25

Indoor Air Quality

I. CHANGING TIMES

Societies' concern with air quality has evolved from medieval times, when breathing smelting fumes was a major hazard, to where we are today (see Chapter 1). In modern society, a parallel effort has been under way to improve air quality in the outside or ambient air, which is the principal focus of this book, and in the industrial occupational setting in manufacturing and other traditional jobs. A combination of events is moving many countries to consider the quality of air in other locations where we live parts of our lives. Attention is now being refocused on "indoor" air quality.

In developing countries, priorities have often differed from those of wealthier nations. Industrialization, water and food supply, sanitation, infrastructure improvements, and basic health care are often the focus of the leaders of a country. In some areas, the availability of a job is much more problematic than some consideration about the quality of the air in the workplace or the home. Many dwellings in developing countries do not have closable windows and doors, so the outdoor and indoor air quality issues are different. In some houses where cooking is done by firewood or charcoal, the air quality outdoors may be considerably better than that inside the smoky residence. The evolution of our modern society and the concomitant changes in lifestyle, workplace, and housing improvements place concerns about indoor air quality in a different category than for developing countries and from the times of our ancestors.

For many industrialized countries, efforts to improve the outdoor air quality have been under way for the majority of this century. In many locations around the world, significant improvements have taken place. Air quality in many major cities such as London, New York, and Chicago has improved from the conditions present in the first half of the twentieth century. Mechanisms and control programs are in place in the developed countries to continue the improvement of ambient air quality. Considerable effort and energy have been expended to characterize, evaluate, and control air pollution emissions to the atmosphere.

Buildings and their design have undergone major changes. Fifty years ago, central heating and windows which could be opened and closed depending on the season were the norm for commercial buildings. Now we have multistory buildings with central heating and air conditioning and sealed glass exterior walls. Residential housing has undergone similar design and structural changes, in some cases resulting in dwellings that may have poorer indoor air quality.

New residences and commercial buildings are designed and built with energy conservation as a major design criterion. New materials have been developed and are being used in construction. Although these modifications have helped to save energy, a consequence of some of these modifications is slower exchange of air with the outside. This helps considerably with the heating or cooling system because energy must condition this "new" air which is introduced into the structure. However, the decreased air exchange rates usually translate into dirtier air.

A second consideration is the change in lifestyle for individuals in industrialized societies. We are no longer a society dependent on occupations which require us to be outdoors for a significant part of our day. Over the past two decades, studies of daily activities have consistently shown for urban populations that, on average, we spend about 90% of our time indoors in our homes, cars, offices, factories, public buildings such as restaurants, malls, and others. Any given individual activity profile may differ significantly from this average.

Exposure assessment techniques now attempt to include as many as possible of the locations in which individuals now spend time. The concept involves identification of microenvironments which are important for potential exposure. For example, exposure to CO would include time spent in commuting, parking garages, in residences with gas stoves, as well as time spent outdoors. This approach classifies time spent in these microenvironments and the typical concentrations of CO in these locations.

II. FACTORS INFLUENCING INDOOR AIR QUALITY

Several factors influence the quality of air indoors: the rate of exchange of air with air from outdoors, the concentration of pollutants in outdoor air, the rate of emissions from sources indoors, the rate of infiltration from soil gases, and the rate of removal in the indoor environment (Fig. 25.1).

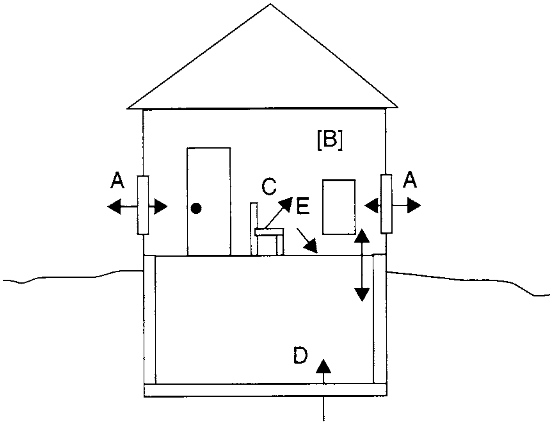

Fig. 25.1. Representation of home with various sources and sinks for indoor air pollutants: A, exchange; B, indoor concentration; C, outgassing of building and furniture materials; D, infiltration from soils; E, removal on interior surfaces.

