clear improvement in perceived air quality when temperature is reduced from higher temperatures to 20–21°C (68–70°F).

2.3. What Constitutes Poor Indoor Air Quality. Indoor air quality is a public health issue without a widely accepted definition of good air quality or a statement of health goals. Presumably the goal of ambient air quality standards—to protect public health, including the health of sensitive populations such as asthmatics, children and the elderly (19)—is also applicable to indoor air.

Private- and public-sector definitions of indoor air quality have been established for people who own and operate buildings. The American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE) defines acceptable IAQ as: "Air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction" (20).

In a guideline document for building owners and managers, the U.S. Environmental Protection Agency has defined good indoor air quality for commercial buildings to include: "introduction and distribution of adequate ventilation air, control of airborne contaminants, maintenance of acceptable temperature and relative humidity... Good indoor air quality enhances occupant health, comfort, and workplace productivity" (21).

What constitutes poor IAQ therefore depends on many factors, including the physiological and psychological health of the breather (ie, the indoor occupant). Certain combinations of contaminant sources, inadequate ventilation, poor maintenance, and susceptible occupants lead to poor indoor air quality. Residential, commercial, and institutional buildings therefore need to be designed, operated and maintained for those who are sensitive or susceptible, but not necessarily for those who are extremely sensitive. The same requirements apply to the materials buildings are made from, and the products buildings contain.

Although their toxicities vary over several orders of magnitude, most of the individual contaminants discussed in the indoor air literature seem to be of concern at concentrations ranging roughly from 1–1000 ppb (1–5000 $\mu g/m^3$) for gases and from 1–100 $\mu g/m^3$ for particle-associated constituents. Given the potentially synergistic activities of contaminants in a mixture, guideline concentrations for total organic vapors from 300 μg (22) to 4000 $\mu g/m^3$ (23) have been suggested.

Poor thermal conditions can also affect the perception of air quality. See, eg, ref. 24 and its cited references for more information on this interrelationship. As a minimum, it seems prudent to maintain temperature and relative humidity within ASHRAE Standard 55 thermal comfort guidelines (25).

2.4. Standards and Guidelines for Indoor Air Quality. Governmental regulatory bodies have set very few indoor air quality standards. The U.S. Food and Drug Administration (FDA) has set an indoor limit of 100 $\mu g/m^3$ of ozone for spaces where ozone is being generated (26), and the EPA guideline of 4 pCi/L for radon has become a *de facto* standard, but there are few others.

Several indoor air quality guidelines have been suggested; the suggestions are often simply a list of outdoor (ambient) air quality standards or workplace standards, such as appended to ASHRAE's ventilation standard 62 (20). Researchers who specialize in sensory irritation effects have proposed Recommended Indoor Levels (RILs) for ~70 nonreactive volatile organic chemicals (27) and ~30 microbial organic chemicals (28). See ref. 29 for a more comprehensive review of guidelines and specific values for vapors of selected organic acids, phenols, and glycol ethers. Guidelines for mold contamination are most often based on observational data; see, eg, ref. 30.

Lacking definitive IAQ standards, outdoor (ambient) air quality standards serve as a starting point. However, fewer than 50 chemicals are covered by USEPA standards (31) or WHO/European guidelines (32). EPA National Ambient Air Quality Standards cover only six species, one of which—particulate matter—is not composition specific. Furthermore, these standards may be insufficiently protective, especially where cumulative exposure to a contaminant is of concern. This is because the typical person in developed societies spends ~90% of his/her time indoors. Since indoor concentrations are often higher than outdoor concentrations, indoor exposure (concentration × time) can be 10 or more times outdoor exposure.

Industrial workplace guidelines such as Threshold Limit Values (TLVs) are generally not applicable to residential, commercial, or institutional settings. They allow much higher concentrations than would be acceptable to the broad range of people who occupy typical "indoor" spaces. They may be useful in evaluating short-term exposures to people who maintain and renovate buildings during periods when cleaning or coating materials are being used and emissions are high. Concentrations should be much lower when normal occupants are in the building.

Minimum ventilation rates required by building codes, many of which are based on ASHRAE Standard 62, Ventilation for Acceptable Indoor Air Quality (20), have historically been based primarily on the amount of outdoor air required to maintain body odor levels acceptable to at least 80% of visitors to the space (5). A section in the Scope of Standard 62 recognizes the complexity of IAQ problems in modern buildings by stating the following: "Acceptable indoor air quality may not be achieved in all buildings meeting the requirements of this standard for one or more of the following reasons: (*a*) because of the diversity of sources and contaminants in indoor air; (*b*) because of the many other factors that may affect occupant perception and acceptance of indoor air quality, such as air temperature, humidity, noise, lighting, and psychological stress; and (*c*) because of the range of susceptibility in the population" (33).

Perhaps the primary way indoor air quality will be regulated in the future is through emission standards—established by regulatory bodies or private sector organizations—for materials and products. Outdoor air is regulated to a large extent by emissions standards, so it will not be surprising to see indoor air take a similar path. The main difference may be the greater involvement of the private sector; see the following section on source management for more discussion.

2.5. Methods of Providing Good Indoor Air Quality.

There are three basic ways to reduce exposures to indoor contaminants:

- Manage **sources** to prevent or reduce emissions.
- Provide **ventilation** to dilute and exhaust contaminants effectively.
- Remove contaminants by **air cleaners**.

