25 Aerosol Measurement in the Workplace

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INTRODUCTION

Industrial hygiene can be defined as the identification, evaluation, and control of occupational health hazards. It encompasses the complete process from a hazardous material being made accessible through use or lack of containment; to control of the exposure route; through exposure and dose; and finally to health effects resulting from received dose. Exposure may be through ingestion, inhalation, or dermal contact, although it is the inhalation route that is of prime importance when considering aerosols. Traditionally, workplace aerosols have been categorized as fumes (fine particles and agglomerates generated through combustion and vapor condensation), smokes (solid and liquid particles arising from incomplete combustion), dusts (solid particles generated through mechanical means), sprays (liquid aerosols with relatively large particle sizes, usually produced through mechanical means), and mists (liquid aerosols with finer particles, generally produced through condensation or atomization) (Vincent, 1995). Aerosols containing biological organisms, or bioaerosols, are also considered as a separate category, and are covered in more depth in Chapter 24. These definitions tend to be used as descriptors rather than as discrete classifications, and when considering sampling and health effects their use can be somewhat misleading. For example, a size selective sampler will not differentiate between a fume, smoke, or mist, and the distinction between health effects arising from a fume and a submicron dust can be somewhat blurred.

Historically there have been a number of different approaches to measuring aerosols generated in the workplace (Walton and Vincent, 1998). From the early 1900s through the 1950s and beyond, particle number was the dominant metric of exposure assessment, with

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devices such as the konimeter (Le Roux, 1970; Hewson, 1996), impinger (Greenburg and Smith, 1922), and thermal precipitator (Green and Watson, 1935; Hamilton, 1956) finding widespread use. Analysis was generally accomplished by using light microscopy, with electron microscopy finding increasing use as the instrument was developed. Although exposure to fibers is still assessed on a particle number basis, current sampling and analysis methods are dominated by the use of collection on filters and mass analysis (gravimetric or, for specific elements or compounds, by chemical analysis). Many of the methods employed are the same as or similar to those used in other areas of aerosol measurement. However, workplace aerosols, and the aims of applied measurement techniques, differ somewhat from those found in other circumstances. In most cases the bulk aerosol composition is known or can be deduced from the processes or products in use. The mass concentrations involved are typically an order of magnitude or so greater than those in the general environment. Finally, sampling is carried out specifically for assessing human exposure rather than characterizing the aerosol itself.

While philosophies and approaches may differ, there is a great deal of commonality between methods used in the workplace and those used in other areas of aerosol measurement. Thus, techniques and applications described elsewhere in this book will frequently be directly relevant to workplace sampling. Chapters 7, 9, 10, 12, and 15 are particularly pertinent, providing detailed information on approaches to aerosol monitoring; filter collection; inertial, gravitational, centrifugal, and thermal sampling; and direct-reading techniques using optical particle detection, respectively. Chapter 26 on measurements in mines covers a subfield of industrial hygiene, while Chapters 23, 24, and 27 on nonspherical particle measurement, bioaerosol measurement, ambient aerosol sampling and aerosol exposure measurement are all relevant to the workplace. In this chapter, the emphasis is therefore on the basic sampling philosophies and methods used on a daily basis in the workplace.

AEROSOL EXPOSURE MEASUREMENT IN THE WORKPLACE

Biologically Relevant Sampling

Aerosol sampling in the workplace is ultimately concerned with measuring that aspect of the aerosol that leads to specific health effects. Thus, the method and metric used aim to provide biologically relevant information. Aerosol particles can cause health problems when deposited on the skin and eyes, but generally the most sensitive route of entry into the body is through the respiratory system. The biological effects resulting from deposition of an aerosol in the *respiratory tract* will depend on the dose received and the body's response to the deposited particles. Physiological response to an aerosol depends on the chemical and physical nature of the particles and the location of the interaction (i.e., deposition region). The ultimate goal of industrial hygiene aerosol measurement is therefore to ascertain the dose of aerosol delivered to the body and to evaluate whether the dose or potential dose is sufficient to cause adverse health effects.

The respiratory system deposition region is primarily governed by particle size and shape. The health response may be a function of mass, chemical composition, or morphology and possibly particle size and surface chemistry. Ideally dose should be expressed in terms of the most appropriate metric. However, additional restraining factors on industrial hygiene aerosol measurements include the practical and economic application of measurement methods. In practice, it is simpler to measure penetration to the relevant areas of the respiratory system rather than dose, thus giving a measure of the *potential* dose. Mass and bulk chemical composition are easier to measure than parameters such as particle shape and surface area, and correlation between health effects and particle number and mass concentration (e.g., Bedford and Warner, 1943) indicates mass to be a suitable metric in many cases. Asbestiform fibers present an exceptional case where dose is best represented by particle number and shape, and accordingly a number and morphology-based metric is used (see Chapters 12 and 23).

Deposition Regions

The respiratory system is an effective size-selective aerosol sampler in its own right, and it is fallacious to assume that all airborne particles will enter it. Large particles are excluded from entering the nose and mouth (the nasopharyngeal region) through inertial separation. Aspiration is a function of a number of parameters, including particle size, external air speed, orientation to the prevailing air movement direction, and breathing rate and volume. However, for external wind speeds of a few m/s and lower, the probability of a particle entering the mouth or nose (termed *inhalable particles*) may be generalized as being around 100% for particles with aerodynamic diameters of a few micrometers and below, reducing to around 50% at 100 μm aerodynamic diameter (Vincent et al., 1990).

Aerosol deposition in the nasopharyngeal region is dominated by inertial impaction, although interception and (for particles in the nanometer size range) diffusion also contribute. Further inertial separation and interception occurs as the particles pass into the trachea and the upper lungs (tracheobronchial region). Although population variance is high (Lippmann, 1977), penetration into the tracheobronchial region may be typified by particles smaller than approximately 10 μm aerodynamic diameter (Lippmann, 1977; ISO, 1995). As the airways bifurcate to ever finer branches toward the alveolar region, aerosol particles are predominantly removed from the flow through a combination of impaction, interception, charge effects, and diffusion. In the preceding regions, deposited particles are cleared primarily by the action of cilia transporting them along to the upper airways. Particles depositing in the alveolar, or gas exchange, region are cleared either through the action of alveolar macrophages engulfing them and transporting them to ciliated airways (phagocytosis) or by dissolution in the lung fluid. Particle deposition is through impaction and diffusion, and penetration to the alveolar region is restricted to particles around 5 μm and less aerodynamic diameter (Lippmann, 1977; ISO, 1995). The clearance mechanism employed in the alveolar region, together with the close proximity of the bloodstream, leads to a number of health effects specific to particle deposition within this region.

