chapter eleven

Aerosols in the industrial environment

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Contents

11.1 Introduction

Aerosol exposure has been associated with occupational illness since the earliest times, and remains a major source of ill health within the workplace to this day. Recognition of

1-56670-611-4 / 05 / $0.00+$1.50

the hazards airborne particles present can be traced back to the ancient Greeks and Egyptians.[1] In the 4th century BC, Hippocrates (ca. 460–370 BCE) recorded details of occupational diseases associated with aerosols, including lead poisoning.[2,3] Plinius Secundus (Pliny the Elder, 23–79) is recorded as recognizing the harmfulness of inhaling dust in the 1st century AD, noting the use of loose bladders wrapped round refiners' faces to prevent inhalation of "fatal dust."[4] However, it was not until the 15th and 16th centuries that a clear understanding began to emerge on the relationship between aerosol exposure and occupational health. Around this time, technical and economic developments in Europe led to an increased demand for gold and lead. As mines became deeper, the injuries and poor health associated with mining became more obvious. The writings of the founders of modern occupational hygiene such as Paracelsus (1493–1541), Agricola (1495–1555), and Ramazzini (1633–1714) are clearly influenced by the incidence of ill health and death associated with mining at the time. However, they also extend to many other industries. Without exception, aerosols are acknowledged by these authors as presenting a major health hazard to workers in industrial environments. Ramazzini, in particular, documents many occupations where the inhalation of "…very fine particles inimical to human beings…" is a problem,[5] including the inhalation of metal particles, gypsum, flour, stone dust, and tobacco dust.

The industrial revoution of the late 19th and early 20th centuries introduced new and greater exposures to aerosols, and increasing awareness of the associated hazards. Mining was undertaken with increased intensity — particularly for coal — and exposure to soot, metal fumes, and aerosols such as cotton dust increased markedly. Alice Hamilton carried out seminal research in the early 1900s into the health of workers in America, and readily understood the close association between aerosol exposure and ill health. Her work laid the foundation for occupational hygiene in the United State.[3] At the same time, researchers such as Tyndall, Aitken, and Rayleigh were laying the foundations for modern aerosol science that would provide the means to understand and control occupational aerosols.

An understanding of aerosol toxicity and how to measure and control exposures developed rapidly over the 20th century, and much of the research from this period defines how we now approach occupational aerosols. Although the current understanding of occupational hygiene has expanded significantly from previous centuries, aerosols are still perceived as one of the highest profile health hazards. Numerous aerosols are widely understood to be harmful to health if inhaled, including lead particles, asbestos, diesel smoke, crystalline silica, a wide range of chemicals and metals, radon progeny, bacteria, viruses, fungal spores, and endotoxins. Unlike gases or vapors, aerosols pose a particularly complex hazard, as probable dose and toxicity are associated with particle size, shape, and chemical structure, as well as composition. Toxicity depends on the dose received, and the body's response to the deposited particles. Biological response will depend in turn on the chemical and physical nature of the particles, and on the deposition region.

Deposition region is primarily governed by particle size and shape (Chapters 6–8). Response may be a function of particle size, number, surface area, mass, morphology, chemical composition, and/or surface chemistry. Dose therefore needs to be measured in terms of the most appropriate standard of measurement or metric. As an example of the importance of particle size and chemical nature, SiO_2 presents a relatively low risk when present in its amorphous form, while the crystalline form is highly toxic. However, particles of crystalline silica larger than a few micrometers in diameter present a lower health risk, as the probability of entering the lower lungs when inhaled decreases. Dose depends on actual deposition in the respiratory system, interactions with the lung fluid, and removal mechanisms. In practice, it is more convenient to measure penetration to the relevant areas of the respiratory system rather than dose. Although not ideal, this approach results in a measure of potential dose, and provides an indicator of maximum potential risk.

Many chronic respiratory diseases are classified as pneumoconiosis — a broad term from the Greek meaning " dust in lungs." Severe forms of pneumoconiosis are associated with fibrotic lung change. The current definition of the disorder refers to an accumulation of dust in the lungs, and the tissue reaction to its presence — essentially associating it with solid, relatively insoluble particles that are respirable (i.e., are capable of penetrating to the terminal bronchioles and beyond, where gas exchange takes place). Most insoluble dusts are associated with pneumoconiosis at sufficiently sustained exposure levels. The least harmful of these dusts have little biological interaction with the lungs, and are generally classified as nuisance dusts or particles not otherwise classified (PNOCs). However, a number of dusts do interact with the respiratory system to a significant degree, leading to specific forms of pneumoconiosis, including asbestosis (asbestos inhalation), silicosis (crystalline silica inhalation), siderosis (iron particle or fume inhalation), and berylliosis (from inhaling beryllium compounds).

Silicosis and asbestosis are associated with a wide range of occupations, and deserve further mention. SiO_2 is the most abundant mineral on earth, with much of it present in a free (i.e., unattached to another mineral) crystalline form. Thus, any occupation that leads to dust being formed from rock, stone, or natural mineral products such as bricks and mortar has an associated risk of crystalline silica exposure. While amorphous silica is classified as a nuisance dust, the crystalline form is highly toxic in the lungs, leading to silicosis. The disease was known to the Greeks and Egyptians,[6] and in modern times it peaked in the late 19th and early 20th centuries, coinciding with the industrial revolution. Current work practices have lowered the incidence of silicosis significantly, although the prevalence of crystalline silica still results in exposures leading to the disease. Classic silicosis results from low to moderate exposure over 20 years or more, and primarily leads to an increased disposition to mycobacterial infections and progressive massive fibrosis.[7] Accelerated silicosis results from higher exposures over 5–10 years, and progressive respiratory illness is virtually certain, even following cessation of exposure. Very high exposures over as little as a year can lead to acute silicosis, resulting in progressive respiratory illness and death in a few years following exposure.

The term asbestos covers a group of commercially recognized fibrous hydrated silicates (fibrous polymorphs of chrysotile, amosite, crocidolite, fibrous tremolite, fibrous anthophyllite, and fibrous actinolite). All these materials are asbestiform, that is, they are capable of shedding increasingly fine fibers down to the fibrils that form the mineral, allowing a single inhaled fiber to divide into many thin fibers in the lungs. Fibers may be relatively straight, as in the case of crocidolite and other amphiboles, or curved, as is found with chrysotile. Asbestos can be used to form materials that are excellent insulators against heat, cold, and noise, have good dielectric properties, great tensile strength, are flexible, and resist corrosion by alkalis and most acids. Correspondingly, the material has been used since ancient times, and is currently associated with over 3000 commercial applications.[8] Recognition of the extreme toxicity of inhaled asbestos fibers in the latter part of the 20th century has led to a great reduction in its use. Today, most potential exposures in North America and Europe arise during asbestos abatement, although it is still mined, and used in applications such as lining brakes, asbestos cement, and roofing tiles. As well as being associated with asbestosis (fibrosis of the lungs), exposure can also lead to malignant mesothelioma, and all types of lung cancer. Toxicity is associated with the shape of the fibers, leading to exposure controls based on the number and shape of particles inhaled. Other minerals that show properties similar to asbestos exist and are in use, but are not formally classified as such. These include vermiculite (a group of silicate materials that expand on heating and can be contaminated with asbestiform minerals) and zeolite (hydrated aluminum silicates that may occur in a fibrous form). Both materials are associated with lung disease, lung cancer, and mesothelioma.[9]

Man-made vitreous fibers (MMVFs) provide a fabricated nonasbestiform substitute for asbestos, particularly for thermal and acoustic insulation. While MMVFs can have similar sizes and aspect ratios as asbestos fibers, they are often relatively soluble by comparison, leading to reduced lung residence times. By nature they are not crystalline and do not shed smaller fibers. Although animal studies have shown significant toxicity for some of these fibers, significant human toxicity has yet to be established.[10]

Unlike the dusts associated with pneumoconiosis, soluble particles and droplets are relatively short-lived in the lungs, and tend to lead to material-specific reactions that are less well associated with the physical nature of the particles. These may range from pulmonary irritation to systemic toxicity. Inhalation of isocyanates, for instance, may lead to a response ranging from transient irritation to chronic sensitization and reduced lung function. Lead, on the other hand, is a systemic poison, and toxicity is associated with the transport of material from the respiratory system to specific target organs.

A number of aerosols lead to short-term flu-like symptoms following inhalation, which are usually classified under the umbrella term of "inhalation fever." Symptoms are self-limiting, but can be temporarily debilitating. Agents include endotoxins, metal and metal oxide fumes (in particular, zinc oxide fumes, leading to metal fume fever), pyrolysis products of polytetrafluoroethylene (PTFE), and moldy grain dust. Workers usually build up tolerance to the exposure, although symptoms can recur following an absence of exposure, such as a weekend or short break away from work. Inhalation fever is usually distinguished from acute lung injury, although a number of agents associated with it can lead to acute injury following sufficiently high or prolonged exposures. Exposure to cotton dust is a case in point, with prolonged and excessive exposure leading to byssinosis. Symptoms occur a few hours following exposure, and are more acute after a period of nonexposure (leading to the colloquial term *Monday Morning Asthma*). Permanent dyspnea may develop following several years of exposure.

Inhalation of fungal spores can also lead to an acute response following high temporal exposures, and presents a particular hazard when the rapid spread of fungal growth in buildings occurs.[11] Biological aerosols are also widely associated with the airborne transmission of infections. The risk of infection following inhalation is associated with the number of viable organisms entering the respiratory system, leading to methods of measuring exposure geared to identifying inhaled organisms capable of reproducing.[12,13] However, the biological material associated with the organisms may also elicit a toxic response in its own right, requiring much broader classification of inhaled bioaerosols.

In recent years, interest has been shown in a group of aerosols characterized by low-solubility particles smaller than 100 nm in diameter (often termed ultrafine particles). Laboratory-based research has shown that on a mass-for-mass basis, chemically inert materials such as TiO_2 increase in toxicity with decreasing particle size.[14,15] There are indications that the toxicity of similar low-solubility materials is associated with the surface area of the particles.[16–18]

11.2 Exposure metrics

There is wide variation in the types of aerosols found in occupational settings, and in the mechanisms by which they interact with the body to elicit a biological response. As a result, sampling an aerosol and relating concentration to the health risk posed is not as clear cut as it may be for a gas or vapor. Ideally, aerosol sampling in the workplace should enable quantification of that aspect of the aerosol that leads to specific health effects. While there are many potential exposure metrics applicable to aerosols, mass concentration has been shown to correlate well with health effects in the past[19] and is now widely accepted as the predominant metric for characterizing occupational aerosol exposure. Notable exceptions are fibrous aerosols, including asbestos and MMVFs, and viable bioaerosols, where associations between respiratory disease and exposure are closely linked to particle number and (in the case of fibers) shape. In both cases, number concentration provides a better indicator of the hazard associated with inhalation exposure.