Source management includes selecting, using, and maintaining building materials and furnishings, consumable products and equipment, and is generally the most effective option once building ventilation rates meet standards.

Although direct exhaust ventilation of areas with strong sources such as smoking lounges, kitchens, bathrooms, and copy machine rooms can be very beneficial, general ventilation of a building at rates above standards provides relatively little reduction of exposure. General ventilation provides especially little reduction from sources that are physically close to people, because the effect of dilution is so small over short distances.

Highly effective air cleaning can be very expensive, will depend on effective distribution of air in the space being treated, and is not generally feasible for gases and vapors at the relatively low average concentrations in buildings.

3. Contaminants in Modern Buildings

3.1. We Breathe a Complex Mixture.

Table 1 summarizes the types of contaminants found in indoor air. Note that there is a wide range of natural and synthetic substances in both the gaseous and particulate phases. In many respects the list is similar to the spectrum found in outdoor air, but most substances are present at higher concentrations. This is because there are many sources indoors, and dispersion from indoor sources is less in the confinements of a building than in the relatively unrestricted outdoors. In the extreme, when a source is very close to a person, the person can be in the "plume" of emissions, where the concentration is very high. See references 50–53 for example summaries of data in indoor air contaminant concentrations.

The comparison with industrial exposures is less similar. Indoor contaminants are more numerous but generally at lower concentrations than in industrial workplaces. Despite the generally lower concentrations, and the fact that contaminants are usually present below any known sensory irritation or other health effects, reactions to and perceptions of poor indoor air quality are common.

Researchers and regulators have speculated that there are additive or synergistic effects among the many chemicals present. Odor studies of bioeffluents have shown that individual species may be present below their odor threshold concentrations, but the total mixture of them can lead to the perception of poor indoor air quality (54). Some sensory irritation research based on both animal experiments (55,56) and human studies (57,58) also support this theory, but the agonistic effects found to date have been smaller than would explain people's responses in the field.

Table 1. **Types of Contaminants in Indoor Air**

Type	Examples	Typical indoor concentration (BDL = below detection limit)	References
Products of Combustion			
gaseous oxides	nitrogen oxides, sulfur oxides	2–20 μg/m^3. NO_x higher when indoor combustion present; SO_x higher only when S-containing fuels burned	34
	carbon monoxide	BDL-1 ppm. Concentrations above about 2 ppm may indicate an outdoor source or leaking heating system.	
smoke	cigarette; wood, kerosene, coal (emissions from unvented appliances or leakage from vented appliances)	0–100 μg/m^3	
other products of incomplete combustion	gaseous and particulate species ranging from low MW, volatile substances like aldehydes to high MW, semivolatile substances that are mostly constituents of particles (eg, PAHs)	when present due to infiltration from outdoor air, generally <1 μg/m^3. When present due to indoor sources such as cooking, cigarette smoking, or poorly ventilated wood or coal burners, concentrations can be >1 μg/m^3 for extended periods, and up to 100 μg/m^3 for several hours. See references for further details.	35
Synthetic Chemical Contaminants			
vapor-phase	"volatile organic compounds" (VOCs)	100–1000 μg/m^3 (total). Can be higher in new or newly renovated buildings.	36
particle-phase	Pesticides, phthalates, PCBs, latex, synthetic fibers	BDL-1 μg/m^3 (total).	37–40
Natural Contaminants			
human bioeffluents	ammonia, hundreds of gaseous organics	see references.	41
microbial vapor-phase byproducts	hundreds of gaseous organics	See articles on MVOCs in Proceedings of the 9th International Conference on IAQ and Climate (2002).	
biogenic particles	allergens from animals, pollen, insect fragments, molds, fungi, bacteria (eg, TB, Legionella), viruses	data limited; see references.	42–47
soil gases[a]	radon, humic gases	radon: 0.5–5 pCi/L. average in U.S. homes is ~1.5 pCi/L.	
Natural and Synthetic Fibers			
	asbestos, synthetic vitreous fibers, cellulose, carpet and upholstery	see references.	48,49

[a] Soil gases, which are drawn into buildings mostly by pressure differentials between the ground and indoors, can also contain volatile synthetic chemicals from leaking underground storage tanks or pipelines, waste sites, etc.

Table 2. **Categories of Indoor Sources**

Source category	Examples
combustion sources	smoking, unvented appliances (gas, kerosene), leaking vented appliances
materials	building materials, furnishings, consumer products (sources of organic vapors and particles); moist materials (sources of microbes and their products of respiration and decay)
activities	painting, polishing, spraying, cooking, use of machines or solvents
outdoor sources	infiltration of contaminants via outdoor air or soil gas, evaporation of contaminants from domestic water, tracking in pesticides on shoes or clothing
indoor chemical reactions	ozone reactions with unsaturated hydrocarbons emitted from cleaning agents, flooring materials, and furniture[a]

[a]Refs. 59–61.

3.2. Sources. Many different types of materials are used in the construction, furnishing, maintenance, and operation of a building. In addition, there are various activities by occupants. As potential sources of indoor air quality problems, these items can be grouped into five categories: combustion sources, materials, activities, outdoor sources, and indoor chemical reactions. Examples are listed in Table 2. At a given time, emissions from an individual source in any of these categories can dominate the impact on indoor air quality in a building.

