1

Introduction

The microscopic particles that float in the air are of many kinds: resuspended soil particles, smoke from power generation, photochemically formed particles, salt particles formed from ocean spray, and atmospheric clouds of water droplets or ice particles. They vary greatly in their ability to affect not only visibility and climate, but also our health and quality of life. These airborne particles are all examples of *aerosols*. An aerosol is defined in its simplest form as a collection of solid or liquid particles suspended in a gas. Aerosols are two-phase systems, consisting of the particles and the gas in which they are suspended. They include a wide range of phenomena such as dust, fume, smoke, mist, fog, haze, clouds, and smog. The word *aerosol* was coined in about 1920 as an analog to the term *hydrosol*, a stable liquid suspension of solid particles. Although the word *aerosol* is popularly used to refer to pressurized spray-can products, it is the universally accepted scientific term for particulate suspensions in a gaseous medium and is used in that sense in this book.

Aerosols (first data row of Table 1.1) are one of the several types of particulate suspensions listed in Table 1.1. All are two-component systems having special properties that depend on size of the particles and their concentration in the suspending medium. All have varying degrees of stability that also depend on particle size and concentration.

An understanding of the properties of aerosols is of great practical importance. It enables us to comprehend the process of cloud formation in the atmosphere, a key link in the hydrological cycle. Aerosol properties influence the production, transport, and ultimate fate of atmospheric particulate pollutants. Measurement and control of particulate pollutants in the occupational and general environments require the application of this knowledge. Aerosol technology has commercial application in the manufacture of spray-dried products, fiber optics, and carbon black; the production of pigments; and the application of pesticides. Because the toxicity of inhaled particles depends on their physical as well as their chemical properties, an understanding of the properties of aerosols is required to evaluate airborne particulate hazards. The same knowledge is used in the administration of therapeutic aerosols for the treatment of respiratory and other diseases.

Aerosol technology is the study of the properties, behavior, and physical principles of aerosols and the application of this knowledge to their measurement and control. The particulate phase of an aerosol represents only a very small fraction of its total mass and volume, less than 0.0001%. Bulk properties of aerosols, such as viscosity and density, differ imperceptibly from those of pure air. Consequently, to study the properties of aerosols, one must adopt a *microscopic point of view*. This reduces the problem of understanding the complex properties of aerosols to that of understanding the properties of individual particles. The microscopic approach considers one particle at a time and deals with questions about the forces on that particle, its motion, and its interaction with the suspending gas, with electromagnetic radiation, and with other particles.

Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles, Third Edition.
William C. Hinds and Yifang Zhu.

Table 1.1 Types of Particulate Suspensions.

	Type of Suspended Particles		
Suspending Medium	**Gas**	**Liquid**	**Solid**
Gas	—	Fog, mist, spray	Fume, dust
Liquid	Foam	Emulsion	Colloid, suspension, slurry
Solid	Sponge	Gel	Alloy

At the beginning of the 20th century, the study of aerosols was at the forefront of physical science because aerosols represented the smallest observable division of matter. Aerosol science contributed to the early understanding of Brownian motion and diffusion, Millikan's measurement of the charge on the electron, and Wilson's cloud chamber experiments for the study of ionizing radiation. This classical period of aerosol science research continued through the first half of the century, concluding with the publication of *The Mechanics of Aerosols* by Fuchs in 1955. Following World War II, and particularly during the 1970s and 1980s, aerosol technology grew in importance because of an increased environmental awareness and a concern for the health effects arising from air pollution in community and occupational environments. The field expanded rapidly in the 1980s to include the use of aerosols in high-technology production processes and a concern for aerosol contamination in the semiconductor industry (clean technology). The decade of the 1990s has seen increased research on the properties of ultrafine particles (<0.1 μm) and on the effect of aerosols on global climate. Aerosol technology has become an important tool in understanding the effect we have on our environment and the impact of that environment on us. In the 2000s and 2010s, substantial new research has been carried out on organic aerosols, engineered nanoparticles, and remote sensing of aerosols.