The source of indoor air pollutants may be inside the building, or they may be transported into the interior space from the outside. Sources located indoors include building materials, combustion sources, furnishings, and pets. Emissions of organic gases are higher with increased temperature and humidity but usually decrease with age of the structure or furnishings. Construction materials and the composition of furnishings inside the building may give off or outgas pollutants into the interior airspace, e.g. glues or adhesives. Natural gas for cooking and kerosene space heaters release NO and CO_2 even when operating properly. Molds may grow in the ventilation ducts and be distributed throughout a building.

Radon from the soil can enter buildings through cracks in the foundation when the pressure inside is lower than in the soil. The rate of infiltration depends on the soil type, the building structure, and the pressure differential between the soil and the building.

Air is exchanged between indoors and outdoors by several ways: natural ventilation, mechanical ventilation, and infiltration or exfiltration. Natural ventilation involves movement of air through building openings like doors, windows, and vents. Mechanical ventilation involves fans and heating and air-conditioning systems. Infiltration and exfiltration represents undesirable movement of air in and out of the structure. Buildings are characterized as "tight" when infiltration rates are low.

The air exchange rate influences the concentration of indoor pollutants in two ways. At higher air exchange rates, the pollutants inside a structure are removed from the interior. As long as the ambient outside air has lower pollutant concentrations, high exchange rates help lower indoor air pollutant levels. However, if the pollutant concentration outside is elevated, then an increase in the air exchange rate will bring these materials into the building; e.g. an idling vehicle adjacent to an air intake will transfer exhaust fumes into the building. At lower exchange rates, pollutants released from sources inside the building can contribute to higher levels of indoor pollutants.

The concentration of indoor pollutants is a function of removal processes such as dilution, filtration, and destruction. Dilution is a function of the air exchange rate and the ambient air quality. Gases and particulate matter may also be removed from indoor air by deposition on surfaces. Filtration systems are part of many ventilation systems. As air is circulated by the air-conditioning system it passes through a filter which can remove some of the particulate matter. The removal efficiency depends on particle properties; including size and surface characteristics, such as electrostatics. In addition, some reactive gases like NO_2 and SO_2 are readily adsorbed on interior surfaces of a building or home.

III. INDOOR AIR POLLUTANTS

Table 25.1 shows the major categories of indoor air pollutants and sources. Table 25.2 shows a summary of reported indoor air pollutant concentrations compiled by the US Environment Protection Agency. Information in this table is not meant to be representative of typical indoor concentrations but only examples of measurements obtained by investigators and reported in the literature.

Airborne material affecting the quality of indoor air may be classified as gases or particulate matter. Gases which may be potential problems are radon, CO, NO_2, and hydrocarbons. Particulate matter may come from tobacco smoke, mold spores, animal dander, plant spores, and others as shown in Table 25.1. Other factors interact to influence our perception of indoor air quality, including humidity, temperature, lighting, and sound level.

TABLE 25.1

Indoor Air Pollutants and Typical Sources

Pollutant	Source
Combustion gases—CO and NO	Combustion—furnace, cooking stove, space heater, etc.
VOCs	Outgassing of building materials, coatings, wall and floor coverings, and furnishings
Formaldehyde and other aldehydes and carbonyls	Outgassing of pressed wood and insulation foam
Pesticides	Household products
Particulate matter	Combustion
Biological agents—molds, spores, and dander	Contaminated ventilation systems, ceiling tile and walboard, outdoor and indoor plant materials, and pets
Environmental tobacco smoke (ETS)	Smoking in building
Radon	Infiltration from soil beneath structure
Asbestos	Construction coatings, tile, and insulation