Particle Characteristics and Biological Response

Although particle aerodynamic diameter dominates deposition within the respiratory tract, the subsequent effect on health is a combination of physical particle characteristics and biological response. On deposition, the body may react to the chemical substances contained within the particle, interact with the particle surface, or be influenced by physical parameters such as size and morphology.

Highly soluble particles and droplets will be rapidly assimilated by the body, particularly in the alveolar region. Local effects, such as irritation and inflammation, and systemic responses may become manifest over very short time periods. The gradual release of agents from low-solubility particles will have a much longer response time. However, low-solubility particles may also act as vectors for the transport of high-solubility solids, liquids, and gases present as thin surface layers, thus leading to a response not indicated by the bulk aerosol particle properties alone. For example, adsorption of nitrogen oxides and sulfur dioxide onto particles can lead to health effects at levels normally considered safe.

Very low-solubility particles are more likely to have health effects associated with their physical characteristics. Lung overload phenomena are associated with the physical limitations of the lungs' clearance mechanisms as opposed to chemical interactions with the deposited particles (Morrow, 1994). Particle shape is a factor for fibrous aerosols (Blake et al., 1998) (see Chapter 23). It also influences available surface area, which may be related to toxicity through surface interactions (Lison et al., 1997) or increased solubility. Where open agglomerates of particles exist, including those resulting from combustion (such as diesel exhaust particulates), metal processing, welding, or fine powder production, the aerosol may have a very high specific surface area and be formed from particles able to penetrate to the

alveolar region. In some fine powders, including ultrafine titanium dioxide, carbon blacks, and fumed silicas, specific surface areas in excess of $2 \times 10^5 m^2/kg$ [$200 m^2/g$] are achieved among particles with aerodynamic diameters less than 4 μm. In comparison, an aerosol of spherical particles 4 μm in diameter and with unit density would have a specific surface area of $1.5 \times 10^3 m^2/kg$ [$1.5 m^2/g$]. There is evidence that for some low-solubility materials toxic response may be associated with surface area or even particle number (Oberdörster et al., 1994; Lison et al., 1997; Donaldson et al., 1998). However, little is known of the role of what may be termed *available surface area*, which will be influenced by particle surface structure and biological mechanisms.

Some of the responses observed on inhaling aerosols are reversible; some may be chronic. Some effects are cumulative; others are not. For some substances, there may be an exposure level below which no effects are observed (a "no-effect" level). For others, notably carcinogens, there may be no identifiable no-effect level. For a class of substances known as *sensitizers*, relatively high exposure levels may be experienced without obvious effect until a person becomes "sensitized" to the substance. Following sensitization, exposure to very low levels may result in a significant biological response.

Biologically relevant exposure monitoring requires the range of interactions and responses, together with aerosol dose and particle form, to be taken into account. It can be seen that in principle there are a number of particle characteristics that will influence the toxicity of inhaled particles. Although characteristics such as size, morphology, surface area, and structure may be influential, current technology lacks the means to characterize workplace aerosols as completely as may be desirable. Fortunately, the specificity of many workplace aerosols enables successful exposure monitoring to be carried out by linking a related metric (such as mass concentration) to empirical dose–response data. The extent to which this approach is tenable where toxicity data are sparse is questionable, however.

Sampling Conventions

The accurate measurement of aerosol exposure via inhalation requires sampling devices that match particle deposition to the relevant areas of the respiratory system. However, aerosol deposition is highly dependent on the individual (Lippmann, 1977) and not trivial to replicate in a sampling device. Broad standards have therefore been developed describing representative penetration characteristics of aerosol particles through the respiratory system as a function of aerodynamic diameter. These standards provide a basis for estimating the aerosol concentration potentially available to cause harm within specific areas of the respiratory system and underlie many industrial hygiene aerosol sampling methods.

Early estimates of penetration into what was considered the most vulnerable part of the system—the alveolar region—were proposed in the 1950s and 1960s, resulting in the British Mines Research Council (BMRC) and the American Conference of Government Industrial Hygienists (ACGIH) conventions describing respirable aerosols (BMRC, 1952; ACGIH, 1968). More recently, the International Standards Organization (ISO, 1995) and the ACGIH (1998) arrived at convergent conventions describing the probability of particles penetrating to the nasopharyngeal, tracheobronchial, and alveolar regions. However, it was not until the early 1990s that international consensus was reached on particle penetration standards between the ISO, ACGIH, and the European Committee for Standardization (CEN). The resulting conventions describe penetration as a function of particle aerodynamic diameter into the respiratory system (*inhalable* aerosol), into the tracheobronchial region (*thoracic* aerosol), and into the alveolar region (*respirable* aerosol), with thoracic and respirable aerosol as subfractions of the inhalable aerosol. These particle-size–dependent fractions shown in Figure 25–1 are now widely used as the standards to which industrial hygiene aerosol samplers should conform (ISO, 1995).

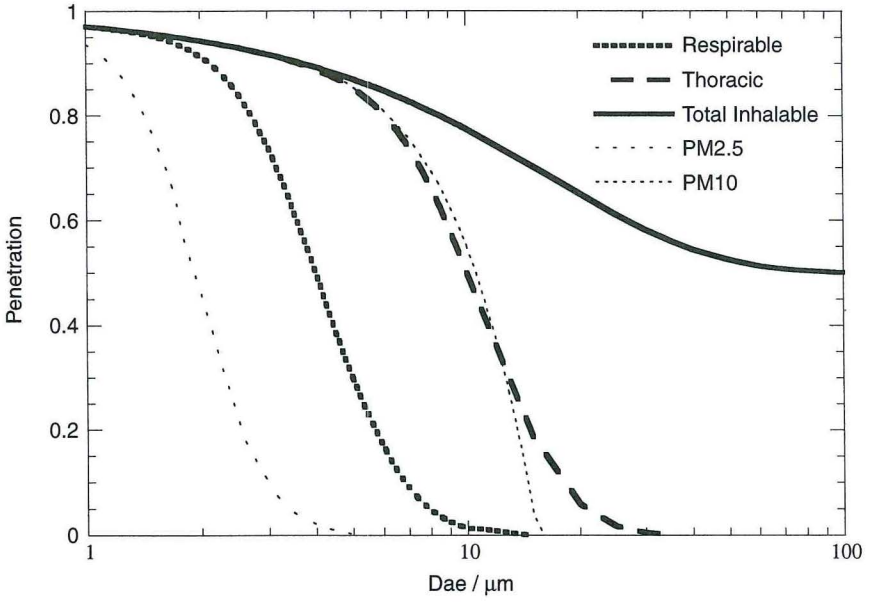

Fig. 25–1. International workplace sampling conventions (ISO 1995). Environmental conventions are also shown for comparison (chapter 27).