Recent research on response to low-solubility ultrafine and high specific surface area particles has challenged the general acceptance of mass as the predominant exposure metric. It has been suggested that response may be associated with the number of deposition sites within the lungs, leading to particle number concentration being an appropriate exposure metric.[20] However, there is increasing evidence that the surface area of low-solubility particles plays a key role in triggering biological responses in the lungs and elsewhere in the body. A number of studies indicate response vs. aerosol surface area to be independent of particle size for low-solubility materials, suggesting that surface area may be a more appropriate exposure metric for such aerosols.[16,17] Using surface area rather than mass concentration to measure exposure will be particularly important for aerosols with a high surface-area-to-mass ratio (specific surface area) if these results are found to be applicable to occupational aerosols. Examples within this category include aerosols resulting from combustion (such as diesel exhaust particulates), metal and metal oxide particles from hot processes such as smelting and welding, and particles formed during fine-powder production. Some fine powders, including ultrafine titanium dioxide, carbon blacks, and fumed silicas, have specific surface areas in excess of 2×10^5 m^2/kg. The use of ultrafine aerosols in the rapidly developing field of nanotechnology is also likely to pose new exposure problems requiring the consideration of alternative exposure metrics such as surface area.[21,22]

11.3 Size-selective sampling

Measuring aerosol exposure against an appropriate metric provides information on the hazard posed by an aerosol, but to estimate the risk associated with exposure, particle-size-dependent penetration within the respiratory system must be accounted for (Chapter 7). For instance, an aerosol of 50 μm diameter quartz particles may pose a significant health hazard on a mass concentration basis, but the low probability of 50 μm particles penetrating to the alveolar region of the lungs would lead to a low risk of silicosis following repeated exposure. Occupational exposures are conventionally expressed as the fraction of an aerosol capable of penetrating to a specific region of the respiratory system, thus giving a measure of the maximum potential risk the aerosol poses.[23] Weighting aerosol samples by penetration probability as a function of particle size is possible if measurements have sufficient size resolution, as may be the case with cascade impactor measurements. A simpler, more direct method is to use a sampling device such as a cyclone with an engineered bias toward specific particle sizes. If the particle size selectivity of an aerosol sampler matches the penetration probability of a given region of the respiratory system, the resulting samples will provide a good estimate of the health risk presented by an aerosol.

Aerosol penetration to specific regions of the respiratory tract forms a basis for standards against which size-selective occupational aerosol samplers can be designed and tested. Early estimates of penetration into the alveolar region — perhaps the most vulnerable part of the respiratory system — were proposed in the 1950s and 1960s, resulting in the British Medical Research Council (BMRC) and the American Conference of Governmental Industrial Hygienists (ACGIH) conventions describing respirable aerosols [24,25] (Figure 11.1). Over the following 30 years, a number of standards were proposed and used for size-selective sampling relevant to the upper, mid, and lower

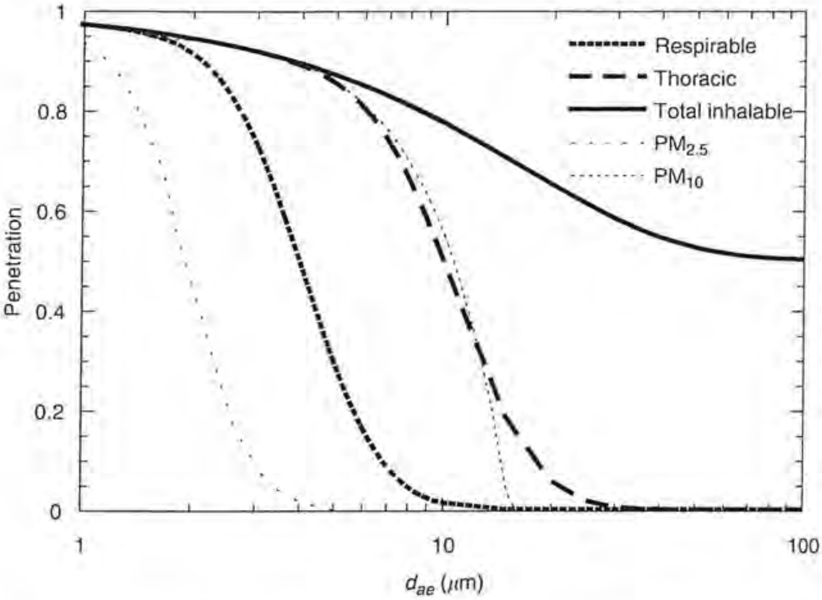

Figure 11.1 Comparison of different respirable sampling conventions.

airways, resulting in somewhat divergent standards in some cases. In the early 1990s, international consensus was reached on particle penetration standards between the International Standards Organization (ISO), ACGIH, and the European Committee for Standardization (CEN). The resulting conventions describe penetration as a function of particle aerodynamic diameter into the entire respiratory system (inhalable aerosol), into the tracheobronchial region (thoracic aerosol), and into the alveolar region (respirable aerosol), with thoracic and respirable aerosol defined as subfractions of the inhalable aerosol. These are now widely used as the standards to which industrial hygiene aerosol samplers should conform.[26] A review of the basis for these conventions was developed by the ACGIH.[27]

The inhalable convention is based on particle penetration through the mouth and nose of a breathing manikin over a range of wind speeds and orientations with respect to the wind, and is defined as

$$SI(d_{ae})=0.5\times(1+e^{-0.06d_{ae}}) \tag{11.1}$$

for $0 < d_{ae} < 100$ μm. $SI(d_{ae})$ is the fraction of particle entering the system as a function of aerodynamic diameter d_{ae} (Figure 11.2).

Both the thoracic and respirable conventions are expressed as subfractions of the inhalable convention, and are based on lung penetration modeling and measurements (see Chapters 6 and 8). The thoracic convention is given as

$$\begin{gathered} ST(d_{ae})=SI(d_{ae})\times(1-F(x)) \\ x=\frac{\ln(d_{ae}/\Gamma)}{\ln(\Sigma)} \end{gathered} \tag{11.2}$$

$ST(d_{ae})$ is the fraction of particles penetrating beyond the larynx as a function of aerodynamic diameter. $F(x)$ is a cumulative log-normal distribution, with a median aerodynamic diameter Γ of 11.64 μm and a geometric standard deviation Σ of 1.5 (Figure 11.2).

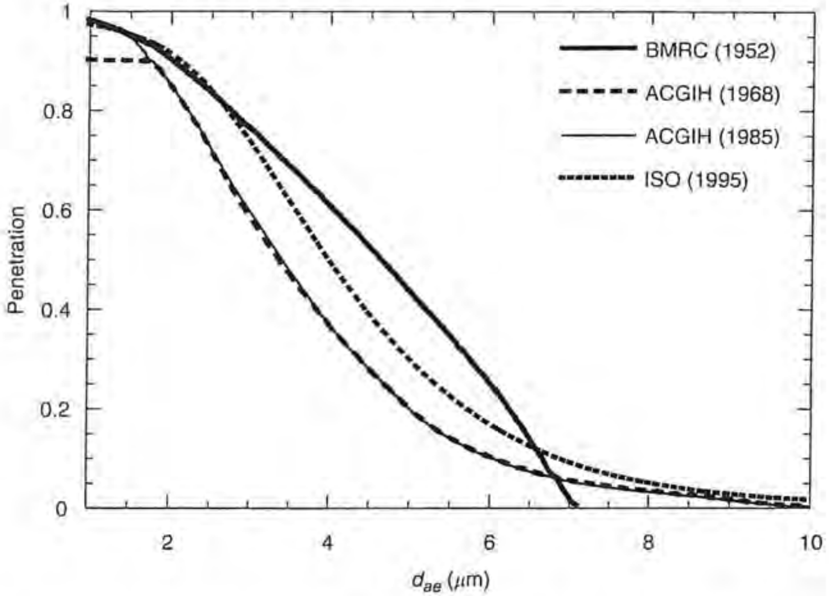

Figure 11.2 Occupational aerosol sampling conventions.[26] The PM_{10} and $PM_{2.5}$ ambient sampling size-selection curves are shown for comparison.

The respirable convention $SR(d_{ae})$ is similarly given as

$$SR(d_{ae}) = SI(d_{ae}) \times (1 - F(x))$$
$$x = \frac{\ln(d_{ae}/\Gamma)}{\ln(\Sigma)} \qquad (11.3)$$

where the cumulative log-normal distribution has a median aerodynamic diameter Γ of 4.25 μm and a geometric standard deviation Σ of 1.5 (Figure 11.2). A respirable convention for susceptible groups is also defined, with $\Gamma = 2.5$ μm. Standards relating to penetration to the tracheobronchial and extrathoracic regions are defined by the difference between the respirable and thoracic conventions (tracheobronchial), and the thoracic and inhalable conventions (extrathoracic), respectively.

Of the three primary sampling conventions, the inhalable convention is least well supported by experimental data. The current convention is based on data collected at wind speeds between 0.5 and 4 m/s, with sampler performance averaged over all orientations to the prevailing wind.[28] Measurements have indicated that air movement in many workplaces lies below the range used to establish the inhalable convention.[29] Determination of aerosol inhalability at low air velocities has indicated that the current convention may not be a good indicator of particle penetration into the respiratory system in all cases.[30,31] In the study by Aitken et al.,[31] inhalability under low wind speeds was consistently found to be greater than the inhalable convention, and was dependent on breathing rate. The convention is also not defined above 100 μm, creating ambiguity over how larger particles should be treated. Aitken and Donaldson[32] have shown that very large particles may enter the nose or mouth as projectiles, and should be considered as being inhalable if airborne (although it has been suggested that few particles larger than 100 μm in diameter will reach the mouth[33]). Above 100 μm, inhalability reduces when averaged over all orientations, reaching zero around 300 μm.[32,34]

The thoracic and respirable samplers are influenced far less by external conditions, and are generally accepted as suitable approximations of aerosol penetration within the general population. The thoracic convention is very similar to the PM_{10} convention used for environmental sampling.[35]

11.4 Exposure regulations

Health-based aerosol exposure limits follow country-specific systems, but in the majority of cases they follow a similar philosophy.[36] In the United States, the Occupational Safety and Health, and Mines Safety and Health Administrations (OSHA and MSHA) enforce permissible exposure limits (PELs). PELs are based on health effects data, but economic and technological feasibility factors are also taken into consideration. The National Institute for Occupational Safety and Health (NIOSH) recommended exposure limits (RELs) are also used, as are the voluntary threshold limit values (TLVs®) published by the ACGIH. RELs and TLVs are primarily based on health effects data. NIOSH RELs are time-weighted average (TWA) concentrations for up to a 10 h workday during a 40 h workweek, while OSHA PELs are TWA concentrations that must not be exceeded during any 8 h work shift of a 40 h workweek. The ACGIH TLVs are 8 h TWA concentrations for a normal 8 h workday and a 40 h workweek, to which nearly all workers may be exposed continuously during their working lifetime, without adverse effects. In the U.K., a two-tier system of occupational exposure standards (OES) and maximum exposure limits (MELs) is employed.[37] Each represents an 8 h TWA exposure limit. An OES is set where a no-effect level can be identified for a substance, thus giving an exposure limit below which adverse effects are not expected (as for the ACGIH TLVs). MELs are employed where there is no clear no-effect level. As some health effects are manifested at whatever exposure limit is chosen (above zero), the choice of a limit is in essence a political decision. Reflecting the nature of substances having MELs, there is an obligation on U.K. industries to keep exposures as low as reasonably practicable, even when this results in a target exposure significantly below the limit. Similarly, the ACGIH defines a threshold limit value-ceiling (TLV-C) for some substances, which should not be exceeded in any part of the overall exposure. Other countries use exposure evaluation systems and limits similar to those used in the U.S. and U.K.

