

WORKPLACE AEROSOL MEASUREMENT

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25.1 INTRODUCTION

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).

These definitions tend to be used as descriptors rather than discrete classifications, and when considering measurement 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 submicrometer dust can be somewhat blurred. Workplace aerosols present potential health impacts through ingestion, inhalation, or dermal contact, although it is the inhalation route that is of prime importance when considering aerosol measurement.

Early workplace measurement (Walton and Vincent 1998) relied on particle number as the dominant metric with devices such as the konometer (Le Roux 1970; Hewson 1996), impinger (Greenburg and Smith 1922), and thermal precipitator (Green and Watson 1935; Hamilton 1956) being used to collect samples and optical microscopy used to count numbers of particles. Although exposure to fibers is still assessed on a particle number basis, current sampling and analysis methods are dominated by the use of aerodynamic sizing of the aerosol followed by collection on filters and mass analysis (gravimetric, or by chemical analysis for specific elements or compounds). Mass is a suitable metric for assessing the dosage of systemic poisons, for example metals or pesticides, but it may be less suitable for assessing dosage for other end points. The main reason that mass is used is simply that gravimetric or chemical analysis is more accurate and more amenable to automation and instrumental analysis.

Workplace aerosol measurement, while similar to other areas of aerosol measurement, differs somewhat in application and circumstance. 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 greater than those in the general environment. Finally, sampling is carried out specifically for assessing human exposure, rather than characterizing the aerosol itself or the physical or chemical processes associated with it.

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 6 to 10 and 14 are particularly pertinent, providing detailed information on approaches to aerosol monitoring, filter collection, inertial, gravitational, centrifugal and thermal sampling, and direct-reading techniques. Chapters 23, 24, 26, 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 on the basic sampling philosophies and methods used on a routine basis in the workplace and the application of direct-reading monitors in workplace aerosol measurement.

25.2 AEROSOL EXPOSURE MEASUREMENT IN THE WORKPLACE

25.2.1 Health Relevant Sampling

Workplace aerosol measurement involves the collection and analysis of samples, but ultimately concerns specific health effects caused by workers' exposure to aerosols. Thus, the method of sampling and metrics used aim to provide health

relevant information. Aerosol particles can enter the body through the skin, eyes, and gastrointestinal system, but generally the most sensitive route of entry into the body is through the respiratory system. The health 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 (see Chapter 38). Physiological response to an aerosol is dependent on the chemical and physical nature of the particles and the location of the interaction (i.e., deposition region). The ultimate goal of workplace 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, surface area, and surface chemistry. Ideally dose should be expressed in terms of the most appropriate metric. However, practical and economic restraints factor into the decision of appropriate aerosol 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 (Chapters 23). Recently, there has been concern that the health impacts of inhaled nanometer-scale aerosol particles—particularly those associated with some classes of emerging nanotechnologies—are not well-characterized by mass concentration measurements, but require exposure to be assessed in terms of alternative parameters (Maynard and Kuempel 2005; Maynard et al. 2006; Fissan et al. 2007; Maynard and Aitken 2007; Oberdöster et al. 2007).

25.2.2 Deposition Regions

The respiratory system is an effective size-selective aerosol sampler in its own right, and it is false 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 diffusion (for particles in the nanometer size range) 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 towards 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 typically cleared either through the action of alveolar macrophages engulfing them, or 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. Not all particles that enter the respiratory track are deposited; a portion, depending on size, are exhaled in the breath [International Commission on Radiological Protection (ICRP) 1995].

Aerosol characteristics such as size, morphology, surface area, and structure are also influential; however, 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 (Maynard and Aitken 2007). The extent to which this approach is tenable where toxicity data are sparse is questionable however.

25.3 SAMPLING CONVENTIONS

The 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. More recently, similar standards have been proposed with modifications to take into account deposition as well as penetration (Vincent 2005), and these standards are under discussion within the International Organization for Standardization, but they have not been accepted at this time. The existing aerosol penetration 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 Organization for Standardization (ISO 1995) and the ACGIH (ACGIH 1998) arrived at convergent conventions describing the probability of particles penetrating to the nasopharyngeal, tracheobronchial, and alveolar regions. However, it wasn't until the early 1990s that international consensus was reached on particle penetration standards among 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).

