24

Industrial Hygiene

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INTRODUCTION

Definition of Industrial Hygiene

Industrial hygiene is both a science and an art. Industrial hygiene encompasses the total realm of control, including the recognition and evaluation of those factors of the environment emanating from the place of work which may cause illness, lack of well being, or discomfort either among workers or among the community as a whole. In short, industrial hygiene can be defined as the identification, evaluation, and control of occupational health hazards. Industrial hygiene aerosol sampling differs from general aerosol measurements in several ways. First, in evaluating the industrial environment, the aerosol contaminant is almost always known, or it can be deduced from a knowledge of the process or product in use. Only in limited cases is the sampling performed to identify an unknown contaminant. Second, industrial hygiene sampling today is mainly performed by the use of portable, battery-operated air sampling equipment. This equipment is usually worn by the worker for the duration of the work shift to define the exposure of that individual. This is known as personal breathing zone air sampling. The personal breathing zone is that air that would most nearly represent the air inhaled by the worker and is usually considered to be either less than about 30 cm from the workers mouth or a distance of four to six feet from the floor. Lastly, the concentrations encountered in industrial hygiene are usually higher than those encountered in community air sampling but much lower than that potentially present in monitoring the effluent of a stack or other process vent.

Historical Perspectives

Air sampling equipment for the measurement of aerosols has evolved over the past several decades in the direction of miniaturization and automation. First (1988) cites the example of the Greenberg–Smith impinger, which was the workhorse of aerosol sampling in the 1920s. This device was too large and heavy to permit its use as a personal aerosol sampling instrument. It was supplanted a decade later by the smaller and lighter midget impinger which required a pump and motor only one-tenth the size of the earlier equipment. For aerosols, he notes, the midget impinger has been largely replaced by the use of

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[1] Any mention of commercial names or products does not constitute an endorsement by the National Institute for Occupational Safety and Health.

filter media contained in disposable cassettes with airflow provided by portable, battery-operated pumps. Electronic controls permit the automated start-up and shut-off of the pump, record the sampling time, monitor pump performance, and control the pump speed to compensate for the increase in the pressure drop across the filter as the contaminant is collected. The increased miniaturization and automation has not been limited to personal sampling equipment. In the past, real-time (direct-reading) aerosol sampling instruments have been limited by their size and power requirements to measurements made in a fixed location in the work environment. Portable real-time instruments have been developed to measure aerosol concentration and/or particle size distribution. These instruments can be carried into the work site and measurements can be made in the breathing zone of the worker. Even smaller aerosol measuring instruments have been developed which can be worn by the worker. These instruments may have data recording and averaging capabilities. They can also provide a warning to the worker if concentrations exceed a preset alarm condition so that the worker can leave the hazardous environment and action can be taken to alleviate the hazard.

The evolution of industrial hygiene measurement practice from fixed-location (area) monitoring to personal sampling arises from the general inadequacy of area sampling for monitoring worker exposures. Area monitoring does not yield adequate exposure estimates for the individual worker because of temporal and spatial variation of aerosol contaminants in the work environment. Industrial aerosol mass and size distributions must not be assumed to be the same in all locations or at different times. Often, the individual's own work activities are the source of aerosol contamination. A dust-producing source located at arm's length results in a rapidly decreasing concentration with increasing distance from the worker. Tebbens (1973) notes that it is the likelihood of large temporal and spatial errors which led to the concept of personal sampling, that is, attaching the sensing element directly to the worker.

PURPOSES OF SAMPLING

Industrial hygiene sampling is performed for a wide variety of reasons: to determine if a risk to worker health exists; to comply with regulatory requirements; to monitor continued performance of good work practices and engineering controls; to gather data for use in epidemiological studies; and to identify highly hazardous jobs or specific work tasks so that corrective actions may be taken. The above reasons imply that what is measured and how the measurement is made is relevant to the biological effects of the hazardous material.

Toxicological Considerations

Contaminants enter the body by skin absorption, ingestion, and inhalation. Inhalation is the most common route of entry for industrial dusts (although for certain contaminants, most notably lead, ingestion can also play an important role). The effects of inhaled aerosols depend on the specific chemical species, the concentration, the duration of the exposure, and the site of deposition within the respiratory system. Particle size is the most important factor affecting the location of deposition.

The health effects produced by exposure to a toxic aerosol vary based on the duration of exposure. Acute effects occur within a few minutes or hours of exposure. In some instances, the acute effects may be easily reversed; in others, irreparable harm may be done to the worker. For example, an aerosol of an irritant such as anhydrous ammonia and water has reversible, acute effects at low levels of exposure and possible death due to respiratory arrest at high levels (Rom and Barkman 1983). Chronic effects may take years or a lifetime to develop and are not usually reversible. For example, death due to lung cancer may not occur until 5–35 years after the onset of work with asbestos (Rom and Barkman 1983).

Local effects occur when inhaled contaminants produce a toxic effect at the site of contact. An example of a local effect within the respiratory system is silicosis, a disease of the lung resulting from inhalation of crystalline silica (Jones 1983). A toxic effect, known as a systemic effect, may also be caused at sites within the body far removed from the point of entry. An example of a systemic effect is the toxic consequence for the blood-forming organs and the nervous system resulting from an overexposure to lead fumes ([illegible] 1983). The chemical and biological properties of the aerosol determine if the effect produced will be at the site of deposition or at some other location within the body. For example, the solubility of aerosol particles within the fluids of the lung may determine the availability of the chemical to the bloodstream. Particle size distribution affects not only the site of deposition but also the chemical reactivity, since the total surface area of a given mass of dust increases as the particle size decreases (Hinds 1982). Since the toxic effect depends on the site of deposition, the aerosol measurement techniques and the control technologies must target the particle sizes producing the undesirable effect.

Deposition of Particles in the Respiratory System

The determination of the health consequences of exposure to an aerosol requires an analysis of the inhalation and deposition of the aerosol within the human respiratory system. The toxic action of an aerosol may be related to the number of particles, their surface area, or the mass deposited. Many occupational diseases are associated with the deposition of particles within a certain region of the respiratory tract. The aerosol properties associated with the location of deposition in the respiratory system are particle size and density. The parameter most closely associated with this regional deposition is the aerodynamic diameter, d_a, defined as the diameter of a sphere of unit density possessing the same terminal settling velocity as the particle in question.

Many particles present in the air do not enter the respiratory tract because of the size-selective sampling of the nose and the mouth. Still others are removed in the upper respiratory tract. The concept of size-selective air sampling calls for measurement of particles in industrial aerosols of the size that are associated with a specific health effect. This concept can be traced to proposals from the British Medical Research Council and the U.S. Atomic Energy Commission in the 1950s defining respirable dust (Morrow 1964). More recently, the International Standards Organization (ISO) (Ogden 1983) and the American Conference of Governmental Industrial Hygienists (ACGIH) (ACGIH 1985, 1991) have proposed definitions of dust size ranges for use in sampling industrial aerosols. For chemical substances present in inhaled air as suspensions of solid particles or droplets, the potential hazard depends on the particle size as well as on mass concentration. The ACGIH has defined three particle-size-selective threshold limit values (PSS TLVs): inhalable particulate mass TLVs (IPM TLVs) for those materials that are hazardous when deposited anywhere in the respiratory tract; thoracic particulate mass TLVs (TPM TLVs) for those materials that are hazardous when deposited anywhere within the lung airways and the gas-exchange region; and, respirable particulate mass TLVs (RPM TLVs) for those materials that are hazardous when deposited anywhere in the gas-exchange region.