TABLE 25.2

Summary of Reported Indoor Air Pollutant Concentrations

	Measured concentration				
Pollutant	Minimum	Maximum	Mean	Types of building	Reference[d]
Radon			0.8 pCi L^{-1}	Residences	EPA (1987d)
	0.5 pCi L^{-1}	2000 pCi L^{-1}		Residences	EPA (1987b)
	0.14 pCi L^{-1}	4.11 pCi L^{-1}	—	New public buildings	Sheldon *et al.* (1988)
	0.3 pCi L^{-1}	1.68 pCi L^{-1}	—	Old public buildings	Sheldon *et al.* (1988)
	—	—	1.7–2.4 pCi L^{-1}	Three office buildings	Bayer and Black (1988a)
ETS (as respirable	—	—	28 $\mu g\ m^{-3(1)a}$	Residences	NRC (1986b)
suspended particulate	—	—	74 $\mu g\ m^{-3(2)}$	Residences	NRC (1986b)
or RSP)	—	—	32 $\mu g\ m^{-3(3)}$	Residences	DHHS (1986)
	—	—	50 $\mu g\ m^{-3(4)}$	Residences	DHHS (1986)
(as nicotine)	—	—	0.7–3.2 ppb	Three office buildings	Bayer and Black (1988a)
Biological contaminants	—	564–5360 CFU m^{-3b}		Three office buildings	Bayer and Black (1988a)
Formaldehyde	—	131–319 $\mu g\ m^{-3}$	78–144 $\mu g\ m^{-3}$	Residences	Hawthorne *et al.* (1984)
	ND[c]	192 ppb	—	New public buildings	Sheldon *et al.* (1987)
	ND	103 ppb	—	Old public buildings	Sheldon *et al.* (1987)
	—	—	25–39 ppb	Three office buildings	Bayer and Black (1988a)
Benzene	—	120 $\mu g\ m^{-3}$	20 $\mu g\ m^{-3}$	Various	Wallace *et al.* (1983)
Carbon tetrachloride	—	14 $\mu g\ m^{-3}$	2.5 $\mu g\ m^{-3}$	Various	Wallace *et al.* (1983)
Trichloroethylene	—	47 $\mu g\ m^{-3}$	3.6 $\mu g\ m^{-3}$	Various	Wallace *et al.* (1983)
Tetrachloroethylene	—	250 $\mu g\ m^{-3}$	10 $\mu g\ m^{-3}$	Various	Wallace *et al.* (1983)

(continued)

TABLE 25.2 (*Continued*)

Pollutant	Measured concentration Minimum	Measured concentration Maximum	Mean	Types of building	Reference[d]
Chloroform	—	200 μg m^{-3}	8 μg m^{-3}	Various	Wallace *et al.* (1983)
Dichlorobenzenes	—	1200 μg m^{-3}	41 μg m^{-3}	Various	Wallace *et al.* (1983)
Pesticides					
Diazionon	ND	8.9 μg m^{-3}	1 4 μg m^{-3}	Residences	Lewis *et al.* (1986)
Chlordane	ND	1.7 μg m^{-3}	0.51 μg m^{-3}	Residences	Lewis *et al.* (1986)

[a] (1) 73 residences without smokers; (2) 73 residences with smokers; (3) nonsmokers not exposed to ETS; and (4) nonsmokers exposed to ETS.

[b] Summation of mesophilic bacteria, fungi, and thermophilic bacteria. CFU: colony-forming units.

[c] ND: not detected.

[d] *References*

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Source: US Environmental Protection Agency Report to Congress on Indoor Air Quality, EPA/400/1-89/001c, August 1989.

IV. EFFECTS OF INDOOR AIR POLLUTANTS

Effects of indoor air pollutants on humans are essentially the same as those described in Chapter 11. However, there can be some additional pollutant exposures in the indoor environment that are not common in the ambient setting. From the list in Table 25.1, radon exposure indoors present a radiation hazard for the development of lung cancer. Environmental tobacco smoke (ETS) has been found to cause lung cancer and other respiratory diseases. Biological agents such as molds and other toxins may be a more likely exposure hazard indoors than outside.

When present, arguably the most hazardous indoor pollutant is asbestos. Chronic exposures are directly associated with mesothelioma, lung cancer, and asbestosis. That is why governments at all levels have aggressively implemented programs to protect children and others in schools and other indoor microenvironments from exposures to airborne asbestos fibers. Asbestos is discussed in detail in Chapter 2.

Mold is ubiquitous, but indoor exposures need not be high. Mold's growth is usually increased with increasing temperature and humidity under environmental conditions, but this does not mean molds cannot grow in colder conditions. Species may be of wide range of colors and often elicit particles and gases that render odors, often referred to as "musty." Like other fungi, molds reproduce by producing spores that are emitted into the atmosphere. Living spores are disseminated to colonize growth wherever conditions allow. Most ambient air contains large amounts of so-called "bioaerosols," i.e. particles that are part of living or once living organisms. In the instance, the bioaerosols are live mold spores, meaning that inhalation is a major route of exposure.

Indoor sources of molds include leaking pipes and fixtures, damp spaces such as those in basements and crawl spaces, heating, air conditioning and ventilation (HVAC) systems, especially those that allow for condensation from temperature differentials between surfaces and ambient air, kitchens, and showers.

Some molds produce toxic substances called mycotoxins. There is much uncertainty related to possible health effects associated with inhaling mycotoxins over a long-time periods. Extensive mold growth may cause nuisance odors and health problems for some people. It can damage building materials, finishes, and furnishings and, in some cases, cause structural damage to wood.

