Chapter

4

This chapter will take approximately 3 hours to complete.

Particulate Matter Sampling

4.1 Introduction

O B J E C T I V E S

Terminal Learning Objective

The student will be able to identify the procedures of particulate matter sampling.

Enabling Learning Objectives

4.1 View the principle of inertial collection.

4.2 Identify and classify the inertial sampling devices.

4.3 View collection efficiency and penetration efficiency of inertial sampling devices.

4.4 Identify limitations and sources of error in inertial collection.

4.5 View filtration sampling.

4.6 View gravitational sampling.

4.7 Describe the principles and applications of electrostatic precipitation.

4.8 Describe the thermal precipitators.

4.9 Summarize the fundamental principles for sampling for PM in the atmosphere.

This chapter provides a definition for the subclasses of particulate matter (PM), addresses the rationale for size fractionation of particulates, and discusses particulate matter sampling techniques in ambient air. PM is the generic term for a broad class of chemically, physically, and biologically diverse substances that exist as discrete particles (liquid droplets or solids) over a wide variation in the size of the particles. EPA typically characterizes the physical and chemical characteristics of PM through various pump-based and direct-reading continuous techniques. When suspended in air, PM is typically referred to as "aerosol." Acute and chronic health effects have been positively associated with PM exposure. Because health effects and visibility are related to particle size, concentration, and chemical composition, EPA extensively characterizes PM.

Particles are usually characterized by their size diameter. PM size ranges from molecular clusters of approximately 0.001 micrometers (μm) in diameter to particles of approximately 100 μm. Particles less than about 0.001 μm act more like gases, and thus are not treated as particulate matter; while particles greater than 100 μm, due to their size and mass, are easily removed and are typically not released as an air emission. Because particles are present in many shapes and sizes, EPA methods characterize particles by their aerodynamic diameter, which is defined as the diameter of a sphere with a unit density (density of water= 1000 kg/m^3) that will settle in still air at the same rate as the particle in question.

Particle size is important because of the adverse health effects associated with particles in certain size ranges. The deposition of particles in the respiratory system is shown in Figure 4-1. Basically, the smaller the particle, the more likely it will penetrate deeper in the lung. Particles much greater than 100 μm are typically not inhaled, while smaller particles, typically less than 4 μm, can interfere with oxygen gas-exchange in the lung alveolar region. Figure 4-2 shows the penetration ability of particles in the lung, defined by commonly-used size-based particle terms.
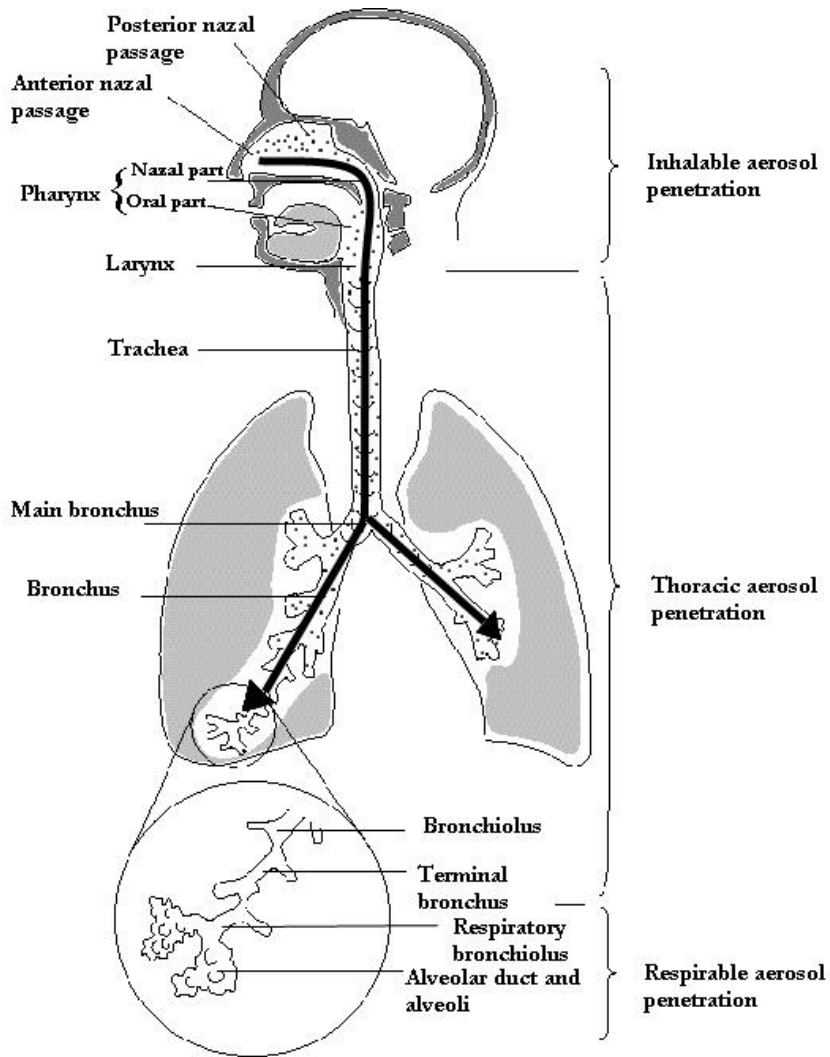
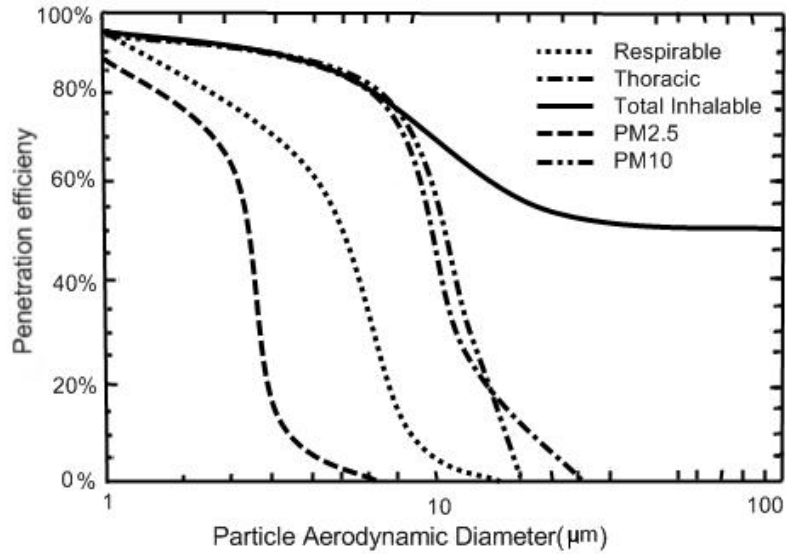**Figure 4-1. Respiratory collection of particles.**

Figure 4-2. Modeled lung deposition as a function of particle size.

Inhalable, thoracic, and respirable particles, which describe where particles are likely to deposit in the lung, are terms used more commonly in industrial hygiene (occupational-related PM exposures), while $PM_{2.5}$ and PM_{10} are terms used by EPA to describe particles up to 2.5 μm and up to 10 μm, respectively. These EPA size fractions are also described with the terms "coarse" (10 μm – 2.5 μm) and "fine" (<2.5 μm). Exposure to large particles can cause coughing and sneezing, while smaller particles can bypass the body's defense mechanisms and disrupt cellular processes.

In addition to being characterized by their size, particles can also be described by their origin or formation mechanism, chemical composition, and physical properties, as well as in terms of what is measured by a particular sampling technique. Figure 4-3 presents particle size distributions of several significant sources of particulate emissions.
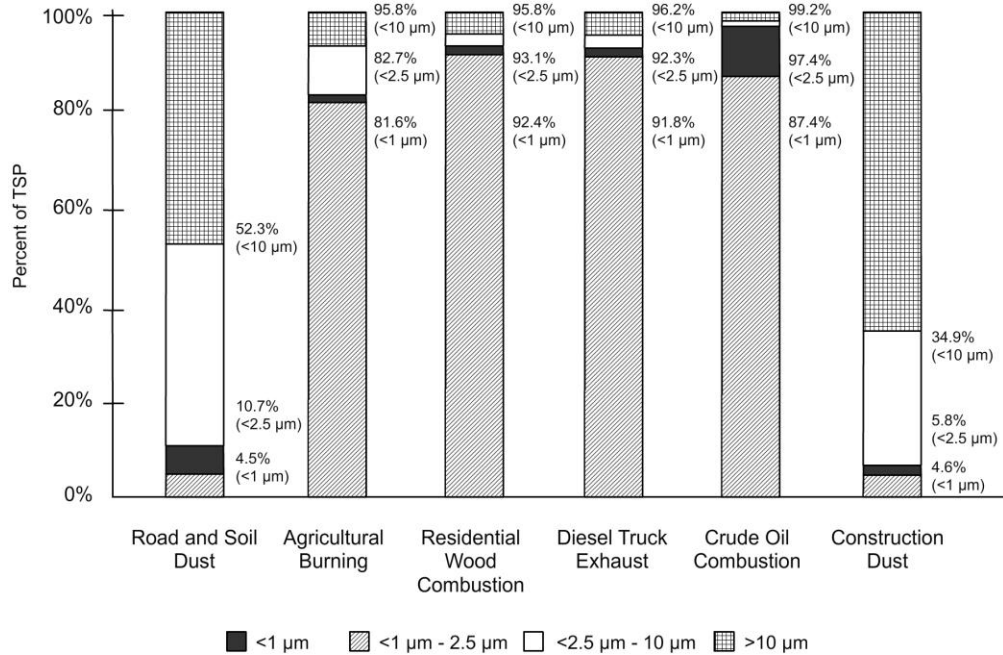
Figure 4-3. Particle size distributions of sources of particulate emissions.

Figure 4-4 shows the idealized size distribution of particles in ambient air (Chow, 1997). More specifically, the figure shows the relative concentration of $PM_{2.5}$, PM_{10}, and TSP size fractions in ambient air. These distinct curves are commonly referred to as "modes." The mass collected is proportional to the area under the size distribution within each size range. Although large particles contribute most to the mass concentration, as shown in Figure 4-4, there are typically many more small particles in ambient air on a number of particles per unit volume basis.
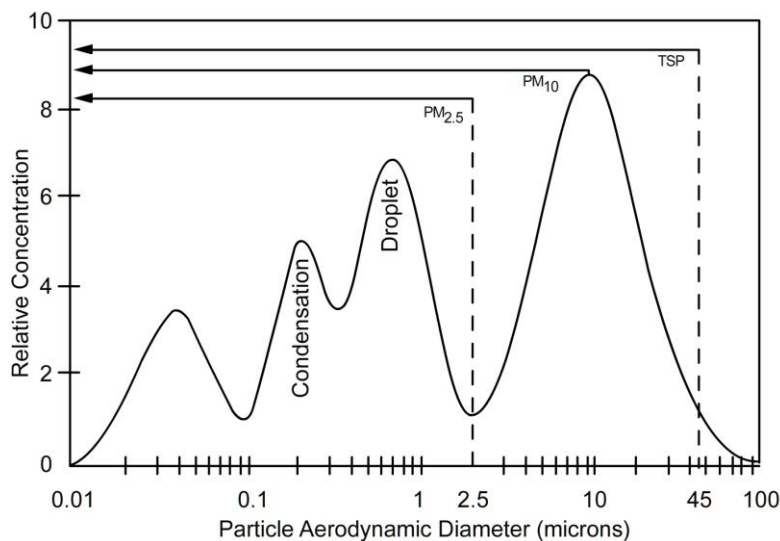
Figure 4-4. Idealized size distribution of particle in ambient air.

Inherent to pump-based sampling, no sampling device is able to collect all particles in a desired size range with 100% efficiency. For example, particle size selection devices, such as a Well Impactor Ninety Six (WINS) or Very Sharp Cut Cyclone (VSCC) used in $PM_{2.5}$ sampling, are designed to collect 50% of particles of 2.5 μm aerodynamic diameter size while allowing the remaining 50% to pass through the device. The collection efficiency of these devices increases at particle sizes greater than 2.5 μm, while particles less than 2.5 μm pass through the device with greater penetration efficiency until finally collected on a collection plate or filter. $PM_{2.5}$ is then determined to be the mass concentration of particles collected on a filter that passed through the WINS or VSCC (collection plates and filters capture particles at ~100% collection efficiency). A detailed discussion on collection and penetration efficiency is provided later in this chapter. Examples of collection efficiency curves for typical PM sampling devices are shown in figures 4-8 and 4-11.

The original National Ambient Air Quality Standards (NAAQS) for particulate matter were first established in 1971, and were measured based on the use of total suspended particulate (TSP) samplers known as high-volume samplers. The high-volume sampler, which is based on a filtration technique, typically captures particles up to 45 μm and usually up to a nominal size of 25 to 45 μm. In 1979, EPA added PM_{10} to TSP as the indicator for particles, where PM_{10} refers to particles with a mean aerodynamic diameter less than or equal to 10 μm. Although the TSP standard was revoked in 1987, TSP measurements continue to be taken for various sampling purposes.

On July 18, 1997, EPA promulgated new PM standards which included NAAQS for particulate matter with an aerodynamic diameter less than or equal to 2.5 μm, referred to as $PM_{2.5}$. In 2006, PM_{10} and $PM_{2.5}$ standards were revised to their current values (Chapter 7).

In this chapter, the discussion of particulate matter sampling will include inertial collection techniques, along with filtration, gravitational, and precipitation techniques. Discussion of sampling devices within each category will be restricted to those commonly used in ambient air sampling. Specific methods for sampling/monitoring of PM will be discussed in Chapter 5.

Principles of Inertial Collection
A number of factors and general principles associated with liquid and solid aerosol particles are helpful in most effectively selecting and using an ambient air sampling device. In addition to the size and nature of the particles, other important aspects to consider include the theory of inertial impaction, particle settling, the effects of thermal and electrical forces, and the theory of filtration. A discussion of these general aspects begins with the topic of inertial collection.

Inertial collectors are designed to give a size-representative sample of particles in the atmosphere using the principle that particles in a gas stream are more dense than the fluid (air) in which they are suspended. A particle moving in an air stream with approximately the same velocity as the air stream has more momentum (mass × velocity) than the volume of air that it displaces because of its higher mass. The momentum, or inertia, possessed by a particle in a moving air stream will cause the particle to be deflected less than the air in the vicinity of

the particle when the air stream undergoes a sudden change in direction. Such a deflection will occur when an obstacle is placed directly in the path of an aerosol stream. If the resulting deflection of the particle from the air trajectory around the obstacle is great enough (large angle of deflection), the particle will strike the obstacle. High incident velocities will increase the momentum of particles in the air stream, thereby enhancing their removal. High velocities can be attained by passing the air stream through an orifice (jet) prior to the stream striking the obstacle, as shown in Figure 4-5.
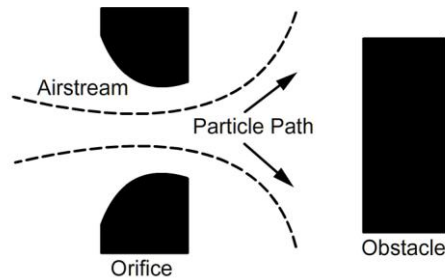

Figure 4-5. Particle collection by impaction.

Under the proper conditions, most of the particles within a certain size range that can be made to strike the obstacle will become attached to and remain on the collection surface.

A practical discussion of inertial sampling devices follows, including examples of numerous particulate matter collectors used in ambient air sampling.

4.2 Inertial Sampling Devices

The inertial collection process is subdivided into two main types: impaction and impingement. The distinction is made by the manner in which the sample material is retained in the sampling device.

Impaction Devices

Impaction devices collect and retain particles from an aerosol stream on a collecting surface. The collecting surface is removed from the instrument and the sample analysis is, in many cases, performed directly on the collecting surface. Particle adhesion is caused primarily by electrostatic attraction and by molecular surface phenomena known as Van der Waals forces. Some loss of large particles occurs with high aerosol velocities. It is believed that in the case of small particles (several micrometers or less), nearly all of those striking the collecting surface are retained on the surface. The collection surface in many impaction devices is coated with a thin film of oil or light grease to aid in particle retention. In some devices, retention is aided by passing the incoming particles through a zone of moisture-saturated air; moist particles adhere more readily to a collection

surface. Coating of the plates and water saturation of the particles affect the calibration of an impactor and must be accounted for if the impactor is to be used for determining particle size distributions.