These three particulate mass fractions are quantitatively defined by ACGIH (1991) as follows:

1. Inhalable particulate mass (IPM) consists of those particles that are captured according to the following collection efficiency regardless of sampler orientation with respect to wind direction:

$$\mathrm{SI}(d_a) = 50\% \times (1 + \exp(-0.06 d_a)) \quad \text{for } 0 < d_a \leq 100\ \mu\text{m} \qquad (24\text{-}1)$$

where $\mathrm{SI}(d_a)$ is the collection efficiency in percent and d_a is the aerodynamic diameter in µm.

2. Thoracic particulate mass (TPM) consists of those particles that are captured according to the following collection efficiency:

$$\mathrm{ST}(d_a) = \mathrm{SI}(d_a) \times (1 - F(x)),$$
$$x = \frac{\ln(d_a/\Gamma)}{\ln(\Sigma)} \qquad (24\text{-}2)$$

where $\mathrm{ST}(d_a)$ is the collection efficiency in percent, the mass median aerodynamic diameter, Γ, is 11.64 µm, the geometric standard deviation, Σ, is 1.5, and $F(x)$ is the cumulative probability function of a standardized lognormal variable, x.

3. Respirable particulate mass (RPM) consists of those particles that are captured according to the following collection efficiency:

$$\mathrm{SR}(d_a) = \mathrm{SI}(d_a) \times (1 - F(x)),$$
$$x = \frac{\ln(d_a/\Gamma)}{\ln(\Sigma)} \qquad (24\text{-}3)$$

where $\mathrm{SR}(d_a)$ is the collection efficiency in percent, the mass median aerodynamic diameter, Γ, is 4.25 µm, the geometric standard deviation, Σ, is 1.5, and $F(x)$ is the cumulative probability function of a standardized lognormal variable, x.

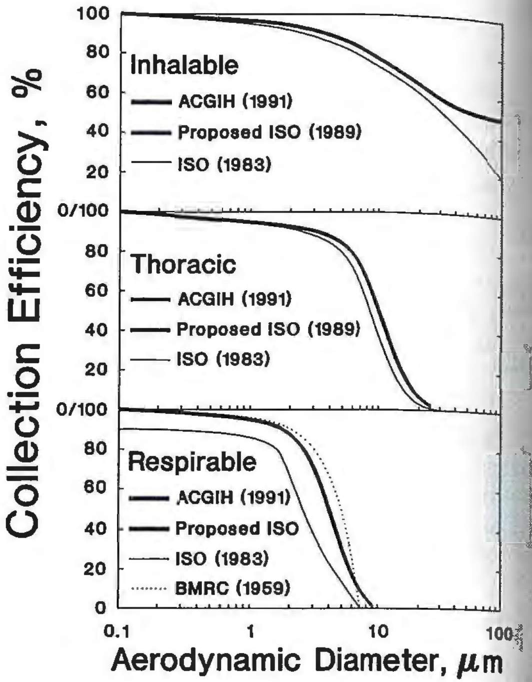

FIGURE 24-1. American Conference of Governmental Industrial Hygienists (ACGIH), British Medical Research Council (BMRC), and International Organization for Standardization (ISO) Size-Selective Sampling Criteria.

These performance criteria are described graphically in Fig. 24-1.

An international convention for particle-size-selective sampling was proposed, which requires the resolution of the differences between the firmly established British Mine Research Council (BMRC) and ACGIH particle size-selective sampling in the workplace (Soderholm 1989; Lippmann 1989*a*). The proposed definitions differ approximately equally from the BMRC and old ACGIH definitions and is at least as defensible when compared to available human data. Much international confusion will be avoided once ISO adopts the RPM, TPM, and IPM definitions recommended by Soderholm (1989) and adopted by ACGIH (Soderholm 1991). The ACGIH and ISO RPM, TPM, and IPM collection efficiency curves and the BMRC RPM collection efficiency curve are shown graphically in Fig. 24-1.

Occupational Exposure Limits

Industrial hygienists employ various criteria for the evaluation of the hazards posed by workplace exposures. 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 Governmental Industrial Hygienists' (ACGIH) Threshold Limit Values® (TLVs®). These criteria cite the levels of exposure to which workers may be exposed. NIOSH

RELs are time-weighted average (TWA) concentrations for up to a 10 h workday during a 40 h workweek (NIOSH 1990). OSHA PELs are TWA concentrations that must not be exceeded during any 8 h work shift of a 40 h workweek (U.S. DOL 1986). The AGGIH TLVs are 8 h TWA concentrations for a normal 8 h workday and 40 h workweek, to which nearly all workers may be exposed, day after day, without adverse effects (ACGIH 1991). Even below these various exposure limits, a small percentage of workers may experience adverse health effects because of individual susceptibility, a pre-existing medical condition, and/or a hypersensitivity (allergy). In addition, some materials may act in combination with other workplace exposures to produce undesirable health effects even if the occupational exposures to individual contaminants are controlled at the level set by the evaluation criterion. For example, gases such as the oxides of nitrogen and sulfur dioxide may adsorb on dust particles and produce health effects at levels normally considered safe. Also, some substances are absorbed by direct contact with the skin and mucous membranes, and, thus, potentially increase the overall exposure. Unfortunately, the terms "health effects" and "lung deposition" are often used interchangeably. In addition to lung deposition, the toxicology of the particulate must be taken into account. The ACGIH is examining their occupational exposure limits for chemical substances which exist as dusts, mists, or fumes to determine which size range is of health concern and, therefore, which size range should be measured.

Measurement of Concentration

The measurement of the concentration of an industrial aerosol requires both collection and analysis. The collection phase involves the transport of a representative sample of the workplace aerosol into the sampling device, separation of the particles from the air stream, and an accurate measurement of the volume of air sampled. In traditional aerosol sampling, the analysis is performed in a laboratory on the accumulated sample. A large-enough air volume must have been sampled in order to have a sufficient quantity of contaminant for analysis. In real-time aerosol sampling (with direct-reading instruments) the analysis is either performed continuously or in a series of short, consecutive samples or "batches". Many instruments do not separate the dust particles from the air stream but measure the particles *in situ*. All instruments have a limited range of concentration and often a limited size range, which they are able to measure.

Measurement of Particle Size

Particle size distribution can be described by the number, surface, or volume (mass) of particles as a function of particle diameter. The diameter can in turn be given on the basis of a calibration aerosol of known particle size distribution or the actual aerosol measured (e.g., as a projected area or aerodynamic diameter). The aerodynamic diameter is particularly useful in industrial hygiene when considering the deposition of particles in the lung, the fate of particles in aerosol samplers, and the removal efficiency in air pollution control equipment. Size distribution may also vary spatially. Larger particles may be found near a contaminant source but may not be transported far.

In industrial hygiene practice, coarse estimates of particle size are often determined by identifying the process of generation. For example, most of the airborne copper produced by a grinding operation is supermicrometer-sized and may be classified as a "dust", while most of the copper generated during the melting of an alloy is submicrometer-sized and may be termed a "fume" (Tossavainen 1976; Walworth 1945).

To supplement aerosol sampling, bulk samples of settled dust may be collected from work surfaces, or samples may be retrieved from dust collectors attached to local exhaust systems. In addition, bulk samples may assist the industrial hygienist in choosing an appropriate method for sampling the chemical species of the aerosol (NIOSH 1973). These samples may be analyzed by optical or electron microscopy, or resuspended and analyzed by techniques such as sedimentation, light scattering, or time-of-flight spectrometry. Unfortunately, since these bulk samples have been size-selectively deposited, they may not be representative of the particle size distribution of the aerosol present in the work environment (NIOSH 1973).