The inhalable convention is based on particle penetration through the mouth and nose of a breathing mannequin over a

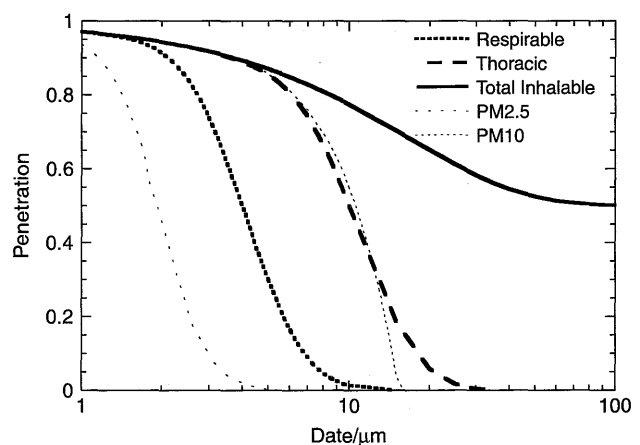


Figure 25-1 International workplace sampling conventions (ISO 1995). Environmental conventions are also shown for comparison (Chapter 26).

range of wind speeds and orientations with respect to the wind, and is defined as

$$SI(d_{ae}) = 0.5 \times (1 + e^{-0.06d_{ae}}) \quad (\text{Eq. 25-1})$$

for $0 < d_{ae} < 100 \mu\text{m}$. $SI(d_{ae})$ 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

$$ST(d_{ae}) = SI(d_{ae}) \times [1 - F(x)]$$

$$x = \frac{\ln(d_{ae}/\Gamma)}{\ln(\Sigma)} \quad (\text{Eq. 25-2})$$

$ST(d_{ae})$ 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 $11.64 \mu\text{m}$ and a geometric standard deviation (GSD) Σ of 1.5.

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

$$SR(d_{ae}) = SI(d_{ae}) \times [1 - F(x)]$$

$$x = \frac{\ln(d_{ae}/\Gamma)}{\ln(\Sigma)} \quad (\text{Eq. 25-3})$$

where the cumulative lognormal distribution has a MMAD Γ of $4.25 \mu\text{m}$, and a GSD Σ of 1.5. A respirable convention for susceptible groups is also defined, with $\Gamma = 2.5 \mu\text{m}$, although this has not been implemented in any exposure standards as yet. Penetration to the tracheobronchial and extrathoracic regions can be defined by the difference between the respirable and thoracic conventions (tracheobronchial), and the thoracic and inhalable conventions (extrathoracic). Further information on particle size-selective sampling for workplace contaminants may be found in ACGIH (1998). The greatest impact of moving to particle size-selection for sampling is to be expected from adopting the inhalable convention, because of the potentially large difference in mass collection between samplers designed to meet the inhalable convention and those that were not. Werner et al. (1996), Lidén et al. (2000a), and Sivulka et al. (2007) can be consulted for further discussion of this issue, which has yet to be definitively resolved. Recently, the inhalable convention has come under scrutiny for a number of reasons. Firstly, the upper limit of the size range of interest ($100 \mu\text{m}$) is an arbitrary selection, and particles larger than this can be airborne and therefore are available for possible inhalation. In addition, when considering the appropriate fraction of these particles there is a further issue of a large difference in inhalation efficiency between breathing through the mouth and

through the nose. Heavy exertions lead to mouth breathing, or a combination of mouth and nose breathing, and a certain proportion of people breathe naturally through the mouth as a result of constricted passage in the nose. Therefore, it might be argued that the standard should account for mouth breathing, which is the more conservative estimate. However, even if this is accepted, our understanding of the efficiency of mouth breathing may be based on historical observations or experiments with groups of workers whose physiology is different from that of modern workers due to changes in workforce age distribution, fitness, gender, ethnicity, and so on. (Lidén and Harper 2006). All studies of the inhalability of very large particles indicate a maximum size of inhalability, whether for nasal or oral breathing, while studies of sampler performance have not indicated a similar minimum, and this leads to problems in the assessment of exposures to coarse dust, for example wood dust (Harper and Muller 2002; Harper et al. 2004). Secondly, the convention was based upon inhalation from moving air. Although initial studies included more slowly moving air (0.5 m/s), more recently, it has been shown that air velocities in the majority of workplaces are less than 0.3 m/s , averaging around 0.1 m s^{-1} (Baldwin and Maynard 1998; Lidén et al. 2000b). Since that time there has been research on inhalability under calm air conditions (Aitken et al. 1999), as well as investigations of sampler performance under these conditions (Kenny et al. 1999a). However, calm air is not the same as slowly moving air, and experiments covering the latter situation are only now underway (Witschger et al. 2004; Schmees et al. 2008; Sleeth and Vincent 2009).

With increasing concern over potential health impacts associated with inhaling nanometer-scale aerosols, there has been some discussion over the need for a nanoparticle (or ultrafine particle) sampling convention. The rationale is that there is increasing evidence for inhaled particles between approximately $1\text{--}100 \text{ nm}$ in diameter being associated with impacts to the respiratory and cardiovascular systems (Chapter 38; Delfino et al. 2005; Mills et al. 2007; Oberdörster et al. 2007). It can be argued that selectively sampling particles smaller than 100 nm may provide a better indicator of potential risk associated with exposure to nanometer-scale particles. However, as yet, no physiological basis for such a sampling convention exists— 100 nm is an arbitrary upper size limit that has little bearing on differentiating between particles that exhibit different modes of action within the body, either through where they deposit, or how they behave having deposited in the respiratory system.