For substances that may potentially lead to health effects following short exposures or high peak exposures, short-term exposure limits (STELs) are set to complement the 8–10 h TWA limits. Samples are taken over shorter time periods — typically 15 min — and are collected during periods when the concentration of contaminant is likely to be highest.

Aerosol exposure in the workplace can be reduced by controlling emissions, or by using personal protective equipment (PPE). Controlling emissions is generally the preferred approach, either by removing the source, applying control measures such as containment or local exhaust ventilation (LEV), or substituting materials with less harmful ones. For instance, NIOSH recommends that respiratory protection be used only when engineering controls are not technically feasible, such as during the installation or repair of engineering controls, or when an emergency or other temporary situations arise.[38] Respirators are the least preferred method against worker protection to air contaminants because of the difficulties generally encountered during implementation of an effective respiratory protection program. Reliable protection depends on the cooperation of the workers to adhere to critical program guidelines.

11.5 Measurement technologies

11.5.1 Samplers

Aerosol samplers are generally defined as devices that collect aerosol particles for subsequent analysis. Historically, there have been a great number of different methods used to sample aerosols in the workplace,[39] and this is reflected in the broad range of devices currently in use. However, with a few exceptions most devices in use today fall into one of four main categories: size-selective samplers, size-differentiating samplers such as cascade impactors, general industrial aerosol samplers (with no clearly defined size selectivity), and biological aerosol samplers. Within these categories, devices may require placement at a static location (static or area samplers) or be worn on the person (personal samplers). Current thinking tends to favor personal samplers as providing a more representative estimate of aerosol exposure, although there are specific instances where static samplers are used. Personal sampler placement is recommended within the breathing zone, defined as a region within 30 cm from the mouth and nose (Chapter 4).[40] Most samplers are positioned on the left or right side of the chest, and occasionally in the center of the chest. Placing samplers to the side and above the head (for instance, on a helmet) has also been proposed for welding and mining.[41,42] OSHA states that for welding, the air sampler should be placed inside the helmet if either no respirator is used or a negative pressure respirator is used.[43]

11.5.1.1 General aerosol samplers

One of the early aerosol samplers in common use was the impinger. This was originally developed as an area sampler,[44] but miniaturized so that it could be worn by workers and operated at a flow rate of 2.8 l/min (Figure 11.3).[45] Air was pulled through a nozzle that was immersed in a liquid, usually water, and was aimed at the bottom surface of a glass chamber. Particles entering the sampler were impacted onto the bottom surface and washed into the liquid. The sampler had a lower particle size cutoff of about 1 μm so fumes and vapors may not have been efficiently collected.[46] The particles in the final liquid suspension were analyzed in a special cell under a light microscope at X100 magnification. At this magnification, only the larger dust particles could be counted and were reported in millions of particles per cubic foot. This device was widely used for various dusts, including coal mine dust and asbestos, until the development of membrane filter methods. It is currently used primarily for sampling bioaerosols and chemically unstable particles, for example, isocyanates. Impingers have been widely evaluated to determine their efficiency and internal losses for bioaerosol sampling,[47–49] and a tangential impinger has been developed specifically to increase the likelihood of bacterial viability (Figure 11.3, Biosampler, SKC Inc.[50]).

Historically, little attempt was made to carry out size-selective sampling other than for respirable aerosol, resulting in many samplers with poor or poorly defined size selectivity

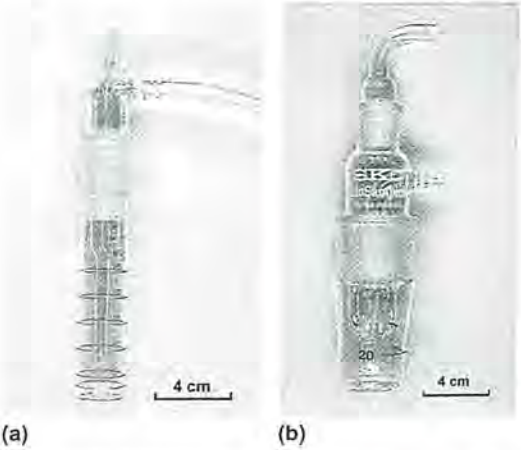

Figure 11.3 Glass impingers: (a) midget impinger and (b) biosampler (SKC Inc., U.S.A.).

being used. Generic filter holders are still widely used, both as "open-faced" samplers (filter face not enclosed) and "closed-faced" samplers (filter protected by a cover through which the aerosol is sampled) (Figure 11.4). The 37 mm filter holder is widely used in the closed form in the United States, and in the open form across Europe. Although the size selectivity of the sampler does not match any sampling convention,[51] its low cost and simplicity has led to its continued widespread use. These cassettes are also commonly used as the sample collection device on size-selective aerosol samplers. Both conductive and nonconductive filter cassettes are available, with the nonconductive variety being prone to electrostatic losses as collected material adheres to the cassette rather than being collected on the filter. Demange et al.[52] reported an average of 30% losses to the walls of nonconducting 37 mm cassettes. The push-fit filter cassettes are also prone to leakage unless assembled properly.[53,54]

The 25 mm cowled sampler (Figure 11.5) is a specialized general sampler used widely for asbestos and fibrous aerosol sampling. Sampling efficiency in calm air is not strongly dependent on particle size for aerodynamic diameters below 20 μm.[55,56] Uneven deposition within the sampler has been seen as a function of orientation[57] (the sampler is usually used facing down). Fiber samples are nominally taken at 2 l/min, although it is common for the sampler to be used at different flow rates to ensure optimal loading of the filter.[58]

Most aerosol samplers are used on the assumption that the collected aerosol will remain stable between collection and analysis. This is clearly not the case when sampling volatile particles, where deposited particles may evaporate during and following the sampling process. The conventional method of dealing with this is to place a sorption tube

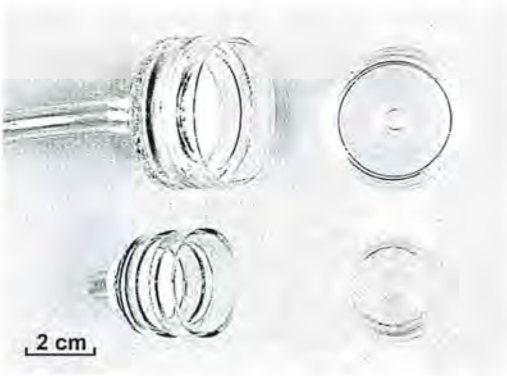

Figure 11.4 Filter holder-based personal aerosol samplers.

Figure 11.5 25 mm cowled sampler.

behind the sample filter, allowing total aerosol and vapor concentration of a particular substance to be measured. However, using this approach it is not possible to directly infer partitioning between the condensed and vapor phase in the workplace atmosphere. One solution proposed to collect volatile aerosols while minimizing evaporative losses has been to use a coaxial electrostatic precipitator[59–61] (Figure 11.6). The sampler consists of a central positive electrode and outer casing that is grounded. Particles entering the sampler are first charged, and then deposited on the outer electrode. Airflow close to the wall surface is low, reducing the rate of evaporation from deposited particles. After sampling, the sampler is sealed at both ends to prevent vapor release, and the component of interest is removed by washing out with a suitable solvent. The sampler has proved to be useful for measuring exposure to JP-8 aviation fuel, particularly in cold environments where the use of a conventional sampler can lead to substantial aerosol evaporation from the collection media.[60]

Most aerosol samplers rely on the use of a pump to move air through the sampling device. Several samplers that do not require a pump have been developed for personal sampling. These passive samplers are particularly attractive in that they can be made much smaller and lighter than conventional units. However, their size selectivity depends on local air movement and generally does not conform to any specific sampling convention.[62–66] Table 11.1 lists a selection of nonspecific personal aerosol samplers.

Figure 11.6 Coaxial electrostatic precipitator, designed for collecting volatile aerosols.

Table 11.1 A Selection of Nonspecific Personal Aerosol Samplers (the List is not Inclusive)

Sampler	Flow Rate (l/min)	Notes	References
37 mm cassette (open)	2	Standard filter cassette, worn facing down at 45° to the body. Conducting versions available. Figure 11.4.	51
37 mm cassette (closed)	2	Standard filter cassette with a cap containing a 2 mm diameter inlet. Figure 11.4.	51
Passive sampler	—	Electret-based sampler relying on aerosol charge and naturally occurring air movements. Correlation is good with some size-selective samplers.	65,153
Coaxial electrostatic precipitator		Designed to sample volatile aerosols. Figure 11.6.	60
Cowled sampler	2 (typical)	Used in the main for fiber sampling. Size selectivity not quantified. Figure 11.5	55,56

References provide information on sampler performance.

11.5.1.2 Inhalable samplers

Measurements of the aspiration efficiency of breathing mannikin established the ideas of inhalability and inhalable aerosol in the 1970s and 1980s.[67–69] As measurements were performed, efforts were made to develop a personal sampler that matched the mannikin's aspiration. The result was a sampler developed at the UK Institute of Occupational Medicine and referred to as the IOM inhalable sampler[70] (SKC Inc.; Figure 11.7). Air is sampled through a 15 mm diameter inlet at 2 l/min. The filter is held within a cartridge, and the whole filter cartridge assembly is weighed, allowing all particles entering the sampling inlet to be measured. Cartridges of either conductive plastic or stainless steel are available, with the latter being more weight stable.[71] The IOM inhalable sampler generally agrees with the inhalable convention at wind speeds between 0.5 and 2.6 m/s.[51,70] However, at low wind speeds there is a marked divergence, with the sampler oversampling.[72] The open inlet is susceptible to large particles entering through their own inertia (projectiles), and is some cause for concern when sampling near sources of such particles.[32]

Preventing projectiles from entering the IOM inhalable sampler has been addressed by considering placing screens in front of the inlet.[32] A similar approach has been used in the Button sampler (Figure 11.8; SKC Inc., U.S.A.[73]). This sampler consists of a 25 mm filter holder with a hemispherical perforated screen covering the sampling inlet. The screen serves a fourfold purpose — reduction of aspiration dependency on wind speed, formation of a uniform deposit on the filter, reduction of internal deposits, and exclusion of large projectiles from the sample. Tests have indicated a good agreement between the sampler and the inhalable convention.[74]

The CIP-10 sampler (Figure 11.9, ARELCO, France) avoids the aspiration of large particles by using a convoluted inlet design, which also serves as an inhalable fraction

Figure 11.7 IOM personal inhalable sampler (SKC Inc., U.S.A.).

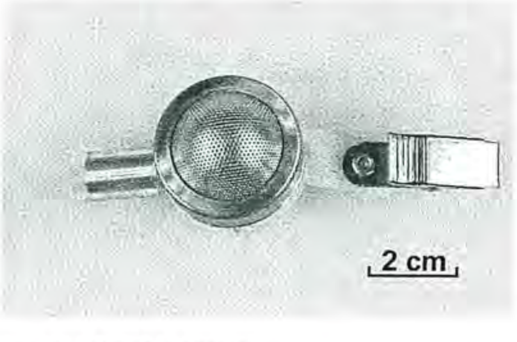

Figure 11.8 Button sampler, for inhalable aerosol.

