

CHAPTER 11

AIR CONTAMINANTS

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AIR contamination is a concern for ventilation engineers when it causes problems for building occupants. Engineers need to understand the vocabulary used by the air sampling and building air cleaning industry. This chapter focuses on the types and levels of air contaminants that might enter ventilation systems or be found as indoor contaminants. Industrial contaminants are included only for special cases. Because it is not a building air concern, the effects of refrigerants on the atmosphere are not included in this chapter; see Chapter 29 for discussion of this topic.

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 other materials (permanent atmospheric impurities) from natural processes such as wind erosion, sea spray evaporation, volcanic eruption, and metabolism or decay of organic matter. The concentration of permanent atmospheric impurities varies, but is usually lower than that of anthropogenic air contaminants.

Anthropogenic outdoor air 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. These outdoor air contaminants can also be transmitted to the indoor environment. In addition, the indoor environment can exhibit a wide variety of local contaminants, both natural and anthropogenic.

Contaminants that present particular problems in the indoor environment include allergens (e.g., dust mite or cat antigen), tobacco smoke, radon, and formaldehyde.

Air composition may be changed accidentally or deliberately. In sewers, sewage treatment plants, agricultural silos, sealed storage vaults, 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 10 further details environmental health issues.

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.

CLASSES OF AIR CONTAMINANTS

Air contaminants are generally classified as either particles or gases. (Particles dispersed in air are also known as **aerosols**. In common usage, the terms *aerosol*, *airborne particle*, and *particulate contaminant* are interchangeable.) The distinction between particles and gases is important when determining removal strategies and equipment. Although the motion of particles is described using the same equations used to describe gas movement, even the smallest of particles (approximately 3 nm) are much larger than individual gas molecules, and have a much greater mass and a much lower diffusion rate. Conversely, particles are typically present in much fewer numbers than even trace levels of contaminant gases.

The **particulate** class covers a vast range of particle sizes, from dust large enough to be visible to the eye (100 μm) to submicroscopic particles that elude most filters (a few nanometers). Particles may be liquid, solid, or have a solid core surrounded by liquid. They are present in the atmosphere at concentrations ranging from 100 particles/cm³ (mass concentration of a few μg/m³) in the cleanest environments to millions per cubic centimetre and several hundred μg/m³ in polluted urban environments. The following traditional particulate contaminant classifications arise in various situations, and overlap. They are all still in common use.

- **Dusts, fumes, and smokes** are mostly solid particulate matter, although smoke often contains liquid particles.
- **Mists, fogs, and smogs** are mostly suspended liquid particles smaller than those in dusts, fumes, and smokes.
- **Bioaerosols** include primarily intact and fragmentary viruses, bacteria, fungal spores, and plant and animal allergens; their primary effect is related to their biological origin. Common indoor particulate allergens (dust mite allergen, cat dander, house dust, etc.) and endotoxins are included in the bioaerosol class.
- Particulate contaminants may be defined by their size, such as **coarse** or **fine**; **visible** or **invisible**; or **macroscopic**, **microscopic**, or **submicroscopic**.
- Particles may be described using terms that relate to their interaction with the human respiratory system, such as **inhalable** and **respirable**

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 (i.e., their boiling point is less than ambient temperature at ambient pressure)
- **Vapors**, which are normally solid or liquid under ambient indoor or outdoor conditions (i.e., their boiling point is greater than ambient temperature at ambient pressure), 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.

Air contaminants can also be classified according to their sources; 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 such special classes include both particulate and gaseous contaminants.

This chapter also covers background information for selected special air contaminant classes (Chapter 10 deals with applicable indoor health and comfort regulations).

- Outdoor air contaminants
- Industrial air contaminants
- Nonindustrial indoor air contaminants and indoor air quality
- Flammable gases and vapors
- Combustible dusts
- Radioactive contaminants
- Soil gases

In the 2008 *ASHRAE Handbook—HVAC Systems and Equipment*, Chapter 28 discusses particulate air contaminant removal, and Chapter 29 covers industrial air cleaning. Chapter 45 in the 2007 *ASHRAE Handbook—HVAC Applications* deals with gaseous contaminant removal.

PARTICULATE CONTAMINANTS

PARTICULATE MATTER

Airborne particulate contamination ranges from dense clouds of desert dust storms to completely invisible and dilute cleanroom particles. It may be anthropogenic or completely natural. It is often a mixture of many different components from several different sources. A much more extensive discussion of particulate contamination by the EPA (2004) is available at <http://cfpub2.epa.gov/ncea/cfm/recordisplay.cfm?deid=87903>.

Particles occur in a variety of different shapes, including spherical, irregular, and fibers, which are defined as particles with aspect ratio (length-to-width ratio) greater than 3. In describing particle size ranges, *size* is the diameter of an assumed spherical particle.

Solid Particles

Dusts are solid particles projected into the air by natural forces such as wind, volcanic eruption, or earthquakes, or by mechanical processes such as crushing, grinding, demolition, blasting, drilling, shoveling, screening, and sweeping. Some of these forces produce dusts by reducing larger masses, whereas 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. *Dust* is also used as a catch-all term (house dust, for example) that can have broad meaning.

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 submicrometre airborne primary particles that may agglomerate into larger particle (1 to 2 μm) clusters if aged at high concentration.

Bioaerosols are airborne biological materials, including viruses and intact and fragments of bacteria, pollen, fungi, and bacterial and fungal spores. Individual **viruses** range in size from 0.003 to 0.06 μm , although they usually occur as aggregates and are associated with sputum or saliva and therefore are generally much larger. Most individual **bacteria** range between 0.4 and 5 μm and may be found

singly or as aggregates. Intact individual **fungal** and **bacterial** spores are usually 2 to 10 μm , whereas **pollen** grains are 10 to 100 μm , with many common varieties in the 20 to 40 μm range. The size range of **allergens** varies widely: the allergenic molecule is very small, but the source of the allergen (mite feces or cat dander) may be quite large.

Liquid Particles

Mists are aggregations of 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.

Fogs are clouds of 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 (ETS) consists of a suspension of 0.01 to 1.0 μm (mass median diameter of 0.3 μm) solid and liquid particles that form as the superheated vapors leaving burning tobacco condense, agglomerate into larger particles, and age. Numerous gaseous contaminants are also produced, including carbon monoxide.

Smog commonly refers to air pollution; it implies an airborne 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 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, visibility, effects, or measurement instrument. Ambient atmospheric particulate contamination is classified by aerosol scientists and the EPA by source mode, with common usage now recognizing two primary modes: coarse and fine.

Coarse-mode aerosol particles are largest, and are generally formed by mechanical breaking up of solids. They generally have a minimum size of 1 to 3 μm (EPA 2004). Coarse particles also include bioaerosols such as mold spores, pollen, animal dander, and dust mite particles that can affect the immune system. Coarse-mode particles are predominantly primary, natural, and chemically inert. Road dust is a good example. Chemically, coarse particles tend to contain crustal material components such as silicon compounds, iron, aluminum, sea salt, and vegetative particles.

Fine-mode particles are generally secondary particles formed from chemical reactions or condensing gases. They have a maximum size of about 1 to 3 μm . Fine particles are usually more chemically complex than coarse-mode particles and result from human activity. Smoke is a good example. Chemically, fine aerosols typically include sulfates, organics, ammonium, nitrates, carbon, lead, and some trace constituents. The modes overlap, and their definitions are not precise. In addition, some aerosol researchers recognize additional modes. Figure 1 shows a typical urban distribution, including the chemical species present in each mode.

Recently, there has been increased interest in even smaller particles, known as **ultrafine-mode** particles, or **nanoparticles**. Ultrafines have a maximum size of 0.1 μm (100 nm) (EPA 2004). The U.S. National Nanotechnology Initiative (NNI 2008) also uses this definition for nanoparticles.

The size of a particle determines where in the human respiratory system particles are deposited, and various samplers collect particles that penetrate more or less deeply into the lungs. Figure 2 illustrates the relative deposition efficiencies of various sizes of particles in the human nasal and respiratory systems. The **inhalable mass** is made up of particles that may deposit anywhere in the respiratory system, and is represented by a sample with a median cut point of 100 μm . Most of the inhalable mass is captured in the nasal passages. The **thoracic particle mass** is the fraction that can penetrate to the lung airways and is represented by a sample with a median cut point of 10 μm (PM_{10}). The **respirable particle mass** is the fraction that can penetrate to the gas-exchange region of the lungs, which ACGIH (1989) defines as having a median cut point of 4 μm . The EPA no longer uses the term *respirable*. Their current concern is with particles having a median cut point of 2.5 μm ($\text{PM}_{2.5}$), which they refer to as **fine particles**.

Particles differ in density, and may be irregular in shape. It is useful to characterize mixed aerosol size in terms of some standard particle. The **aerodynamic (equivalent) diameter** of a particle, defined as the diameter of a unit-density sphere having the same gravitational settling velocity as the particle in question (Willeke and Baron 1993), is commonly used as the standard particle size. Samplers that fractionate particles based on their inertial properties, such as impactors and cyclones, naturally produce results as functions of the aerodynamic diameters. Samplers that use other sizing principles, such as optical particle counters, must be calibrated to give aerodynamic diameter.

The tendency of particles to settle on surfaces is of interest. Figure 3 shows the sizes of typical indoor airborne solid and liquid particles. Particles smaller than 0.1 μm behave like gas molecules, exhibiting irregular motion from collisions with air molecules and having no measurable settling velocity. Particles in the range from 0.1 to 1 μm have calculable settling velocities, but they are so low that settling is usually negligible, because normal air currents counteract any settling. By number, over 99.9% of the particles in a typical atmosphere

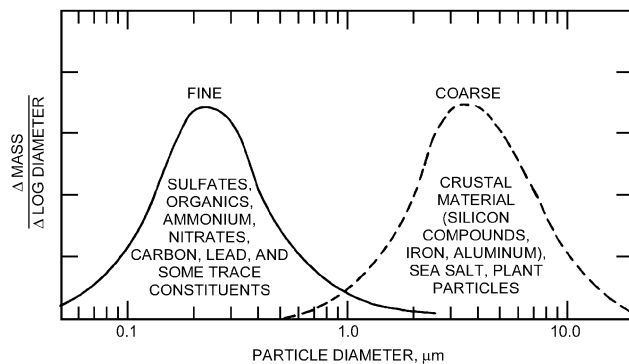


Fig. 1 Typical Urban Aerosol Composition by Particle Size Fraction
(EPA 1982; Willeke and Baron 1993)

are below 1 μm (i.e., fewer than 1 particle in every 1000 is larger than 1 μm). Particles between 1 and 10 μm 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 some weed seeds, which remain suspended longer because their aerodynamic behavior is similar to that of smaller particles (they have aerodynamic diameters smaller than their physical dimensions suggest.)