25.3.1 Sampling Against Exposure Conventions

The relevance of workplace aerosol measurement relies on selection of an appropriate sampling device. Filter selection, pump selection and use, sampling strategy, and sample handling play an important role in determining the accuracy and

suitability of sampling devices. Useful sources of information include ACGIH (1995) and ACGIH (1998).

25.3.2 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 prior to acceptance of the current conventions. Many such samplers continue to be in use as they are prescribed by national regulations, or their use is preferred to maintain traceability to historic measurement methods, whose results may have been used to develop risk assessments. Some 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)]. Performance tests of existing samplers have given mixed results in the laboratory (Kenny et al. 1997; Görner et al. 2001).

The development of inhalable samplers has been hampered by the complexities of how external conditions, such as wind speed and direction, affect aspiration, together with the difficulties of making penetration measurements with particles up to 100- μm aerodynamic diameter or larger. 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). The IOM sampler has significant shortcomings. For instance the filter is very accessible to accidental or deliberate sample tampering, plastic cassettes have severe instability in weighing (Smith et al. 1998; Li and Lundgren 1999; Lidén and Bergman 2001), there is evidence for significant projectile and large particle entry (Lidén and Kenny 1994; Aitken and Donaldson 1996; Aizenberg et al. 2001), and it can give extremely variable results when external winds are directional (Roger et al. 1998). It is included in the UK method for determining dust gravimetrically (Health and Safety Executive 1997), where the entire capsule is weighed, and, by reference, in the UK method for metals analysis (Health and Safety Executive 2006). However, in this latter method, no guidance is given on how to account for particulate that has collected on internal surfaces of the sampler other than on the filter. This is a problem where these “wall deposits” are a significant part of the sample, since, by design they are intended to be an integral part of the sample. The issue of wall deposits has come to the forefront as the IOM sampler is compared to the traditional closed-face 37-mm cassette used in the United States and some European countries as a result of changes in limit values to reflect sampling in accordance with the inhalable convention (Harper and Demange 2007). Field studies of

the closed-face cassette sampler side by side with the IOM sampler show much better agreement when the filter deposits alone are compared (Harper et al. 2007) or the filter deposits and the wall deposits are compared for both (Demange et al. 2002). The cheap and disposable closed-face cassette has many practical advantages over more expensive and necessarily re-usable samplers. Internal capsules such as the AccucapTM from SKC¹ or the WoodchekTM from MSA are available for use in the closed-face cassette to ensure all particles are included in gravimetric analysis, including those that might otherwise have deposited on the walls of the sampler. Otherwise, for chemical analysis where the filter is digested, it may be necessary to wipe the internal surfaces of the sampler with a small piece of filter or wipe material and add this to the digestion step (Harper 2006).

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 Aerosol 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, 2001), but it is unclear if it samples in accordance with the inhalable convention in the field (Harper and Muller 2002; Linnainmaa et al. 2008). 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). These boundaries are in essence set by comparing the mass fraction of a lognormal aerosol—characterized by its MMAD and GSD—that would be sampled by a device, to 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. When sampler accuracy and bias lie within acceptable bounds, a basis is provided for determining acceptable 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

¹Refer to Appendix I for complete manufacturers’ addresses indexed to a three-letter code.

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 because poor correlation exists between the two types of sampling (Kissell and Sacks 2002; Rodes and Thornburg 2005). 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 be dependent 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 6). Table 25-1 summarizes many of the workplace sampling devices currently available or in use, and gives some indication as to their application.

Sampler selection, however, may be constrained when compliance type measurements are required. To simplify compliance type measurements, many governments mandate that a specific type or types of samplers operated at prescribed flow rates be used to collect samples for analysis. In the United States, for example, respirable particulates are collected using Dorr-Oliver cyclones at a flow rate of 1.7 L/min or SIMPEDS-type cyclones at a flow rate of 2.2 L/min to estimate an ISO respirable-size fraction of particulates for analysis [NIOSH Manual of Analytical Methods (NMAM) 2003]. Specific government regulations should be consulted before compliance sampling is conducted.

25.3.3 Filter and Substrate Selection

Industrial hygiene aerosol samples are generally collected onto a filter, within 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 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 7 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; Li and Lundgren 1999; Lidén and Bergman 2001; Linnainmaa et al. 2008). 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 10 samples, with a minimum of three blanks). It is advisable to condition filters 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. 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.

Other sources of bias during weighing of filters include electrostatic attraction, where substrates are highly charged, and buoyancy effects. Electrostatic charge buildup may be significant for substrate materials such as polyvinyl chloride (PVC) and polytetrafluoroethylene (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 anti-static source prior to weighing.