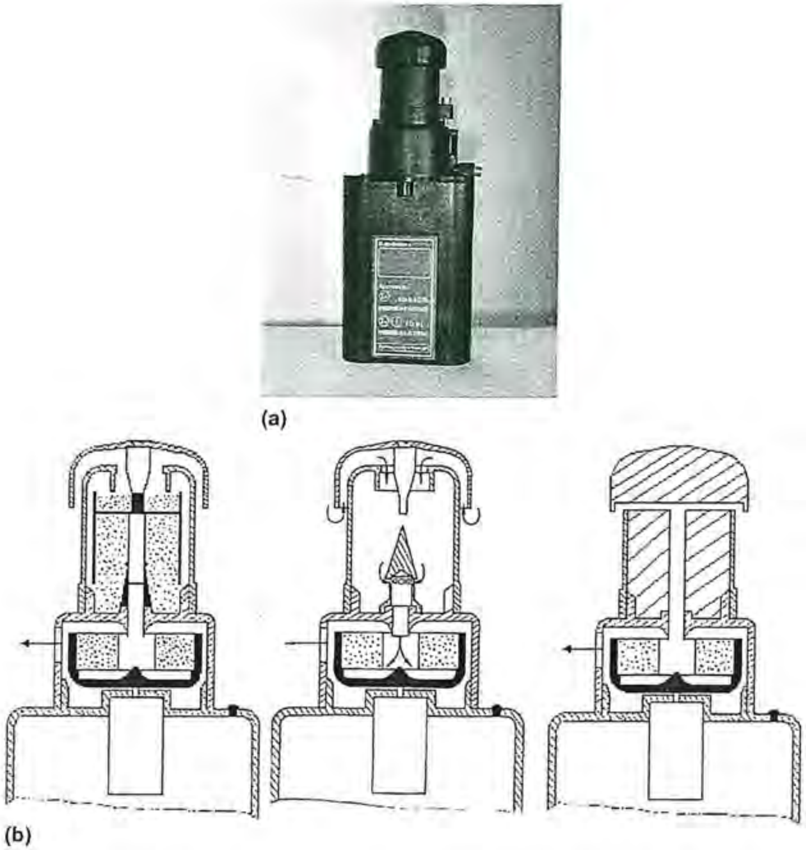

Figure 11.9 CIP-10 sampler (ARELCO, France), showing schematics of the three size-selective sampling heads: (a) respirable selector, (b) thoracic selector, and (c) inhalable selector.

preseparator. Air movement through the sampler is driven by a rapidly rotating foam ring held in a cup, acting as a centrifugal pump. With this arrangement, sampling rates up to 10 l/min are achievable. Sampling can only be achieved with a low pressure drop across the device, preventing the use of conventional filters to collect the sampled aerosol. Instead, the rotating foam is used to collect the particles. Reasonable agreement is seen between the sampler and the inhalable convention,[51,75,76] although submicrometer particles penetrate the foam and are not collected efficiently.

Various other inhalable samplers are in use, including the GSP inhalable sampler, the conical inhalable sampler (CIS, based on the GSP, JS Holdings, U.K.), and the PAS-6 inhalable sampler (Figure 11.10). These three samplers all use a conical inlet, and appear not to be as susceptible to external wind speed as other devices.[51] Table 11.2 lists a selection of inhalable personal samplers.

11.5.1.3 *Thoracic samplers*

Very few exposure limits are referenced to the thoracic fraction, and thus there are correspondingly few thoracic samplers available. One of the first to find widespread use was the vertical elutriator used to sample cotton dust. This is a static sampler operated at 7.4 l/min, and does not show good agreement with the thoracic sampling convention.[77]

The CIP-10 personal sampler was designed as a modular system, capable of being configured to match a range of sampling conventions.[75] A modified sampling head is

Figure 11.10 Conical inlet inhalable samplers: (a) PAS-6, (b) GSP sampler, and (c) conical inhalable sampler (CIS, JS Holdings, U.K.).

Table 11.2 A Selection of Inhalable Personal Aerosol Samplers

Sampler	Flow Rate (l/min)	Notes	References
IOM inhalable	2	Uses filter cassette. Susceptible to large projectiles. Wind speed dependent. Figure 11.7.	51,70,72
CIP-10I	10	Rotating porous foam acts as an air mover, and collection medium. Figure 10.9.	51,76,92
GSP inhalable	3.5	Conical inlet sampler. Figure 11.10b.	51
Conical inhalable	3.5	Based on the GSP sampler. Figure 11.10c.	51
Seven hole Sampler	2	Also known as the multiorifice, or UKAEA sampler.	51
Single hole	2	Used for lead aerosol sampling in the U.K.	51
PAS-6		Conical inlet sampler. Figure 11.10a.	51
Button sampler	4	Perforated inlet reduces wind speed dependence and intersampler variability, and leads to a uniform filter deposit. Figure 11.8.	73, 154

References provide information on sampler performance.

available for the device, allowing it to be used as a thoracic sampler at 7 l/min (in this configuration it is referred to as the CIP-10T).[78] A static version of the sampler — the CATHIA sampler — allows sampling onto a 25 mm filter with an external pump. The sampler shows reasonable agreement with the thoracic convention,[78] but a tendency to oversample in calm air.[55] The GK2.69 cyclone (Figure 11.11, BGI Inc., U.S.A.) is an alternative personal sampler designed to follow the thoracic convention at 1.6 l/min. It has been used for measuring metal working fluids.[79] It also doubles as a respirable sampler when operated at 4.2 l/min. Samples are collected on a 37 mm filter, and the sampling efficiency is close to the thoracic convention under calm air conditions.[55]

Figure 11.11 GK 2.69 cyclone (BGI Inc., U.S.A.). The sampler may be used for either respirable or thoracic aerosol sampling.

Research on aerosol separation in porous polyurethane foams (PUF) has indicated that penetration is predictable based on foam porosity and face velocity,[80,81] and PUF has subsequently been used in several personal aerosol samplers. The IOM thoracic sampler uses a 24 mm length of 30 pores per inch (ppi) PUF behind an inhalable inlet, collecting the penetrating aerosol onto a 37 mm filter. When operated at 2 l/min, the sampling efficiency is close to the thoracic convention, but the sampler tends to over-sample in calm air conditions.[55] The same idea has been used to modify the IOM inhalable sampler by placing an appropriate foam plug in the inlet.[82] Measurements using a 17.5 mm diameter, 10 mm deep, 45 ppi foam plug indicated that the sampler followed the thoracic convention reasonably well, although the sharpness of the penetration function led to a large predicted sampler bias for aerosols with mass median aerodynamic diameters much larger and smaller than 10 μm.[55] PUF inserts are available for the IOM inhalable sampler, and the GSP and CIS samplers, allowing them to be used as thoracic or respirable sampling devices.

Thoracic samplers can potentially be used to sample fibrous aerosols, allowing fibers to be sampled while preventing large compact particles and clumps of fibers from reaching the collection substrate.[83] It is thought that such an approach may increase the precision of fiber concentration measurements where large numbers of clumps and compact particles are present.[84-86] Maynard[87] has demonstrated that a number of currently available thoracic samplers may be suitable for fiber sampling, although deposition inhomogeneity on the collection substrate when using cyclones may contribute to measurement errors. Jones et al.[88] have shown that using thoracic samplers to sample for asbestos leads to results comparable with conventional techniques, although in this study there was little evidence for an increase in precision when using size-selective sampling.

PM_{10} samplers used for ambient aerosol sampling have similar size selection characteristics to thoracic samplers, and may be used in their stead with little reduction in sampling accuracy.[35] Versions of the personal environmental monitor (PEM) model 200 (MSP Corp., U.S.A.) allow personal PM_{10} sampling at either 4 l or 10 l/min (Figure 11.12). Table 11.3 lists a selection of personal thoracic samplers.

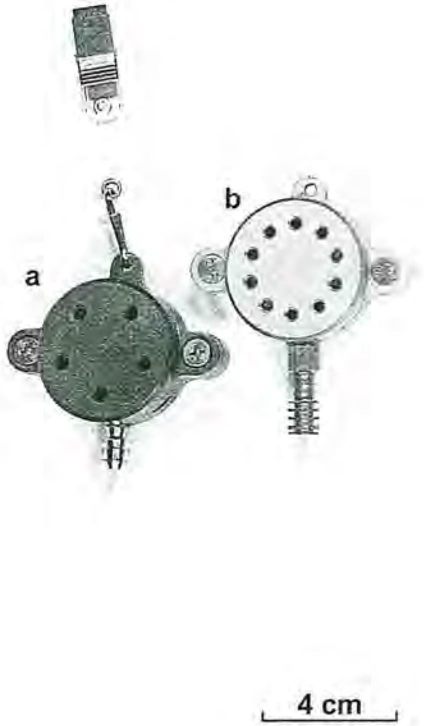

Figure 11.12 Personal PM_{10} impactors: (**a**) 4 l/min and (**b**) 10 l/min (MSP Corp., U.S.A.).

Table 11.3 A Selection of Thoracic Aerosol Samplers

Sampler	Flow Rate (l/min)	Notes	References
Elutriator	7.4	Static sampler. Specific to cotton dust.	77
CIP-10T	7	CIP-10I with a thoracic separation stage. Figure 11.9.	78
CATHIA	7	Static version of the CIP-10T.	78
IOM thoracic	2	Separation based on PUF	55
GK 2.69 cyclone	1.6	Can also be used as a respirable sampler (Table 11.4). Figure 11.11.	55
PEM Model 200	4, 10	PM_{10} personal sampler. Figure 11.12.	35
IOM inhalable + thoracic foam	2	IOM inhalable sampler with a size-selective PUF insert.	55

All samplers are personal except for the elutriator and the CATHIA. References provide information on sampler performance.

11.5.1.4 Respirable samplers

It has long been recognized that particles capable of reaching the alveolar region of the lungs are potentially more harmful than those depositing in the upper airways, and as a result many respirable aerosol samplers have been developed and used. One of the earliest was the U.K. Mines Research Establishment (MRE) MRE 113A horizontal elutriator, developed to monitor the concentration of respirable aerosol in mines (Figure 11.13). This sampler is still used as the main sampling method in U.K. mines and is the reference sampler in U.S. coal mines. As the BMRC respirable convention was developed from elutriation theory, this sampler shows close agreement with the old convention, but only fair agreement with the current international convention (see Figure 11.1). This device is only used as an area sampler as it is relatively large.

The SIMPEDS or Higgins and Dewell (U.K.) and Dorr-Oliver (U.S.A.) cyclones are both personal respirable samplers that have a long and continued history of use (Figure 11.14). Both were designed to follow older sampling conventions. However, both show good agreement with the current international respirable convention when operated at 2.2 and 1.7 l/min, respectively.[89,90] The Dorr-Oliver cyclone is constructed from nonconducting nylon, raising the possibility of electrostatic losses within the sampler. In addition,

Figure 11.13 MRE 113A respirable sampler.