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. Because settling velocities are small, the atmosphere's ability 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 micrometers. Particles above 40 μm are known as the screen sizes, and those below are known as the subscreen or microscopic sizes.

Table 1 Approximate Particle Sizes and Time to Settle 1 m

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 to 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

Note: Spores, bacteria, and virus sizes are for the typical complete unit. As entrained in the air, they may be smaller (fragments) or larger (attached to debris, enclosed in spum, etc.)

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

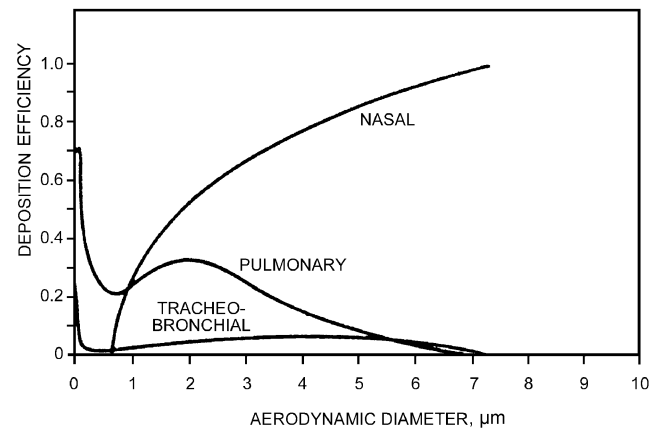


Fig. 2 Relative Deposition Efficiencies of Different-Sized Particles in the Three Main Regions of the Human Respiratory System, Calculated for Moderate Activity Level
(Task Group on Lung Dynamics 1966)

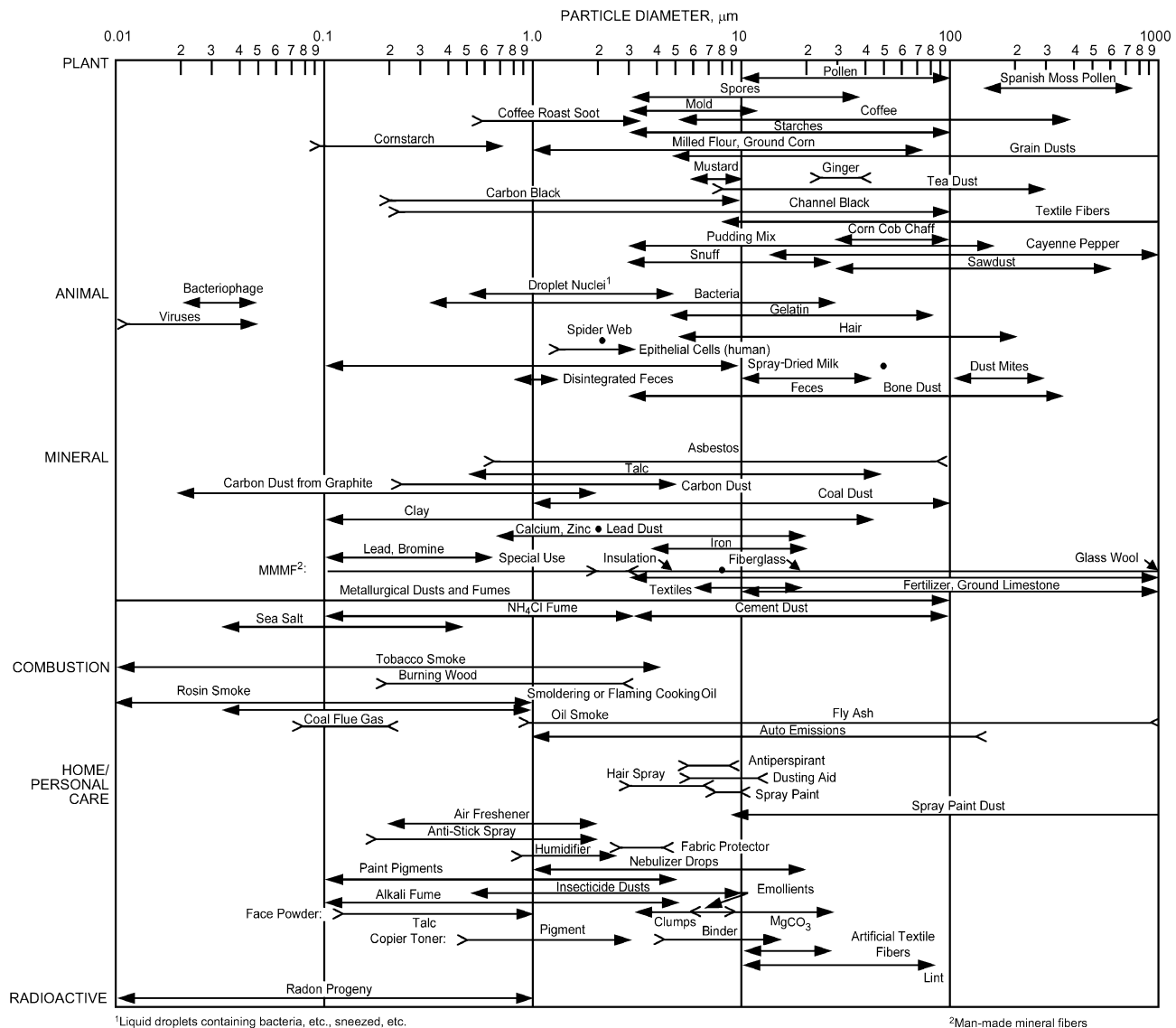


Fig. 3 Sizes of Indoor Particles
(Owen et al. 1992)

Table 2 Relation of Screen Mesh to Sieve Opening 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

Particle Size Distribution

The particle size distribution in any sample can be expressed in several different ways. Figure 4 shows particle count data for typical coarse and fine atmospheric contamination plotted to show particle number, total particle surface area, and total particle volume as a function of particle size.

Note the differences between the three curves. Figure 4 demonstrates that particles 0.1 µm or less in diameter typically make up about 80% of the number of particles in the atmosphere but contribute only about 1% of the volume or mass. Also, 0.1% of the number of particles larger than 1 µm typically 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

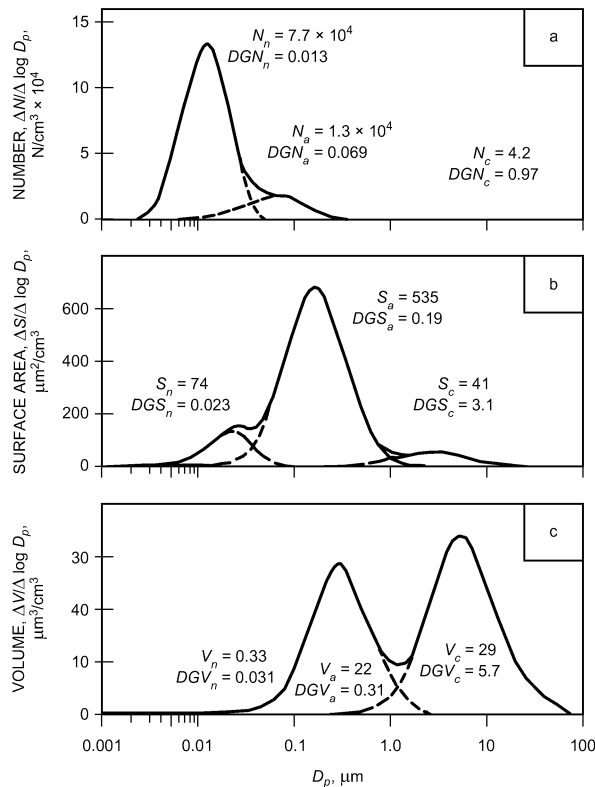
and is the size most likely to remain in the lungs (see Figure 2 and Chapter 10). Of possible concern to the HVAC industry is the fact that most of the staining effect on ceilings, walls, windows, and light fixtures results from particles less than 1 µm in diameter. Fouling of heat transfer devices and rotating equipment involves particles in this size range and larger. 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 a mass or particle count in a given volume of air. Mass units are milligrams per cubic metre of air sampled (mg/m³) or micrograms per cubic metre of air sampled (µg/m³); 1 mg/m³ = 1000 µg/m³. Particle counts are usually quoted for volumes of 0.1 ft³, 1 ft³, 1 L, or 1 m³ 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. **Direct gravimetric measurement**, in which a



Data are plotted by particle number N (plot A), surface area S (plot B), and volume V (plot C). D_p is particle diameter in microns. Legends show geometric mean diameters (DG) for each distribution, and particle number, surface area, or volume in mode.

Fig. 4 Typical Urban Outdoor Distributions of Ultrafine or Nuclei (n) Particles, Fine or Accumulation (a) Particles, and Coarse (c) Particles
(Whitby 1978)

dusty air sample is drawn through a preweighed filter, is a common technique in industrial workplaces that often contain significant numbers of large particles. If the total airstream is drawn through the test filter, the sample is known as the **total mass**; if a size-selective inlet is used on the filter, the sample is characterized by the inlet used (PM_{2.5}, PM₁₀, respirable, etc.). Gravimetric methods have the advantage of providing an integrated sample (over the sample duration) and of providing a direct measure of the mass concentration (mass/volume). In general, gravimetric methods are not real-time, although some innovative samplers use secondary methods (e.g., beta attenuation, crystal vibration frequency changes) to infer mass on a real-time basis. Further, gravimetric methods require increasing test effort (sample duration and balance quality) as the mass concentration drops toward office and indoor air levels.

