

CHAPTER 12

AIR CONTAMINANTS

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AIR IS COMPOSED mainly of gases. The major gaseous components of clean, dry air near sea level are approximately 21% oxygen, 78% nitrogen, 1% argon, and 0.04% carbon dioxide.

Normal outdoor air contains varying amounts of foreign materials (permanent atmospheric impurities). These materials can arise from natural processes such as wind erosion, sea spray evaporation, volcanic eruption, and metabolism or decay of organic matter. The natural contaminant concentrations in the air that we breathe vary but are usually lower than those caused by human activity.

Man-made outdoor contaminants are many and varied, originating from numerous types of human activity. Electric power-generating plants, various modes of transportation, industrial processes, mining and smelting, construction, and agriculture generate large amounts of contaminants.

Contaminants that present particular problems in the indoor environment include, among others, tobacco smoke, radon, and formaldehyde.

Air composition may be changed accidentally or deliberately. In sewers, sewage treatment plants, tunnels, and mines, the oxygen content of air can become so low that people cannot remain conscious or survive. Concentrations of people in confined spaces (theaters, survival shelters, submarines) require that carbon dioxide given off by normal respiratory functions be removed and replaced with oxygen. Pilots of high-altitude aircraft, breathing at greatly reduced pressure, require systems that increase oxygen concentration. Conversely, for divers working at extreme depths, it is common to increase the percentage of helium in the atmosphere and reduce nitrogen and sometimes oxygen concentrations.

At atmospheric pressure, oxygen concentrations less than 12% or carbon dioxide concentrations greater than 5% are dangerous, even for short periods. Lesser deviations from normal composition can be hazardous under prolonged exposures. [Chapter 9](#) further details environmental health issues.

CLASSES OF AIR CONTAMINANTS

The major classes of air contaminants are particulate and gaseous. The **particulate** class covers a vast range of particle sizes from dust large enough to be visible to the eye to submicroscopic particles that elude most filters. Particulates may be solid or liquid. The following traditional contaminant classifications are subclasses of particulates:

The preparation of this chapter is assigned to TC 2.3, Gaseous Air Contaminants and Gas Contaminant Removal Equipment, in conjunction with TC 2.4, Particulate Air Contaminants and Particulate Contaminant Removal Equipment.

- **Dusts, fumes, and smokes**, which are mostly solid particulate matter, although smoke often contains liquid particles
- **Mists, fogs, and smogs**, which are mostly suspended liquid particles smaller than those in dusts, fumes, and smokes
- **Bioaerosols**, including viruses, bacteria, fungal spores, and pollen, whose primary impact is related to their biological origin
- Particle size definitions such as **coarse** or **fine**, **visible** or **invisible**, and **macroscopic**, **microscopic**, or **submicroscopic**
- Definitions that relate to particle interaction with the human respiratory system, such as **inhalable** and **respirable**

These classes, their characteristics, units of measurement, and measurement methods are discussed in more detail in this chapter.

The **gaseous** class covers chemical contaminants that can exist as free molecules or atoms in air. Molecules and atoms are smaller than particles and may behave differently as a result. This class covers two important subclasses:

- **Gases**, which are naturally gaseous under ambient indoor or outdoor conditions
- **Vapors**, which are normally solid or liquid under ambient indoor or outdoor conditions, but which evaporate readily

Through evaporation, liquids change into vapors and mix with the surrounding atmosphere. Like gases, they are formless fluids that expand to occupy the space or enclosure in which they are confined. Typical gaseous contaminants, their characteristics, units of measurement, and measurement methods are discussed in detail later in this chapter.

Air contaminants can also be classified according to their sources; their properties; or the health, safety, and engineering issues faced by people exposed to them. Any of these can form a convenient classification system because they allow grouping of applicable standards, guidelines, and control strategies. Most of the following classes include both particulate and gaseous contaminants. This chapter covers the background information for these classes, while [Chapter 9](#) deals with the applicable indoor health and comfort regulations. The classes are

- Industrial air contaminants
- Nonindustrial indoor air contaminants (including indoor air quality)
- Flammable gases and vapors
- Combustible dusts
- Radioactive contaminants
- Soil gases

PARTICULATE CONTAMINANTS

PARTICULATE MATTER

Airborne particulate matter is not a single substance but a complex mixture of many different components, usually from several different sources. Particles can be anthropogenic or natural in origin. **Anthropogenic** particles are those produced by human activities, including fossil fuel combustion, industrial processes, and road dust. Particles from **natural** sources do not involve human activity. They include wind-blown dust and smoke from forest fires.

Particles can be generated by primary or secondary processes. Particles from **primary processes** are those emitted directly into the air. Particles from **secondary processes** are those formed from condensable vapors and chemical reactions.

Details on the different particle types are given below.

Types of Solid Particles

Dusts are solid particles projected into the air by natural forces such as wind, volcanic eruption, or earthquakes, or by mechanical processes including crushing, grinding, demolition, blasting, drilling, shoveling, screening, and sweeping. Some of these forces produce dusts by reducing larger masses, while others disperse materials that have already been reduced. Particles are not considered to be dust unless they are smaller than about 100 μm . Dusts can be mineral, such as rock, metal, or clay; vegetable, such as grain, flour, wood, cotton, or pollen; or animal, including wool, hair, silk, feathers, and leather.

Fumes are solid particles formed by condensation of vapors of solid materials. Metallic fumes are generated from molten metals and usually occur as oxides because of the highly reactive nature of finely divided matter. Fumes can also be formed by sublimation, distillation, or chemical reaction. Such processes create airborne particles smaller than 1 μm . Fumes permitted to age may agglomerate into larger clusters.

Bioaerosols include airborne viruses, bacteria, pollen, and fungus spores. **Viruses** range in size from 0.003 to 0.06 μm , although they usually occur in colonies or attached to other particles. Most **bacteria** range between 0.4 and 5 μm and are usually associated with large particles. **Fungus** spores are usually 2 to 10 μm , while **pollen** grains are 10 to 100 μm , with many common varieties in the 20 to 40 μm range.

Types of Liquid Particles

Mists are small airborne droplets of materials that are ordinarily liquid at normal temperatures and pressure. They can be formed by atomizing, spraying, mixing, violent chemical reactions, evolution of gas from liquid, or escape as a dissolved gas when pressure is released. Small droplets expelled or atomized by sneezing constitute mists.

Fogs are fine airborne droplets, usually formed by condensation of vapor, which remain airborne longer than mists. Fog nozzles are named for their ability to produce extra fine droplets, as compared with mists from ordinary spray devices. Many droplets in fogs or clouds are microscopic and submicroscopic and serve as a transition stage between larger mists and vapors.

The volatile nature of most liquids reduces the size of their airborne droplets from the mist to the fog range and eventually to the vapor phase, until the air becomes saturated with that liquid. If solid material is suspended or dissolved in the liquid droplet, it remains in the air as particulate contamination. For example, sea spray evaporates fairly rapidly, generating a large number of fine salt particles that remain suspended in the atmosphere.

Complex Particles

Smokes are small solid and/or liquid particles produced by incomplete combustion of organic substances such as tobacco, wood, coal, oil, and other carbonaceous materials. The term smoke is applied to a mixture of solid, liquid, and gaseous products, although technical literature distinguishes between such components as soot or carbon particles, fly ash, cinders, tarry matter, unburned gases, and gaseous combustion products. Smoke particles vary in size, the smallest being much less than 1 μm in diameter. The average is often in the range of 0.1 to 0.3 μm .

Environmental tobacco smoke consists of a suspension of 0.01 to 1.0 μm (mass median diameter of 0.3 μm) liquid particles that form as the superheated vapors leaving the burning tobacco condense. Also produced are numerous gaseous contaminants including carbon monoxide.

Smog commonly refers to air pollution; it implies an air mixture of smoke particles, mists, and fog droplets of such concentration and composition as to impair visibility, in addition to being irritating or harmful. The composition varies among different locations and at different times. The term is often applied to haze caused by a sunlight-induced photochemical reaction involving the materials in automobile exhausts. Smog is often associated with temperature inversions in the atmosphere that prevent normal dispersion of contaminants.

Sizes of Airborne Particles

Particle size can be defined in several different ways. These depend, for example, on the source or method of generation, the visibility, or the effects.

Particles can be classified as coarse or fine. Coarse particles are larger, and are generally formed by mechanical breaking up of solids. They generally have a minimum size of 1 to 3 μm (EPA 1996). Fine particles are generally formed from chemical reactions or condensing gases. These particles have a maximum size of about 1 to 3 μm . Fine particles are usually more chemically complex, anthropogenic, and secondary in origin, while the coarse particles are predominantly primary, natural, and chemically inert. Coarse particles also include bioaerosols such as mold spores, pollen, animal dander, and dust mite particles that can affect the immune system.

The differences between fine and coarse particles lead to a bimodal distribution of particles in most environments with concentration peaks at about 0.25 μm and 5 μm . [Figure 1](#) shows a typical urban distribution including the chemical species present in each mode.

The size of a particle determines where in the human respiratory system the particle is deposited. The **inhalable mass** is made up of

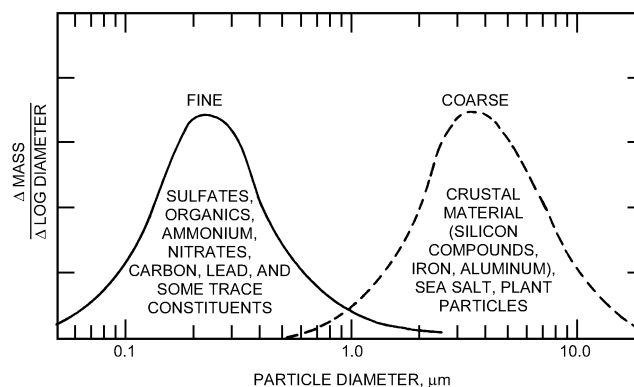


Fig. 1 Typical Urban Aerosol Composition by Particle Size Fraction
(EPA 1982, Willeke and Baron 1993)

particles that may deposit anywhere in the respiratory system and is represented by a sample with a median cut point of $100\ \mu\text{m}$. The **thoracic particle mass** is that fraction which can penetrate to the lung airways and is represented by a sample with a median cut point of $10\ \mu\text{m}$. The **respirable particulate mass** is that fraction that can penetrate to the gas-exchange region of the lungs and is represented by a sample with a median cut point of $4\ \mu\text{m}$ (ACGIH 1998). Figure 2 illustrates the relative deposition efficiencies of various sizes of particles. The characteristics described above were used by the EPA in development of their outdoor PM_{10} and $\text{PM}_{2.5}$ standards.

Most particles are irregular in shape, and it is useful to characterize their size in terms of some standard particle. For example, the **aerodynamic (equivalent) diameter** of a particle is defined as the diameter of a unit-density sphere having the same gravitational settling velocity as the particle in question (Willeke and Baron 1993).