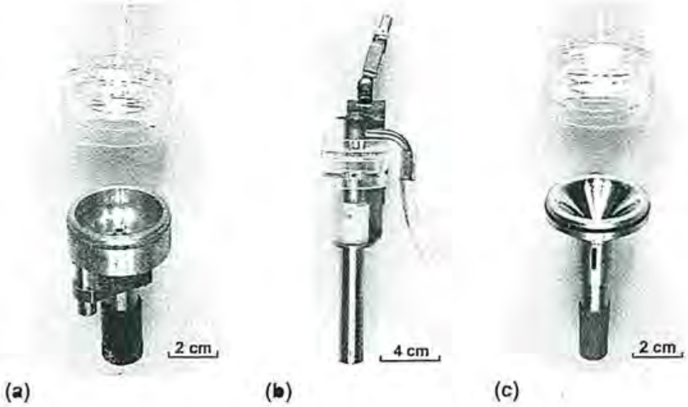

Figure 11.14 Respirable cyclone samplers: (a) Higgins and Dewell or SIMPEDS cyclone, (b) Dorr-Oliver (nylon) cyclone, and (c) SKC aluminum cyclone (SKC Inc., USA).

because the primary application for this cyclone does not require it, the manufacturer has little interest in high dimensional accuracy and so slight changes in cyclone dimension occasionally occur.

Cyclones lend themselves well to personal sampler design, and recent years have seen a number of improved samplers emerge. A novel extension of the cyclone principle is the virtual cyclone[91] (Figure 11.15, Omega Specialty, U.S.A.). Sampled air is passed round a 90° bend. Large particles are inertially separated from the flow, and collected in a large collection chamber. Respirable particles closely follow the airflow through the device, and are collected on a filter at the outlet. As the device does not rely on separated particles depositing on internal surfaces, it is potentially less prone to overload than other comparable samplers.

PUF preseparators are also used in respirable samplers. The CIP-10 sampler is available in a respirable form (as the CIP-10R) with a PUF preseparator in the sampling head. The sampling characteristics of the device are good,[92] although there is a possibility of nonrespirable particles migrating to the sample media under heavy agitation. It is also possible to convert the IOM inhalable sampler into a respirable sampler by inserting an appropriate PUF disk into the inlet.[93] Chen et al.[94] developed a sampler using two sections of PUF having different porosities in parallel to match the respirable curve more exactly (Figure 11.16). Table 11.4 lists a selection of personal respirable samplers.

11.5.1.5 *Multifraction samplers*

A small number of samplers are available that allow all three size fractions to be collected simultaneously. The PERSPEC[95,96] is a personal sampler designed to deposit different aerosol fractions in different regions on a 47 mm filter. Aerosol sampled at 2 l/min is winnowed in a highly divergent clean sheath flow, leading to deposition position on the filter being particle size dependent. When the filter is cut using an appropriate tool, the weight of material collected in different regions enables estimates to be made of the selected aerosol fractions.[97]

Sequential PUF sections of differing porosity and length are used in the IOM personal multifraction sampler to separate out the three different fractions.[80] The device uses an inhalable inlet, and thus the mass of all particles collected in the PUF sections and on the

Figure 11.15 Virtual cyclone respirable aerosol sampler (Omega Specialty, U.S.A.).

Figure 11.16 Foam cyclone respirable sampler (Omega Specialty, U.S.A.).

Table 11.4 A Selection of Respirable Personal Aerosol Samplers.

Sampler	Flow Rate (l/min)	Notes	References
CIP-10R	10	CIP-10I with a respirable separation stage. Figure 11.9.	92
SIMPEDS cyclone	2.2	Also known as the Higgins and Dewell (HD) cyclone. Figure 11.14.	89,90,155
SKC cyclone	1.9 – 2.75	Sampling flow rate depends on cyclone type and respirable convention used. Figure 11.14.	154
GK 2.69 cyclone	4.2	Can also be used as a thoracic sampler (Table 11.3). Figure 11.11.	55
Dorr-Oliver (10 mm) cyclone	1.7	Sampler constructed from nonconducting nylon. Figure 11.14.	89
MRE 113A (gravimetric dust sampler)	2.5	Static sampler. Use limited to sampling in mines. Figure 11.13.	156
IOM inhalable + respirable foam	2	IOM inhalable sampler with a size-selective PUF insert.	157
Foam cyclone	2	Cowled sampler with size-selective PUF Figure 11.16.	94
Virtual cyclone	3.3	Provides a good match with the respirable convention slope. Figure 11.15.	91

All samplers are personal except for the MRE113A. References provide information on sampler performance.

backing filter gives the inhalable fraction. The PUF sections are designed so that aerosol reaching the backing filter represents the respirable fraction, while that in the adjacent PUF section and filter combined gives the thoracic fraction. The same idea has been proposed for PUF inserts for the IOM personal inhalable sampler,[72] although it is not clear how the shallowness of the PUF disks will necessarily affect overload and measurement accuracy within the sampler.

The RESPICON sampler (Figure 11.17, TSI Inc., U.S.A.) presents a third approach to multifraction sampling.[98] Aerosol is passed through two virtual impactors in series. Particles of sufficient inertia are passed through to the next stage, while those that follow the major flow are collected on a filter. Thus, unlike a conventional cascade impactor, large particles collect on the final filter and small particles on the first stage of the impactor. All particles entering the device represent the inhalable fraction. Particles collecting on the first-stage filter represent the respirable fraction, while those on the first- and second-stage

Figure 11.17 Respicon® three-fraction aerosol sampler (TSI Inc., U.S.A.).

filters represent the thoracic fraction. About 10% of the smaller particles are deposited on each of the last two stages, and the results obtained have to be adjusted accordingly.

Cascade impactors provide somewhat more detailed information on particle size distribution (Chapter 3), but may be used to derive exposure to the three aerosol fractions. These are generally capable of giving the size distribution of an aerosol between around 0.1 and 15 μm aerodynamic diameter and above. Static cascade impactors such as the Anderson eight-stage impactor and the multiorifice uniform deposit impactor (MOUDI; MSP Corp., St. Paul, MN) have found relatively widespread use in the workplace. The Anderson impactor consists of eight multiorifice stages with cut points between 0.4 and 10 μm when operated at 28.3 l/min. Collection is usually onto aluminum foils, although other substrates are available. The use of multiorifices in the Anderson impactor allows deposits to be distributed with relative evenness onto substrates. This is taken further within the MOUDI, where many orifices per stage, together with rotating substrates, lead to highly uniform deposits. The MOUDI is available in an 8-stage or 10-stage version, and is capable of making aerosol size distribution measurements down to 0.056 μm at 30 l/min. An extension of the MOUDI — the nanoMOUDI — has recently become available from the manufacturer that adds stage cut points of 10, 18, and 32 nm.

Aerosol size distributions within the breathing zone are generally of greater relevance to health than static samples, and three cascade impactors have been developed to enable personal aerosol size distribution measurements to be made. The Marple personal cascade impactor (Anderson, U.S.A., Figure 11.18)[99] is configurable with up to eight stages, and will provide information on particle size distribution down to 0.5 μm at a flow rate of 2 l/min. The personal inhalable dust spectrometer (PIDS) is similar in concept to the Marple impactor, although the slot-shaped impactor jets of the Marple device are replaced by circular jets.[100] Cut points in the eight stages of the PIDS range from 0.9 to 19 μm at 2 l/min. Another personal cascade impactor designed for "home" use is the personal cascade impactor sampler (PCIS).[101] This device has cut points between 0.25 and 2.5 μm and operates at 10 l/min, making it particularly well suited to sampling low aerosol concentrations, and is commercially available as the Sioutas cascade impactor (SKC Inc., U.S.A.).

Cascade impactors are of limited use for measuring aerosol size distributions up to the limit of the inhalable convention (100 μm aerodynamic diameter), because the cut point of

Figure 11.18 Marple personal cascade impactor (Anderson, U.S.A.). An impaction stage is shown to the right; each stage collects particles from the previous stage nozzle and has slot nozzles for the subsequent stage.

the upper stage of most of these devices is relatively low. Extrapolation of measured size distributions above this cut point is dependent on assumptions about the sampled aerosol and the aspiration efficiency of the device, and is generally not reliable. However, the PIDS was designed with an inlet designed to follow the inhalable convention.[100] It may be assumed that summing all deposits within the PIDS impactor gives a measure of the inhalable aerosol mass, and subsequent analysis of the deposits gives the size distribution as a function of inhalable aerosol. Such an approach is advantageous to industrial hygiene measurements, where ultimately measurements need to be related to the mass of particles inhaled. Vincent and co-lookers[102,103] have approached this by inserting a PUF plug with known separation characteristics into the inlet of an Anderson cascade impactor.

Analysis of cascade impactor data is a complex issue, to which there may not be a completely satisfactory solution. There is a long tradition in industrial hygiene of fitting the impactor data by assuming that a log-normal distribution is the true underlying distribution. This was done graphically for many years, but the availability of increased computer power has allowed more complex fitting of the data.[104] The simplest approach is to assume that the 50% cut point of each stage is an absolute value and that no particles smaller than that cut point deposit on subsequent stages. One can further assume that the size distribution of the dust measured can be represented by one or two log-normal size distribution modes. A simple spreadsheet program can be used to extract the mass median aerodynamic diameter (MMAD) and the geometric standard deviation (σ_g) for each mode.[105] However, the accuracy of this approach is questionable because of several confounding factors: the cut point of each stage is not an absolute value, that is, there is an overlap in the collection efficiency for adjacent stages; there are losses of particles within the cascade impactor; particle bounce can cause large particles to end up on stages downstream of their intended target stage; and there is variability associated with measurement of the particle mass on each stage. The first two factors can be accommodated by the accurate assessment of collection efficiency of each stage and of losses within the impactor. This information has been published for some cascade impactors.[99–101] Even with this information, the inversion or deconvolution of the data is complex because, with overlap in stage collection efficiencies and the presence of noise in the data, there is no single correct answer, i.e., the problem is ill-conditioned. There is an extensive literature on attempting to provide the best solution, and the technique recommended by Kandlikar and Ramachandran[106] in their literature review is the first-order regularization technique. An alternative to the regularization method for a single log-normal distribution is the nonlinear least-squares approach, which allows the calculation of accuracy estimates.[107] These relatively simple approaches take into account the stage efficiencies as well as the expected level of measurement error for the mass collected on each stage.

If there is clearly a single log-normal mode in the particle size distribution, either the regularization or nonlinear least-squares methods can give a reasonably accurate MMAD and σ_g. However, fitting a more complex distribution, for example, with two modes, is problematic because five or more parameters must be determined with only seven or eight degrees of freedom (from the number of stages). In many instances, it is probably better not to try to extract information about log-normal modes that might be present. There is usually a large range of distributions that can fit the data equally well. If the cascade impactor data are used to estimate the respirable, thoracic, and inhalable fractions, it may be more accurate not to try to fit the size distribution, but rather to use just the raw mass data and assume a sharp cut for each stage.

11.5.1.6 *Sample analysis*

Aerosol sample analysis methods are matched to the sampled material and the appropriate exposure metric. Samples are generally collected onto a filter, within a PUF, or onto an impenetrable impaction substrate such as aluminum or mylar (which is usually coated with a layer of grease or oil to prevent particle bounce).