Any subject that touches upon such diverse phenomena as sunsets, silicosis, rain, cascade impactors, global climate change, cross pollination, electrostatic precipitation, and rainbows is not a simple one. Aerosol technology draws on physics, chemistry, physical chemistry, and engineering. It uses some tools, concepts, and terminology of powder technology. It is used in the fields of occupational hygiene, air pollution control, inhalation toxicology, atmospheric physics and chemistry, and radiological health.

A dual system of units is used in this book, with the primary system being the the International System of Units (SI units, or meter-kilogram-second units). Because of a tradition of using cgs (centimeter-gram-second) units in this field, especially in the United States, cgs units are included in square brackets, and some equations and most examples are presented both ways.

Figures 1.1–1.5 show sources of aerosols paired with microscope photographs of the particles produced. They illustrate the range of aerosol-producing activities and the sometimes complex nature of the resulting particles.

1.1 Definitions

Aerosols can be subdivided according to the physical form of the particles and their method of generation. There is no strict scientific classification of aerosols. The following definitions correspond roughly to common usage and are precise enough for most scientific description.

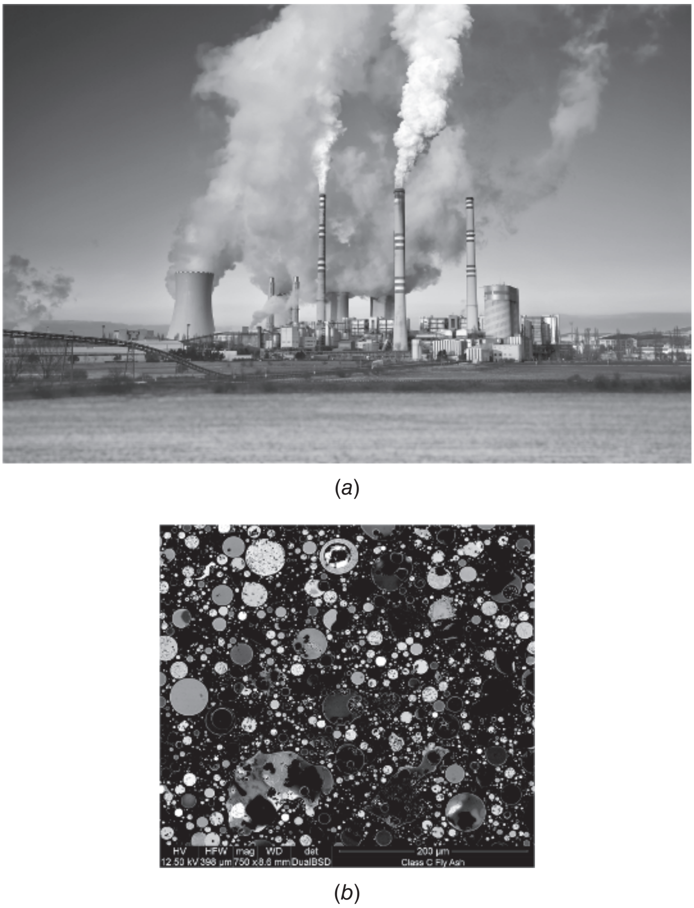

Figure 1.1 (*a*) Coal-burning power plant. (*b*) Scanning electron microscope (SEM) photograph of coal fly ash particles. (*a*) Source: kamilpetran/Adobe Stock: (*b*) Source: wabeggs/Wikimedia Commons.

Aerosol A suspension of solid or liquid particles in a gas. Aerosols are usually stable for at least a few seconds and in some cases may last a year or more. The term *aerosol* includes both the particles and the suspending gas, which is usually air. Particle size ranges from about 0.002 to more than 100 µm.

Bioaerosol An aerosol of biological origin. Bioaerosols include viruses, viable organisms, such as bacteria and fungi, and products of organisms, such as fungal spores and pollen.