25.3.4 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 batteries. The achievable flow rates of pumps varies among manufacturers, but most will provide flows of 1.67×10^{-5} to 5×10^{-5} m³/s [1–3 L/min] against a pressure drop of 6.25 kPa [25 in H₂O] for periods of up to 8 h. Personal pumps are available that will achieve flow rates of up to 2.2×10^{-4} m³/s [15 L/min], but there is always a trade-off between sampling flow rate, sampling time, sustainable pressure drop, battery capacity, 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), most pumps incorporate pulsation dampers. Wood (1977) presents

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
<i>Inhalable Samplers</i>						
IOM Inhalable	3.3 [2]	Personal	SKC	Good	Uses filter cassette (plastic version is reported to have weight stability issues). Susceptible to large projectiles. Wind speed dependant.	Mark and Vincent 1986; Kenny et al. 1997; Kenny et al. 1999a
IOM Inhalable Static CIP-101	5 [3] 17 [10]	Static Personal	CAS ARE	Good	Rotating porous foam acts as an air mover and collection medium.	Mark et al. 1985 Courbon et al. 1988; Kenny et al. 1997 Kenny et al. 1997
GSP Inhalable	5.8 [3.5]	Personal	STR	Good	Different sampling cones are available for different flow rates.	Kenny et al. 1997 Kenny et al. 1997
Conical Inhalable Sampler Seven Hole	5.8 [3.5] 3.3 [2]	Personal Personal	CAS, BGI Various	Good Fair	Based on the GSP sampler. Also known as the multi-orifice, or UKAEA sampler.	Kenny et al. 1997 Kenny et al. 1997
Single Hole PAS-6	3.3 [2]	Personal	Various	Poor	Used for lead aerosol sampling in the UK.	Kenny et al. 1997
Button Sampler	6.7 [4]	Personal	KOE SKC	Fair Good	Perforated inlet reduces wind speed dependence and inter-sampler variability, and leads to a uniform filter deposit. Flow rate can be a problem to achieve or maintain over longer time periods, even with the glass-fiber filters recommended by the manufacturer.	Kenny et al. 1997 Hauck et al. 1997; Aizenberg et al. 2000
<i>Thoracic Samplers</i>						
Elutriator	12.3 [7.4]	Static	GMW	Poor	Specific to cotton dust.	Robert 1979
CIP-10T	12 [7]	Personal	ARE	Fair	CIP-101 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	Not commercially available	Fair	IOM inhalable sampler with a size-selective polyurethane foam insert.	Maynard 1999
<i>Respirable Samplers</i>						
CIP-10R	17 [10]	Personal	ARE	Good	CIP-101 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

(Continued)

TABLE 25-1 Continued

Sampler	Flow Rate (10^{-5} m ³ /s [L/min])	Deployment	Manufacturer or Distributor (see Appendix I)	Agreement with Convention	Notes	References
SKC Cyclone		Personal	SKC	Good	Variants 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 non-conducting nylon.	Bartley et al. 1994
MRE 113A (Gravimetric Dust Sampler)	4.2 [2.5]	Static	CAS	Fair	Use limited to UK mines.	Dunmore et al. 1964
IOM Inhalable + Respirable Foam	3.3 [2]	Personal	SKC	Good	IOM inhalable sampler with a size-selective polyurethane foam insert. Foam has weight stability issues.	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	Not commercially available		Uses centrifugal particle separation.	John and Kreisberg 1999 (PM-2.5 operation)
FSP-10	17 [10]	Personal/ static	STR	Good		BIA 2002
<i>Miscellaneous Samplers</i>						
37-mm Cassette (Open)	3.3 [2]	Personal/ static	Various		Standard filter cassette, worn facing down at 45° to the body, but facing forward may give a better approximation to the inhalable convention. Wall deposits should be accounted for where necessary. Static-dissipative versions available.	Kenny et al. 1997
37-mm Cassette (Closed)	3.3 [2]	Personal/ static	Various		Standard filter cassette as above with a cap containing a 4-mm diameter inlet. Internal capsules to account for wall deposits are available.	Kenny et al. 1997
Static Sampler for "Total" Aerosol	Variable	Static	CAS		Open faced filter. Widely used in the UK.	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; Brown et al. 1995
Cowled Sampler	3.3 [2] (Typical)	Personal/ static	Various		Used in the main for fiber sampling. Size selectivity not quantified.	
Respicon	5.2 [3.1]	Personal	TSI		Virtual impactor and filter measures all three sampling conventions.	Koch 1998

TABLE 25-2 Filter Selection for Industrial Hygiene Aerosol Sampling

Substrate or Cassette	Typical Application	Weight Stability ^a	Pressure Drop ^a
Glass fiber filter	General collection Gravimetric analysis	***	**
Quartz-fiber filter	Chemical analysis	***	**
Cellulose ester membrane filter	Imaging, fiber sampling, digestion for metals analysis	**	***
PVC membrane filter	General collection Gravimetric analysis	****	***
Teflon membrane filter	Gravimetric analysis Chemical analysis	****	**
Polycarbonate filter	Particle imaging	****	*
Silver membrane filter	Chemical analysis, X-ray diffraction 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
Stainless steel cassette	IOM inhalable sampler	****	N/A
PVC Accucap™	Gravimetric analysis	****	***
Woodchek™ (PVC filter and aluminum cone)	Gravimetric analysis	****	***

^aA higher star rating indicates better weight stability or lower pressure drop.

a useful review of personal sampling pumps carried out in 1977, and apart from advances in flow control technology, basic pump mechanisms are the same.