Personal liquid impinger samplers are still occasionally used, allowing the aerosol to be directly collected into a liquid suspension. Because of the difficulties of handling and using liquid collection media in the field, the application of impingers for nonbiological aerosols is generally limited to isocyanate aerosols,[108,109] which are chemically unstable and must be immediately reacted with a complexing agent for accurate assessment. Impingers are also used for bioaerosols, but not usually as personal samplers.

Filters may be held in a cartridge within the sampler, as is the case with the IOM inhalable sampler, or may be mounted directly into the sampling head. Chemical analysis of aerosol components is usually component specific.[110] Analysis of metals is usually by spectroscopic analysis; atomic emission spectroscopy is frequently used, and mass spectrometry provides a more sensitive alternative. Crystalline silica is quantified using either x-ray powder diffraction or infrared spectroscopy. Radioactive aerosols are generally collected on filters, and characterized using off-line radiation detectors (see Chapter 13). Other chemical species are analyzed using a range of standard analytical techniques, including gas chromatography, high-performance liquid chromatography (HPLC), and so on. Viable biological organisms are generally characterized by the number of colony-forming units (CFUs) collected, following incubation on a suitable culture medium,[111,112] while the total concentration of specific organisms can be determined using techniques such as PCR.[113-116] Where samples are characterized on the collection substrate, care needs to be taken to ensure that the sample is presented appropriately for analysis, and background levels of the analyte (or any confounding components) are at suitably low levels. In many cases, collected particles are transferred to an appropriate medium for subsequent analysis, requiring the collection substrate to be matched to the preparation process.

Gravimetric analysis is used to characterize exposure to nuisance dusts, where specific chemical speciation is not required. The accuracy of gravimetric samples may be affected by water adsorption onto substrates and filter cartridges, and by losses or gains in material during transit.[117,118] In particular, cellulose ester membrane filters, PUFs, and conducting plastic filter cartridges are particularly prone to weight changes following water uptake.[71,119] Substrates such as mylar have been found to outgas substantially following removal from storage, and may take several days to reach a stable weight before being useable for gravimetric sampling. To combat bias from such sources, it is common practice to weigh a number of control or blank filters with each set of sample filters (typically one blank per ten samples, with a minimum of three blanks). Filters should be conditioned in the weighing area (preferably a temperature- and humidity-controlled environment) for up to 24 h before weighing to allow them to reach an equilibrium weight.[120,121] Desiccation is generally not advisable prior to filter weighing, as weight changes after removal of the filter can be sufficiently rapid to lead to significant weighing errors.[71] Where possible, blank filters should be transported with the sample substrates and exposed to the same conditions, to minimize bias resulting from handling, transport, and changes in environment.[122]

Other sources of bias include electrostatic attraction where substrates are highly charged, and buoyancy effects. Electrostatic charge buildup may be significant for substrate materials such as PVC and PTFE, particularly when working at low relative humidity. In all instances, samples should be neutralized using a source of bipolar ions. A common approach is to place samples close to a radioactive antistatic source prior to weighing. Buoyancy corrections only become necessary when the volume of the sample exceeds around 0.1 cm^3. For most substrates, this is not a problem, although it may be significant when using large integral filter cartridges or substrate supports.

Asbestos and other fibrous aerosols are characterized in terms of particle number concentration and aspect ratio. Fiber detection and analysis following collection is carried out using either phase contrast microscopy (PCM), polarized light microscopy (PLM), scanning electron microscopy (SEM), or transmission electron microscopy (TEM), depending on what information is required from the sample. PCM is most frequently used to measure airborne concentrations of fibers in occupational settings, as it is relatively quick and inexpensive. To image fibers in a light microscope, they are collected on cellulose ester filters that are chemically cleared on a glass slide, and to provide contrast when imaging the fibers (usually a liquid or resin with a refractive index close to that of the filter is used to impregnate the sample and fill the gap between the sample and the cover slip). The use of PCM allows fibers thicker than around 0.25 μm to be detected, and enables the number of fibers collected to be estimated. The exact definition of fibers in the context of exposure standards varies with the standard used. OSHA and NIOSH "A" asbestos counting rules [123] allow all particles longer than 5 μm with an aspect ratio equal to or greater than 3:1 to be counted, while the Environmental Protection Agency (EPA) uses the definition of particles longer than 0.5 μm with an aspect ratio greater than 5:1. The EPA method is used primarily for evaluating the cleanliness of locations being cleared of asbestos-containing materials and is not designed to provide concentrations that have health relevance. NIOSH "B" counting rules allow particles larger than 3 μm in diameter to be discounted when characterizing MMVF samples (which OSHA treats as a nuisance dust).

The measurement of asbestos by PCM involves the preliminary assumption that all fibers detected are asbestos, since asbestos fibers often cannot be accurately discriminated from other fibers. During the 1960s and 1970s, most occupational asbestos operations still created high levels of exposure and this assumption was valid. However, in recent years, the exposure levels have dropped significantly and other fibers may constitute a significant fraction of fibers sampled in workplaces and asbestos abatement or removal sites. NIOSH recommends the use of TEM to determine the fraction of asbestos fibers in a sample and apply that fraction to the PCM fiber count to obtain the final asbestos fiber count.[123]

There are a number of error sources encountered in fiber counting, including sampling error, nonuniformity on collection filters, and human counting error. As a result, the errors associated with measuring airborne fiber concentration can be relatively high. To minimize errors, several interlaboratory proficiency schemes exist to ensure that analytical laboratories are operating within acceptable accuracy limits (e.g., RICE (the UK Regular Inter-Laboratory Counting Exchange), AFRICA (the international Asbestos Fiber Regular Interchange Counting Arrangement), PAT (American Industrial Hygiene Association (AIHA) Proficiency Analytical Testing), and AAR (AIHA Asbestos Analysts Registry) programs). One of the limitations of PCM is that fibers around 0.25 μm in diameter are hard to detect with 100% efficiency. In principle, fiber counting using TEM or SEM overcomes this limitation, allowing fibers with diameters down to nanometer widths to be detected and counted.[123,124] However, somewhat inexplicably interlaboratory comparisons with TEM analysis have shown poorer accuracy over PCM.[125]

One of the advantages of SEM and TEM analysis is that analytical systems such as X-ray energy dispersive spectroscopy (EDS or EDX) and selected area electron diffraction (SAED) allow elemental analysis of fibers, and thus identification of fiber type/source. Optical PLM can also be used to identify asbestos fibers from nonasbestos fibers (asbestos fibers appear bright under cross-polarization), and goes some way toward identifying asbestos types. However, PLM can only be applied to fibers thicker than about 1 μm in diameter and cannot be used on the same sample used for PCM counting.

11.5.2 *Direct reading instruments*

11.5.2.1 *Personal exposure measurements*

Most occupational exposure measurements are made using traditional sampling and laboratory analysis techniques. This approach, while providing accurate measurements, often requires days or weeks to provide feedback on specific exposure situations. Quite often, the aerosol concentration in a workplace is highly variable and sources of the aerosol are close to the workers or associated with the workers' activities. Direct reading instruments are often used to aid in the development and optimization of dust control systems. Direct reading instruments have the potential to provide immediate feedback to the workers regarding their environment. If the workers can associate specific locations or actions with high aerosol concentration, then, by taking appropriate action, they may be able to quite significantly reduce their exposures.

Several approaches to direct reading instrumentation have been used to provide real-time readout. When sufficiently small instruments were not available, some researchers used larger instruments and placed them in the vicinity of the worker, extracted aerosol from the neighborhood of the worker and ducted it to the instrument, or put the instruments into a holster or backpack and placed them on the worker. A variety of physical mechanisms can be used to detect aerosol particles, and some of these have been incorporated into small portable commercial instruments. In many cases, these instruments are small enough to be worn by a worker.

11.5.2.2 *Light scattering instruments*

Light scattering detection of dust provides the advantage of designing instruments that have a quick response and are relatively inexpensive. The disadvantage of these instruments is that the response depends strongly on the dust particles' size, shape, and refractive index.[126] Most of these parameters are not only difficult to predict for a given occupational setting, but may also change with time. The effect of particle size can be accommodated to some extent by using an optical particle counter (OPC), which indicates particle optical diameter, a parameter approximately proportional to aerodynamic diameter. However, when the dust characteristics are not expected to change significantly, calibration of a light scattering instrument may result in good measurement accuracy.[127]

11.5.2.2.1 Optical particle counters The interaction between light and airborne particles is complex and except for some simple particle shapes, such as spheres and fibers, cannot be accurately predicted. However, there are some generalizations that can be made based on spherical particles and on experimental evidence. The amount of light scattered from a particle is a complex function of particle size, shape, and refractive index, as well as instrumental factors such as light beam size, shape, and intensity, and detector sensitivity and measurement angle. When the particle is smaller than the wavelength of light, this is called the Rayleigh scattering regime and the amount of light scattered increases proportional to the 6th power of the particle diameter. Thus, the lower limit of single-particle detection occurs because most light sources cannot scatter enough light from small particles to be detected by a detector. Inexpensive instruments that detect single particles (OPCs) typically do not detect particles smaller than 0.3 μm. By using a higher powered laser and more efficient detectors, more expensive instruments can detect down below 0.1 μm diameter. Another technique for increasing sensitivity is to decrease the wavelength of the light source. When shorter wavelength LEDs or solid-state lasers become less expensive, these may be incorporated into handheld instruments as well. A typical handheld OPC is shown in Figure 11.19.

When the particle is larger than the wavelength of light, this is called the Mie scattering regime and the amount of light scattered increases very roughly with the particle diameter. However, the interaction of light with a spherical or another regularly shaped particle, can produce resonances within the particle, and the amount of light scattered to

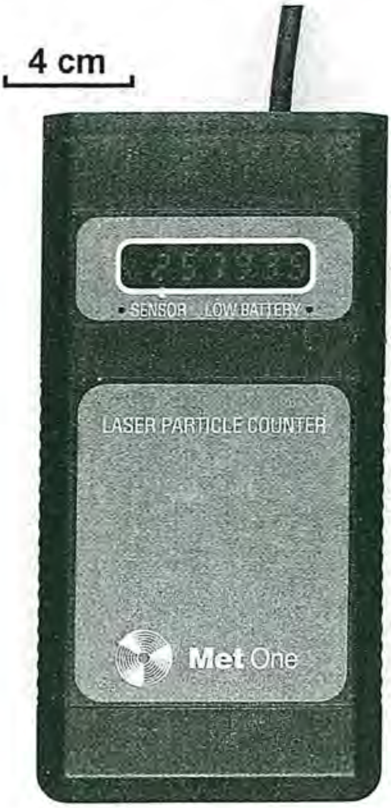

Figure 11.19 Met One handheld optical particle counter (Met One, U.S.A.).

a detector is a complex function of size. While the scattering of spherical particles can be predicted theoretically with great accuracy, irregularly shaped particles have a less well-defined scattering efficiency and cannot be predicted. The absorption component of the refractive index plays an important role in the amount of light scattered; for instance, a coal particle scatters less light and appears smaller optically than a glass particle when measured by an OPC. Thus, the amount of light scattered is only an approximate indicator of particle size. Although many OPCs indicate that they detect particles, for example, larger than 5 μm, this is not an accurate measure and is only approximately correct for the particles with which the instrument was calibrated.