Normal daily activities of individuals cause higher personal exposures to both particles and gas contaminants than would be expected from measurements of undisturbed air. Personal activities frequently bring individuals close to air contaminant sources, and also generate particles. Sampling near a person requires special care because the degree of exposure also depends on particle transport as air flows around the body because of convective forces, air turbulence, and obstructions nearby (Rodes and Thornburg 2004).

Optical particle counters (OPCs) are widely used and likely to become more so. They are very convenient and provide real-time, size-selective data. Individual aerosol particles are illuminated with a bright light as they singly pass through the OPC viewing volume. Each particle scatters light, which is collected to produce a voltage pulse in the detector. The pulse size is proportional to the particle size, and the electronics of the OPC assign counts to size ranges

based on the pulse size. ASHRAE *Standard 52.2* defines a laboratory method for assessing the performance of media filters using an OPC to measure particle counts up- 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. It is important to sample isokinetically in fast-moving airstreams, such as found in air ducts. This involves sizing the OPC sampling inlet so that the speed of sampled air entering the device is the same as that of air moving past the OPC. If this is not done, the OPC samples inaccurately, capturing too few particles when sampling speed is greater than surrounding air speed, and too many when sampling speed is less than that of the surrounding air.

Counters are also used to test cleanrooms for compliance with the U.S. General Services Administration's (GSA) *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; for more information, see Chapter 16 of the 2007 *ASHRAE Handbook—HVAC Applications*.

Modern OPCs use laser light scattering to continuously count and size airborne particles and, depending on design, can detect particles down to 0.1 μm (ASTM *Standard F50*). Like all aerosol instruments, OPCs should be used with awareness of their limitations. They report particle size from a calibration curve that was developed from a particle having particular optical properties. Actual ambient aerosol particle size is usually close to that indicated by an OPC, but significant errors are possible. Further, many OPCs were developed for cleanroom applications and can become overloaded in other applications. In general, they do not inform the user when they are out of range.

A **condensation nucleus counter (CNC)** 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). CNCs provide total particle numbers, and cannot directly provide particle sizing information.

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, dust color, and available contrast. 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 sampling instruments such as the cascade impactor have been successful in sizing particulates, including fogs and mists. Each method of measuring particle size distribution gives a different value for the same size particle, because different properties are actually measured. For example, a microscopic technique may measure longest dimension, whereas impactor results are based on aerodynamic behavior (ACGIH 2001).

Chemical analysis of particles follows protocols for analysis of any solid material. At industrial concentrations, adequate samples can be obtained from ducts and dust collectors. Because larger particles settle faster than smaller particles, the size and nature of deposited particles often change as suspended particles move away from a source. For instance, near the inlet of an outside air intake, deposited particles will probably be larger and have a coarse composition (e.g., road dust might predominate), whereas further into the duct, fine-mode aerosols would predominate (e.g., condensed oil fume and soot). At the lower concentrations of workplaces, samples are usually collected onto filters, and the filter deposit is analyzed. The filter material must be chosen to not interfere with the analysis. After sample preparation, analysis methods for gaseous contaminant analysis generally apply.

Typical Particle Levels

Particle counters, which detect particles larger than about 0.1 μm , indicate that the number of suspended particles is enormous. A room with heavy cigarette smoke has a particle concentration of 3×10^7 particles per cubic foot. Even clean air typically contains over 10^6 particles/ ft^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. Indoor particle 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.

Wallace (1996) reviewed the effect of outdoor particle penetration and activities on indoor concentrations, and Riley et al. (2002) discussed the influence of air exchange rates and filtration on indoor concentrations in residential and commercial buildings. For further information, see the section on Nonindustrial Indoor Air Contaminants, NRC (1981), and Spengler et al. (1982).

BIOAEROSOLS

Bioaerosol refers to any airborne biological (generally microscopic) particulate matter. Though often thought of as originating as microorganisms (fungi, bacteria, viruses, protozoa, algae), bioaerosols may also be derived from plants (pollen and plant fragments), and animals (hair, dander, and saliva from dogs and cats; dust mites). In addition to the intact organisms (e.g., bacteria), their parts (fungal spores and fragments), components (endotoxins, allergens), and products (dust mite antigen-containing fecal pellets and fungal mycotoxins) may be included in the definition. The antigen or toxin to which the body reacts may be quite small; trace amounts are all that are required for many allergic or toxic reactions. Public interest has focused on airborne microorganisms responsible for diseases and infections, primarily bacteria and viruses. These are discussed in more detail in Chapter 10, including sources, transmission and health effects.

Bioaerosols are universally present in both indoor and outdoor environments. Although the organisms that are sources of bioaerosols are living, reproducing organisms, bioaerosols themselves do not have to be alive to cause allergic, toxic, or inflammatory responses. In fact, as little as 1 to 10% of outdoor bioaerosol is thought to be viable (Jaenicke 1998; Tong and Lighthart 1999). Furthermore, fragments of bioaerosols may be transported while attached to inert particles, and may be important from an exposure standpoint.

Problems of concern to engineers occur when microorganisms grow and reproduce indoors, or when large amounts of bioaerosol enter a building from outdoors. Buildings are not sterile, nor are they meant to be. The presence of bacteria and fungi outdoors in soil, water, and atmospheric habitats is normal. For example, spores of the fungus *Cladosporium* are commonly found on leaves and dead vegetation and are almost always found in outdoor air samples. Often, 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 and pollen can also enter on shoes and clothing and be transferred to other surfaces in buildings. Through infiltration, pollens can be quite problematic indoors, often depending on the season. Pollens discharged by weeds, grasses, and trees (Hewson et al. 1967; Jacobson and Morris 1977; Solomon and Mathews 1978) can cause hay fever. Bioaerosols have properties of special interest to air-cleaning equipment designers (see Chapter 28 of the 2008 *ASHRAE Handbook—HVAC Systems and Equipment*).

Some bioaerosols originate indoors. Many allergens, such as cat, dog, and dust mite allergens, either originate indoors or have indoor reservoirs (bedding and fleecy materials). Much attention has been given to fungi, which include yeasts, molds (filamentous fungi), and mildews, as well as large mushrooms, puffballs, and bracket fungi.

Table 3 Common Molds on Water-Damaged Building Materials

Mold Species	Mold Species
<i>Alternaria alternata</i>	<i>Memnoniella echinata</i>
<i>Aspergillus sydowii</i>	<i>Paecilomyces variotii</i>
<i>Aspergillus versicolor</i>	<i>Penicillium aurantogriseum</i>
<i>Chaetomium globosum</i>	<i>Penicillium chrysogenum</i>
<i>Cladosporium cladosporioides</i>	<i>Penicillium citrinum</i>
<i>Cladosporium sphaerospermum</i>	<i>Penicillium commune</i>
<i>Eurotium herbariorum</i>	<i>Stachybotrys chartarum</i>
<i>Eurotium repens</i>	<i>Ulocladium chartarum</i>

Source: Health Canada (2004).

All fungi depend on external sources of organic material for both energy requirements and carbon skeletons, but very small quantities can be sufficient. Thus, they increase in number when supplied with a suitable food source such as very small quantities of dirt/dust, paper, or wood. Sufficient nutrients are almost always readily available in buildings. For growth to occur, sufficient water must also be available in the material. Adequate moisture content of a material may be attained when the relative humidity is high (typically, the equilibrium relative humidity of a porous material with the surrounding air is greater than 60%), on water incursion from a roof leak or condensation, or when water spills. Note that controlling humidity in a space per se is not sufficient to limit fungal growth; the moisture content of the substrate material must be controlled. Some species of mold that often grow on water-damaged building materials are listed in Table 3.

Mycotoxins are secondary metabolites produced by some filamentous fungi. Some are very toxic (e.g., aflatoxin) and some are beneficial (e.g., penicillin). There are hundreds of different mycotoxins, and more are being identified all the time. Mycotoxins can cause disease and death in humans and other animals, primarily when consumed in foods. However, inhalation exposure of fungal spores and fragments containing mycotoxins has been raised as a potential concern as a bioaerosol contaminant.

Bacteria are much simpler organisms than fungi, and generally require more water for growth, often growing in liquids or periodically wetted surfaces. Whereas fungi actively release spores into the environment from contaminated surfaces, bacteria are generally aerosolized by reentrainment of the water in which they are growing. Cooling towers, evaporative condensers, and domestic water service systems all provide water and nutrients for amplification of bacteria such as *Legionella pneumophila*. Growth of bacterial populations to excessive concentrations is generally associated with inadequate preventive maintenance or leaks creating standing water. *Legionella* is well studied, and ASHRAE has issued a position paper on its control (ASHRAE 1998).

Drain pans and cooling coils may also be sources of bacteria. Growth can occur in the water and the organism then can become aerosolized in water droplets. The most common source of bacteria as bioaerosols, especially in closed occupied spaces, may be droplet nuclei caused by actions such as sneezing, or carried on human or animal skin scales.

Endotoxins are components of the cell walls of a fairly large group of bacteria classified as Gram-negative (i.e., crystal violet dye, used in a Gram stain test, does not affect their color). Endotoxin exposure has been associated with a number of adverse health effects. Humidifier fever has been associated with inhalation of endotoxins (Apter 1997; Teeuw 1994).

Units of Measurement

Microorganisms such as bacteria and molds are usually measured either as total culturable or total countable bioaerosol. **Culturable** (viable) bioaerosols are those that can be grown in a laboratory culture. Results are normally reported as number of colony-forming

units (CFU) per unit sample volume (m^3 for air samples), area (cm^2 for surface samples) or mass (g for bulk samples).

Countable bioaerosols (viable plus nonviable) include all particles that can be identified and counted under a microscope. Results are reported as number of particles per unit sample volume, area, or mass, as above.

Allergens are usually expressed as their weight (in ng) per unit volume; endotoxins are expressed as EU or endotoxin units.

Sampling

Sampling when bioaerosols are suspected as a contaminant may include direct plating of observed microbial growth, collection of bulk or surface samples, or air sampling. Surface sampling is useful for bioaerosol detection, because the surface may constitute a long-time duration sampler. The principles of sampling and analysis for bioaerosols are presented in depth by Macher (1999). AIHA (1996) gives assessment guidelines for collecting microbiological particulates.

