General Considerations for Respiratory and Ventilation Protection against Airborne Weapons of Mass Destruction

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Chapter 23

General Considerations for Respiratory and Ventilation Protection Against Airborne Weapons of Mass Destruction

Herman Cember and Mark D. Hoover

Introduction

This chapter summarizes general considerations for respiratory and ventilation protection against airborne weapons of mass destruction (WMD), including protection from chemical, biological, and radiological (CBR) agents. Concerns for dispersion of toxic industrial materials (TIMs) by terrorists are also discussed. Information from a number of important guidance documents on respiratory and ventilation protection is excerpted and summarized in a companion chapter (Hoover and Cember 2004).

General Mechanisms for Dispersion of CBR Agents

General mechanisms for dispersion of CBR agents into the air, into ventilation systems, onto and between surfaces, and into the breathing zones of people are illustrated in Fig. 23.1. A major purpose for dispersing a CBR agent is to terrorize a population and cause severe social and economic disruptions because of the perceived and real consequences of
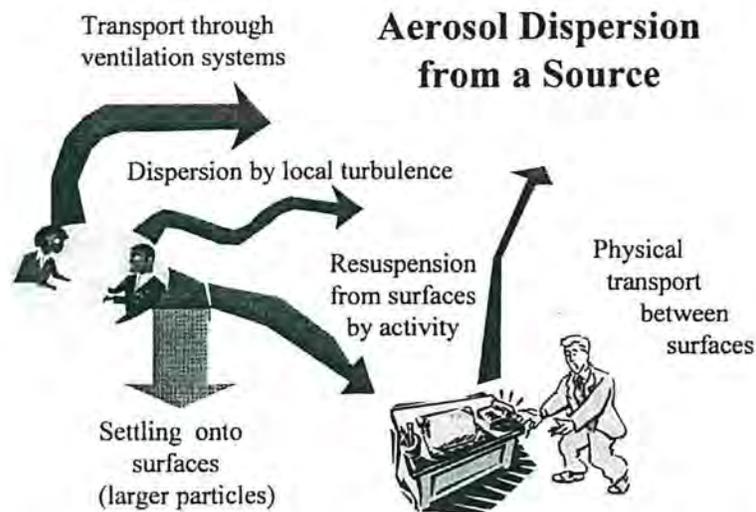

Fig. 23.1. Illustration of the mechanisms of aerosol dispersion from a source within or into an indoor environment.

human exposure to the agent. CBR material and method of release determine the particle size and dispersion of the agent. Near the source of release for an agent, or in the early phase of a release, large particles can comprise a significant component of the airborne concentration. Farther from the source, or at later time periods, larger particles may have already settled by gravitational forces and the remaining aerosol may have a significantly smaller size distribution. Resuspension of particles from surfaces may be important at the onset of an event if contaminated surfaces are the source of the agent. Resuspension may become important at later times if surfaces have become contaminated during the event. Resuspension is generally an inefficient process. Ratios of the concentration of particles on an extensive surface (amount per square meter) to the concentration of particles in the air above the surface (amount per cubic meter) can be in the range of 10^{-4} to 10^{-6}, depending on the diameter of the particles, the elapsed time since their initial deposition, the nature and moisture content of the surface, and the amount of energy applied (see, for example, DOE 1994). In the case of highly pathogenic biological materials such as anthrax or highly radioactive materials such as ^{238}Pu, even low rates of resuspension can result in airborne concentrations of health significance (see, for example, Scott et al. 1997; Scott and Fencl 1999). If the mass of individual particles or spores is on the order of picograms, then billions of particles are associated with milligrams of mass. If individuals must be protected from inhaling only a few particles, then airborne concentrations must be kept low or respiratory protection must be highly efficient.

Physical Forms of CBR Agents

Consistent with general aerosol principles, CBR agents can be in the form of dusts, fumes, mists, smokes, vapors, gases, or combinations of these forms.

Dusts

Dusts are solid particles produced by mechanical disintegration of large lumps or dispersion of previously pulverized material. The particle diameter range of atmospheric dusts is usually relatively large, approximately 0.1 μm to 20 μm. Particles with diameters greater than 50 μm have high gravitational settling velocities and are called "inertials." Airborne dusts from explosion or collapse of buildings may contain asbestos, silica, or other materials of health concern. Anthrax spores can be dispersed as dusts ranging in size from individual spores to large clumps, or as mixtures of spores with other materials. Radioactive particles have the basic properties of nonradioactive dusts (Hoover and Newton 2001) and can be dispersed by explosive or nonexplosive radiological dispersal devices (RDDs), improvised nuclear devices (INDs), damage to nuclear power or other facilities containing radioactive materials, or by nuclear weapons.

Fumes

Fumes are released when solid materials undergo a change of state by sublimation or evaporation, followed by condensation. Most condensation/evaporation processes produce relatively small particles. Fumes range in size from approximately 0.01 μm to 0.1 μm. The degree of fuming increases with temperature. Chemical reactions may be involved. For example:

$$Pb \text{ (metal)} \rightarrow Pb \text{ (vapor) and}$$
$$2Pb \text{ (vapor)} + O_2 \rightarrow 2PbO \text{ (fume)}$$
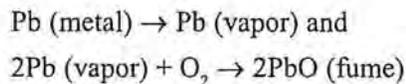
Smokes

Smokes are airborne combustion products of any size. Terrorist attacks can result in releases of smoke from combustion of buildings, airplanes, trains, or other structures or vehicles and their contents. Burning plastics can release toxic and corrosive smoke, as well as gases and vapors. Chemical smoke agents are used as military obscurants and can also be used by terrorists. Some solids and liquids are specially formulated to release chemical smokes as CBR agents.