The tendency of particles to settle on surfaces is a property of interest. Figure 3 shows the sizes of typical indoor airborne solid and liquid particles. Particles smaller than $0.1\ \mu\text{m}$ behave like gas molecules exhibiting Brownian motion due to collisions with air

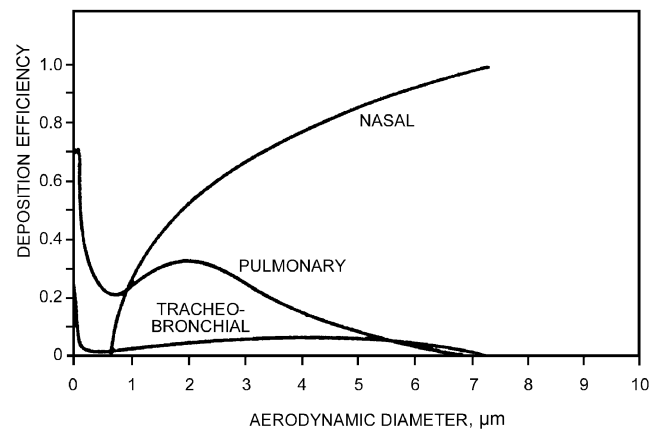


Fig. 2 Relative Deposition Efficiencies of Different Sized Particles in the Three Main Regions of the Human Respiratory System, Calculated for Moderate Activity Level (Task Group on Lung Dynamics 1966)

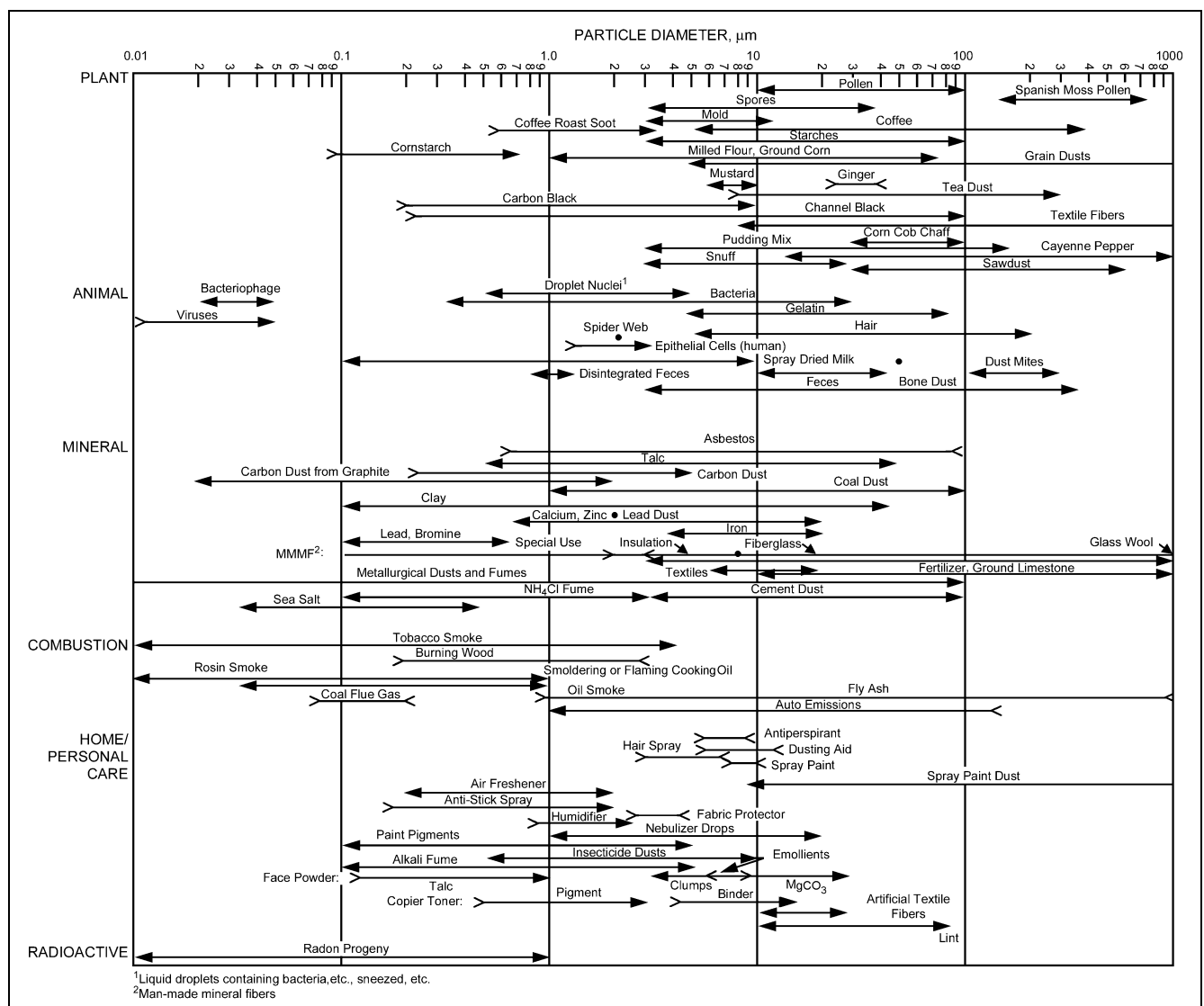


Fig. 3 Sizes of Indoor Particles (Owen et al. 1992)

Table 1 Approximate Particle Sizes and Their Times to Settle One Metre

Type of Particle	Diameter, μm	Settling Time
Human hair	100 to 150	5 s
Skin flakes	20 to 40	
Observable dust in air	>10	
Common pollens	15 to 25	
Mite allergens	10 to 20	5 min
Common spores	2 to 10	
Bacteria	1 to 5	
Cat dander	1±0.5	10 h
Tobacco smoke	0.1 to 1	
Metal and organic fumes	<0.1 to 1	
Cell debris	0.01 to 1	
Viruses	<0.1	10 days

Source: J.D. Spengler, Harvard School of Public Health.

Table 2 Relation of Screen Mesh to Particle Size

U.S. Standard sieve mesh	400	325	200	140	100	60	35	18
Nominal sieve opening, μm	37	44	74	105	149	250	500	1000

molecules and having no measurable settling velocity. Particles in the range from 0.1 to 1 μm have settling velocities that can be calculated but are so low that settling is usually negligible, since normal air currents counteract any settling. By number, over 99.9% of the particles in a typical atmosphere are below 1 μm (this means fewer than 1 particle in every 1000 is larger than 1 μm).

Particles in the 1 to 10 μm range settle in still air at constant and appreciable velocity. However, normal air currents keep them in suspension for appreciable periods.

Particles larger than 10 μm settle fairly rapidly and can be found suspended in air only near their source or under strong wind conditions. Exceptions are lint and other light fibrous materials, such as portions of certain weed seeds, which remain suspended longer. [Table 1](#) shows settling times for various types of particles.

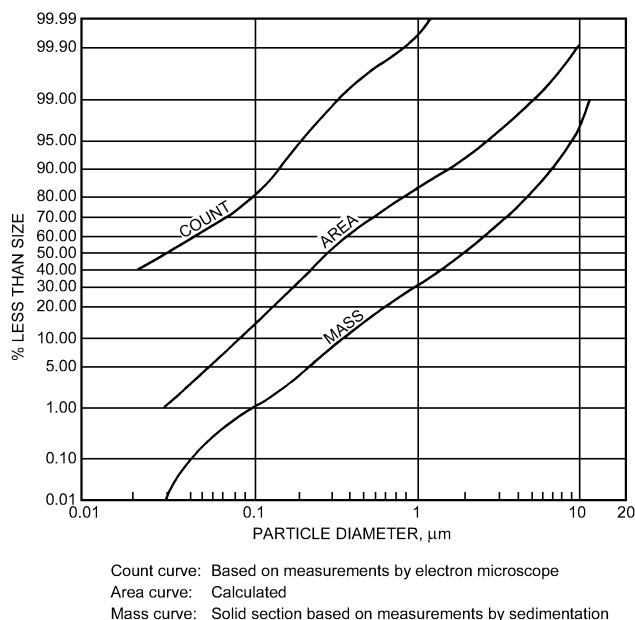
Most individual particles 10 μm or larger are visible to the naked eye under favorable conditions of lighting and contrast. Smaller particles are visible only in high concentrations. Cigarette smoke (with an average particle size less than 0.5 μm) and clouds are common examples.

Direct fallout in the vicinity of the dispersing stack or flue and other nuisance problems of air pollution involve larger particles. Smaller particles, as well as mists, fogs, and fumes, remain in suspension longer. In this size range, meteorology and topography are more important than physical characteristics of the particles. Since settling velocities are small, the ability of the atmosphere to disperse these small particles depends largely on local weather conditions.

Comparison is often made to screen sizes used for grading useful industrial dusts and granular materials. [Table 2](#) illustrates the relationship of U.S. standard sieve mesh to particle size in micrometres. Particles above 40 μm are the screen sizes, and those below are the subscreen or microscopic sizes.

Particle Size Distribution

The particle size distribution in any sample can be expressed as the percentage of the number of particles smaller than a specified size, area, or mass. The upper curve of [Figure 4](#) shows these data plotted for typical atmospheric contamination. The middle curve shows the percentage of the total projected area of the particles contributed by particles less than a specified size. The lower curve shows the percentage of the total particle mass contributed by those particles less than a given size. Thus, for particles 10 μm and larger, 4% by mass, a 90% arrestance filter essentially removes 90% of 4% for an efficiency by mass of 3.6%.

**Fig. 4 Particle Size Distribution of Atmospheric Dust**
(Whitby et al. 1955, 1957)

The differences among values presented by the three curves should be noted. For example, particles 0.1 μm or less in diameter (but still above electron microscope minimum detection size of about 0.005 μm) make up 80% of the number of particles in the atmosphere but contribute only 1% of the mass. Also, the 0.1% of particles by number larger than 1 μm carry 70% of the total mass, which is the direct result of the mass of a spherical particle increasing as the cube of its diameter. Although most of the mass is contributed by intermediate and larger particles, over 80% of the area (staining) contamination is supplied by particles less than 1 μm in diameter, which is in the center of the respirable particle size range and is the size most likely to remain in the lungs. (See [Chapter 9](#).) Of possible concern to the HVAC industry is the fact that most of the staining effect on ceilings, walls, windows, and light fixtures, as well as fouling of heat transfer devices and rotating equipment, results from particles less than 1 μm in diameter. Suspended particles in urban air are predominantly smaller than 1 μm (aerodynamic diameter) and have a distribution that is approximately log-normal.

Units of Measurement

The quantity of particulate matter in the air can be determined as mass or particle count in a given volume of air. Mass units are milligrams per cubic metre of air sampled (mg/m^3) or micrograms per cubic metre of air sampled ($\mu\text{g}/\text{m}^3$). $1 \text{ mg}/\text{m}^3 = 1000 \mu\text{g}/\text{m}^3$. Particle counts are usually quoted for volumes of 0.1 ft^3 , 1 ft^3 , or 1 litre and are specified for a given range of particle diameter.

Measurement of Airborne Particles

Suitable methods for determining the quantity of particulate matter in the air vary depending on the amount present and on the size of particles involved.

The particle mass (total or respirable) is easily determined by measuring the mass of a filter before and after drawing a known volume of dusty air through it. This method is widely used in industrial workplaces, where there may be significant numbers of large particles, but is not sensitive enough for evaluating office environments.

Optical particle counters are widely used and likely to become more so since ASHRAE adopted *Standard 52.2*. This standard defines a laboratory method for assessing the performance of media

filters using an optical particle counter to measure particle counts upstream and downstream of the filter in 12 size ranges between 0.3 and 10 μm . Filters are then given a **minimum efficiency reporting value** (MERV) rating based on the count data.

Counters are also used to test cleanrooms for compliance with Federal *Standard* 209E and ISO *Standard* 14644-1. Cleanrooms are defined in terms of the number of particles in certain size ranges that they contain. [Chapter 16 of the ASHRAE Handbook—Applications](#) has further information on cleanrooms.

Optical particle counters use laser light-scattering to continuously count and size airborne particles and can detect particles down to 0.1 μm (ASTM *Standard* F 50). A **condensation nucleus counter** can count particles to below 0.01 μm . These particles, present in great numbers in the atmosphere, serve as nuclei for condensation of water vapor (Scala 1963).

Another indirect method measures the **optical density** of the collected dust based on the projected area of the particles. Dust particles can be sized with graduated scales or optical comparisons using a standard **microscope**. The lower limit for sizing with the light field microscope is approximately 0.9 μm , depending on the vision of the observer, the dust color, and the contrast available. This size can be reduced to about 0.4 μm by using oil immersion objective techniques. Dark field microscopic techniques reveal particles smaller than these, to a limit of approximately 0.1 μm . Smaller submicroscopic dusts can be sized and compared with the aid of an electron microscope. Other sizing techniques may take into account velocity of samplings in calibrated devices and actual settlement measurements in laboratory equipment. The electron microscope and various sampling instruments such as the **cascade impactor** have been successful in sizing particulates, including fogs and mists.

Each of the various methods of measuring particle size distribution gives a different value for the same size particle, since different properties are actually measured. For example, a microscopic technique may measure longest dimension, while impactor results are based on aerodynamic behavior (ACGIH 2001).