Two-Stage Impactor
Figure 4-6 shows a schematic of a two-stage impactor. The air stream containing the various size particles flows through the first large jet nozzle and impacts on a collection plate oriented perpendicular to the axis of the nozzle. At the first nozzle exit, the air stream is deflected sharply by the collection plate. Larger particles continue forward and are collected on the first plate, while the smaller particles follow the air stream into the second nozzle, which has a smaller jet and a higher velocity, allowing the smaller particles to be collected on the second collection plate.
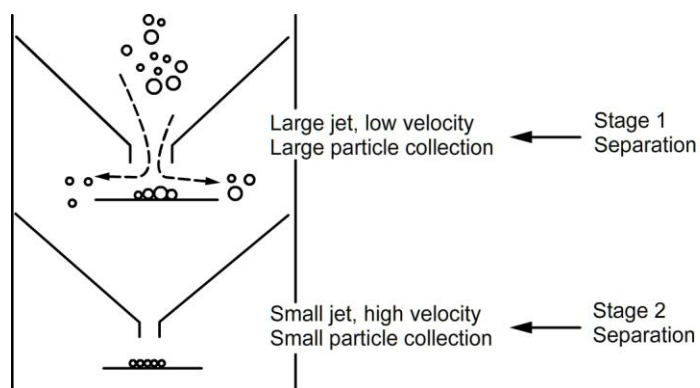

Figure 4-6. Two-stage impactor.

Andersen Cascade Impactor
An example of a multi-stage impactor is the Andersen standard sampler. This sampler usually contains six to eight stages (i.e., collection plates) with numerous, successively smaller, evenly distributed holes (orifices) in each stage. A constant flow rate is maintained through the Andersen sampler which causes the aerosol stream velocity to increase at each stage, resulting in a deposition of particles in size fractions. Each stage of the sampler consists of a perforated disc located above a collection medium (Figure 4-7). The sample air passes through the openings in the disc and must then make an abrupt change of direction over the collection medium. The particles possessing too great a momentum to continue in the air stream are impacted on the collection surface. The collection surface can be coated with a light oil, silicone grease, filter media, aluminum foil, or wax to help increase the collection efficiency. The thickness of the coating is not important, as long as it is at least the thickness of the particle that is to be collected. However, a heavy coating is not recommended since this will likely clog the orifices. Such coatings may also interfere with subsequent chemical analysis and the size ranges of particles collected.

The greatest limitation of the Andersen sampler is the relatively low flow rate, 0.028 cubic meters per minute (1 cubic foot per minute, or cfm), that must

be maintained. Such a flow rate limits the amount of sample that can be collected. Figure 4-8 shows the collection efficiency of each stage of the Andersen cascade impactor operated at a flow rate of 1 cfm, over the particle size range of 0.3 μm to 11 μm.
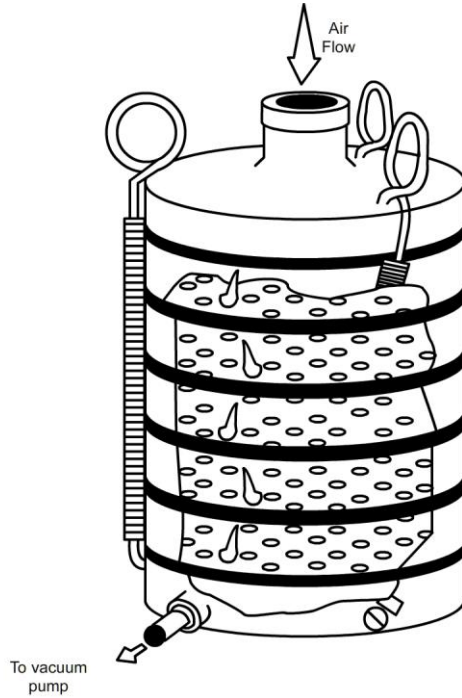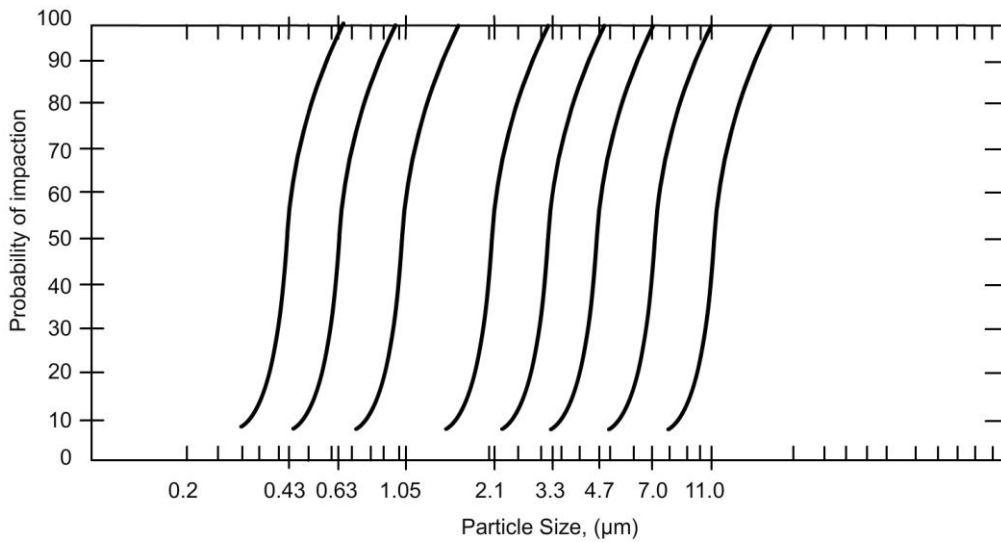

Figure 4-7. Andersen cascade impactor.

Figure 4-8. Collection efficiency of each of 8 stages (i.e., collection surfaces) of an Andersen cascade impactor operated at 1 cfm.

High-Volume Andersen Cascade Impactor

A modification of the Andersen sampler has led to the high-volume (hi-vol) Andersen impactor, which is typically operated at a flow rate of 0.57 m^3/min (20 cfm). This sampler consists of five stages with the typical Andersen perforated discs. Below the discs are gaskets and collection surfaces (Figures 4-9 and 4-10). The collection surfaces, usually glass fiber filters or aluminum foil, are supported by the plates themselves; i.e., the collection surface for plate 1 is supported by plate 2, and so on. To allow unrestricted aerosol flow, the collection surface has holes that line up with the orifices of the plate supporting it. The five stages are held together by a central bolt and are aligned by four evenly spaced rods. The impactor is mounted on a hi-vol sampler. An 8- by 10-inch filter mounted on the hi-vol sampler is the back-up filter for the impactor. Figure 4-11 shows the collection efficiency of the hi-vol Andersen impactor operated at 20 ft^3/min over the particle size range of 0.75 μm to 8 μm.
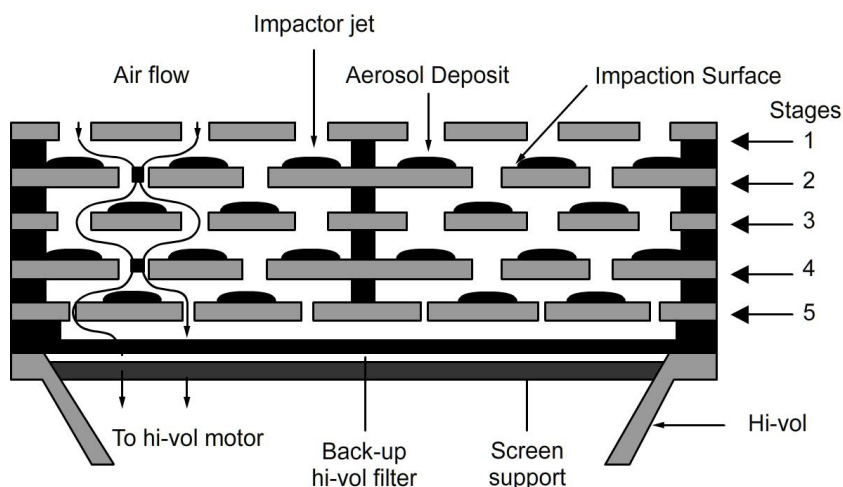

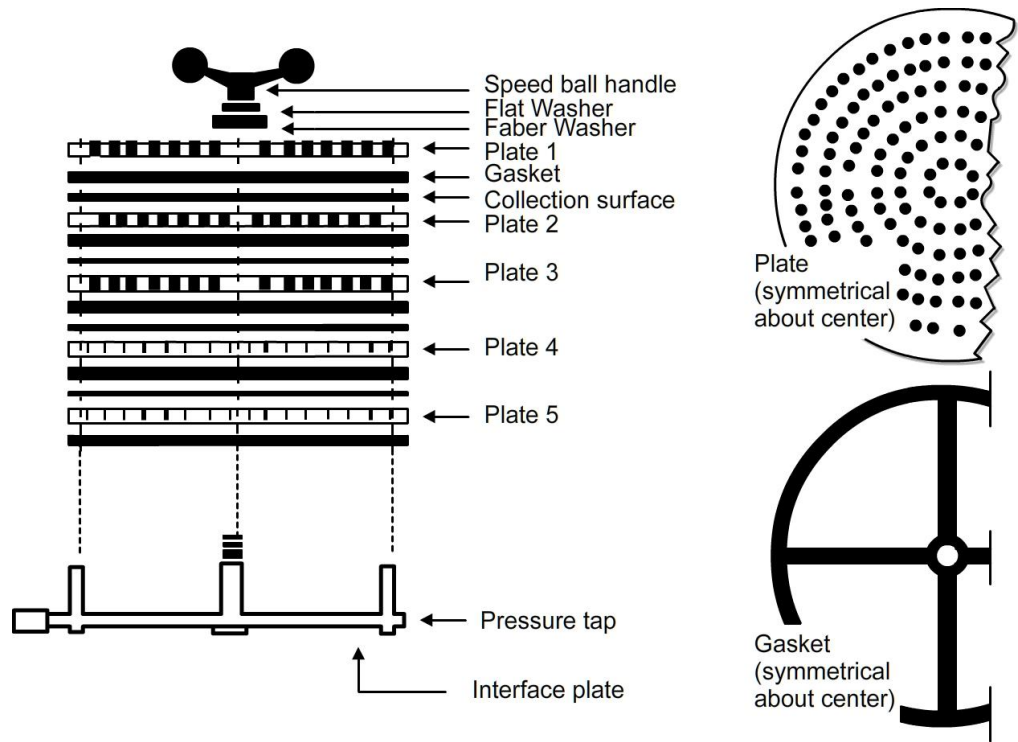**Figure 4-9. Cross-sectional view of a hi-vol Andersen impactor.**

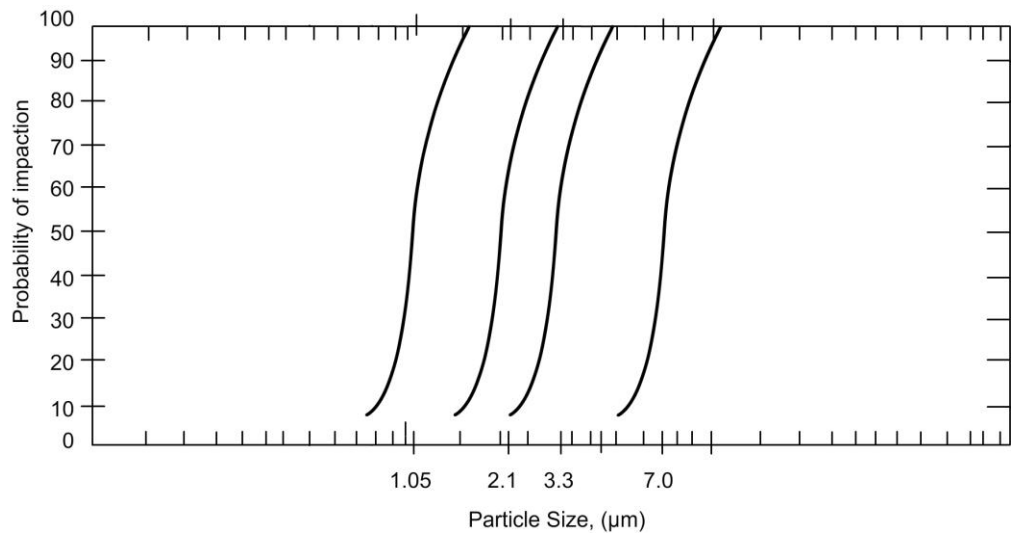Figure 4-10. Expanded view of a hi-vol Andersen impactor.

Figure 4-11. Collection efficiency of a hi-vol Andersen impactor operated at 20 cfm.

Multiple-Slit High-Volume Cascade Impactor

Another high-volume cascade impactor utilizes a typical high-volume sampler with an adapter comprised of six stages with successively smaller slit openings. Behind each slit is a filter for retaining particles. The sixth stage of this impaction device uses a typical hi-vol filter for collection of small particles.

The air sample is drawn through the slits and collection filters (Figure 4-12). The slits become increasingly narrower, thus causing the velocity to increase at each stage so particles of decreasing size are impacted on each successive filter. The distance from the slits to the collection filter becomes smaller with each stage to increase the collection efficiency. This impactor incorporates the advantage of hi-vol sampling (high flow rate [1.13 m^3/min, 40 cfm] and, therefore, large sample size) and the advantage of impactor sampling (particle sizing).
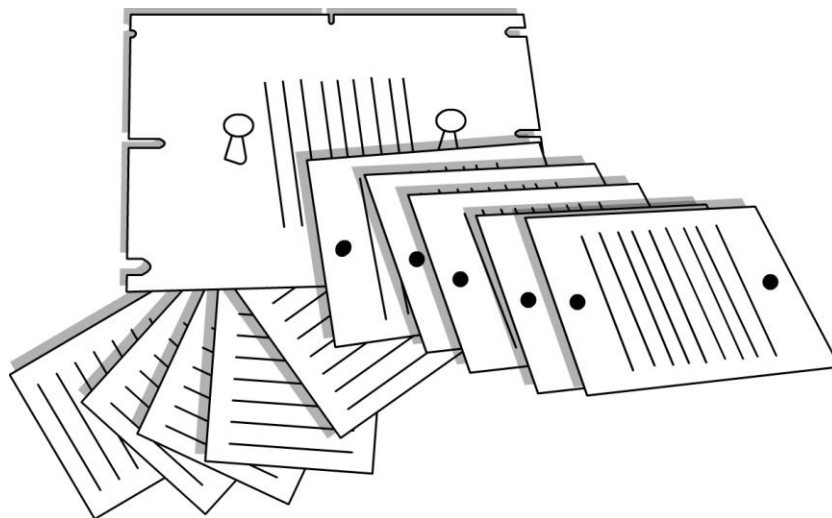
Figure 4-12. Multiple-slit high-volume cascade impactor.

Automated Cascade Impactor

Cascade impactors that provide somewhat real-time particulate matter concentrations have been developed by using oscillating quartz crystals as impaction surfaces. Particles impacting on the crystals cause their oscillation frequencies to change. The amount of change in frequency of a crystal is proportional to the mass of the particles collected on the crystal. Therefore, this relationship can be used to measure particle concentration. However, the proportional relationship is only valid over a certain frequency range and depends on the physical characteristics of the particles collected (e.g., dry versus sticky). One such impactor is depicted in Figure 4-13. It provides concentration measurements for particles in ten size ranges (from 0.5 to 35 μm) by using ten impactor stages, each having an oscillating quartz crystal that is connected to the sampler's electronic display.
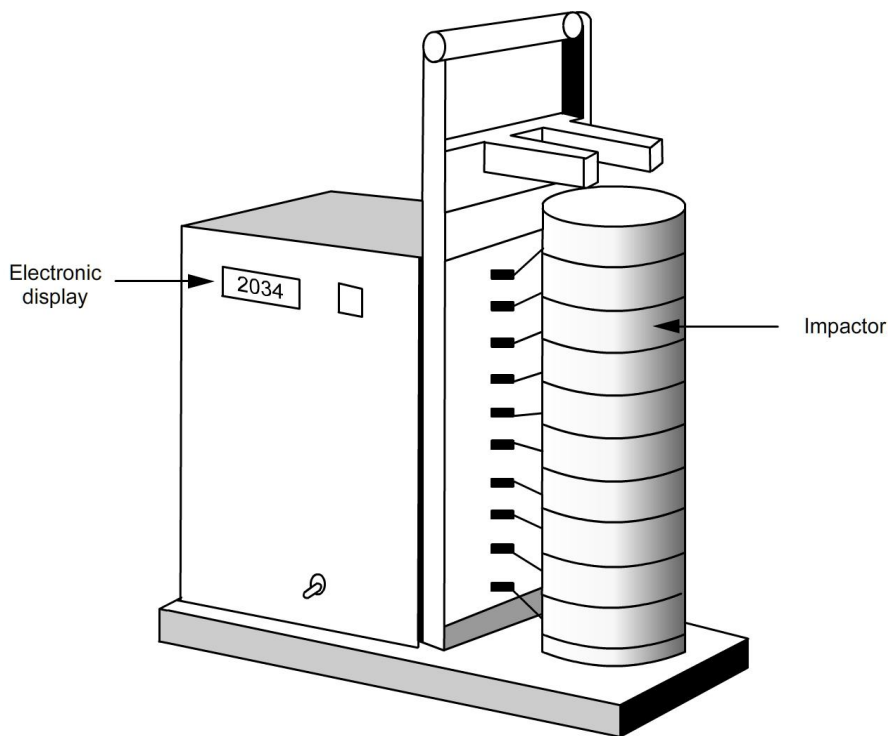
Figure 4-13. Quartz crystal cascade impactor.