Mists

Mists are liquids dispersed in air as droplets of any size. Dispersion can be by splashing, spraying, or by nebulization from special devices. Dispersion of liquids can result in exposure to the droplets themselves, to dusts from drying of solids that were dissolved or suspended in the droplets, or to vapors that evaporate from the droplets.

Vapors

Vapors from evaporation of liquid materials can exist at concentrations up to their saturation vapor pressure at the prevailing temperature. Supersaturated vapors typically condense to form a liquid particle aerosol or fog. Some agents such as hydrogen cyanide and sarin are relatively volatile and vaporize quickly at room temperature. Others such as VX have a low vapor pressure and persist for long periods as liquids. Some vapors have higher specific gravity than air and concentrate near the floor or ground. The volatilities of chemical warfare agents cover a very large range. For example, the approximate amount of agent that can be held in air (mg/m^3) at 25°C is 1,000,000 for hydrogen cyanide, 22,000 for sarin (GB), 3,900 for soman (GD), 900 for sulfur mustard, 610 for tabun (GA), and 10 for VX

(Takfuji and Kok 1997). Some vapors, such as sarin, have higher density than air and concentrate near the floor or gound.

Gases

Although most CBR agents are encountered in solid, liquid, or vapor form, some such as chlorine are a gas a room temperature. Hydrogen cyanide will also be a gas in many situations because its boiling point is only 26°C.Radioactive gases include radon, argon, iodine, and ruthenium tetroxide.

Classes and Actions of CBR Agents

In addition to having a range of physical characteristics, CBR agents have a range of health impacts (e.g., Sidell et al. 1997; Ellison 2000a,b; Transport Canada 2000):

- *Nerve agents* such as sarin (agent GB), soman (agent GD), tabun (agent GA), and V-gas (agent VX) are the most toxic of the known chemical agents and can cause death within minutes of exposure by interfering with the enzyme acetylcholinesterase.
- *Vesicants (blister agents)* such as Lewisite (agent L), mustard (agent H or HD), and phosgene oxime (agent CX) cause inflammation, blisters, and general destruction of tissues.
- *Urticants or nettle agents* such as phosgene oxime (agent CX, also a vesicant) produce instant and sometimes intolerable pain upon contact with skin and mucous membranes.
- *Blood agents* such as arsine (agent SA), cyanogen (no military designation), hydrogen cyanide (agent AC), or hydrogen sulfide (no military designation) stop the transfer of oxygen from the blood system to the rest of the body by inhibiting the enzyme cyto-chrome oxidase or by destroying red blood cells.
- *Choking agents* such as metal fumes such as nickel carbonyl (no military designation) or solid, liquid, or gaseous halogens such as chlorine (agent Cl) can injure an unprotected person by causing membranes to swell or the lungs to become filled with liquid (pulmonary edema).
- *Incapacitating agents* such as agent BZ alter or disrupt the higher regulatory activity of the central nervous system.
- *Tear agents* such as acrolein (no military designation), mace (agent CN), and pepper spray (agent OC) cause tears and intense eye pain and may also irritate the respiratory tract and skin.
- *Vomiting agents* such as Adamsite (agent DM) can cause regurgitation, as well as coughing, sneezing, pain in the nose and throat, nasal discharge, and/or tears, as well as dermatitis on exposed skin.
- *Corrosive smoke agents* such as titanium tetrachloride (agent FM smoke) and sulfur trioxide-chlorosulfonic acid (agent FS smoke) cause inflammation and general

destruction of tissues and can lead to swelling of lung membranes, pulmonary edema, and death following inhalation.

- *Toxins* can act in a variety of ways. Neurotoxins, such as botulinum toxin (toxin A), which blocks the release of acetylcholine, and brevetoxins (toxin B), which activate the sodium channel, disrupt the nervous system. Cytotoxins such as ricin (a protein synthesis inhibitor) and aflatoxins (inhibitors of nucleic acids) destroy and damage tissue. Biomediator toxins cause the body to release excessive, and therefore harmful, amounts of chemicals that are normally produced by the body.
- *Pathogens* include bacteria such as anthrax, brucellosis, cholera, and diphtheria; viruses such as chikungunya (typically carried by mosquitoes), Congo-Crimean Hemorrhagic Fever (carried by ticks), and various hemorrhagic fevers such as Ebola; fungi such as histoplasmosis; and rickettsiae such as typhus, Rocky Mountain Spotted Fever, and Q fever.

Categories and Concerns for Toxic Industrial Materials (TIMS)

Toxic industrial materials (TIMs), frequently referred to as toxic industrial chemicals (TICs), provide an array of widely available materials other than CBR agents that have harmful effects on humans. As noted by Fattah et al. (2000), a TIM is a *specific type* of industrial chemical, that is, one that has a LCt_{50} value (lethal concentration for 50% of the population multiplied by exposure time) less than 100,000 mg-min/m^3 in any mammalian species and is produced in quantities exceeding 30 tons per year at one production facility. Like CBR agents, TIMs have a range of health impacts (see, for example, Steumpfle et al. 1998). To provide a basis for hazard assessment, TIMs are ranked into one of three categories:

- *High Hazard* indicates a widely produced, stored, or transported TIM that has high toxicity and is easily vaporized. Examples are ammonia, chlorine, ethylene oxide, formaldehyde, hydrogen sulfide, fuming nitric acid, phosgene, sulfur dioxide, and sulfuric acid.
- *Medium Hazard* indicates a TIM that may rank high in some categories but lower in others such as number of producers, physical state, or toxicity. Examples are acrolein, carbon monoxide, diketene, methyl bromide, nitrogen dioxide, phosphine, sulfur trioxide, and titanium tetrachloride.
- *Low Hazard* indicates that this TIM is not likely to be a hazard unless specific operational factors indicate otherwise. Examples are arsenic trichloride, bromine, dimethyl sulfate, isopropyl isocyanate, nitric oxide, parathion, tetraethyl lead, toluene 2,4-diisocynate, and toluene 2,6-diisocyanate.