The volumetric flow rate of sampling pumps needs to be set under the same conditions of temperature and humidity as sampling will be carried out and with the sampling device attached (including filter). Although many pumps incorporate a visual indication of flow rate such as a rotameter or digital display, these should be used for indication purposes only, and the sampling flow measured or calibrated using a primary standard such as a bubble flow meter or newer electronic flow meters, traceable to national or international standards. 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 UK specify flows to be set to $\pm 1.67 \times 10^{-6} \text{ m}^3/\text{s}$ [$\pm 0.1 \text{ L}/\text{min}$] in all cases (HSE 1997).

25.4 DIRECT-READING INSTRUMENTS

Perhaps the most recent changes in workplace aerosol measurement have been in the area of real-time measurement. A report of the United States Secretary of Labor's Advisory Committee on the Elimination of Pneumoconiosis Among Coal Mine Workers listed several recommendations dealing with the need for continuous respirable dust monitors to help protect workers' health (US Department of Labor 1996). In addition, a National Institute for Occupational Safety and Health (NIOSH) Criteria Document lists improved sampling devices as a research need pertinent to coal miner respiratory health and prevention of disease (NIOSH 1995). Monitors 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), Walton and Vincent (1998), and Maynard and Baron (2004), provide a broad summary of techniques commonly used in the workplace. However, many devices described in earlier chapters may be applied to the workplace if unique aspects of the workplace are taken into account.

Several approaches have been taken to address these unique aspects. An early effort used impaction sampling and beta-attenuation analysis of the deposit to determine short term aerosol measurements (Volkwein and Behum 1978). More promising technologies emerged that included light-scattering dust monitors, (Lehocky and Williams 1996; Tsao et al. 1996) and lately a person-wearable tapered-element oscillating microbalance (Volkwein et al. 2004, 2006). The principal goal of each of these efforts has been to develop an instrument that will give short term or real-time measurements of worker aerosol exposure. A further unique requirement for some workplace sampling may require intrinsic safety design such that Underwriters Laboratory or MSHA certification for use in potentially explosive environments can be secured. Detailed descriptions of the operational principles of these techniques may be found in Chapters 12 and 13 of this book.

25.4.1 Light Scattering

The theory of these instruments based on light scattering from particles has been summarized in Chapter 13. Several of the monitors have been characterized in the laboratory for different dusts (Keeton 1979; Marple and Rubow 1981, 1984; Kuusisto 1983; Rubow and Marple 1983). The relationship of the instruments' response to dust concentration is not simple but depends on particle size, particle composition, and on instrument design and manufacturing differences. Significant changes in dust particle characteristics such as shape, size, surface properties, and density can affect the instrument's correlation with mass concentration and require calibration of the instrument for each type of dust measured (Williams and Timko 1984). These factors have limited the use of photometers to dust-source identification and control

technology evaluation. They are not useful for monitoring compliance with dust standards.

For routine walk-through 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 in low to high aerosol loadings, and identifying exposure hot spots. 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 (*TFS*), to pumped devices such as the Microdust Pro (*CAS*), to instruments incorporating data loggers [e.g., the DustTrack (*TSI*) and Data-RAM (*TFS*)] or person-wearable SIDEPAK™ (*TSI*). Most devices are compact, with the majority 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 or the Mie scattering regime) the light scattered from an aerosol is roughly proportional to the scattering volume (Chapter 14; 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™ (*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, 2002; Rando et al. 2005). 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. Calibration is usually performed by carrying out parallel gravimetric sampling, and applying an adjustment factor to the photometer to ensure 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. Calibration accuracy will further depend on the uniformity of the aerosol characteristics over the sample collection interval.

25.4.2 Tapered Element Oscillating Microbalance

The theory of the Tapered Element Oscillating Microbalance (TEOM, *R&P*) is summarized in Chapter 12. Despite its currently limited application to the mining industry, this technology offers a notable advantage of direct, near-real-time measurement of dust mass in the field. Since dust exposure standards are based on dust mass, this attribute of the TEOM is significant. Interest in the development of a prototype TEOM personal dust monitor began 25 years ago (Patashnick and Rupprecht 1983) as a device configured for strictly an end-of-shift measurement. It was not a real-time monitor, but used the oscillating microbalance principle to “weigh” the collection filter before and after dust sampling. The Bureau of Mines (BOM) evaluated this prototype system in the laboratory for end-of-shift applications (Williams and Vinson 1986). The effective standard deviation of repeated measurements was 1.6 μg . Tests at controlled temperature and humidity showed less than 20 μg of drift during an 8-h shift.

These early attempts to construct a person-wearable form of the TEOM required a substantial mass in the base of the tapered element to dampen the vibrations; this reduced the concepts “wearability.” A proprietary development by *R&P* solved the need for a substantial base mass by electronically dampening the base vibration and enabling development of a person-wearable TEOM-based personal dust sampler. The PDM 3600 dust sampler for miners is now available from *TFS* (Volkwein et al. 2004, 2006).