In recent years, incidences of buildings with mold contamination have been especially newsworthy. Materials with sufficient organic matter and moisture can be breeding places for various microbials that generate undesirable odors. When drying conditions cause spore formation, activities and ventilation systems can spread airborne spores that cause allergic reactions or disease. A recent review article provides a good overview of this issue and references for further details (62). Many research papers at the 9th International Conference on Indoor Air Quality and Climate, held in Monterey, Calif. in July 2002, reported on this issue. See "General References" section.

There is a growing body of data—some published, much proprietary—on emissions of gaseous and particulate contaminants from a variety of indoor sources. The most common way to generate such data is to put sample of products into chambers through which controlled amounts of clean air are passed. Concentrations of emitted contaminants in the air exiting the chambers are measured. In the most detailed studies, emissions are measured as a function of time, temperature, airflow rate, amount of sample per unit volume of chamber, and relative humidity. ASTM and the European Community have published guideline procedures for emissions testing (63,64). See refs. 65 and 66 for summaries of publicly available data.

Another potential source of indoor contaminants is air-phase chemical reactions. Although the intensity of ultraviolet (uv) light is generally much lower indoors than outdoors, there are apparently indoor conditions in which measurable formation of secondary pollutants occurs. Investigations into this phenomenon have accelerated since the mid-1990's, when Weschler and others published preliminary research results (59–61). Several papers at the 9th International

Conference on Indoor Air Quality and Climate presented updated research results. See “General References” section.

4. Ventilation as a Control Method

4.1. Types of Ventilation.

Historically, ventilation has been the primary mode of indoor air quality and climate control (67). Only in the past two decades have the complementary roles of air cleaning (other than for equipment protection) and source management been recognized and practiced.

Ventilation, as defined by ASHRAE (68), is “the process of supplying air to or removing air from a space for the purpose of controlling air contaminant levels, humidity, or temperature within the space.” Ventilation can be either natural or mechanical. Natural ventilation is “ventilation provided by thermal, wind, or diffusion effects through doors, windows, or other intentional openings in the building.” Mechanical ventilation is defined as “ventilation provided by mechanically powered equipment, such as motor-driven fans and blowers, but not by devices such as wind-driven turbine ventilators and mechanically operated windows.” Infiltration and exfiltration, defined as air leakage inward or outward “through cracks and interstices and through ceilings, floors, and walls of a space or building”, occurs in addition to intentional ventilation. While infiltration/exfiltration increases the air exchange of a space, it is so irregular and unpredictable that it is not normally considered in assessing the effectiveness of air quality control.

Most single-family residences and small multiple-family units in North America are ventilated by infiltration/exfiltration or naturally ventilated, except for exhaust fans in bathrooms and kitchens. The heating and air-conditioning systems of these buildings are usually designed as closed systems (although the duct systems are notoriously leaky, and often provide substantial, unintentional, mechanical ventilation). Most commercial and institutional buildings in North America are mechanically ventilated by heating, ventilating, and air-conditioning (HVAC) systems; natural ventilation of such buildings is more common in Europe.

Ventilation works in two fundamental ways to control indoor air quality: by dilution, and by direct exhaust. The dilution mode relies on relatively low concentrations of contaminants in the air supplied to the space to dilute contaminants generated in the space. Outdoor air is generally cleaner, hence bringing in outdoor air is an important part of general dilution ventilation. Direct exhaust ventilation is common in areas where there are strong indoor sources; air from those areas is captured and exhausted directly from the building. Good overall ventilation design and operating practice is to exhaust air near strong sources, transfer air from low-concentration to higher concentration areas in a building, locate air intakes to provide good-quality outdoor air, and operate the ventilation system during periods of high emissions such as maintenance activities. For an overview of ventilation strategies, see reference 69.

As with any strategy for indoor air quality control, the fundamental goal of ventilation is, as ASHRAE puts it, to provide “indoor air quality that will be acceptable to human occupants” and to “minimize the potential for adverse health effects"(68). See reference 70 for an excellent overview of ventilation, health, and comfort.

4.2. ASHRAE Ventilation Standard. ASHRAE Standard 62, Ventilation for Acceptable Indoor Air Quality, provides state-of-knowledge guidance from the scientific and technical communities on ventilation system design and operation practices that will help provide good air quality in commercial and residential buildings. Its state-of-knowledge guidance is the best available basis for ventilation system requirements in mechanical sections of building codes for North America. It is also used widely internationally.

Standard 62 has evolved considerably since its first publication in 1973 (71). It is continually reviewed and updated to reflect new information from research and field experience. Recent addenda have created a new section on construction-generated contaminants and ventilation system start-up, a new section on ventilation system operation and maintenance, and new requirements for equipment-related particle filtration.

Table 3 summarizes selected values of minimum ventilation rates for selected spaces out of ~90 different spaces in commercial, institutional, and residential buildings covered by the standard. This table is meant only to illustrate the variety of spaces and rates covered; see the full standard for complete listings and details. Note that the ventilation rates listed are for the outdoor air portion only. With recirculation, the total ventilation rates in buildings are often ~5 times higher.

Currently, the lowest per-person outdoor air rate is 8 L/s; the highest is for smoking lounges, at 30 L/s per person. Spaces with highly irregular or low occupancies or strong sources (such as the example above of malls and arcades) have requirements based on floor area. ASHRAE is considering a revision of these prescriptive rates to separately account for contaminants from people and from other sources; the separate rates would then be added to obtain the total outdoor air rate.