The same principles that affect collection of an inert particulate aerosol sample 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, and appropriate control samples are collected. The most representative samples are those collected in breathing zones over the range of aerosol concentrations. Personal sampling (in the breathing zone of a worker) is generally preferable, but area sampling (e.g., on a table) over representative periods is more commonly performed. Some investigators attempt to replicate exposure conditions through disturbance of the environment (semiaggressive sampling), such as occurs when walking on carpets, slamming doors, and opening books or file cabinets.

The sampling method selected affects the measured count. Methods that rely on counting analysis usually report higher concentrations than those that use culturing analysis, because of the inclusion of nonviable particles. There is no single, ideal bioaerosol sampler, but rather several complementary techniques that may be appropriate in any particular application. Collection directly on **filter paper** is simple and direct, but may dehydrate some organisms and underestimate exposure for live counting techniques. **Glass impingers** are an effective and standard method, but may overestimate exposure because the liquid contact and agitation can break clusters into smaller individual organisms, which are then each counted as a separate entity. **Slit-to-agar samplers** may give a more accurate culturable colony count, but do not measure nonculturable organisms or fragments, parts, or components. 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. Some multihole impactors require application of a positive hole correction factor to the raw counts to compensate for multiple organisms focused aerodynamically and landing in the same place on the media. Because not all microorganisms can grow on the same media, impactors that separate samples must be collected for each. Liquid impingement subculturing allows plating one sample on multiple media. Filter cassette samplers are useful for some hardy microorganisms or components (e.g., endotoxins) and allergen analyses. Filter cassettes can also be used for spore counts.

Nonculture methods for fungal spores and pollen grains generally involve exposing an adhesive-coated glass slide or plate for a specific time period, then counting calibrated areas under the microscope, and calculating the number in a measured volume of air. Measurement methods for pollen are not discussed further here, because data are widely available in the public domain.

Some viruses, bacteria, algae, and protozoa are more difficult to culture than fungi, and air-sampling methodology for these organisms may not be practical. For example, *Legionella* requires special nutrients and conditions for growth, and thus may be difficult to

Table 4 Example Case of Airborne Fungi in Building and 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/ m^3 = colony-forming units per cubic metre of air. Culture media, for this example, was malt extract agar (ACGIH 1989).

recover from air. To further complicate the issue, not all fungi grow on any one media, so media selection may be important.

Rank-order assessment is used to interpret air-sampling data for microorganisms (Macher 1999). 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 a source for that organism. An example is shown in Table 4.

Control

Control of bioaerosols is a complex issue. Generally, particulate removal devices and controls are effective in collecting and removing bioaerosols, including allergens (Foarde et al. 1994). The key to effective removal is that the bioaerosol must reach the removal device. Surprisingly, this fact is often overlooked.

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 atmospheres with very low particulate levels.

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

Ultraviolet (UV) radiation is also used for control of airborne microorganisms, to prevent cross-infection in hospitals, to protect cleanrooms, and to assemble and launch space probes under sterile conditions. The key to effective use of UV lights is ensuring that the organism receives a sufficient dose of irradiation. Microorganisms vary widely in their susceptibility of UVC. Vegetative bacteria are readily killed; bacterial spores are much more difficult; fungal spores are extremely hard to kill. Surface kill is generally readily achieved because time is not a factor in attaining a sufficient dose to kill. Achieving kill of airborne contaminants is much more complicated. Banks of lights may be required to achieve sufficient dose to kill bacterial or fungal spores in a moving airstream.

Sometimes, chemicals (**biocides** or **antimicrobials**) are also used to control microbial growth. In the United States, biocides and antimicrobials should be registered with the EPA under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA). Uses for which an antimicrobial is approved should be stated on the label. Label claims are approved by the EPA based on efficacy data from specific standardized tests submitted by the manufacturer on a specific product. Standard efficacy testing of an antimicrobial is frequently done only on the active ingredient in the antimicrobial, and not on the entire product as it is going to be used. Although not required, an effective assessment of antimicrobial efficacy on a material should also include a use test.

In a study of antifungal treated air filters, Foarde (1999) found that antifungal treatment may be masked by dust loading of the filters. Dust creates a physical barrier between the antifungal and the organism. Furthermore, only two of the three antimicrobial treatments inhibited growth. Clearly, it is helpful for industry and consumers to

have information on how a particular product or material is expected to perform in a particular application.

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. That is, its vapor pressure is greater than ambient pressure at ambient temperature. 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. The vapor pressure is below ambient pressure at ambient temperature. Examples include benzene, carbon tetrachloride, and water. Differences between the two classes reflect their preferred states:

- For a strong source, the concentration of a gas in air in a confined space can rise above one atmosphere. Thus, even nontoxic gases can be lethal if they completely fill a space, displacing 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 (low vapor pressure), tend to condense on surfaces and be adsorbed.

Gaseous contaminants can also usefully be divided into organic and inorganic types. **Organic** compounds include all chemicals based on a skeleton of carbon atoms. Because carbon atoms easily combine to form chain, branched, and ring structures, there is a wide variety of organic compounds. Despite the variety, they all have similarities that can be used in sampling, analysis, and removal. Chemists subclassify organic compounds based on families having similar structure and predictable properties. Organic gaseous contaminants include gases such as methane, but the majority are vapors.

All other gaseous contaminants are classified as **inorganic**. Most inorganic air contaminants of interest to ventilation engineers are gases (mercury is an important exception). Major chemical families of inorganic and organic gaseous contaminants, with examples of specific compounds, are shown in [Table 5](#), along with information about occurrence and use. Some organics belong to more than one class and carry the attributes of both.

Another useful gaseous contaminant classification is polar versus nonpolar. There is a continuous distribution between the extremes. For **polar** compounds, charge separation occurs between atoms, which affects physical characteristics as well as chemical reactivity. Water is one of the best examples of a polar compound, and consequently polar gaseous contaminants tend to be soluble in water. **Nonpolar** compounds are much less soluble in water, but dissolve in nonpolar liquids. This classification provides the basis for dividing consumer products that contain organic compounds into water-based and solvent-based. Contaminant classes in [Table 5](#) that are strongly polar include acid gases, chemicals containing oxygen (e.g., alcohols, aldehydes, ketones, esters, organic acids), and some nitrogen-containing chemicals. Nonpolar classes include all hydrocarbons (alkyl, alkene, cyclic, aromatic), chlorinated hydrocarbons, terpenes, and some sulfur-containing chemicals.

Because no single sampling and analysis method applies to every (or even most) potential contaminant, having some idea what the contaminants and their properties might be is very helpful. Contaminants have sources, and consideration of the locale, industries, raw materials, cleaners, and consumer products usually provides some guidance regarding probable contaminants. Material safety data sheets (MSDS) provide information on potentially harmful chemicals that a product contains, but the information is often incomplete. Once a

potential contaminant has been identified, the *Merck Index* (Budavi 1996), the *Toxic Substances Control Act Chemical Substance Inventory* (EPA 1979), *Dangerous Properties of Industrial Materials* (Sax and Lewis 1988), and *Handbook of Environmental Data on Organic Chemicals* (Verschueren 1996) are all useful in identifying and gathering information on contaminant properties, 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 an organic one, may have several scientific names. To reduce confusion, the Chemical Abstracts Service (CAS) assigns each chemical a unique five- to nine-digit identifier number. [Table 6](#) shows CAS numbers and some physical properties for selected gaseous contaminants. Boiling points and saturated vapor pressures are important in predicting airborne concentrations of gaseous contaminants in cases of spillage or leakage of liquids. For example, because of its much higher volatility, ammonia requires more rigorous safety precautions than ethylene glycol when used as a heat exchange fluid. In laboratories where several acids are stored, hydrochloric acid (hydrogen chloride) usually causes more corrosion than sulfuric or nitric acids because its greater gaseous concentration results in escape of more chemical. Additional chemical and physical properties for some of the chemicals in [Tables 5](#) and [6](#) can be found in [Chapter 33](#).

Harmful Effects of Gaseous Contaminants

Harmful effects may be divided into four categories: toxicity, irritation, odor, 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 10](#).

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 10](#).

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 12](#). Note that controlling gaseous contaminants because they constitute a nuisance odor is fundamentally different from controlling a contaminant because it has a demonstrated health effect. Odor control frequently can use limited-capacity “peak-shaving” technology to drop peaks of odorous compounds below the odor threshold. Later reemission at a low rate is neither harmful nor noticed. Such an approach may not be acceptable for control of toxic materials.

Damage to Materials. Material damage from gaseous pollutants includes corrosion, embrittlement, or discoloration. Because these 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, because any loss of color or texture changes the essence of the object. Libraries and archives are also vulnerable, as are pipe organs and textiles. Consult [Chapter 21](#) in the 2007 *ASHRAE Handbook—HVAC Applications* for additional information and an exhaustive reference list.