Industrial hygienists have a wide variety of techniques at their disposal for determining the particle size of aerosols. Instruments usually do not measure particle diameter directly, but infer the particle size indirectly using differing physical principles: particle inertia (time-of-flight spectrometer and cascade impactor), light scattering (single-particle optical counter), and projected-area microscopy (optical and electron microscope). Many of these instruments are limited to ranges spanning roughly one to one- and one-half decades of particle size (Pui and Liu 1988). Since industrial aerosols may span a wide size range, and the industrial hygienist may only be interested in a limited portion of the industrial aerosol, erroneous conclusions regarding the size distribution can easily be drawn, particularly for particles near the lower and upper particle size ranges of the instrument. This is primarily due to detection problems and sampling efficiency near the upper and lower size limits of an instrument. Small particles may not be detected by the instrument with the same efficiency as large particles. Large particles may not be collected with the same efficiency as small particles (Pui and Liu 1988).

Spatial and Temporal Resolution

Exposure estimate problems in industrial hygiene monitoring arise when the sampling device cannot be attached directly to the worker, the contaminant concentration is not constant in space, the worker's location (or breathing zone) is not constant in time, or the contaminant generation rate is not constant in time (Bhaskar, Ramani, and Jankowski 1988; Whitney 1972). In addition, side-by-side sampling has shown significant variation in the measured mass concentration (Raynor, Ogden, and Hayes 1975).

Present personal sampling and analytical methods for most industrial dusts are intended for long sampling periods, i.e., full-shift sampling (8–10 h). While generally adequate for exposure assessment, these methods are of limited use in the evaluation of potential emission points or in the study of the temporal or time-related characteristics of a process (Gressel, Heitbrink, and McGlothlin 1988).

Sampling Strategies

As a matter of convention, exposure measurements for chronic hazards are usually taken for the duration of a single work shift. A TWA mass concentration (c_m) refers to the average mass concentration of a substance during a normal 8–10 h workday. A TWA c_m can be determined from a single full-shift sample, or it can be calculated from a series of consecutive samples (Leidel, Busch, and Lynch 1977). The following equation can be used to calculate the TWA from multiple consecutive samples of the same environment:

$$c_m = \frac{\sum_{i=1}^{n} c_{mi} \times t_i}{\sum_{i=1}^{n} t_i} = \frac{\sum_{i=1}^{n} c_{mi} \times t_i}{t} \tag{24-4}$$

where t_i is the duration of sample i in minutes, c_{mi} is the mass concentration of sample i in mg/m^3, and t is the total sampling time in minutes.

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.

To determine compliance with an occupational exposure limit (OEL), Leidel, Busch, and Lynch (1977) recommend calculating the 95% one-sided lower confidence limit (LCL) and the 95% one-sided upper confidence limit (UCL).

LCL and UCL are computed as follows:

$$\mathrm{LCL}\,(95\%) = \chi - t_{\alpha} \times \mathrm{CV_T}$$

$$\mathrm{UCL}\,(95\%) = \chi + t_{\alpha} \times \mathrm{CV_T} \tag{24-5}$$

$$\chi = \frac{C_{\mathrm{m}}}{\mathrm{OEL}}$$

where $t_{\alpha} = 1.645$ when $\alpha = 0.95$, and $\mathrm{CV_T}$ is the coefficient of variation for the sampling/analytical method.

If LCL and χ are above unity, then the exposure is classified 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, then the exposure is classified as possible overexposure.

Some substances have short-term exposure limits (STEL) or ceiling values that are intended to supplement the TWA where there are recognized toxic effects from high short-term exposures. Samples of materials which represent acute hazards are collected for shorter time periods, typically 15 min or less, and are collected during periods when the concentration of contaminant is expected to be highest. Other STELs are for carcinogens; these substances do not have an 8 h TWA. Real-time instruments are particularly useful for identifying the periods of peak exposure.

Example 24-1

What is the time-weighted average exposure calculated from the following data? Is the worker's exposure in compliance with an occupational exposure limit of 50 μg/m^3? Three consecutive air samples for lead are collected on filter cassettes in the breathing zone of a worker in a brass foundry with the following results:

TABLE 24-1 Example Filter Cassette Sampling Data for a Worker in a Brass Foundry

Sample Sequence Number	Sample Time (min)	Sample Flow Rate (l/min)	Sample Volume (l)	Mass Collected (μg)	Mass Concentration (μg/m^3)
001	60	2.0	120	30	250
002	180	2.0	360	36	100
003	240	2.0	480	5	10

Answer. The TWA mass concentration for the work shift is calculated from Eq. 25-4:

$$\begin{aligned} c_{\mathrm{mTWA}} &= \left[\frac{(250\ \mu\mathrm{g/m^3} \times 60\ \mathrm{min}) + (100\ \mu\mathrm{g/m^3} \times 180\ \mathrm{min}) + (10\ \mu\mathrm{g/m^3} \times 240\ \mathrm{min})}{60\ \mathrm{min} + 180\ \mathrm{min} + 240\ \mathrm{min}}\right] \\ &= 74\ \mu\mathrm{g/m^3} \end{aligned}$$

The reader should note that this 8 h TWA mass concentration is greater than the occupational exposure limit of 50 μg/m^3. To verify noncompliance, the one-sided lower confidence limit (LCL) must be calculated using Eq. 25-5 and compared to unity. If the industrial hygienist used NIOSH Method 7105

(Eller 1989), CV_T equals 0.068:

$$\chi = \frac{74\ \mu g/m^3}{50\ \mu g/m^3} = 1.48$$

$$\text{LCL (95\%)} = 1.48 - (1.645 \times 0.68)$$
$$= 1.37$$

Because LCL is greater than unity, the exposure average is classified as noncompliant and appropriate action must be taken to reduce the worker's exposure to lead.

TRADITIONAL SAMPLING METHODS

Aerosol measurement requires the transport of a representative sample of the workplace aerosol into the sampling device, separation of the particles from the air stream, and an accurate measurement of the volume of air sampled. The following sections deal with the transport and measurement of the aerosol sample, the separation and collection of the dust particles, and factors which may cause a bias of the sample.

Air Mover and Sampler Calibration

Present-day personal sampling devices usually rely on either diaphragm or piston-type pumps to draw air. The pump is connected to a direct current (dc) motor, supplied by a battery pack of rechargeable nickel–cadmium cells. The flow rates of pumps vary among manufacturers, but most will provide flows of 1–3 l/min against pressures of 6.25 kPa (25 in of water) for periods up to 8 h. Some pumps incorporate a rubber bladder to minimize flow pulsations, which may adversely affect the performance of size-separating devices (e.g., respirable dust samplers) (Bartley et al. 1984).

Olin, Sem, and Christenson (1971) defined the ideal instrument for measuring the mass concentration of an industrial aerosol as having four characteristics. First, the instrument should be automatic, reliable, and able to be operated unattended. Second, instantaneous measurements or an average measurement over a short time (e.g., 5–10 min) should be an option. Third, the analog readout signal should be capable of remote transmission and recording, reading directly in units of μg/m³. Fourth, the detection of mass concentration should be direct, rather than by a correlation of parameters such as visibility with mass concentration.

Many sampling pumps incorporate a visual indication of flow rate. Usually, this is a rotameter which is affected by the fluid's specific gravity (density of gas/density of the air). Specific gravity is a function of the pressure in the rotameter. Thus, the rotameter should be calibrated for the conditions of use with the same sampling train (e.g., cyclone, cassette, filter media, cassette fittings, and connecting tubing) as that used in the field (McCammon 1989). The observed flow rate (Q_r) is then converted to flow rate (Q_n) at "normal" temperature and barometric pressure (Matheson 1983). During use at the sampling site, the temperature and barometric pressure should be recorded at the sampling site so that Q_n can be converted to the actual flow rate (Q_s) through the sampler or air mover. The following correction factors should be applied to the rotameter readings (Matheson 1983):

$$Q_n = Q_r \times \sqrt{\frac{SG_r}{SG_n} \times \frac{T_r}{T_n} \times \frac{P_n}{P_r}}$$

$$Q_n = Q_r \times \sqrt{\frac{SG_r}{SG_n} \times \frac{T_r}{T_n} \times \frac{P_n}{P_r}} \times \sqrt{\frac{SG_n}{SG_s} \times \frac{T_n}{T_s} \times \frac{P_s}{P_n}} \qquad (24\text{-}6)$$

$$Q_s = Q_n \times \sqrt{\frac{SG_n}{SG_s} \times \frac{T_n}{T_s} \times \frac{P_s}{P_n}}$$

for conditions r, n, and s, where r are the conditions when the rotameter was calibrated, n are the conditions of normal temperature and pressure, and s are the conditions of actual sampling; SG is the specific gravity (unitless), T is the absolute temperature in °K, and P is the absolute pressure in kPa.