Cloud A visible aerosol with defined boundaries.

Dust A solid-particle aerosol formed by mechanical disintegration of a parent material, such as by crushing or grinding. Particles range in size from submicrometer to more than 100 µm and are usually irregular.

Fume A solid-particle aerosol produced by the condensation of vapors or gaseous combustion products. These submicrometer particles are often clusters or chains of primary particles. The latter are usually less than 0.05 µm. Note that this definition differs from the popular use of the term to refer to any noxious contaminant in the atmosphere.

Haze An atmospheric aerosol that affects visibility.

Mist and Fog Liquid-particle aerosols formed by condensation or atomization. Particles are spherical with sizes ranging from submicrometer to about 200 µm.

(*a*)

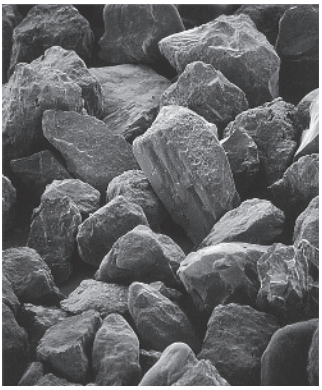

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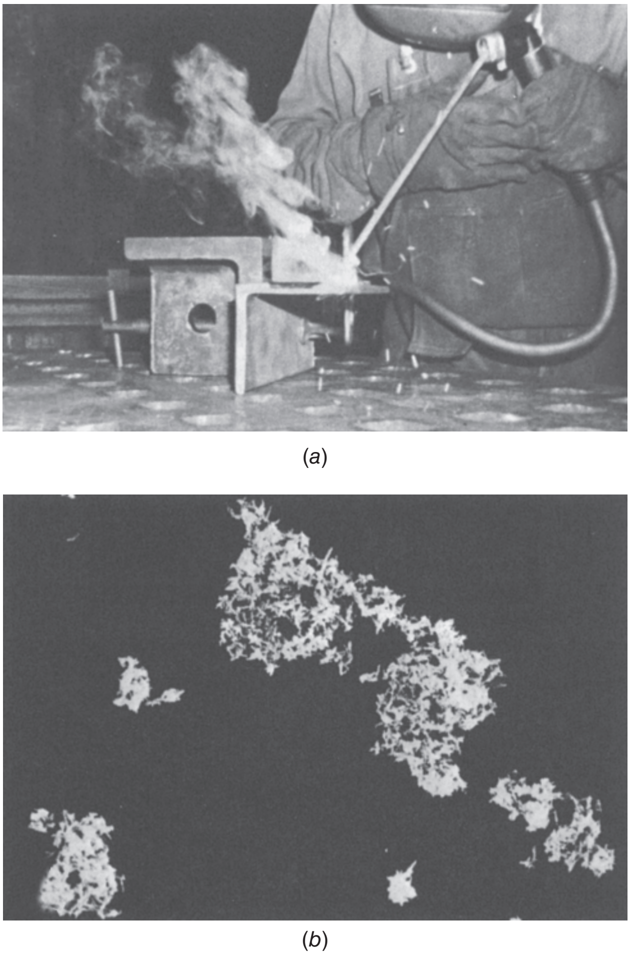
Figure 1.2 (*a*) Granite cutting. (*b*) SEM photograph of quartz particles. Magnification 2650×. (*a*) Source: kalpis/Adobe Stock. (*b*) Source: Susumu Nishinaga/Science Source.

Smog 1. A general term for visible atmospheric pollution in certain areas. The term was originally derived from the words *smoke* and *fog*. 2. *Photochemical smog* is a more precise term referring to an aerosol formed in the atmosphere by the action of sunlight on hydrocarbons and oxides of nitrogen. Particles are generally less than 1 or 2 μm.

Smoke A visible aerosol resulting from incomplete combustion. Particles may be solid or liquid, are usually less than 1 μm in diameter, and may be agglomerated like fume particles.