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

$$SI(d_{ae}) = 0.5 \times \left(1 + e^{-0.06 d_{ae}}\right) \tag{25–1}$$

for $0 < d_{ae} < 100\,\mu m$. $SI(d_{ae})$ is the fraction of particle entering the system as a function of aerodynamic diameter d_{ae}.

Both the thoracic and respirable conventions are expressed as subfractions of the inhalable convention and are based on lung penetration measurements. The thoracic convention is given as

$$\begin{aligned} ST(d_{ae}) &= SI(d_{ae}) \times [1 - F(x)] \\ x &= \frac{\ln(d_{ae}/\Gamma)}{\ln(\Sigma)} \end{aligned} \tag{25–2}$$

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

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

$$\begin{aligned} SR(d_{ae}) &= SI(d_{ae}) \times [1 - F(x)] \\ x &= \frac{\ln(d_{ae}/\Gamma)}{\ln(\Sigma)} \end{aligned} \tag{25–3}$$

where the cumulative lognormal distribution has an MMAD Γ of 4.25 μm and a GSD Σ of 1.5. A respirable convention for susceptible groups is also defined, with $\Gamma = 2.5$ μm, although this has not been implemented in any exposure standards as yet. Standards relating to penetration to the tracheobronchial and extrathoracic regions are defined by the difference between the respirable and thoracic conventions (tracheobronchial) and between the thoracic and inhalable conventions (extrathoracic). Further information on particle size-selective sampling for workplace contaminants may be found in ACGIH (1998).

Occupational Exposure Limits

Health-based aerosol exposure limits follow country-specific systems, but in the majority of cases follow a similar philosophy (Vincent, 1998). In the United States, the primary sources of occupational exposure limits for the workplace are (1) National Institute for Occupational Safety and Health (NIOSH) recommended exposure limits (RELs); (2) the U.S. Department of Labor (OSHA and MSHA) permissible exposure limits (PELs), and (3) the American Conference of Government Industrial Hygienists' (ACGIH) threshold limit values (TLVs). NIOSH RELs are time-weighted average (TWA) concentrations for up to a 10 h work day during a 40 h work week. OSHA PELs are TWA concentrations that must not be exceeded during any 8 h work shift of a 40 work week. The ACGIH TLVs are 8 h TWA concentrations for a normal 8 h workday and a 40 h work week, to which nearly all workers may be exposed, day after day, without adverse effects.

In the United Kingdom, a two-tier system of occupational exposure standards (OES) and maximum exposure limits (MELs) is employed (HSE, 1999). 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 there will be a degree of resultant health effects manifest whatever exposure limit is chosen (above zero), the choice of 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.

Even below these various exposure limits, a small percentage of workers may experience adverse health effects due to individual susceptibility, a pre-existing medical condition, and/or a hypersensitivity (allergy). In addition, some materials may act in synergy with other substances to produce undesirable health effects, even if the occupational exposures to individual contaminants are controlled at the level set by the evaluation criteria. For example, gases such as oxides of nitrogen and sulfur dioxide may adsorb on dust particles and produce health effects at levels normally considered safe. Furthermore, some substances are absorbed by direct contact with the skin and mucous membranes and thus potentially increase the overall exposure. For substances that may potentially lead to health effects following short exposures, or high peak exposures, short-term exposure limits (STELs) are generally set to complement the 8 to 10 TWA limits. These are generally sampled over shorter time periods—typically 15 min—and are collected during periods when the concentration of contaminant is likely to be highest.

SAMPLING AGAINST EXPOSURE CONVENTIONS

The accuracy and relevance of aerosol samples taken within the workplace predominantly rely on selection of an appropriate sampling device. However, filter selection, pump selection and use, sampling strategy, and sample handling also play a role in determining the accuracy and suitability of samples. Useful sources of information include the ACGIH (1995, 1998).

Matching the Sampler to Sampling Requirements

A number of the industrial hygiene aerosol samplers introduced to the market in recent years have been developed and tested against international sampling conventions (ISO, 1995). However, many devices are still available that were brought into use before acceptance of the current conventions. Some of these agree reasonably well with the relevant convention, and others have been brought into line by altering the sampling flow rate (e.g., the SIMPEDS respirable cyclone; Bartley et al., 1994; Maynard and Kenny, 1995). Others, such as the closed-face 37 mm filter cassette, show poor agreement with the current conventions (Kenny et al., 1997).

The analytical development of inhalable samplers has been hampered by the complexities of how external conditions affect aspiration, together with the difficulties of making penetration measurements with particles up to 100 μm aerodynamic diameter. The IOM personal inhalable sampler was the first sampler built to match the inhalable convention and was developed following aspiration measurements with a breathing mannequin (Mark and Vincent, 1986). Although the sampler has shortcomings (e.g., it is very accessible to sample tampering, and there is evidence for significant projectile entry in some environments), it is still regarded as a benchmark sampler. More recent samplers such as the CIP10-I (***ARE***)* address some of the problems inherent in the IOM inhalable sampler, but still fall short of the ideal. Samplers such as the button sampler (***SKC***) have been developed specifically to reduce intersampler variability and wind speed dependence common to a number of inhalable samplers (Aizenberg et al., 2000). Samplers following the thoracic and respirable conventions have been easier to engineer. The development of an empirical understanding of particle penetration through cyclones and polyurethane foams in particular has led to sampling devices that match the respirable and thoracic conventions reasonably well (Vincent et al., 1993; Kenny and Gussman, 1997; Chen et al., 1998; Maynard, 1999).