The actual volume of air sampled at the work site is determined using Q_s and sampling time and is used in calculating the exposure (c_m). The accuracy of determination of the concentration of a toxic substance in air is no greater than the accuracy with which the air volume is measured. Therefore, an accurate calibration of the airflow rate through the sampling train is necessary. The frequency of calibration depends on the use, abuse, and handling to which the pump is subjected. Primary standards, such as a spirometer or soap bubble meter, are recommended for calibration. The soap bubble meter is often used for field calibration. Figure 24-2 shows the field calibration setup for (A) a cyclone assembly having a cassette with a personal sampling pump and (B) a cassette with a personal sampling pump. McCammon (1989) and Lippmann (1989*b*) provide detailed instructions for the calibration of personal sampling pumps.

Flow decreases as the filter loading increases. Modern sampling pumps have flow sensors which change pump speed to compensate for the increased pressure drop and maintain constant volumetric flow rate. Older sampling pumps lack these controls, and, therefore, require periodic manual adjustments (usually of a flow control valve) to maintain a constant airflow rate (Lippmann 1989*c*).

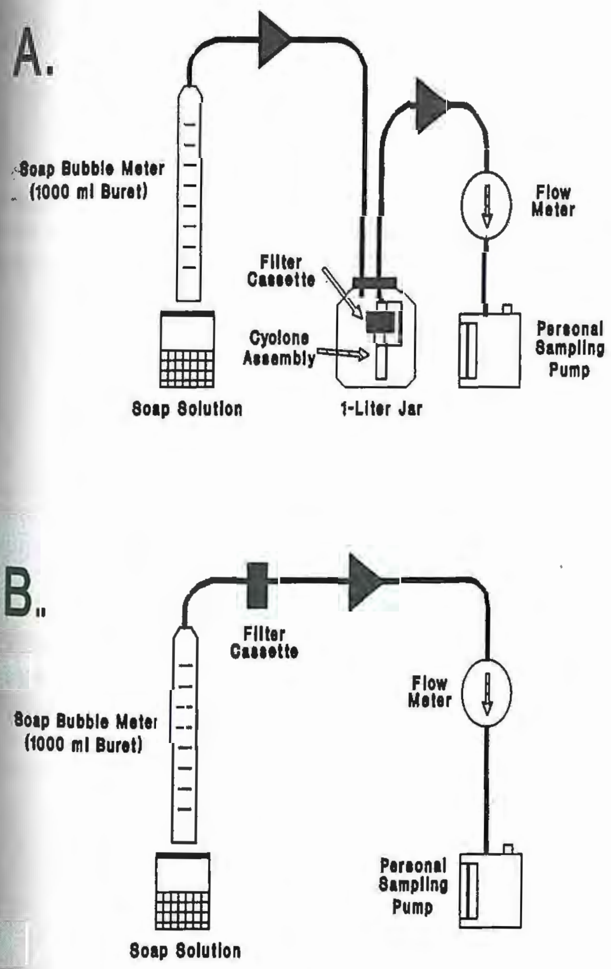

FIGURE 24-2. Arrangement for Flow Rate Calibration of Sampling Pumps with (A) Cyclone Assembly with a Filter Cassette and (B) Filter Cassette.

Preclassifiers

Preclassifiers are devices used to alter the size distribution of the airborne dust presented to the collection device. The preseparation of the industrial aerosol is performed so that the measured concentration reflects airborne particles of the size associated with a particular health effect or with any effect or the particle-size-selective TLV. Three types of devices are used as preclassifiers in industrial hygiene: cyclone, elutriator, and impactor (John 1984).

Cyclone

A cyclone removes particles larger than a desired size range from an air stream by particle inertia. Aerosol enters the cyclone through a tangential inlet and follows a cycloidal path before exiting through an axial opening. Large particles are forced toward the walls of the cyclone. Excess deposits on the walls fall into a dust pot. The smaller, respirable particles remain in the cyclone's air stream. The 10-mm diameter nylon cyclone is the most common preclassifier used in the United States. When operated at 1.7 l/min, the removal characteristics of this device approximately follow the ACGIH criteria for respirable dust. By design, this device is highly efficient for the removal of larger particles (i.e., greater than 10 µm) and is not efficient for particles below about 2 µm (Lippmann 1989*a*). The 10-mm nylon cyclone followed by a filter cassette is used to measure pneumoconiosis-producing dusts (Hering 1989; Carsey, Shulman, and Lorberau 1987). In general, a full-shift sample is required to obtain a quantifiable mass of particulate, but the minimum sampling time can be calculated using Eq. 24-4. Larger cyclones (i.e., 0.5–1 in) can be used with stationary aerosol samplers operated at higher flow rates to collect a larger-volume air sample (Pasceri 1973).

Elutriator

An elutriator removes large particles from the air stream by particle settling (Wright 1954). Two configurations are used: vertical and horizontal. Elutriators are too large in size to be used with personal sampling devices. Cylindrical vertical elutriators are used for the sampling of cotton dust (Wesley et al. 1978; NIOSH 1975). Particles with terminal settling velocities less than the upward flow of aerosol are collected; large particles and lint are removed from the air stream. Penetration curves for the vertical elutriator have been measured by Claasen (1981) and Robert (1979). Horizontal elutriators consist of a series of horizontal plates, stacked at equal spacings. Particles are removed from the air stream as they settle onto the plates (Hering 1989). The Mining Research Establishment (MRE) elutriator, a gravimetric respirable dust sampler, incorporates a horizontal elutriator which meets the British Medical Research Council (BMRC) criteria for respirable dust (Lynch 1970; Ogden, Birkett, and Gibson 1978). This instrument is important because the U.S. Federal Coal Mine Health and Safety Act of 1969 standard of 2.0 mg/m^3 for coal dust is based on this instrument (U.S. Public Law 91-173 1969). Since the MRE unit is too large to be a personal sampler, a 10 mm nylon cyclone and a filter are used, and the mass concentration obtained from the filter is multiplied by a conversion factor (1.38) to obtain equivalence to the MRE instrument (CMCRC 1980; Knight and Lichti 1970; Tomb et al. 1973).

Impactor

In an impactor, the sample air stream passes through a nozzle and impacts on a collection surface. Large particles strike the surface and are collected, while small particles remain airborne. There are, at present, no samplers that fall within the ACGIH IPM criteria over the range 0–100 µm (ACGIH 1985). Because of the size of many of these samplers, they are generally used for area sampling. Cascade impactors (i.e., multiple stages) provide the industrial hygienist with an estimate of the size distribution of the aerosol. Chan, D'Arcy, and Siak (1990) used a seven-stage cascade impactor to characterize the size distributions and mass concentrations of machining fluid aerosols in an automotive transmission manufacturing plant. The industrial aerosols were found to be polydisperse and generally bimodally distributed with no distinct seasonal ination. Recently, smaller versions of impactors have been developed and tested in the breathing zone of workers for respirable dust sampling (Baron 1983; Marple and McCormack 1983; Rubow et al. 1987). Macher and Hansson (1987) modified a personal impactor to collect bioaerosols. This method proved to be quite labor intensive, and the modifications resulted in a loss of collection efficiency over the personal dust sampler.