Spray A droplet aerosol formed by the mechanical breakup of a liquid. Particles are larger than a few micrometers.

In this book the preceding distinctions are usually not necessary, and the general term *aerosol* is used. Liquid particles are referred to as *droplets*. The term *particulate matter* refers to either solid particles or liquid droplets. A *primary aerosol* has particles that are introduced directly into



(*a*)

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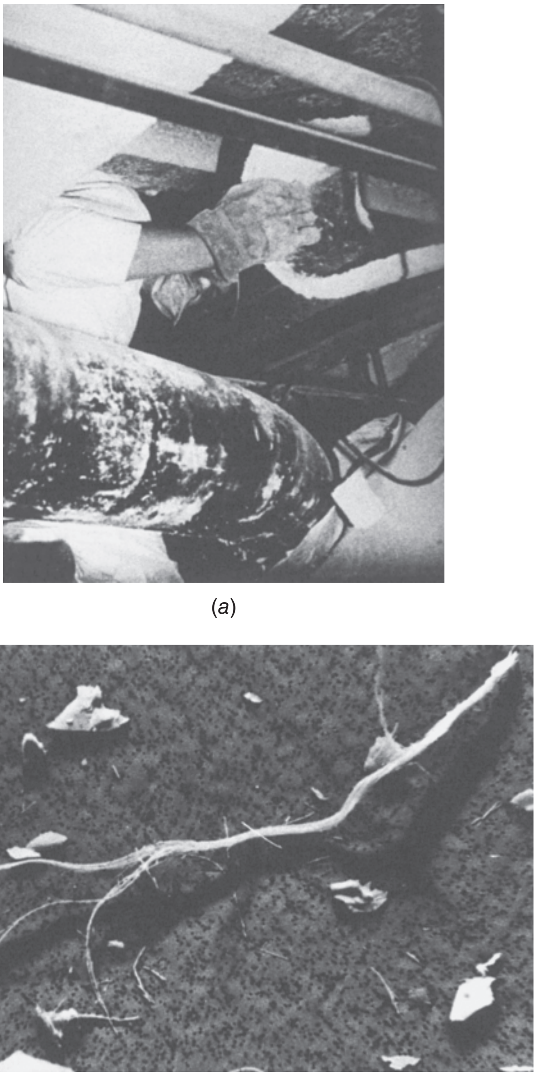
Figure 1.3 (*a*) Arc welding. (*b*) SEM photograph of iron-oxide particles. Magnification 2300×.

the atmosphere, whereas a *secondary aerosol* has particles that are formed in the atmosphere by chemical reactions of gaseous components (gas-to-particle conversion). A *homogenous aerosol* is an aerosol in which all particles are chemically identical. *Monodisperse aerosols* have particles that are all the same size and can be produced in the laboratory for use as test aerosols. Most aerosols are *polydisperse,* with a wide range of particle sizes, and statistical measures should be used to characterize their particle size.

In this text, *standard conditions* are defined as a temperature of 293 K [20°C] and an atmospheric pressure of 101 kPa (1Pa = 1N/m^2) [760 mm Hg].

1.2 Particle Size, Shape, and Density

Particle size is the most important parameter for characterizing the behavior of aerosols. All properties of aerosols depend on particle size, some very strongly. Furthermore, most aerosols cover a wide range of sizes; a hundredfold range between the smallest and largest particles of an aerosol is common. Not only do aerosol properties depend on particle size, but the nature of



(*a*)

(*b*)

Figure 1.4 (*a*) Removal of asbestos pipe covering. (*b*) SEM photograph of asbestos fibers. Magnification 1250×.

the laws governing these properties may change with particle size. This emphasizes the need to adopt a microscopic approach and characterize properties on an individual particle basis. Average properties can then be estimated by integrating over the size distribution. An appreciation of how aerosol properties vary with particle size is fundamental to an understanding of their properties.