Exposure of the Human Respiratory Tract

Although many agents are potentially hazardous through ingestion, contact with eyes and skin, and uptake through broken skin, exposure through the respiratory tract is frequently the primary concern. The human respiratory tract (HRT) is the structural system whose function is the intake of atmospheric oxygen for use in the metabolic activities of the body's cells and removal of spent oxygen in the form of carbon dioxide. Because the respiratory tract serves as a portal of entry of atmospheric gases into the body, it also serves as a portal of entry of airborne particulate and gaseous contaminants. Considerations for respiratory protection against CBR and other agents include the relationship between what is in the air and what is deposited in the lung; the sites of deposition of particles; the fate of the inhaled contaminants, including their residence times in the respiratory tract and their clearance pathways; their solubility in body fluids; their absorption into the blood; the distribution of the absorbed contaminant within the body and the elimination from the body; the nature of any chemical interactions with tissue and other biochemical molecules; and the resulting chemical, biological, or radiation dose of the inhaled contaminant. Regardless of the route of exposure, it is useful to remember Paracelsus' dictum that the dose determines the poison (see, for example, Ottoboni 1997). Everything is toxic and nothing is toxic, and only the size of the dose determines the toxic effects of that substance. Minimizing exposure through respiratory and ventilation protection is a primary objective.

Lung Models

Several successively more sophisticated models of the HRT have been proposed by the International Commission on Radiological Protection (ICRP). First was the ICRP 2 model, a two-compartment model that was described in 1959 (ICRP 1959). It was designed for the purpose of calculating limiting values for the concentration of radioactive particles in the workplace. The lung was modeled as a 10-cm-radius sphere that weighed 1 kg.

The ICRP 30 model (ICRP 1979), which was adopted in 1978, was also designed to calculate occupational limits for radioactive aerosols. However, the ICRP 30 respiratory tract was modeled by three compartments: nasopharyngeal, tracheo-bronchial, and pulmonary regions. The trachea, a tube about 10 cm long and 1.6 cm in diameter, lies inside the thoracic cavity and joins the nasopharyngeal airway to the lung. At its lower end, the trachea bifurcates into two primary bronchi, which are short tubes about 1 cm in diameter leading to three lobes on the right side of the lung and two lobes on the left side of the lung. The primary bronchi divide into smaller secondary bronchi at each lobe. These airways continue to bifurcate within the lungs to tubes of successively smaller diameter until the terminal bronchioles, which are about 0.5 mm in diameter. The inside surfaces of this tracheo-bronchial region are characterized by the presence of special cells called ciliated epithelium and other specialized cells called goblet cells. The epithelial cells have hairlike filaments called cilia, about 50 μm long. The goblet cells secrete mucous that blankets the

inside surface of the airways to a depth of about 60 μm. The cilia move in a synchronized beating motion that propels the mucous blanket toward the throat, with a velocity that approaches about 1 cm per minute in the trachea. The ciliary "escalator" is the means by which particles are cleared from the upper airways. In the pulmonary, or gas-exchange region of the lung, the terminal bronchioles bifurcate into respiratory bronchioles, which bifurcate to form alveolar ducts. Gas exchange takes place mainly in the alveoli, which are outpouchings of the alveolar duct on the order to 100 to 200 μm in diameter. There are several hundred million alveoli, which provide a total surface of about 100 to 200 m^2 for gas exchange. Capillaries are wrapped around the alveoli, and oxygen and carbon dioxide diffuse through the single-celled alveolar and capillary walls.

The ICRP 30 model considered the role of particle size on the deposition in each compartment. This model also considered a range of three different particle solubility rate classes (D, days; W, weeks; and Y, years) and included solubility in consideration of activity transfer from the lungs to the blood. Finally, the ICRP 30 model used newer biokinetic data in calculating clearance from the lungs. Like the earlier lung model, the ICRP 30 model considered the lung to be a single blood-filled tissue that weighs 1 kg. Also like the earlier model, it was not meant to be used in interpreting bioassay data. The airborne radioactivity limits currently used by the U.S. Nuclear Regulatory Commission (NRC 1991) are based on the ICRP 30 model.

In 1994, the ICRP published a still more sophisticated five-compartment ICRP 66 human respiratory tract model (HRTM) (ICRP 1994). As noted in the guide for practical application of the new HRTM (ICRP 2002), this new ICRP 66 respiratory tract model for use in radiological protection describes the processes that are involved when a radioactive material is inhaled, including the flow of air in and out of the lungs, the deposition of material from inhaled air to the lining of the respiratory tract, and its subsequent transfer to the gastrointestinal (GI) tract, or to the blood. The "model" describes what happens to the material in terms of equations and so permits radiation doses to be calculated. It is also used with models for other parts of the body to calculate how much of the material is present in other organs, and the doses they receive. This model can be used retrospectively to determine the inhalation intake of radioactive material from bioassay measurements, and prospectively to assess the radiation risk from current or future inhalation of radioactive material.

