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AIR SAMPLING FOR PARTICULATES

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Exposure to airborne contaminants in the work environment has been linked to a wide spectrum of occupational diseases. A serious problem has existed over the years in occupational health in that much of the medical and epidemiological research data collected on workers has not had companion occupational environmental data collected in the time interval over which exposures occurred. The evaluation of worker exposure to potentially hazardous agents in the workplace is essential to establishing cause/effect relationships between an occupationally related illness and a specific agent(s). Existing gaps in worker exposure data have greatly limited the establishment and promulgation of proper occupational health standards for our nation's work force.

The purpose of this chapter is to describe current procedures and methods employed by industrial hygienists to assess, measure, and characterize worker exposure to potentially hazardous contaminants in the occupational environment. The chapter is divided into two sections: sampling techniques for gases and vapors and techniques for particulate sampling.

INTRODUCTION

Particulates of concern relative to respiratory diseases are those suspended in air which can be inhaled. This includes all particles, solid or liquid, in a size range capable of being inhaled and deposited in the nasopharyngeal and/or tracheobronchial region, or penetrating the tracheobronchial tree and being deposited in the alveolar regions of the lung. An aerosol is any system of liquid or solid particles dispersed in a stable aerial suspension. An aerosol must be of fine enough particle size and consequent low settling velocity to possess considerable stability as an aerial suspension (34).

Particulate material can be classified, according to its physical state and evolutionary character, into liquid aerosols or solid particulates. Liquid aerosols are generally classified as fogs or mists. Liquid aerosols are normally formed by condensation from a gaseous to a liquid state (fog), or by dispersion of a liquid due to splashing or foaming, by atomization, and by gas entrainment of a liquid (mists). Solid particulates are further subdivided according to particle size and method of evolution into dusts, fumes, and smokes.

Dusts. Dusts are formed from solid organic or inorganic materials when the parent material (the material from which they are formed) is reduced in size through some mechanical process such as crushing, drilling, grinding, blasting, and pulverizing. Dusts vary in size from visible to submicroscopic, but the composition of individual particles is not changed because of the size reduction process *per se.* Airborne dusts range in size from < 0.1 to 25 μm in diameter.

Fumes. Fumes are extremely fine, solid particulates formed by processes such as combustion or condensation. The term is generally applied to the condensation of metals from their gaseous state after volatilization and the subsequent formation of metal oxides. Examples are metallic fumes formed from welding and thermal cutting operations. Fumes generally range in size from 0.001 to 1.0 μm.

Smoke. Smoke refers to airborne particulates resulting from the incomplete combustion of organic materials. Smoke particles are usually less than 0.5 μm in diameter.

An aerosol's nature is an important factor in developing or selecting methods for characterization of the environment. Particulate sampling is performed by drawing a measured volume of air through a collecting device for removal of the particles of interest, or as discussed in a later section, some direct reading instruments pass the aerosol through a sensing region without particle removal (30). The particulate concentration is arrived at by the weight or number of particles collected per unit volume of air sampled. Mass determinations are made by gravimetric or chemical analysis as appropriate. The number of particles per unit volume is determined by counting the number of particles in a known portion of the sample. Although in the past, particle counts have been used to assess health hazards from inhalation of insoluble particulates, the mass of the material entering the lung provides the best estimate of toxic effect (1).

The fraction of particles in inspired air which is retained in the respiratory tract and the site of deposition is dependent upon 1) the aerodynamic properties of the particle, i.e., the size, shape, and density; 2) the size and shape of the airways; and 3) the pattern of breathing, namely, nose versus mouth breathing (27). The aerodynamic size or diameter is equal to the diameter of a unit density, spherical particles having the same settling velocity as the particle in question. Unless otherwise specified, all sizes mentioned relate to the aerodynamic size or diameter of a given particle. The aerodynamic properties of a particle determine its mobility regardless of its apparent size and shape. Thus, a relatively large, loose aggregate of particles may behave aerodynamically the same as a much smaller dense particle.

The aerodynamic properties of particles determine the relative ease with which they are removed by the physical mechanisms of inertial impaction, sedimentation, and diffusion (6)(33). For particles with an aerodynamic size of 5 to 30 μm, inertial impaction is the primary mechanism responsible for deposition in the respiratory tract. The inertia of inhaled particles will tend to cause them to resist changes in direction and impact upon the airway walls where airflow is deflected by branching. Deposition by inertial impaction for a given aerodynamic particle size will increase with increases in air velocity; thus, this mechanism operates primarily in the nasal chamber and upper respiratory tract.

Sedimentation, or gravity settling, is the second mechanism responsible for particle deposition in the respiratory tract (6). When a particle is released from rest and falls in air, it will accelerate to a terminal settling velocity where the downward force of gravity is balanced by the opposing aerodynamic drag of air through which the particle is falling. When respirable particles reach terminal settling velocity, they are removed as they are deposited on airway walls or alveolar surfaces. Deposition in the respiratory tract from sedimentation predominates for particles in the 0.5 to 5.0 μm range that are not effectively removed by impaction and deposition from sedimentation usually occurs in the tracheobronchial region.

The third mechanism promoting particle deposition in the lungs is diffusion or Brownian motion. All airborne particles are moving at random, owing to their constant bombardment by gas molecules in air. Particles smaller than 0.5 μm, and especially those less than 0.1 μm, have such a small volume and mass that they have significant Brownian motion; this tends to cause them to be deposited readily (30). Deposition by diffusion predominates in the alveolar region, but it also occurs in the tracheobronchial region.

The aerodynamic properties of a fiber present a special case with regard to site of deposition. A fiber can be characterized by its long length to width (or aspect) ratio (which in the case of asbestos has been defined at an aspect ratio of 3:1). As with other particles, the settling velocity of a fiber is largely dependent on its diameter (43). Fibers in a moving airstream tend to align their length parallel to the direction of air flow and behave much the same as a spherical particle of the same cross-sectional diameter. If the fiber shape is curved or curled, it will have an end-on aspect equal to the width of the curl or curvature and will have a much greater chance for deposition than straight fibers.