Typical Particle Levels

Particle counters, which detect particles larger than about 0.1 μm , have indicated that the number of suspended particles is enormous. A room with heavy cigarette smoke has a particle concentration of 10^9 particles per cubic metre. Even clean air typically contains over 35×10^6 particles/ m^3 . If smaller particles detectable by other means, such as an electron microscope or condensation nucleus counter, are also included, the total particle concentration would be greater than the above concentrations by a factor of 10 to 100.

Extensive measurements have been made of outdoor pollution, but limited data have been gathered on indoor pollution not associated with specific industrial processes. Indoor levels are influenced by the number of people and their activities, building materials and construction, outside conditions, ventilation rate, and the air-conditioning and filtration system. For further information, see the section on Nonindustrial Indoor Air Contaminants, Spengler et al. (1982), and NRC (1981).

BIOAEROSOLS

Bioaerosols are airborne microbiological particulate matter derived from fungi, bacteria, viruses, protozoa, algae, pollen, mites, and their cellular or cell mass components. Bioaerosols are universally present in both indoor and outdoor environments. Problems of concern to engineers occur when microorganisms grow and reproduce indoors.

Microorganisms break down complex molecules found in dead organic materials to simple substances such as carbon dioxide, water, and nitrates. These components are then used by photosyn-

thetic organisms such as plants and algae. Thus, the presence of bacteria and fungi in soil, water, and atmospheric habitats is normal. Spores of *Cladosporium*, a fungus commonly found on leaves and dead vegetation, are almost always found in outdoor air samples. They are found in variable numbers in indoor air, depending on the amount of outdoor air that infiltrates into interior spaces or is brought in by the HVAC system. Outdoor microorganisms can also enter on shoes and clothing and be transferred to other surfaces in buildings.

Public interest has focused on airborne microorganisms responsible for diseases and infections, primarily bacteria and viruses. This is discussed in more detail in [Chapter 9](#). A variety of airborne microorganisms are of economic significance and can cause product contamination or loss. In the food processing industry, yeast and mold can reduce the shelf life of some products. Refined syrups can be damaged by mold scums. Wild yeast can destroy a batch of beer. Antibiotic yields can be reduced by foreign organisms in the culture mix.

Fungi

Much attention has been given to fungi, which include yeasts, molds, and mildews, as well as large mushrooms, puffballs, and bracket fungi. All fungi depend on external sources of organic material for both energy requirements and carbon skeletons. Thus, they cannot increase in number unless supplied with a suitable food source such as small quantities of dust, paper, or wood. Reproduction also requires appropriate temperatures (20 to 40°C) and the presence of water, high air humidity (typically greater than 60%), and/or high moisture content in the food source.

Bacteria

Cooling towers, evaporative condensers, and domestic water service systems all provide water and nutrients for amplification of microorganisms such as *Legionella pneumophila*. Growth of microbial populations to excessive concentrations is generally associated with inadequate preventive maintenance of these systems, at least in cooling towers. A body of literature has identified characteristics of indoor plumbing and heating systems associated with frequent isolation of *Legionella* species, including blind ends, scale, upright electric water heaters, and lower water temperatures. The survival of *Legionella* is enhanced by a variety of parameters including but not limited to warm temperatures, particular algal and protozoan associations, and symbiotic relationships with certain aquatic plants (Fliermans 1985). Evidence has indicated that amoebae and other protozoa act as natural hosts and amplifiers for *Legionella* in the environment (Barbaree et al. 1986). ASHRAE (1989) has further information on the topic.

Bacteria from the soil are likely to be spore-formers and are capable of surviving in hostile environments. Other airborne bacteria, especially within closed occupied spaces, may originate from droplet nuclei caused by actions such as sneezing or be carried on human or animal skin scales.

Pollen

Pollen grains discharged by weeds, grasses, and trees (Hewson et al. 1967, Jacobson and Morris 1977, Solomon and Mathews 1978) and capable of causing hay fever have properties of special interest to air-cleaning equipment designers (see [Chapter 24 of the ASHRAE Handbook—Systems and Equipment](#)). Whole grains and fragments transported by air range between 10 and 50 μm ; however, some measure as small as 5 μm , and others measure over 100 μm in diameter. Ragweed pollen grains are fairly uniform in size, ranging from 15 to 25 μm .

Most pollen grains are hygroscopic and, therefore, vary in mass with the humidity. Illustrations and data on pollen grains are avail-

able in botanical literature. Geographical distribution of plants that produce hay fever is also recorded.

The quantity of pollen in the air is generally estimated by exposing an adhesive-coated glass plate outdoors for 24 h, then counting calibrated areas under the microscope. Methods are available for determining the number of pollen grains in a measured volume of air. However, despite their greater accuracy, these methods have not replaced the simpler gravity slide method used for most pollen counts. Counting techniques vary, but daily pollen counts reported in local newspapers during hay fever season usually represent the number of grains found on 180 mm² of a 24 h gravity slide.

Hay fever sufferers may experience the first symptoms when the pollen count is 10 to 25; in some localities, maximum figures for the seasonal peak may approach 1000 or more for a 24 h period, depending on the sampling and reporting methods used by the laboratory. Translation of gravity counts by special formulas to a volumetric basis (i.e., number of grains per unit volume of air) is unreliable, due to the complexity of the modifying factors. When such information is important, it should be obtained directly by a volumetric instrument. The number of pollen grains per cubic yard of air varies from 2 to 20 times the number found on 1 cm² of a 24 h gravity slide, depending on grain diameter, shape, specific gravity, wind velocity, humidity, and physical placement of the collecting plate.

Pollen grains can be removed from the air more readily than the dust particles prevalent in outdoor air or those produced by dusty processes, since a larger fraction of them are in the size range easily removed by building HVAC filters.

Whole-grain pollens are easily removed from the outside air entering a ventilation system with medium-efficiency [35 to 45% (MERV 9 to 11)] filters selected to remove 99% of particles 10 µm and greater. Once they have entered a building, whole-grain pollens settle rapidly, reducing concentrations without the need for air cleaning. On resuspension from occupant activities, the whole-grain pollens may disintegrate into fragments, which may possibly be controlled effectively with a high-efficiency [70 to 95% (MERV 12 to 14)] filter capable of removing a high percentage of particles in the 0.3 to 3.0 µm range.

Sampling for Bioaerosols

Sampling for biological agents such as fungi and bacteria can include visual observation of colonies, collection of bulk or surface samples, or air sampling. The principles of sampling and analysis for microorganisms are reviewed by Chatigny (1983). ACGIH (1989) and AIHA (1996) have developed assessment guidelines for the collection of microbiological particulates. An introduction is given below.

Preassessment. Sampling for microorganisms should be undertaken when medical evidence indicates the occurrence of diseases such as humidifier fever, hypersensitivity pneumonitis, allergic asthma, and allergic rhinitis. A walk-through examination of the indoor environment for visual detection of possible microbial reservoirs and amplification sites should be performed before sampling. Note that a visual examination will miss reservoirs that are behind walls. If a reservoir or amplifier is visually identified, it is useful to obtain bulk or source samples from it. Also, removal of clearly identified reservoirs and amplifiers is preferable to complicated and costly air-sampling procedures.

Air Sampling. The same principles that affect the collection of an inert particulate aerosol also govern air sampling for microorganisms. Air sampling is not likely to yield useful data and information unless the sample collected is representative of exposure. The most representative samples are those that are collected in breathing zones over the range of aerosol concentrations. Presently, no personal sampling method has been proposed that is sensitive enough for any bioaerosol (Burge 1995). Thus, ambient sampling designs that obtain reasonable estimates of exposures of

given populations over representative periods are necessary. Because *Legionella* requires special nutrients for growth and does not produce resistant spores, this bacterium is difficult to recover from air.

Concentrations of microorganisms in the atmosphere vary from a few to several hundred per cubic metre, depending on many factors. The sampling method for microorganisms has an effect on the measured count. Collection on **dry filter paper** can cause count degradation because of the dehydration loss of some organisms. **Glass impingers** may give high counts because agitation can cause clusters to break up into smaller individual organisms. **Slit samples** may give a more accurate colony count.

The viability and/or antigenicity of the microbial particulates must be protected during sampling. In general, **culture plate impactors**, including multiple- and single-stage devices as well as **slit-to-agar samplers**, are most useful in office environments where low concentrations of bacteria and fungi are expected. Because not all microorganisms will grow on the same media, liquid impingement subculturing may be more suitable. **Filter cassette samplers** are useful for microorganisms or components of microorganisms (i.e., endotoxins), although binding to glass and plastic has been reported (Milton et al. 1990). Filter cassettes can also be used for spore counts. Area sampling is often used. Some investigators attempt to replicate exposure conditions through disturbance of the environment (semiaggressive sampling) such as occurs through walking on carpets, slamming doors, and opening books or file cabinets.

Viruses, many bacteria, algae, and protozoa are more difficult to culture than fungi, and air-sampling methodology for these agents is less well known and defined (ASTM 1990).

Data Interpretation. Rank order assessment is a method used to interpret air-sampling data for microorganisms (ACGIH 1989). Individual organisms are listed in descending order of abundance for a complainant indoor site and for one or more control locations. The predominance of one or more microbes in the complainant site, but not in the control sites or outdoors, suggests the presence of an amplifier for that organism. In the example in Table 3, *Tritirachium* and *Aspergillus* were the predominant fungi represented in complainant locations in an office building, where *Cladosporium* and *Fusarium* dominated outdoor collections. In this case, *Tritirachium* and *Aspergillus* were being amplified in the building. In addition to comparing individual organisms, indoor-outdoor ratios of overall quantities of culturable microorganisms are useful.

Control of Bioaerosols

When maximum removal of airborne microorganisms is either necessary or desirable, high-efficiency particulate air (HEPA) or ultralow penetration air (ULPA) filters are used. These filters create essentially sterile atmospheres and are more frequently employed than chemical scrubbers and ultraviolet radiation for control of airborne microorganisms. They have been used to prevent cross-infection in hospitals, to protect clean rooms from contamination, and to assemble and launch space probes under sterile conditions.

Table 3 Example Case of Airborne Fungi in Building and in Outdoor Air

Location	cfu/m ³	Rank Order Taxa
Outdoors	210	<i>Cladosporium</i> > <i>Fusarium</i> > <i>Epicoccum</i> > <i>Aspergillus</i>
Complainant Office #1	2500	<i>Tritirachium</i> > <i>Aspergillus</i> > <i>Cladosporium</i>
Complainant Office #2	3000	<i>Tritirachium</i> > <i>Aspergillus</i> > <i>Cladosporium</i>

Notes:

cfu/m³ = Colony-forming units per cubic metre of air.

Culture media was malt extract agar (ACGIH 1989).

In many situations, total control of airborne microorganisms is not required. For these applications, there are various other types of high-efficiency dry media extended-surface filters that will provide the necessary efficiency. These filters have lower pressure differentials than HEPA filters operating at the same face velocity and, when properly selected, will remove the contaminants of concern.

GASEOUS CONTAMINANTS

The terms gas and vapor are both used to describe the gaseous state of a substance. **Gas** is the correct term for describing any pure substance or mixture that naturally exists in the gaseous state at normal atmospheric conditions. Examples are oxygen, helium, ammonia, and nitrogen. **Vapor** is used to describe a substance in the gaseous state whose natural state is a liquid or solid at normal atmospheric conditions. Examples include benzene, carbon tetrachloride, and water. There are differences between the two classes that reflect their preferred states:

- The concentration of gases in air is limited only by the strength of the source, so that gases can completely fill a space, driving out the oxygen necessary for survival.

- Vapors can never exceed their saturated vapor pressure in air. The most familiar example of a vapor is water, with relative humidity expressing the air concentration as a percentage of the saturated vapor pressure.
- Vapors, because their natural state is liquid or solid, have a tendency to condense on surfaces and be adsorbed.

Gaseous contaminants can also be divided into organic and inorganic types. **Organic** compounds include all chemicals based on a skeleton of carbon atoms. Since carbon atoms easily combine to form chain, branched, and ring structures, there is a bewildering variety of organic compounds. They include gases such as methane, but the majority are vapors. All other gaseous contaminants are classified as **inorganic**. Most of the inorganic air contaminants of interest to engineers are gases.