PM$_{2.5}$ Inertial Particle Size Separator
EPA's Federal Reference or Federal Equivalent Method (FRM or FEM) sampler for PM$_{2.5}$ provides for the measurement of the mass concentration of particulate matter with an aerodynamic diameter less than or equal to a nominal 2.5 μm in ambient air over a 24-hour sampling period. A Well Impactor Ninety-Six (WINS impactor) configured in EPA-approved samplers is an EPA FRM for sampling PM$_{2.5}$ (see Chapter 5 for FRM and FEM designation criteria). In 2006, the EPA approved the Very Sharp Cut Cyclone (VSCC) as a FRM alternative to the WINS impactor when used in EPA-approved samplers. The FRM sampler pulls ambient air at 16.67 lpm into a specially-shaped inlet and through a WINS impactor or VSCC, where the suspended particulate matter in the PM$_{2.5}$ size range is separated for collection on a polytetrafluoroethylene (PTFE) filter, also known as a Teflon® filter. Figure 4-14 shows the inlet of the sampler, which only allows for the collection of particles less than 10 μm. Figure 4-15 illustrates the WINS particle impactor and filter holder assembly. The well of the assembly contains a 37 mm diameter glass fiber filter that is immersed in 1 mL of low volatility, low viscosity diffusion oil. The oiled glass fiber filter helps remove particles between 2.5 and 10 μm in diameter by preventing the bouncing of the incoming particles off the loaded impactor. Oil used in the WINS impactor can crystallize in cold environments, therefore allowing particles greater than 2.5 μm to collect on the PTFE filter.

Ambient
Air Flow

Flow to WINS Impactor
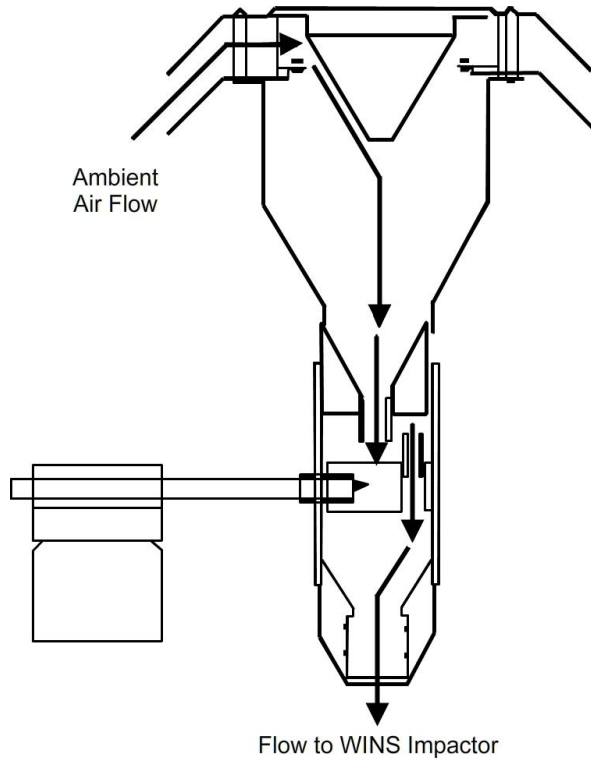
Figure 4-14. Inlet of PM$_{2.5}$ inertial particle size separator.

From Aerosol Inlet

Impactor Nozzle

Fine
Particles
≤2.5 µm
Collected on
PTFE Filter

Impactor Well

Coarse Particles, >2.5 µm
Collected on
Glass Fiber Filter with Oil
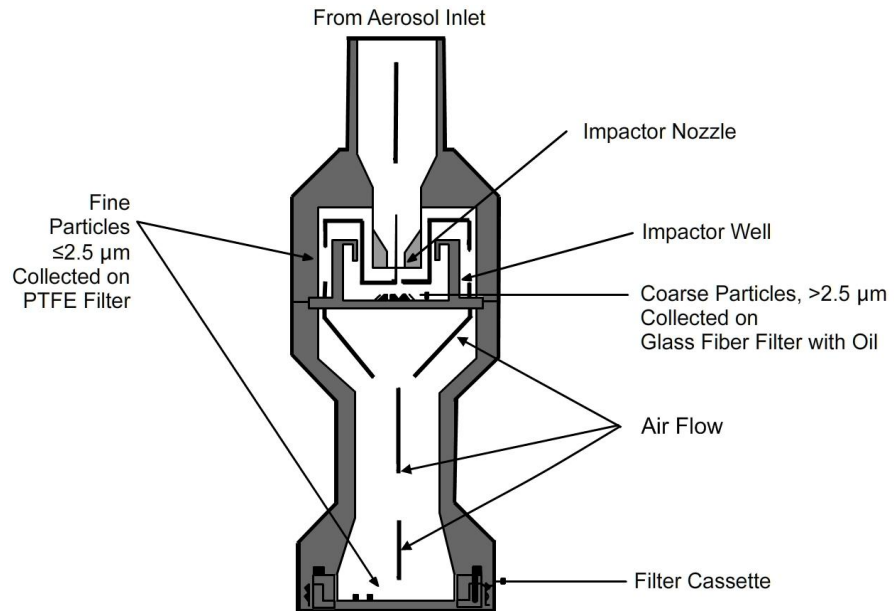
Air Flow

Filter Cassette

Figure 4-15. WINS particle impactor and filter holder assembly.

Impingement Devices

Impingement devices differ from impactors because the jet and striking surface are immersed in a collecting fluid such as water. The particles that are removed from the aerosol stream are wetted by and retained in the fluid. Most impingers in use are variations of the instrument developed by Greenburg and Smith (Balzer 1972). The Greenburg-Smith type of impinger consists of a glass cylinder with a small concentric glass tube insert. A glass jet and impingement plate are attached to one end of the tube, which is immersed in the collecting fluid. These impingers collect a sample at flow rates of about 0.1 to 1 ft^3/min.

Impingers are most commonly used in collecting dusts, mists, and fumes in the evaluation of occupational health hazards. In addition to collecting soluble gases and particulate matter, the Greenburg-Smith impinger efficiently collects insoluble particles that are greater than 2 μm in diameter.

Centrifugal Separation Devices

Centrifugal separation is a variation of the inertial collection process in which particles are removed from an air stream by the centrifugal force created by moving an aerosol rapidly through a circular path.
Several types of sampling devices employ the principle of centrifugal separation.

Cyclone Samplers

Cyclone samplers are small versions of the large cyclones used in air cleaning. The cyclone shown in Figure 4-16 contains no moving parts and is designed so that air drawn through it moves in either a circular or a helical path of decreasing radius, thereby increasing its collection efficiency for small particles. As the gas stream surges through the cyclone, particles are separated at the inside surface of the cyclone's wall where the gas velocity approaches zero due to the created centrifugal force. In most cyclone samplers, the particles adhere to the wall or drop into a collection space below the cyclone's chamber.

Most cyclones are not efficient collectors of particles, having diameters less than 2 or 3 μm, depending on particle density. However, small cyclones can be designed to collect particles below 1 μm in diameter. The collection efficiency of a cyclone sampler is strongly dependent on flow rate.
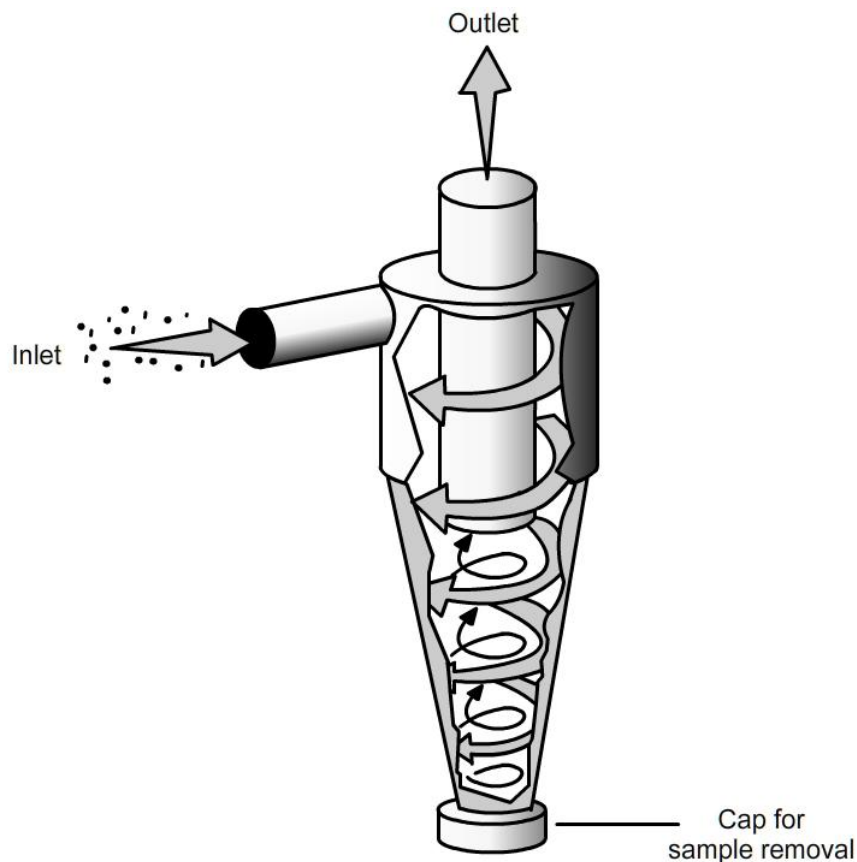
Figure 4-16. Cyclone sampler.

The Very Sharp Cut Cyclone (VSCC) $PM_{2.5}$ fractionator is a centrifugal separation device used to collect $PM_{2.5}$. The flow schematic of the VSCC is shown in Figure 4-17.

The VSCC can be used in place of WINS impactors in EPA-approved samplers, and obtained dual Federal Reference Method (FRM) and Federal Equivalent Method (FEM) status on December 18, 2006. Prior to this date, VSCCs used in these samplers were designated as a FEM (see Chapter 5 for FRM and FEM designation criteria). The VSCC $PM_{2.5}$ fractionator penetration efficiency is very similar to that of the EPA-designed WINS $PM_{2.5}$ impactor (Figure 4-18); however, no oil is used in the VSCC. Consequently, it is preferred over the WINS impactor in cold environments where WINS impactor oil can crystallize. Operation of the VSCC is limited to 30 days of operation between cleanings.
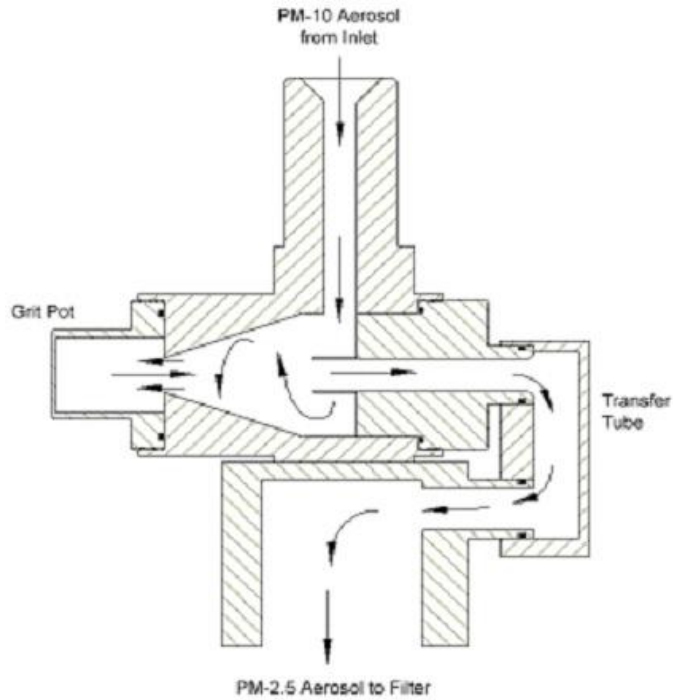
Figure 4-17. Flow schematic of VSCC PM$_{2.5}$ fractionator.
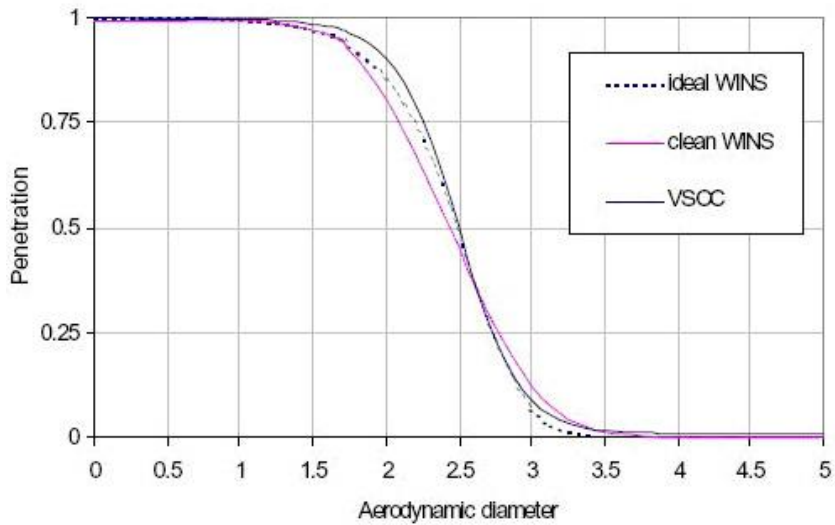
Figure 4-18. Penetration efficiency of VSCC PM$_{2.5}$ fractionator and WINS PM$_{2.5}$ impactor.

Virtual Impactors—Dichotomous Sampler

In the virtual impaction method, instead of the larger particles impacting onto a solid collection surface, they impact into a slowly pumped void and are later

collected on a filter downstream. Thus, these larger particles impact through a non-existent void, or virtual surface. As depicted in Figure 4-19, the smaller (fine) particles follow the streamlines of the faster flow (F_f); the larger (coarse) particles are impacted into the slower flow (F_c). A small fraction of the fine particles is impacted and collected with the coarse particles. This can be mathematically corrected when determining fine and coarse particulate concentrations.
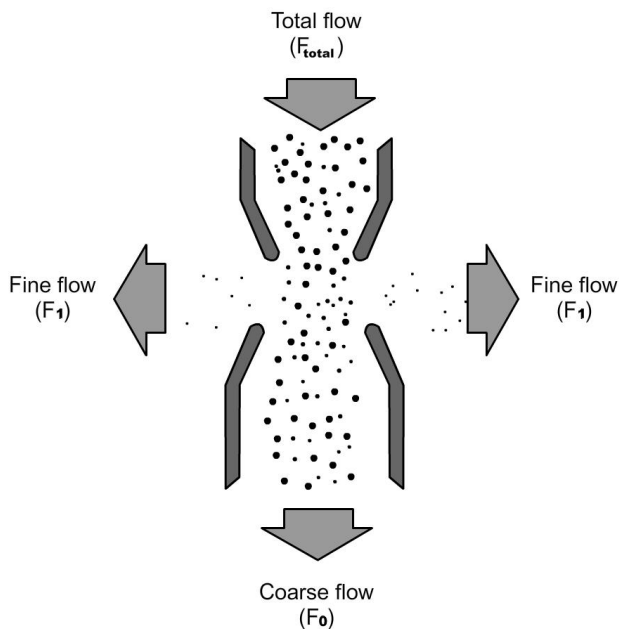
Figure 4-19. Schematic of virtual impactor.