Table 3. **Selected Outdoor Air Requirements for Ventilation**[a]

	Outdoor air requirement[b]			
Space type	cfm per person	L/s per person	cfm per ft^2	L/s per m^2
fast food cafeteria	20	10		
bars, lounges	30	15		
hotel bedroom			30 cfm per room	15 L/s per room
office space	20	10		
malls, arcades			0.20	1.00
classrooms	15	8		
hospital patient rooms	25	13		
residential living areas	≥15 (and 0.35 air changes/h)	≥7.5 (and 0.35 air changes/h)		

[a] From ASHRAE Standard 62-2001
[b] cfm = cubic feet/minute; L/s = liters/second; ft^2 and m^2 refer to floor area.

In addition to the prescriptive rates described above, Standard 62 provides an Indoor Air Quality Procedure for designers who have information on sources, emission rates and compositions, toxicity data for the emissions, and health-based criteria. In principle, this procedure enables greater rigor in calculating ventilation rates for healthful indoor air and enables consideration of the benefits of "clean" materials and air cleaning systems. At present, its application is limited by the lack of health-based criteria for maximum acceptable concentrations of many of the air contaminants found indoors.

4.3. Ventilation and IAQ Models. Various computer-based models for ventilation calculations have been developed. One of the most widely used is CONTAM (72). Characteristics of the building, meteorological conditions, HVAC system design, and indoor sources can be entered, then air flows and contaminant concentrations throughout the building over time are calculated by a series of mass balance calculations.

There are also a number of simpler mass-balance models that are designed more for IAQ calculations. These require the user to enter ventilation flows. See ref. 73 for a review. There are also computational fluid dynamics (CFD) models used by researchers to estimate conditions at individual points in a space. For most practical uses, however, the space-average concentrations provided by mass-balance models are sufficient.

4.4. The Relationship With Energy. Based on the U.S. Department of Energy data summarized by ref. 74, ~36% of total primary energy consumed in the United States is used to heat, cool, light and operate equipment in residential and commercial buildings. Even at current low energy prices, this costs >$230 billion per year. During the short-lived energy cost spikes in the 1970s, energy conservation was increased by tightening buildings to reduce infiltration and by reducing ventilation rates. Those energy conservation efforts tended to increase indoor relative humidity and contaminant levels, and highlighted the important relationship between energy conservation and indoor air quality. As real energy prices increase in the future—as they inevitably will—there will be increased interest in reducing ventilation rates. Given what we now know about indoor air quality, any future reductions in ventilation rates will have to be accompanied by either reduction in emissions from indoor sources, or increased use of air cleaning, or both.

4.5. Effectiveness of Ventilation. The effectiveness of ventilation in controlling indoor air quality has limitations. As noted previously, exhaust ventilation can be quite effective if the capture efficiency is high. Dilution ventilation generally works best if airflow is from low concentration areas toward high concentration areas, but this may not be practical, especially if the locations of major sources change with time. Furthermore, since much of ventilation air is recirculated, contaminants tend to get distributed throughout the building (or at least the portion of the building served by a given air handling system). As also mentioned previously, dilution ventilation has very little effect on emissions from sources close to a person (eg, clothing, cosmetics, office machines, bedding or flooring materials for infants).

Most ventilation systems are designed for complete mixing of air supplied to the space. If a space with poor air quality is being supplied with 50% of the rate specified by code, increasing the rate to code requirements will only reduce contaminant concentrations by ~50%. Increasing the rate to double the code requirement (even if mechanically possible) will only provide another 50% reduction. That level of reduction further assumes that the outdoor air that is being used for the dilution has a zero concentration of the contaminant, is similarly free of additional contaminants, and is not overly humid. The bottom line with respect to ventilation effectiveness is this: Substantial reductions (say of 80–95%) of contaminant concentrations will require reducing emissions from indoor sources or cleaning the air. These approaches are the subject of the following sections.

5. Source Management as a Control Method

5.1. Prevention of Emissions. In principle, preventing IAQ problems by managing indoor sources can be very effective. The objective is to use materials and products with low (or no) emissions of substances that might cause odor, sensory irritation, or other health problems. Over the past two decades, research and development of product testing procedures and exposure prediction models have produced useful tools for evaluating the acceptability of building materials, furnishings, and other products used in buildings. Emission testing and prediction of occupant exposures has become a key step in the design of some buildings (75). This section describes how materials and products can be evaluated to help prevent IAQ problems.

Emissions prevention involves many parties, throughout the whole life cycle of a building. Manufacturers of materials and products need to know how to test and certify that their products are not just low emitting, but have low adverse health impact. Specifiers such as architects, builders, and purchasing agents for building owners need information on low emitting and low impact building materials, furnishings, and consumable products. Public health officials who are increasingly involved with air quality problems in buildings need similar information to pass along to the general public.

5.2. General Selection Criteria for Indoor Materials. Any building materials, furnishings, maintenance materials, or other contents of a building are selected with various physical, aesthetic, economic and environmental criteria in mind. Examples of such criteria are listed in Table 4. Hundreds (sometimes thousands) of material selections need to be made for a typical building, and several of these criteria often conflict.