25.4.3 Other Direct-Reading Instruments and Methods

While mass-based criteria are dominant for workplace aerosol measurements, there is growing recognition that other metrics may be more appropriate for nanometer-sized particulates such as surface area or number count. Recent developments in condensation particle counter (CPC) technology have led to a commercially available portable device with logging capabilities, suitable for semi-quantitative particle number measurements. The Model 3007 (*TSI*) is designed to provide near-instantaneous measurements of particle concentration between 10 nm and approximately 1000 nm. 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. Other metrics under consideration include measurement of particulate surface area (Litton 2002; Ku and Maynard 2005; Maynard and Aitken 2007) or specific surface area equivalent dose (Oberdörster 2001) as used in the Model 3550, *TSI* Nanoparticle Surface Area Monitor (Shin et al. 2007; Asbach et al. 2009).

25.5 PARTICLE SIZE MEASUREMENT

Full characterization of the size distribution of an aerosol may be carried out during non-routine investigations using a range of available methods described in previous chapters (see Chapters 8, 11, and 13 to 17). Although many instrument types have been used in the workplace (Mark et al. 1984), cascade impactors (Chapter 8) 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- μm and 15- μm aerodynamic diameter and above. For area sampling, cascade impactors such as the Thermo Scientific Andersen impactor (*TFS*) and the Multi-Orifice Uniform Deposit Impactor (*MOUDI*; *MSP*) have found relatively widespread use in the workplace. The Andersen consists of eight multi-orifice stages with cutpoints between 10 μm and 0.4 μm when operated at $4.72 \times 10^{-4} \text{ m}^3/\text{s}$ [28.3 L/min]. Collection is usually onto aluminum foils, although other substrates are available. The use of multi-orifices 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 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 $5 \times 10^{-4} \text{ m}^3/\text{s}$ [30 L/min].

Aerosol size distributions within the breathing zone are generally of greater relevance to health than area samples, and small cascade-style impactors have been developed to enable personal aerosol size distribution measurements to be made. The Marple personal cascade impactor (*TFS*) (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 $3.33 \times 10^{-5} \text{ m}^3/\text{s}$ [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). The *PIDS* is not currently commercially available. Cutpoints in the 8 stages of the *PIDS* range from 0.9 μm to 19 μm at $3.33 \times 10^{-5} \text{ m}^3/\text{s}$ [2 L/min]. The Sioutas personal cascade impactor (*SKC*) is a more recent development that provides 50% cutpoints at 2.5 μm , 1.0 μm , 0.50 μm , and 0.25 μm , giving a versatile device capable of measuring exposure against a range of sampling conventions (Misra et al. 2002). In addition, a newer Mini*MOUDI*TM (*MSP*) impactor offers a person-wearable instrument with size data down to 0.01 μm .

Cascade impactors are of limited use for measuring aerosol size distributions to the upper limit of the inhalable convention (100- μm aerodynamic diameter), due to the relatively low cutpoint of the upper stage in most cases. Extrapolation of measured size distributions above this cutpoint 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 (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.

In cases where 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 multi-fraction sampler uses aerosol separation within polyurethane foams to achieve this (Vincent et al. 1993; Kenny et al. 1999b). Aerosol is sampled through a 15-mm diameter inhalable inlet at $3.33 \times 10^{-5} \text{ m}^3/\text{s}$ [2 L/min]. In the original concept, two polyurethane foam selectors of different grades placed in series separate the thoracic and respirable sub-fractions. 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. However, a version with thoracic foam is currently unavailable. 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 is dependent 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 sub-fractions 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 (Koch et al. 1998, 2002; Rando et al. 2005). A modified version has been developed (RespiconTM, *HUN*) that allows real-time monitoring of each fraction using light scattering (Koch et al. 1998). A very recent development is a novel coarse particle sampler that incorporates diffusive sampling of ultrafine or nano-scale particulate (Gorbunov et al. 2009).

25.5.1 Sampling Strategy

Workplace aerosol measurements fall broadly into personal exposure assessment or engineering evaluation of controls. While general measurement requirements may seem similar, specific strategies should be tailored to the needs of the sampling.

25.5.1.1 Personal Monitoring While “static” or “area” sampling with fixed-point samplers is still used in many situations, it is now widely preferred that representative aerosol

sampling to monitor personal exposure 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 give a better representation of worker exposure. However, Vincent notes that placement of sampling devices in this region does not guarantee representative sampling, and large 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; Vinson et al. 2007). A novel approach to sampling is to place a small device at the end of a personal “hands-free” microphone headset so that it is located much more centrally within the breathing zone (Lidén and Sourakka 2009).

In mining, for example, personal exposure monitoring is preferable to area monitoring (Leidel et al. 1977). Dust concentrations have been shown to change dramatically over times of a few seconds and distances of just 0.6 m in underground coal mines (Kost and Saltsman 1977). Therefore, to meaningfully approximate a worker’s dust exposure, personal monitoring is the preferred strategy (Kissell and Sacks 2002).