The most recent use for virtual impaction has been in the EPA's efforts to develop a sampler that will separate and collect particulate matter both above and below a 2.5 μm aerodynamic diameter. These efforts have led to the development of the dichotomous sampler. As its name implies, the dichotomous sampler separates particles into two size ranges: fine particles (less than 2.5 μm aerodynamic diameter) and coarse particles (2.5 to 10 μm aerodynamic diameter), as shown in Figures 4-20 and 4-21. Dichotomous samplers use lower flow rates than other PM_{10} samplers and smaller PTFE (Teflon®) filters.
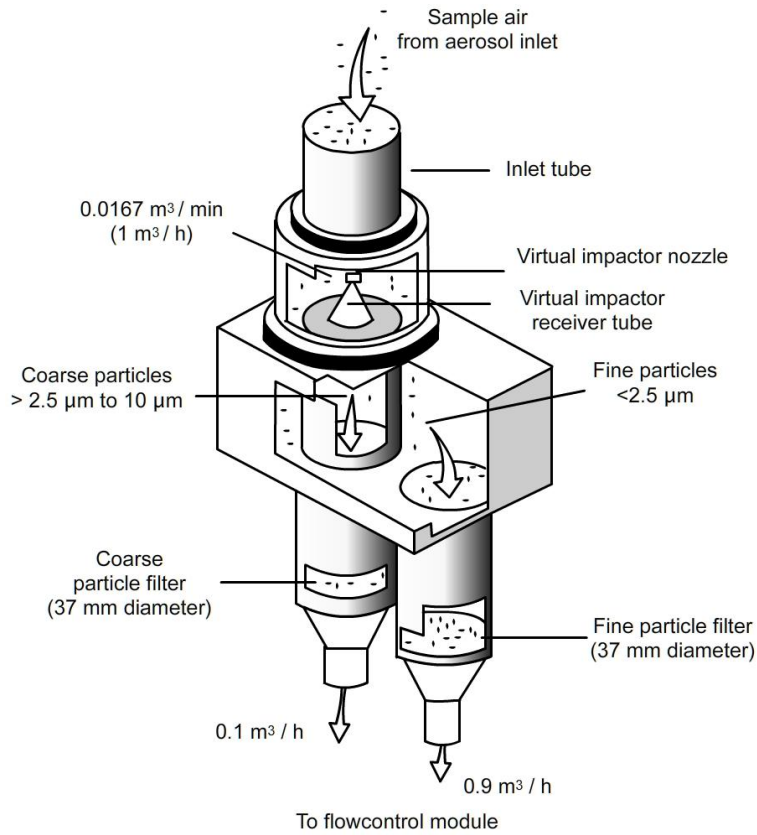
Figure 4-20. Diagram of the sampling module of a dichotomous sampler.
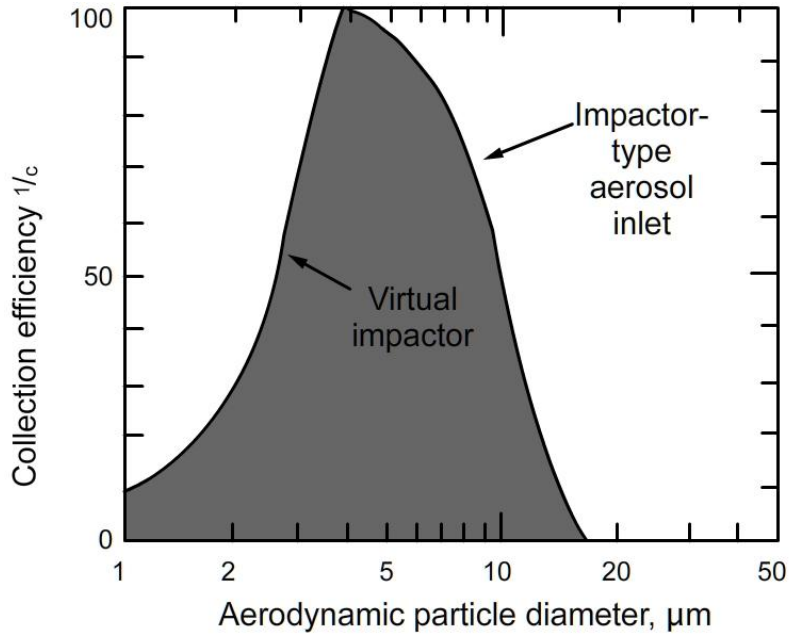
Figure 4-21. Collection efficiencies for a dichotomous sampler.

Virtual impactors have several advantages over conventional impactors:

- Problems associated with conditional impaction, such as particle bounce and reentrainment, nonuniform particle deposition, and cumbersome sample handling, are essentially eliminated.
- Uniform particle deposition onto the filters is ideally suited for photo-excited x-ray fluorescence (a nondestructive chemical analysis technique) and beta-gauge mass measurement.
- No grease or oil is needed to improve collection efficiency (this reduces potential sample contamination).
- Filters can be chosen to eliminate or minimize interferences.

Teflon® membrane filters are normally used to collect both coarse and fine particles because of the following advantages:

- Their collection efficiency for particles above 0.01 μm is greater than 99%.
- They have an extremely stable mass for high gravimetric accuracy.
- They have a negligible tendency to absorb or react with gases (therefore, low artifact formation of nitrate and sulfate).
- They contain minimal impurities to interfere with analyses for chemical and elemental species.
- They have low mass-per-unit area (desirable for gravimetric, x-ray fluorescence, and beta-gauge measurements).

However, these Teflon® membrane filters will not support themselves; therefore, they are bonded to a thin annular polyester ring.

Two aerosol inlets are available for providing 10 μm cut points (50% collection efficiencies) for dichotomous samplers. One type functions as a single-stage impactor (Figure 4-22). After entering the inlet and passing through a bug screen, particles in the sample air are accelerated as they pass through a nozzle to an impactor target module. Because of their momentum, particles having diameters greater than the inlet's 10 μm cut point impact onto the surface (target) of the impactor module. Smaller particles rise through the impactor module and pass to the virtual impactor of the dichotomous sampler. The other aerosol inlet uses a cyclone to remove particles having diameters greater than its 10 μm cut point from the sample air before the air enters the virtual impactor. Because of their symmetrical designs, both inlets are wind-direction insensitive. Also, wind speeds from 2 to 24 km/hr have a negligible effect on the cut point of both inlets.

Rain hat —

Particles all sizes

Bug
Screen

Impaction nozzle —

Particles > 10μm

Impactor
target module

Particles ≤ 10μm

To virtual
impactor
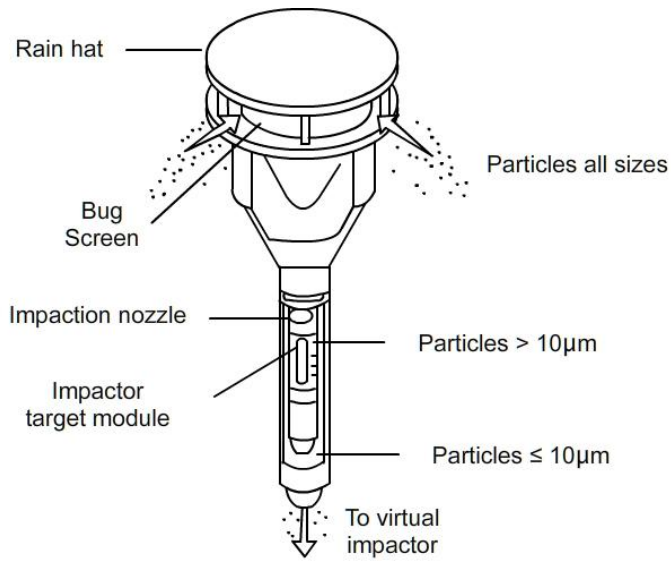
Figure 4-22. Impactor-type aerosol inlet for dichotomous sampler.

Figures 4-23 and 4-24 depict a manual dichotomous sampler. Samplers that automatically change fine and coarse particle filters at preset time intervals are also commercially available.

Sample inlet

Virtual impactor

Flow
control
module

Filter holders —

Connections
for flowcontrol
module
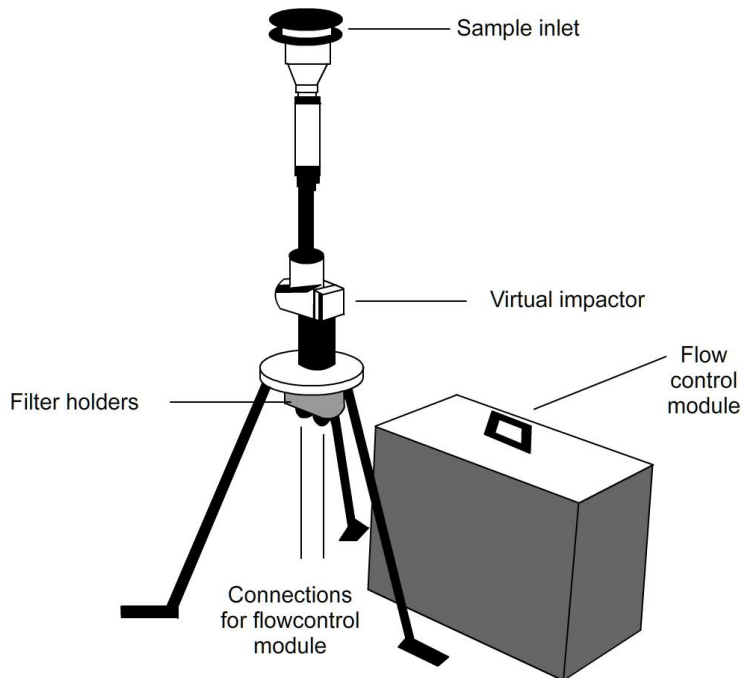
Figure 4-23. Dichotomous sampler.
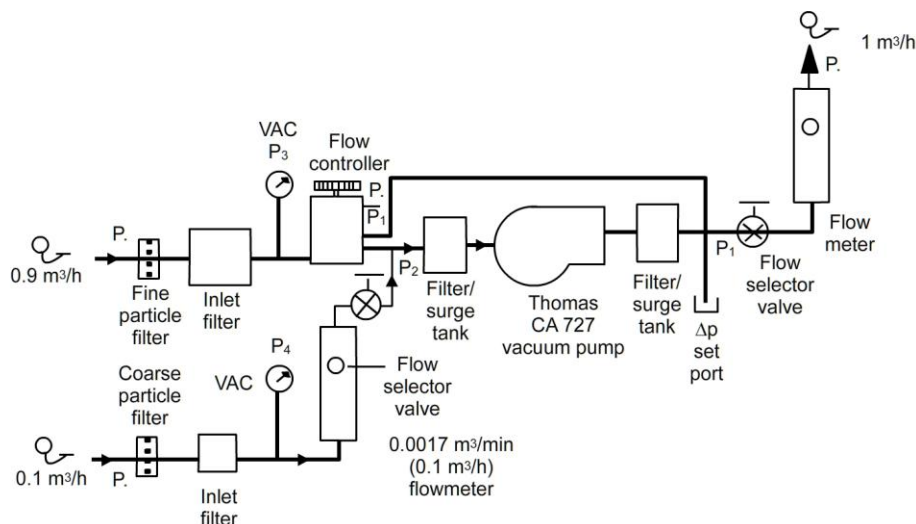
Figure 4-24. Flow schematic of dichotomous sampler.

4.3 Collection Efficiency and Penetration Efficiency of Inertial Sampling Devices

Though the principle is the same for all types of inertial sampling devices, the parameters associated with collection efficiency are somewhat different for the basic single-stage or cascade impactor than for the air centrifuge or cyclone. The discussion in this section is confined to the jet type of impactor, and this discussion may not be applicable to other types without modification. In this section, discussions of particle size refer to the aerodynamic diameter or Stokes diameter, unless otherwise stated. The aerodynamic diameter is the diameter that a unit density particle of spherical shape would have if it behaved the same as the particle being studied. The Stokes diameter for a particle is the diameter of a sphere that has the same density and settling velocity as the particle being studied. The collection efficiency of an impaction device is a function of several parameters (discussed later in this section).

Definition of Collection Efficiency and Penetration Efficiency
The collection and penetration efficiency of an impaction device can be described by the ratio of the number of particles striking an obstacle to the number that would strike if the stream lines were not deflected.

For the purposes of this discussion, collection efficiency will simply be defined as the fraction of the particles in an incident aerosol stream that is retained on the collection surface of the sampling device. Penetration efficiency will be defined as the fraction of the particles in an incident aerosol stream that passes through the collection surface of the sampling device. Essentially, collection and penetration efficiencies are opposites.

The collection efficiency of impaction can be plotted as a function *I*, the

inertial impaction parameter, to give a collection efficiency curve for an impaction device. Collection and penetration efficiencies can be calculated for individual devices such as the WINS and VSCC (Figure 4-18), and for multi-stage devices such as the Andersen sampler (Figure 4-8) and high-volume Andersen sampler (Figure 4-11).

Impactor Performance Characteristics

Instead of plotting efficiency of impaction against *I*, it can be plotted against particle size for a given device, since *I* is a function of particle size and several other parameters. The efficiency of impaction when plotted against particle size follows a sigmoid (or S-shaped) curve, such that there is a minimum size below which no particles are collected and a maximum size above which all particles are collected. For a well-designed impactor, the range between these two sizes is sufficiently narrow that a functional size separation is made. The most effective way to describe the ability of an impactor stage to separate particle sizes is to show the efficiency of collection as a function of size.

Properties of Aerosols Affecting Inertial Collection Efficiency

For a given collection device, several properties of the *aerosol* affect the efficiency of collection:

Particle Size

For any device there is a minimum particle size below which no particles are collected and a maximum particle size above which all particles are collected or removed from the sampling stream. Above 50 μm, some particle loss occurs by impaction on the walls of the sampling device. Particles and droplets greater than about 200 μm are seldom found on the sample collection area because they are shattered or lost on the walls of the device. Particles below about 0.5 μm in diameter are difficult to collect with impaction devices because their momentum is not appreciably different from that of the air. Consequently, under many sampling configurations, particles in this size range are able to deflect obstacles in a similar manner as air molecules. Most impacting devices have a high collection efficiency for particles with diameters greater than 0.5 μm. Collection efficiencies of nearly 100% are claimed for several impaction devices for particles in the size range from 0.5 to 10 μm.

Particle Density

Impaction devices are efficient collectors of high density particles; they have been used to selectively sample work atmospheres of plutonium dusts. Sub-micrometer particles of high density can be efficiently collected, since they are equivalent to unit density particles of much greater size.

Aerosol Fluid Properties

The physical properties of the gas in which the particles are dispersed will affect the collection efficiency of an inertial collector. For example, any factor which affects the gas's viscosity, such as temperature, will in turn affect the collection efficiency.

Properties of the Collecting Device Influencing Collection Efficiency
Impactors and impingers are designed for sampling a variety of aerosols. Collection efficiency for a particular aerosol can be optimized by design considerations.

Jet Size
The impaction jet size will influence the collection efficiency by affecting the velocity with which the incident air stream strikes the collection surface. As jet size decreases, the impaction velocity increases, as shown in Equation 4-1.

(Eq. 4-1) $$v = Q/A$$

Where: v = *air velocity*
   Q = *volumetric flow rate*
   A = *cross-sectional area of the air stream*

   In a multi-stage impaction device, jet velocities range from several meters per second in the first stage to greater than 50 meters per second in the last stage. The corresponding jet cross-sectional areas range from about 70 mm^2 in the first stage to less than 5 mm^2 in the last stage in a typical multi-stage impaction device.
   Multi-stage impaction devices are available at a variety of flow rates. Flow rate and design characteristics will greatly influence the collection efficiency of an air sampling device.

Jet Shape
Studies of impaction efficiency showed only small differences in collection efficiency between round and rectangular jets.

Jet to Collection Surface Distance
The distance between the jet opening and the collection surface controls the degree of deflection of the aerosol stream. By decreasing the distance between the jet and the collection surface, the angle of deflection of the aerosol stream is increased. A large deflection angle is required to remove the smaller particles from an aerosol stream. In the common cascade impactor with a single jet at each stage, the distance from the jet to the collection surface is decreased at each successive stage.

Collection Surface
Detailed studies of collection efficiency as a function of the shape of the collecting surface have been performed for spherical, cylindrical, and flat surfaces with round and rectangular shapes. For most applications, flat collection surfaces are used because particle retention is greatest on these surfaces and microscope slides are sometimes required in collections for particle size analysis.

4.4 Limitations and Sources of Error in Inertial Collection

Inherent Errors in Sample Collection

Inertial impaction is the dominant particle collection method in collection-plate and filter-based samplers. Although inertial impaction is widely used, there are several inherent sources of error in the impaction process that should be understood by individuals involved with the sampling and analysis of PM. These limitations are discussed below.

Particle Shattering

Large particles (greater than 200 μm) and agglomerates are readily shattered upon impaction, and, at the high velocities attained in some impaction devices, particles with diameters as small as two or three micrometers can be shattered. In studies where the number of particles per unit volume of air is of interest, shattering of particles upon collection results in erroneously high results. In size distribution studies, there will appear to be fewer large particles and more small particles than actually exist in the aerosol.