Sensitive persons may experience allergic reactions, similar to common pollen or animal allergies, flu-like symptoms, and skin rash. Molds may also aggravate asthma. Rarely, fungal infections from building-associated molds may occur in people with serious immune disease. Most symptoms are temporary and eliminated by correcting the mold problem, although much variability exists on how people are affected by mold exposure. Particularly sensitive subpopulations include:

- Infants and children
- Elderly people

- Pregnant women
- Individuals with respiratory conditions or allergies and asthma
- Persons with weakened immune systems (e.g. chemotherapy patients, organ or bone marrow transplant recipients, and people with HIV infections or autoimmune diseases)

Persons cleaning mold should wear gloves, eye protection, and a dust mask or respirator to protect against breathing airborne spores (Fig. 8.18). A professional experienced in mold evaluation and remediation, such as an industrial hygienist, may need to be consulted to address extensive mold growth in structures. It is important to correct large mold problems as soon as possible by first eliminating the source of the moisture and removing contaminated materials, cleaning the surfaces, and finally drying the area completely.

If visible mold is present, then it should be remediated, regardless of what species are present and whether samples are taken. In specific instances, such as cases where health concerns are an issue, litigation is involved, or the source(s) of contamination is unclear, sampling may be considered as part of a building evaluation. Sampling is needed in situations where visible mold is present and there is a need to have the mold identified. A listing of accredited laboratories can be found at www.aiha.org/LaboratoryServices/html/lists.htm.

Radon gas is formed in the process of radioactive decay of uranium. The distribution of naturally occurring radon follows the distribution of uranium in geological formations. Elevated levels have been observed in certain granite-type minerals. Residences built in these areas have the potential for elevated indoor concentrations of radon from radon gas entering through cracks and crevices and from outgassing from well water.

Radon gas is radioactive and emits alpha particles in the decay process. The elements resulting from radon decay are called radon daughters or progeny. These radon daughters can attach to airborne particles, which can deposit in the lung. The evidence supporting the radon risk of lung cancer comes from studies of uranium mine workers, in whom elevated rates of lung cancer have been observed. When an analysis of the potential exposure to radon inside homes was conducted by the US Environmental Protection Agency, an estimate of 5000–20 000 excess lung cancer deaths was projected annually [1]. The risk is associated directly with increased lifetime doses; i.e. the longer the time spent living in a residence with elevated levels of radon, the higher the risk. Indoor levels of radon range from less than 1–200 pCi L^{-1}. Levels as high as 12 000 pCi L^{-1} have been observed but most levels are much lower. The US Environmental Protection Agency has established an action level of 4 pCi L^{-1} for indoor radon, and if a home screening test shows concentrations below 4 pCi L^{-1}, no remedial action is suggested.

Environmental tabacco smoke (ETS), sometimes referred to as "second-hand smoke" or "passive smoking" represents the exposure to tobacco smoke by individuals other than the smoker. For decades, the US Surgeon General has indicated that smoking is a cause of lung cancer and cardiovascular disease for individuals who smoke. The US Environmental Protection Agency has also concluded that ETS is a lung carcinogen for others breathing it.

The presence of biological contaminants gained widespread recognition with the outbreak of Legionnaires' disease in Philadelphia, Pennsylvania in 1976. In that year, 221 persons attending a convention of Legionnaires developed pneumonia symptoms and 34 subsequently died. The agent, a bacterium later named *Legionella pneumophila,* was found in the cooling tower of the hotel's air-conditioning system. This bacterium has subsequently been responsible for other outbreaks of Legionnaires' disease. The bacteria in water supplies may be eliminated by suitable treatment procedures. *Legionnella* represents one of many types of biological agents which can cause allergic reactions and illness in the indoor environment.

One of the more difficult challenges remaining is the characterization of "sick building" syndrome. On numerous occasions, some employees in certain office buildings or other workplaces have developed a combination of symptoms including respiratory problems, dryness of the eyes, nose, and throat, headaches, and other nonspecific complaints. In such situations a substantial portion of the workers may exhibit these symptoms, which decrease in severity or stop when the worker is away from the building over the weekend or for longer periods. Investigations into the cause of these symptoms sometimes provide explanations, uncover ventilation problems, or identify an irritant gas. But many of these problem buildings are very difficult to understand and additional research is necessary to understand the cause-and-effect relationships.