Major chemical families of gaseous pollutants and examples of specific compounds are shown in [Table 4](#). The *Merck Index* (Budavi 1996), the *Toxic Substances Control Act Chemical Substance Inventory* (EPA 1979), and *Dangerous Properties of Industrial Materials* (Sax and Lewis 1988) are all useful in identifying contaminants,

Table 4 Major Chemical Families of Gaseous Air Pollutants (with Examples)

Inorganic Pollutants		
1. Single-element atoms and molecules	11. Chlorinated hydrocarbons	19. Aromatic hydrocarbons
chlorine	carbon tetrachloride	benzene
radon	chloroform	toluene
mercury	1,1,1-trichloroethane	<i>p</i> -xylene
2. Oxidants	tetrachloroethylene	naphthalene
ozone	dichlorobenzene	benz- α -pyrene
nitrogen dioxide	12. Halide compounds	20. Terpenes
3. Reducing agents	methyl bromide	2-pinene
carbon monoxide	methyl iodide	limonene
4. Acid gases	13. Alcohols	21. Heterocyclics
carbon dioxide	methanol	ethylene oxide
sulfur dioxide	ethanol	tetrahydrofuran
sulfuric acid	2-propanol (isopropanol)	1, 4-dioxane
hydrochloric acid	phenol	pyrrole
hydrogen sulfide	ethylene glycol	pyridine
nitric acid	14. Ethers	nicotine
5. Nitrogen compounds	ethyl ether	caffeine
ammonia	methoxyvinyl ether	22. Organophosphates
hydrazine	<i>n</i> -butoxyethanol	malathion
nitrous oxide	15. Aldehydes	tabun
6. Miscellaneous	formaldehyde	sarin
arsine	acetaldehyde	soman
	acrolein	23. Amines
	benzaldehyde	trimethylamine
	16. Ketones	ethanolamine
	2-propanone (acetone)	cyclohexylamine
	2-butanone (MEK)	morpholine
	methyl isobutyl ketone (MIBK)	24. Monomers
	chloroacetophenone	vinyl chloride
	17. Esters	methyl formate
	ethyl acetate	ethylene
	vinyl acetate	methyl methacrylate
	methyl formate	25. Mercaptans and other sulfur compounds
	diethyl phthalate (DOP)	bis-2-chloroethyl sulfide (mustard gas)
	18. Nitrogen compounds other than amines	ethyl mercaptan
	nitromethane	carbon disulfide
	acetonitrile	carbonyl sulfide
	acrylonitrile	26. Organic acids
	urea	formic acid
	uric acid	acetic acid
	skatole	butyric acid
	putrescine	27. Miscellaneous
	hydrogen cyanide	phosgene
	peroxyacetal nitrite (PAN)	
Organic Pollutants		
7. <i>n</i> -Alkanes		
methane		
<i>n</i> -butane		
<i>n</i> -hexane		
<i>n</i> -octane		
<i>n</i> -hexadecane		
8. Branched alkanes		
2-methyl pentane		
2-methyl hexane		
9. Alkenes and cyclic hydrocarbons		
butadiene		
1-octene		
cyclohexane		
4-phenyl cyclohexene (4-PC)		
10. Chlorofluorocarbons		
R-11 (trichlorofluoromethane)		
R-114 (dichlorotetrafluoroethane)		

including some known by trade names only. Chemical and physical properties can be found in reference books such as the *Handbook of Chemistry and Physics* (Lide 1996). Note that a single chemical compound, especially if it is an organic compound, may have several scientific names. To reduce confusion, the Chemical Abstracts Service (CAS) has assigned each chemical a unique identifier number containing five to nine digits.

Harmful Effects of Gaseous Contaminants

Harmful effects may be divided into four categories: toxicity, odor, irritation, and material damage.

Toxicity. The harmful effects of gaseous pollutants on a person depend on both short-term peak concentrations and the time-integrated exposure received by the person. Toxic effects are generally considered to be proportional to the exposure dose, although individual response variation can obscure the relationship. The allowable concentration for short exposures is higher than that for long exposures. Safe exposure limits have been set for a number of common gaseous contaminants in industrial settings. This topic is covered in more detail in the section on Industrial Air Contaminants and in [Chapter 9](#).

Irritation. Although gaseous pollutants may have no discernible continuing health effects, exposure may cause physical irritation to building occupants. This phenomenon has been studied principally in laboratories and nonindustrial work environments and is discussed in more detail in the section on Nonindustrial Indoor Air Contaminants and in [Chapter 9](#).

Odors. Gaseous contaminant problems often appear as complaints about odors, and these usually are the result of concentrations considerably below industrial exposure limits. Odors are discussed in more detail in [Chapter 13](#).

Damage to Materials. Material damage from gaseous pollutants may take such forms as corrosion, embrittlement, or discoloration. Because such effects usually involve chemical reactions that need water, material damage from air pollutants is less severe in the relatively dry indoor environment than outdoors, even at similar gaseous contaminant concentrations. To maintain this advantage, indoor condensation should be avoided. However, some dry materials can be significantly damaged. These effects are most serious in museums, as any loss of color or texture changes the essence of the object. Libraries and archives are also vulnerable, as are pipe organs and textiles. Ventilation is often a poor method of protecting collections of rare objects because these facilities are usually located in the centers of cities that have relatively polluted ambient outdoor air. Gaseous compounds known to be harmful include ozone, nitrous oxides, sulfur dioxide, hydrochloric acid, many volatile organic compounds, and hydrogen sulfide. Various concerns about material damage by indoor air pollutants are discussed by Lull (1995), Walsh et al. (1977), Chiarenzelli and Joba (1966), NTIS (1982, 1984), Braun and Wilson (1970), Jaffe (1967), Grosjean et al. (1987), American Guild of Organists (1966), Mathey et al. (1983), Haynie (1978), Graminski et al. (1978), and Thomson (1986).

Unlike the human body, conservation items have no repair mechanism, yet they are expected to have a longer life than people. This is one reason the acceptable levels of contaminants in museums, archives, and other conservation applications are very low—1 to 2 orders of magnitude below U.S. EPA standards (Mathey et al. 1983, Thomson 1986). Achieving these levels and measuring performance is difficult. Lull (1995) discusses ventilation and air cleaning specifically for conservation environments.

Units of Measurement

Concentrations of gaseous contaminants are usually expressed in the following units:

ppm = parts of contaminant by volume per million parts of air by volume

ppb = parts of contaminant by volume per billion parts of air by volume

1000 ppb = 1 ppm

mg/m³ = milligrams of contaminant per cubic metre of air

µg/m³ = micrograms of contaminant per cubic metre of air

The conversions between ppm and mg/m³ are

$$\text{ppm} = [8.309(273.15 + t)/Mp] \text{ mg/m}^3 \quad (1)$$

$$\text{mg/m}^3 = [0.1204Mp/(273.15 + t)] (\text{ppm}) \quad (2)$$

where

M = relative molecular mass of contaminant

p = mixture pressure, kPa

t = mixture temperature, °C

Concentration data is often reduced to standard temperature and pressure (i.e., 25°C and 101.325 kPa), in which case

$$\text{ppm} = (24.45/M)(\text{mg/m}^3) \quad (3)$$

Measurement of Gaseous Contaminants

The concentration of contaminants in the air needs to be measured to determine whether the indoor air quality conforms to occupational health standards (in industrial environments) and is acceptable (in nonindustrial environments).

Measurement methods for airborne chemicals that are important industrially have been published by several organizations including OSHA (1995) and NIOSH (1994). Methods typically involve sampling air with pumps for several hours to capture the contaminant on a filter or in an adsorbent tube, followed by laboratory analysis for detection and determination of contaminant concentration. Concentrations measured in this way can usefully be compared to 8 h industrial exposure limits.

The measurement of gaseous contaminants at the lower levels acceptable for indoor air is not always as straightforward. Relatively costly analytical equipment may be needed, and it must be calibrated and operated by experienced personnel.

Currently available sampling techniques are listed in [Table 5](#) with details of their advantages and disadvantages. Analytical techniques are shown in [Table 6](#) with information on the types of contaminants to which they apply.

The first two techniques in [Table 5](#) combine sampling and analysis in one piece of equipment and give immediate results on-site. The other sampling methods require laboratory analysis following the field work. Equipment employing the first technique in [Table 5](#) can be coupled with a data logger to perform continuous monitoring and to obtain average concentrations over a time period. Most of the sampling techniques can capture several contaminants. Several allow pollutants to be accumulated or concentrated over time so that very low concentrations can be measured.

Some analytical techniques are specific for a single pollutant, while others are capable of providing concentrations for many contaminants simultaneously. Note that formaldehyde requires different measurement methods from other volatile organic compounds.

Measurement instruments used in industrial situations should be able to detect contaminants of interest at about one-tenth of threshold limit value (TLV) levels. If odors are of concern, detection sensitivity must be at odor threshold levels. Procedures for evaluating odor levels are given in [Chapter 13](#).

When sampling and analytical procedures appropriate to the application have been selected, a pattern of sampling locations and times must be carefully planned. The building and air-handling system layout and the space occupancy and use patterns must be considered so that representative concentrations will be measured.

Table 5 Gaseous Contaminant Sampling Techniques

Technique ^a	Advantages	Disadvantages
1. Direct flow to detectors	Real-time readout, continuous monitoring possible Several pollutants possible with one sample (when coupled with chromatograph, spectroscope, or multiple detectors)	Average concentration must be determined by integration No preconcentration possible before detector; sensitivity may be inadequate On-site equipment complicated, expensive, intrusive
2. Colorimetric detector tubes	Very simple, relatively inexpensive equipment and materials Immediate readout Integration over time	Rather long sampling period normally required One pollutant per sample Relatively high detection limit Poor precision
3. Capture by pumped flow through solid absorbent; subsequent desorption for concentration measurement	On-site sampling equipment relatively simple and inexpensive Preconcentration and integration over time inherent in method Several pollutants possible with one sample	Sampling media and desorption techniques are compound-specific Interaction between captured compounds and between compounds and sampling media; bias may result Gives only average over sampling period, no peaks
4. Collection in evacuated containers	Very simple on-site equipment No pump (silent) Several pollutants possible with one sample	Gives only average over sampling period, no peaks
5. Collection in nonrigid containers (plastic bags) held in an evacuated box	Simple, inexpensive on-site equipment (pumps required) Several pollutants possible with one sample	Cannot hold same pollutants
6. Cryogenic condensation	Wide variety of organic pollutants can be captured Minimal problems with interferences and media interaction Several pollutants possible with one sample	Water vapor interference
7. Passive diffusional samplers	Simple, unobtrusive, inexpensive No pumps; mobile; may be worn by occupants to determine average exposure	Gives only average over sampling period, no peaks
8. Liquid impingers (bubblers)	Integration over time Several pollutants possible with one sample	May be noisy

Sources: NIOSH (1977, 1994), Lodge (1988), Taylor et al. (1977), and ATC (1990).

^aAll techniques except 1 and 2 require laboratory work after completion of field sampling. Only technique 1 is adaptable to continuous monitoring and able to detect short-term excursions.

Traynor (1987) and Nagda and Rector (1983) offer guidance in planning such surveys.

VOLATILE ORGANIC COMPOUNDS

The entire range of organic indoor pollutants has been categorized as indicated in [Table 7](#) (WHO 1989). No sharp limits exist between the categories, which are defined by boiling-point ranges. **Volatile organic compounds** (VOCs) have attracted considerable attention in nonindustrial environments. They have boiling points in the range approximately 50 to 250°C, and vapor pressures greater than about 10⁻³ to 10⁻⁴ mm Hg.

Sources of VOCs include solvents, reagents, and degreasers in industrial environments; and furniture, furnishings, wall and floor finishes, cleaning and maintenance products, and office and hobby activities in nonindustrial environments.

Berglund et al. (1988) found that the sources of VOCs in nonindustrial indoor environments are confounded by the variable nature of emissions from potential sources. Emissions of VOCs from indoor sources can be classified by their presence and rate patterns. For example, emissions are continuous and regular from building materials and furnishings (e.g., carpet and composite-wood furniture); whereas emissions from other sources can be continuous but irregular (e.g., paints used in renovation work), intermittent and regular (e.g., VOCs in combustion products from gas stoves or cleaning products), or intermittent and irregular (e.g., VOCs from carpet shampoos) (Morey and Singh 1991).