Particle Bounce, Reentrainment of Particles, and Wall Loss

Particle bounce occurs when a particle strikes, but bounces off of the filter, collection plate, or another collected particle. If too much particulate matter collects on the sample collection surface, subsequent particles that are supposed to impact on collection surfaces may be lost by reentrainment when they strike particles already collected. Specifically, phenomenon called "ghost depositing" can occur when particles bounce off the collection area and are redeposited by eddy currents a few millimeters on either side of the sample. When aerosols containing mists or droplets are being sampled, care must be taken to avoid collection of too much material. If too many droplets are collected, they will merge on the collection surface. The individual drops will be lost for size analysis and some material may be lost by run-off.

At high impaction velocities, a small fraction of the particles collected may be reentrained in the air stream. This occurs most often with fragments of large particles that have shattered upon striking the collection surface. Some of the pieces of the shattered particles may be lost from the sample by impacting on the walls of the instrument. A few of the large particles may impact directly on the walls of the instrument and as a result are not collected. Generally, particle bounce, particle reentrainment, and wall loss lead to less than true concentration estimates of PM.

Limited Sample Quantity

The small quantity of sample collected also restricts the choice of analytical methods to those with high sensitivity. Care must be taken to preserve all sample material intact, since with only a few micrograms of sample, the loss of any particulate matter becomes significant.

Some types of inertial samplers, such as cyclones, are not so limited in this respect. Some of these can collect gram quantities of particulate matter.

Poor Particle Resolution for Size Analysis
Particles that collect close to and on top of each other will introduce error in concentration and size studies through the inability to distinguish between individual particles and clumps of particles when examined optically. However, if a representative portion of the collected material is properly remounted, these problems can be minimized.

Errors Associated with the Calibration of Collection Devices

All PM collection devices must be calibrated before obtaining particle size or mass distribution information. Specifically, the particle collection efficiency as a function of the desired parameter (e.g., size or mass) must be determined. One method of calibration is to determine empirically the collection efficiency in the laboratory. In this procedure, a known quantity of a monodisperse aerosol (a gas stream with only one size particle suspended in it) is passed through the impactor or other collection device at a manufacturer-specified flow rate. For cascade impactors, the amount of material collected on each stage is weighed. By varying the size of the monodisperse aerosol, the cut points for each collection device or cascade impactor stage can be determined.

Detailed studies of theoretical collection efficiencies for several types of impaction devices have been performed. The efficiency curves that have been derived for several types of impactors show varying agreement with experimental curves. These curves are usually given in terms of an inertial collection parameter or equivalent particle size such as the one in Figure 4-8. If a particular curve is to be used in a sampling application, the user should be satisfied that the curve is valid for that particular application. Most commercially available inertial samplers are provided with a curve of collection efficiency. In most cases, the methods used to obtain these curves will not be known to the user. Without specific knowledge of the manner in which the curves were obtained, care should be exercised in the application.

Errors in Sample Analysis

PM samples from inertial collection devices can be analyzed in several ways, ranging from simple gravimetry (weighing) to advanced chemical processes such as ion chromatography. The error associated with the analytical procedure should be considered in the overall error assessment of the sampling procedure. The information desired in an investigation may require the use of an inertial collection device, which in turn may limit the choice of analytical procedure. The reverse could also occur; i.e., the information desired, such as particle distribution, may dictate the use of an impaction device to collect the sample. One should be aware of the limitations and errors associated with each analytical procedure that is considered.

Size-Selective Inlets and Devices for Aerosol Sampling

As discussed earlier in this chapter, numerous size-selective inlets and devices are available for particulate matter sampling. A sampler inlet is the initial piece of

equipment where particulate matter enters the sampler. An example of a size-selective inlet is a PM_{10} hat placed on a high-volume sampler (Figure 4-25). This size-selective inlet has a similar collection efficiency curve as the VSCC and WINS, but with 50% collection at 10 μm. The VSCC and WINS are examples of size-selective devices for $PM_{2.5}$ (discussed previously). The particular choice of size-selective inlet and device is generally made based upon a number of concerns such as monitoring objective, particle size, and expected particulate matter concentrations. An excellent summary of available devices is addressed in the draft "EPA Guideline on Speciated Particulate Monitoring" (Chow 1997). Table 4-1 taken from this guideline shows the variety of size-selective inlets available, the inlet manufacturer, operating principle, the cut point, and flow rate, with selected comments.
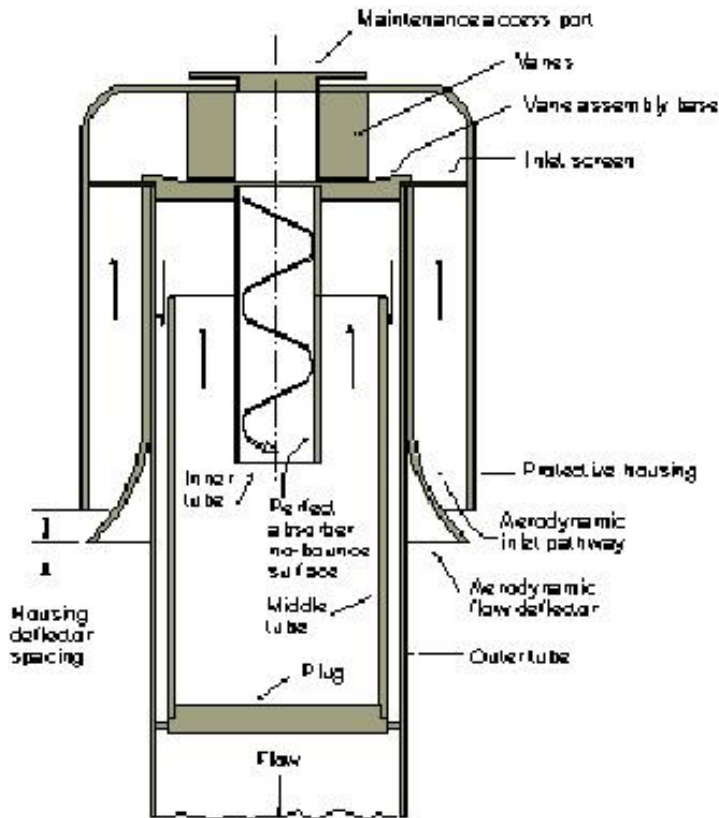
Figure 4-25. High-volume sampler with PM_{10} inlet.

Table 4-1. Size-selective inlets for aerosol sampling.

Inlet Identifier (Manufacturer)	References	Operating Principle	d50 (μm); Slope (no unit)	Flow Rate (L/min)	PM$_{10}$ Reference of Equivalence Reference No.	Comments
High-Volume SA[a] or GMC[c] Model 320 (Graseby Andersen, Atlanta, GA)	McFarland et al. (1980)	Impactor	15; 1.5	1,133	None	Single-stage, not greased shim.
SA or GMW Model 321A	McFarland and Oritz (1984); Hayes et al. (1988)	Impactor	10.2; 1.45	1,133	RFPS-1287-065	Two-stage with greased shim.
SA or GMW Model 321B	Hayes et al. (1988); McFarland and Ortiz (1987)	Impactor	9.7; 1.40	1,133	RFPS-1287-064	Two-stage with greased shim.
SA or GMW Model 1200	Purdue (1988); Wedding et al. (1988); Mathai et al. (1988); Hoffman et al. (1988); Hayes et al. (1988)	Impactor	9.7; 1.40	1,133	RFPS-1287-063	Single-stage with greased shim (body hinged).

GMW Wedding PM$_{10}$ (General Metal Works, Village of Cleves, OH)	Woods et al. (1986)	Cyclonic Flow	8.8; --	1,133	None	No inlet cleaning port.
Wedding IP$_{10}$PM$_{10}$ (Wedding & Associates, Fort Collins, CO)	Wedding and Weignand (1985); Woods et al. (1986)	Cyclonic Flow	9.6; 1.37	1,133	RFPS-1087-062	Inlet cleaning port on top of inlet.
Medium-Volume						
SA 254 Medium-Volume PM$_{10}$ Inlet	Olin and Bohn (1983)	Impactor	10; 1.6^d	113	RFPS-0389-071	Several small screws must be removed to clean.
Wedding Medium Flow PM$_{10}$ Inlet	Wedding et al. (1983)	Cyclonic Flow	9.5; 1.12	113	None	Has a cleaning port. Can use a bottle brush to clean.
Bendix 240 Cyclone (Sensidyne, Inc., Clearwater, FL)	Chan and Lippman (1977); Mueller et al. (1983)	Cyclonic Flow	2.5; 1.7	113	None	Plastic cup acts as a hopper to collect large particles

Low-Volume						
SA 246B	McFarland and Ortiz (1984); Van Osdell and Chen (1990)	Virtual Impactor	10.2; 1.41	16.7	RFPS-0789-073 EQPM-0990-076	Top unscrews to allow access to impaction surface.
Sierra-Anderson 224 and 245	McFarland et al. (1978); Olin (1978)	Virtual Impactor	2.5; --	16.7	None	Virtual impactor can be re-assembled backwards when taken apart for cleaning.
AirMetrics Inc. (Springfield, OR)	Chow and Watson (1996)	Direct Impactor	10; 2.5	5; 5	None	Nylon impactor needs to be cleaned and regreased after every 72 hours of sampling.
WINS (Well Impactor- Ninety Six)	U.S. EPA (1997b)	Direct Impactor	2.5; 1.18[d]	16.7	None	Inlet used in $PM_{2.5}$ FRM.
USEPA/HEAD Impactor	Koutrakis et al. (1990)	Direct Impactor	2.1; 1.08[d]	10	None	Oiled glass impactor needs to be replaced after every 24 hours of sampling.

Wedding TP$_{10}$	Wedding et al. (1982)	Cyclonic Flow	9.9; 1.32[d]	16.7	EQPM-0391-081	Plastic cap acts as a hopper to collect large particles.
Bendix Unico 18	Chan and Lippmann (1977)	Cyclonic Flow	2.5; 1.83[d]	18	None	
AIHL Cyclone (Air & Industrial Hygiene Laboratory, Berkeley, CA)	John and Reishcl (1980)	Cyclonic Flow	2.2; 1.87[e] 2.5; 1.38[e] 3.5; 1.40[e]	26.6 21.7 15.4	None	Screw-on cap acts as a hopper to collect large particles.
Stacked Filter Unit (Corning CoStar [formerly Nuclepore Corp.], Cambridge, MA)	Flocchini et al. (1981); John et al. (1983); Cahill et al. (1990)	Selective Filtration	2 to 3; --	10	None	Uses large pore (8μm) etched in polycarbonate filters.
BGI-4 (BGI Inc., Waltham, MA)	Blackman and Lippmann (1974); Hering (1995)	Cyclonic Flow	4; --	2.3	None	Generally used in personal sampling applications.
MSA (Mine Safety Appliances Co., Pittsburgh, PA)	Blackman and Lippmann (1974); Hering (1995)	Cyclonic Flow	3.5; --	2	None	Generally used in personal sampling applications.

Sensidyne Model BDX 99R (Sensidyne Inc., Clearwater, FL)	Blackman and Lippman (1974); Hering (1995)	Cyclonic Flow	3.5; --	1.7	None	Also known as Dorr-Oliver design. Generally used in personal sampling applications.
SKC Cat. No. 225-01-02 (SKC Inc., Eighty Four, PA)	Blackman and Lippman (1974); Hering (1995)	Cyclonic Flow	5; --	1.9	None	Generally used in personal sampling applications.
MST Low Flow Rate Sharp Cut Impactor (Harvard Impactor) (Air Diagnostic and Engineering, Harrison, ME)	Marple et al. (1987)	Direct Impactor	2.5; 1.02[d] 10; 1.11[d]	4, 10, 20 4,10	None None	Oiled aluminum impactor plate needs to be replaced after every 24 hours of sampling. Designed for use in indoor air pollution health studies.

a.   See Table 4-5 for Federal Register citation and notice date.
b.   Sierra-Andersen, Atlanta, GA.
c.   General Metal Works, Atlanta, GA.
d.   Slope $= \sqrt{d_{16}/d_{84}}$, as defined in text.
e.   Slope is estimated based on $\sqrt{d_{10}/d_{90}}$.
f.   Inlet for Modules A, B, and C of IMPROVE samplers.

4.5 Filtration Sampling

Introduction

Filtration sampling, which is actually a combination of filtration/impaction sampling, is the most widely used approach for the collection of atmospheric particulates. Filter-based sampling methods are widely used since filters are relatively low in cost, easily stored, and used for subsequent simple and/or complex analyses of collected PM.

Filters capture particles from an air stream by a number of different mechanisms. These mechanisms include inertial impaction, direct interception, diffusional deposition, electrical attraction, and gravitational attraction. The predominant mechanism depends on the flow rate, the composition and nature of the particles, particle size, and the type of filter media.

Topics to be discussed in this section include the basic advantages and disadvantages of air sampling with filters, filtration theory, and some of the criteria necessary for the selection of a filter medium to be used in a specific sampling program. Although the term "filter media" can be extended to cover a large number of media, such as glass fiber, quartz fiber, Teflon®, filter thimbles, and granular beds, this discussion will be confined to the more common media used for particulate matter sampling.

General Considerations

Advantages

Filter sampling for particulate matter has several advantages over other methods. A primary one is the feasibility of handling large volume rates of flow. Some dust sampling instruments, such as midget impingers and thermal precipitators, do not have this capability for large flow rates. Also, after collection, the filtered sample is usually readily available for direct observation.

The number of sizes of filters available has proved to be another advantage. By changing the size of the filter media, the volume of air samples can be varied while maintaining the same linear flow rate through the filter. The selection of sizes also allows filter borders to be designed for use in a variety of situations. This is a definite advantage when the sampling space confines limit accessibility. The variability among filters extends beyond the matter of size alone. Appropriate filters can be obtained that are capable of sampling a wide range of environmental conditions of temperature, humidity, and dust loadings. Further, filters can be found that are adaptable to analysis schemes ranging from microscopic examination to elaborate chemical separation schemes.

Disadvantages

The use of filter media for sampling is not without its difficulties. One disadvantage is related to the variation in physical and chemical properties of filters in any given filter type. In the case of an impaction instrument, once its operating characteristics have been determined, these should remain relatively

fixed. On the other hand, in sampling with filters, the media is changed between each sample collection. Although filters that minimize the variability between individual filters of a specific type can be obtained, it is more common to find some differences in performance, particularly between different lots of filters.

Another case in which filters are at a disadvantage is in conjunction with selective particle sizing. A cascade impactor can be designed so that particles of different size ranges can be collected on different stages of the impactor. Such a size separation cannot be done with filter media, although some gradations are possible.

The Theory of Filtration

The most common misconception about air filtration is that it is primarily a sieving mechanism. If this were the case, only particles larger than the pore size would be trapped and the theory of collection would be relatively simple. Actually, except for the kitchen strainer, very few media could be classified as pure mechanical strainers. In air filtration, a number of mechanisms contribute to the collection of particulate matter. The degree to which each one contributes is a function of a number of parameters, discussed below. For a more complete discussion of filtration theory, see R. D. Cadle's book, *The Measurement of Airborne Particulates* (Wiley-Interscience, 1975).

Diffusion

Diffusion is defined as the irregular movement of particles suspended in a fluid, where the fluid is ambient air. The collection of particles on a filter by diffusion depends on a particle concentration gradient between the filter and the air passing between the fibers. The highly concentrated particles in the air stream diffuse to the filter fiber where the concentration is near zero. The diffusion theory further postulates that when the particle comes in contact with the filter, it remains there. The contribution made by diffusion depends on the transit time of particles through the filter, with a longer time resulting in greater diffusion contribution. The amount of diffusion will then depend on linear rate of flow, filter thickness, size of particle, inter-fiber distance, and particle concentration in the air.

Direct Interception

Direct interception is the part of the filter collection mechanism that is analogous to mechanical straining. The interception mechanism takes place when a particle following its air movement streamline comes within a distance from the filter material which is equal to, or less than, the particle radius, so that it comes in contact with the filter medium. As with simple straining, this type of collection predominates where the particles are greater in diameter than the inter-fiber distance, or pore size. The effectiveness of direct interception increases with increasing particle size.

Inertial Collection

As a particle is carried by an air stream, it possesses a certain amount of inertia, depending on its mass and velocity. When a sufficient inertial force has been established, the particle will, as the air stream turns, leave its streamline and

continue on its previous path. If the inertia of a particle causes it to strike a filter fiber during the passage of the air stream around the fiber, the particle will be collected. The mechanism of inertial collection plays a major part where high linear velocities of airflow are present. Increasing the particle size and decreasing the fiber diameter (or pore diameter) improves the effect of inertial collection.