The "base unit" for particle size is the micrometer (μm) or its older equivalent, the micron (μ), which is 10^{-6} m, 10^{-4} cm, or 10^{-3} mm. The micron is no longer acceptable as an SI unit. Particle size can refer to particle radius, but in this book it refers to particle diameter. For consistency it is expressed in micrometers for all particle sizes, even though nm is more appropriate for particles less than 0.1 μm. Particle diameter is given the symbol d or, where confusion with other symbols might arise, the symbol d_p. It is customary to refer to particle size in micrometers, but calculations

(*a*)

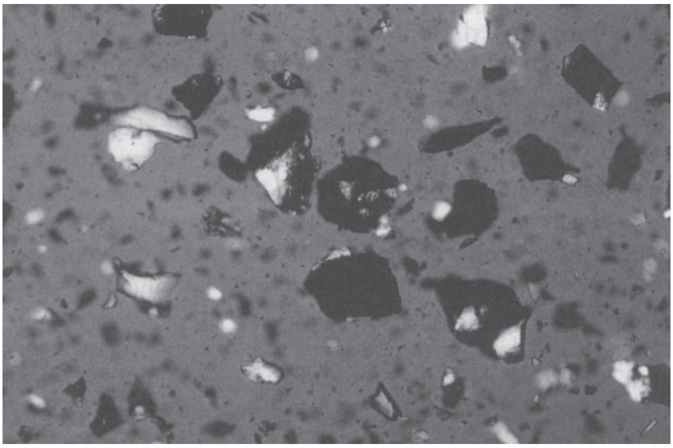


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Figure 1.5 (a) Volcanic eruption of Mount St. Helens, May 1980. (b) Optical microscope photograph of volcanic ash. Magnification 125×. Source: USGS photograph by Austin Post. Reprinted from *Mount St. Helens: Five Years Later*. Courtesy of Eastern Washington University Press and W. C. McCrone and J. G. Delly, *The Particle Atlas*. Reprinted by permission from McCrone Research Institute.

require converting micrometers to meters (SI units) by multiplying by 10^{-6} or to centimeters (cgs units) by multiplying by 10^{-4}.

Figure 1.6 shows size ranges for aerosols and other phenomena. A major dividing line is 1 μm, which marks the upper limit of the submicrometer range (less than 1.0 μm) and the lower limit of the micrometer size range (1–10 μm). Figure 1.6 covers a size range of 10^7, from gas molecules to millimeter-sized particles. The particle sizes of the aerosols shown in the figure range from 0.01 to

100 µm, the size range addressed in this book. In general, dusts, ground material, and pollen are in the micrometer range or larger, and fumes and smokes are submicrometer. The smallest aerosol particles approach the size of large gas molecules and have many of their properties. Ultrafine particles cover the range from large gas molecules to about 100 nm (0.001 to 0.1 µm). Particles less than 50 nm are called nanometer particles or nanoparticles. Particles greater than 10 µm have limited stability in the atmosphere, but still can be an important source of occupational exposure because of a worker's proximity to the source. The largest aerosol particles are visible grains that have properties described by the familiar Newtonian physics of baseballs and automobiles. The dot over the letter *i* has a diameter of about 400 µm, and the smallest grains of flour that one can see under normal conditions are 50–100 µm. The finest wire mesh sieves have openings of about 20 µm. The wavelength of visible light is in the submicrometer size range, about 0.5 µm.