An OPC detects the light scattered from a particle as the particle passes through a small detection volume. Several factors play a role in the detection efficiency of the OPC and its ability to handle a desired range of concentrations. If more than one particle passes through the detection volume at a time, these coincident particles are detected as a single larger particle, reducing the accuracy of the count. Thus, there is a limited range of concentrations for most particle counters. The upper limit is determined by coincidence, often represented by a 10% coincidence level, that is, 10% of the detected counts are of two or more particles. The lower concentration limit is determined by the acceptable statistical error of counting relatively few particles. Thus, an OPC that is used for clean rooms might have a high sampling rate through a relatively large detection volume to maximize the number of particles detected. On the other hand, for many workplace situations, the particle number concentration can be high, so an OPC for this application should have a small detection volume and low flow rate. Otherwise, a dilution system is needed to match the OPC to the concentration being measured.

Relatively inexpensive OPCs are available. Instruments that detect all particles above a cutoff size, such as 0.3 or 0.5 μm, provide a simple indication of total count. More sophisticated instruments may have several selectable lower size cutoffs (Figure 11.20). Some instruments provide up to six size bins so that a size distribution can be measured. More than six size bins are not useful for most applications because of the imprecision in light scattering response as a function of particle size. One example of a handheld instrument that measures particle size distribution is the GRIMM 1.10 series of OPCs (Figure 11.20a, Grimm Technologies Inc., Germany). These instruments not only measure size distributions, but the software allows the calculation of several dust fractions, such as thoracic,

(a) (b)

Figure 11.20 Handheld size-differentiating optical particle counters: (a) Grimm Series 1.10 dust monitor (Grimm Technologies, Germany) and (b) HHPC-6 optical particle sizer (ARTI, U.S.A.).

respirable, and $PM_{2.5}$. They also have a built-in filter sampler that can be used to calibrate the dust mass response. Another example of a similar instrument is the ART Instruments HHPC-6 handheld OPC (Figure 11.20b, ARTI, U.S.A.). The HHPC-6 is a six-channel handheld device that measures and displays size-resolved aerosol concentration in real time. Both of these instruments can download logged data to a computer for further analysis.

11.5.2.2.2 Photometers Photometers (also called nephelometers) rely on the same light scattering that OPCs measure, except that the detection volume is sufficiently large that the scattering from many particles is detected simultaneously. The integrated scattering signal provides an indication of concentration. The total light scattering detected in such an arrangement is a function of the number, sizes, and refractive indices of all the particles present in the detection volume. Thus, if an unknown airborne material is being detected, the mass concentration of that material cannot be predicted. However, if the material is from a source that is well characterized, or at least constant, the photometer can be calibrated to give a reasonably accurate estimate of mass concentration. Photometer response as a function of aerosol mass concentration is only weakly dependent on particle size in the transition region between Rayleigh and Mie scattering (roughly 0.3 to 10 μm). Beyond these limits, response depends on the size distribution of the aerosol, and the method is generally inappropriate for measuring aerosols dominated by particles outside this region.

The simplicity and rapid response of photometers make them attractive for detecting sources, evaluating controls, and evaluating time-dependent concentrations. Some instruments depend on local air motion to propel the aerosol to the sensor, but, generally, use of a pump to actively pull the aerosol through the sensor provides a more accurate and quicker response (as in the DustTrack (TSI Inc., U.S.A.) shown in Figure 11.21).[128] The size-dependent mass response of these instruments is somewhat similar to the response

Figure 11.21 DustTrak aerosol photometer (TSI Inc., U.S.A.).

required for respirable sampling, so, once calibrated for a specific dust, they can be used to obtain respirable mass concentrations with reasonable accuracy. This approach was described by Baron[129] and has been used for borate aerosols,[130] coal dust,[131] environmental and home aerosols,[127] and fire smoke.[132] Monitoring dust close to a source is more problematic because the size distribution and character of the dust is more likely to change with time, thus reducing the accuracy of calibration. This was noted for personal exposure correlations with filter samplers in home environments.[127]

It must be remembered that these direct reading instruments detect all aerosol particles with little difference in response due to chemical, biological, radiological, or morphological differences in composition. Therefore, when a specific component of the total aerosol present is being investigated, photometers or OPCs may provide a poor indication of the concentration of that component. This is often true in occupational settings where many potential sources of aerosol exist. It has also been noted in the environmental field, where personal exposure includes not only aerosol from the ambient environment but also aerosol from the personal environment, for example, clothing, home, office, and car. Thus, personal measurements may not be appropriate with a nonspecific direct-reading instrument in these cases.

11.5.2.3 Tapered element oscillating microbalance

The tapered element oscillating microbalance (TEOM®, Rupprecht and Patashnick, NY) has been used in the environmental field for many years and has been accepted as providing an accurate and rapid indication of airborne particle mass. This device collects particles on a filter attached to the end of a vibrating tube; the vibrational frequency is directly related to the mass of particles collected. Research is ongoing to refine and miniaturize the TEOM to develop an instrument that a person can wear.[42] The first attempt to produce such an instrument was under a contract funded by the Bureau of Mines and NIOSH.[133] In this development, the sensor was worn by a miner and, after the work shift, the sensor was placed in a readout unit. The technique provided accurate results, but was expensive for a device that was not direct-reading. More recently, NIOSH funded the development of a personal dust monitor (PDM) for use in coal mines. The PDM is integrated with the miner's lamp system, with the inlet mounted on the helmet and the detector and pump combined with the lamp battery pack (Figure 11.22). This minimizes the inconvenience to the miner and allows periodic readout of the instrument during the work shift; however, only the final measurement at the end of the work shift would be used for compliance

Figure 11.22 TEOM personal dust monitor (R&P Co., U.S.A.).

with the coal mine dust standard of 2 mg/m^3. Preliminary tests showed good agreement with conventional respirable dust measurements using a 10-mm nylon cyclone sampler.[42]

11.5.2.4 *Condensation particle counter*

The condensation particle counter was one of the original instruments developed to detect airborne particles in the late 1800s,[134] but has only recently become available in a handheld direct-reading instrument. A condensation particle counter contains a condensation section, in which particles enter a supersaturated vapor (e.g., butanol or isopropanol) region and the vapor condenses on the particles, allowing them to grow to a uniform size on the order of 1–3 μm in diameter. Once the particles have grown, they can be readily detected using an optical particle counter. This technique allows a count of all particles present from approximately 1 μm in diameter down to a lower diameter limit in the range of a few to 20 nm. Typically, the number concentration of particles in the submicrometer range is much larger than the concentration of larger particles, so this technique is used to monitor primarily smokes and fumes.

The handheld instruments currently available are similar in style and available from the same manufacturer. The P-TRAK (Model 8525, TSI Inc., St. Paul, MN) is a handheld device that counts particles continuously and gives a concentration in the range of $0–5 \times 10^5$ particles per ml with a lower particle diameter limit of 20 nm. A more sophisticated version of this instrument (Model 3007, TSI Inc.; Figure 11.23) has a flow-controlled pump, an upper concentration limit of 1×10^5, and a detection limit of 10 nm.[135] These instruments can be useful for detecting and developing controls for sources of submicrometer particles, such as welding fumes, diesel fumes, and cigarette and other fire smoke.

11.5.2.5 *Pressure drop sensor*

When filters collect particles from an aerosol, the particles tend to clog the openings of the filter and increase the pressure drop across the filter. Volkwein et al.[136] used this principle to develop a small and inexpensive direct-reading respirable dust dosimeter (RDD), primarily for use in coal mines (Figure 11.24). Once the RDD is calibrated for a specific type of dust, it can provide accurate measurement of that dust. The accuracy of the measurement depends on the dust concentration and measurement period, since the product of these two factors determines the dust load on the sensor filter and, hence, the pressure drop. At concentrations below the 2 mg/m^3 standard for coal mine dust, several minutes may be required to obtain enough pressure drop change to produce an updated reading. However, this is still adequate for many situations. A major disadvantage of this method is that it is dependent on the size distribution of the dust. Within a single coal mine, good agreement with the conventional coal mine sampler was obtained. However, different calibration responses were obtained for some mine dusts.[137] In addition, when submicrometer particles such as cigarette smoke or

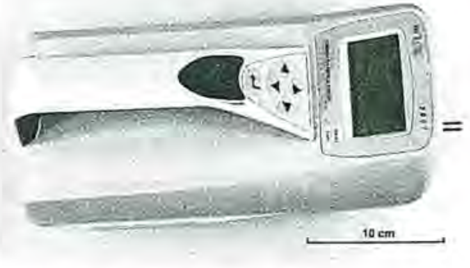

Figure 11.23 Model 3007 portable CPC (TSI Inc., U.S.A.).

Figure 11.24 Respirable dust dosimeter.

welding fumes were sampled, the RDD produced a much larger pressure drop response. Therefore, if significant submicrometer aerosols are mixed with dust, the instrument is not capable of giving meaningful results.

11.5.2.6 *Aerosol surface area measurement*

Laboratory-derived associations between the surface area of inhaled insoluble particles and toxicity are leading to increased interest in the real-time measurements of aerosol surface area. Although off-line measurements of bulk material surface area have been possible for some time using the BET method,[138] instruments capable of measuring aerosol surface area in the field are not widely available at present. BET has been used with some success for measuring aerosol surface area. However, it requires the collection of relatively large amounts of material, internal surfaces are included in the measurement, and the collection/support substrate may contribute significantly to the measured surface area — particularly where the quantity of material analyzed is small. The first instrument designed specifically to measure aerosol surface area was the epiphaniometer[139,140] (Matter Engineering, Switzerland). This device measures the Fuchs or active surface area of the aerosols by measuring the attachment rate of radioactive ions. As yet it is unknown how relevant active surface area is to health effects following inhalation exposure. Below approximately 100 nm, active surface scales as the square of particle diameter, and thus is probably a good indicator of actual particle surface area for ultrafine particles. However, above approximately 1 μm it scales as particle diameter, and so the relationship with actual particle surface area is lost.[139] The epiphaniometer is not well suited to widespread use in the workplace due to the inclusion of a radioactive source.

The same measurement principle may be applied in the aerosol diffusion charger/electrometer.[141] The LQ1-DC diffusion charger (Matter Engineering, Switzerland) uses this combination to measure the attachment rate of unipolar ions to particles, and from this the aerosol active surface area is inferred.[141,142] This instrument is also available in a portable form as the DC2000CE, complete with rechargeable battery and built-in data logger (Figure 11.25). A similar instrument, the 3070a electrical aerosol detector (EAD), has also recently been developed by TSI Inc. (MN, U.S.A.). As in the case of the LQ1-DC, the sampled aerosol is charged using a unipolar ion source, and the mean charge is measured. However, the EAD has been shown to have a response much closer to particle diameter d to the power 1.16 ($d^{1.16}$). Recent research has indicated that the EAD's response may match the surface area of particles depositing in the lungs.[143]

Figure 11.25 DC 2000 CE portable aerosol active surface area monitor (Matter Engineering, Switzerland).