In recognition that no sampler will agree with the current workplace sampling conventions at all times, performance criteria are under development to set acceptable bounds on how well a device performs (CEN, 1998). The mass fraction of a lognormal aerosol characterized by its MMAD and GSD that would be sampled by a device may be compared with the mass that would be sampled by an ideal sampler (i.e., one following the convention perfectly). The comparison gives the sampler's bias as a function of aerosol size distribution (Bartley and Breuer, 1982; Lidén and Kenny, 1992; Maynard and Kenny, 1995). Incorporating errors inherent in sampler performance measurements and typical usage into calculations of bias allows the sampler's accuracy as a function of the aerosol size distribution to be estimated. Ensuring that sampler accuracy and bias lie within acceptable bounds then gives a basis for determining good and poor sampler performance.

From the available samplers that lie within acceptable performance criteria, the choice of device will depend largely on the sampling requirements. Two general types of sampling are used in the workplace, fixed location sampling (also called *static* or *area sampling*) or personal sampling, where the sampler is placed on the worker. Static and personal samplers should not be interchanged, except where otherwise indicated. High flow-rate samplers should be used to increase the aerosol detection limit, for instance, during short-term sampling or when the sampled material has a low exposure limit (although the detection limit will also depend on the filter used and the analysis method). Where high air velocities are expected, samplers with a sampling efficiency that are not as prone to wind speed should be selected. Other considerations should include whether the aerosol charge is likely to affect sampling (e.g., Baron and Deye, 1990; Puskar et al., 1991), whether projectiles are likely to enter the sampling orifice and be included in the sample, and whether there is a possibility of significant sample loss during transport (see Chapter 7). Table 25–1 summarizes many of

*See Appendix I for full manufacturer addresses referenced to the italicized three-letter codes.

TABLE 25–1. Summary of Industrial Hygiene Aerosol Samplers

Sampler	Flow Rate (10^{-5} m^3/s [L/min])	Deployment	Manufacturer or Distributor (see Appendix I)	Agreement with Convention	Notes	References
Inhalable samplers						
IOM Inhalable	3.3 [2]	Personal	***SKC***	Good	Uses filter cassette. Susceptible to large projectiles. Wind speed dependent	Mark and Vincent (1986), Kenny et al. (1997, 1999a)
IOM Inhalable static	5 [3]	Static	***CAS***	Good		Mark et al. (1985)
CIP-10I	17 [10]	Personal	***ARE***		Rotating porous foam acts as an air mover and collection medium	Courbon et al. (1988), Kenny et al. (1997)
GSP Inhalable	5.8 [3.5]	Personal	***STR***	Good		Kenny et al. (1997)
Conical Inhalable Sampler	5.8 [3.5]	Personal	***CAS, BGI***	Good	Based on the GSP sampler	Kenny et al. (1997)
Seven Hole	3.3 [2]	Personal	Various	Fair	Also known as the multiorifice or UKAEA sampler	Kenny et al. (1997)
Single Hole	3.3 [2]	Personal	Various	Poor	Used for lead aerosol sampling in the United Kingdom	Kenny et al. (1997)
PAS-6	3.3 [2]	Personal	***KOE***	Fair		Kenny et al. (1997)
Button sampler	6.7 [4]	Personal	***SKC***	Good	Perforated inlet reduces wind speed dependence and intersampler variability and leads to a uniform filterdeposit	Hauck et al. (1997), Aizenberg et al. (2000)
Thoracic samplers						
Elutriator	12.3 [7.4]	Static	***GMW***	Poor	Specific to cotton dust	Robert (1979)
CIP-10T	12 [7]	Personal	***ARE***	Fair	CIP-10I with a thoracic separation stage	Fabriès et al. (1998)
CATHIA	12 [7]	Static	***ARE***	Fair	Static version of the CIP-10T	Fabriès et al. (1998)
IOM Thoracic	3.3 [2]	Personal	***IOM***	Fair	Separation based on polyurethane foam	Maynard (1999)
GK 2.69 Cyclone	2.7 [1.6]	Personal	***BGI***	Good	Can also be used as a respirable sampler—see below	Maynard (1999)
Modified SIMPEDS cyclone	1.3 [0.8]	Personal	Not commercially available	Good	Developmental modification to the SIMPEDS cyclone	Maynard (1999)
IOM Inhalable + thoracic foam	3.3 [2]	Personal	***SKC***	Fair	IOM inhalable sampler with a size-selective polyurethane foam insert	Maynard (1999)

Respirable samplers						
CIP-10R	17 [10]	Personal	***ARE***	Good	CIP-10I with a respirable separation stage	Courbon et al. (1988)
SIMPEDS Cyclone	3.7 [2.2]	Personal	Various	Good	Also known as the Higgins and Dewell (HD) cyclone	Lidén and Kenny (1993), Bartley et al. (1994), Maynard and Kenny (1995)
SKC Cyclone		Personal	***SKC***	Good	Variant of the SIMPEDS cyclone	Lidén (1993)
GK 2.69 Cyclone	7 [4.2]	Personal	***BGI***	Good	Can also be used as a thoracic sampler—see above	Maynard (1999)
Dorr-Oliver (10 mm) Cyclone	2.8 [1.7]	Personal	Various	Good	Sampler constructed from nonconducting nylon	Bartley et al. (1994)
MRE 113A (Gravimetric Dust Sampler)	4.2 [2.5]	Static	***CAS***	Fair	Use limited to U.K. mines	Dunmore et al. (1964)
IOM Inalable + respirable foam	3.3 [2]	Personal	***SKC***	Good	IOM inhalable sampler with a size-selective polyur ethane foam insert	Kenny et al. (1999b)
Foam respirable sampler	3.3 [2]	Personal	Not commercially available	Good	Cowled sampler with size-selective polyurethane foam plugs	Chen et al. (1998)
Virtual Cyclone		Personal	Not commercially available	Good	Provides a good match with the respirable convention slope	Chen et al. (1999)
Spiral sampler	4.2 [2.5]	Personal	***SKC***		Uses centrifugal particle separation	John and Kreisberg (1999) ($PM_{2.5}$ operation)
Miscellaneous samplers						
37 mm Cassette (open)	3.3 [2]	Personal/static	Various		Standard filter cassette, worn facing down at 45° to the body. Conducting versions available	Kenny et al. (1997)
37 mm Cassette (closed)	3.3 [2]	Personal/static	Various		Standard filter cassette with a cap containing a 2 mm diameter inlet	Kenny et al. (1997)
Static sampler for "total" aerosol	Variable	Static	***CAS***		Open-faced filter. Widely used in the United Kingdom	Mark et al. (1986)
Passive sampler	—	Personal/static	HSE, UK		Electret-based sampler relying on aerosol charge and naturally occurring air movements. Correlation is good with some size-selective samplers	Brown et al. (1994, 1995)
Cowled sampler	3.3 [2] (typical)	Personal/static	Various		Used in the main for fiber sampling. Size selectivity not quantified	

the workplace sampling devices currently available or in use and gives some indication as to their application.