Example What is the ratio of the volume of a 10-µm spherical particle to that of a 0.1-µm particle?

$$\text{Volume} = \frac{\pi d^3}{6}$$

$$\text{Ratio} = \frac{(\pi/6)d_{10}^3}{(\pi/6)d_{0.1}^3} = \left(\frac{d_{10}}{d_{0.1}}\right)^3 = \left(\frac{10}{0.1}\right)^3 = 10^6$$

Liquid aerosol particles are nearly always spherical. Solid aerosol particles usually have complex shapes, as shown in Figs. 1.1–1.5. In the development of the theory of aerosol properties, it is usually necessary to assume that the particles are spherical. Correction factors and the use of equivalent diameters enable these theories to be applied to nonspherical particles. An *equivalent diameter* is the diameter of the sphere that has the same value of a particular physical property as that of an irregular particle. For approximate analysis, shape can usually be ignored, as it seldom produces more than a twofold change in any property. Particles with extreme shapes, such as long, thin fibers, are treated as simplified nonspherical shapes in different orientations. The complex shape of some fume and smoke particles can be characterized by their fractal dimension. (See Section 20.2.)

The remaining physical property of interest is *particle density*, usually expressed in kg/m^3 [g/cm^3]. Particle density refers to the mass per unit volume of the particle itself, not of the aerosol (the "density" of which is called concentration, as described in the next section). Liquid particles and crushed or ground solid particles have a density equal to that of their parent material. Smoke and fume particles may have apparent densities significantly less than that predicted from their chemical composition. This is a result of the large amount of void space in their highly agglomerated structure, which may resemble a cluster of grapes. In this book, particles are assumed to have *standard density* ρ_0—that is, the density of water, 1000 kg/m^3 [1.0 g/cm^3]—unless specified otherwise.

1.3 Aerosol Concentration

The most commonly measured aerosol property, and the most common one for health and environmental effects, is the *mass concentration,* the mass of particulate matter in a unit volume of aerosol. Common units are g/m^3, mg/m^3, and µg/m^3. The mass concentration is equivalent to the density of the ensemble of aerosol particles in air; however, the latter term is not used because of possible confusion with particle density.