Table 5 Major Chemical Families of Gaseous Air Contaminants

No.	Family	Examples	Other Information
Inorganic Contaminants			
1.	Single-element atoms and molecules	Chlorine, radon, mercury	Chlorine is a strong respiratory irritant used as a disinfectant. Radon is an important soil gas. Mercury is the vapor in fluorescent light bulbs and tubes.
2.	Oxidants	Ozone, nitrogen dioxide	Both members are corrosive and act as respiratory irritants.
3.	Reducing agents	Carbon monoxide	Carbon monoxide is a toxic fuel combustion product.
4.	Acid gases	Carbon dioxide, hydrogen chloride, hydrogen fluoride, hydrogen sulfide, nitric acid, sulfur dioxide, sulfuric acid	Carbon dioxide and hydrogen sulfide are only weakly acidic. Hydrogen sulfide is the main agent in sewer gas. Other members are corrosive and respiratory irritants. Some are important outdoor contaminants.
5.	Nitrogen compounds	Ammonia, hydrazine, nitrous oxide	Ammonia used in cleaning products. It is a strong irritant. Hydrazine is used as an anticorrosion agent. Nitrous oxide (laughing gas) is used as an anesthetic.
6.	Miscellaneous	Arsine, phosphine	Arsine and phosphine are used in the semiconductor industry.
Organic Contaminants			
7.	<i>n</i> -Alkanes	Methane, propane, <i>n</i> -butane, <i>n</i> -hexane, <i>n</i> -heptane, <i>n</i> -octane, <i>n</i> -nonane, <i>n</i> -decane, <i>n</i> -undecane, <i>n</i> -dodecane	<i>n</i> -Alkanes are linear molecules and relatively easily identified analytically. Along with the far more numerous branched alkanes, they are components of solvents such as mineral spirits.
8.	Branched alkanes	2-methyl pentane, 2-methyl hexane	There are many different ways of linking atoms in the carbon skeleton, so this family is very numerous. Members are difficult to separate and identify. Many occur as components of products such as gasoline, kerosene, mineral spirits, etc.
9.	Alkenes and cyclic hydrocarbons	Ethylene, butadiene, 1-octene, cyclohexane, 4-phenyl cyclohexene (4-PC)	Ethylene gas is produced by ripening fruit (and used in the fruit industry). Some liquid members are components of gasoline, etc. 4-PC is responsible for "new carpet" odor.
10.	Chlorofluorocarbons	R-11 (trichlorofluoromethane), R-12 (dichlorodifluoromethane), R-114 (dichlorotetrafluoroethane)	These have been widely used as refrigerants, but are being phased out because of their ozone-depleting potential.
11.	Chlorinated hydrocarbons	Carbon tetrachloride, chloroform, dichloromethane, 1,1,1-trichloroethane, trichloroethylene, tetrachloroethylene, <i>p</i> -dichlorobenzene	Dichlorobenzene, an aromatic chemical, is a solid used as an air freshener. The others shown here are liquids and are effective nonpolar solvents. Some are used as degreasers or in the dry-cleaning industry.
12.	Halide compounds	Methyl bromide, methyl iodide	Members of this family are of low combustibility. Some are used as flame retardants.
13.	Alcohols	Methanol, ethanol, 2-propanol (isopropanol), 3-methyl 1-butanol, ethylene glycol, 2-butoxyethanol, phenol	Alcohols are strongly polar. Some (including 2-butoxyethanol) are used as solvents in water-based products. Phenol is used as a disinfectant. 3-methyl 1-butanol is emitted by some molds.
14.	Ethers	Ethyl ether, methyl tertiary butyl ether (MTBE), 2-butoxyethanol	Ethyl ether and 2-butoxyethanol are used as solvents. MTBE is added to gasoline to improve combustion in vehicle motors.
15.	Aldehydes	Formaldehyde, acetaldehyde, acrolein, benzaldehyde	Formaldehyde, acetaldehyde, and acrolein have unpleasant odors and are strong irritants.
16.	Ketones	2-propanone (acetone), 2-butanone (MEK), methyl isobutyl ketone (MIBK), 2-hexanone	Ketones are medium-polarity chemicals. Some are useful solvents. Acetone and 2-hexanone are emitted by some molds.
17.	Esters	Ethyl acetate, vinyl acetate, butyl acetate	Esters are medium-polarity chemicals. Some have pleasant odors and are added as fragrances to consumer products.
18.	Nitrogen compounds other than amines	Nitromethane, acetonitrile, acrylonitrile, urea, hydrogen cyanide, peroxyacetal nitrite (PAN)	This family includes several different types of chemicals, and there are few common properties. Acetonitrile is used as a solvent; urea is a metabolic product; PAN is found in vehicle exhaust.
19.	Aromatic hydrocarbons	Benzene, toluene, <i>p</i> -xylene, styrene, 1,2,4 trimethyl benzene, naphthalene, benz- α -pyrene	Benzene, toluene, and xylene are widely used as solvents and in manufacturing, and are ubiquitous in indoor air. Naphthalene is used as moth repellent.
20.	Terpenes	α -pinene, limonene	A variety of terpenes are emitted by wood. The two listed here have pleasant odors and are used as fragrances in cleaners, perfumes, etc.
21.	Heterocyclics	Ethylene oxide, tetrahydrofuran, 3-methyl furan, 1, 4-dioxane, pyridine, nicotine	Most heterocyclics are of medium polarity. Ethylene oxide is used as a disinfectant. Tetrahydrofuran and pyridine are used as solvents. Nicotine is a component of tobacco smoke.
22.	Organophosphates	Malathion, tabun, sarin, soman	The listed members are components of agricultural pesticides and occur as outdoor air contaminants.
23.	Amines	Trimethylamine, ethanolamine, cyclohexylamine, morpholine	Amines typically have unpleasant odors detectable at very low concentrations. Some (cyclohexylamine and morpholine) are used as antioxidants in boilers.
24.	Monomers	Vinyl chloride, ethylene, methyl methacrylate, styrene	These have the potential to be released from their respective polymers (PVC, polythene, perspex, polystyrene) if materials are heated.
25.	Mercaptans and other sulfur compounds	Bis-2-chloroethyl sulfide (mustard gas), ethyl mercaptan, dimethyl disulfide	Sulfur-containing chemicals typically have unpleasant odors detectable at very low concentrations. Ethyl mercaptan is added to natural gas so that gas leaks can be detected by odor. Mustard gas has been used in chemical warfare.
26.	Organic acids	Formic acid, acetic acid, butyric acid	Formic and acetic acids (vinegar) are emitted by some types of wood. Butyric acid is a component of "new car" odor.
27.	Miscellaneous	Phosgene, siloxanes	Phosgene is a toxic gas released during combustion of some chlorinated organic chemicals. Siloxanes occur widely in consumer products, including adhesives, sealants, cleaners, and hair and skin care products.

Table 6 Characteristics of Selected Gaseous Air Contaminants

Contaminant	Chemical and Physical Properties				
	Family ^a	CAS ^b number	BP, ^c °F	Sat. VP ^d	M ^e
Acetaldehyde	15	75-07-0	68	1.2	44
Acetone	16	67-64-1	133	0.3	58
Acrolein	15	107-02-8	124	3.6	56
Ammonia	5	7664-41-7	-28	9.9	17
Benzene	19	71-43-2	177	0.1	78
2-Butanone (MEK)	16	78-93-3	175	0.1	72
Carbon dioxide	4	124-38-9	Sub ^f	>40	44
Carbon monoxide	3	630-08-0	-312	>60	28
Carbon disulfide	25	75-15-0	116	0.5	76
Carbon tetrachloride	11	56-23-5	170	0.15	154
Chlorine	1	7782-50-5	-30	7.7	71
Chloroform	11	67-66-3	142	0.2	119
Dichlorodifluoromethane	10	75-71-8	-20	6.4	121
Dichloromethane	12	75-09-2	104	0.6	85
Ethylene glycol	13	107-21-1	387	0.0001	62
Ethylene oxide	21	75-21-8	56	1.7	44
Formaldehyde	15	50-00-0	-2	5.1	30
<i>n</i> -Heptane	7	142-82-5	209	0.06	100
Hydrogen chloride	4	7647-01-0	-121	46.4	37
Hydrogen cyanide	18	74-90-8	79	1.0	27
Hydrogen fluoride	4	7664-39-3	67	1.2	20
Hydrogen sulfide	4	7783-06-4	-77	20.2	34
Mercury	1	7439-97-6	674	<0.00002	201
Methane	7	74-82-8	-263	>100	16
Methanol	13	67-56-1	149	0.2	32
Nitric acid	4	7697-37-2	187	0.07	63
Nitrogen dioxide	2	10102-44-0	70	1.1	46
Ozone	2	10028-15-6	-170	>60	48
Phenol	13	108-95-2	360	0.0005	94
Phosgene	27	75-44-5	47	1.9	90
Propane	7	74-98-6	-44	9.3	44
Sulfur dioxide	4	7446-09-5	14	4.2	64
Sulfuric acid	4	7664-93-9	639		98
Tetrachloroethylene	11	127-18-4	250	0.02	166
Toluene	19	108-88-3	231	0.04	92
Toluene diisocyanate	18	584-84-9	484	0.00001	174
1,1,1-Trichloroethane	11	71-55-6	165	0.2	133
Trichloroethylene	11	79-01-6	188	0.1	131
Vinyl chloride monomer	24	75-01-4	8	3.5	63
Xylene	19	106-42-3	281	0.01	106

^aChemical family numbers are as given in Table 5.^bCAS = Chemical Abstracts Services.^cBP = boiling point at 14.7 psia (1 atm) pressure.^dSat. VP = saturated vapor pressure at 77°F, atm.^eM = molecular weight.^fSub = solid sublimates at -109°F.

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

Conversions between ppm and mg/m³ are

$$\text{ppm} = [0.6699(459.7 + t)/Mp] \text{ (mg/m}^3\text{)} \quad (1)$$

$$\text{mg/m}^3 = [1.493(Mp)/(459.7 + t)] \text{ (ppm)} \quad (2)$$

where

M = relative molecular weight of contaminant

p = mixture pressure, psia

t = mixture temperature, °F

Concentration data are often reduced to standard temperature and pressure (i.e., 77°F and 14.7 psia), in which case,

$$\text{ppm} = (24.46/M) \text{ (mg/m}^3\text{)} \quad (3)$$

Using the 70°F standard temperature more familiar to engineers results in a conversion factor between ppm and mg/m³ of 24.14 in Equation (3).

Equations (1) to (3) are strictly true only for ideal gases, but generally are acceptable for dilute vaporous contaminants dispersed in ambient air.

Measurement of Gaseous Contaminants

The concentration of contaminants in air must be measured to determine whether 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 NIOSH (1994) and OSHA (1995). Methods typically involve sampling air with pumps for several hours to capture contaminants 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.

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 sample collection techniques are listed in Table 7, with information about their advantages and disadvantages. Analytical measurement techniques are shown in Table 8, with information on the types of contaminants to which they apply. Tables 7 and 8 provide an overview of gaseous contaminant sampling and analysis, with the intent of allowing informed interaction with specialists.

Techniques 1, 2, and 8 in Table 7 combine sampling and analysis in one piece of equipment and give immediate, on-site results. The other sampling methods require laboratory analysis after the field work. Equipment using the first technique can be coupled with a data logger to perform continuous monitoring and to obtain average concentrations over a time period. Most of the sample collection techniques can capture several contaminants. Several allow pollutants to accumulate or concentrate over time so that very low concentrations can be measured.