Historically, environmental criteria have not played a major role in materials selection. In recent years, however, the balance has shifted to give environmental considerations greater weight. For example, the American Institute of Architects (AIA) has developed an Environmental Resource Guide. Intended for architects, it attempts to describe life-cycle environmental impacts of materials used in buildings. The AIA life-cycle concept includes total environmental impacts during production, use, and disposal of the materials (77).

5.3. Emissions Criteria for Indoor Materials. From an indoor environmental point of view, there are several characteristics that could be considered in describing an “ideal” material. Such characteristics are listed in Table 5.

Table 4. **Selection Criteria for Indoor Materials**[a]

Attribute	Examples
physical	strength
	durability
	heat transmission
	light transmission
	maintainability
	effectiveness (eg, as a cleaning agent)
aesthetic	color
	texture
	odor
	noise
economic	initial cost
	maintenance cost
	operating cost (eg, energy)
environmental	emissions to air
	water and waste impacts
	support of microbial growths
	life-cycle impacts

[a] See Ref. 76.

Not many materials will have all of these characteristics, of course. Compromises will usually have to be made, and many that at first seem undesirable may turn out to be quite acceptable. For example, a material with a high initial emission rate but rapid decay may be quite acceptable if used in a manner that does not lead to high exposures, either during use or from reemissions from interior surfaces that have adsorbed the emissions. Examples of material and product selection criteria that have been used in both the public and private sectors are summarized in ref. 78.

Whether the emissions from any source will lead to “acceptable” indoor concentrations and occupant exposures will depend on a number of considerations,

Table 5. **Desirable Characteristics of Indoor Materials**

Factor	Desirable characteristic
emission properties	low emission rates
	low toxicity of emissions
“sink” properties[a]	nonsorbent
	if sorbent, not reemitting
	if not reemitting, nonnutrient
microbial properties	hydrophobic
	nonnutrient
	cleanable
physical properties	as needed for the application
aesthetic properties	as desired for the application
cost	reasonable

[a] Ability of a material to adsorb or absorb vapors from the air. Sinks can be essentially irreversible, or reversible (reemitting). Sinks that reemit sorbed contaminants can be significant sources when the strength of original sources has decreased.

viz: (*a*) emission rates; (*b*) the toxicity or irritation potential of substances emitted; (*c*) ventilation rates; (*d*) physical relationships between the source, the persons present, and the space they occupy (the proximity of the source to people breathing its emissions can greatly affect the amount of dispersion and dilution of emissions, and therefore the concentrations actually breathed); and (*e*) the sensitivity of the occupants.

These factors are highly variable from building to building, and often from area to area within a building. Therefore, product acceptability is essentially a situation-specific issue. The best currently available approach to evaluating indoor materials and products is to test their emission rates, and predict pollutant concentrations in the building where they are to be used. Various indoor air quality prediction models (79–81) are available, but for most purposes the simpler models such as (79) are sufficient.

If emissions data are not available for a particular product of interest, various emissions models are available for estimating emissions rates. See ref. 82 and 83 for a review of these models.

Starting from the best available IAQ criteria, modeling can estimate the maximum advisable emission rate (eg, milligrams per hour of chemical or physical pollutants, or colony forming units per hour of microbial pollutants). The emission rate then usually needs to be divided by the amount of material or product to be used; that will yield an emission factor (emission rate of contaminant per unit of product). The most common units for emission factors are μg/h per m^2, kg, or number of items used.

This maximum advisable emission factor can then become the IAQ basis for selection of indoor materials and products. Since emissions from many materials change greatly with time, the time dependency of the emission factor should be considered. For most situations, emissions at the time when building occupants are first exposed are the most relevant.

In spite of the lack of a solid data base on acceptable concentrations of complex mixtures of substances, many builders, architects and consumers are asking for lists of, or guidelines on, "low emitting" or "clean" materials and products. At present, however, there are not enough published emission rate data to list specific recommended products. Therefore, classification schemes such as shown in Table 6 [adapted from ref. 78] can be used for judging whether products are acceptably low emitting. Acceptability in this case is based primarily on the work of Mølhave that suggested a mucous membrane irritation threshold for total organic vapors in the range of 160–5000 μg/m^3 (84); Seifert's suggested target level of 300 μg/m^3 (85); and Alarie's suggestion of 4000 μg/m^3 for nonreactive organic vapors (86). Assuming 1000 μg/m^3 to represent the range of their recommendations, and accounting for multiple sources with one dominant source, a maximum contribution from any single source type of 500 μg/m^3 is used in Table 6.

Values in Table 6 should be taken as gross guidelines and careful note should be made of the explanatory comments. Many users may want to adopt the conceptual framework of the table, and establish a classification scheme to meet their specific applications.