PULMONARY DEPOSITION

Experimental studies and models to predict the extent of particle deposition within the respiratory tract have been reported in various articles, reviews, and symposia by Brown, et al. (7), Landahl, et al. (20), Altshuler, et al. (3), Van Wijk and Patterson (37), Weibel (41), Davies (12)(13), Lippmann and Albert (25), Lippmann (23), Casarett (8), and others. Hatch and Gross (19) summarized characteristics of particle deposition at various depths within the respiratory system as follows:

1. Particles larger than 10 μm equivalent diameter are essentially all removed in the nasal chamber and therefore have little probability of penetrating to the lungs. Upper respiratory efficiency drops off as size decreases and becomes essentially zero at about 1 μm.
2. The efficiency of particle removal is high in the pulmonary airspaces, being essentially 100% down to around 2 μm. Below this size, it falls off to a minimum at about 0.5 μm. It increases again as the force of precipitation by diffusion increases with further reduction in size.
3. The percentage penetration of particles into the pulmonary airspaces rises from essentially zero at 10 μm to a maximum at and below about 1 μm where it equals the fraction of tidal air which reaches the lungs.
4. The percentage of inhaled particles which penetrate to and are deposited in the pulmonary airspaces has a maximum value between 1 and 2 μm. Larger particles are deposited in the lungs in lesser degree because they are trapped higher up in the respiratory tract. Lung deposition of finer particles falls off because the local efficiency of removal decreases as size diminishes below 2 μm.
5. Below 0.5 μm, the probability of deposition in the pulmonary airspaces rises in proportion to the increase in the force or precipitation by diffusion with decreasing size.
6. The relative amount deposited and the distribution of the collected particles in the respiratory system changes with breathing frequency and tidal volume. Upper respiratory trapping increases as the rate of inspired airflow goes up with faster breathing frequency. The magnitude of deep-lung deposition increases with slow, deep breathing because of the larger fraction of tidal air which reaches the pulmonary spaces and the longer transit time of air into and out of the lungs.

STANDARDS AND CRITERIA FOR RESPIRABLE DUST SAMPLES

Two types of samples referred to as "respirable" and "total" gained considerable importance with the promulgation of occupational exposure standards requiring mass particulate sampling. Prior to the adoption of mass particulate sampling, insoluble pneumoconiosis dusts were evaluated using the impinger method. With impinger sampling, air is drawn through a liquid (usually water or alcohol) at a known flow rate over a measured period of time. After collection of the dust particles in the impinger solution, the dust particles in a portion of the sample solution are counted microscopically and used to calculate the airborne dust concentration expressed in millions of particles per cubic foot (mppcf) of air. Although this method is useful in determining the dust concentration to which workers are exposed, it is tedious, imprecise, and more importantly, a mass determination is a better indicator of health risk. Likewise, since total mass concentrations may be determined principally by larger particles which cannot penetrate the upper respiratory tract and thus cannot damage the deep lung tissue, total dust has been judged not to be a reliable measure of hazard from exposure to the insoluble pneumoconiosis-producing dusts.

Three different criteria have been specified for "respirable" dust measurement: that of the British Medical Research Council (BMRC), which was later adopted by the Johannesburg International Conference on pneumoconiosis in 1959; that of the U.S. Atomic Energy Commission's Office of Health and Safety, adopted at a 1961 Los Alamos conference; and that adopted in 1968 by the American Conference of Governmental Industrial Hygienists.

As stated in the recommendations of the Johannesburg Conference (28) the BMRC criterion is:

> measurements of dust in pneumoconiosis studies should relate to the 'respirable fraction' of the dust cloud, this fraction being defined by a sampling efficiency curve which depends on the falling velocity of the particles and which passes through the following points: effectively 100% efficiency at 1 micrometer and below, 50% at 5 micrometers, and zero efficiency for particles of 7 micrometers and upwards; all the sizes refer to equivalent diameters. (The equivalent diameter of a particle is the diameter of a spherical particle of unit density having the same falling velocity in air as the particle in question.)

According to Davies, a size selective sampling device meeting the criteria would generate a curve of sampling efficiency versus aerodynamic size as illustrated in Figure I-9 and is defined by the percentage removed by the selective sampler as follows (11):

% Rejection	Diameter (μm)
10%	2.2
20	3.2
30	3.9
40	4.5
50	5.0
60	5.5
70	5.9
80	6.3
90	6.9
100	7.1

*For spheres of unit density

The BMRC criterion for a size selective sampler is met by a horizontal elutriator device consisting of stacked parallel plates (18)(39). Although the rejection curve is theoretical, it can be approximated by carefully built commercial devices.

The Atomic Energy Commission Standard defined "respirable dust" as that portion of inhaled dust which penetrates to the nonciliated portions of the lung (19). This criterion for respirable dust sampling was developed for evaluation of insoluble internal radiation emitters and was not intended for particles which are readily soluble in body fluids and those which are chemical intoxicants (23). The criterion adopted defined "respirable dust" as follows:

Size* (μm)	Respirable (%)
10	0
5	25
3.5	50
2.5	75
2	100

*Sizes referred to are equivalent to an aerodynamic diameter having the properties of a unit density sphere.

The Los Alamos curve is illustrated along with the BMRC curve in Figure I-9. The Los Alamos curve was not developed with any particular size selective sampler in mind; however, it is approximated by several cyclone inertial collectors (39). Mathematically it has been shown that the mass collected on the second stage of an instrument meeting the AEC criterion will be slightly less than that passing an instrument meeting the BMRC criterion (4)(40).