V. CONTROL OF INDOOR AIR POLLUTANTS

The control and regulation of indoor air quality are influenced by individual property rights and a complicated mosaic of federal, state, and local government jurisdiction with conflicts, overlaps, and gaps in addressing these issues. Table 25.3 shows a large number of agencies and departments involved in indoor air quality control efforts at the federal level.

Government can institute certain laws and regulations for the citizens' wellbeing. Environmental and occupational examples abound, such as clean water and air legislation and workplace safety and health regulations. As the extension of this role into the home occurs, implementation and enforcement become more problematic. Examples of proactive regulatory approaches are building codes, zoning, consumer product standards, and safety requirements. Table 25.4 shows what various parties, from the individual to the federal government, can do to improve indoor air quality. Many of these efforts focus on education, improved materials, and better design of products and structures.

The technological control strategies are related back to Fig. 25.1. If the hazard is the result of elevated concentrations, then the technological solution is to reduce or remove the sources or dilute or remove the agent.

TABLE 25.3

Indoor Air Responsibility of Federal Agencies

Point of impact	Agency/Activity	Comments
Direct control of indoor concentrations and/or exposures	OSHA air standards	Limited to industrial environments
	BPA radon action level	Limited to residents in BRA's weatherization program
	NASA air standards	Adopted OSHA standards
Control of emissions by restricting activities or product composition	EPA drinking water MCLs for radon and VOCs	Indoor air exposures considered in determining drinking water levels
	EPA pesticide restrictions	Restricts use and sales of pesticides which may cause indoor air pollution
	CPSC consumer product bans	Bans on use of some potential indoor pollutants in consumer products
	Smoking restrictions imposed by DOD, DOT, and GSA	Restricts smoking in specified indoor environments
	VA restrictions on asbestos use	Restricts use of asbestos in VA buildings
Control through assessment and mitigation procedures	EPA asbestos rules	Provides for the assessment and mitigation of asbestos hazards in schools
	GSA building assessments	Investigates GSA-controlled buildings for indoor air problems
	NIOSH building assessments	Responds to air quality health complaints
	DOD/USAF chlordane assessments	Investigates USAF facilities for chlordane problems
	NASA HVAC system maintenance	Assesses and corrects HVAC operation to optimize indoor air quality
Effort to increase knowledge of indoor air quality problems and controls	Research efforts by EPA, CPSC, DOE, HHS, BPA, DOT, NASA, NIST, NSF, TVA, HUD, and GSA	
	Information dissemination by EPA, CPSC, DOE, HHS, BPA, HUD, TVA, FTC, NASA, NIST, and NIBS	

OSHA, Occupational Safety and Health Administration; BPA, Bonneville Power Administration; NASA, National Aeronautics and Space Administration; MCL, Maximum Contaminant Levels; VOC, Volatile Organic Compounds; CPSC, Consumer Products Safety Commission; DOD, Department of Defense; DOT, Department of Transportation; CSA, General Services Administration; VA, Veterans Administration; NIOSH, National Institute of Occupational Safety and Health; USAF, United States Air Force; HVAC, Heating Ventilation and Air Conditioning; DOE, Department of Energy; HHS, Health and Human Services; NIST, National Institute of Standards and Technology; NSF, National Science Foundation; TVA, Tennessee Valley Authority; HUD, Housing and Urban Development; FTC, Federal Trade Commission; NIBS, National Institute of Building Sciences.
Source: US Environmental Protection Agency Report to Congress on Indoor Air Quality, EPA/400/1-89/001c, August 1989.

TABLE 25.4

Stakeholder Interests in Improving Indoor Air Quality

Individuals	Consumer and health professionals	Manufacturers	Building owners and managers	Builders and architects	State and local governments	Federal government
Find low-emission products in purchasing decisions	Be knowledgeable of symptoms, effects, and mitigation and advise clients	Adopt test procedures and standards to minimize product and material emissions	Adopt ventilation maintenance procedures to eliminate and prevent contamination and ensure and adequate supply of clean air to building occupants	Adopt indoor air quality as a design objective	Conduct studies of specific problems in state or local area and adopt mitigation strategies	Conduct research and technology transfer programs
Maintain and use products to minimize emissions	Develop information and education programs for constituent publics	Adequately label products as to emission level and proper use and maintenance of products	Use zone ventilation or local exhaust for indoor sources	Ensure compliance with indoor air quality ventilation standards	Establish building codes for design, construction, and ventilation requirements to ensure adequate indoor air quality	Coordinate actions of other sectors