Collection Techniques

Most aerosol sampling methods require that the dust particles be separated from the air stream for analysis. Filtration, impaction, and precipitation are three typical methods of accomplishing this separation in industrial hygiene.

Filtration

The separation of particles from an aerosol sample is most commonly achieved by the use of filtration. Filter media are available in both fibrous (typically glass) and membranous forms. A common misconception is that aerosol filters work like microscopic sieves in which only particles smaller than the holes can get through. Particle removal occurs by collision and attachment of particles to the surface of the fibers or membrane. Sampling filter media may have pore sizes of 0.01–10 µm. The efficiency of fibrous filters is a function of the face velocity. For particles less than 1 µm, the overall efficiency decreases with increasing face velocity. For particles greater than approximately 1 µm, the filter collection efficiency is greater than 99%. The overall efficiency of membrane filters is approximately 100% for particles larger than the pore size. Filters for use in industrial hygiene are usually supplied as disks of either 25 or 37 mm diameter. Since the pressure drop across the filter increases with the air velocity through the filter, the use of a 37-mm diameter filter for a given volumetric flow rate results in a lower pressure drop and is generally recommended. The use of the smaller (25 mm) filter concentrates the deposit of the contaminant into a smaller total area, thus increasing the area density of particles. Thus, the 25-mm diameter filters are recommended when the analysis is by microscopy (Beckett 1980; Hunsaker et al. 1988). Membrane filters may be used singularly or in combination with a preclassifier to eliminate large particles and analyzed gravimetrically, chemically, or microscopically (Harris and Maguire 1968, Wesley et al. 1978; Carsey, Shulman, and Lorberau 1987).

Membrane filters are manufactured in a variety of pore sizes from polymers such as cellulose ester, polyvinyl chloride, and polycarbonate. Because membrane filters are thin, they lack rigidity and must be used with a support pad. The choice of a filter medium depends on the contaminant of interest and the requirements of the analytical technique. For gravimetric analysis, nonhygroscopic materials such as glass fibers, silver, or polyvinyl chloride membranes should be selected. For analysis by microscopy, or for acid digestion for the analysis of metals, cellulose ester membranes are the usual choice. When several analyses are to be performed on the same filter, some compromises may be necessary (NIOSH 1973). For instance, if a sample is to be analyzed for metals as well as for total mass, a polyvinyl chloride filter may be selected, even though it may be more difficult to digest than a cellulose ester membrane, which cannot be used for gravimetric analysis because it is hygroscopic (Eller 1989). Filtration can also be used for the determination of certain fungi and endospore-forming bacteria. Desiccation-resistant organisms can be washed from the surface of smooth-surface polycarbonate filters and can then be cultured, or the filter may be examined microscopically (Wolf et al. 1959; Fields et al. 1974; Lundholm 1982; Palmgren et al. 1986).

Filters are often held in disposable plastic filter cassettes during aerosol sampling. Some of the styles used in the U.S. are shown in Fig. 24-3. With the exception of the coal mine respirable dust sampler (D), these styles are available for both 25- and 37-mm diameter filters (Hinds 1982; Treaftis et al. 1984). The

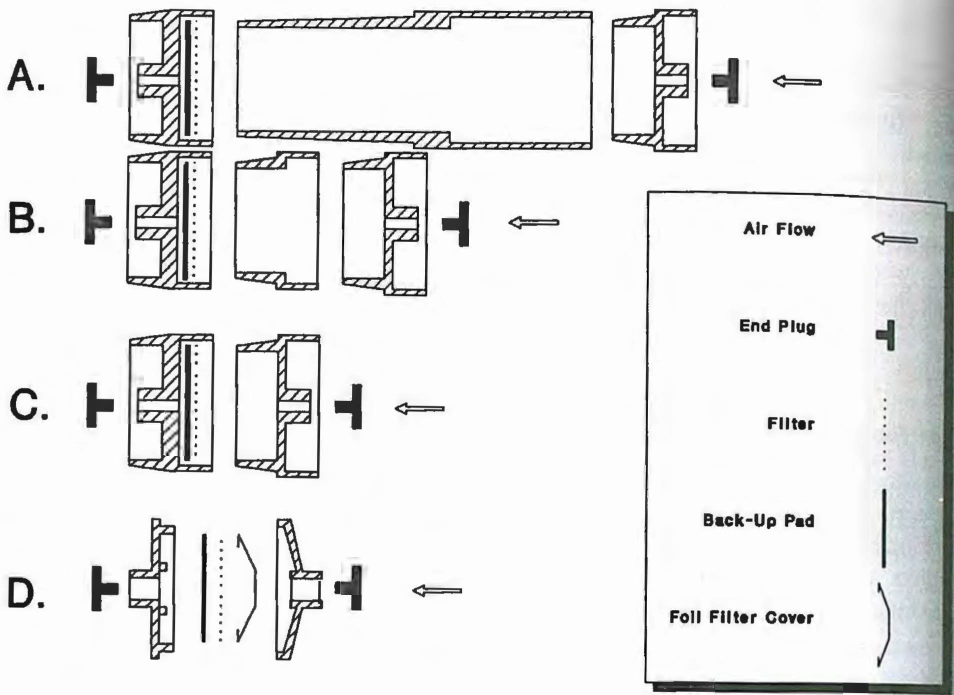

FIGURE 24-3. Filter Cassettes Used in Industrial Hygiene: A. 3-piece Cassette with Extended Cowl for Open-Faced Sampling; B. 3-piece Cassette for Open or Close-Faced Sampling; C. 2-piece Cassette for Close-Faced Sampling and for Use with 10 mm Nylon Cyclone; and D. Coal Mine Dust Cassette for Use with 10 mm Nylon Cyclone. Note that the Foil Filter Cover is Crimped onto the Filter and the Two are Weighed as a Unit.

two-piece cassette (C) is intended for closed-face use only. Because of size limitations, the two-piece cassette (C) and the coal mine dust sampler (D) are the only cassettes that fit into the apparatus with the 10-mm nylon cyclone. The three-piece cassette (B) can be used either open or closed-face. Closed-face sampling is performed by removing the end plug and is used when the particulates will be analyzed chemically and/or gravimetrically. Open-face sampling is performed by removing the end plug and the plastic cover and is used when the particulate must be uniformly deposited (i.e., for microscopic analysis). If used in the open-face mode then, in order to protect the filter, the plastic cover should be retained for use when sampling is concluded. Wide variations between open- and closed-face sample pairs have been documented in environmental sampling as compared to the small variations when on a mannequin (Beaulieu et al. 1980). The closed-face cassette reduces accidental contamination by large amounts of nonairborne and rapidly settling dust and the possibility of tampering. It is for this reason that Doemeny and Smith (1981) recommend the use of a closed-face cassette in the majority of filter sampling methods. To promote a uniform deposition of particles on the filter, extended cowls (A) are also used when the sample is analyzed by microscopy. These cowls should be made of conductive materials to minimize the accumulation of electrical charge and subsequent undesirable electrostatic effects (Baron 1987; Baron and Deye 1990). In addition, the cowl is used to reduce the direct impaction of large particles on the filter and to protect the filter from fingers. As with the standard three-piece cassette, the plastic cover and plug should be used to prevent contamination of the sample by subsequent storage and handling. All plastic cassettes should be securely assembled and sealed with a cellulose shrink band or tape around the seams of the cassette to prevent leakage past the filter.

Impaction

Impaction is used to separate a particle from a gas stream, based on its inertia. As discussed in the section on preclassifiers, an impactor consists of a nozzle and a target. Impactors are usually classified by their cutoff diameter, or the particle diameter at which 50% passes through the device (Hinds 1982). Thus, impactors should be selected so that the minimum size particle expected to be present will be collected. The midget impinger is an example of an impactor. Once the workhorse of field sampling, the midget impinger still finds use in the collection of reactive aerosols (e.g., isocyanates), where chemical solutions are used to dissolve and form stable compounds with the reactive species (Moseley [illegible], Skarping, Smith, and Dalene 1985). Impingers are also useful for the collection of viable aerosols (White et al. 1975; Lembke et al. 1981; Henningson et al. 1988).