The ICRP 66 model is applicable to all members of the population, covers a broad range of particle sizes from 0.0006 μm to 100 μm, considers the effects of physiological exertion on respiratory kinetics, considers impairment of pulmonary function, uses up-to-date physiologically based biokinetic data, considers the lung to be a complex organ with several different tissues of different radiosensitivities, and calculates the effective dose to the lung based on the relative sensitivity of each of the irradiated tissues. Absorption of materials into blood and other body fluids is addressed by three broad categories: type F, fast; type M, medium; and type S, slow. Finally, the ICRP 66 model considers gases as well as aerosols. The basic treatments of particle size, regional deposition, retention and translocation of materials in the respiratory tract are relevant to nonradioactive agents.

Respiration

The respiratory process involves intake and exhalation of air. During inhalation, chest muscles and the diaphragm cause the volume of the thoracic cavity to increase, thereby decreasing the air pressure within the lungs and allowing the outside air to rush in. When the muscles are relaxed, the chest volume decreases, thereby increasing the intra-thoracic pressure above atmospheric pressure and forcing air out. The total pressure difference is about 6 mm Hg (about 0.24 pounds per square inch). Other respiratory parameters (including selected reference values for an adult male taken from ICRP 66) are:

- Respiratory frequency, ranging for an adult male from 12 breaths per minute during sleeping or sitting, to 20 per minute during light exercise, and to 26 per minute during heavy exercise;
- Tidal volume, the volume of air inhaled and exhaled, typically 500 mL, ranging for an adult male from 625 mL during sleep, to 750 mL during sitting, to 1,250 mL during light exercise, and to 1923 mL during heavy exercise;
- Ventilation rate, ranging for an adult male from 7.5 L min^{-1} during sleep, to 9 L min^{-1} during sitting, to 25 L min^{-1} during light exercise, and to 50 L min^{-1} during heavy exercise;
- Expiratory reserve volume, the volume of air that can be exhaled after a normal exhalation, typically 1,000 mL;
- Inspiratory reserve volume, the volume of air that can be inhaled after a normal inhalation, typically 2,500 mL;
- Vital capacity, the sum of the tidal volume, expiratory reserve volume, and inspiratory reserve volume, typically 4,000 mL;
- Residual volume, the volume of air that remains in the lungs after a maximum expiration, typically 1,200 mL; and
- Total, sum of the vital capacity and residual volume, typically 5,200 mL.

The exact values for these parameters depend on a person's gender, age, size, level of fitness, and degree of exertion. ICRP 66 also includes standard scenarios that illustrate a range of breathing conditions for different work and environmental situations. These may be relevant for emergency responders and members of the public. For example, breathing conditions for an adult male being exposed in the indoor home environment are assumed to involve 55% sleeping, 15% sitting, 30% light exercise, and a total mean ventilation rate of about 13 L min^{-1}. Standard occupational work for an adult male is assumed to involve 31.3% sitting and 68.8% light exercise, resulting in a mean ventilation rate of 20 L min^{-1}. An occupational exposure involving heavy work is assumed to involve 87.5% light exercise, 12.5% heavy exercise, and a mean ventilation rate of 28 L min^{-1}. Illustrations of how different breathing conditions influence deposition in the respiratory tract are can be found in ICRP 66.

The Lognormal Distribution for Airborne Particle Size

Unless they are specially made in a laboratory to be uniformly sized, aerosols tend to have a lognormal size distribution. This means that the distributions of particle count, surface area, or mass are statistically normal when plotted against the logarithm of particle diameter, rather than against particle diameter itself. This is intuitively so because the original source material or agglomerates of fragmented material can range in size to many orders of magnitude larger than the smallest particle size, because large amounts of energy are required to break large particles into smaller and smaller fragments, and because particle diameters cannot be smaller than the fundamental diameters of their molecules or atoms. Note that environmental sampling data for chemicals and other materials have also been shown to be lognormally distributed (see, for example, Esmen and Hammad 1997).

It is useful to be aware of and able to assess and interpret the degree of dispersion of particle size for CBR agents. Relationships that are familiar from the normal distribution (e.g., 50% of the values lie between $\pm 0.675\sigma$, 68% between $\pm 1\sigma$, 90% between $\pm 1.64\sigma$, 95% between $\pm 1.96\sigma$, 97.5% between $\pm 2.24\sigma$, 99% between $\pm 2.58\sigma$, 99.9% between $\pm 3.29\sigma$, and 99.99% between $\pm 3.89\sigma$) are readily transformed for use with the lognormal distribution. For example, because 95% of a normally distributed population is contained within $\pm 1.96\sigma$ above and below the mean value, 95% of a lognormally distributed population is contained between diameter $d_g/\sigma^{1.96}$ and diameter $d_g \cdot \sigma_g^{1.96}$.

For example, for the distribution

$$d_g = 3 \ \mu m, \quad \sigma_g = 2,$$

95% of the population is included between

$$3 \ \mu m/2^{1.96} = 0.77 \ \mu m$$

and

$$3 \ \mu m \cdot 2^{1.96} = 11.67 \ \mu m.$$

Such information can guide in the selection of appropriate sampling devices, respiratory protection, and air cleaning or filtration systems.