Many “wet” emission sources (paints and adhesives) have very high emission rates immediately after application, and rates drop quite steeply with time until the product has cured or dried. New “dry” materials (carpets, wall coverings, and furnishings) also emit chemicals at higher rates until aged. Decay of these elevated VOC concentrations to what can be considered normal constant-source

levels can take weeks to months, depending on emission rates, surface areas of materials, and ventilation protocols. Renovation activities can cause similar increases of somewhat lower magnitude. The total VOC concentration in new office buildings at the time of initial occupancy can be 50 to 100 times that present in outdoor air (Sheldon et al. 1988a, 1988b). In new office buildings with adequate outdoor air ventilation, these ratios often fall to less than 5:1 after 4 or 5 months of aging. In older buildings with continuous, regular, and irregular emission sources, indoor/outdoor ratios of total VOCs may vary from nearly 1:1 when maximum amounts of outdoor air are being used in HVAC systems to greater than 10:1 during winter and summer months when minimum amounts of outdoor air are being used (Morey and Jenkins 1989, Morey and Singh 1991).

While direct VOC emissions are usually the primary source of VOCs in a space, some materials act as sinks for emissions and then become secondary sources as they reemit adsorbed chemicals (Berglund et al. 1988). Adsorption may lower the peak concentrations achieved, but the subsequent desorption prolongs the presence of indoor air pollutants. Sink materials include carpet, fabric partitions, and other fleecy materials, as well as ceiling tiles and wallboard. The type of material and compound affects the rate of adsorption and desorption (Colombo et al. 1991). Indoor air quality models using empirically derived adsorption and desorption rates have been developed to predict the behavior of sinks. Experiments conducted in an IAQ test house confirmed the importance of sinks when trying to control the level of indoor VOCs (Tichenor et al. 1991). Longer periods of increased ventilation lessen sink and reemission effects.

Because of the large number of VOCs usually found indoors and the impossibility of identifying all of them in samples, the concept of total VOC or TVOC was developed. Some researchers have used it to represent the sum of all detected VOCs. TVOC concentrations can also be determined by using methods such as photoionization

Table 6 Gaseous Contaminant Concentration Measurement Methods

Method	Description	Typical Application
1. Gas chromatography (Using the following detectors)	Separation of gas mixtures by time of passage down an absorption column	
Flame ionization	Change in flame electrical resistance due to ions of pollutant	Volatile, nonpolar organics
Flame photometry	Measures light produced when pollutant is ionized by a flame	Sulfur, phosphorous compounds
Photoionization	Measures ion current for ions created by ultraviolet light	Most organics (except methane)
Electronic capture	Radioactively generated electrons attach to pollutant atoms; current measured	Halogenated organics Nitrogenated organics
Mass spectroscopy	Pollutant molecules are charged, passed through electrostatic magnetic fields in a vacuum; path curvature depends on mass of molecule, allowing separation and counting of each type	Volatile organics
2. Infrared spectroscopy and Fourier transform infrared (FTIR) spectroscopy	Absorption of infrared light by pollutant gas in a transmission cell; a range of wavelengths is used, allowing identification and measurement of individual pollutants	Acid gases Many organics
3. High-performance liquid chromatography (HPLC)	Pollutant is captured in a liquid, which is then passed through a liquid chromatograph (analogous to a gas chromatograph)	Aldehydes, ketones Phosgene Nitrosamines Cresol, phenol
4. Colorimetry	Chemical reaction with pollutant in solution yields a colored product whose light absorption is measured	Ozone Oxides of nitrogen Formaldehyde
5. Fluorescence and pulsed fluorescence	Pollutant atoms are stimulated by a monochromatic light beam, often ultraviolet; they emit light at characteristic fluorescent wavelengths, whose intensity is measured	Sulfur dioxide Carbon monoxide
6. Chemiluminescence	Reaction (usually with a specific injected gas) results in photon emission proportional to concentration	Ozone Nitrogen compounds Several organics
7. Electrochemical	Pollutant is bubbled through reagent/water solution, changing its conductivity or generating a voltage	Ozone Hydrogen sulfide Acid gases
8. Titration	Pollutant is absorbed into water	Acid gases
9. Ultraviolet absorption	Absorption of UV light by a cell through which the polluted air passes	Ozone Aromatics Sulfur dioxide Oxides of nitrogen Carbon monoxide
10. Atomic absorption	Contaminant is burned in a hydrogen flame; a light beam with a spectral line specific to the pollutant is passed through the flame; optical absorption of the beam is measured	Mercury vapor

Sources: NIOSH (1977,1994), Lodge (1988), Taylor et al (1977), and ATC (1990).

and flame ionization that do not separate chemicals. All methods for TVOC determination are intrinsically of low to moderate accuracy due to variations in detector response to different classes of VOCs. Both theoretical and practical limitations of the TVOC approach have been discussed (Hodgson 1995, Otson and Fellin 1993).

Wallace et al. (1991) showed that individual VOC concentrations in homes and buildings are 2 to 5 times those of outdoors, and personal TVOC exposures were estimated to be 2 to 3 times greater than general indoor air concentrations. Normal daily activities carried out by individuals are the cause of these higher personal exposures. Personal activities frequently bring individuals close to air contaminant sources. The degree of exposure also depends on how air flows around the body due to convective forces, air turbulence, and obstructions nearby (Rodes et al. 1991).

Individual organic compounds seldom exceed 0.05 mg/m^3 ($50 \text{ }\mu\text{g/m}^3$) in air. An upper extreme average concentration of TVOCs in normally occupied houses is approximately 20 mg/m^3 . The Large Buildings Study by the U.S. EPA (Brightman et al. 1996) developed the VOC sample target list shown in Table 8 to identify

common VOCs that should be measured. Lists of common indoor VOCs prepared by other organizations are similar.

A VOC enrichment factor (VEF) has been described to quantify VOC concentrations due to building sources beyond those expected as bioeffluents (Batterman and Peng 1995). A VEF > 1 describes the overabundance, while a VEF < 1 denotes the depletion of VOCs compared to VOCs expected as bioeffluents. Bioeffluents alone should produce a VEF of 1. The VEF ranged from 0.6 to 17.1 for the 20 office building studies reviewed.

Because chlorofluorocarbons (CFCs) are hydrocarbons with some hydrogen atoms replaced by chlorine, bromine, and fluorine atoms, they are classed as organic chemicals. They have been widely used as heat transfer gases in refrigeration applications, blowing agents, and propellants in aerosol products (including medications and consumer products) and as expanders in plastic foams. CFCs are discussed in Chapter 19 and in ASHRAE Standards 15 and 34. During the 1970s and 1980s, strong evidence was found linking use of CFCs to depletion of the earth's stratospheric ozone layer. CFCs add chlorine and bromine atoms to the atmosphere, which accelerate the natural ozone destruction rate. Ozone deple-

Table 7 Classification of Indoor Organic Pollutants

Description	Abbreviation	Boiling Point Range, °C
Very volatile (gaseous) organic compounds	VVOC	<0 to 50–100
Volatile organic compounds	VOC	50–100 to 240–260
Semivolatile organics (pesticides, polynuclear aromatic compounds, plasticizers)	SVOC	240–260 to 380–400

Source: WHO (1989).

Note: Polar compounds and VOCs with higher relative molecular masses appear at the higher end of each boiling-point range.

tion is linked to increases in the amount of ultraviolet radiation (UV-B) reaching the earth's surface. Increasing UV-B can adversely affect human health, most notably by causing malignant melanoma and cataracts, harm the environment, and decrease crop production. As a result, CFCs are now being phased out. New refrigerants with lower ozone reduction potential are being used, including hydrochlorofluorocarbons (HCFCs). In addition, there has been a return to refrigerants such as ammonia and propellants such as butane and hexane.

Exposure to CFCs and HCFCs occurs mainly through inhalation and can occur from leaks in refrigeration equipment or during servicing of HVAC systems.

Controlling Exposures to Volatile Organic Compounds

Much can be done to reduce building occupants' exposures to emissions of VOCs from building materials and products and to prevent outdoor VOCs from being brought into buildings. The control principles of substitution, isolation, and ventilation apply. Control measures include careful planning; specifications; and selection, modification, and treatment of products, as well as special installation procedures and proper ventilation system operation. [Chapter 45 of the ASHRAE Handbook—Applications](#) provides full details.

Levin (1989, 1991) has written extensively about designing new buildings for good indoor air quality. Reducing VOC emissions by careful selection and installation of building materials and furnishings is a most effective strategy for controlling IAQ. Advances in product formulation and emission testing are leading to products claimed to be low-polluting, nontoxic, and environmentally safe. Requiring the submission of emission testing data by manufacturers for building products, whether for a new building, for a building renovation or remodeling, or for substitution of a consumable product (housekeeping supplies), is becoming accepted practice. Eliminating the sources of VOCs prevents them from becoming a problem in the first place.

Gas-phase air filtration has been applied to control industrial gaseous contaminants for many years. The application of this technology to nonindustrial building HVAC is of interest for improving IAQ, whether it is to provide ventilation without the need to use more outdoor air or to help clean poor-quality outdoor air. Activated carbon and potassium permanganate-impregnated alumina are effective adsorbents that can be used, based on the contaminant mixture present (Liu and Huza 1995, Muller and England 1995, VanOsdell and Sparks 1995). Portable air cleaners with sorbent sections are only marginally effective (Shaughnessy et al. 1994). Photocatalytic reactors capable of destroying VOCs are being studied (Peral et al. 1997). These reactors use ultraviolet light and a catalytic surface, such as titanium dioxide, to convert organic pollutants to CO₂ and water.

Ventilation has traditionally been considered the primary means for controlling indoor VOC contaminants. Dilution ventilation is an effective way to control normal constant-emission sources present in buildings, assuming no unusually strong sources. Compliance

Table 8 Example Sample Contaminant Target List

benzene	styrene
<i>m</i> -, <i>p</i> -xylene	<i>p</i> -dichlorobenzene
1,2,4-trimethylbenzene	<i>n</i> -undecane
<i>n</i> -octane	<i>n</i> -nonane
<i>n</i> -decane	ethylacetate
<i>n</i> -dodecane	dichloromethane
butylacetate	1,1,1-trichloroethane
chloroform	tetrachloroethylene
trichloroethylene	carbon disulfide
trichlorofluoromethane	acetone
dimethyl disulfide	2-butanone
4-methyl-2-pentanone	methyl tertiary butyl ether
limonene	naphthalene
α -, β -pinene	4-phenylcyclohexene
propane	butane
butyl cellosolve	ethanol
isopropanol	phenol
formaldehyde	siloxanes
toluene	

with ASHRAE *Standard 62* should satisfy indoor dilution ventilation requirements. Local exhaust ventilation is effective for controlling known, unavoidable point emissions sources. It is prudent to isolate office machines, such as photocopiers and laser printers, food service equipment, such as microwave ovens and coffee makers, and work areas, such as graphics and photographic labs, using dedicated local exhaust systems that vent to the outside and away from outdoor air intakes.

A good ventilation protocol during renovation or remodeling includes using a single-pass (100% outdoor air) system during and at the finish of these activities, continuing until enough time has passed to lower emitted concentrations to near background. This practice minimizes sink effects and secondary emissions.

Prudent practice and administrative control should be used to minimize the generation of VOCs in indoor air during occupied hours whenever possible. Scheduling the use of volatile organic products, housekeeping activities, and pesticide application when occupant density is lowest should be considered. VOC-containing supplies should be stored in well-ventilated areas other than HVAC mechanical rooms or plenums.

INORGANIC GASES

Several inorganic gases are of concern because of their effects on human health and comfort and on materials. These include carbon dioxide, carbon monoxide, oxides of nitrogen, sulfur dioxide, ozone, and ammonia. Most have both outdoor and indoor sources.