Manufacturers need to make clean products, but the definition of "clean" is—and will remain—elusive. As a general guideline, it seems prudent to try

Table 6. **A Classification of Low Emitting Materials and Products**[a,b]

Material or product	Maximum emissions[c]
flooring materials	0.6 mg/h per m^2
floor coatings	0.6 mg/h per m^2 [d,e]
wall materials	0.4 mg/h per m^2
wall coatings	0.4 mg/h per m^2 [d]
movable partitions	0.4 mg/h per m^2
office furniture	2.5 mg/h per workstation
office machines (central)	0.25 mg/h per m^3 of space
ozone emissions	0.01 mg/h per m^3 of space
office machines (personal)	2.5 mg/h per workstation
ozone emissions	0.1 mg/h per workstation

[a] See Ref. 78.
[b] Based on emissions of total organic vapors, except as noted.
[c] This column lists default values for use where predictive modeling of IAQ impacts is not done. For specific indoor situations, modeling is generally preferable to using these defaults, and may yield very different values for maximum emissions. Values for particularly noxious organic compounds will also be lower than those shown.
[d] Many varnishes, paints, waxes and other wet coatings have emission factors substantially higher than this, immediately after application. These coatings might still be considered "low-emitting" if their emission factors drop below this level within several hours. However, the frequent presence of other surfaces that adsorb coating vapors and subsequently re-emit them complicates the classification of coatings.
[e] Basic Assumptions: Indoor air is well mixed; ventilation rate is 0.5 exchange of outdoor air per hour; maximum prudent increment in indoor concentration of organic vapors from any single source type is 500 $\mu g/m^3$; maximum prudent increment of ozone is 20 $\mu g/m^3$ (0.01 ppm); volume of concern for dispersion of emissions from furniture and machines at workstations is 10 m^3.

to keep a product's emissions to rates that—with normal use in occupied spaces—would lead to indoor concentrations less than $\sim$500 $\mu g/m^3$ for low toxicity gases and vapors, and below the ambient air quality standard for sulfur dioxide (the most restrictive standard) for moderate-toxicity gases and vapors. Using the same logic for particles, a product's emissions would lead to indoor concentrations below the particulate matter ambient air quality standards. For practical purposes, this may amount to eliminating volatile, moderate-toxicity substances from indoor products.

Occupant exposures to emissions from periodic building maintenance and other work and personal activities can also be high. These periodic, short-term exposures, in addition to initial emissions from new materials, are thought by some to be the triggering causes of many "sick" buildings that are investigated—without success—several weeks or months after complaints are first expressed.

Degradation of materials leading to particle emissions and biocontamination of materials that have become soiled and wet can also be potentially severe sources of IAQ problems. Therefore, maintainability, durability, and susceptibility to microbial growth are important (and often overlooked) factors in selection of materials for good indoor air quality.

5.4. Emissions Testing. If emission factors are to be used in material selection, data from emissions testing are needed. Proper testing involves the use of environmental chambers with carefully controlled airflows and environmental conditions. Many researchers have been using such chambers in recent years, and limited amounts of data are publicly available. See ref. 87 for a listing of publications through 1997 and ref. 88 for typical values of volatile organic compound emissions derived from the published literature.

A few commercial testing laboratories such as Air Quality Sciences in Atlanta do emission testing for product manufacturers, designers, or building owners. Several manufacturers are also set up to test their own products. They generally follow the ASTM guidelines mentioned previously (89). An important alternative is to use a mouse bioassay to obtain data on sensory irritation effects of emissions (86). This has the benefit of giving a direct biological response to complex mixtures of contaminants. Procedures for this type of testing are described in ASTM Standard 981-84 (90).

Emission rate testing and exposure modeling has become a significant step in the design of some new and renovated office buildings. When coupled with appropriate attention to ventilation system design and operation, aesthetic and ergonomic factors, and building maintenance, occupant complaints that characterize “sick buildings” are almost certain to be reduced. However, this process is currently hampered by the lack of data on emissions and clear understanding of relationships between exposure to emitted substances and health or sensory irritation.

5.5. Product Testing and Labeling. Either type of testing—chemical emission rate or animal bioassay—can be used as the basis for labeling indoor materials and products. Labels can show numerical values for emission factors or intensities of biological responses under standard testing conditions. They are conceptually similar to energy efficiency labels on household appliances or gasoline mileage ratings of automobiles in that they would serve as an indicator of the quality of a material or product for indoor use, from the standpoint of IAQ impacts. A notable example is the “green label” program of the Carpet and Rug Institute (97). A summary of their emissions limits, based on periodic testing of products from production lines, is shown in Table 7.

5.6. Building Design, Operation, and Maintenance. Many indoor air quality (IAQ) problems can be prevented during building design. While the importance of proper design of ventilation systems has long been recognized, selection of materials and products is now receiving increased attention. It is important to avoid sources with emissions that are too great to be diluted and exhausted by ventilation, or removed by affordable air cleaning devices. This is especially true for sources that are close to occupants, such as office furniture, furnishings, office supplies, and personal care products.

Prevention of IAQ problems can often be most cost-effectively accomplished at the design, operation, and maintenance stages of the lifecycle of a building. This is widely recognized in publications by architects (3), ventilation engineers (92), and regulators (93). Selection of materials, as discussed above, is important at the design stage. Levin presents an excellent outline of a step-by-step process for good design in ref. 94.