Particle Kinetics

Fig. 23.2 illustrates the general particle mechanisms that contribute to collection of particles in the respiratory tract, as well as by ventilation filtration and air cleaning systems. Those mechanisms include gravitational settling and impaction (aerodynamic properties), diffusion (a thermodynamic property), interception (a basic matter of particle size), and electrostatic attraction.

Gravitational Settling

When a particle on the order of 0.1 μm diameter or larger is dispersed in free air, it becomes subject to the gravitational force, f_g (in units of newtons or dynes), in the downward direction:

$$f_g = m \cdot g$$

where m is the mass of the particle (kg or g) and g is the gravitational acceleration term (9.8 m s^{-2} or 980 cm s^{-2}).
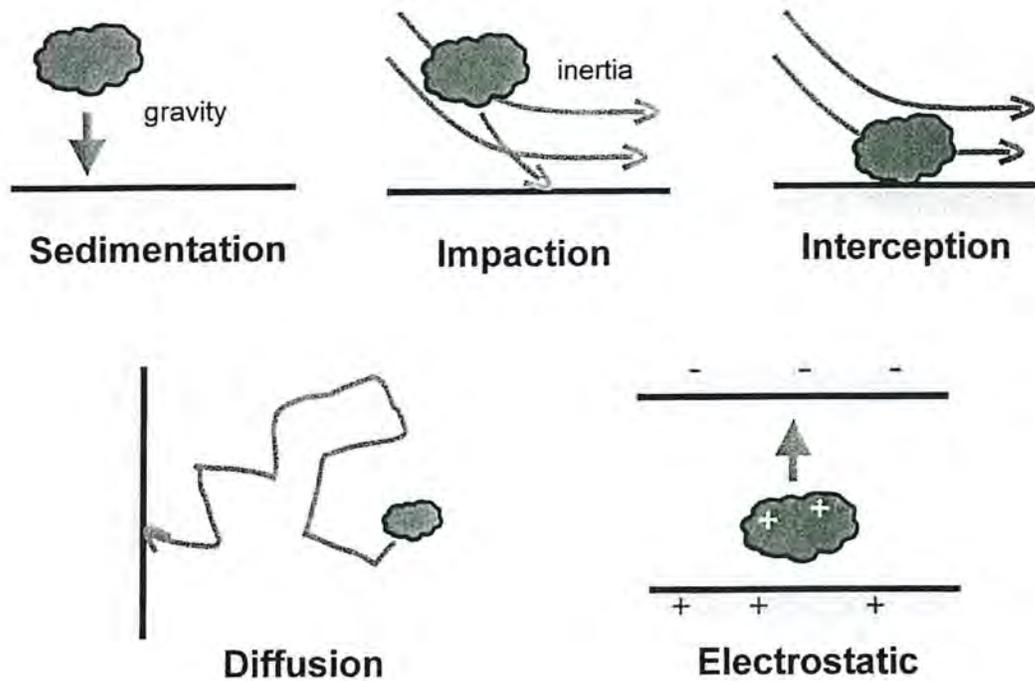

Fig. 23.2. Fundamental mechanisms of particle collection in the environment, in air filtration and air cleaning systems, and in the human respiratory tract.

Movement of the particle in response to the gravitational force results in a counteracting resistive force, f_r, on the particle surface due to the viscosity of the air. For the case of a falling sphere under conditions of laminar (non-turbulent) flow (neglecting certain effects where particles smaller than about 1 μm diameter can "slip" to some extent between the surrounding gas molecules, rather than encountering a continuum of gas molecules), the resistive force, in newtons or dynes, is given by Stokes' law:

$$f_r = 3\pi\eta vd,$$

where η is the viscosity of air (18.5 μPa•s or 185 μpoise), v is particle velocity (m s^{-1} or cm s^{-1}), and d is particle "diameter" (m or cm).

When the falling particle attains a velocity such that the resistive force is equal to the gravitational force, then

$$3\pi\eta vd = m \cdot g$$

and the particle will continue to fall at a constant velocity, called the terminal settling velocity, v_t:

$$v_t = d^2\rho g/18\eta$$

where ρ is the particle density (kg m^{-3} or g cm^{-3}).

Terminal settling velocity is attained almost instantaneously, and is very small for small particles. For example, the terminal settling velocity for a 1-μm-diameter particle of specific gravity 1 is:

$$v_t = \frac{d^2\rho g}{18\eta}$$

$$v_t = \frac{(10^{-6}m)^2 \cdot 1x10^3 \frac{kg}{m^3} \cdot 9.8 \frac{m}{s}}{18 \cdot 18.5x10^{-6} \frac{kg}{m \cdot s}}$$

$$= 2.9x10^{-5} m/s$$

$$= 0.0029 cm/s$$

$$= 0.0058 ft/\min.$$

Because the particle size effect is proportional to the square of the diameter, the terminal settling velocity for 1-, 10-, 100-, and 1,000-μm-diameter particles of unit density will be 2.9×10^{-5}, 2.9×10^{-3}, 0.29, and 29 m s^{-1}, respectively. Thus, particles larger than 100 μm in diameter are likely to fall rather quickly due to gravitational effects. Note, however, that air currents can counteract gravitational settling. Because the terminal settling velocity of small particles is very much less than ventilation or ambient air currents, small particles may be considered to behave like their surrounding air currents. Even in rooms where the ventilation system has been turned off, air currents from temperature gradients can cause particles to remain airborne much longer than predicted by simple Stokes settling. Thus, direct

measurements or computational fluid dynamics calculations may be needed to understand the details of particle behavior in specific situations.