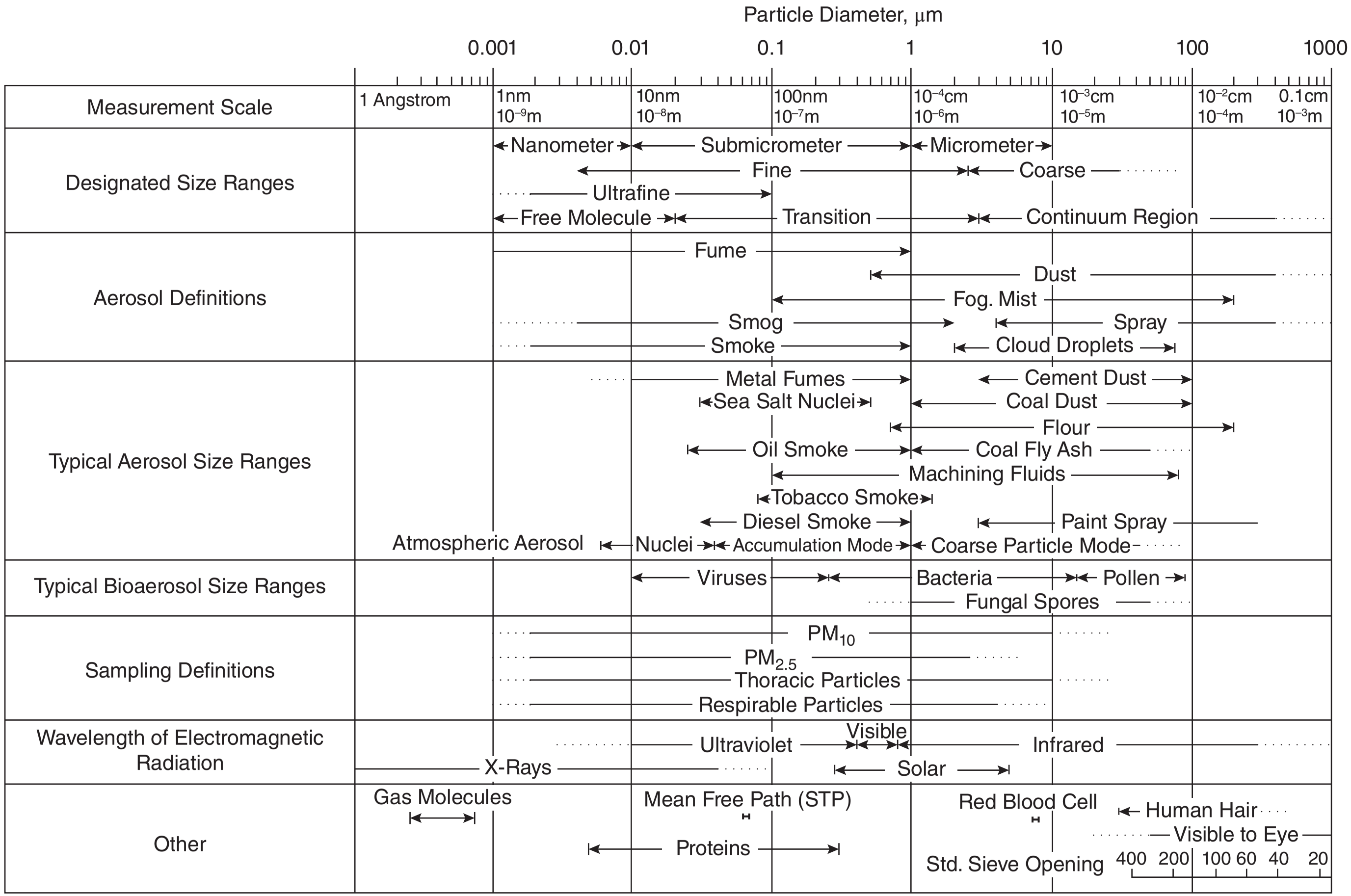

Figure 1.6 Particle size ranges and definitions for aerosols.

Table 1.2 Examples of Mass Concentration Expressed in Parts per Million[a].

	Mass Concentration, Mass/Volume (mg/m^3)	Parts per Million, Volume/Volume (ppm)	Parts per Million, Mass/Mass (ppm)
U.S. PM$_{2.5}$ annual standard	0.012	1.2×10^{-5}	9.6×10^{-3}
Threshold limit value for nuisance dusts			
(Particulates not otherwise classified)	10	0.01	8
Uncontrolled stack effluent (typical)	10,000	10	8,000

a) Standard-density spheres.

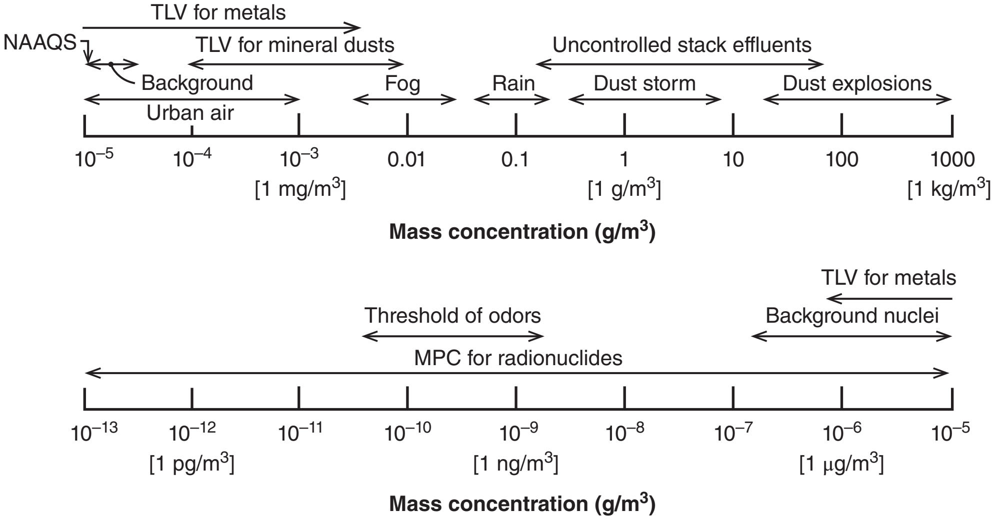

Figure 1.7 Range of aerosol concentrations (NAAQS=National Ambient Air Quality Standards, TLV=Threshold Limit Values, MPC=Maximum Permissible Concentration).