Some analytical measurement techniques are specific for a single pollutant, whereas others can provide 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, published annually by ACGIH. If odors are of concern, detection sensitivity must be at odor threshold levels. Procedures for evaluating odor levels are given in Chapter 12.

When sample collection and analytical procedures appropriate to the application have been selected, a building-specific pattern of sampling locations and times must be carefully planned. Building and air-handling system layout and space occupancy and use patterns must be considered so that representative concentrations will be measured. Nagda and Rector (1983) and Traynor (1987) offer guidance in planning such surveys. Note that information in Tables 7 and 8 is not sufficient in itself to allow preparation of a measurement protocol.

Table 7 Gaseous Contaminant Sample Collection Techniques

Technique*	Advantages	Disadvantages
Active Methods		
1. Direct flow to detectors	Real-time readout, continuous monitoring possible Several pollutants possible with one sample (when coupled with chromatograph, spectroscopy, or multiple detectors)	Average concentration must be determined by integration No preconcentration possible before detector; sensitivity may be inadequate On-site equipment often complicated, expensive, intrusive, and requires skilled operator
2. Capture by pumped flow through colorimetric detector tubes, papers, or tapes	Very simple, relatively inexpensive equipment and materials Immediate readout Integration over time	One pollutant per sample Relatively high detection limit Poor precision Requires multiple tubes, papers, or tapes for high concentrations or long-term measurements
3. Capture by pumped flow through solid adsorbent; 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 Subsequent concentration measurement required
4. Collection in evacuated containers	Very simple on-site equipment No pump (silent) Several pollutants possible with one sample	Subsequent concentration measurement required Gives average over sampling period; no peaks Finite volume requires multiple containers for long-term or continuous measurement
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 some pollutants Subsequent concentration measurement required Gives average over sampling period; no peaks Finite volume requires multiple containers for long-term or continuous measurement
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 Subsequent concentration measurement required Gives average over sampling period; no peaks
7. Liquid impingers (bubblers)	Integration over time Several pollutants possible with one sample if appropriate liquid chosen	May be noisy Subsequent concentration measurement required Gives average over sampling period; no peaks
Passive Methods		
8. Passive colorimetric badges	Immediate readout possible Simple, unobtrusive, inexpensive No pumps, mobile; may be worn by occupants to determine average exposure	One pollutant per sample Relatively high detection limit Poor precision May require multiple badges for higher concentrations or long-term measurement
9. Passive diffusional samplers	Simple, unobtrusive, inexpensive No pumps, mobile; may be worn by occupants to determine average exposure	Subsequent concentration measurement required Gives average over sampling period; no peaks Poor precision

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

*All techniques except 1, 2, and 8 require laboratory work after completion of field sampling. Only first technique is adaptable to continuous monitoring and able to detect short-term excursions.

VOLATILE ORGANIC COMPOUNDS

The entire range of organic indoor pollutants has been categorized by volatility, as indicated in Table 9 (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 of approximately 120 to 480°F and vapor pressures greater than about 4×10^{-5} to 4×10^{-6} in. Hg. [Note that the U.S. Environmental Protection Agency (EPA) has a specific regulatory definition of VOCs (*Code of Federal Regulations* 40CFR51.100) that must be consulted if regulated U.S. air emissions are the matter of interest. Although similar to the definition here, it is more complex, with some excluded compounds and specified test methods.]

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. Which gas contaminants are likely in an industrial environment can usually best be identified from the nature of the industrial processes, and that is the recommended first step. This discussion focuses on indoor VOCs because they are usually more difficult to identify and quantify.

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, but rates drop

Table 8 Analytical Methods to Measure Gaseous Contaminant Concentration

Method	Description	Typical Application (Family)
Gas chromatography (using the following detectors)	Separation of gas mixtures by time of passage down absorption column	
Flame ionization	Change in flame electrical resistance caused by ions of pollutant	Volatile, nonpolar organics (7-27)
Flame photometry	Measures light produced when pollutant is ionized by a flame	Sulfur (25), phosphorous (22) compounds Most organics (7-27), except methane
Photoionization	Measures ion current for ions created by ultraviolet light	Halogenated organics (11, 12) Nitrogenated organics (18, 23)
Electronic capture	Radioactively generated electrons attach to pollutant atoms; current measured	
Mass spectroscopy	Pollutant molecules are charged, passed through electrostatic magnetic fields in vacuum; path curvature depends on mass of molecule, allowing separation and counting of each type	Volatile organics (7-27 with boiling point < 149°F)
Infrared spectroscopy, including Fourier transform IR (FTIR) and photoacoustic IR	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 (4, 26), carbon monoxide (3) Many organics; any gas with an absorption band in the infrared (7-27)
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 (15), ketones (16) Phosgene (27) Nitrosamines (18, 23) Cresol, phenol (13)
Colorimetry	Chemical reaction with pollutant in solution yields a colored product whose light absorption is measured	Ozone (2) Oxides of nitrogen (2) Formaldehyde (15)
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 (4) Carbon monoxide (3)
Chemiluminescence	Reaction (usually with a specific injected gas) results in photon emission proportional to concentration	Ozone (2) Nitrogen compounds (5, 18, 23) Some organics (7-27)
Electrochemical	Pollutant is bubbled through reagent/water solution, changing its conductivity or generating a voltage	Ozone (2) Hydrogen sulfide (4) Acid gases (4, 26)
Titration	Pollutant is absorbed into water and known quantities of acid or base are added to achieve neutrality	Acid gases (4, 26) Basic gases (5, 23)
Ultraviolet absorption	Absorption of UV light by a cell through which the polluted air passes is measured	Ozone (2) Aromatics (19) Sulfur dioxide (4) Oxides of nitrogen (2) Carbon monoxide (3)
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 (1)
Surface acoustic wave, flexural plate wave, etc.	Contaminant adsorption on a substrate alters the resonant vibration frequency or vibration transmittance characteristics	
Chemiresistor (metal oxide)	Contaminant interacts with coated metal oxide surface at high temperature, changing the resistance to electrical current	Carbon monoxide (3), hydrogen sulfide (4), organic vapors (7-27)

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

Table 9 Classification of Indoor Organic Contaminants by Volatility

Description	Abbreviation	Boiling Point Range, °F
Very volatile (gaseous) organic compounds	VVOC	<32 to 120–212
Volatile organic compounds	VOC	120–212 to 460–500
Semivolatile organics (pesticides, polynuclear aromatic compounds, plasticizers)	SVOC	460–500 to 720–750

Source: WHO (1989).

Notes:

Polar compounds and VOCs with higher mol weight appear at higher end of each boiling-point range.

The EPA use a different definition of VOC for regulatory purposes.

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 normal constant-source levels can take weeks to months, depending on emission rates, surface areas of materials, and ventilation protocols. Renovation 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).

Although 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 wall-board. 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. VanOsdell (1994) reviewed research studies of indoor VOCs as part of ASHRAE research project RP-674, and found more than 300 compounds had been identified indoors and that there was no agreement on a short list of key VOCs.

The large number of VOCs usually found indoors, and the impossibility of identifying all of them in samples, led to the concept of **total VOC (TVOC)**. Some researchers have used TVOC to represent the sum of all detected VOCs. TVOC concentrations are often reported as everything detected in the air by analysis methods such as photoionization detectors (PID) or flame ionization detectors (FID). Therefore, all methods for TVOC determination are intrinsically of low to moderate accuracy because of variations in detector response to different classes of VOCs. Despite the limitations, TVOC can be useful, and is widely used for mixed-contaminant atmospheres. 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 resulting from normal daily activities were estimated to be 2 to 3 times greater than general indoor air concentrations.

Personal activities frequently bring individuals close to air contaminant sources. In addition, exposure from contaminated air jets depends on the complex airflows around the body, including the main flow stream, air turbulence, and obstructions nearby (Rodes et al. 1991). Individual organic compounds seldom exceed 0.05 mg/m³ (50 µg/m³) in indoor air. An upper extreme average concentration of TVOCs in normally occupied houses is approximately 20 mg/m³.

The Large Buildings Study by the U.S. EPA (Brightman et al. 1996) developed the VOC sample target list shown in Table 10 to identify common VOCs that should be measured. Lists of common indoor VOCs prepared by other organizations are similar.

Because chlorofluorocarbons (CFCs) are hydrocarbons with some hydrogen atoms replaced by chlorine 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. Exposure to CFCs and HCFCs occurs mainly through inhalation, and can occur from leaks in refrigeration equipment or during HVAC maintenance.

Volatile organic compounds produced by microorganisms as they grow are referred to as **microbial VOCs (MVOCs)**. Of particular interest are those emitted by fungi contaminating water-damaged buildings. Most MVOCs produced are mixtures of compounds that are common to many different species (as well as to industrial chemicals). However, there are also compounds specific to a particular genus or species. Analysis for MVOCs is generally

Table 10 VOCs Commonly Found in Buildings

Benzene	Styrene
<i>m-, p-xylene</i>	<i>p</i> -dichlorobenzene
1,2,4-trimethylbenzene	<i>n</i> -undecane
<i>n</i> -octane	<i>n</i> -nonane
<i>n</i> -decane	Ethyl acetate
<i>n</i> -dodecane	Dichloromethane
Butyl acetate	1,1,1-trichloroethane
Chloroform	Tetrachloroethylene
Trichloroethylene	Carbon disulfide
Trichlorofluoromethane	Acetone
Dimethyl disulfide	2-butanone
Methyl isobutyl ketone	Methyl tertiary butyl ether
Limonene	Naphthalene
α - β -pinene	4-phenyl cyclohexene
Propane	Butane
2-butoxyethanol	Ethanol
Isopropanol	Phenol
Formaldehyde	Siloxanes
Toluene	

Source: Brightman et al. (1996).

by gas chromatography/mass spectrometry (GC/MS) with thermal desorption.

MVOCs include a variety of chemical classes including alcohols, ketones, organic acids, and heterocyclic compounds, among others. Many have extremely low odor thresholds. Examples in Table 5 include acetone, ethanol, 3-methyl 1-butanol, 2-hexanone, and 3-methyl furan. More information on MVOCs can be found in Horner and Miller (2003).