Carbon dioxide (CO₂) or carbonic acid gas is produced by human respiration. It is not normally considered to be a toxic air contaminant, but it can be a simple asphyxiant (by oxygen displacement) in confined spaces such as submarines. CO₂ is found in the ambient environment at 330 to 370 ppm. Levels in the urban environment may be higher due to emissions from gasoline and, more often, diesel engines. Measurement of CO₂ in occupied spaces has been widely used to evaluate the amount of outdoor air supplied to indoor spaces. In ASHRAE *Standard 62*, a level of 1000 ppm (or 650 ppm above outdoor air) has been suggested as being representative of delivery rates of 7 L/s per person of outside air when CO₂ is measured at equilibrium concentrations and at occupant densities of 10 people per 100 m² of floor space. Measuring CO₂ level before it has reached steady-state conditions can lead to inaccurate conclusions regarding the amount of outside air used in the building.

Carbon monoxide (CO) is an odorless, colorless, and tasteless gas produced by the incomplete combustion of hydrocarbons. It is a common ambient air pollutant and is very toxic. Common indoor sources of CO include gas stoves, kerosene lanterns and heaters, mainstream and sidestream tobacco smoke, woodstoves, and unvented or improperly vented combustion sources. Building makeup air intakes located at street level or near parking garages can entrain CO from automobiles and carry it to the indoor environment.

The major predictors of indoor CO concentrations are indoor fossil fuel sources, such as gas furnaces, hot water heaters, and other combustion appliances; attached garages; and weather inversions. Levels in homes only rarely exceed 5 ppm. In one sample of randomly selected homes, 10% failed a backdrafting test (Conibear et al. 1996). Under backdrafting conditions, indoor CO sources may contribute to much higher, dangerous levels of CO.

Oxides of nitrogen (NO_x) indoors result mainly from cooking appliances, pilot lights, and unvented heaters. Sources generating carbon monoxide (CO) often produce nitric oxide (NO) as well. Underground or attached parking garages can also contribute to indoor concentrations of NO_x . An unvented gas cookstove contributes approximately 0.025 ppm of nitrogen dioxide (NO_2) to a home. During cooking, 0.2 ppm to 0.4 ppm peak levels may be reached (Samet et al. 1987). Ambient air pollution from vehicle exhausts in urban locations can contribute NO_x to the indoor environment in makeup air. Oxides of nitrogen also are present in mainstream and sidestream tobacco smoke. Nitric oxide and nitrogen dioxide are of most concern.

Sulfur dioxide (SO_2) can result from the emissions of kerosene space heaters; the combustion of fossil fuels such as coal, heating oil, and gasoline; or burning any material containing sulfur. As a result, sulfur dioxide is a common ambient air pollutant in many urban areas.

Ozone (O_3) is a photochemical oxidant that forms at ground level when hydrocarbons and oxides of nitrogen react with ultraviolet radiation in sunlight to produce photochemical smog. Ozone can be emitted by the electrical or coronal discharges from office equipment including laser printers and photocopiers. It can also be generated when ozone-generating devices—often marketed as portable air cleaners and ionizers—are used in the indoor environment (Esswein and Boeniger 1994).

Controlling Exposures to Inorganic Gases

Three methods of control for inorganic gaseous contaminants should be considered: source control, ventilation control, and removal by filters. **Source control** involves limiting (or removing) the source of the problem; for example, gas cookstoves should not be used for space heating (often a problem in low-income urban residences). Another example is limiting automobile parking around building makeup air intakes. Source control should always be the primary consideration. But source control is not always feasible when there are many diverse contaminant sources as in new buildings where the building itself or building furnishings may be the prime contributors to the problem.

Ventilation control involves bringing clean dilution air into the occupied space or directly exhausting air contaminants at the point of generation. ASHRAE *Standard* 62 provides guidance in applying the Ventilation Rate Procedure and the Indoor Air Quality Procedure for ventilation control.

Where neither source control nor ventilation control appear likely to control gaseous air contaminants, **air filtration** should be investigated. Gas-phase air filtration involves dry scrubbing to remove contaminants by adsorption onto several sorbents, including granular activated carbon (GAC), potassium permanganate-impregnated alumina (PIA), and alkaline-impregnated carbon filters. Muller and England (1995), Liu and Huza (1995), VanOsdell

(1995), and Coutant et al. (1994) review various filtration procedures.

No one media is effective for the broad range of gaseous contaminants found indoors. Granular activated charcoal is generally an agent of choice for nonpolar compounds and is a suitable choice for O_3 and NO_2 but not for SO_x and NO. Permanganate-impregnated alumina is more appropriate for SO_x and NO.

Ozone can be best controlled by local exhaust ventilation for demonstrated sources of ozone, such as photocopiers and equipment creating coronal discharges. Routine cleaning of attractor plates in an electrostatic precipitator and ensuring adequate pre-filters can reduce ozone generation and limit arcing in this type of particle removal equipment. The use of ozone-generating devices as a means of air cleaning or purification has not been documented as a prudent means of air contaminant control considering the potential health effects of the use of ozone indoors (Esswein and Boeniger 1994). The Food and Drug Administration (FDA 1990) specifically limits the use of ozone in concentrations greater than 50 ppb in areas intended for continuous occupancy, such as residences, offices, schools, and hospitals.

Carbon monoxide exposure control strategies primarily involve identification and control of CO emissions directly at their source. Local exhaust ventilation is an appropriate and effective control in most cases. For example, automobile repair garages commonly use a tailpipe exhaust extension to control the CO exposure of the mechanics working in the repair bays. Relocating building makeup air intakes or limiting vehicle access are reasonable means to prevent entrainment of automobile exhausts into building HVAC systems.

Carbon monoxide, however, is a common pollutant of ambient air. As a result, direct control by dilution may not be feasible if ambient air is heavily contaminated with CO. Diesel or natural gas may be substituted for gasoline engines to reduce CO where specific sources from engine exhaust are identified or are a concern. Adequate venting of any combustion sources is critical to prevent the buildup of CO indoors. CO may be monitored by a properly calibrated, direct-reading CO monitor, colorimetric indicator tubes, or passive diffusion sampling badges.

Exposure controls for carbon dioxide are generally limited to situations where exposure concentrations are expected to exceed 3 to 5%. CO_2 is not encountered at levels harmful to humans in the ambient environment. It is normally present at 350 to 375 ppm, and slightly higher in congested cities. With the exception of an intentional or accidental CO_2 “dump” from a fire suppression system or in a dry ice manufacturing facility, CO_2 is not encountered in significant concentrations that require specific engineering controls. However, CO_2 is denser than air and can persist for some time in low areas such as trenches, depressions, and pits. This characteristic creates a simple asphyxiation hazard because CO_2 displaces oxygen.

SPECIAL TYPES OF AIR CONTAMINANTS

OUTDOOR AIR CONTAMINANTS

The total amount of suspended particulate matter in the atmosphere can influence the loading rate of air filters and their selection. The amount of soot that falls in U.S. cities ranges from 7 to 70 Mg/km^2 per month. Soot fall data indicate effectiveness of smoke abatement and proper combustion methods and serve as comparative indices of such control programs. However, the data are of limited value to the ventilating and air-conditioning engineer, since they do not accurately represent airborne soot concentrations.

Concentrations of outdoor pollutants are important, as they may determine indoor concentrations in the absence of indoor sources. [Table 9](#) presents typical urban outdoor concentrations of some com-

Table 9 Typical Outdoor Concentrations of Selected Gaseous Air Pollutants

Pollutant	Typical Concentration, $\mu\text{g}/\text{m}^3$		Pollutant	Typical Concentration, $\mu\text{g}/\text{m}^3$
Acetaldehyde	20		Methylene chloride	2.4
Acetone	3		Nitric acid	6
Ammonia	1.2		Nitric oxide	10
Benzene	8		Nitrogen dioxide	51
2-Butanone (MEK)	0.3		Ozone	40
Carbon dioxide	612 000 ^a		Phenol	20
Carbon monoxide	3 000		Propane	18
Carbon disulfide	310		Sulfur dioxide	240
Carbon tetrachloride	2		Sulfuric acid	6
Chloroform	1		Tetrachloroethylene	2.5
Ethylene dichloride	10		Toluene	20
Formaldehyde	20		1,1,1-Trichloroethane	4
n-Heptane	29		Trichloroethylene	15
Mercury (vapor)	0.005		Vinyl chloride monomer	0.8
Methane	1 100			
Methyl chloride	9		Xylene	10

^aNormal concentration of carbon dioxide in air. The concentration in occupied spaces should be maintained at no greater than three times this level (1000 ppm).

Sources: Braman and Shelley (1980), Casserly and O'Hara (1990), Chan et al. (1990), Cohen et al. (1989), Coy (1987), Fung and Wright (1990), Hakov et al. (1987), Hartwell et al. (1985), Hollowell et al. (1982), Lonnemann et al. (1974), McGrath and Steele (1987), Nelson et al. (1987), Sandalls and Penkett (1977), Shah and Singh (1988), Singh et al. (1981), Wallace et al. (1983), and Weschler and Shields (1989).

Table 10 Primary Ambient Air Quality Standards for the United States

Contaminant	Long Term		Short Term	
	Concentration, $\mu\text{g}/\text{m}^3$	Averaging Period	Concentration, $\mu\text{g}/\text{m}^3$	Averaging Period, h
Sulfur dioxide	80	1 year	365	24
Carbon monoxide			10 000	1
			40 000	8
Nitrogen dioxide	100	1 year		
Ozone ^a			235	1
Hydrocarbons				
Total particulate (PM ₁₀) ^b	75	1 year	260	24
Lead particulate	1.5	3 months		

^aStandard is met when the number of days per year with maximum hour-period concentration above 235 $\mu\text{g}/\text{m}^3$ is less than one.

^bPM₁₀ = particulates below 10 μm diameter

mon gaseous pollutants. Higher levels might be found if the building under consideration were located near a major source of contamination such as a power plant, a refinery, or a sewage treatment plant. Note that levels of sulfur dioxide and nitrogen dioxide, which are often attached to particles, may be reduced by about half by building filtration systems. Also, ozone is a reactive gas that can be significantly reduced by contact with ventilation system components (Weschler et al. 1989).

The U.S. Environmental Protection Agency has identified several important outdoor contaminants as **criteria pollutants**. The list includes suspended particulate matter, lead particulate matter, ozone, nitrogen dioxide, sulfur dioxide, carbon monoxide, and total hydrocarbons. Standards have been set for these contaminants, as shown in Table 10, and levels measured at a large number of locations in the United States are published by the EPA each year (40 CFR 50).

Daily concentrations of VOCs in outdoor air can vary drastically (Ekberg 1994). These variations are due to vehicle traffic density, wind direction, industrial emissions, and photochemical reactions.

Table 11 Characteristics of Selected Gaseous Air Pollutants

Pollutant	Chemical and Physical Properties		
	Family ^a	BP ^b , °C	M ^c
Acetaldehyde	15	21	44
Acetone	16	56	58
Acetonitrile	18	82	41
Acrolein	15	52	56
Acrylonitrile	18	77	53
Allyl chloride	12	44	77
Ammonia	5	-33	17
Benzene	19	80	78
Benzyl chloride	12	179	127
2-Butanone (MEK)	16	79	72
Carbon dioxide	4	-78	44
Carbon monoxide	3	-192	28
Carbon disulfide	25	46	76
Carbon tetrachloride	11	77	154
Chlorine	1	-34	71
Chloroform	11	124	119
Chloroprene	12	120	89
p-Cresol	13	305	108
Dichlorodifluoromethane	10	-30	121
Dioxane	21	100	68
Ethylene dibromide	12	131	188
Ethylene dichloride	12	84	99
Ethylene oxide	21	10	44
Formaldehyde	15	97	30
n-Heptane	7	98	100
Hydrogen chloride	4	-121	37
Hydrogen cyanide	18	26	27
Hydrogen fluoride	4	19	20
Hydrogen sulfide	4	-60	34
Mercury	1	357	201
Methane	7	-164	16
Methanol	13	64	32
Methyl chloride	12	74	133
Methylene chloride	12	40	85
Nitric acid	4	84	63
Nitric oxide	2	-152	30
Nitrogen dioxide	2	21	46
Ozone	2	-112	48
Phenol	13	182	94
Phosgene	27	8	90
Propane	7	-42	44
Sulfur dioxide	4	-10	64
Sulfuric acid	4	270	98
Tetrachloroethane	11	146	108
Tetrachloroethylene	11	121	166
o-Toluidene	23	199	107
Toluene	19	111	92
Toluene diisocyanate	18	251	174
1,1,1-Trichloroethane	11	113	133
Trichloroethylene	11	87	131
Vinyl chloride monomer	24	-14	63
Xylene	19	137	106

Source: See Table 2, Chapter 45, ASHRAE Handbook—Applications.