As a matter of convention, personal exposure measurements for chronic hazards are usually taken for the duration of a single work shift. An 8-h Time Weighted Average (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 Short Term Exposure Limit (STEL)) is calculated by:

$$c_m = \frac{\sum_{i=1}^n c_{mi} \times t_i}{T}, \quad \sum_{i=1}^n t_i = \text{full shift duration (Eq. 25-4)}$$

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 .

EXAMPLE 25-1

Calculation of an 8-h TWA exposure. Three consecutive air samples for lead are collected at $3.3 \times 10^{-5} \text{ m}^3/\text{s}$ [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 equation 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 where 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

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

using Equation 25-4.

For purposes of determination of compliance with occupational exposure limits, it is generally desirable to sample the workers assumed to be at maximum risk. Where 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:

$$\begin{aligned} \text{LCL}(95\%) &= \chi - t_\alpha \times CV_T \\ \text{UCL}(95\%) &= \chi + t_\alpha \times CV_T \end{aligned} \quad (\text{Eq. 25-5})$$

$$\chi = \frac{c_m}{\text{OEL}}$$

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

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

Sample	Time On	Time Off	Flow Rate ($10^{-5} \text{ m}^3/\text{s}$ [L/min])	Sample Duration (min)	Sample Volume (L)	Mass Collected (μg)	Mass Concentration ($\mu\text{g}/\text{m}^3$)
#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	Time On	Time Off	Flow Rate ($10^{-5} \text{ m}^3/\text{s}$ [L/min])	Sample Duration (min)	Sample Volume (L)	Mass Collected (μg)	Mass Concentration ($\mu\text{g}/\text{m}^3$)
#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	

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.

25.5.1.2 Evaluation of Workplace Controls Use of personal compliance type sampling results to judge the effectiveness of a control intervention may be misleading (Kissell 2003). Area sampling may be most appropriate for characterization of a workplace aerosol or for the evaluation of an engineering control. The chief advantage of area sampling is the elimination of the human variable in interpretation of the results. Other benefits include the use of a larger variety of instruments, and shorter sampling time periods.

Walk-through evaluations using real-time monitors are used to obtain an overview of environment and to target specific areas, operations, or personnel for monitoring. More detailed strategy should be used to measure or verify the effectiveness. This strategy should account for variables such as aerosol generation rate (production), transport, dilution, sampler location, and other factors (Kissell 2003). Sound statistical design and error analysis should also be a part of the evaluation (Robson et al. 2001).

25.6 CURRENT TRENDS

25.6.1 Diesel Particulate in the Workplace

In 1988, NIOSH recommended that whole diesel exhaust be regarded as a potential occupational carcinogen and that reductions in workplace exposure would reduce cancer risks (NIOSH 1988). Exposure to elevated concentrations of diesel exhaust has also been linked to health effects such as eye and nose irritation, headaches, nausea, and asthma (Kahn 1988; Wade and Newman 1993). Considerable debate has recently taken place regarding what should be the appropriate metric for measurement of diesel particulate matter (DPM) in the workplace.

In the mining workplaces, MSHA has chosen to regulate engine emissions in coal mines and to set a limit on ambient

particulate carbon levels in all other mines (Stephenson 2006). The OSHA has no workplace ambient occupational limits for diesel particulate matter in general industry. The US Environmental Protection Agency (USEPA), however, regulates diesel engine emissions and includes diesel particulate as part of their particulate matter (PM) standards.

Personal exposure to DPM in the workplace may be sampled using a personal sampling pump with an impactor-classified filter sample followed by NIOSH method 5040 analysis of the carbon components of the filter (Noll 2005). This provides a TWA measurement of the total, organic, and elemental carbon present on the filter.

The measurement challenge, from the point of view of health effects and regulation and control of particulate matter, lies in the ability to distinguish between particulates generated by the process and ambient diesel particulates. This becomes especially problematic if the process particulates contain carbon. The aerosol scientist must also deal with the changing particulate size and particulate speciation, which change with changes in control technologies and fuel blends.

The development of handheld oscillating microbalance systems for respirable dust monitoring in mining has been successful. While inlet and classification of inhalable and thoracic fractions will require special consideration using this technology, there is some optimism that the handheld oscillating microbalance may be capable of sensing the submicrometer DPM fraction of mine aerosols (Wu and Gillies 2008). This work involved placing a 0.8-micrometer cutpoint impactor on the inlet of a monitor and measuring only the mass of the submicrometer aerosol. When continuous side-by-side measurements of respirable and submicrometer aerosol were conducted, source apportionment between combustion and commutation aerosols was possible in near real time.