Cascade impactors consist of a stack of impaction stages: each stage consists of one or more nozzles and a target or substrate. The nozzles may take the form of holes or slots. The target may consist of a greased plate, filter material, or nutrient media contained in Petri dishes (for the growth of microorganisms). Each succeeding stage collects smaller particles than the one preceding it. A filter may be used as the final stage so that all particles not impacted on the previous stages are collected. The target may be weighed to determine the collected mass, or it may be washed and the wash solution analyzed chemically. Filter media used as the target material offer the advantage of a lower tare weight; filter media can also be digested for chemical analysis of the deposited particles. Filters also induce more particle bounce than greased or oiled plates although fibrous filters usually have the same cut diameter. Although personal cascade impactors are available, these devices are not as widely used in personal sampling as filters (Baron 1983; Marple and McCormack 1983; Rubow et al. 1987).

Industrial hygienists are more likely to employ stationary cascade impactors or individual impactors used in survey instruments, either as the primary collection mechanism, or as a preseparator (for example, to remove nonrespirable particles from the sampled air stream). Impactors are also used for the collection of airborne microorganisms. These impactors contain up to 400 holes, through which the air jets impact onto nutrient media with one or more bacterial or fungal colonies forming at some of the impaction sites. Since more than one particle may have been deposited at a given site, correction factors are needed to adjust for the possibility of multiple organisms collecting at each site (Macher 1989).

Precipitation

Precipitation uses an external force field, typically either thermal or electrical, to separate particles from a sampled air stream. Historically, these devices were used as survey instruments; some of these devices allowed collection directly on a microscope slide (Poppoff 1954; Alfheim and Lindskog 1984).

Sampling Bias

Commonly used cassette samplers mounted on the lapel do not necessarily measure either the total aerosol concentration or the inhalable fraction; performance varies with the specific sampler and the ambient-air velocity. The fraction of aerosol which enters the nose and/or mouth has been referred to as the "inspirable" fraction. More recently, however, there has been a general international agreement that the term should be "inhalable" (Vincent and Mark 1990). Ogden (1983) reports that a sampler similar to that of a closed-face 37-mm cassette operated at 2 l/min has a sampling efficiency of 50% for a 15 µm particle, and 10% for a 35 µm particle when the wearer faces a wind of 1 m/s. The superceded ACGIH performance criteria include sampling efficiencies of about 70% and

50% for 15 and 35 µm particles, respectively (ACGIH 1991). Vincent and Mark (1990) studied a variety of aerosol samplers in relation to the ISO particulate-size-selective criteria recommendations previously mentioned (ISO 1983). They found that an aluminum 25-mm open-face cassette, 25-mm closed-face cassette, and a 25-mm closed-face cassette with seven 4-mm holes drilled in the front cover, matched the 1983 ISO Inhalable Particulate Mass curve quite well for low wind speed (0.5 µm/s) and for particles with aerodynamic diameters up to about 15 µm. Several European samplers (both personal and area) show promise as inhalable dust samplers (Vincent and Mark 1990).

Electrostatic effects can also result in sample bias. Baron (1987) found that aerosol charge is capable of producing a significant sampling error in asbestos fiber sampling. Cornett et al. (1989) noted fiberglass deposition on the inside surface of 50-mm conductive cowls used in conjunction with 25-mm mixed cellulose ester filters. When the extension cowls were washed, an overall increase of 16.5% was observed in the weight of fibers deposited. In 88% of the cases, fibers on the cowl were visible to the naked eye. Blackford, Harris, and Revell (1985) presented data on the reduction of dust losses within the cassette of the SIMPEDS personal dust sampler. Hunsaker et al. (1988) showed that under conditions of minimal electrostatic deposition onto cassette walls, the NIOSH 7400 method exhibits a nonuniform distribution of fibers within a 60° wedge. It is conceivable that the selection of counting fields in particular regions of the filter allow a distinction between compliance and noncompliance.

METHODS OF ANALYSIS

Microscopy

Microscopy ranks as one of the important tools in the analysis of aerosols. Historically, microscopy was used to count particles collected in impinger solutions. Today, microscopy is the principal technique used for the differentiation of fibers from other dust particles. Optical microscopy is limited to the detection of particles larger than about 0.3 µm. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) allow the measurement of smaller particles (Middleton 1982; Warner 1988; Stewart 1988). In addition, electron microscopy allows elemental analysis on a particle by particle basis. Depending on the specific technique used, particles may be analyzed directly on the filter, or a sample preparation procedure may be employed to resuspend the particles for redeposition on a specific substrate.

In direct analysis of filter samples, particles are counted in f discrete, randomly selected microscope fields, each of known area a. The number of particles on the filter, N, and the number concentration of particles in air, c_n, are determined by the following equations:

$$N = n\left(\frac{A}{fa}\right)$$

$$c_n = \left(\frac{n}{Qt}\right)\left(\frac{A}{fa}\right) = \frac{N}{Qt} \qquad (24\text{-}7)$$

where n is the total number of particles counted, Q the volumetric flow rate, t the sampling time, and A the effective filter area (i.e., the area available for collection and not obscured by the filter holder).

Because this technique assumes that particles are distributed randomly on the filter, care must be exercised in sampling to ensure uniform deposition by the use of appropriate collection devices, e.g., open-faced cassettes using conductive cowls (Cornett et al. 1989). Hunsaker et al. (1988) suggests developing a standardized method of field selection for asbestos fiber counting, such as counting lines oriented radially or strictly within the inner portions of the filter, because of the nonuniform distribution of fibers within a 60° wedge.

The precision of the particle count depends on the total number of particles counted. Particle counting (for total counts greater than about 16 particles) obeys Poisson statistics: the variance of this distribution is equal to the mean. Under ideal conditions, the relative standard deviation (RSD) in percent is, fore, given as

$$RSD = n^{-1/2} \times 100\% \qquad (24\text{-}8)$$

where n is the particle count. For example, if n is increased from 16 to 100 particles, the RSD would be reduced from 25% to 10%. For reliable analysis, particles deposited on the filter can be increased by using a higher flow rate in sampling, which is limited only by particle overlap on the filter. Counting statistics can also be enhanced by counting more fields. Reducing the magnification lowers resolution and also results in an increasing area of the filter and, hence, the number of particles counted (if the particles remain visible). Equation 24-8 applies both to the relative standard deviation for individual size intervals as well as the total particle count. Because industrial aerosols usually follow a lognormal size distribution (i.e., fewer large particles than small particles), it is often advantageous to perform the size analysis at two or more levels of magnification, computing the particle distribution in discrete stages.

Chemical and Gravimetric

In chemical and gravimetric analysis of filter samples, the total mass (or total mass of the specific chemical) is measured. The time-weighted average mass concentration c_m is determined by dividing the total mass collected, m, by the volume of air sampled, Qt:

$$c_m = \frac{m}{Qt} \qquad (24\text{-}9)$$

Gravimetric analysis is performed by weighing the filter before sampling (the tare weight), and again after sampling to determine the weight gain. As mentioned earlier, not all filter media are suitable for gravimetric analysis because of the tendency of some materials to absorb water (Sass-Kortsak, [illegible], and Purdham 1989). An accurate gravimetric determination requires strict [illegible] conditioning procedures. Filters are usually equilibrated at the relative humidity of the weighing room (e.g., 50% RH). Gravimetric sensitivity is limited not only by the sensitivity of the balance but also by the tare weight of the filter relative to the sample weight and by the weight stability of the filter. (Roach 1973; Vaughan, Milligan, and Ogden 1989).