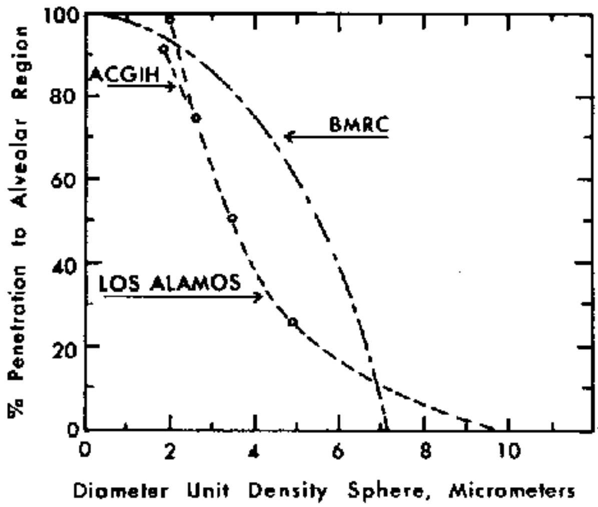

Figure I-9. "*Respirable*" dust mass measurement sampling criteria (1).

In 1968, the American Conference of Governmental Industrial Hygienists (ACGIH) adopted a quartz TLV for respirable dust in milligrams per cubic meter (mg/m^3) (1). This allowed an alternate mass concentration method for evaluation of quartz, cristobalite, and tridymite (three forms of crystalline-free silica) to supplement the method based on particle count concentrations. The alternate concentration TLV proposed was:

(1) for respirable dust in mg/m^3

$$\frac{10\ mg/m^3}{\%\ \text{Respirable Quartz} + 2}$$

NOTE: Both concentration and % Quartz for the application of this limit are to be determined from the fraction passing a size-selector with the following characteristics:

Aerodynamic Diameter (μ)	≤2.0	2.5	3.5	5.0	10
% passing selector	90	75	50	25	0

(2) for "total dust" respirable and nonrespirable:

$$\frac{30\ mg/m^3}{\%\ \text{Quartz} + 2}$$

NOTE: For both cristobalite and tridymite: Use one-half the value calculated from the count or mass formulae for quartz.

It can be seen in Figure I-9 and from the specification that the size selective characteristics of the ACGIH and the AEC criteria differ only at 2 μm: the ACGIH allows for 90% passing the size-selector versus 100% for the AEC criterion.

The ACGIH recommendation was not designed to fit a particular sampling instrument. However, the small cyclone closely approximates these criteria and is commonly used for this purpose. Standards promulgated under the Occupational Safety and Health Act of 1970, the Coal Mine Health and Safety Act of 1969, and the Federal Mine Safety and Health Act of 1977, require "respirable" dust sampling for evaluation of pneumoconiosis-producing dusts. For certain toxic dusts that are highly soluble in body fluids, the absorbed dose is most important and "total" dust samples are more appropriate.

METHODS OF COLLECTION

A particulate sampling train consists of the following components (30): air inlet, particulate separator or collecting device, air flowmeter, flowrate control valve, and air mover or pump. Of these, the most important component is the particulate separator. The sampling efficiency and reliability of the separator must be high. The pressure drop across the collector should be low in order to keep to a minimum the size of the required vacuum source, motor, and power supply. The separator may consist of a single element (such as a filter or impinger), or there may be two or more elements in a series (such as a two-stage cyclone or multi-stage impactor) so as to characterize the particulate into different size ranges.

There are a variety of techniques that have been used or suggested for collecting airborne particulates. This review will discuss techniques used in the collection of airborne particulates rather than specific instruments. The techniques have been grouped into seven general categories based on the physical forces employed for collection. Overlap exists among some categories. Table I-41 presents a summary of the techniques with operating priciples and examples.

Filters

The use of filters has become the most common method of collecting airborne particulates. Advantages include low cost, simplicity, small space requirement for storage, and a wide choice of available filter media and sizes.

Several mechanisms are involved in filtration. These include direct interception, inertial impaction diffusion, electrical attraction, and gravitational forces. One or more of these mechanisms will predominate in a given case and will depend on the flow rate, the nature of the filter, and the nature of the aerosol (22). For example, with fibrous filters and membrane filters, particles are removed from the gas stream primarily be impaction and diffusion mechanisms. The principles of direct interception and electrostatic deposition may also be present but, in the case of fiber and membrane filters, usually are less important. Retention of particles by impaction and diffusion mechanisms is largely dependent upon particle size.

Since a variety of mechanisms are involved in filtration, the collection efficiency of a given filter for a given particle size should vary with face velocity and particle size (22). A typical efficiency curve for a given filter and aerosol may be high at low velocities (primarily due to diffusion). With increasing face velocity, the efficiency would first fall off and then, with higher velocities, begin to rise as a result of inertial collection effects. At very high velocities, forces exerted on the particle by the flowing gas stream may be greater than the forces of adhesion and re-entrainment of the collected particle may occur. A similar efficiency curve will result from a given filter and a given face velocity; i.e., for small particles, a high collection efficiency exists; as particle size increases, the efficiency of the filter at first drops off and then increases for larger size particles. Several types of filter materials are virtually 100% efficient for essentially all particle sizes. Information regarding the specifications and performance characteristics of most types of commercially available filter material is presented in tabular form in "Air Sampling Instruments for Evaluation of Atmospheric Contaminants" (22).