Filter and Substrate Selection

Industrial hygiene aerosol samples are generally collected onto a filter, within a polyurethane foam, or onto an impenetrable impaction substrate such as Mylar (which is usually coated with a layer of grease or oil to prevent particle bounce). 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. Selection of a suitable collection substrate is governed by the sampling equipment used and by the subsequent sample analysis. Low-power lightweight pumps require filters with relatively low pressure drops at the operating flow rate. Gravimetric analysis requires a high degree of weight stability in changing environmental conditions. Chemical analysis requires that the collected material can be released from the substrate and/or that background levels of the analyte are low. Sample analysis by microscopy requires deposited particles to lie on the surface of the substrate. Chapter 9 gives further details of filter properties and selection. Table 25–2 summarizes the properties of filters, collection substrates, and filter holders commonly used within the workplace.

The accuracy of gravimetric samples may be affected by water adsorption onto substrates and filter holders and by losses or gains in material during transit (see Chapter 7) (van Tongeren et al., 1994; Awan and Burgess, 1996). In particular, cellulose ester membrane filters, polyurethane foams, and conducting plastic filter cassettes are particularly prone to weight changes following water uptake (Vaughan et al., 1989; Smith et al., 1998). To combat bias from such sources, it is common practice to weigh a number of control, or blank, filters with each

TABLE 25–2. Filter Selection for Industrial Hygiene Aerosol Sampling[a]

Substrate or Cassette	Typical Application	Weight Stability	Pressure drop
Cellulose fiber filter	General collection Gravimetric analysis	**	**
Cellulose nitrate filter	General collection Gravimetric analysis		
Glass fiber filter	General collection Gravimetric analysis	***	**
Quartz fiber filter	Chemical analysis	**	**
Cellulose ester membrane filter	Imaging, fiber sampling	***	***
PVC membrane filter	Chemical analysis	*	*
Teflon membrane filter	Gravimetric analysis Chemical analysis	**	*
Polycarbonate filter	Particle imaging	**	****
Silver membrane filter	Chemical analysis	**	****
Polyurethane foam	Various samplers	****	*–****
Mylar impaction substrate	Impaction substrate	**	N/A
Aluminum foil impaction substrate	Impaction substrate	**	N/A
Conducting plastic cassette	IOM inhalable sampler, conical inhalable sampler	****	N/A
Aluminum cassette	IOM inhalable sampler	*	N/A
Stainless steel cassette	IOM inhalable sampler	*	N/A

[a] A higher star rating indicates better weight stability or lower pressure drop.

set of sample filters (typically one blank per 10 samples, with a minimum of three blanks). It is advisable to condition filters in the weighing area (preferably in a temperature- and humidity-controlled environment) for up to 24 h before weighing to allow them to reach an equilibrium weight. It is generally not advisable to desiccate the filters before weighing, as weight changes after removal of the filter can be sufficiently rapid to lead to significant weight change during weighing (Smith et al., 1998). Where possible, blank filters should be transported with the sample substrates and exposed to the same conditions in order to minimize bias resulting from handling, transport, and changes in environment.

Other sources of bias include electrostatic attraction, where substrates are highly charged, and buoyancy effects. Electrostatic charge build-up may be significant for substrate materials such as PVC and PTFE, particularly when working at low relative humidity. In all instances, samples should be electrically neutralized using a source of bipolar ions. A common approach is to place samples close to a radioactive antistatic source before weighing. Buoyancy corrections only become necessary when the volume of the sample exceeds around 10^{-7} m^3 [0.1 cm^3]. For most substrates this is not a problem, although it may be significant when using large integral filter holders or substrate supports.

Pump Selection

Present-day personal sampling devices usually rely on either diaphragm or piston-type pumps to draw air through them. The pump is connected to a direct current (dc) motor, supplied by a battery pack of rechargeable nickel-cadmium cells. The achievable flow rates of pumps vary among manufacturers, but most will provide flows of 1.67×10^{-5} to 5×10^{-5} m^3/s [1 to 3 L/min] against a pressure drop of 6.25 kPA [25 inches of H_2O] for periods of up to 8 h. Personal pumps are available that will achieve flow rates of up to 1.67×10^{-4} m^3/s [10 L/min], but with current technology there is always a trade-off between sampling flow rate, sampling time, sustainable pressure drop, and pump weight. Most currently available pumps regulate the selected flow to minimize the impact of changes in temperature, pressure, and filter loading on the flow rate and the total volume of air sampled. Regulation is achieved in a number of ways, including using feedback from pressure drop across the filter, atmospheric temperature and pressure, pump rotational rate, and power usage. As the performance of some size-selective samplers is adversely affected by pulsations in the sampling flow (e.g., Bartley et al., 1984), some pumps incorporate flow dampers. Wood (1977) presents a useful review of personal sampling pumps, carried out in 1977, and, apart from limited advances in control technology, it still reflects much of the hardware available today.

The volumetric flow rate of sampling pumps needs to be set with the sampling device attached (including filter) and under the same conditions of temperature and humidity as sampling will be carried out under. Although many pumps incorporate a visual indication of flow rate such as a rotameter, this should be used for indication purposes only and the sampling flow measured and set using a primary standard such as a bubble flowmeter. Typically, the set flow rate is expected to be within 5% of the target flow rate, although the most recent guidelines on sampling in the United Kingdom specify flows to be set to $\pm 1.67 \times 10^{-6}$ m^3/s [±0.1 L/min] in all cases (HSE, 1997).