Electrical Force
If the aerosol particle has an electrical charge, and the filter fiber has a charge of opposite sign, the particle will be attracted to the filter media. Many investigators believe that such a mechanism has a part to play in the filter sampling of air. Experiments have indicated that both atmospheric particles and filter media possess electrical charges, and that collection does occur by this means. The magnitude of the effect is not well known, but it probably does contribute to the process of collecting particles smaller than the pore size.

Combined Factors
During actual filtration, all four of the above-mentioned collection mechanisms are working together so that it is often difficult to separate one from another. Furthermore, other mechanisms occur that complicate the situation. All four of the methods of collection that have been discussed postulate that once a particle touches the filter material, it stays there. This is not entirely so — there is some reentrainment of particles resulting from the airflow through the filter, picking up and carrying material that has been previously deposited some distance before the particles are once more entrapped by the filter fibers. Increasing the filter face velocity (the velocity across the face or surface of the filter) will increase the chances of reentrainment. All of the above mentioned collection mechanisms result in the accumulation of PM on the filter.

Collection Efficiency of Filters
In the sampling of air particulate matter by filtration, not all particles in the air are collected. That is to say, the collection mechanisms that have been discussed are not 100% efficient. It is, therefore, not sufficient just to know what volume of air was passed through the filter. The fraction of the airborne particles collected must also be known. Collection efficiency may be stated in terms of several parameters. The most common is to determine the *percent penetration* (percent passing through the filter) of a certain particle size as a function of the linear velocity (volume rate of flow divided by the filter area) through the filter. Another way of presenting the efficiency would be to have *percent collection* of a certain particle size as a function of linear velocity through the filter. Percent penetration and percent collection efficiencies are useful in laboratory settings with known particle size distributions; however, they are difficult to use for ambient air since particle size distribution information is rarely known outdoors.

There is one other type of filter collection efficiency reported in literature. This is a *mass collection efficiency* based entirely on the percentage of the mass of the airborne particles that is collected. This can be grossly misleading because the small particles predominate in number, and yet, constitute a minor fraction of the total particulate matter mass. The only time a mass collection efficiency would represent a total particle collection efficiency would be if all the particles were of

the same size.

Theory of Collection Efficiency

Before continuing the discussion of collection efficiency, it is necessary to discuss the theory of collection efficiency for the various collection mechanisms previously mentioned, and also, the effect of various parameters on collection. Figure 4-26 shows a qualitative picture of the theoretical percent penetration versus linear velocity that might be expected for a given filter and an aerosol with a specific size particle. By referring to this graph, and the associated notes, the interrelation of the various mechanisms can be examined.
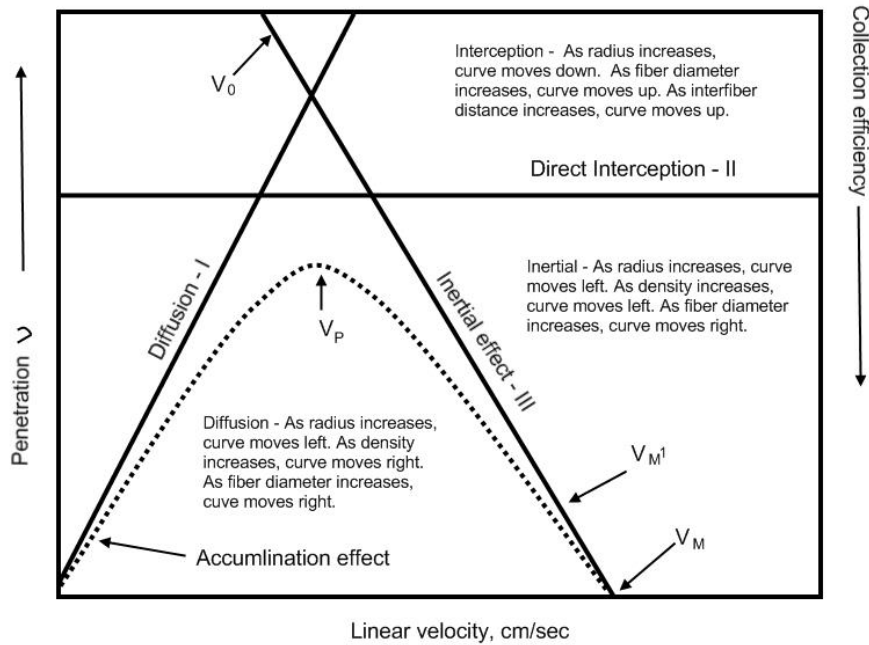
Figure 4-26. Filtration mechanisms.

Diffusion Efficiency. The diffusion line I of Figure 4-26 shows how the diffusion mechanism is affected by linear velocity. As the velocity increases, the diffusion mechanism decreases. As previously mentioned, this is due to the shorter transit time through the filter at the higher flow rates. The diffusion function always passes through the origin, but the slope varies with the particle radius, the filter fiber diameter, and the distance between filter fibers.

As the particle radius increases, the slope becomes greater, thus resulting in a reduced diffusion effect for a given linear velocity. This is because larger particles are not as readily affected by diffusion mechanisms as are smaller particles.

The effects of fiber diameter and inter-fiber distance are quite similar. As either of these two parameters increases, the influence of the diffusional mechanism increases and the slope of the line decreases. A greater fiber diameter increases the diffusion effect because, for a given linear velocity, the particle spends a longer time passing by a filter fiber. The effect of inter-fiber distance is

similar, as it too affects the transit time of the particle by a filter fiber. The greater the open space in the filter is, the larger the inter-fiber distance. Therefore, for a given overall linear velocity, the velocity in the open space of the filter is less for larger inter-fiber distance, and transit time is longer.

Direct Interception Efficiency. As previously mentioned, direct interception is analogous to simple mechanical straining. Direct interception is shown in line II of Figure 4-26. It shows that there would not be any effect by changing linear velocity on this collection mechanism.

The effects of the particle radius and inter-fiber distance on the interception mechanism are quite simple. As the particle radius increases, the percent penetration decreases, as would be expected for straining. As inter-fiber distance increases, the percent penetration increases for a mechanical straining.

The relation between particle penetration and fiber diameter for interception is somewhat more involved. As the fiber diameter increases in size, the air flowlines are affected at an increasing distance upstream from the fiber. This may cause some of the flowlines to diverge from a path that would have brought the particle within contact distance of the fiber. Therefore, as the fiber diameter increases, the collection efficiency due to interception decreases.

Inertial Effect Efficiency. The inertial collection of particles depends on the particles leaving their air flowlines and contacting a filter fiber due to their inertial forces. For a particle of a given size, this effect would start to show at some velocity, V_P, and would reach a maximum at some greater velocity, V_M. The fact that the effect increases with velocity is due to the dependence of inertial forces on both mass and velocity. Although Figure 4-26, line III, shows a zero percent penetration for this mechanism at V_M, the penetration might be significant, depending on the inter-fiber distance. If a larger inter-fiber distance existed, the maximum effect might occur at some point V_{M1}, in which case a definite amount of penetration would occur.

The effect of increasing particle radius in inertial collection is improved collection for a given linear velocity. This is related to the fact that the larger the particle, the greater the probability of it coming within a distance from the filter fiber where it will make contact. Table 4-2 lists the collection efficiency of some filter media as a function of particle size.

The effect of increasing particle density also improves inertial collection. Like the effect of velocity, this is due to the increase of inertial forces, thus causing greater deviation from the air flowlines.

As the filter fiber diameter increases, the effect of inertial collection decreases. With the air flowlines being affected at a greater distance upstream from the fiber, the change in their trajectory is much more gradual and, therefore, the tendency of inertial forces to cause a particle to leave a flowline is less.

Table 4-2. Collection efficiency of commonly used filter types for particles > 0.3 μm diameter.
Measurements made via Royco particle counter.[a]

Collection Efficiency (%) for Commonly Used Filter Types										
			Particle Size (μm) in equivalent diameters							
Filter	Size (mm)	No. of trials	0.32	0.4	0.5	0.64	0.8	1.0	1.3	1.6
0.8 μ Nucleopore	47	1	82	96	99	99	100	100	100	100
5.0 μ Nucleopore	90	1	83	95	98	97	98	100	100	100
3.0 μ MF millipore (SS)	90	3	99.93	99.98	100	100	100	100	100	100
5.0 μ MF millipore (SM)	47	1	100	100	100	100	100	100	100	100
5.0 μ MF millipore (SM)	90	1	100	100	100	100	100	100	100	100
5.0 μ Teflon® millipore (LS)	90	1	99	99.6	100	100	100	100	100	100
8.0 μ MF millipore (SC)	47	1	96	99	99	99	96	99	100	—
10 μ Teflon® millipore (LC)	90	1	96	99	99	99	100	100	100	100
1.2 μ Silver membrane	47	2	99.9	100	100	100	100	100	100	100
S&S 0.45 (B6A) cellulose acetate	47	1	100	100	100	100	100	100	100	100
Gelman GA-1 cellulose acetate	47	1	99	100	100	100	100	100	100	100
Glass fiber filters										
Gelman A	47	2	99.8	99.8	99.6	99.7	99.1	99	99	97
Gelman A	25	1	100	100	100	100	100	100	100	100
Gelman A acid washed	25	1	99.9	100	100	100	100	100	100	100
Reeves angel # 900 AF	47	1	99.9	100	99.9	100	100	100	100	100
MSA 1106 BH	47	1	100	100	100	100	100	100	100	100
S&S #25 acid washed	47	3	26	53	65	64	69	71	79	88
TFA[b]	47	2	38	67	80	81	83	85	84	87
Whatman 41	47	1	63	83	90	84	89	81	94	100
S&S green ribbon #559	47	1	69	84	88	87	93	98	97	100

a.   Face velocity in cm/sec for 25-, 47-, and 90-mm filters is 0.82, 0.31, and 0.11, respectively.

b.   After sampling 500 ft³ of room air, the filtration efficiency of TFA increased to 90% for 0.3 μm particles with other values in the range of 80 to 90% for sizes up to 1.6 μm. This efficiency was not significantly altered by discharging the filter over a radioactive source.

Overall Efficiency. In filter sampling, all of the collection mechanisms are taking place simultaneously and their effects are algebraically additive. The overall relation between percent penetration and linear velocity might well look like the dotted line in Figure 4-26.

From this overall efficiency curve, there appears to be some velocity, V_P, where a maximum penetration occurs. It should be pointed out, however, that if the direct interception effect is dominant enough, the overall efficiency curve may well have a flat plateau, rather than a single velocity of maximum penetration.

The mechanism of electrical forces has not been covered in this discussion of the theory of collection efficiency. The degree to which it will change the overall efficiency is dependent on many factors. The theoretical aspect of this effect is beyond the scope of this discussion, but it may play an important part in overall efficiency in certain instances.

Experimental Collection Efficiencies
Several investigators have studied the actual collection efficiencies of filter media, and their results are reported in the literature (ACGIH 1985, Caroff 1973, Liu 1978, Ramskill 1951). A degree of caution must be exercised in utilizing this experimental data. A number of different types of particulate matter have been used, including dioctyl phthalate (DOP) smoke, atmospheric dust, duraluminum dust, radon daughter products, polystyrene aerosols, and lead fumes. The experimental results of the various investigators often appear to be in great disagreement for many of the filter media, and these differences should be evaluated in selecting an efficiency value to use.

One additional complicating factor should be mentioned in relation to filter efficiency. During the time that the sampler is running, the increasing amount of particles that accumulate on the filter will cause the collection efficiency to improve as sampling continues. This is due to the adherence of particles on previously collected particles, commonly known as the filter cake effect. As this occurs, however, filter cake thicknesses that are too large can increase the resistance of the filter and thus decrease the collection efficiency. The decreased collection efficiency for large cake thicknesses can result from clogging the filter, particle bounce, and other escape mechanisms. When the filter cake is too thick, the high resistance across the filter can lead to a reduced flow rate. Most pumps currently used at monitoring locations are able to compensate for typical sample loading resistances (i.e., pressure drop associated with the buildup of the filter cake), and thus maintain desired flow rate.

Characteristics of Filter Media
A great number of individual types of filter papers are available. For particulate matter sampling, in general, they fall into four main categories: cellulose fiber, glass fiber, mixed fiber, and membrane filters. These various categories will be discussed in terms of their general characteristics, sampling considerations, and analysis considerations. (See Table 4-7 at the end of the section.)

Cellulose Fiber Filters

The filter papers in this category are typically called chemical filters. They were designed for use in "wet" chemistry where liquid-solid separations were desired. Although not designed with air sampling in mind, a number of these filters have seen extensive application in this area (see Table 4-3).

Table 4-3. Cellulose fiber filters.

Filter	Void size (microns)	Fiber diameter (microns)	Thickness (microns)	Weight per unit area (mg/cm²)	Ash content (%)	Maximum operating temp. (°C)	Tensile strength	Flow resistance 100 ft/min (in. H_2O)
Whatman							1.67 kg/cm	
1	2+	—	130	8.7	0.06	150		40.5
4	4+	—	180	9.2	0.06	150		11.5
32	1-	—	150	10.0	0.025	150		38 (1 fm)
40	2	—	150	9.5	0.01	150		54
41	4+	—	180	9.1	0.01	150	1.41 kg/cm	8.1
42	>1	—	180	10.0	0.01	150		46 (28 1 fm)
44	>1	—	150	8.0	0.01	150		40 (28 1 fm)
50	1	—	100	10.0	0.025	150		49 (28 1 fm)
541	4+	—	130	8.2	0.008	150	2.24 kg/cm	—
S&S 604	—	—	200	—	0.03	80		8.5
MSA Type S	—	—	100.0		1.3	120		6.5
Cellulose	—	—	1000		1.3	120		
Corrugated	—	—						
Cellulose	—	—	1000		1.3	120		
MSA BM-2133			1830	32.7	0.12		0.58 kg/cm	9.1
IPC 1478	—	Av. 17	560-760	14.6	0.04	120	0.18 kg/cm	0.31
Gelman W-41	24							

Sampling Considerations. Cellulose fiber filters are made of purified cellulose pulp, which can easily ignite, thus rendering them ineffective at high operating temperatures. The low ash content of these filters makes them highly suitable to analysis where heat or chemical ashing is a required preparation. These filters generally have a high affinity for moisture. This limitation means that the relative humidity must be controlled while weighing the filters to ensure there is no error introduced by absorbed moisture. Recent studies show that cellulose filters irreversibly absorb water; thus, a control blank is required when humidity is a problem. Cellulose filters also enhance the artifact formation of sulfate and nitrate.

Specific Filters. Whatman 41 filter paper is the most widely used of the cellulose fiber filters. Whatman 41 has become the preferred substitute for glass fiber filters for high-volume sampling, because of its good collection efficiency and acceptability for further chemical analyses. It has also received wide use in all types of metals analysis, including neutron activation analysis, because of the low blanks or background levels of metals on the clean filters. This filter has also found applications as the tape used with paper tape samplers for the determination of soiling index.

The Mine Safety Appliances (MSA) type "S" filter is well adapted to high-volume sampling because of the low pressure drop associated with this technique. This filter is difficult to handle because of its bulkiness, and its variable ash content and organic binder make it unsuitable for some chemical analyses.

TFA filters have also been used for high-volume sampling when extensive chemical analysis is required. Whatman 41 is preferred over this filter because of the higher collection efficiency (see Table 4-2).

Glass Fiber Filters
These filter papers are made from finely spun glass fiber by combining the fiber with an organic binder and compressing this material in a paper machine. These filters have seen increasing use in air sampling.

Sampling Considerations. Glass fiber filters have the ability to withstand high temperatures (up to 540°C), thus making them most attractive for stack sampling. Quartz fiber filters, a subset of glass fiber filters, are able to withstand up to 1000°C. Consequently, quartz fiber filters are used in speciation samplers (discussed in Chapter 5) for the quantification of carbon by thermal-optical methods. Glass fiber filters are further typified by high collection efficiency. In some cases, the organic binder may interfere with subsequent analysis, so the filter is flash-fired to remove the binder material. This causes some loss in tensile strength and usually requires that a backing material be used during sampling. The glass filters are non-hygroscopic, thus allowing them to be used in areas where humidity is high. Being glass also makes them the filter choice for most corrosive atmospheres. All of the filters in this category are quite fragile and must be handled with care.