Building operation and maintenance activities are important in assuring overall cleanliness, moisture control (to prevent microbial problems), and the use of appropriate cleaning materials and methods. Operation and maintenance guidelines have been published by ASHRAE for both the commissioning/start-up

Table 7. **"Green Label" Emissions Criteria Established by the Carpet and Rug Institute**[a]

Product	Emitted contaminant	Maximum emission factor[b]
carpet	4-phenylcyclohexene	0.05
	styrene	0.4
	formaldehyde[c]	0.05
	TVOCs[d]	0.5
carpet adhesives	formaldehyde	0.05
	2-ethyl-1-hexanol	3.0
	TVOCs	10.0
carpet cushions	4-phenylcyclohexene	0.05
	formaldehyde	0.05
	BHT (butylated hydroxytoluene)	0.30
	TVOCs	1.00
vacuum cleaners	dust	emissions that create 100 μg/m^3 of dust in the room[e]

[a] *www.carpet-rug.com*
[b] Emission factor units, except for vacuum cleaners, are mg/h of contaminant per m^2 of product.
[c] The formaldehyde criterion for carpet is intended to prove that none is used in the product.
[d] Total Volatile Organic Compounds. Usually sampled by thermally desorbable solid sorbents and analyzed by gas chromatography–mass spectrometry.
[e] Specifically, this criterion is worded: "The dust containment protocol evaluates the total amount of dust particles released into the surrounding air by the action of the brush rolls, through the filtration bag, and any air leaks from the vacuum cleaner system. This protocol requires that a vacuum cleaner will release into the surrounding environment no more than 100 micrograms of dust particles per cubic meter of air...".

and occupancy phases of a building's life cycle (92,95,96). Others have also addressed the impacts of cleaning and other operations and maintenance activities (97,98).

6. Air Cleaning as a Control Method

6.1. General Comments. The third approach to providing good indoor air quality is air cleaning. Air cleaners can either be stand-alone units for treating air in a single room or a portion of it, or central-system units that are built into the heating, ventilating, and air-conditioning (HVAC) system. For the indoor situations covered by this article, mask-type filters are not considered.

If ventilation conditions meet standards and indoor sources are being managed to the extent practical, air cleaning may provide additional health benefit. This finding is especially true if there are indoor sources that are particularly difficult to manage. In general, however, air cleaning has many of the same types of limitations as ventilation: Large volumes of air need to be processed to remove or destroy very small concentrations of contaminants. To be effective, air cleaner intakes need to be close to sources of key contaminants, the device needs to process a sufficient amount of air relative to the volume of the space being treated, and it must have reasonable collection or destruction efficiency and capacity.

As with the other options, air cleaners also need to be easy to operate and maintain, and be reasonably economical. A particular restriction on central-system air cleaners is pressure drop. Since very large volumes of air are handled in HVAC systems and power requirements for air handling are large, there is very little margin for incremental pressure drops in most systems. A pressure drop of 2.5 cm (1 in.) of water is considered the approximate practical limit for air cleaners. General HVAC system filters, which are installed to remove dust to protect equipment and prevent build-up on heat exchanger surfaces, normally have pressure drops <2.5 cm.

Air cleaners can be designed to remove particles or remove/destroy gaseous contaminants. Devices for general particle removal, infectious particle removal, and gaseous contaminant treatment are discussed in the following sections. Devices that operate by generating ions or ozone are also marketed, but their effectiveness is suspect. Ozone-generating devices should not be used in occupied spaces (99).

6.2. Particle Filtration. There are two general types of particle removal devices used in buildings: fabric filters and electrostatic precipitators. Designs have been adapted from similar devices used in industrial applications. The most common form for filters is the pleated type, although extended-area bag filters are used in some large buildings. Electrostatic precipitators, sometimes referred to as "electronic" air cleaners when marketed for residential applications, are physically similar to, but lighter in construction than industrial units; they also operate at lower voltages. Air cleaners for commercial buildings are often sold in modules designed to handle $\sim 1\ m^3/s$ (~ 2000 cfm) of air, and installed in banks when greater airflows are needed.

Good general references to design, operation and maintenance of these devices for commercial and institutional buildings can be found in (101). EPA and Consumers Union have published reports on the performance of residential devices (102,103).

ASHRAE Standard 62, in addressing commercial large residential, and institutional buildings, requires particle filters or air cleaners with a minimum efficiency reporting value (MERV) of 6 or more "…upstream of all cooling coils or other devices with wetted surfaces through which air is supplied to an occupiable space" (104). That standard also allows reduction of ventilation rates when acceptable air cleaners are used (105).

Although testing methods for particle removal efficiency have been available for many years, a widely accepted test method that measures efficiency as a function of particle size has only been in place since 1999. ASHRAE Standard 52.2 (106) is an important improvement, since it measures filter efficiency for particles from 0.3 to 10-μm diameter, in 12 size ranges. This covers the respirable range nicely, and includes the 0.3–1-μm sizes that are difficult to collect by low to medium efficiency filters. Standard 52.2 gives efficiency ratings in MERV values that range from 2 (for low efficiency filters such as furnace filters in residential applications) to 6–9 (for medium efficiency filters such as pleated types) to 16 (hospital grade) to 18 (HEPA) and 20 (ULPA).

ASHRAE Standard 52.2 does not cover electrostatic precipitator-type air cleaners. In principle, "ESPs" can be very effective in removal of the full range of respirable particles, and have much lower pressure drop than filters. Ozone generation from arcing can occur, but most commercial units have adjustable voltage to control that. Some low-cost units for residential and commercial building applications have poor airflow distribution, which allows some particles to bypass the charging zone and compromises performance (107,108). A testing procedure similar to Standard 52.2, with provisions to also measure ozone generation, is needed for these devices.

6.3. Control of Infectious Particles. Person-to-person transmission of bacterial and viral respiratory diseases occurs mainly via airborne particles that are evaporative residuals of droplets created by coughing and sneezing. These "droplet nuclei" are typically 1–3 μm in diameter. Like other particles, their concentrations can be controlled by ventilation, source management (ie, care of infected persons), and particle air cleaners.