Aerodynamic Equivalent Diameter

As noted in the equation for v_t, particle density also contributes in a linear fashion to gravitational settling. For example, the terminal settling velocity for 1-, 10-, 100-, and 1,000-μm-diameter uranium particles (U_2O_3, specific gravity 8.3) will be 2.44×10^{-4}, 0.0244, 2.44, and 244 m s^{-1}, respectively, which is a factor of 8.3 greater than the terminal settling velocities of unit density particles of the same size.

To simplify considerations of particle behavior, particularly in the respiratory tract and for particle sampling and filtration, it is convenient to treat two particles of different sizes, shapes, and densities as aerodynamically equivalent if they have the same terminal settling velocity in air. For convenience, the aerodynamic equivalent diameter of a particle is defined is the diameter of a unit density sphere whose v_t is the same as that of the particle in question. As a first approximation, the aerodynamic equivalent diameter of a particle, d_{ac}, has the following relationship to its physical diameter, d_p:

$$d_{ac} = d_p \, \rho^{1/2}.$$

Thus, a U_2O_3 particle with specific gravity 8.3 and a physical diameter of 5 μm will have an aerodynamic diameter that is approximately 14.4 μm. Such differences can be important when using air-sampling devices that estimate particle physical size (for example, light scattering techniques) to characterize aerosols of unknown composition.

Thermodynamic Equivalent Diameter

Molecules of air are in a constant state of motion, with their speed dependent on temperature, and continuously collide with one another. For air at a temperature of 25°C and a pressure of 760 mm Hg, the mean free path (mean distance traveled between air-molecule collisions) is 0.067 μm. As particle sizes decrease to this order of magnitude, the effects of being struck by the moving air molecules overwhelms the effects of gravity on the particle. Under these conditions, particle motion is controlled by the bombarding air molecules, and the particles move about in random directions. This motion is called Brownian motion, and the process of particle movement is called diffusion.

The relative importance of gravitational settling and diffusion as a function of physical particle size is illustrated in Fig. 23.3. For example, a 1-μm-diameter, unit density sphere that settles approximately 30 μm in 1 s will diffuse a distance of about 7 μm in the same time period. If the particle size is reduced to 0.1 μm, the particle would settle less than 1 μm, while diffusing more than 30 μm. Because diffusion is a thermodynamic process, thermodynamic equivalent diameter is used to characterize particle size in the range where particle motion is dominated by diffusion. Diffusion of a particle in any given medium

depends on both the temperature and the particle size. The thermodynamic diameter of a particle of interest is defined as the diameter of a spherical particle that has the same diffusion coefficient in air as the particle of interest. Whereas aerodynamic diameter was approximately equal to the physical diameter of a particle times the square root of its density, the thermodynamic diameter of a particle is approximately equal to its physical size.

Fig. 23.4 illustrates the different roles that particle size and particle density play for deposition in the human respiratory tract in the thermodynamic and aerodynamic regimes. For small particle diameters in the thermodynamic regime, total deposition in the respiratory tract is identical for particles of equal thermodynamic diameter, regardless of their density. For particles of larger thermodynamic diameter, aerodynamic forces become dominant and deposition in the respiratory tract is influenced by particle density. Conversely, for large particle diameters in the aerodynamic regime, aerodynamic diameter takes density into account and total deposition in the respiratory tract is identical for particles of equal aerodynamic diameter, regardless of their thermodynamic diameter. Note that the particle size range of minimal deposition corresponds to the intermediate region where neither inertial effects nor diffusion effects are dominant. This region also corresponds to the particle sizes that are most difficult to remove by filtration or air cleaning.
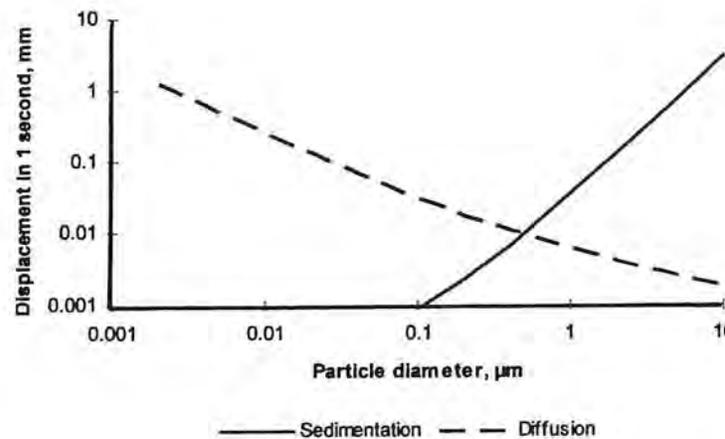