Chemical analysis usually requires that the filter be ashed so that the sample can be presented to an instrument for analysis. In the case of metals, the filter is destroyed using an acid, and the resulting solution is analyzed by atomic absorption spectrometry (Owen, Delaney, and Neff 1951). Because of the differing requirements of various analytical procedures, often separate filters are required for the sampling of multicomponent work atmospheres (Eller 1989). If the industrial hygienist has an estimate of mass concentration, Eq. 24-4 can be rearranged to solve for either Q or t such that the filter will not be overloaded or underloaded.

The industrial hygienist should note that, according to Soderholm (1988), aerosols are inherently unstable. Four types of processes associated with aerosol instability are coagulation, deposition of particles on surfaces, deposition and evaporation of vapor from surfaces, and vapor/particle interactions. Coagulation occurs as particles collide and stick together, resulting in a decrease in particle number concentration, but no change in the mass concentration. Particles are deposited either gravitationally, inertially, or diffusionally on surfaces. Deposition of vapor and evaporation of high vapor pressure mists are primarily functions of the diffusion coefficients and the thickness of the diffusion boundary layer. Finally, particle/vapor interactions involve mass transfer due to mass imbalances of substances on the surface (Soderholm 1988).

Example 24-2

What would be the minimum sample time to measure silica at a suspected concentration of 100 μg/m^3, if the minimum quantifiable mass is 50 μg per filter?

Answer. Since silica is a hazard to the lung, the respirable fraction is measured using a 10-mm nylon cyclone followed by a filter cassette and a sampling pump operating at 1.7 l/min. Equation 24-9 can then be rearranged to solve for time *t*:

$$t = \frac{m}{Qc_m}$$

$$= \left[\frac{50\ \mu\text{g}}{1.7\ \text{l/m} \times 100\ \mu\text{g/m}^3 \times 10^{-3}\ \text{m}^3/\text{l}}\right]$$

$$= 294\ \text{min}$$

Biological

Methods for the determination of viable organisms rest on the ability of the organism to remain viable and reproduce. Organisms are collected in impingers, on filters, on microscope slides, or on nutrient media in Petri plates (Chatigny et al. 1989). After sampling, quantifying airborne microorganisms is accomplished by diluting and plating the collection fluid or by using a membrane filtration plating technique when the expected microbial load is low (i.e., < 60 cells per 20 ml of impinger fluid) (Blomquist, Palmgren, and Strom 1987; Morey 1990). In the latter method, the membrane filter is placed on a sterile pad saturated with nutrient broth in a sterile Petri dish. The plate is incubated at the appropriate temperature and the colonies counted. Microorganisms collected on membrane filters can either be eluted with sterile buffered water or plated directly on a sterile pad saturated with nutrient broth in a sterile Petri dish (U.S. EPA 1978). These filters or impingers can be used over a wide range of airborne concentrations. More commonly, the organisms are collected directly on nutrient media used as collection targets in impactors (Chatigny et al. 1989). The nutrient media are incubated and the number of colony-forming units (CFUs) are counted by the naked eye or under low magnification. CFUs are visible groups of cells that initiated from a single cell. Nutrient media are available from commercial supply houses for the cultivation, isolation, and differentiation of specific microorganisms (Baron and Finegold 199
Differential media support the growth of va ous species, while providing an environm that makes it easier to distinguish among different organisms. Selective media contain agents that prevent or inhibit the growth of certain organisms, while permitting the growth of others. Individual colonies can be isolated and identified by morphological and biochemical characteristics. More details on the measurement of bioaerosols can be found in Chapter 21.

REAL-TIME MEASUREMENT

Real-time aerosol instruments are used for a variety of tasks in industrial hygiene. Baron (1988, 1989) and Pui and Liu (1988) summarized the advances in particle measuring and sampling instruments. Aerosol photometers and piezoelectric instruments can be used as survey instruments. Aerosol photometers (and, more recently, condensation nuclei counters) have been used in respirator fit testing (Willeke, Ayer, and Blanchard 1981; NIOSH 1987; Ernstberger, Gall, and Turok 1988). Aerosol photometers have been used in conjunction with video recording as a powerful study tool to identify operations or activities causing exposure (Gressel et al. 1987; Gressel, Heitbrink, and McGlothlin 1988).

Concentration Measurements

Piezoelectric devices, such as TSI Model 3800 (TSI, Inc., St. Paul, MN), are available for the measurement of respirable aerosols (Sem, Tsurubayashi, and Homma 1977; Swift and Lippmann 1989). Particles which pass a preclassifier (< 3.5 μm) are deposited onto a quartz collection crystal by electrostatic precipitation. Particles collected on the surface increase the mass of the crystal and thereby cause a shift in the oscillation frequency of the crystal. This shift is directly proportional to the mass loading. Since piezoelectric devices respond directly to mass, no correction for the particle density is required. These devices are not continuous samplers but collect samfor discrete periods. Sem, Tsurubayashi, Homma (1977) found that for piezoelec- devices calibrated with welding smoke, and laboratory data showed good agree- (±10%) with parallel filter samples of aerosols, including electric arc welding asbestos mill dust, oil mist, walnut abrasive dust, powdered metal dust, and dust. The piezoelectric device con- measured tobacco smoke 15% low. ental data also showed that sensor ing must not exceed certain limits. For aerosols, the limit is 4 mg-min/m^3 (e.g., with a concentration of 2 mg/m^3 or 24 s concentration of 10 mg/m^3) (Sem, ubayashi, and Homma 1977).

osol photometers are versatile direct- ing instruments for indicating aerosol ation. The measurement is based on nt of light scattered by the aerosol les. Light scatter is a function of the ive index, density, and shape of the les sampled. In environments of high ive humidity, the instrument will detect vapor as well as the particles (Dimmick A beam of light inside the instrument is d onto a view volume, through which stream passes. The air stream can be ped through the sensitive volume or al- to passively circulate through it. The unt of light scattered is measured by a sitive detector. The concentration ed is equivalent to the concentration bration aerosol. The optical charac- of common aerosol photometers are that they are most sensitive to respirable ls. As a first approximation, the aerosol ers respond roughly to particle vol- the instrument readings can be cor- for particle density by multiplying by of the actual particle density to the ty of the factory calibration aerosol. otometers have an analog output can be electronically recorded. Light photometers have been used to ize penetration through HEPA fil- mann and Bergman 1988), nuisance osure (Gressel et al. 1987), and fume exposure (Glinsmann and thal 1985).

Particle Size Measurement

Real-time cascade impactors are available using quartz crystals as the target material. They consist of several inertial impactors of decreasing cutoff diameter (Carpenter and Brenchley 1972; Fairchild and Wheat 1984). The collection surface in each stage is a greased quartz collection crystal coupled to a reference crystal located outside of the sample stream. High-frequency oscillations of the two crystals are mixed, resulting in a beat signal of lower frequency. Particles collected on each stage increase the mass of the measurement crystal and thereby cause a shift in the oscillation frequency of the crystal. This results in a shift in the beat frequency directly proportional to the mass loading. O'Brien, Baron, and Willeke (1986) used such a device for measuring the size distribution and concentration of the aerosol produced during the high speed grinding of gray iron castings.