Ventilation rates that meet code requirements for body odor and humidity control (typically, ~8–10 L/s per person) have been widely assumed to be sufficient for control of infectious agents, but some studies have shown otherwise (109). Increasing ventilation above code requirements incurs energy and cost penalties, and the increased dilution leads only to modest reductions.

Particle air cleaners with high removal efficiencies and recirculation rates can reduce droplet nuclei concentrations if located and operated so as to properly distribute the clean exhaust air. The effective ventilation rate of the space is increased, perhaps by a factor of 2–4, but this may not be sufficient for spaces occupied by infected persons. Noise and drafts can also be a drawback to these devices (110).

Another type of control system is ultraviolet germicidal irradiation (UVGI). Air is passed over lamps emitting light in the uv-C region (typically, ~254-nm wavelength). These devices are often installed in the upper-room mode, where lamps are mounted near the ceiling. Natural convection in the room circulates the air across the lamps. The theory and application of this technology is thoroughly reviewed in (111,112). A method for evaluating the efficacy of UVGI has been developed (113), and chamber studies have indicated that UVGI, both by itself and in combination with air filtration, can be effective in removing or inactivating airborne bacteria (114). Further experiments and field studies are needed to determine efficacy in practice.

6.4. Gas/Vapor Removal. The possibilities for removing gases or vapors are much more limited than for particles. The most frequently considered (and used) approach is adsorption, particularly by activated carbon. However, the capacity of activated carbon for gases and vapors in the low ppm to high ppb range is too limited to make it a practical option for most applications. There are statements in the indoor air literature that "...activated carbon can absorb large quantities of indoor air pollutants, even at the low concentrations of these substance found in indoor air. As an example, it is not uncommon for activated carbon to adsorb as much as 20 to 30 percent of its weight in contaminants on exposure to indoor air pollutants before losing its ability to adsorb additional contaminant" (115).

However, the relevant performance criterion is capacity before reasonable breakthrough. Careful experiments with hexane at 11, 2, and 0.4 ppm inlet concentrations in air at relative humidity of 50% have been reported for a typical coconut shell carbon. At 30% breakthrough, the carbon had capacities of 10, 6, and 3% contaminant, respectively (116). Therefore, for design purposes it would seem advisable to count on a capacity of no >2–3% contaminants by weight, which translates into bed lives of a few months. At roughly $1500/year for each module serving 1 m^3/s, this is a costly option. See ref. 117 for example calculations, including costs.

Activated carbon has been used successfully to reduce ozone emissions from copy machines. In this application, the contaminant concentration is relatively high, its affinity for carbon is great, and the volume of air treated is small compared to room air recirculation rates. (Catalytic beds are now also used for that application.)

Chemisorption has been considered for many years as a possible technology. In theory, adsorbed contaminants are chemically converted to substances that do not desorb. One of the major barriers to this technology is developing an adsorbent and reactive surface for the wide range of contaminants found in indoor air. Potassium permanganate-impregnated alumina, developed for industrial applications, has been marketed for many years to reduce indoor concentrations of acid gases such as nitric oxide, sulfur dioxide and hydrogen sulfide as well as formaldehyde (118). There is little well-documented performance data from the field, so the effectiveness of this chemisorption option is unknown.

Room temperature catalysis is another, conceptually similar, technology that has been investigated for some time as a way to reduce indoor concentrations of vapor-phase organic compounds. The version of this technique that has gotten most attention is photocatalytic oxidation. Current technology requires far too much uv energy—and therefore far too much cost—to be practical (117).

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ASHRAE Journal. Contains frequent articles on indoor air quality and thermal comfort; focuses mostly on ventilation-related aspects.

Other journals such as *Environmental Science and Technology, Journal of the Air and Waste Management Association, Environmental Pollution*, and *Atmospheric Environment* also have occasional articles on indoor air quality. In addition, there are numerous trade periodicals and newsletters.

Proceedings of the International Conferences on Indoor Air Quality and Climate. Contain concise summaries of the current science and technology of indoor air quality, as presented at the triennial Indoor Air conferences. The most recent conference was in July 2002; information on proceedings is available at *www.indoorair2002.org*.

There are many sites on the internet that contain information on indoor air quality, but they should be used with caution. Some of the useful sites are listed below:

American Conference of Governmental Industrial Hygienists, *www.acgih.org* (See especially information on TLVs.)

American Institute of Architects, *www.aiaonline.com* (Use search engine for construction industry news on indoor air quality issues.)

American Lung Association, *www.lungusa.org/air/*

American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), *www.ashrae.org*

Building Owners and Managers Association, *www.boma.org* (Use search engine for indoor air.)

Carpet and Rug Institute *www.carpet-rug.com/* (See especially "green label" testing programs.)

Housing and Urban Development, *www.hud.gov* (Use search engine for indoor air.)

National Institute of Standards and Technology, *www.nist.gov/* (From subject index, go to "indoor air quality".)

National Resources Defense Council, *www.nrdc.org* (Use search engine for indoor air.)

North American Insulation Manufacturers Association, *www.naima.net*

Sheet Metal and Air Conditioning Contractors of North America, *www.smacna.org* (Use search engine for indoor air.)

U.S. Environmental Protection Agency, *www.epa.gov/iaq; www.epa.gov/iaq/iaqinfo.html#iaqinfo.*

W. Gene Tucker
James Madison University