Sampling Strategy

While "static" or "area" sampling with fixed point samplers is still used in many situations, it is now widely accepted that representative aerosol sampling in the workplace should be carried out in the breathing zone—frequently defined as a region of the body not more than 0.3 m from the mouth and nose (Vincent, 1995). Breathing zone measurements generally give a better representation of worker exposure. However, Vincent (1995) notes that placement of sampling devices in this region does not guarantee representative sampling, and large

EXAMPLE 25–1: CALCULATION OF AN 8H TWA EXPOSURE

Three consecutive air samples for lead are collected at 3.3×10^{-5} m^3/s [2 L/min] onto filters in the breathing zone of a worker in a brass foundry, with the results shown in Table 25–3.

The shift started at 08:00 and finished at 18:00. Breaks were taken between 09:30 and 10:00, 12:00 and 12:30, and 15:00 and 15:30. The work pattern was split into different tasks in the morning and the afternoon. Using Eq. 25–4, calculate the 8 h TWA exposure level over the total duration of the shift (600 min).

The assumption is made that during breaks exposure is zero. During the afternoon period, when no sampling was carried out, it is assumed that exposure is similar to that measured by sample 3. Table 25–4 therefore gives a complete account of the day's exposure.

The 8 h TWA mass concentration is therefore given as

$$c_m = \left[\frac{(111\times 90)+(0\times 30)+(104\times 120)+(0\times 30)+(17\times 150)+(0\times 30)+(17\times 150)}{8\times 60}\right]$$
$$= 57\,\mu g/m^3$$

using Eq. 25–4.

TABLE 25–3. Example Gravimetric Sample Data for a Worker in a Brass Factory

Sample No.	Time On	Time Off	Flow rate (10^{-5} m^3/s [L/min])	Sample Duration (min)	Sample Volume (L)	Mass Collected (μg)	Mass Concentration (μg/m^3)
1	08:00	09:30	3.3 [2]	90		20	
2	10:00	12:00	3.3 [2]	120		25	
3	12:30	15:00	3.3 [2]	150		5	

TABLE 25–4. Complete Account of a Worker's Exposure to Lead in a Brass Factory (from Table 25–3)

Sample No.	Time On	Time Off	Flow rate (10^{-5} m^3/s [L/min])	Sample Duration (min)	Sample Volume (L)	Mass Collected (μg)	Mass Concentration (μg/m^3)
1	08:00	09:30	3.3 [2]	90	180	20	111
1a (break)	09:30	10:00		30	—	0	0
2	10:00	12:00	3.3 [2]	120	240	25	104
2a (break)	12:00	12:30		30	—	0	0
3	12:30	15:00	3.3 [2]	150	300	5	17
3a (break)	15:00	15:30		30	—	0	0
4 (Est. from #3)	15:30	18:00		150	—	5 (est.)	17
Total				600	75		

variations in sampled aerosol concentration can be seen across the front of the body, depending on worker orientation, placement of the aerosol source, and local air movements (Raynor et al., 1975).

As a matter of convention, exposure measurements for chronic hazards are usually taken for the duration of a single work shift. An 8 h TWA mass concentration (c_m) relates to the process whereby exposure occurring within a 24 h period is treated as being equivalent to a single uniform exposure over 8 h. A TWA mass concentration can be determined from a single full-shift sample, or it can be calculated from a series of consecutive samples (Leidel et al., 1977). Where sampling gaps occur over a shift, exposures during these periods should be estimated from adjacent measurements or from additional information (see Example 25–1). The TWA for a given time period (e.g., 8 h, or 15 min for a STEL) is calculated by

$$c_m = \frac{\sum_{i=1}^{n} c_{mi} \times t_i}{T}, \quad \sum_{i=1}^{n} t_i = \text{full shift duration} \tag{25–4}$$

where T is the given reference period (in minutes), t_i is the duration of sample i in minutes, and c_{mi} is the mass concentration of sample i.

For purposes of determination of compliance with occupational exposure limits, it is generally desirable to sample the workers assumed to be at maximum risk. When the maximum-risk employees cannot be ascertained, employees should be selected at random. Leidel et al. (1977) recommend calculating the 95% one-sided lower confidence limit (LCL) and the 95% one-sided upper confidence limit (UCL). These are calculated as follows:

$$\begin{aligned} \text{LCL}(95\%) &= \chi - t_\alpha \times CV_T \\ \text{LCL}(95\%) &= \chi + t_\alpha \times CV_T \\ \chi &= \frac{c_m}{\text{OEL}} \end{aligned} \tag{25–5}$$

where $t_\alpha = 1.645$ when $\alpha = 0.95$, CV_T is the coefficient of variation for the sampling/analytical method, and OEL is the exposure limit. If LCL and χ are above unity, then the exposure is classified as noncompliant. If UCL and χ are below unity, then the exposure is classified as compliant. Finally, if unity lies between LCL and χ, or between UCL and χ, the exposure is classified as possible overexposure.

MEASUREMENT OF SIZE DISTRIBUTION

Full characterization of the size distribution of an aerosol may be carried out during nonroutine investigations using a range of available methods described in previous chapters (see Chapters 10, 13, and 15–19). Although many instrument types have been used in the workplace (Mark et al., 1984), cascade impactors (see Chapter 10) are often the instrument of choice, giving an indication of the mass-weighted size distribution of an aerosol. Impactors 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 Andersen eight-stage impactor (***AND***) and the Micro Orifice Uniform Deposit Impactor (MOUDI) (***MSP***) have found relatively widespread use in the workplace. The Andersen consists of eight multiorifice stages with cut points between 10 and 0.4 μm when operated at 4.72×10^{-4} m^3/s [28.3 L/min]. Collection is usually onto aluminum foils, although other substrates are available. The use of multiorifices in the Andersen 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- or 10-stage version and is capable of making aerosol size distribution measurements down to 0.056 μm at 5×10^{-4} m^3/s [30 L/min].

Aerosol size distributions within the breathing zone are generally of greater relevance to health than static samples, and two cascade impactors have been developed to enable personal aerosol size distribution measurements to be made. The Marple personal cascade impactor (***AND***) (Rubow et al., 1987) 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 3.33×10^{-5} m^3/s [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 (Gibson et al., 1987). Cut points in the eight stages of the PIDS range from 0.9 to 19 μm at 3.33×10^{-5} m^3/s [2 L/min].

Cascade impactors are of limited use for measuring aerosol size distributions up to the limit of the inhalable convention (100 μm aerodynamic diameter) due to the relatively low cut point of the upper stage in most cases. Extrapolation of measured size distributions above this cut point depends 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 (Gibson et al., 1987). 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 the inhalable aerosol. Such an approach is advantageous to industrial hygiene measurements, where ultimately measurements need to be related to the mass of particles inhaled.