25.6.2 Toxic Materials

Workplace assessment of toxic aerosols such as beryllium, silica, and radioactive aerosols, is problematic when the toxic limit values approach the level of detection of the

substance. Chapter 28 provides specific information on monitoring radon and radioactive aerosols. The general solution of sampling a larger volume of air and concentrating the sample to provide sufficient quantity for quantitative analysis is limited in personal sampling because of equipment size constraints. Misra et al. (2002) describes the use of a $1.5 \times 10^{-4} \text{ m}^3/\text{s}$ [9 L/min] flow-rate pump and impactor manufactured by SKC to enable collection of larger samples from a person-wearable device. Maynard (1999) describes the use of GK 2.69 (BGI) respirable cyclone using a $7 \times 10^{-5} \text{ m}^3/\text{s}$ [4.2 L/min] flowrate which also enables larger samples for analysis. A $1.67 \times 10^{-4} \text{ m}^3/\text{s}$ [10 L/min] cyclone is also available (BIA 2002). Such portable, higher flow-rate samplers improve the limits of detection for high toxicity aerosols. Alternatively, more sensitive analytical techniques are required to assess personal exposure of toxic materials in the workplace.

25.6.3 Engineered Nanomaterials

Toxicological information on responses to inhaled nanometer-scale low solubility particles is challenging the applicability of current sampling conventions and philosophies (Maynard and Aitken 2007). 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 (see Chapter 38 for more details; Maynard and Kuempel 2005; Oberdörster et al. 2005, 2007). These studies appear to support some epidemiology investigations of the general population, indicating correlation between inhalation of fine particles and health effects (Dockery et al. 1993; Wichmann and Peters 2000; Pekkanen and Kulmala 2004; Delfino et al. 2005; Penttinen et al. 2006). The extent to which such findings are applicable to exposure within the workplace is not apparent at present, although there is increased concern that new nanoscale materials—specifically those associated with the emerging field of nanotechnology—could present new and unusual occupational hygiene risks (Maynard 2007). As yet, few data are available on occupational exposures to engineered nanomaterials. There is evidence that materials such as carbon nanotubes and carbon black are not readily aerosolized (Kuhlbusch et al. 2004; Maynard et al. 2004; Bello et al. 2009), although these data are not generalizable, and may not apply to all situations where these materials are handled. Based on research in progress, a number of publications are anticipated over the next few years that provide a clearer picture of conditions under which exposure to airborne engineered nanomaterials might occur.

Occupational health agencies such as NIOSH in the United States have begun to formulate guidelines for the safe handling of engineered nanomaterials (NIOSH 2006). Similar guidelines are becoming available from industry-based groups (e.g., the DuPont/Environmental Defense

Fund Nano Risk Framework; Dupont 2007) and from consensus standards bodies (ISO 2006; ASTM 2007; ISO 2008). These begin to outline the challenges and possible solutions associated with measuring and controlling exposure to airborne engineered nanomaterials in the workplace.

25.6.4 Sampling Aerosol and Vapor

In some cases it is necessary to assess exposures to aerosol and vapor simultaneously. This situation can occur when a volatile liquid or a solid with significant vapor pressure is sprayed, or when a vapor can give rise to a condensation aerosol, or when a volatile substance is absorbed on other particulates. The most typical examples are the isocyanates used in spray-on finishes, or toluene di-isocyanate, which, while volatile, can be found attached to polyurethane aerosol in foam manufacture. In this particular case, it is important not only to collect both aerosol and vapor fractions simultaneously, but to also derivatize the isocyanate group quickly so that further reaction does not take place. Thus, an impinger filled with liquid reagent followed by a filter also coated with reagent is the standard sampling apparatus. Less reactive aerosol–vapor combinations can be sampled using a diffusion denuder, followed by a filter, although these are not common as personal samplers because of their generally large size. An improvement may be a novel design of dichotomous sampler (Kim and Raynor 2009).

25.6.5 Penetration versus Deposition

While penetration of particles to the airways system is a measure of exposure, it is not a good measure of dose for certain particle sizes. This is because of a deposition minimum that occurs at around $0.3 \mu\text{m}$ AED at the intersection of the two major mechanisms of particle capture: diffusion for small particles and interception and impaction for larger particles. As long as mass is the preferred metric, then this deposition minimum likely has little effect on sampling to meet the inhalable convention, because the much larger particles are associated with very much larger masses. However, for smaller particles, the deposition minimum becomes important. Vincent (2005) discusses the impact of accounting for deposition on the current thoracic and respirable sampling conventions and how this would require the development of novel sampling techniques, and also discusses the potential impact on any proposed ultrafine or nanoparticle sampling convention.

25.7 LIST OF SYMBOLS

<i>SI</i>	inhalable penetration fraction
<i>ST</i>	thoracic penetration fraction
<i>SR</i>	respirable penetration fraction

c	concentration
d	diameter
UCL	upper confidence limit
LCL	lower confidence limit
Γ	mass median aerodynamic diameter
Σ	geometric standard deviation
η	efficiency
χ	ratio of the concentration mean divided by the occupational exposure limit
ae	aerodynamic diameter
R	respirable
T	thoracic
I	inhalable

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