Another common measure of concentration is *number concentration*, the number of particles per unit volume of aerosol, commonly expressed as number/cm^3 or number/m^3. An older unit is mppcf (million particles per cubic foot). Concentrations of ultrafine particles, bioaerosols, and fibers are expressed in terms of number concentration.

Unlike the situation with gaseous contaminants, volume ratio or mass ratio in parts per million (ppm) is not used for aerosols, because two phases are involved and aerosol concentrations are numerically very low when expressed in this way. It is informative, however, to make such calculations for some standard concentrations, as shown in Table 1.2. Note that, on a volume basis, a dense combustion plume is 99.999% pure air.

Figure 1.7 shows the extremely wide range (from 10^{-13} to 10^3 g/m^3) of aerosol concentrations that one encounters in practice.

If you have not already done so, now is a good time to read the preface, which contains important information about this book and how to use it.

Problems

1.1 How many 1.0-μm-diameter particles are required per cubic centimeter of aerosol for the mass concentration to be 10 mg/m^3? Assume that the particle density is 1000 kg/m^3 [1 g/cm^3].
ANSWER: 19,100/cm^3.

1.2 In smoking one nonfilter cigarette, a person inhales 350 mL of aerosol containing 20 mg of tobacco smoke particles. If these particles are standard-density spheres 0.4 μm in diameter, how many particles does the smoker inhale from one cigarette? What is the mass concentration of the smoke? Make a ratio comparison of this smoke concentration to the U.S. PM$_{2.5}$ standard (primary annual mean) of 12 μg/m^3.
ANSWER: 6.0×10^{11}, 0.057 kg/m^3 [57 g/m^3], 4.8×10^6.

1.3 How many molecules are in a 0.1-μm diameter water droplet?
ANSWER: 1.8×10^7.

1.4 By what factor does the total surface area of a 5-cm-diameter sphere of coal increase on being dispersed into 0.1-μm-diameter spheres?
ANSWER: 5×10^5.

1.5 A person inhales approximately 20 mg of tobacco smoke particles from one cigarette. If smoke particles are standard-density spheres 0.4 μm in diameter, what is the surface area of this amount of smoke?
ANSWER: 0.30 m^2 [3000 cm^2].

1.6 How many particles would be present in a cubic meter of aerosol at the concentration of the U.S. PM$_{2.5}$ standard of 12 μg/m^3 if the particles are (a) 0.1 μm, (b) 1.0 μm, and (c) 10 μm in diameter? Assume standard density.
ANSWER: (a) 2.3×10^{10}, (b) 2.3×10^7, (c) 2.3×10^4.

1.7 If aerosol particles were considered to be extremely large gas molecules, what would be the gram molecular weight of a "gas" of 1.0-μm particles having a density of 1000 kg/m^3?
ANSWER: 3.2×10^{11} g/mole.

1.8 Derive an expression for the surface area per kilogram of material as a function of particle size. Assume that the material is divided into spheres, each having a diameter d and a density $\rho = 1000$ kg/m^3 [1.0 g/cm^3]. What is the surface area of 1 g of 0.1-μm-diameter particles?
ANSWER: 60 m^2.

1.9 Determine the ratio of the surface area of a sphere to that of a fiber with the same volume. Assume that the fiber is a cylinder with a diameter equal to 20% of the diameter of the sphere. Assume that the sphere and the fiber have standard density.
ANSWER: 0.3.

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Aerosol Science and Engineering, Springer, China.
Journal of Aerosol Science, Elsevier, Exeter, U.K.