^aChemical family numbers are as given in Table 4.

^bBP = boiling point at 101.325 kPa (1 atm) pressure

^cM = molecular mass

INDUSTRIAL AIR CONTAMINANTS

Many industrial processes produce significant quantities of air contaminants in the form of dusts, fumes, smokes, mists, vapors, and gases. [Table 11](#) lists chemical and physical properties of some common gaseous industrial contaminants.

Particulate and gaseous contaminants are best controlled at the source so that they are neither dispersed through the factory nor allowed to increase to toxic concentration levels. Dilution ventilation is much less effective than local exhaust for reducing contamination from point source emissions and is used for control only when sources are distributed and not amenable to capture by an exhaust hood. For sources generating high levels of contaminants, it may also be necessary to provide equipment that reduces the amount of material discharged to the atmosphere (e.g., a dust collector for particulate contaminants and/or a high dwell time gas-phase media bed for solvent vapors). Control methods are covered in [Chapters 24](#) and [25 of the ASHRAE Handbook—Systems and Equipment](#) and [Chapters 30](#) and [45 of the ASHRAE Handbook—Applications](#).

Zero concentration of all contaminants is not economically feasible. Absolute control of all contaminants cannot be maintained, and workers can assimilate small quantities of various toxic materials without injury. Industrial hygiene science is based on the fact that most air contaminants become toxic only if their concentration exceeds a maximum allowable limit for a specified period. Allowable limits in industrial environments are covered in [Chapter 9](#).

Although the immediately dangerous to life and health (IDLH) toxicity limit is rarely a factor in HVAC design, HVAC engineers should consider it when deciding how much recirculation is safe in a given system. Ventilation airflow must never be so low that the concentration of any gaseous contaminant could rise to the IDLH level. Another toxic effect that may influence design is the loss of sensory acuity due to gaseous contaminant exposure. For example, high concentrations of hydrogen sulfide, which has a very unpleasant odor, effectively eliminate a person's ability to smell the gas.

Carbon monoxide, which has no odor to alert people to its presence, affects psychomotor responses and could be a problem in areas such as air traffic control towers. Clearly, waste anesthetic gases should not be allowed to reach levels in operating suites such that the alertness of any of the personnel is affected. NIOSH recommendations are frequently based on such subtle effects.

NONINDUSTRIAL INDOOR AIR CONTAMINANTS

Indoor air quality in residences, offices, and other indoor, non-industrial environments has become a widespread concern (Spengler et al. 1982, NRC 1981). Exposure to indoor pollutants can be as important as exposure to outdoor pollutants because a large portion of the population spends up to 90% of their time indoors and because indoor pollutant concentrations are frequently higher than corresponding outdoor contaminant levels.

Symptoms of exposure include coughing; sneezing; eye, throat, and skin irritation; nausea; breathlessness; drowsiness; headaches; and depression. Rask (1988) suggests that when 20% of a single building's occupants suffer such irritations, the structure is suffering from **sick building syndrome** (SBS). Case studies of such occurrences have consisted of analyses of questionnaires submitted to building occupants, measurements of contaminant levels, or both of these. Some attempts to relate irritations to gaseous contaminant concentrations are reported (Lamm 1986, Cain et al. 1986, Berglund et al. 1986, Molhave et al. 1982). The correlation of reported complaints with gaseous pollutant concentrations is not strong; many factors affect these less serious responses to pollution. In general, physical irritation does not occur at odor threshold concentrations.

Characterization of indoor air quality has been the subject of numerous recent studies. ASHRAE *Indoor Air Quality (IAQ) Conference Proceedings* discuss indoor air quality problems and some practical controls. ASHRAE *Standard 62* addresses many indoor air quality concerns. [Table 12](#) illustrates the sources, levels, and indoor-to-outdoor concentration ratios of several contaminants found in indoor environments. [Chapter 9](#) has further information on indoor health issues.

Table 12 Sources, Possible Concentrations, and Indoor-to-Outdoor Concentration Ratios of Some Indoor Pollutants

Pollutant	Sources of Indoor Pollution	Possible Indoor Concentration	I/O Concentration Ratio	Location
Carbon monoxide	Combustion equipment, engines, faulty heating systems	100 mg/kg	>>1	Skating rinks, offices, homes, cars, shops
Respirable particles	Stoves, fireplaces, cigarettes, condensation of volatiles, aerosol sprays, resuspension, cooking	100 to 500 µg/m ³	>>1	Homes, offices, cars, public facilities, bars, restaurants
Organic vapors	Combustion, solvents, resin products, pesticides, aerosol sprays	NA	>1	Homes, restaurants, public facilities, offices, hospitals
Nitrogen dioxide	Combustion, gas stoves, water heaters, driers, cigarettes, engines	200 to 1000 µg/m ³	>>1	Homes, skating rinks
Sulfur dioxide	Heating system	20 µg/m ³	<1	Removal inside
Total suspended particles without smoking	Combustion, resuspension, heating system	100 µg/m ³	1	Homes, offices, transportation, restaurants
Sulfate	Matches, gas stoves	5 µg/m ³	<1	Removal inside
Formaldehyde	Insulation, product binders, particleboard	0.05 to 1.0 mg/kg	>>1	Homes, offices
Radon and progeny	Building materials, groundwater, soil	0.1 to 100 nCi/m ³	>>1	Homes, buildings
Asbestos	Fireproofing	<10 ⁶ fiber/m ³	1	Homes, schools, offices
Mineral and synthetic fibers	Products, cloth, rugs, wallboard	NA	—	Homes, schools, offices
Carbon dioxide	Combustion, humans, pets	3000 mg/kg	>>1	Homes, schools, offices
Viable organisms	Humans, pets, rodents, insects, plants, fungi, humidifiers, air conditioners	NA	>1	Homes, hospitals, schools, offices, public facilities
Ozone	Electric arcing	20 µg/kg	<1	Airplanes
	Ultraviolet light sources	200 µg/kg	>1	Offices

Source: NRC (1981).

^aConcentrations listed are only those reported indoors. Both higher and lower concentrations have been measured. No averaging times are given. NA indicates that it is not appropriate to list a concentration.

A knowledge of sources frequently present in different types of buildings can be useful during investigations of the causes of SBS. Common nonindustrial indoor sources are discussed in some detail below. Technical advances have allowed generation rates to be measured for a number of these sources. These rates are necessary inputs for design of control equipment, and full details are given in [Chapter 45 of the ASHRAE Handbook—Applications](#).

Building materials and furnishing sources have been well studied. Particleboard, which is usually made from wood chips bonded with a phenol-formaldehyde or other resin, is widely used in current construction, especially for mobile homes, carpet underlay, and case goods. These materials, along with ceiling tiles, carpeting, wall coverings, office partitions, adhesives, and paint finishes emit formaldehyde and other VOCs. Latex paints containing mercury have been shown to emit mercury vapor. While the emission rates for these materials decline steadily with age, the half-life of emissions is surprisingly long. Black and Bayer (1986), Nelms et al. (1986), and Molhave et al. (1982) report on these sources.

Ventilation systems may be a source of VOCs (Molhave and Thorsen 1990). The interior of the HVAC system can have large areas of porous material used as acoustical liner that can adsorb odorous compounds. This material can also hold nutrients and, with moisture, can become a reservoir for microorganisms. Microbial contaminants produce characteristic VOCs, called microbial VOCs (MVOCs), associated with their metabolism. Other HVAC components, such as condensate drain pans, fouled cooling coils, and some filter media, may support microbiological life. Deodorants, sealants, and encapsulants are also sources of VOCs in HVAC systems.

Equipment sources in commercial and residential spaces have generation rates that are usually substantially lower than in the industrial environment. As these sources are rarely hooded, emissions go directly to the occupants. In commercial spaces, the chief sources of gaseous contaminants are office equipment, including dry-process copiers (ozone), liquid-process copiers (VOCs), diazo printers (ammonia and related compounds), carbonless copy paper (formaldehyde), correction fluids, inks, and adhesives (various VOCs), spray cans, cosmetics, and so forth (Miksch et al. 1982). Medical and dental activities generate pollutants from the escape of anesthetic gases (nitrous oxide and isoflurane) and from sterilizers (ethylene oxide). The potential for asphyxiation is always a concern when compressed gases are present, even if that gas is nitrogen.

In residences, the main sources of equipment-derived pollutants are gas ranges, wood stoves, and kerosene heaters. Venting is helpful, but some pollutants escape into the occupied area. The pollutant contribution by gas ranges is somewhat mitigated by the fact that they operate for shorter periods than heaters. The same is true of showers, which can contribute to radon and halocarbon concentrations indoors.

Cleaning agents and other consumer products can act as contaminant sources. Commonly used liquid detergents, waxes, polishes, spot removers, and cosmetics contain organic solvents that volatilize slowly or quickly. Mothballs and other pest control agents emit organic vapors. Knoeppel and Schauenburg (1989), Black and Bayer (1986), and Tichenor (1989) report data on the release of these volatile organic compounds (VOCs). Field studies have shown that such products contribute significantly to indoor pollution; however, a large variety of compounds is in use, and few studies have been made that allow calculation of typical emission rates. Pesticides, both those applied indoors and those applied outdoors to control termites, also pollute building interiors.

Tobacco smoke is a prevalent and potent source of indoor air pollutants. Almost all tobacco smoke arises from cigarette smoking. Environmental tobacco smoke (ETS), sometimes called second-hand smoke, is the aged and diluted combination of sidestream smoke (the smoke from the lit end of a cigarette and the smoke that escapes from the filter between puffs) and mainstream smoke (the smoke exhaled by a smoker). Emission factors for ETS compo-

nents, the ratio of ETS components to marker compounds, and apportionment of ETS components in indoor air are reported in the literature by Heavner et al. (1996), Hodgson et al. (1996), Martin et al. (1996), and Nelson et al. (1994).

Occupants, both humans and animals, emit a wide array of pollutants by breath, sweat, and flatus. Some of these emissions are conversions from solids or liquids within the body. Many volatile organics emitted are, however, reemissions of pollutants inhaled earlier, with the tracheobronchial system acting like a physical adsorber.

Floor dust, which is different from the dust in the air, has been found to be a sink (adsorption medium) and secondary emission source for VOCs. Floor dust is a mixture of organic and inorganic particles, hair and skin scales, and textile fibers. The fiber portion of floor dust has been shown to contain 169 mg/kg TVOC, and the particle portion 148 mg/kg (Gyntelberg et al. 1994). These VOCs were correlated to the prevalence of irritative (sore throat) and cognitive (concentration problems) symptoms among building occupants. One hundred eighty-eight compounds were identified from thermal desorption of office dust at 121°C (Wilkins et al. 1993). Household dust was found to be similar in composition (Wolkoff and Wilkins 1994).

Contaminants from other sources include chloroform from water; tetrachloroethylene and 1,1,1-trichloroethane from cleaning solvents; methylene chloride from paint strippers, fresheners, cleaners, and polishers; α -pinene and limonene from floor waxes; and 1-methoxy-2-propanol from spray carpet cleaners. Formaldehyde, a major VOC, has many sources, but pressed wood products appear to be the most significant.

FLAMMABLE GASES AND VAPORS

The use of flammable materials is widespread. Flammable gases and vapors (NFPA *Standard* 325M) can be found in sewage treatment plants, sewage and utility tunnels, dry-cleaning plants, automobile garages, and industrial finishing process plants.

A flammable liquid's vapor pressure and volatility or rate of evaporation determine its ability to form an explosive mixture. These properties can be expressed by the **flash point**, which is the temperature to which a combustible liquid must be heated to produce a flash when a small flame is passed across the surface of the liquid. Depending on the test methods, either the open cup or closed cup flash point may be listed. The higher the flash point, the more safely the liquid can be handled. Liquids with flash points under 21°C should be regarded as highly flammable.