Fig. 23.3. Comparison of the relative importance of particle motion from the gravitational sedimentation (vertical displacement) and diffusion mechanisms (root mean square distance the particle travels as a result of Brownian motion) as a function of particle diameter for unit density spheres (from Raabe 1994). Note that logarithmic scales are required on both axes to address orders-of-magnitude differences in the degrees of displacement and particle diameters of interest.
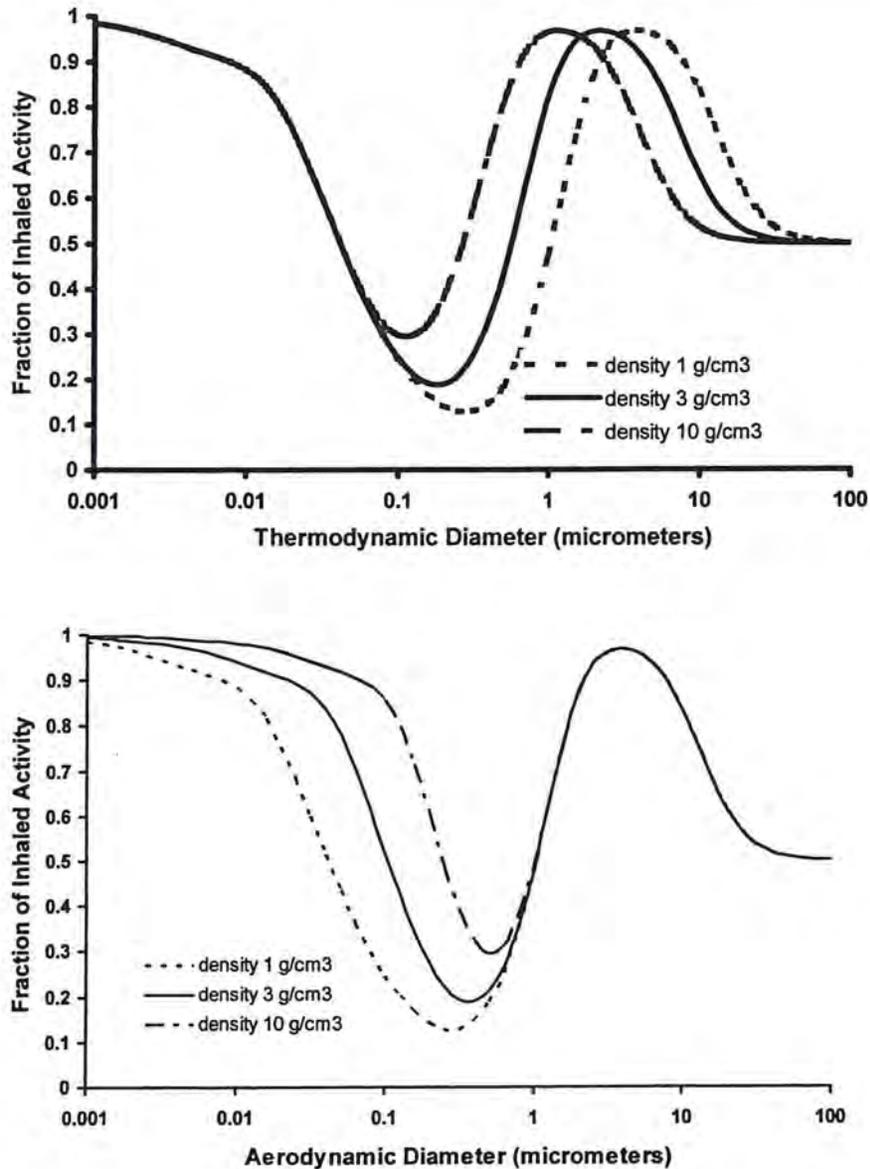
Fig. 23.4. Comparison of the influence of thermodynamic diameter and aerodynamic diameter for monodisperse spheres of three different densities for the total fraction of inhaled material deposited in the respiratory tract as predicted by the Human Respiratory Tract Model (ICRP 1994) for a reference person doing light work. Note that thermodynamic diameter is not an appropriate measure of particle size for diameters greater than 1 μm (where inertial effects dominate particle deposition) and that aerodynamic diameter is not an appropriate measure of particle size for diameters less than 0.1 μm (where diffusion dominates particle deposition). (See ICRP 2002 for similar presentations.)

Filtration and Air Cleaning

Filtration generally refers to removal of liquid or solid particles and *air cleaning* generally refers to removal of gases and vapors. The basic relationships between particle size and aerodynamic and thermodynamic behavior of concern for deposition in the respiratory tract are relevant to the collection efficiency of filtration and air cleaning systems for respiratory and ventilation protection. Diffusion is the primary mechanism for collecting gases and vapors with sorbent filters. Inertial impaction and interception are the primary mechanisms for collecting larger particles with fiber or other types of filters. A region of minimum collection efficiency exists (similar to that illustrated in Fig. 23.4 for the respiratory tract) for particle sizes on the order of 0.1 to 0.3 μm. The exact value of the most penetrating particle size depends on the characteristics of the filter (e.g., fiber diameter and packing density) and decreases slightly for higher face velocities (the velocity at which air enters the filter). If only very large or very small particles are of concern, then even filters with a low minimum efficiency may be adequate for some applications.

Filtration Considerations

The American Society of Heating, Ventilating, and Air Conditioning Engineers (ASHRAE) has developed a standard test method (ANSI/ASHRAE 52.2-1999) to describe and rate air filters according to their collection efficiency over three size ranges: Range 1 (0.3 to 1 μm), Range 2 (1 to 3 μm), and Range 3 (3 to 10 μm). In a position statement on bioterrorism, the National Air Filtration Association (NAFA 2003) discusses the use of these tests in preparing for bioterrorism events and notes that the standard provides a tool for selecting an appropriate filter for a specific application. As summarized in Table 23.1, the collection efficiency of a filter in each of the three ranges can be used to assign the filter a Minimum Efficiency Reporting Value (MERV) on a scale of 1 to 20. Although higher MERV values indicate higher collection efficiencies, the MERVs are not the mathematical result of an efficiency formula; interpreting the meaning of a MERV requires consulting the table of MERV definitions. Because filter collection efficiency increases for mechanical filters (but not for electrostatic filters) as the filter loads (see, for example, NIOSH 2003), collection efficiency in each size range for MERV determination is a composite efficiency based on testing of clean and incrementally loaded filters.