Analysis Considerations. Glass fiber filters, because of the high silicate content, are extremely difficult to ash by chemicals or heat. Therefore, extraction procedures are performed on these filters to remove the sample for subsequent chemical analysis. Overall, flash-fired glass fiber filters, because they are non-hygroscopic, can be used in corrosive atmospheres and are free of organic binders that are widely used for ambient air sampling.

The pH of the filter will affect the collection of the sample. It has been recommended that neutral pH (6.5 < pH < 7.5) filters be used because there is less absorption of acid gases onto the filter. Significantly different results can be obtained when sampling side-by-side with filters of different pH values.

Specific Filters. The MSA 1106 BH is one of the flash-fired glass fiber filters and, therefore, is free of organic binder. The Gelman Spectro Grade Type A Glass Fiber Filter is a neutral pH glass fiber filter rated as ultra-pure for metals analysis to minimize interference with trace metal background values. (Each box of 8- by 10-inch filters contains assay information on trace metals for the enclosed filters.) Spectro grade filters do not absorb detectable amounts of SO_2 from the atmosphere, thereby minimizing its effect. A summary of the physical characteristics of some commonly-used glass fiber filters is given in Table 4-4.

Mixed Fiber Filters
These filters possess the characteristics of the individual fibers composing them. The chemical analysis of mixed fiber filters also depends on the individual fiber constituents. General characteristics of a number of the members of this category are given in Table 4-5.

Table 4-4. Glass fiber filter characteristics.

Filter	Void size (microns)	Fiber diameter (microns)	Thickness (microns)	Weight per unit area (mg/cm²)	Ash content (%)	Maximum operating temp. (°C)	Tensile strength	Flow resistance 100 ft/min (in. H$_2$0)	Benzene extract/ 100 in.² (mg)
MSA									
1106B*			180-270	6.1	- 95	540	3.5 lb/in.	19.8	17.3
1106BH#			180-460	5.8	- 100	540	1.5 lb/in.	19.8	0.6
									0.6
Gelman									
A#			380	9.3	99.4	480		18.9	
E*			380	10.0	98.1	480		18.9	
G			810	11.6		480		3.0	
M			580	10.8		480		6.1	
H			510	12.7		480		21.7	
Whatman									
AGF/A#	>1		340	5.3	100	540	1.29 lb/in.		0.8
AGF/B#	>1		840	15.0	100	540	3.14 lb/in.		3.2
AGF/D	>1		460	5.5	100	540	0.56 lb/in.	2.3@2 1fm	
AGF/E	>1		890	15.0	100	540	1.07 lb/in.		
AGF/F	>1		380	6.3	100	540	0.73 lb/in.		
H&V									
H≅93		0.6	460-560	9.3	96-99	540	2.5 lb/in.		
H≅94		0.5≅3	380	8.2	96-99	480	2.5 lb/in.		
S&S									
24*									
26#			200	6.05					0.3
27*			125-180		98	400			
29#			127	5.4	98	400			0.6

without organic binder
* with organic binder

Table 4-5. Mixed fiber filter characteristics.

Filter designation	Composition	Void size (microns)	Fiber diameter (microns)	Thickness (microns)	Weight per unit area (mg/cm²)	Ash content (%)	Maximum operating temp. (°C)	Tensile strength	Flow resistance at 100 ft/min [~50 cm/sec] (in. H$_2$0)
H&V H≅70, 9 mil	Cellulose asbestos		0.1-35	230	8.2	20-25	150	2.5 lb/in.	17
H≅70, 18 mil	Cellulose asbestos		0.1-35	460	15.4	20-25	150	4.0 lb/in.	26
H≅64	Cellulose asbestos		0.1-35	830-1090	22.7	15-20	150	2.0 lb/in.	15
H≅90	Cellulose glass		9-35	685	13.4	70	150	3.2 lb/in.	0.4
H≅91	Cellulose glass		1.5-35	710	13.5	80	150	3.5 lb/in.	0.89
N≅15	Synthetic fiber & glass		0.5-15	1270	24.9	15	150	1.0 lb/in.	9.9
5≅G	Synthetic fiberglass & cotton		0.5-15	685	14.5	4-6	150	gauze backed	2.0
MSA glass & cellulose	Glass & cellulose			1000			120		
Whatman ACG/A	Glass & cellulose	>1		330	5.5		150	270 gm/cm	0.9 (20 1 fm)
ACG/B	Glass & cellulose	>1		990	19.5		150	330 gm/cm	2.6 (20 1 fm)
H&V CWS≅6	Cellulose asbestos			762		11%			17
H&V AEC≅1	Cellulose asbestos			762		13%			13.3
VM≅100 Gelman	Vinyl metracel	10.0							
VM≅1	Vinyl metracel	5.0							

Membrane Filters
This filter media consists of dry gels of cellulose esters, usually produced as cellulose acetate or cellulose nitrate, polyvinyl chloride, acrylonitrile, and Teflon®. The filters are cast on a smooth, flat substrate and exposed to a controlled atmosphere. This process can control both the internal membrane structure and pore size. Some filters are formed with pores while others are formed as sheets with pores formed later.

Sampling Considerations. Membrane filters are typically very brittle and require careful handling. In air sampling, they should be backed by some support structure to avoid breakage. The filters are not well suited to sampling at elevated temperatures, as they have an operating temperature range comparable to cellulose fiber filters (see Table 4-6).

The particle size collected by membrane filters has been found to be much smaller than the pore size; this is thought to be due to electrostatic forces.

Membrane filters have appreciable pressure drops, and this may limit the volume of air that can be sampled. Another factor limiting the volume of air that can be sampled is the build-up of a second layer of dust on the filter surface. This layer has a tendency to slough off, causing loss of part of the sample.

Analysis Consideration. One advantage of membrane filters is that they are primarily surface collectors and are not prone to absorption interferences when analyzed under spectrometric methods. The membrane filters lend themselves very readily to particle size analysis by microscopy. By using an immersion oil with an index of refraction (N_D) equal to that of the filter, the filter can be made transparent to light, thus allowing light-transmitted microscopic analysis. However, care must be taken to ensure that the N_D of the particle is not the same as the N_D of the immersion oil.

Membrane filters can also be readily ashed and leave very little residue. This can be a definite advantage in some analysis schemes. Most membrane filters are also readily soluble in many organic solvents, thus allowing removal of particulate matter with little problem.

Commonly Used Filter Media for Particulate Sampling and Analysis
The 1997 draft "EPA Guideline on Speciated Particulate Monitoring" (Chow 1997) includes a discussion on the commonly used filter media for particulate sampling and analysis, including $PM_{2.5}$ and PM_{10}. A summary table taken from this reference, presenting filter type, filter size, physical characteristics, chemical characteristics, and compatible analysis methods is included here as Table 4-7.

Table 4-6. Membrane filter media.

Filter	Pore size (microns)	Index refraction	Thickness (microns)	Weight per unit area (mg/cm³)	Ash content (%)	Maximum operating temp. (°C)	Tensile strength	Flow resistance, 100 ft/min (in. H₂O)
Millipore SM	5.0	1.495	170	3.6	0.0001	125	100 psi	19
SS	3.0	1.495	170	3.8	0.0001	125	150 psi	38
WS	3.0		150	4.9	"	"		-100
RA	1.2	1.512	150	4.2	"	"	300 psi	62
AA	0.80	1.510	150	4.7	"	"	350 psi	91 (39)*
DA	0.67	1.510	150	4.8	"	"	400 psi	120
HA	0.45	1.510	150	4.9	"	"	450 psi	210
WH	0.45		150	5.7	0.0001	"		-270
							0.41 kg/cm²	11
Gelman AM≅1	5.0		200	3.6		"	0.72 kg/cm²	33
AM≅3	2.0		200	6.6		"		73
AM≅4	0.65		200			"		
AM≅5	0.65		200			"		
AM≅6	0.40		200	5.8		"		
S&S AF≅600	7.5		180-250	6.3-8.7	0.01	Continuous 100		
AF≅400	4.0		180-250	6.3-8.7	0.01	Peak 200		
AF≅250	2.0		160-210	5.6-7.3	0.008	"		
AF≅150	0.85		160-210	5.6-7.3	0.008	"		
AF≅100	0.70		Av-150	Av 5.3	0.007	"		
AF≅50	0.60		Av-135	Av 4.7	0.006	"		
AF≅30	0.40		Av-120	Av 4.2	0.005	"		
Gelman GM≅1	5.0	1.49				Dry 176		
GM≅3	1.2	1.49				176		
GM≅4	0.80	1.49				176		
GM≅6	0.45	1.49				176		
GM≅8	0.20	1.49				176		
GM≅9	0.10	1.49				176		
GM≅10	0.05	1.49				176		

*Alternate value reported.

Table 4-7. Commonly used filter media for particulate sampling and analysis.

Filter Type, (Major Manufacturer, and Catalog No. or Trade Name)	Filter Size	Physical Characteristics	Chemical Characteristics	Compatible Analysis Methods[a]	No. of Filters per Box
Ringed Teflon[®]-membrane (Gelman Scientific; Ann Arbor, MI; Teflon[®] R2PJ047, R2PJ037)	25 mm 37 mm 47 mm	Thin membrane stretched between polymethlypentane ring. White surface, nearly transparent. Minimal diffusion of transmitted light. High particle collection efficiencies. Cannot be accurately sectioned. 1.2, 2.0, 3.0, 5.0 and 10µm pore sizes (determined from liquid filtration). Melts at ~60°C. High flow resistance.	Usually low blank levels, but several contaminated batches have been found. Made of carbon-based material, so inappropriate for carbon analysis. Inert to adsorption of gases. Low hygroscopicity. Low blank weight.	Gravimetry, OA, XFR, PIXE, INAA, AAS, ICP/AES, ICP/MS, IC, AC	50 50 50
Ringed Teflon[®]-membrane (Pallflex, Putnam, CT)	25 mm 37 mm 47 mm	Thin film of Teflon[®] attached to polyolefin ring without adhesive.	Made of carbon-based material, so inappropriate for carbon analysis. Inert to adsorption of gases. Low hygroscopicity. Low blank weight.	Gravimetry, OA, XRF, PIXE, INAA, AAS, ICP/AES, ICP/MS, IC, AC	25 25
Backed Teflon[®] membrane, (Gelman Scientific, Ann Arbor, MI; "Zeflour"; 2µm, P5PJ037 or P5PJ047; 1µm, P5PL037 or P5PL047)	37 mm 47 mm 20.3 × 25.4cm	Thin membrane mounted on thick polypropylene backing. White opaque surface, diffuses transmitted light. High particle collection efficiencies. Melts at ~60°C. High flow resistance. 1 µm and 2 µm pore sizes.	Usually low blank levels. Made of carbon-based material, so inappropriate for carbon analysis. Inert to adsorption of gases. Higher background levels for XRF and PIXE than Teflon[®] owing to greater filter thickness. Low hygroscopicity. High blank weight.	Gravimetry, XRF, PIXE, INAA, AAS, ICP/AES, ICP/MS, IC, AC	50 50 25

Backed Teflon® membrane, (Pallflex, Putnam, CT)	25 mm 37 mm 47 mm	TFE porous membrane on TFE support. Smooth surface. 0.30 μm @ 99% efficiency.	Neutral pH. Usually low blank levels. Made of carbon-based material, so inappropriate for carbon analysis. Inert to adsorption of gases. Higher background levels for XRF and PIXE than Teflon®, due to greater filter thickness. Low hygroscopicity. High blank weight. Retains average tare weight of 7.6 grams.	Gravimetry, XRF, PIXE, INAA, AAS, ICP/AES, ICP/MS, IC, AC	50 50
Nylon membrane, (Gelman Scientific, Ann Arbor, MI: "Nylasorb", #66509)	47 mm 90 mm	Thin membrane of pure nylon. White opaque surface, diffuses transmitted light. 1μm pore size. Melts at ~60°C. High flow resistance.	High HNO_3 collection efficiency. Passively adsorbs low levels of NO, NO_2, PAN, and SO_2. Low hygroscopicity. Low blank weight.	IC, AC	100 50
Silver membrane (Millipore Corp., Marlborough, MA)	25 mm[b] 37 mm[c]	Thin membrane of sintering, uniform metallic silver particles. Grayish-white surface diffuses transmitted light. Melts at ~350°C. High flow resistance.	Resistant to chemical attack by all fluids. Passively adsorbs organic vapors. Low hygroscopicity. High blank weight.	Gravimetry, XRD	50 25
Cellulose esters membrane (Millipore Corp., Marlborough, MA; "Nitrocellulose")	37 mm 47 mm[d]	Thin membrane of cellulose nitrate mixed esters, and cellulose acetate. White opaque surface diffused transmitted light. 0.025, 0.05, 0.1, 0.22, 0.30, 0.45, 0.65, 0.80, 1.2, 3.0, 5.0, and 8.0 μm pore sizes. Melts at ~70°C. High flow resistance.	High hygroscopicity. Negligible ash content. Dissolves in many organic solvents. Low blank weight.	Gravimetry, OM, TEM, SEM, XRD Biomedical applications	100 100

Polyvinyl Chloride membrane (Millipore Corp., Marlborough, MA)	25 mm 37 mm 47 mm	Hospital-grade polyvinyl chloride membrane. White opaque surface, diffuses transmitted light. 0.2, 0.6, 0.8, 2.0, and 5.0 μm pore sizes. Melts at ~50°C. High flow resistance.	Dissolves in some organic solvents. High hygroscopicity. Low blank weight.	XRD	100 100 100
Polycarbonate membrane, (Corning CoStar, [formerly Nuclepore Corp.], Cambridge, MA; #111129) (Poretics, Minnetonka, MN)	25mm 37mm 47mm[b]	Smooth, thin, polycarbonate surface with straight through capillary holes. Used for particle size classification. Light gray surface, nearly transparent. Minimal diffusion of transmitted light. Low particle collection efficiencies, <70% for some larger pore sizes. Retains static charge. 0.1, 0.3, 0.4, 0.6, 1.0, 2.0, 3.0, 5.0, 8.0, 10.0, and 12.0 μm uniform pore sizes. Melts at ~60°C. Moderate flow resistance.	Low blank levels (made of carbon-based material, so inappropriate for carbon analysis). Low hygroscopicity. Low blank weight.	Gravimetry, OA, OM, SEM, XRF, PIXE	100 100 100
Pure quartz-fiber (Pallflex Corp., Putnam, CT; 2500 QAT-UP)	25 mm 37 mm 47 mm 20.3 × 25.4 cm	Mat of pure quartz fibers. White opaque surface, diffuses transmitted light. High particle collection efficiencies. Soft and friable edges flake in most filter holders. Melts at >900°C. Moderate flow resistance.	Pre-washed during manufacture - low blank levels for ion. Contains large and variable quantities of Al and Si. Some batches contain other metals. Passively adsorbs organic vapors. Adsorbs little HNO_3, NO_2, and SO_2. Low hygroscopicity.	ICP/AES, ICP/MS, IC, AC, T, TOR, TMO, TOT, OA	100 25 25 25

Mixed quartz-fiber (Whatman Corp., Hillsboro, OR; QM/A #1861865)	37 mm 47 mm 20.3 × 25.4 cm	Quartz (SiO_2) fibers with ~5% borosilicate content. White opaque surface, diffuses transmitted light. High particle collection efficiencies. Some batches can melt at ~500°c. Effects on thermal carbon analysis are unknown. Becomes brittle when heated. Low flow resistance.	High blank weight. Contains large and variable quantities of Na, Al, and Si in all batches. Variable levels of other metals are found in many batches. Passively adsorbs organic vapors. Adsorbs little HNO_3, NO_2, and SO_2. Low hygroscopicity. High blank weight.	Gravimetry, XRF, PIXE, AA, ICP/AES, ICP/MS for some metals, IC, AC, T, TOR, TMO, TOT	100 100 25
Cellulose-fiber 41 (Whatman Corp., Hillsboro, OR; #1441047)	25 mm 47 mm	Thick mat of cellulose fibers, often called a "paper" filter. White opaque surface, diffuses transmitted light. Low particle collection efficiencies, <70% for some variations of this filter. High mechanical strength. Burns at elevated temperatures (~150°C, exact temperature depends on nature of particle deposit). Variable flow resistance.	High purity, low blank levels. Made of carbon-based material, so inappropriate for carbon analysis. Adsorbs gases, especially water vapor. Most appropriate for adsorbing gases such as HNO_3, SO_2, NH_3, and NO_2 when impregnated with reactive chemicals. High hygroscopicity. High blank weight.	Gravimetry, XRF, PIXE, INAA, AAS, ICP/AES, ICP/MS, IC, AC	100 100
Cellulose-fiber 31ET (Whatman Corp., Hillsboro, OR; #3031F915	47 mm 46×47 cm		High purity, low blank levels. Made of carbon-based material, so inappropriate for carbon analysis. Adsorbs gases, especially water vapor. Most appropriate for adsorbing gases such as HNO_3, SO_2, NH_3, and NO_2 when impregnated with reactive chemicals. High hygroscopicity. High blank weight.	Gravimetry, XRF, PIXE, INAA, AAS, ICP/AES, ICP/MS, IC, AC	100 25