Single-particle optical counters (OPC) size particles based on the amount of light scattered by individual particles. A beam of light inside the instrument is focused onto a view volume, through which the particles pass one at a time. The amount of light scattered by each particle is measured by a photosensitive detector. The particle size distribution is then determined from an analysis of the photodetector output by a multichannel (pulse height) analyzer. The size indicated is equivalent to the size of a calibration aerosol, typically latex spheres. The estimation of the aerodynamic diameter of an unknown aerosol from the diameter obtained from an optical particle counter (scattered-light-equivalent) is difficult as it is dependent on the shape and complex index of refraction of the unknown particles and on instrumental characteristics such as the geometry of the optical system and the photodetector sensitivity. One approach to determination of the aerodynamic size with single-particle optical counters (Marple and Rubow 1976) involves an empirical calibration using specially designed impactors. Particle distributions are measured with and without an impactor mounted on the counter inlet. The counter channel containing one-half as many counts with the impactor as without corresponds to the cutoff size of the impactor. Various calibration points can be obtained by using different nozzles to change the cutoff size of the impactor. Crouch (1987) and O'Brien, Baron, and Willeke (1987) used OPCs to measure the size distribution and concentration of airborne particles in aerosols from grinding gray iron castings. Skillern (1971) used three different light-scattering aerosol photometers for testing high-efficiency filters and clean-room atmospheres, but frequent checking by optical or electron microscopy was necessary to identify the actual particle size distribution of the aerosol.

Time-of-flight aerosol spectrometers, such as the APS Model 33B and the Aerosizer MACH 2 (TSI, Inc., St. Paul, MN, and Amherst Process Industry, Inc., Amherst, MA), share some characteristics of optical particle counters: particles are counted one at a time, using a light source and a photomultiplier tube. The lower detection limits of both instruments are limited by the amount of light scattered by an individual particle. Although OPCs and time-of-flight aerosol spectrometers are both based on light scattering, the measured quantity is different. The time-of-flight aerosol spectrometer sizes particles by measuring the transit time between two planes of laser light as the particles leave an accelerating flow field. This time is proportional to the aerodynamic size (Remiarz et al. 1983).

The maximum concentration that can be measured by both optical particle counters and time-of-flight spectrometers is limited by coincidence—the simultaneous presence of two or more particles in the viewing volume. The coincidence of two particles in an OPC causes a single larger particle to be counted (Willeke and Liu 1976); coincidence in time-of-flight aerosol spectrometers results in randomly sized particles (Remiarz et al. 1983); and phantom particles are created when particle concentrations exceed 100 particles/cm^3 (Heitbrink, Baron, and Willeke 1991). These instruments incorporate circuitry or software logic to reduce this effect.

O'Brien, Baron, and Willeke (1986) compared four methods of aerosol measurement. Samples of an industrial aerosol from a grinding operation of gray iron castings were analyzed by a scattering aerosol spectrometer (OPC), and a time-of-flight spectrophotometer (APS), a piezoelectric microbalance cascade impactor (QCM), and a scanning electron microscope (SEM). Plots of number concentration and mass concentration versus aerodynamic diameter show large differences among the instruments. For particle sizes less than 0.3 μm, OPCs indicated an increase in the number of particles with decreasing particle size, while SEM showed the opposite trend. The QCM was of questionable accuracy below 0.5 μm. The counting efficiency of the APS dropped off below 1.0 μm and dipped at about 8.0 μm, due to internal circuitry and logic software. The QCM underestimated the aerosol concentration by a factor of about 2. The slopes of the particle size distribution between 1.0 and 7.0 μm obtained on the APS, OPC, and QCM were similar, while the SEM slope was almost linear on the mass-weighted plot. It was concluded that a combination of instruments can be used to get an estimate of the true particle size distribution.

Surveys/Calibration

Most real-time devices are used as survey instruments. Aerosol photometers and piezoelectric instruments can be used to identify and prioritize potential sources of exposure to dust. Since these instruments are not specific for individual chemical species and the period of measurement is necessarily brief, they may not reflect actual exposures measured by long-term sampling techniques. These measurements can be used to identify areas or operations potentially causing exposures.

Since aerosol photometers do not measure mass directly, they should be calibrated before use. Ideally, this can be accomplished by placing the instrument in a calibration chamber, where an aerosol generator produces a known concentration of the contaminant of interest (Pui and Liu 1988). Realistically, very industrial hygienists have access to such [illegible], so field calibration is necessary. In calibration, the instrument is placed in the work environment, and a parallel measurement is made by a reference method (e.g., membrane filter). The output of the instrument is recorded for the identical sampling period of the reference. After the sampling is completed, the instrument output is averaged and compared to the results obtained by the reference method. The ratio of the reference method to the instrument average is the calibration factor. Some real-time aerosol instruments have available calibration accessories to facilitate field calibration (e.g., a reference filter device) (Skillern 1971; Gero and Tomb [illegible]). In using the calibration factor, one assumes that the particle size distribution and composition do not change appreciably between calibration and sampling conditions.

Respirator Fit Testing

Another application of aerosol measurement involves fit-testing a respirator. Because each person's face is unique, one style or size of respirator will not provide the optimum protection for all workers. In an attempt to optimize the selection of a respirator for an individual worker, various test schemes have been developed to measure respirator fit. The simpler procedures involve the use of amyl acetate (banana oil), saccharin, or an irritant smoke to challenge the respirator and rely on the subjective response of the wearer to evaluate the fit (Marsh 1984*a*, 1989*b*; Myers 1986). Two quantitative fit-test methods commonly challenge respirators with either a liquid aerosol in the di-2-ethylhexyl phthalate test method or a solid aerosol in the sodium chloride test method. Air samples are continuously drawn off from the probe into the mask and fed to a photometer for challenge aerosol detection. Protection factors are determined by calculating the challenge aerosol concentration outside the mask to concentration sampled inside the mask (Kolesar et al. [illegible]; Lowry et al. 1977).

[illegible] quantitative fit-test procedures have [illegible] which utilize an aerosol generator (typically corn oil), a portable exposure chamber, and an aerosol photometer. The respirator is modified with a fitting which permits sampling within the face piece. The photometer is connected to both the exposure chamber and the respirator. The ratio of the aerosol concentration in the chamber to that within the respirator is used as an index of fit. A recent improvement in quantitative fit testing (Willeke, Ayer, and Blanchard 1981) does away with the aerosol generator and exposure chamber. Since the concentration of submicrometer-sized particles in the atmosphere is relatively stable (for the duration of a test), ambient aerosol is used as the challenge atmosphere and the concentration of particles in the 0.02–1 μm size range is measured using a miniaturized condensation nucleus counter.

Task/Exposure Analysis

One purpose of real-time aerosol monitoring is to relate some measurement of exposure to some work activity or to a particular piece of equipment, to determine some dynamic property of the work environment or to contrast exposure differences caused by the introduction of a control measure (Gressel, Heitbrink, and McGlothlin 1988). The aerosol measurement is correlated with some variable affecting the exposure. Aerosol photometers have been used in conjunction with video recording as a powerful study tool to identify operations or activities causing exposure. The concentration data can be recorded and entered into a spreadsheet for manipulation and analysis. Observational data can likewise be entered into the spreadsheet. The qualitative data may originate from careful note taking or they may be obtained after-the-fact by an observation of time-superimposed videotapes. This permits a calculation of the contribution of the various factors to the exposure scenario, allowing the identification and subsequent control of the offending tasks (Gressel, Heitbrink, and McGlothlin 1988).

FUTURE TRENDS

The establishment of criteria for size-selective sampling by the American Conference of

Governmental Industrial Hygienists may lead to changes in conventional sampler technology. The implementation of these new samplers by industrial hygienists will depend on the adoption of particle size-specific occupational exposure limits by the ACGIH and various governmental agencies. An increasing awareness of sample loss caused by electrostatic forces will increase the use of samplers made with conductive materials. The trend toward miniaturization and automation of sampling equipment will likely continue, especially for real-time instruments. Task/exposure analysis, largely a research tool in the 1980s, should be adopted by more practicing industrial hygienists in the 1990s. This will spur the demand and subsequent development of still smaller instruments with built-in data recording capabilities. The lack of specificity of real-time monitors will remain a problem in the foreseeable future, with little progress likely for real-time chemical analysis.

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