(continued)

TABLE 25.4 *(Continued)*

Individuals	Consumer and health professionals	Manufacturers	Building owners and managers	Builders and architects	State and local governments	Federal government
Exercise discretionary control over ventilation to ensure clean air supply	Substitute materials to minimize emissions from products manufactured	Develop specific procedures for use of cleaning solvents, paints, herbicides, insecticides, and other contaminants to protect occupants	Adopt low emission requirements in procurement specifications for building materials from manufacturers	Enforce and monitor code compliance	Coordinate actions of other sectors, encourage, or require specific sectors to take actions toward mitigation	
Be knowledgeable of indoor air quality problems and take actions to avoid personal exposure	Develop training programs for commercial users to ensure low emissions	Adopt investigatory protocols to respond to occupant complaints	Contain or ventilate known sources	Educate and inform building community, health community, and public about problems and solutions		
	Conduct research to advance mitigation technology					

Source: US Environmental Protection Agency Report to Congress on Indoor Air Quality, EPA/400/1-89/001c, August 1989.

Control techniques are discussed for agents mentioned earlier—radon, ETS, and biological agents—and also for volatile organic compounds (VOCs). Radon enters the residence by two principal routes: infiltration from soil beneath the structure and outgassing from well water during showers. Elevated levels of radon are generally observed in basements or first-floor rooms. The mitigation techniques available include increased ventilation of the crawl space beneath the first floor, soil gas venting from beneath a basement floor, and sealing of all openings to the subsurface soil. These steps reduce the entry of radon into the home. Elevated levels of radon in well water can be removed by aeration or filtration by absorbent-filled columns.

Control of ETS is complicated because of the personal behavior of individuals. For public buildings and facilities like offices, restaurants, and malls, many governmental bodies are placing restrictions on smoking in these areas, which can range from complete bans to requiring a restaurant to have a portion of a dining area for smokers and the remainder for nonsmokers. The difficulty for the restaurant owner is ensuring that the nonsmoking section is free of ETS. Education is the primary approach to "control" in the home. Information about the effects of ETS on family members, especially the health of pregnant women, unborn and young children, has modified the behavior of some smokers.

Control of biological agents is multifaceted. In the case of *Legionnella*, cleaning and maintenance of heating and air-conditioning systems are generally sufficient to reduce the risk of this disease. In home heating and air-conditioning systems, mold and bacteria may be present and controlled with maintenance procedures and increasingly available technologies (e.g. UV disinfection). Growth may be inhibited by lower humidity levels. Keeping a house clean lowers the presence of dust mites, pollen, dander, and other allergens.

For VOCs, control options are multiple. Source reduction or removal includes product substitution or reformulation. Particleboard or pressed wood has been developed and used extensively in building materials for cabinet bases and subflooring and in furniture manufacturing for frames. If the product is not properly manufactured and cured prior to use as a building material, VOCs can outgas into the interior of the residence or building. Other sources of VOCs may be paints, cleaning solutions, fabrics, binders, and adhesives. Proper use of household products will lower volatile emissions.

In many of the industries associated with building or household products, efforts are under way to reduce the potential for subsequent VOC release to the interior of residences or commercial buildings. Modification of the manufacturing process, solvent substitution, product reformulation, and altering installation procedures are a few of the approaches available.

When VOCs are present indoors at elevated concentrations, modification of ventilation rates is a control option for diluting and reducing these concentrations. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) has established standards for ventilation rates for outside air per individual. The guideline is 15 cfm per person [2]. This guideline is designed to bring sufficient fresh air into a building to minimize the buildup of contaminants and odors.

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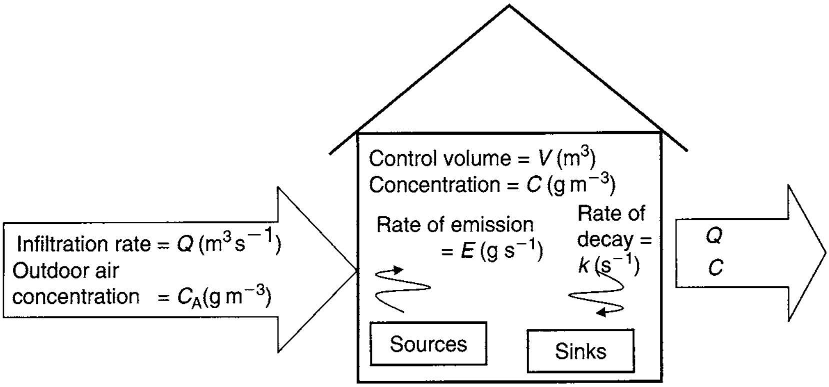
QUESTIONS