When the specific health-related fractions of the aerosol are of more concern than a detailed analysis of particle size distribution, a number of samplers allow simultaneous measurement of all three fractions. The IOM personal multifraction sampler uses aerosol separation within polyurethane foams to achieve this (Vincent et al., 1993). Aerosol is sampled through a 15 mm diameter inhalable inlet at 3.33×10^{-5} m^3/s [2 L/min]. Two polyurethane foam selectors of different grades placed in series then separate the thoracic and respirable subfractions. The sampler enables the inhalable fraction to be measured by weighing deposits in both foams and the backup filter. The combined deposits on the filter and adjacent foam give the thoracic fraction, and the filter alone gives the respirable aerosol fraction. A similar approach using polyurethane foams has been developed for use with the conventional IOM inhalable sampling head (Kenny et al., 1999b). An alternative approach is used by the Personal Spectrometer (PERSPEC) (Prodi et al., 1988, 1989). The inhalable aerosol fraction is introduced to a highly divergent flow of clean air and deposited onto a 47 mm filter. Deposition position depends on particle size; thus by weighing the complete filter the inhalable fraction can be determined, or by weighing specific areas of the filter (after cutting them out) different subfractions can be measured (Kenny and Bradley, 1994). The Respicon sampler (***TSI***) achieves separation of the three aerosol size fractions using a series of virtual impactors. A modified version has been developed (Respicon TM, ***HUN***) that allows real-time monitoring of each fraction using light scattering (Koch et al., 1998).

USE OF DIRECT-READING INSTRUMENTS

Instruments giving a near-instantaneous, or rapid, measure of aerosol properties (commonly referred to as *real-time measurement instruments*) are widely used in the workplace. Vincent (1995) and Walton and Vincent (1998) provide a broad summary of techniques commonly used in the workplace. However, it is possible to find examples of most devices described in earlier chapters being applied in the workplace.

For routine measurements, aerosol photometers are widely used and available from an increasing number of manufacturers. Their use covers checking short-term, task-specific, or

instantaneous exposure levels and identifying exposure hot spots. Systems have also been developed that combine photometer measurements with simultaneous video filming of workers, allowing direct comparison between work tasks and exposure levels (Gray et al., 1992; Gressel et al., 1993; Heitbrink et al., 1993; Unwin et al., 1993). The implementation of the measurement method has various guises, from passive instruments relying on convection to bring particles into the sensing zone (as with the Mini-RAM, and the later personal data-RAM, ***MIE***), to pumped devices such as the Microdust Pro (***CAS***), to instruments incorporating data loggers (e.g., the DustTrack [***TSI***] and Data-RAM [***MIE***]). Most devices are compact, with most being portable and a number of them being suitable for personal sampling.

Over a relatively narrow size range (approximating to the upper end of respirable size fraction) the light scattered from an aerosol is roughly proportional to the scattering volume (see Chapter 15; Baron, 1994). Thus, after correcting for density, scattered light may be used as an indirect measure of mass concentration. The method is relatively good for measuring respirable aerosol concentration, but becomes tenuous when used for the thoracic subfraction and potentially misleading when used to measure the inhalable aerosol mass concentration (the sensitivity to equivalent aerosol masses represented by 20 μm particles is approximately a factor of 10^2 lower than the sensitivity to 2 μm particles). Instruments such as the Respicon TM (***HUN***) go some way to overcoming this size dependence of photometry by selectively concentrating larger particles through the use of virtual impaction (Koch et al., 1998). In some situations it is feasible to calibrate a photometer to the inhalable mass concentration, but only when the fine particles detected form a constant fraction of the inhalable aerosol. Optical single-particle detection and sizing instruments such as the Grimm "Work-check" (***GRI***) overcome some of the limitations of photometers, but their sensitivity is still restricted to a similar range of particle sizes.

In all cases it is advisable to calibrate photometers before using them with different aerosols, as particle size distribution, shape, and refractive index will affect measurements (see Chapter 15). Calibration is usually performed by carrying out parallel gravimetric sampling and applying an adjustment factor to the photometer to ensure that results agree. Many photometers have the facility to collect aerosol passing through the sensing zone on a filter, thus simplifying calibration. Zero offset checks are also recommended before use by placing the photometer in a clean environment: Deposits on the optics and surfaces of the sensing zone can lead to a change in the instrument calibration.

Recent developments in condensation particle counter (CPC) technology have led to a commercially available portable device with logging capabilities, suitable for semiquantitative particle number measurements. The P-Trak (***TSI***) is designed to provide near-instantaneous measurements of particle concentration between 20 nm and approximately 1 μm. Although it is primarily aimed at investigating aerosol number concentration levels and variations and tracking contamination sources in indoor environments, it is also being applied to measuring real-time particle number concentration measurements in the workplace.

Respirator Fit Testing

Both photometers and CPCs are used extensively for measuring the fit factor of respirators. The fit of a respirator can either be measured using a qualitative fit test (QLFT) or quantitative fit test (QNFT) (OSHA, 1998). Both approaches rely on the respirator filter removing the majority of a test agent, leaving gaps in the respirator–face seal as the main route for the agent to penetrate the mask. QLFT methods generally rely on the wearer's perception of a test agent through odor or taste, the most common agents being isoamyl acetate, sodium saccharin, and irritant fume. QNFT methods, on the other hand, use quantitative measurement of the leakage rate around the mask. The first QNFT methods suitable for routine use

exposed the wearer to a controlled atmosphere of dioctyl phthalate (DOP) aerosol and measured the aerosol inside and outside the mask using forward light-scattering photometry (Burgess et al., 1961; Hyatt et al., 1972). HEPA filters were used on the mask to ensure that most of the particles detected within the mask penetrated due to leakage. This method is still used, although alternative aerosol materials such as corn oil and sodium chloride have replaced the use of DOP.