It is not known whether exposure to MVOCs is likely to cause adverse health effects on its own, because MVOCs are not likely to comprise the sole exposure. However, many are quite objectionable and may be irritating. At the very least, they may indicate a potential mold growth problem in a building, and often cause complaints about air quality. Note that MVOCs are distinct from fungal mycotoxins, which are nonvolatile and therefore nonodorous.

Controlling Exposure to VOCs

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. In most cases, the economically and technically preferred hierarchy for indoor contaminant reduction is (1) source control, (2) dilution with ventilation air, and (3) air filtration. With regard to VOCs, source control includes substitution of alternative products, isolation of contamination sources, and local ventilation. This requires careful planning; specifications; and selection, modification, and treatment of products, as well as special installation procedures and proper ventilation system operation. This chapter provides only a brief survey of contaminant control. Chapter 45 of the 2007 *ASHRAE Handbook—HVAC Applications* provides a full discussion.

Levin (1989, 1991) wrote extensively about designing new buildings for good indoor air quality, with an emphasis on **source control**. Reducing VOC emissions by careful selection and installation of building materials and furnishings is a very 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 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. Prudent practice and administrative control should be used to minimize generation of VOCs in indoor air during occupied hours whenever possible. Consider scheduling use of volatile organic products, housekeeping activities, and pesticide

application when occupant density is lowest. VOC-containing supplies should be stored in well-ventilated areas other than HVAC mechanical rooms or plenums.

Local exhaust ventilation is another source control approach effective for controlling known, unavoidable point emissions sources. It is prudent to isolate office machines (e.g., photocopiers, laser printers), food service equipment (e.g., microwave ovens, coffee makers), and work areas (e.g., graphics and photographic labs) using dedicated local exhaust systems that vent to the outside and away from outdoor air intakes. Eliminating sources of VOCs (or air cleaning at the source) prevents them from becoming a problem.

Ventilation has traditionally been considered the primary means for controlling indoor VOC contaminants. General-ventilation **dilution** is routinely applied in buildings in which major sources are under control and no special measures are required; it is an effective way to control normal constant-emission sources present in buildings, assuming no unusually strong sources and good-quality ventilation air. Compliance with ASHRAE *Standards* 62.1 and 62.2 should satisfy indoor dilution ventilation requirements. Provision for large amounts of outdoor ventilation air affects the size of the heating/cooling system.

Gas-phase air **filtration** has been applied to control industrial gaseous contaminants for many years. 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. ASHRAE *Standard* 62.1 provides a calculation procedure for application of air cleaners to reduce the required outdoor air ventilation rates where such a strategy is economically attractive. Additional information is provided in Chapter 45 of the 2007 *ASHRAE Handbook—HVAC Applications*. Activated carbon and potassium permanganate-impregnated alumina are effective and widely available 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) because of low sorbent mass and inadequate mixing to clean all the air in a room. Photocatalytic reactors are able to destroy VOCs (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.

VOC control in buildings begins before building occupancy. A good ventilation protocol during construction, renovation, or remodeling includes using building ventilation systems to flush the work area with extra outdoor air or setting up a single-pass (100% outdoor air) system during and after these activities, continuing until enough time has passed to lower emitted concentrations to near background. This practice minimizes sink effects and secondary emissions.

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 because of 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* 62.1, a level of 1000 to 1200 ppm (or 700 ppm above outdoor air) has been suggested as being representative of delivery rates of 15 cfm per person of outside air when CO₂ is

measured at equilibrium concentrations and at occupant densities of 10 people per 1000 ft² of floor space. Measuring CO₂ level before it has reached steady-state conditions can lead to inaccurate conclusions about the amount of outside air used in the building.

Carbon monoxide (CO) is an odorless, colorless, and tasteless gas produced by 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. Air containing carbon monoxide may also enter the building directly if the indoor space is at negative pressure relative to outdoors. 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. Carbon monoxide can be a problem in indoor ice skating arenas where gasoline- or propane-powered resurfacing machines are used. 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 CO often produce nitric oxide (NO) and nitrogen dioxide (NO₂), 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 to a home. During cooking, 0.2 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; NO and NO₂ are of most concern.

Sulfur dioxide (SO₂) can result from emissions of kerosene space heaters; combustion of fossil fuels such as coal, heating oil, and gasoline; or burning any material containing sulfur. Thus, sulfur dioxide is a common ambient air pollutant in many urban areas.

Ozone (O₃) 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 electrical or coronal discharges from office equipment, including laser printers and photocopiers. It can also form when ozone-generating devices (often marketed as portable air cleaners and ionizers) are used in the indoor environment (Esswein and Boeniger 1994).

Ammonia (NH₃) is a colorless gas with a sharp and intensely irritating odor. It is lighter than air and readily soluble in water. Ammonia is itself a refrigerant and fertilizer and is also a high-volume industrial chemical used in the manufacture of a wide variety of products (e.g., nitrogen fertilizers, nitric acid, synthetic fibers, explosives, and many others). In nature, ammonia is an animal metabolism byproduct formed by decomposition of uric acid. As an indoor air contaminant, ammonia generally originates in synthetic cleaners and as a metabolic byproduct.

Controlling Exposures to Inorganic Gases

As for VOCs, the three methods of control for inorganic gaseous contaminants are (1) source control, (2) ventilation control, and (3) removal by filters. **Source control** for inorganic gases 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 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. As for VOCs, ASHRAE *Standard* 62.1 provides guidance in applying the ventilation rate and indoor air quality procedures 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 impregnated carbon filters. Coutant et al. (1994), Liu and Huza (1995), Muller and England (1995), and VanOsdell and Sparks (1995) review various filtration procedures.

No single type of media is effective for the broad range of indoor gaseous contaminants. Granular activated charcoal is generally an agent of choice for nonpolar compounds, and is suitable for O₃ and NO₂, but not for SO_x and NO, for which permanganate-impregnated alumina is more appropriate.

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. Using ozone-generating devices for 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. Underground parking garages are normally vented directly to the outdoors, with exhaust fans usually controlled by CO sensors. Local exhaust ventilation is an appropriate and effective control in most occupational cases. For example, automobile repair garages commonly use a tailpipe exhaust extension to control CO exposure of mechanics working in the repair bays. In ice skating rinks, electric or lower-emitting natural-gas-powered resurfacing machines can be used. 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 CO build-up 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%. CO₂ is not encountered at levels harmful to humans in the ambient environment. It is normally present at 300 to 500 ppm, and slightly higher in congested cities. With the exception of an intentional or accidental CO₂ "dump" from a fire suppression system or in a dry ice manufacturing facility, CO₂ is not encountered in significant concentrations that require specific engineering controls. However, CO₂ 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 CO₂ displaces oxygen.

AIR CONTAMINANTS BY SOURCE

Some air contaminants are commonly encountered and addressed as groups or single components originating from a source or having other common characteristics. Outdoor air contaminants, though widely varied between locations, are regulated uniformly across the United States and can usefully be considered as a separate category worthy of common consideration. Radioactive air contaminants also vary widely, but they too have many commonalities. This section addresses the commonalities and characteristics of air contaminants as a function of source or their common characteristics.

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 20 to 200 ton/mi² 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, because they do not accurately represent airborne soot concentrations.

Concentrations of outdoor pollutants are important, because they may determine indoor concentrations in the absence of indoor sources. Table 11 presents typical urban outdoor concentrations of some common 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 identified several important outdoor contaminants as criteria pollutants. The list includes suspended particulate matter, lead particulate matter, ozone, nitrogen dioxide, sulfur dioxide, and carbon monoxide. Standards set for

Table 11 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	Phenol	20
Carbon monoxide	3000	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
<i>n</i> -heptane	29	Trichloroethylene	15
Mercury (vapor)	0.005	Vinyl chloride monomer	0.8
Methane	1100		
Methyl chloride	9	Xylene	10

Sources: Braman and Shelley (1980), Casserly and O'Hara (1987), 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 Stele (1987), Nelson et al. (1987), Sandalls and Penkett (1977), Shah and Singh (1988), Singh et al. (1981), Wallace et al. (1985), and Weschler and Shields (1989).

Table 12 Primary Ambient Air Quality Standards for the United States

Contaminant	Long-Term			Short-Term		
	Concentration $\mu\text{g}/\text{m}^3$	Averaging ppm	Averaging Period	Concentration $\mu\text{g}/\text{m}^3$	Averaging ppm	Averaging Period, h
Sulfur dioxide	80	0.03	1 year ^b	365	0.14	24 ^a
Carbon monoxide				10,000	9	
				40,000	35	8 ^a
						1 ^a
Nitrogen dioxide	100	0.053	1 year ^b			
Ozone ^c				235	0.08	8
Total particulate (PM ₁₀) ^d				150		24
Total particulate (PM _{2.5}) ^e	15		1 year ^b			
Lead particulate	1.5		3 months			

Source: EPA (2008)

^aNot to be exceeded more than once a year

^bAnnual arithmetic mean

^cStandard is met when three-year average of fourth-highest daily maximum 8-h average ozone concentrations measured at each monitor in an area over each year is less than or equal to 0.08 ppm.

^dPM₁₀ = particulates below 10 μm diameter.

^ePM_{2.5} = particulates below 2.5 μm diameter.

these contaminants are shown in Table 12, and levels measured at a large number of locations in the United States are published by the EPA each year (*Code of Federal Regulations* 40CFR50).

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

INDUSTRIAL AIR CONTAMINANTS

Many industrial processes produce significant quantities of air contaminants in the form of dusts, fumes, smokes, mists, vapors, and gases. 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 gaseous contaminants). Control methods are covered in Chapters 28 and 29 of the 2008 *ASHRAE Handbook—HVAC Systems and Equipment* and Chapters 30 and 45 of the 2007 *ASHRAE Handbook—HVAC Applications*.

Reduction of concentrations of all contaminants to the lowest level is not economically feasible. Absolute control of all contaminants cannot be maintained, and workers can assimilate small quantities of various toxic materials without injury. The science of industrial hygiene 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 10.