Fibrous filter media used for sampling particulates are available in a wide variety of matrices including cellulose fiber, glass fiber, mixed fiber, and plastic fiber (22). Fibrous type filter media consist of fine, thickly matted fibers and have a low mass per unit face area, making them ideal for gravimetric analyses. Cellulose fiber filters have been used primarily for liquid-solid separations by analytical chemists. They are relatively inexpensive, have a wide range of sizes, excellent tensile strength, and a relatively low ash content. Their major disadvantage is their

Table I-41

SAMPLING TECHNIQUES FOR COLLECTION OF AIRBORNE PARTICULATES

Sampling Technique	Force or Mechanism	Examples
Filters	Combination of inertial impaction, interception, diffusion, electrostatic attraction, and gravitational forces	Various types and sizes of fibrous, membrane, and nuclear pore filters with holders
Impactors	Inertial—Impaction on a solid surface	Single and multi-jet cascade impactors and single-stage impactors
Impingers	Inertial—Impingement and capture in liquid media	Greenburg-Smith and midget impingers
Elutriators	Gravitational separation	Horizontal and vertical type elutriators
Electrostatic Precipitation	Electrical charging with collection on an electrode of opposite polarity	Tube type, point-to-plane, and plate precipitators
Thermal Precipitation	Thermophoresis—particle movement under the influence of a temperature gradient in the direction of decreasing temperature	Various devices have been designed for particulate collection for microscopy analysis
Cyclones	Inertial—Centrifugal separation with collection on a secondary stage	Tangential and axial inlet cyclones in varying sizes.

hygroscopicity, which makes accurate gravimetric analyses difficult. Glass fiber filters have low airflow resistance, reduced hygroscopicity, and minimal interference with analytical chemistry methods making them well suited for gravimetric, chemical, and physical analysis. Silica and some trace metals will interfere and this needs to be considered when selecting glass fiber filter media.

Membrane filters produced by precipitation of a resin under controlled conditions, and nuclepore filters, produced by bombarding polycarbonate sheets with U-235 fission fragments and subsequent controlled etching, are widely used for collecting mineral dust for examination by optical and electron microscopy. Membrane filters are also ideal for gravimetric, chemical, and physical analysis because of their characteristics of very low mass, minimal hygroscopicity, and negligible ash content; and some are completely soluble in organic solvents. Membrane and nuclepore filters differ from fibrous filters in that particle collection takes place at or near the surface of the filter. This is an advantage for microscopic examination but a disadvantage in that as the membrane loads up with particulate, the pressure drop increases and the deposit tends to slough off the filter.

Impactors

Inertial impactors operate on the principle that if particles in a moving airstream are suddenly deflected from a straight course, the momentum of the entrained particles may cause them to deviate from the streamlines of airflow and impact against the deflection surface (29). The particles are said to be "impacted" and the deflecting obstacle is operating as an impaction surface.

Impactors have been in use for many years and are particularly useful for determining the particle distribution of an aerosol. They are constructed as single-stage impactors with very narrow ranges of particulate capture or as a series of jets and impactor plates which provide particle separation into several size ranges. Impactor design may use a single jet or multi-jet nozzle arrangement. The multi-jet variety is often preferred because particle bounce and blow-off are minimized and collection of larger samples is possible (15). Particles adhering to each stage or plate can then be weighed, counted, or analyzed. When an impactor has been properly calibrated for a given aerosol, it is possible to determine the aerodynamic median size characteristic of each stage. A particle analysis may be made by calculating the percent-by-weight on each stage using weighings, radioactivity, or quantitative analysis.

Multiple stage impactors utilize an extension of the theoretical finding that increasing jet velocity, coupled with decreasing jet cross section, results in a predictable size separation.

Impaction devices employ a wide variety of materials for particle collection surfaces: filter paper, glass, stainless steel, nutrient agar, mylar, and teflon. Some collection surfaces are coated with a nondrying adhesive film to insure adequate retention of impacted particles. In most instruments, a high efficiency filter is used as a back-up to collect submicrometer particles smaller than the cut-off size of the last stage.

Impingers

The impinger is one of the oldest devices for measurement of particulate. Greenburg and Smith developed the original version of the impinger in 1922 (17). Littlefield and Schrenk introduced a midget version of the standard impinger in 1928 (26). Use of the impinger for particulate sampling has diminished in recent years; it is usually only selected for situations where the dust count or number of particles expressed in "millions of particles per cubic feet of air (mppcf)" is desired.

The impinger consists of a calibrated glass flask and glass nozzle or jet submerged in a liquid (usually water or alcohol). Air is drawn through the nozzle at a high velocity, the particles impinge on a flat plate or on the glass bottom of the tube, lose their velocity, are wetted, and become trapped by the liquid. A small sample of the liquid is then counted in a special cell using light microscopic techniques. Particles may also be sized in a similar manner.

Particles of 1.0 μm in diameter and greater are efficiently collected by the impinger. The efficiency rapidly drops off for particles smaller than 0.7 μm (14). To obtain the maximum efficiency for small particles, the jet must be operated as a critical orifice so that the particles impinge at or near sonic velocity (29). Such velocities can lead to problems of shattering of coarse particles and aggregates and may give erroneous results (31).

Elutriators

Elutriators have been widely used in two-stage sampling trains, as preselectors at the front of the sampling train, for removal of coarse particulate matter, and for collection of the smaller size fraction on a filter or other suitable device. Elutriators are classified as horizontal or vertical, based upon their design and orientation in operation.

Horizontal elutriators were first recommended for use as a two-stage respirable-dust sampler in 1952 (42). When considering a standard for pneumoconiosis-producing dusts the British Medical Research Council (BMRC) selected the horizontal elutriator as the most appropriate dust sampling instrument for matching experimental lung deposition data. The council defined respirable dust as that passing an ideal horizontal elutriator.

A vertical elutriator developed by Lumsden and Lynch was recommended by NIOSH as the instrument of choice for determining worker exposure to cotton dust (10).

Elutriators function much like inertial separators, except that they operate at normal gravitational conditions whereas inertial separators induce multi g forces by angular acceleration to achieve separation of particles (39). A falling particle will accelerate until it reaches equilibrium with the resistance forces acting against it. This falling speed is defined as the particles' "terminal velocity" and will vary according to the particle diameter and density and the viscosity and density of the airstream. Terminal velocity also varies in a predictable manner dependent upon whether the airflow is streamline, intermediate, or turbulent (14). In practice, particles of specific sizes are removed from an airstream by gravity while smaller particles remain suspended and are collected for subsequent analysis.