Teflon®-coated glass-fiber (Pallflex, Putnam, CT; TX40H120)	37 mm 47 mm	Thick mat of borosilicate glass fiber with a layer of Teflon® on the surface. Glass fiber supporting Teflon® is shiny. High particle collection efficiencies. Glass melts at ~500°C. Teflon® melts at ~60°C. Low flow resistance.	Low blank levels for ions (glass backing and carbon content make it less suitable for elemental and carbon analyses). Inert to adsorption of HNO_3, NO_2, and SO_2. Low hygroscopicity. High blank weight.	Gravimetry, IC, AC	100 100
Glass fiber (Gelman Scientific, Ann Arbor, MI; Type A/E)	25 mm 47 mm 20.3 × 25.4 cm (available in 13 mm to 293 mm sizes)	Borosilicate glass fiber. White opaque surface, diffuses transmitted light. High particle collection efficiencies. Melts at ~500°C. Low flow resistance.	High blank levels. Adsorbs HNO_3, NO_2, SO_2, and organic vapors. Low hygroscopicity. High blank weight.	Gravimetry, OA, XRF, PIXE, INAA, AAS, ICP/AES, IC, AC	500 100 100

a   AAS   =   Atomic Absorption Spectrophotometry
      AC   =   Automated Colorimetry
      IC   =   Ion Chromatography
      ICP/AES =   Inductively-Coupled Plasma with Atomic Emission Spectrophotometry
      ICP/MS =   Inductively-Coupled Plasma with Mass Spectrophotometry
      INAA   =   Instrumental Neutron Activation Analysis
      OA   =   Optical Absorption or Light Transmission (b_{abs})
      OM   =   Optical Microscopy
      PIXE   =   Proton-Induced X-Ray Emissions
      SEM   =   Scanning Electron Microscopy
      T   =   Thermal Carbon Analysis
      TEM   =   Transmission Electron Microscopy
      TMO   =   Thermal Manganese Oxidation Carbon Analysis
      TOR   =   Thermal/Optical Reflectance Carbon Analysis
      TOT   =   Thurman Optical Transmission Carbon Analysis
      XRD   =   X-Ray Diffraction
      XRF   =   X-Ray Fluorescence

b   Available in 0.45 μm pore size.
c   Available in 0.80 μm pore size.
d   Filter disc is available in-size between 13 mm to 293 mm, depending on the pore size.
e   Available by special order.

Sample Problems

Problem 1: Filter Selection
A filter is to be chosen for subsequent analysis by a chemical ashing technique. The maximum vacuum flow resistance the pump can overcome is about 10 in. of water when the face velocity is about 100 ft/min. When dealing with atmospheric sampling, the temperature is not a limiting factor since most filters will operate at temperatures over 100°C (212°F). Which filter, based on the available information, would be the best choice?

Solution: Tables 4-4 and 4-5 show that glass fiber and mixed fiber filters have relatively high ash contents, making them impractical for chemical ashing. Tables 4-3 and 4-6 show that, generally, cellulose fiber filters and membrane filters exceed the requirements of the pumps. Table 4-3 shows that Whatman 41, S&S 604, MSA BM-2133, and the IPC 1478 all have ash contents less than 1% and flow resistances less than 10 in. H_2O. These would all be acceptable, and availability would determine which would be used.

Problem 2: Filter Selection
The pump capacity from Problem 1 has now been doubled so that 20 in. H_2O at 100 ft/min can now be sampled. An efficiency of 100% for all particles down to 0.3 μm is desired. Which filter should be used?

Solution: According to Table 4-2, the 5.0 μm MF Millipore (SM) 47 mm and 90 mm, S&S B6A cellulose acetate, Gelman A 25 mm, and MSA 1106 BH all show apparent particle efficiencies of 100% for all sizes. According to Table 4-4, both the Gelman and MSA filters show an ash content over 95%, and therefore are not acceptable. The S&S B6A does not appear on Tables 4-3 through 4-6, but since the cellulose acetate is a mixed fiber filter, we can assume the ash content is also too high. According to Table 4-6, the 5.0 μ Millipore SM has a low ash content (0.0001%), an acceptable flow resistance (19 in. H_2O), and is the most acceptable filter.

Problem 3: Filter Extraction
A filter is needed for subsequent analysis by acid extraction. The sampling atmosphere is very humid. The flow resistance must be kept below 10 in. H_2O. Which filter should be used?

Solution: Cellulose filters are very hygroscopic, so they should not be used in this situation. Membrane filters have extremely high flow resistances, so they, too, should not be used in this situation. Glass fiber filters are non-hygroscopic and are the filters of choice in water-vapor laden atmospheres. According to Table 4-4, Gelman G or M filters could be used since they both qualify for the low flow resistance requirements.

Summary
No single type of filter is the right one for all air sampling problems. The choice

of filter also depends on the analysis method required for different particulate constituents. In evaluating a filter, one must consider many factors: general filter characteristics, collection efficiency, background filter impurities, sampling conditions, ease of analysis, light absorption characteristics, flow resistance, and the purpose for which the sample is being taken.

4.6 Gravitational Sampling

Gravitational sampling, as briefly discussed here, refers to the amount of precipitation (solid or liquid) which reaches the ground over a stated period of time. The sampling time periods reported for total solids are 24 hours or more, and as much as a 30-day time period. This discussion addresses the use of dustfall buckets or jars for solids, and nonrecording and recording gauges typically used for rainfall.

Dustfall Bucket or Jar
The dustfall bucket had been one of the earliest sampling devices for particulate matter in the atmosphere. Although not widely used by EPA anymore, this method was used extensively in the early days of air monitoring and is still used throughout the world. The bucket or jar was made of resistant material and often placed in a stand to prevent the container from spilling. A wire rim was used to prevent the container from collecting bird droppings. The dustfall bucket is used mostly as a bulk collector for wet (rainwater) and dry (dust) deposition. Results were calculated by filtering the liquid, with subsequent weighing of the remaining solids.

Precipitation Collectors
As reported in EPA's *Quality Assurance Handbook for Air Pollution Measurement Systems, Volume IV-Meteorological Measurements*, EPA/600/R-94/0-38d, revised 1995, the National Weather Bureau Station's precipitation collectors are of two basic types: nonrecording and recording devices. The nonrecording precipitation collector or gauge is constructed of a cylinder, closed at one end and open at the other. The depth of the liquid in the collector is typically measured with a measuring ruler calibrated in subdivisions of centimeters or inches. To improve precipitation resolution as in the case of the standard 8-inch gauge, the collector is constructed to satisfy National Weather Station (NWS) specifications, which require a ratio of 10:1 between the area of the outside collector cylinder and the inside measuring tube. A funnel attached to the gauge directs the precipitation into the collecting tube and minimizes evaporation losses. A specialized nonrecording gauge is available for collecting programs involving the chemical and/or radioactive analysis of precipitation. The collector includes a sensor that detects the start and end of precipitation and automatically releases a lid to open and close the precipitation gauge.

Recording gauges consist of two basic designs based on their operating principles: the weighing-type gauge and the tipping bucket-type gauge. The weighing gauge is known as the Universal gauge because it may be used for liquid

and frozen precipitation. This gauge incorporates a chart drum that is made to rotate either by an 8-day spring-wound clock or a battery-powered clock. A quartz crystal mechanism with gear shafts allows for a wide range of rotation periods from 12 hours to 30 days. In the tipping bucket gauge, the balance of the buckets and the leveling of the bucket frame are critical. Power is typically 6V D.C., and the signal is provided by a switch closure each time the bucket tips (0.01 inches of rainfall per bucket). The accuracy of the gauge is given as 1% for rainfall rates of 1 in./hr or less, 4% for rates of 3 in./hr, and 6% for rates up to 6 in./hr.

4.7 Electrostatic Precipitators

These next two sections address the use of electrostatic and thermal precipitators for the collection of particulate matter. Only a brief discussion is included since these techniques are more commonly used in air cleaning applications or special air monitoring research projects than for routine use in ambient air sampling. The following discussion was extracted from Chapter 15 of the 8th Edition of *Air Sampling Instruments for Evaluation of Atmospheric Contaminants*, Swift and Lippman (1995).

Introduction
Separation of particles from an air stream using electrostatic precipitators is based on the use of electrostatic forces. Since the electrostatic force is placed directly on the particles instead of on the entire gas volume, relatively less energy is needed to collect the particles or to move the gas stream through the collector, compared to other collection mechanisms. For example, in the case of inertial collectors, most of the energy is used to drive the gas through the collector, and high collection efficiency is reflected in very high pressure drops.

Two advantages of electrostatic precipitator samplers compared to filter samplers are: (1) the sampling rate is not affected by mass loading, and (2) the collected sample is in a readily recoverable form. In one type of precipitator sample, the particles are collected on a large surface, where the surface may be covered by a paper or a liquid film depending on the follow-up analysis. On a second type of electrostatic sampler, the electron microscope grid sampler, the sampler collects small samples for particle size distribution analyses. This type of sampler collects representative samples quickly without sample losses and alterations that occur when transferring membrane filter samples to electron microscope grids.

Principles of Electrostatic Precipitation
Two operations are involved in collecting particles by electrostatic precipitation: electrically charging the particles and accelerating the charged particles toward an oppositely charged electrode. A number of mechanisms for charging particles have been used, including friction with solid material, flame ionization, radioactive charging, and high-voltage corona discharge. The most widely used mechanism is the corona discharge because of its efficiency, speed, and

controllability. Figure 4-27 shows an axial view of high-voltage corona discharge. The electric field close to the high voltage wire speeds up free electrons that ionize the gas molecules which end up with the corona glow. The affinity of the charged particles toward the collecting electrode depends on the number of charges acquired, the viscous drag of the air, and the electric field strength.
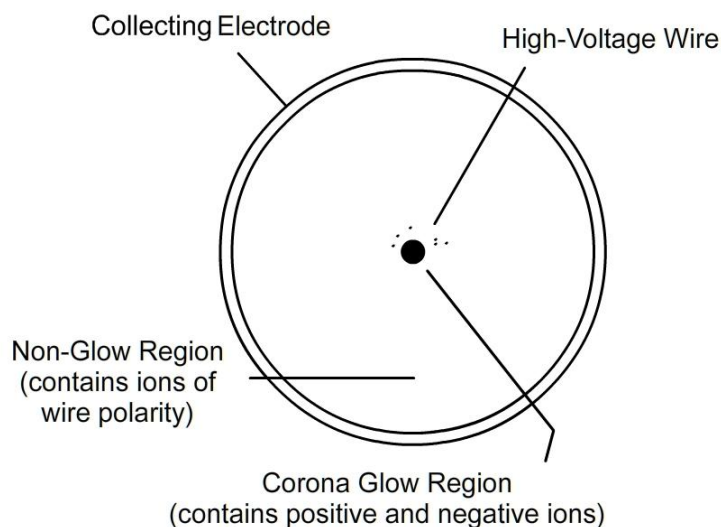

Figure 4-27. Axial view of high voltage corona discharge.

Collection Efficiency

Variables affecting the collection efficiency of electrostatic samplers include such items as current, flow rate, voltage, particle size, particle shape, particle concentration, humidity, pressure, and temperature. High-charging currents, high-voltage gradients, and low flow rates improve the collection efficiency, while very high humidity reduces the collection efficiency because of electrical breakdown that occurs in a humid atmosphere. Maintaining as high a voltage as possible during the entire sampling period, without inducing excessive sparking, will result in the maximum collection efficiency.

Specific Applications

Electrostatic precipitator samplers have been developed for a number of applications, including mass concentration analysis, sampling for radioactive particles, and sampling for particle size analysis. In the past, a field instrument employing a negative corona central electrode was used for the collection of atmospheric samples that allowed for gravimetric mass analysis and subsequent particle speciation. Also, high-volume samplers with sampling rates as high as 10,000 L/min have been designed for gravimetric and other particle analysis. Using this sampler, particles were collected on a rotating plate coated with a thin film of liquid. Swift and Lippman (1995) report that instruments employing electrostatic sampling have been used for the sampling of radioactive particles. Also, because particles travel at various distances in an electrostatic sampler

before reaching a grounded collector, variations in particle size occur along the length of a simple coaxial precipitator. This aspect allows for particle size analysis using the electrostatic precipitator. However, the particle travel distance is also influenced by other variables, such as the linear air velocity in the tube, radial position at which the particle enters the tube, particle dielectric properties, ion density, and voltage gradient. A discussion of several particle sizing electrostatic precipitator samplers is also included in the Swift and Lippman (1995) reference.

4.8 Thermal Precipitators

Introduction

Thermal precipitators collect particles from an air stream by passing the air sample through a narrow channel having a significant temperature gradient perpendicular to the direction of flow. The particles move towards the decreased temperature surface and deposit on it, allowing for subsequent analysis of the collected particles. Figure 4-28 illustrates a schematic view of a thermal precipitator.
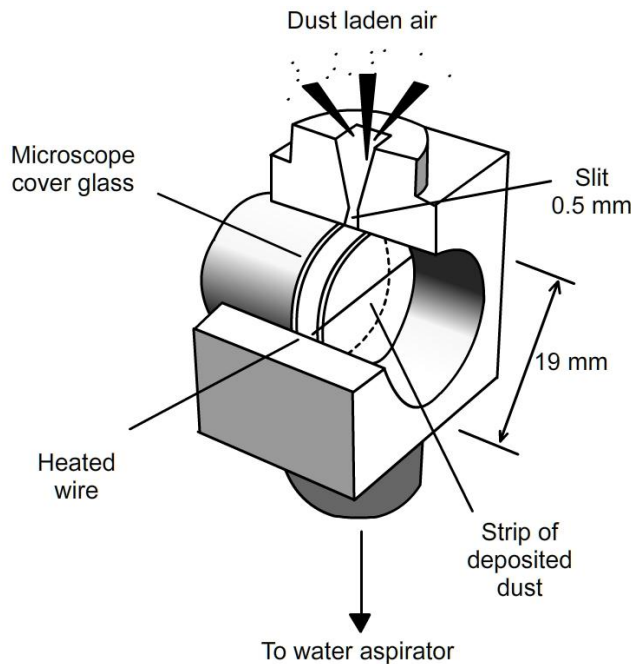

Figure 4-28. Sampling head of thermal precipitator.

Collection Efficiency and Deposition Pattern

Generally all particles 5 to 0.005 μm and less in diameter are collected in a thermal precipitator sampler, provided that the thermal gradient is about 104 K/cm. For particles larger than 5 μm, gravitational and inertial effects may

interfere with the collection efficiency. Also, at wind speeds greater than 6 m/sec, the sample collection efficiency will be reduced. It is interesting to note that because the deposition pattern of particles on the collection surface in a direction parallel to air flow is Gaussian, the particle concentration can be determined by extrapolation of the spatial distribution curve.

Advantages and Disadvantages of Thermal Precipitators

The major advantage of the thermal precipitator is the extremely high collection efficiency, particularly in comparison to liquid impingers and cascade impactors. Also, the low sampling velocity prevents the shattering or breakup of the collected particles during the sampling cycle and particles may be collected on a wide variety of surfaces, allowing for numerous types of special analysis including optical microscopy, electron microscopy, photometry, and radioactivity. Disadvantages of the sampler are that the low sampling rate renders the sampler unsuitable for some analysis, volatile aerosols cannot be collected, and the standard thermal precipitator has poor size selection characteristics. This latter disadvantage is especially important if too large a sample size is taken.

4.9 Summary

This chapter focused on the fundamental principles commonly associated with sampling for PM in the atmosphere. These sampling principles—impaction, centrifugal separation, filtration, diffusion, interception, gravitational settling, and electrical and thermal precipitation—provide for the separation of the particle size fraction of interest from the sample gas stream and are the basis for the operational design of PM sampling instrumentation. In most cases, one or more of the principles are utilized within a sampling instrument in order to properly characterize the particle size fractions of concern.

In Chapter 5, the discussion of PM sampling continues as it relates to specific PM sampling and monitoring instruments, primarily focusing on instruments commonly found at federal, state, local, and tribal PM monitoring locations. These instruments include FRM and FEM samplers for TSP, PM_{10}, and $PM_{2.5}$; $PM_{2.5}$ speciation samplers; and continuous, automated instruments.

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