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 loss of sensory acuity because of 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 working environments such as air traffic control towers and vehicle repair shops. 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, nonindustrial environments has become a widespread concern (NRC 1981; Spengler et al. 1982). 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. Some attempts to relate irritations to gaseous contaminant concentrations are reported (Berglund et al. 1986; Cain et al. 1986; Lamm 1986; Mølhave 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* 62.1 addresses many indoor air quality concerns. Table 13 illustrates sources, levels, and indoor-to-outdoor concentration ratios of several contaminants found in indoor environments. Chapter 10 has further information on indoor health issues.

A knowledge of sources frequently present in different types of buildings can be useful when investigating the causes of SBS. Common nonindustrial indoor sources are discussed in some detail here. Technical advances allow generation rates to be measured for several of these sources. These rates are necessary inputs for design of control equipment; full details are given in Chapter 45 of the 2007 *ASHRAE Handbook—HVAC 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 emit mercury vapor. Although emission rates for these materials decline steadily with age, the half-life of emissions is surprisingly long. Black and Bayer (1986), Mølhave et al. (1982), and Nelms et al. (1986) report on these sources.

Ventilation systems may be a source of VOCs (Mølhave 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 [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.

Table 13 Sources, Possible Concentrations, and Indoor-to-Outdoor Concentration Ratios of Some Indoor Contaminants

Pollutant	Sources of Indoor Pollution	Upper Possible Indoor Concentration*	I/O Concentration Ratio for Upper Concentration	Location
Carbon monoxide	Combustion equipment, engines, faulty heating systems	100 mg/m ³	>>1	Indoor ice rinks, homes, cars, vehicle repair shops, parking garages
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, cleaning products	NA	>1	Homes, restaurants, public facilities, offices, hospitals
Nitrogen dioxide	Combustion, gas stoves, water heaters, gas-fired dryers, cigarettes, engines	200 to 1000 µg/m ³	>>1	Homes, indoor ice rinks
Sulfur dioxide	Heating system	20 µg/m ³	<1	Mechanical/furnace rooms
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	Mechanical/furnace rooms
Formaldehyde	Insulation, product binders, pressed wood products	2 mg/m ³ (2000 µg/m ³)	>>1	Homes, schools, offices
Radon and progeny	Building materials, groundwater, soil	0.1 to 100 nCi/m ³	>>1	Homes, schools
Asbestos	Fireproofing	<10 ⁶ fiber/m ³	1	Homes, schools, offices
Mineral and synthetic fibers	Carpets, clothes, rugs, furnishing materials, wallboard	NA	—	Homes, schools, offices
Carbon dioxide	Combustion appliances, humans, pets	9000 mg/m ³	>>1	Homes, schools, offices, hospitals, public facilities
Viable organisms	Humans, pets, rodents, insects, plants, fungi, humidifiers, air conditioners	NA	>1	Homes, hospitals, schools, offices, public facilities
Ozone	Electric arcing, electronic air cleaners, some copiers, and printers, some UV light sources	400 µg/m ³	<1	Airplanes
			>1	Offices, homes

Source: NRC (1981).

*Concentrations 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.

Equipment sources in commercial and residential spaces have generation rates that are usually substantially lower than in the industrial environment. Because 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); and 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. Black and Bayer (1986), Knoepfel and Schauenburg (1989), 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 (smoke from the lit end of a cigarette and smoke that escapes

from the filter between puffs) and mainstream smoke (smoke exhaled by a smoker). Emission factors for ETS components, 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. (1997), 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 typically contains much larger particles and fibers than 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 ppm TVOC, and the particle portion 148 ppm (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 250°F (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

Use of flammable materials is widespread. Flammable gases and vapors (as defined in NFPA *Standard 30*) 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 flammable 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- 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 higher than 100°F are called **combustible**, whereas those under 100°F are described as **flammable**. Those with flash points less than 70°F 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 flammable (explosive) range before it can be ignited. The **flammable (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. Flashpoint and explosive range data for many chemicals are listed in the *Fire Protection Guide to Hazardous Materials*, published by the National Fire Protection Association (NFPA 2002). Data for a small number of representative chemicals are shown in Table 14.

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 allowed only in rare instances, and after taking appropriate precautions. Some guidance is provided in American Petroleum Institute documents. 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 caused by unforeseen 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 maximum allowable

concentrations are far below the material's lower explosive limit (LEL). For example, proper ventilation for acetone vapors keeps the concentration below the occupational exposure limit of 500 ppm (0.05% by volume). Acetone's LEL 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 hazardous material, preferably at its source, or offset the effects of drafts, equipment movement, and convection currents 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 2007 *ASHRAE Handbook—HVAC Applications* gives more details about equipment for control of combustible materials. Some design, construction, and ventilation issues are also addressed by NFPA *Standard 30*.

COMBUSTIBLE DUSTS

Many organic and some mineral dusts can produce dust explosions (Bartnecht 1989). Explosive dusts are potential hazards whenever uncontrolled dust escapes, and often, a primary explosion results from a small amount of dust in suspension that has been exposed to a source of ignition. Explosibility limits for combustible dusts differ from those for flammable gases and flammable vapors because of the interaction between dust layers and suspended dust. In addition, the pressure and vibration created by an explosion 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). Several methods can be used to prevent the ignition of dust material (Jaeger and Siwek 1999; Siwek 1997):

- Limit the temperature of deposited product.
- Avoid potentially explosive combustible substance/air mixtures.
- Introduce inert gas in the area to lower the oxygen volume content below the limiting oxygen concentration (LOC) or maximum allowable oxygen concentration (MOC), so that ignition of the mixture can no longer take place. Adding inert dusts (e.g., rock salt, sodium sulfate) also works; in general, inert dust additions of more than 50% by weight are necessary. It is also possible to replace flammable solvents and cleaning agents with nonflammable halogenated hydrocarbons or water, or flammable pressure transmission fluids with halocarbon oils.
- Avoid effective ignition sources: eliminate hot sources (hot surfaces or smoldering material) and sources of sparks or electrostatic discharge.

Proper exhaust ventilation design can also be used for preventing high-dust conditions. Forced ventilation allows use of greater amounts of air and selective air circulation in areas surrounding the equipment. Its use and calculation of the minimum volume flow rate for supply and exhaust air are subject to certain requirements, covered in Chapter 30 of the 2007 *ASHRAE Handbook—HVAC Applications*. Ventilation systems and equipment chosen must prevent dust pocketing inside the equipment. When local exhaust ventilation is used, separation equipment should be installed as close to the

Table 14 Flammable Limits of Some Gases and Vapors

Gas or Vapor	Flash Point, °F	Flammable Limits, % by Volume	
		Lower	Upper
Acetone	1	2.5	12.8
Ammonia	Gas	15	28
Benzene (benzol)	12	1.2	7.8
<i>n</i> -Butane	-26	1.9	8.5
Carbon disulfide	-22	1.3	50
Carbon monoxide	Gas	12.5	74
1,2-Dichloroethylene	36	5.6	12.8
Diethylether	-49	1.9	36
Ethyl alcohol	55	3.3	19
Ethylene	Gas	2.7	36
Gasoline	-45	1.4	7.6
Hydrogen	Gas	4.0	75
Hydrogen sulfide	Gas	4.3	44
Isopropyl alcohol	53	2.0	12.7
Methyl alcohol	52	6.0	36
Methyl ethyl ketone	16	1.4	11.4
Natural gas (variable)	Gas	3.8 to 6.5	13 to 17
Naphtha	Less than 0	1.1	5.9
Propane	Gas	2.1	9.5
Toluene (toluol)	40	0.1	7.1
<i>o</i> -Xylene	90	0.9	6.7

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. 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. Penetration of gamma rays depends on their energy, which varies from one type of radioactive element or isotope to another. 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 can penetrate 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), and the dose of radiation from deposited material is measured in rads.

Radioactive materials present distinctive problems. 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 some 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.

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 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 radioactive decay of radium, which is formed through several intermediate steps of decay of uranium and thorium. Radon is widely found in the natural environment, because 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 cracks, joints, and other holes in concrete foundations; directly through porous concrete blocks; through joints and openings in crawlspace ceilings; and through leakage points in HVAC ductwork embedded in slab floors or located in crawlspaces. 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 thermal stack effect, wind, and operation of HVAC equipment. 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 long-term measurement is necessary. When interpreting results, consider 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.

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/m^3 (0.4 pCi/L). The annual average concentration of radon in U.S. homes is about 46 Bq/m^3 (1.25 pCi/L) (EPA 1989). Although several sources of radon may contribute to the annual indoor average, pressure-driven flow of soil gas is 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, their performance is not well characterized, and average reductions in Rn concentrations may be 50% or less. Sealing cracks and joints in slab floors improves performance of subslab depressurization systems. Sealing by itself is often not very effective in reducing indoor Rn.

In houses with crawlspaces, active (fan-forced) or passive crawlspace 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, but other gaseous contaminants may enter buildings along with radon from surrounding soil. Methane from landfills has reached explosive levels in some buildings. Potentially toxic or carcinogenic VOCs, including chlorinated hydrocarbons in the soil because of spills, improper disposal, leaks from storage tanks, and disposal in landfills, can also be transported into buildings (Garbesi and Sextro 1989; Hodgson et al. 1992; Kullman and Hill 1990; Wood and Porter 1987). Pesticides applied to soil beneath or adjacent to houses have also been detected in indoor air (Livingston and Jones 1981; Wright and Leidy 1982). The broad significance of health effects of exposure to these soil contaminants is not well understood.

Although soil gases generally have limited effects when diffusion is the primary mechanism driving entry, there are situations where advective processes are dominant. In such cases, effects on indoor air can be significant (Adomait and Fugler 1997). Pressure-driven airflow produced by thermal or wind drivers on the building affects entry of soil gas into the structure. Soil permeability to vapors, soil gas concentration, and soil-to-building pressure differential are the largest factors influencing indoor concentrations of these gases.

Techniques that reduce Rn entry from soil should also be effective in reducing entry of other soil gases into buildings. Other approaches (e.g., increasing ventilation in the building, such as by slightly opening a window) may help reduce house negative pressure (created by stack effect) with respect to soil gas pressure. Increased ventilation should be used with caution, and only after establishing for the house in question that it will not increase negative pressure where the soil gas enters.

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