In addition to having a low flash point, the air-vapor or air-gas mixture must have a concentration in the explosive range before it can be ignited. The **explosive range** is the range between the upper and lower explosive limits, expressed as percent by volume in air. Concentrations of material above the higher range or below the lower range will not explode. The range for many chemicals is found in *National Fire Code* bulletins published by the National Fire Protection Association (NFPA). Some representative limits of flammability are listed in [Table 13](#).

In designing ventilation systems to control flammable gases and vapors, the engineer must consider the following:

Most safety authorities and fire underwriters prefer to limit concentrations to 20 to 25% of the lower explosive limit of a material. The resulting safety factor of 4 or 5 allows latitude for imperfections in air distribution and variations of temperature or mixture and guards against unpredictable or unrecognized sources of ignition. Operation at concentrations above the upper explosive limit should be resorted to only in rare instances. To reach the upper explosive limit, the flammable gas or vapor must pass through the active explosive range, in which any source of ignition can cause an explosion. In addition, a drop in gas concentration due to unfore-

Table 13 Flammable Limits of Some Gases and Vapors

Gas or Vapor	Flash Point, °C	Flammable Limits, % by Volume	
		Lower	Upper
Acetone	−18	2.6	12.8
Ammonia	Gas	16	25
Benzene (benzol)	−11	1.3	7.5
<i>n</i> -Butane	Gas	1.9	8.5
Carbon disulfide	−30	1.3	44
Carbon monoxide	Gas	12.5	74
1,2-Dichloroethylene	6	9.7	12
Diethylether	−45	1.9	48
Ethyl alcohol	13	4.3	19
Ethylene	Gas	3.1	32
Gasoline	−43	1.4	7.6
Hydrogen	Gas	4.0	75
Hydrogen sulfide	Gas	4.3	45
Isopropyl alcohol	11.7	2.0	12
Methyl alcohol	11	7.3	36
Methyl ethyl ketone	−6	1.8	10
Natural gas (variable)	Gas	3.8	17
Naphtha (benzine)	10	0.9	6.7
Propane	Gas	2.2	9.5
Toluene (toluol)	4	1.2	7.1
<i>o</i> -Xylene	32	1.0	6.0

seen dilution or reduced evaporation rate may place a system in the dangerous explosive range.

In occupied places where ventilation is applied for proper health control, the danger of an explosion is minimized. In most instances, flammable gases and vapors are also toxic, and the maximum allowable concentrations are far below the lower explosive limit of the material. For example, proper ventilation for acetone vapors keeps the concentration below 1000 mg/m³. This is equivalent to 0.1% by mass. The lower explosive limit for acetone is 2.5% by volume.

Proper location of exhaust and supply ventilation equipment depends primarily on how a contaminant is given off and on other problems of the process, and secondarily on the relative density of flammable vapor.

If the specific density of the explosive mixture is the same as that of air, cross drafts, equipment movement, and temperature differentials may cause sufficient mixing to produce explosive concentrations and disperse these throughout the atmosphere. In reasonably still air, heavier-than-air vapors may pool at floor level. Therefore, the engineer must either provide proper exhaust and supply air patterns to control the hazardous material, preferably at its source, or offset the effects of drafts, equipment movement, and convective forces by providing good distribution of exhaust and supply air for general dilution and exhaust. The intake duct should be positioned so that it does not bring in exhaust gases or emissions from ambient sources.

Adequate ventilation minimizes the risk of or prevents fires and explosions and is necessary, regardless of other precautions, such as elimination of the ignition sources, safe building construction, and the use of automatic alarm and extinguisher systems.

[Chapter 30 of the ASHRAE Handbook—Applications](#) gives more details about equipment for control of combustible materials.

COMBUSTIBLE DUSTS

Many organic and some mineral dusts can produce dust explosions (Hartmann 1958). Often, a primary explosion results from a small amount of dust in suspension that has been exposed to a source of ignition; the pressure and vibration created can dislodge large accumulations of dust on horizontal surfaces, creating a larger secondary explosion.

For ignition, dust clouds require high temperatures and sufficient dust concentration. These temperatures and concentrations and the minimum spark energy can be found in Avallone and Baumeister (1987).

Explosive dusts are potential hazards whenever uncontrolled dust escapes, disperses in the atmosphere or settles on horizontal surfaces such as beams and ledges. Proper exhaust ventilation design involves the principles covered in [Chapter 30 of the ASHRAE Handbook—Applications](#). The ventilation systems and equipment chosen must prevent the pocketing of dust inside the equipment. When local exhaust ventilation is used, separation equipment should be installed as close to the dust source as possible to prevent transport of dust in the exhaust system.

RADIOACTIVE AIR CONTAMINANTS

Radioactive contaminants (Jacobson and Morris 1977) can be particulate or gaseous and are similar to ordinary industrial contaminants. Many radioactive materials would be chemically toxic if present in high concentrations; however, in most cases, the radioactivity necessitates limiting their concentration in air.

Most radioactive air contaminants affect the body when they are absorbed and retained. This is known as the **internal radiation hazard**. Radioactive particulates may settle to the ground, where they contaminate plants and eventually enter the food chain and the human body. Deposited material on the ground increases **external radiation exposure**. However, except for fallout from nuclear weapons or a serious reactor accident, such exposure is insignificant.

Radioactive air contaminants can emit alpha, beta, or gamma rays. The alpha rays penetrate poorly and present no hazard, except when the material is deposited inside or on the body. Beta rays are somewhat more penetrating and can be both an internal and an external hazard. The penetration of gamma rays depends on their energy, which varies from one type of radioactive element or isotope to another. A distinction should be made between the radioactive material itself and the radiation it gives off. Radioactive particles can be removed from air by devices such as HEPA and ULPA filters, and radioactive gases by impregnated carbon or alumina (radioactive iodine) and absorption traps, but the gamma radiation from such material is capable of penetrating solid materials. This distinction is frequently overlooked. The amount of radioactive material in air is measured in becquerels per cubic metre (1 becquerel equals 2.702702×10^{-11} curies), while the dose of radiation from deposited material is measured in rads.

Radioactive materials present problems that make them distinctive. High concentrations of radioactivity can generate enough heat to damage filtration equipment or ignite the material spontaneously. The concentrations at which most radioactive materials are hazardous are much lower than those of ordinary materials; as a result, special electronic instruments that respond to radioactivity must be used to detect these hazardous levels.

The ventilation engineer faces difficulty in dealing with radioactive air contamination because of the extremely low permissible concentrations for radioactive materials. For certain sensitive industrial plants, such as those in the photographic industry, contaminants must be kept from entering the plant. If radioactive materials are handled inside the plant, the problem is to collect the contaminated air as close to the source as possible, and then remove the contaminant from the air with a high degree of efficiency, before releasing it to the outdoors. Filters are generally used for particulate materials, but venturi scrubbers, wet washers, and other devices can be used as prefilters to meet special needs.

The design of equipment and systems for control of radioactive particulates and gases in nuclear laboratories, power plants, and fuel-processing facilities is a highly specialized technology. Careful attention must be given to the reliability, as well as the contaminant-removal ability, of the equipment under the special environmental

stresses involved. Various publications of the U.S. Department of Energy can provide guidance in this field.

Radon

A major source of airborne radioactive exposure to the population comes from radon. Radon (Rn) is a naturally occurring, chemically inert, colorless, odorless, tasteless radioactive gas. It is produced from the radioactive decay of radium, which is formed through several intermediate steps of the decay of uranium and thorium. Radon is widely found in the natural environment, as uranium salt precursors are widespread. Radon-222 is the most common isotope of radon. Before it decays, radon can move limited distances through very small spaces, such as those between particles of soil and rock, and enter indoor environments (Nazaroff et al. 1988, Tanner 1980). Additional but secondary sources of indoor radon include groundwater (radon is quite soluble in water) and radium-containing building materials.

Radon gas enters a house or building primarily through leakage paths in the foundation and is transported by pressure-driven flow. Entry occurs through cracks, joints, and other holes in concrete foundations; directly through porous concrete blocks; through the joints and openings in crawl space ceilings; and through leakage points in HVAC ductwork that is embedded in slab floors or located in crawl spaces. Pressure-driven flow is the dominant radon entry mechanism in houses with elevated radon concentrations (Nazaroff et al. 1987). Pressure differences are caused by several factors, including the thermal stack effect, wind, and operation of HVAC equipment. In addition to pressure-driven radon entry, Rn can also diffuse directly through substructural materials (e.g., concrete). The diffusive Rn entry rate is often a significant portion of the total entry rate in houses with low Rn concentrations.

Measurement. Indoor concentrations of radon can vary hourly, daily, and seasonally, in some cases by as much as a factor of 10 to 20 on a daily basis (Turk et al. 1990). Thus, long-term measurements (3 months to 1 year) made during normal home activities generally provide more reliable estimates of the average indoor concentration than do short-term measurements. Two techniques widely used for homeowner measurements are the short-term charcoal canister (up to 7 days), and the long-term alpha-track methods (90 days to 1 year). Generally, short-term measurements should only be used as a screening technique to determine whether a long-term measurement is necessary. The great uncertainties in measurement accuracy with these devices, up to 50% at the radon levels typically found in homes, as well as the natural variability of radon concentrations should be considered in interpreting the results.

Ideally, long-term measurements should be the basis for decisions on installation of radon mitigation systems, and short-term measurements should only be used as a screening method to identify buildings with Rn concentrations that are very high, justifying immediate remedial action. In practice, short-term measurements at the time a building is sold are the basis for most decisions about remedial action.

Typical Levels. The outdoor radon concentration is about 15 Bq/m³ (0.4 pCi/L). The annual average concentration of radon in homes in the United States is about 46 Bq/m³ (1.25 pCi/L) (EPA 1989). While several sources of radon may contribute to the annual indoor average, pressure-driven flow of soil gas constitutes the principal source for elevated concentrations; nonmunicipal water supplies can be a source of elevated indoor radon, but only in isolated instances.

Control. Exposure to indoor Rn may be reduced by (1) inhibiting Rn entry into the building or (2) removing or diluting Rn decay products in indoor air. The most effective and energy-efficient control measures are generally those that reduce Rn entry rates (Henschel 1993). One of the most common effective techniques is active subslab depressurization, in which a fan and piping system draw soil gas from beneath the slab and exhaust the gas outside. This

technique reduces or reverses the pressure gradient that normally draws soil gas and Rn into the building and often reduces indoor Rn concentrations by a large factor (e.g., 5 to 10). Passive control methods such as Rn-resistant construction techniques and/or passive stack subslab depressurization systems are also used; however, the performance of these control methods is not well characterized, and average reductions in Rn concentrations may be 50% or less. Sealing cracks and joints in slab floors improve the performance of subslab depressurization systems. Sealing by itself is often not very effective in reducing indoor Rn.

In houses with crawl spaces, active (fan-forced) or passive crawl space ventilation is often effective in maintaining low indoor Rn concentrations, although other techniques are also used (Henschel 1988, 1993).

SOIL GASES

The radioactive gas radon (Rn) is the best-known soil gas. However, gaseous contaminants other than radon may enter buildings from surrounding soil. Methane from landfills has reached explosive levels in some buildings. Potentially toxic or carcinogenic VOCs in the soil as a consequence of spills, improper disposal, leaks from storage tanks, and disposal in landfills can also be transported into buildings (Wood and Porter 1987, Hodgson et al. 1992, Garbesi and Sextro 1989, Kullman and Hill 1990). Pesticides applied to the soil beneath or adjacent to houses have also been detected in indoor air (Livingston and Jones 1981, Wright and Leidy 1982), and pressure-driven flow is a suspected entry mechanism. The broad significance of the health effects due to exposure to these soil contaminants is not well understood. Techniques that reduce Rn entry from the soil should also be effective in reducing the entry of these contaminants into buildings. Another approach may be to increase ventilation in the building, such as by slightly opening a window. That change in home-use behavior can also help reduce the negative pressure in the house, with respect to the soil gas pressure, created by the stack effect.

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