The horizontal elutriator contains a series of thin rectangular ducts, one above the other, connected in parallel to a common exit (39). Dust-laden air flows at a constant rate across the plates where large particles settle out. Smaller particles are carried through the preselector and are collected on a filter which is either weighed or chemically analyzed.

Vertical elutriation uses the same principle of gravitational force to separate the particles into fractions, but differs in that with vertical elutriation, the gravitational force works in a direction opposite to induced airflow instead of normal to it (32). The vertical elutriator is a vertical tube with parallel sides designed such that particles above a certain design cut-off size will not penetrate the tube. Smaller particles pass through the elutriator stage and are collected on a filter. A variety of filter materials have been used for both vertical and horizontal elutriators.

With elutriators, various sampling efficiencies versus particle size can be accomplished by varying flow rates and sampler dimensions. For both vertical and horizontal elutriators, it is difficult to achieve perfect streamline flow. Also, flow rate is extremely critical: if too high, a disproportionate percentage of larger particles are collected on the filter; if too low, more large particles are removed causing errors on the low side. Elutriators must be operated in a stationary position and thus personal or breathing zone samples are not practicable.

Electrostatic Precipitation

Electrostatic precipitators have been used for many years for particulate sampling and are a modification of the Cottrell Precipitator (9). Electrostatic precipitators operate by imparting one or more electrical charges to particles which are then attracted to a collection electrode of opposite polarity. Although particles may acquire electrical charges by several means, e.g., friction with solid matter, ionization in flames, absorption of energy from ionizing radiation, etc., the high voltage corona discharge is usually employed for electrostatic precipitators. The attraction of the charged particles to the collecting surface is a function of the number of charges acquired, the field gradient, and the viscous drag of air (21).

Electrostatic precipitation differs from other methods discussed in that the electrical forces acting to separate suspended particles from the airstream exert their force directly on the particle and not on the entire gas volume. Therefore, the method requires relatively little power to precipitate the particles or to move the gas stream through the collector. In contrast, mechanical collectors such as cyclones, impactors, impingers, and scrubbers consume most of the power (associated with collection) to move the gas through the collector, and the high collector efficiency is associated with a large pressure drop (21). Advantages of electrostatic precipitators include negligible flow resistance, no clogging of the collector, and precipitation on a metal electrode whose weight is unaffected by humidity.

Electrostatic precipitators have three general electrode configurations: (1) concentric, (2) parallel, and (3) point to plane. The most common configuration used in particulate sampling is the concentric or wire and tube system (3). The tube is usually a light alloy cylinder about 6 inches long and 1½ inches in diameter, positioned horizontally and grounded. The cylinder can be lined with filter media if precipitation on a filter is desired. A stiff wire aligned along the center of the tube and supported at one end serves as the charging electrode. A high DC voltage is applied to the electrode and the corona discharge from the wire tip charges particles in the airstream drawn through the tube. The electrical potential gradient between the charging electrode and the collecting tube causes the particles to be attracted to the inside surface of the tube.

Thermal Precipitation

In thermal precipitation, the airstream is passed through a narrow space which has a significant temperature gradient perpendicular to the direction of flow. The movement of a particle in the direction of decreasing temperature (called thermophoretic velocity) causes the particle to be deposited on a relatively cool collecting surface (36). In a sampling instrument, the air is drawn past a heated wire or plate and the dust collects on a cold glass or metal surface opposite the hot element. A high thermal gradient is needed so the channel between the wire or plate and the collecting surface is kept small. Because the migration velocity induced by the thermal gradient is small, the system is limited to low volumetric flowrates and thus is used only for collecting sufficient particulates for microscopic examination.

Cyclones

Cyclones have found increasing use in recent years as the first stage in two-stage samplers for respirable mass dust exposure determinations. The sampling unit, usually a 10 mm cyclone and filter holder assembly, is attached to a low-flow pump and worn by the worker such that personal samples are obtained. Cyclones are also available for fixed location, high-volume sampling.

General principles of centrifugal and gravitational forces are used in the cyclone sampler to separate aerosols into various size fractions. Air is drawn through the cyclone at a preselected flow rate. The sample enters the cyclone tangentially and as the centrifugal motion of the flow increases, the inertia of the larger, nonrespirable particles forces them to concentrate at the flow periphery where they are separated and collected in a removable section at the bottom of the cyclone. The smaller, respirable particles remain in the cyclone's airstream and are collected on a preweighed filter.

Cyclones are constructed with a variety of materials; the most common are nylon or stainless steel. Plastic cyclones are unacceptable because an electric charge may accumulate on the plastic and alter the collection characteristics (5). The respirable fraction of the dust sample is collected on a variety of high-efficiency filter materials. The nonrespirable portion can also be recovered and weighed, providing "total" dust exposure as well.

There is considerable disagreement about the collection efficiency characteristics of these instruments. Since their efficiency is flowrate dependent, operation at nonstandard flows will cause errors in both total and respirable values (24).

By design, cyclones used for respirable dust sampling are highly efficient for removal of larger particles (i.e., greater than 10 μm) and are not efficient for particles below about 2 μm.

Direct Reading Instruments

The aerosol sampling methods discussed thus far differ from direct reading methods in that the aerosol is removed from the airstream for subsequent analysis, e.g., gravimetric analysis, chemical analysis, or optical or electron microscopy. Direct reading methods are more complex: the sampling and analysis is performed within the instrument and the property of interest is displayed continuously or after a brief sampling period.

Direct reading methods are similar in that the aerosol is either passed through or collects upon a sensing region (35). The presence of the aerosol is detected by a change in some property of the system caused by the particle or particles within the sensing region. The instrument is designed to make use of some relationship between the detected change and some property of the aerosol.