The NIOSH (2003) "Guidance for Filtration and Air Cleaning Systems to Protect Building Environments from Airborne Chemical, Biological, or Radiological Attacks" provides an excellent summary of filtration and air cleaning issues, along with a comprehensive list of key references. Practical considerations include ensuring that air is not allowed to flow around, rather than through, a filter. The guidance notes that electrostatic filters (composed of polarized fibers) may provide an economical alternative for obtaining higher collection efficiency without the higher pressure drops of higher MERV filters. Caution is advised, however, because the collection efficiency of electrostatic filters can degrade with time to

Table 23.1. ANSI/ASHRAE Standard 52.2 Minimum Efficiency Reporting Values (MERVs) for air filters (adapted from ASHRAE 1999).

	Composite average particle collection efficiency in the size range		
MERV	Range 1 0.3 to 1 μm	Range 2 1 to 3 μm	Range 3 3 to 10 μm
1	—	—	< 20%
2	—	—	< 20%
3	—	—	< 20%
4	—	—	< 20%
5	—	—	20 to 35%
6	—	—	35 to 50%
7	—	—	50 to 70%
8	—	—	> 70%
9	—	< 50%	> 85%
10	—	50 to 65%	> 85%
11	—	65 to 80%	> 85%
12	—	> 80%	> 90%
13	< 75%	> 90%	> 90%
14	75 to 85%	> 90%	> 90%
15	85 to 95%	> 90%	> 90%
16	> 95%	> 95%	> 95%
17	> 99.97%	—	
18	> 99.99%	—	
19	> 99.999%	—	
20	> 99.9999%	—	

the underlying mechanical collection efficiency, especially if used at high humidity or exposed to certain chemical vapors, gases, or aerosols.

Air Cleaning Considerations

As noted in the NIOSH (2003) guidance, choosing the appropriate sorbent or sorbents for a gaseous or vapor airborne contaminant is a complex decision that should involve consultation with a qualified professional and consideration of many factors. Important factors include:

- *Specificity of the sorbent for the contaminant.* Not all sorbents work for all contaminants. For example, natural zeolites are hydrophilic and are effective for organic solvents and for low-molecular-weight halides such as chlorinated fluorocarbons (CFCs). They do not have an affinity for non-polar molecules. Synthetic zeolites can be made to be hydrophilic if they are alumina-rich or hydrophobic if they are silica-rich. Activated carbon is non-polar, and therefore effective for organic vapors. However, activated carbon is not effective for volatile, low-molecular-weight gases such as ammonia and formaldehyde. Activated carbon can be impregnated with various materials for

use with specific chemical contaminants. For example, impregnation with copper/silver salts enables collection of phosgene, chlorine, and arsine, and impregnation with phosphoric acid enables collection of ammonia.

- *Compatibility of pore size.* Porous sorbents cannot adsorb molecules larger than their pore size.
- *Contact time.* The agent must spend sufficient time in the vicinity of the sorbent to be captured and controlled by either physical adsorption or chemisorption. This involves considerations such as the velocity of air flow, the depth of the collection layer, and the available surface area of the sorbent. Thinner or less porous layers require lower flowrates to provide adequate residence time for collection by diffusion.
- *Sorbent capacity.* Breakthrough can occur if the collection capacity of the sorbent is exceeded. Calculations of the expected lifetime for the sorbent should be made based on knowledge of the concentration of the agent being presented or measurements of breakthrough should be made. Fattah et al. (2000) provide information about detection methods that may be used to detect concentrations or breakthrough of CBR agents. A mathematical model for predicting chemical breakthrough is available on the Occupational Safety and Health Administration (OSHA) Website (Wood 1999).
- *Competition for sorption sites.* Silica gel and alumina are effective for trapping polar compounds, but they have a high affinity for water. Breakthrough may occur under wet or humid conditions.

Concluding Remarks

The basic physicochemical principles of aerosol science form the underpinnings of effective respiratory and ventilation protection for CBR agents. Information from a number of important guidance documents on respiratory and ventilation protection is excerpted and summarized in a companion chapter (Hoover and Cember 2004).

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DEPARTMENT OF HEALTH & HUMAN SERVICES

National Institute for
Occupational Safety and Health (NIOSH)

Memorandum

Date: August 17, 2004

From: Research Physical Scientist, FSB, DRDS

Subject: Reprint of Publication

To: Deputy Director, DRDS
Thru: Chief, FSB

Attached is a reprint of a book chapter I co-authored which was published in a book entitled Public Protection from Nuclear, Chemical, and Biological Terrorism. The DRDS clearance number is 2004-084B. It is provided for your retention.

REFERENCE:

Cember H, Hoover MD. [2004]. General Considerations for Respiratory and Ventilation Protection against Airborne Weapons of Mass Destruction. Brodsky A, Johnson, Jr RH, Goans RE, eds. Public Protection for Nuclear, Chemical, and Biological Terrorism. Madison, WI: Medical Physics Publishing, pp. 407-425.

Thank you.

Mark D. Hoover, Ph.D.

Attachment:

cc:
Director, DRDS (3)
Director, EID (3)
Librarian, ALOSH (2)
Chief, FSB,DRDS (1)
Chief, LRB,DRDS (1)
Chief, SB,DRDS (1)