The use of a specific aerosol in an enclosed system is somewhat restrictive, and in 1981 Willeke et al., investigated easily generated aerosols, including cigarette smoke, fine carbon particles from high-volume sampling pumps, and fine metal/metal oxide particles generated from the filament of a hair dryer (Willeke et al., 1981). However, the most significant aerosol investigated was the ambient aerosol found in the workplace. Using a CPC to compare the ambient particle number concentration to that inside a respirator being worn, they were able to show that this formed a basis for rapid quantitative fit tests. The ambient air–CPC method is now widely applied, using the PortaCount Respirator Fit Tester (***TSI***). With HEPA filters, penetration is lower than 0.03% for 0.3 μm particles (representing the particle size region of highest penetration). Thus, given a sufficiently high challenge aerosol concentration, fit factors of over 3000 are measurable. Ambient concentrations of submicrometer particles are rarely lower than 10^9 to 10^{10} particles/m^2 [10^3 to 10^4 particles/cm^3] unless the air is highly filtered, allowing fit factors greater than 1000 to be measured under most circumstances. A similar approach has been proposed for measuring leakage around filters in filter cassettes used for workplace sampling (Baron et al., 2001).

Alternative QNFT methods have been proposed and are currently used, including dynamic pressure measurements inside the respirator, large-particle penetration tests, and small-particle penetration tests. A comprehensive review of current and proposed methods may be found in Han et al. (1997).

FUTURE TRENDS

Perhaps the most significant change in industrial hygiene aerosol measurement over the past two decades has been the development and gradual adoption of size-selective sampling conventions. These now enable measurements that have greater biological relevance to be made in the workplace. Although the next few years are likely to see the current position being consolidated, there is scope for the present sampling conventions to be revised. The inhalable convention is limited in its scope and applicability. Its abrupt termination at 100 μm brings into question whether the ingression of large particles and projectiles into more open samplers is acceptable or leads to inaccurate measures of aerosol concentration (Aitken and Donaldson, 1996). In addition, the inability to develop inhalable samplers thus far that follow the convention over a wide range of wind speeds raises the question of whether the standard is unattainable or inappropriate.

At the other end of the size spectrum, toxicological information on responses to nanometer-sized low-solubility particles are challenging the applicability of current sampling conventions and philosophies. Recent toxicology on low-toxicity insoluble materials such as titanium dioxide has indicated that a more appropriate dose metric for depositing in the alveolar region may be particle number or surface area (Oberdörster et al., 1994; Donaldson et al., 1998). These studies appear to support some epidemiological investigations of the general population, indicating correlation between inhalation of fine particles and health effects (Dockery et al., 1993). The extent to which such findings are applicable to exposure within the workplace is not apparent at present. However, to begin to understand the relevance of exposure to very fine particles and the appropriate metric to use for dose, developments in the measurement of exposure in terms of particle number and surface area are necessary. As the debate on the appropriate dose and exposure metric develops, there will

no doubt be further extensions to the manner in which aerosol exposure in the workplace is measured in the subrespirable size range.

Current trends in workplace sampling practice indicate a desire within the industrial hygiene community to adopt methods that provide measurements with greater rapidity and with less effort. In particular there is a growing interest in relating exposure to specific tasks and operations, thus requiring highly sensitive or rapid-response aerosol measurement methods. Such trends are perhaps most obvious in the increased use (and abuse) of direct-reading photometer-based instruments. These provide a rapid indication of exposure, both allowing a more rapid response to problem situations than filter collection and analysis allows, together with a means of avoiding the expense of sample collection and analysis where it is not necessary. However, their attraction has seen their increasing but erroneous use to estimate exposure to inhalable aerosol. This clear need for direct-reading instruments that extend to the inhalable fraction is likely to lead to the development of new devices. Although it is not at all clear at present whether workable technologies will present themselves, there are a number of possible contenders: The application of optical methods may be further increased to large particle sizes through the size-selective concentration of particles and the detection of individual large particles. The development of handheld oscillating microbalance methods is underway, although it is unclear whether there will be collection and sensing problems associated with particles approaching 100 μm in diameter. Aerosol mass sensing methods based on filter pressure drop are being developed for fine particles (Dobroski et al., 1995; Sioutas et al., 1999; Volkwein et al., 1998). At present, the indications are that size-dependent effects will hinder their extension to 100 μm, although size-selective concentration and aerosol-specific calibration may lead to successful applications.

Passive samplers provide another route to simplified exposure measurement and have been under development for some time. They offer the simplicity of a discrete lightweight badge-type sampler with no need for a sampling pump. The passive sampler developed by Brown et al., relies on electrostatic deposition onto a pre-prepared electret material. Aerosol is carried to the deposition zone through convection; thus no pump is required (Brown et al., 1994). Although the device is not designed along size-selective lines, good correlation has been seen with size-selective samplers in some cases, and it is likely that such samplers could be developed into indicative screening devices (Brown et al., 1995).

A different approach to making size-selective sampling more accessible and less expensive is seen in the increasing utilization of porous foam pre-separators. The use of foam allows relatively inexpensive size-separation devices to be constructed and provides the possibility of modifying existing samplers to different applications. Chen et al. (1998) have proposed a porous foam respirable sampler based on the cowled sampler used for asbestos sampling, and foam plugs to convert the IOM inhalable sampler to either a respirable or a thoracic sampler have been investigated (Kenny et al., 1999b). At the same time, new methods of creating size-selective samplers that are better suited to occupational aerosol sampling (e.g., by operating at higher flow rates, giving better agreement with the sampling conventions, providing a more compact, lighter sampler, and operating at lower pressure drops) are under constant development. Recent work includes the investigation of virtual, axial-flow, and tangential-flow cyclones (Chen et al., 1999; Maynard, 2000; Kenny and Gussman, 1997), the development of centrifugal personal samplers (John and Kreisberg, 1999), and the development of inhalable samplers with inlet screens (Kalatoor et al., 1995; Hauck et al., 1997; Aizenberg et al., 2000), reducing the adverse effects of wind speed and large-particle projectiles on samples.

The desire for simplification also extends to standards against which exposure is measured. While the current emphasis is on monitoring worker exposure, the concept of controlling emissions at the source is gaining ground. The application of such thinking to the workplace will possibly result in the use of exposure modeling to estimate exposure risk, accounting for materials used, generation processes involved, emission control measures applied, and dis-

persion in the workplace (Maidment, 1998). The logical end point is the estimation of exposures from materials and processes within the workplace and the relegation of aerosol exposure measurement to a supportive role. However, sufficient questions surround the classification of materials in terms of their ability to form an aerosol during specific processes, together with the containment or release and transport of generated aerosols, to ensure that developments in aerosol measurement methods in the workplace will continue for a number of years to come.

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