There are a variety of direct reading instruments on the market for analyzing airborne particulates according to particle size, aerosol number, and aerosol mass concentration. The sensitivity of these instruments is limited by the random property fluctuations of the accompanying gas molecules and by the noise level of the electronic circuitry which converts the detected change to an electronic signal (35). The accuracy of the method is dependent upon the relationship of the change detected in the sensing zone and the aerosol property measured. This relationship is determined mathematically from the operating principle of the method and verified by an empirical relationship using a well-characterized aerosol system. Because of the wide variation in size, shape, aerodynamic properties, and refractive indices of industrial aerosols, there may be an unknown relationship between the sensing zone change detected and the aerosol property measured so that an inaccurate particle measurement is indicated. Likewise, the user of direct reading instruments must be careful in comparing measurements from instruments having different operating principles, as such comparison is likely to give contradictory information.

Optical Direct Reading Instruments—A significant number of particulate direct reading instruments operate on the principle of the interaction between the particles and visible light (35). These instruments may be categorized according to whether the sensing zone contains one or numerous particles at a given time. Multiparticle instruments include transmissometers, nephelometers, and photometers.

Transmissometers operate on the basis of the extinction of light by particles. These instruments are somewhat limited: in order to get a measurable change in light extinction, the sensing volume must contain a large number of particles. This means there must be either a high concentration of particles or a long path length. Transmissometers are used to monitor particulate stack emissions because of the high particle concentration within the stack.

In integrating nephelometers, the small volume (about 1 L) of illuminated particles and the light scattered at a particular range of angles by the particles is measured by the photoreceptor (38). The instrument is simple in construction and has been adapted for use in studies of urban and rural atmospheric aerosol pollution to measure particles primarily in the 0.1 to 1.0 μm range. Similar to nephelometers, forward scattering photometers are available which employ an incandescent light source and optics similar to dark field microscopy (35). A narrow cone of light converges on an aerosol but is permitted to scatter only in the near forward direction, striking the photocell receptor. The signal from the photocell is converted to mass or number of particles per unit flow rate.

Single particle light scattering instruments all employ a small sensing volume and a light source either from an incandescent lamp or a laser source. In all single particle instruments, it is important to avoid coincidence errors resulting from more than one particle being in the sensing zone simultaneously. The manufacturer usually specifies the maximum number that can be handled without producing coincidence errors.

Electrical Direct Reading Instruments—The acquisition of an electrical charge by a particle is the basis for four types of electrical direct reading instruments: mobility analyzer, contact electrification probe, ion interception chamber, and flame ionization detector. Unipolar ions, radioisotopes, and hydrogen flame have been used to impart a charge to the particles, the amount being generally dependent upon particle size.

Beta Attenuation Direct Reading—Instruments have been designed and are commercially available which detect the mass concentration of an aerosol cloud. Detection is based on the attenuation of beta radiation resulting from collection of a sample of dust between comparative readings of a beta radiation source (32). The instrument uses a cyclone precollector to separate the respirable from the nonrespirable fraction. The respirable particles pass to the second stage through an orifice and are impacted on a polyester impaction disk. The impaction disk is placed between a beta radiation source and a detector. Particles deposited by impaction on the plastic film increasingly absorb the beta radiation reaching a Geiger-Muller detector from a Carbon-14 source. This beta-attenuation principle is advantageous because the penetration of low energy beta radiation depends almost exclusively on the mass-per-unit area of the absorbing substance and on the maximum beta energy of the impinging electrons; however, it is independent of the chemical composition or physical characteristics of the absorbing substances.

Piezoelectric Direct Reading Instruments—An instrument for direct measurement of particulate mass concentration is the piezoelectric crystal mass monitor (35). In the original design of the instrument, particles drawn through an impactor inlet to separate the respirable from nonrespirable fraction, are charged using electrostatic precipitation, and are deposited on the face of a quartz crystal. The crystal is part of an oscillator circuit whose resonant frequency is a linear function of the crystal mass. As particulate mass collects on the crystal face, the frequency changes to reflect the added mass. The rate of frequency change of the crystal is related to airborne mass concentration. Some piezoelectric instruments use a parallel crystal (which is not subjected to particle loading) as a reference standard to correct for temperature, pressure, or humidity changes in the air.

PARTICULATE SIZING

The ability of a particle to reach the deep lung tissue and cause an adverse effect is dependent, in part, upon its size. The characterization of an aerosol by particle size, therefore, is important in understanding the mechanisms of respiratory disease. Sizes generally thought to be "respirable" fall into the range below 10 μm.

The problem of size determination is complicated by the enormous range of sizes encountered in the workplace, e.g., from 0.001 μm for certain metallic fumes to 100 μm for a variety of industrial dusts. Other factors, such as particle density and shape, are also influential in determining the behavior of an aerosol. Any sample of airborne dust may contain a wide range of particle shapes and densities.

Since most dusts encountered in the workplace are irregular in shape, several methods have been developed to determine which dimensions to use for particle diameter. "Martin's diameter" is the length of a line which divides the two dimensional projection of a particle into two equal areas. The line for the initial particle