1. Define "sick building" syndrome.
2. What controls are available to control indoor air quality?
3. Why will the command and control approach not work for residential indoor air quality?
4. Describe an implication of high radon levels during the sale of a home.
5. The mass balance can be determined for any control volume. So, let us consider a house to be such a control volume. We can construct a simple *box model* for this control volume:


Infiltration rate = Q (m^3 s^{-1})
Outdoor air concentration = C_A(g m^{-3})
Control volume = V (m^3)
Concentration = C (g m^{-3})
Rate of emission = E (g s^{-1})
Rate of decay = k (s^{-1})
Sources
Sinks
Q
C

Recall that the mass balance equation is:

Rate of pollutant increase in control volume	=	Rate of pollutant entering control from outdoors	+	Rate of pollutant entering control volume from indoor source emissions	–	Rate of pollutant leaving control volume by leakage to outdoors	–	Rate of pollutant leaving control volume by chemical decay

Stated mathematically, the equation is:

$$V\frac{\mathrm{d}C}{\mathrm{d}t} = QC_{\mathrm{A}} + E - QC - kCV$$

Some k values in inverse seconds for some important indoor pollutants (from Lawrence Berkeley National Laboratory) are:

Formaldehyde (HCHO) $= 1.11 \times 10^{-4}$
Nitric acid (NO) $= 0.0$
Aerosols (fine particles $<0.5\,\mu\mathrm{m}$ aerodynamic diameter) $= 1.33 \times 10^{-4}$
Rn $= 2.11 \times 10^{-6}$
Sulfur dioxide (SO_2) $= 6.39 \times 10^{-5}$
Carbon monoxide $= 0.0$

To find the time-dependent concentration (i.e. the general solution), use:

$$C_{\mathrm{t}} = \frac{(E/V) + C_{\mathrm{A}}(Q/V)}{(Q/V) + k}\left[1 - \exp\left(-\left(\frac{Q}{V} + k\right)t\right)\right] + C_0 \exp\left[-\left(\frac{Q}{V} + k\right)t\right]$$

And, for steady state conditions (i.e. $(\mathrm{d}C/\mathrm{d}t) = 0$), the indoor concentrations are simplified to:

$$C = \frac{QC_{\mathrm{A}} + E}{Q + kV}$$

Further, if the pollutant does not decay appreciably (i.e. $k \approx 0$); it is considered to be a *conservative pollutant*. Many indoor studies use conservative tracers (e.g. perfluorides). So, when outdoor concentrations of a conservative compound are negligible, and the initial indoor concentration is zero, we can further simplify the mass balance to:

$$C_{\mathrm{t}} = \frac{E}{Q}\left[1 - \exp\left(-\left(\frac{Q}{V}\right)t\right)\right]$$

So, let us consider an example. You are heating your apartment with an unvented kerosene heater for 1 h. The air volume of your apartment is $200\,\mathrm{m}^3$. If the heater emits SO_2 at a rate of $50\,\mu\mathrm{g\,s}^{-1}$, and the ambient (outdoor air) and your initial concentrations in your apartment are both $100\,\mu\mathrm{g\,m}^{-3}$, the ventilation (air exchange rate) is $50\,\mathrm{L\,s}^{-1}$, and your ceiling fan is sufficiently mixing the air (i.e. the control volume is assumed to be well-mixed), what is the indoor concentration of SO_2 in your apartment after 1 h?

These conditions allow us to use the time-dependent concentration (i.e. the general solution) equation:

$$C_t = \frac{(E/V) + C_A(Q/V)}{(Q/V) + k}\left[1 - \exp\left(-\left(\frac{Q}{V} + k\right)t\right)\right] + C_0 \exp\left[-\left(\frac{Q}{V} + k\right)t\right]$$