For log-normal aerosol size distributions, it is possible in principle to estimate aerosol surface area by deriving the size distribution from three measurements of different aerosol parameters. This approach has been investigated by Woo et al.[144] using simultaneous measurements of aerosol mass concentration, number concentration, and charge. Maynard has proposed a simplified method of estimating surface area using measurements of aerosol number and mass concentration.[145] By assuming a geometric standard deviation of the aerosol size distribution, a reasonable estimate may be made of aerosol surface area using this approach. However, as the aerosol deviates from a log-normal distribution, errors rapidly become large. Theoretical modeling has suggested that in many cases, surface area concentration estimated using this approach will be within a factor of four of the actual value. Although relatively large, errors of this magnitude may still allow surface area exposures to be placed within broad categories.

11.5.2.7 *Specific applications of direct-reading instruments*

11.5.2.7.1 Sampling cassette leakage testing Sampling cassettes purchased from manufacturers are checked for proper compression and are generally leak free. However, cassette pieces are often purchased so that the sampler can be assembled by the user. It was found in one study that 15% of cassettes assembled by hand exhibited leakage and could have caused underestimation of worker exposure.[53] It was recommended that cassettes be assembled using a press and that bypass leakage around the collection filter be checked using either an optical particle counter or a condensation particle counter and ambient aerosol. The ratio of downstream to upstream particle concentration is an indication of the amount of filter bypass leakage. This leakage can occur because of incomplete compression of the seal at the edge of the cassette or because of cuts in the filter when cassette compression is too great. The amount of aerosol loss is a complex function of particle size, particle type (e.g., liquid, solid), and leak size.[54,146]

11.5.2.7.2 Respirator testing Respirators are devices used to prevent exposure to hazardous gases and aerosols. There are two basic types of respirators: (a) air-supplied respirators, in which clean air is provided to the breathing zone from an external source, and (b) air-purifying respirators, in which air passes through an air-cleaning device, for example, a filter or cartridge. Air-purifying respirators can be further classified as being powered or nonpowered. The nonpowered or negative pressure air-purifying respirators are the most common and use the person's lung suction to pull the air through the cleaning device. Respirators are classified by their assigned protection factor, a number assigned to a particular class of respirator for regulatory purposes.[147] It is a number that estimates by what factor an air contaminant concentration is reduced in a population of properly fitted and trained users. Actual protection factors for properly fitted respirators may be higher than the assigned protection factor or, alternatively, if the respirator is used incorrectly, lower. For aerosols, the efficiency with which the respirator prevents particles from being breathed in is determined by the efficiency of the filter and the sealing efficacy of the mask, that is, the prevention of particles bypassing the filter.

Filter technology allows the production of highly efficient filters, but often the high efficiency comes at the cost of higher pressure drop across the filter and greater production cost. A higher pressure drop across the filter can actually reduce the overall performance of a nonpowered air-purifying respirator because the suction caused by breathing reduces the air pressure inside the respirator and any leaks around the seal are increased. In addition, the higher pressure drop increases the physiological load on the wearer, making it less likely to be used properly.

Respirators are tested and certified by NIOSH by measuring the penetration of 0.3 μm particles through the respirator. Particles of approximately this size are the ones with the greatest likelihood of passing through the filter. Larger particles are collected by impaction and interception, while smaller ones are collected by diffusion. To test respirators for use by workers, either a qualitative or a quantitative fit test is performed. Fit testing is usually carried out by replacing the respirator filter with a high-efficiency (HEPA) filter so that particles detected inside the respirator are due to leakage. Qualitative fit tests are performed by exposing the respirator-equipped worker to an aerosol that the worker can smell or taste, for example, irritant fumes, sodium saccharin, or bitrex. A quantitative fit test is used to determine the factor by which aerosol is reduced inside the respirator. This requires measuring the efficiency of the respirator while it is worn and the worker moves about and speaks. This measurement can be done in several ways. In each case, the fit factor is determined from the ratio of the outside aerosol concentration to the inside concentration. One technique is to create an aerosol of an oil, such as corn oil, in a small tent enclosing the worker and measuring the aerosol concentration inside and outside the respirator using a photometer (e.g., from Air Techniques Inc.). The aerosol is generated using a nebulizer that produces submicrometer droplets.

Willeke and co-workers have investigated several alternative means for testing respirators. The particles that penetrate the leaks around the edge of a respirator are primarily submicrometer in size. Therefore, the most common particles available, namely ambient aerosol particles, were used to develop a test.[148] The condensation particle counter is capable of rapidly and accurately measuring the total number concentration of these particles. The PortaCount (Model 8020, TSI Inc.) can be used to fit test respirators. This device has two ports, one to detect inside a respirator and the other ambient aerosol. The proportion of ambient fine particles that penetrate the respirator provides an indication of the fraction of air leakage around the edge of the respirator. This test has the advantage of being less obtrusive to the worker and quicker to set up and use. Han et al.[149] discuss the details of quantitative fit testing techniques and the advantages and disadvantages of each approach.

11.5.2.7.3 Sampler testing Personal samplers for measuring respirable, thoracic, and inhalable dust require testing to determine their size-dependent characteristics. Two primary aspects of these devices are usually tested: the inlet or aspiration efficiency of the sampler and the internal loss characteristics of the sampler. The aspiration efficiency under most indoor conditions is close to 1 (or 100%) for particles smaller than about 5 μm. Thus, for respirable sampling, aspiration efficiency can be assumed to be 1 unless the sampler is to be used at high wind velocities (e.g., some mines and occasionally in outdoor air). Thoracic and especially inhalable samplers should be tested at a range of wind velocities to ensure accurate sampling. In the case of the inhalable sampler, the external wind velocity is critical to the sampling efficiency of the sampler so that internal loss characteristics are somewhat secondary.

Respirable and thoracic dust samplers are often tested in a stagnant or low-velocity chamber to determine the size-dependent efficiency of the classifier. There are two basic approaches to performing the testing. Traditionally, single-size (monodisperse) particles containing a tracer are generated, collected with the sampler, and then the tracer is measured in the various parts of the sampler, for example, the classifier, connecting pieces, filter, and filter cassette. This is done for several particle sizes over the range of interest near the cutoff of the classifier. This is a relatively tedious approach to testing, but provides useful information about the behavior of the classifier and internal losses in the system.

An alternative approach is to use a polydisperse aerosol and measure the aerosol upstream and downstream of the classifier with an aerodynamic sizing instrument, for example, the aerodynamic particle sizer (APS3321, TSI Inc., U.S.A.). Dilution air is introduced at the top of the chamber, aerosol is injected into a mixing region, the flow is straightened, and the samplers are placed in the test section. The APS is placed below the chamber and can be attached either to the sampler or to a reference inlet port. The aerosol is measured at the two ports and the concentration in each size bin of the classified aerosol distribution is divided by the corresponding size bin of the reference port. This provides a size-dependent penetration of the classifier. Penetration curves for a sampler can be obtained in a matter of minutes by this approach, although setup time and validation of the measurement can take longer.

There are no direct reading aerosol sizing instruments available for larger particles, so inhalable samplers are typically tested in a wind tunnel over a range of wind velocities using the traditional approach of monodisperse dusts with a tracer or gravimetric measurement of the collected material. Because sampler results have been shown to be affected by the human body, samplers are usually placed on a manikin torso to simulate placement on a worker. In addition, the manikin is rotated during sampling to average over wind direction.

11.5.2.7.4 Combined aerosol and video monitoring To reduce the exposure of workers to harmful aerosols, it is important to investigate the detailed interaction between workers and their environment. Although an industrial hygienist may observe a worker during the period that a personal measurement is being taken on that worker, capturing a video image of the worker during the sampling period provides the opportunity for a much more objective and quantitative measure of the exposure as a function of various worker activities and environmental factors. The technique involves using a video camera with time information imprinted on the image and a real-time monitoring system with the output data-logged, also with time information saved.[150,151] The video record can be analyzed to record various activities and occurrences, so that these can be correlated with changes in concentration noted in aerosol concentration data. Quite often, there is a time lag after an event before the concentration changes because of the time that the aerosol takes to reach the monitoring instrument and the instrumental response time. Mathematical analysis of the time lag allows a direct correlation of concentration and activity. Repetitive activities can be averaged to obtain a more accurate evaluation of the time course of exposure. Cooper et al.[152] were able to target specific locations and activities that produced high exposure levels of crystalline silica, and this information was successfully used to apply control measures that significantly lowered exposures. Using a video mixer to place the aerosol concentration data directly on the video image results in a video record of activities and correlated aerosol concentration. Such a video record can be used as a training or feedback tool for workers to demonstrate how their exposure is affected by various activities.

11.6 Summary

The observation of occupational exposure to aerosols has a long history, but great progress has been made in the past several decades in providing a range of measurement instruments and techniques. While dose/response relationships have been established for a wide range of workplace contaminants, there are still uncertainties as to which metric is the most appropriate to measure for specific contaminants. Current research emphasis on the ultrafine aerosol particle range may result in surface area being considered as an important exposure metric.

When attacking the problem of what instruments or approaches are to be used in making workplace measurements, a number of factors have to be considered. The size range of interest, the aerosol metric (size, mass, number surface area, radiological, chemical, or biological activity concentration), and purpose of measurement (compliance with standards, evaluation for source control, personal vs. environmental exposure) all have an impact on the selection of the most appropriate type of measurement technique or instrument. Because aerosol particles have a whole range of properties that can affect their measurability, one needs to have an adequate understanding of the aerosol to be measured and how its properties may affect the selected measurement technique.

The development of readily available, accurate direct-reading measurement tools (e.g., the SMPS and the APS) has spawned a range of classifiers and other aerosol measurement techniques. Many of these are innovative and have definite advantages over the traditional approaches to sampling and measurement. However, one has to be cautious in ensuring that adequate testing of these devices has been performed and that one understands the advantages and drawbacks of any instrument selected. The literature is replete with discoveries of subtle biases introduced by new devices that initially appeared to have clear advantages over traditional approaches. On the other hand, some traditional approaches were not carefully tested when they were originally selected and also have significant drawbacks. Hopefully, with the development of new instrumentation and appropriate testing, clearer choices and better characterized measurement tools will be available in the future.

Disclaimer

Mention of company names or products does not constitute endorsement by the Centers for Disease Control and Prevention.

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Publisher	CRC Pr I Llc	**Subjects**	Aerosols; Toxicology; Handbooks, manuals, etc. Science - Environmental Science
Publication	November 24, 2004		

date	
Binding	Hardcover
Book category	Adult Non-Fiction
ISBN	1566706114
Original list price	$199.95

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2004

Title

Chapter 11: Aerosols in the Industrial Environment

Editor

Harley, N.H.
Ruzer, L.S.

Book Title

Aerosols Handbook: Measurement, Dosimetry, and Health Effects

City

Publisher

CRC Press

Volume

Number of Volumes

Pages

225-264

Series Editor

Series Title

Edition

Fiscal Year

FY05

Translator

Short Title

Reviewed Item

Date Published

November 2004

DART No.

03-247

EPHB No.

Reviewers

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