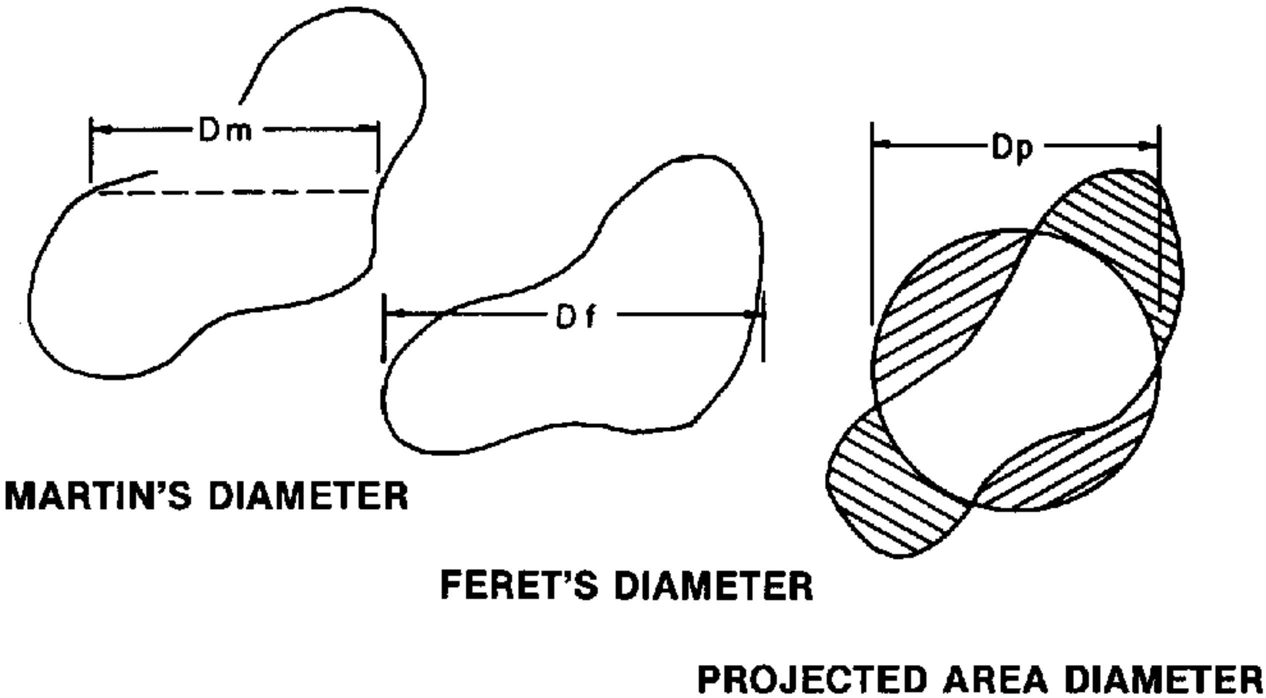

Figure I-10. Geometric diameters for irregularly shaped particles.

measured may be drawn in any direction, but lines for all other particles measured on that observed field must then be drawn parallel to the first (See Figure I-10). "Feret's diameter" is the distance between the extreme boundaries of the particle image. As with Martin's diameter, all measurements should be made in the same direction. The "projected area diameter" is the diameter of a circle having the same cross-sectional area as the particle image (16). Using only the average (mean or median) diameter is not sufficient to adequately describe the aerosol in question. Information about how the particle sizes are distributed about the mean (the standard deviation) is also important. If the particle sizes in an aerosol are normally distributed, i.e., in a bell-shaped fashion as depicted in Figure I-11, then approximately 67% of all particle diameters fall within one standard deviation of the mean, 95% within two standard deviations, and 99.7% within three standard deviations.

However, it has been found that most industrial dusts have particle size distributions skewed toward the smaller size (Figure I-12). Hatch and Gross pointed out that a log-normal distribution more closely approximates size frequency of airborne dusts than does a normal distribution (19). If particle size distribution data are plotted with the logarithm of particle size, the skewed curve is transformed into a symmetrical or bell-shaped curve (Figure I-13). If the assumption of a log-normal distribution is correct, then a cumulative frequency plot of the particle size data on log probability coordinates will be a straight line as shown in Figure I-14. We can then read the geometric mean particle size or 50% size (median size) directly from the graph. Particle size distribution can also be determined graphically by dividing the 84.13% size by the 50% size, or by dividing the 50% size by the 15.87% size. The value obtained is the geometric standard deviation, which, along with the geometric mean particle size, is a satisfactory description of the particle size distribution.

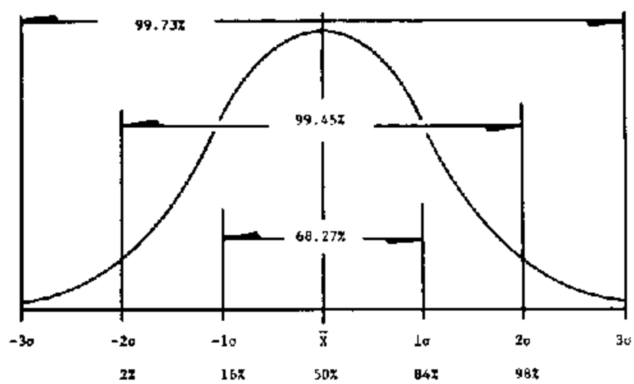

Figure I-11. Normal or bell-shaped distribution. Generally, particle size distributions are not normally distributed.

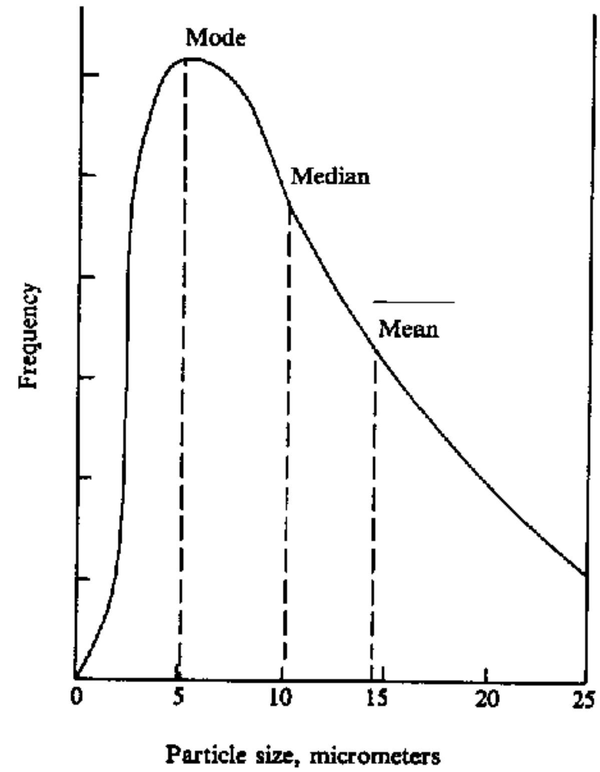

Figure I-12. Skewed particle size distribution of a typical dust.