$$\begin{aligned}
C_t &= \frac{(50\,\mu\mathrm{g\,s^{-1}}/200\,\mathrm{m^3}) + 100\,\mu\mathrm{g\,m^{-3}}(0.050\,\mathrm{m^3\,s^{-1}}/200\,\mathrm{m^3})}{(0.050\,\mathrm{m^3\,s^{-1}}/200\,\mathrm{m^3}) + 6.39 \times 10^{-5}\,\mathrm{s^{-1}}} \\
&\quad \times \left[1 - \exp\left(-\left(\frac{0.050\,\mathrm{m^3\,s^{-1}}}{200\,\mathrm{m^3}} + 6.39 \times 10^{-5}\,\mathrm{s^{-1}}\right)3600\,\mathrm{s}\right)\right] \\
&\quad + \left(100\,\mu\mathrm{g\,m^{-3}}\right)\exp\left(-\left(\frac{0.050\,\mathrm{m^3\,s^{-1}}}{200\,\mathrm{m^3}} + 6.39 \times 10^{-5}\,\mathrm{s^{-1}}\right)3600\,\mathrm{s}\right) \\
&= 876.08(1 - \exp(-1.13)) + 100\ \exp(-1.13) \\
&= 876.08(1 - 0.323) + 100(0.323) \\
&= 593.09 + 32.3 = 625.39\,\mu\mathrm{g\,m^{-3}}
\end{aligned}$$

Question: How long will it take after shutting off the heater (i.e. $E = 0$), to reach the same concentrations of SO_2 as that found outside the house?

6. Assuming that you been working on your car's engine in a garage with the same dimensions and air exchanges as the apartment above, and that the concentrations of carbon monoxide were also 625.39 $\mu g\,m^{-3}$? How long will it take to reach 0 $\mu g\,m^{-3}$ CO, assuming the outdoor concentration is 0 $\mu g\,m^{-3}$ CO? In other words, how long will it take to flush the CO?
   What could you do to increase the flushing rate?
   You may have noticed some interesting things about the mathematics of the time-dependent equation when applied to a conservative pollutant ($k = 0$) at an ambient concentration = 0. So, find the time needed to reach a relatively safe (low, but not zero) indoor CO concentration of 300 ppb, with $k = 0.0000000002/\mathrm{s}$. After all, even conservative gases like CO break down (e.g. by reactions with hydroxyl radicals).
   Compare the results and try to explain any differences in theory *versus* practical applications. What is going on here? Be creative and bold in thinking about the differences. This is one of the interesting differences between engineering and basic science.
7. You are the city engineer sitting in a discussion about a program to give kerosene space heaters to needy people. Recent inspections of target homes show that the air exchange rates (QV^{-1}) at present to be an average 4 per hour. Before the heaters are given away, the city, with the help of a team of volunteers will fix windows, caulk and add insulation so that any home receiving the heater will be at most 1.5 air exchanges per hour. The manufacturer specs show that the heaters will produce 23 mg of carbon monoxide per second. If the average home will use one heater in the living room (500 m^3) and one in each of the three bedrooms (each 400 m^3), do you foresee any problems with this plan? Would you want to live and sleep in a home with these CO concentrations (e.g. based on health standards)? Support your recommendation in a memo to the mayor and city council.
8. Later in the same meeting, you are asked to consider the use of building materials for the new library. The architects call for library panel constructed of fiberboard. It is much more aesthetically appealing than the alternate material (drywall). The fiberboard emits formaldehyde (HCHO) at 360 $\mu g\,m^{-2}h^{-1}$ and the library walls to be covered represent a surface area of 20 000 m^2. The emission rate is expected to drop by 40 $\mu g\,m^{-2}h^{-1}$ each year as the product off gases and the formaldehyde decomposes. The drywall emits no HCHO, but in a few places the drywall will be reinforced with plywood which emits 4 $\mu g\,m^{-2}h^{-1}$ (but only from 1500 m^2 of wall surface). However, the grout used if the

drywall is selected emits radon at a rate of $1 \times 10^{-5} \mu g\, m^{-2} h^{-1}$. (For some additional information about conversion of radiation units to concentrations, see the following website: http://www.hps.org/publicinformation/ate/q2548.html. Remember that the volume being used here is liters, not cubic meters, and that the density of water is much higher than that of air.)

The volume of the library will be 250 000 m^3. Assume that the library air will be well mixed. The library is designed to have 1.2 air exchanges per hour. Recent measurements in the area around the building site have detected $5 \mu g\, m^{-3}$ HCHO in the ambient air. Write a memo to the library planning commission communicating your calculations and estimates, as well as your recommendations about the choice of wall materials. Also, make some recommendations on what corrective actions will need to be taken if they still wish to install the panel as the architects wish, or if they go with the alterative.

In these problems, can you draw any conclusions about the relationship of indoor air quality and energy efficiency (e.g. the role that air exchange rates play in both)? Can you think of some approaches that could ameliorate both air quality and energy efficiency in the same building?