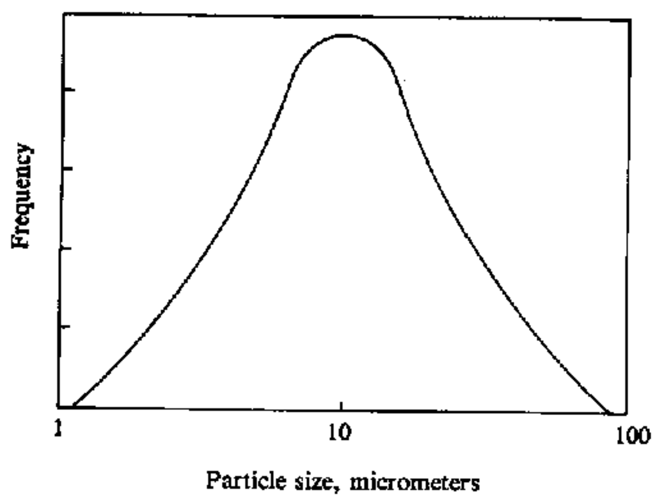

Figure I-13. Particle size distribution of Figure I-12. Plotted with the particle size on the log scale.

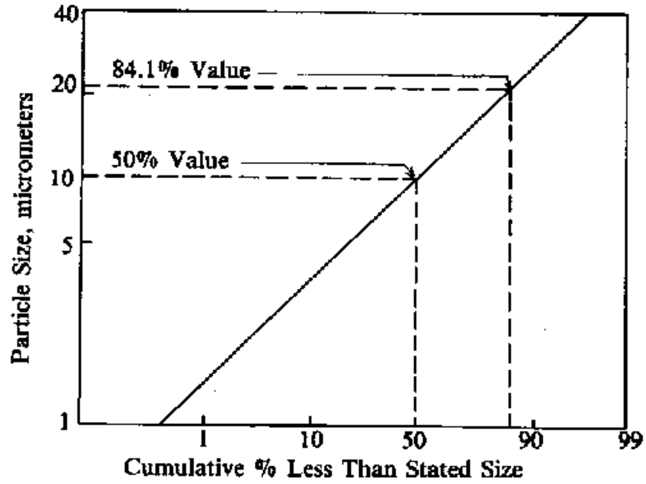

Figure I-14. Cumulative log-probability plot for the particle size distribution of Figure I-12.

Although the optical microscope has been the standard instrument for particle size analysis, there are a variety of other techniques commonly used for this purpose, some of which are described in previous sections (e.g., impactors, elutriators, cyclones, and direct reading devices). The selection of appropriate sampling and analytical instruments will depend on a number of factors related to the purpose of the sampling to be done, the character of the aerosol, the accuracy and precision required, etc. The electron microscope, for example, may find application in size determinations for industrial aerosols that are below the limits of resolution of the light microscope. However, the costs may be prohibitive in cases of limited application.

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SAMPLING MICROBIAL AEROSOLS

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INTRODUCTION

Collecting microbial aerosols is not substantially different from collecting any other airborne particulates. After collection, however, the processing of the sample is all important. These particles have life and the capacity to grow, multiply, and—as parasites—cause undesirable effects in a multiplicity of hosts. No chemical or physical measurement(s) available today can assess all these characteristics. Even detection of their presence often requires the bio-amplification provided by their growth characteristics. Many toxic materials are effective in the ppm ($1/10^6$) or even ppb ($1/10^9$) ranges; microbes may be active in the $1/10^{12}$ to $1/10^{14}$ concentrations. (For example, inhalation of a single tubercle bacillus (10^{-12} to 10^{13} gm) can initiate an active tuberculosis lesion.)

Both indoor and outdoor air are seas of microbial particles. Depending on local conditions, concentrations of viable particles will range from a few per ft^3 to many thousands or even millions. Particles are nearly indistinguishable so that detecting a specific viable and infective type is a little like selecting a specific raindrop in a rainstorm. Only by careful choice of growth and assay precedures, can the microbes of interest be selected out of the collectate.

Some description of the important sources, receptors, and transport mechanisms in the transfer of infectious agents is useful in understanding how infections occur. People, the major subjects of our concern, can be targets, carriers, sources, or vectors. As such, they range from the "Typhoid Mary" carrier, or the person with a cold shedding virus, to the dairy worker whose boots are laden with foot and mouth virus which he spreads through a susceptible animal population. The sources of aerosolized material can include growth sites such as sewage treatment plants, infected surgical wounds, animals, soil, people, and "other warm, moist and nutritive locations"(3). Microbial aerosols can also be dispersed directly from animate carriers or by activities disturbing an infected but normally passive source. For example, many respiratory infections of construction workers have been caused by soil fungi aerosolized at excavation sites.

Table I-42 lists various occupations and some of the diseases workers may acquire through exposure to microbial aerosols. The route of infection may be oral, or through the respiratory system, conjunctiva, or open wounds, etc. Disease descriptions are general and limited to those resulting from infection with viable organisms. Exposure to nonviable organisms can also cause disease (primarily allergies or hypersensitization phenomena). The indication of routes of infection by "contact" includes all other routes. The frequent occurrence of alternate routes is at least one indication as to why it is difficult to establish a direct cause and effect relationship between microbial aerosols and infection.

By and large, with the exception of fungal infections, the airborne route of infection is not the predominant mode. Occupational diseases due to aerogenic exposure to microorganisms or their toxic products may not be the most frequent hazards in work areas, but they are so widespread and the severity so great that they must be given close attention. A variety of occupations provide opportunity for aerogenic exposure. In the case of anthrax infections of goat hair pickers and sorters, most infections were through skin breaks, but an estimated 3% were by the respiratory route (1).

Special emphasis is placed on sampling viral aerosols because sampling for these agents is difficult. The problem is not only the mechanics