Chapter 14

Impactors, Cyclones, and Other Inertial and Gravitational Collectors

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CONTENTS

Overview

Inertial and gravitational collectors include impactors, cyclones, aerosol centrifuges, impingers, and elutriators. In contrast to filters, which generally collect particles of all sizes, these instruments collect particles in characteristic size ranges. They are used for size-selective sampling or size-segregated collection of airborne particles. Size-selective sampling refers to the collection of one specific particle size fraction, such as the collection of respirable particles or particles smaller than a nominal 10 µm (called PM_{10} or American Conference of Governmental Industrial Hygienists—International Standards Organization [ACGIH–ISO] thoracic particles). Size-segregated aerosol collection refers to the physical separation of airborne particles into several size fractions.

Cyclones, elutriators, and single-stage impactors can be used to remove larger particles from the air stream and are commonly followed by a filter for collection of the undersized particles. Some cyclones can be operated to approximate the respirable collection efficiency curve, as discussed in Chapter 5. Other cyclones mimic the thoracic collection efficiency curve. Similarly, elutriators have been used in size-selective sampling to measure respirable or thoracic particle mass. Single-stage impaction heads are used to adapt Hi-Volume samplers for PM_{10} sampling.

Cascade impactors, cascaded cyclones, aerosol centrifuges, and horizontal elutriators can be used to size-fractionate particles with respect to aerodynamic diameter. The multiple stages of a cascade impactor can be analyzed to determine aerosol mass distributions or to assess chemical composition as a function of particle size. Cascaded cyclones have been designed for stack gas sampling in which a robust system is needed to handle the elevated temperatures. Aerosol centrifuges and some horizontal elutriators provide a continuous size spectrum, and they can be used to determine aerodynamic shape factors for irregularly shaped particles. Impingers and impactors are used for collection of bioaerosols. The choice of sampler depends on the application and the analyses to be performed.

The particle separation characteristics of inertial and gravitational collectors depend on particle "aerodynamic diameter," as defined below. The particle collection mechanism pits the particle's aerodynamic resistance against its inertia or an external force. For particles greater than about 0.5 µm, the aerodynamic diameter is generally the quantity of interest because it is the parameter that enters into the equations for particle transport, collection, and respiratory tract deposition. Respirable, thoracic, and inhalable particle sampling, as described in Chapter 5, are based on particle aerodynamic diameter.

This chapter first presents the definition for aerodynamic diameter because this parameter is applicable to all inertial and gravitational collectors. Subsequent sections are devoted to impactors, cyclones, aerosol centrifuges, inertial spectrometers, impingers, and elutriators. Each section gives a basic description of the type of instrument, the theory of operation, its applications, and guidelines for use.

Aerodynamic Diameter

Aerodynamic diameter is defined as the diameter of a smooth, unit density ($\rho_o = 1$ g/cm^3) sphere that has the same settling velocity as the particle. It is dependent on the particle density and particle shape, as well as the particle size. The general expression for the particle aerodynamic diameter, d_a, is:

$$d_a = \left(\frac{\rho\, C}{\rho_o\, C_a}\right)^{1/2} d_p \qquad (1)$$

where: ρ = particle density
ρ_o = 1 g/cm^3
C = Cunningham slip factor (defined below) evaluated for the particle diameter d_p
C_a = Cunningham slip factor evaluated for the particle diameter d_a
d_p = physical diameter for spherical particles and the Stokes diameter (also defined below) for nonspherical particles

The slip factor C is an empirical factor that accounts for the reduction in the drag force on particles due to the "slip" of the gas molecules at the particle surface. It is important for small particles, less than 1 µm in diameter, for which the surrounding air cannot be modeled by a continuous fluid. The slip factor is a function of the ratio between particle diameter and mean free path of the suspending gas; it is given by the following expression:[1]

$$C = 1 + \frac{\lambda}{d_p}\left[2.514 + 0.800\,\exp\left(-0.55\,\frac{d_p}{\lambda}\right)\right] \qquad (2)$$

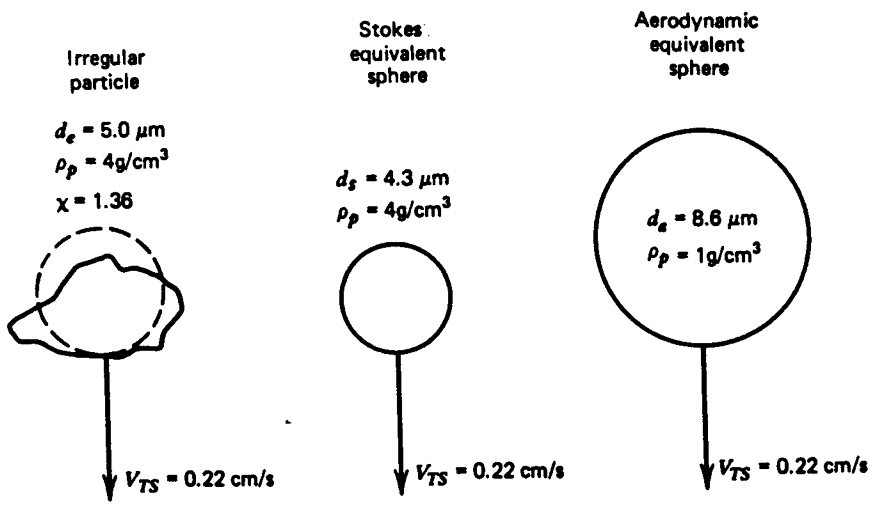

FIGURE 14-1. An irregularly shaped particle and its equivalent Stokes and aerodynamic spheres.[1] Reprinted by permission of John Wiley & Sons, Inc.

where: λ = mean free path of air

At normal atmospheric conditions (i.e., temperature = 20°C, pressure = 1 atmosphere), $\lambda = 0.066$ µm. For large particles ($d_p > 5$ µm), $C = 1$; for smaller particles, $C > 1$.

The particle Stokes diameter d_p is defined as the diameter of a sphere having the same density and settling velocity as the particle. For a smooth, spherically shaped particle, d_p exactly equals the physical diameter of the particle. For irregularly shaped particles, d_p is the diameter that characterizes the aerodynamic drag force on the particle. The relationship between the physical particle size, Stokes, and aerodynamic diameters is illustrated in Figure 14-1.(1) Particles with the same physical size and shape, but different densities, will have the same Stokes diameter but different aerodynamic diameters.

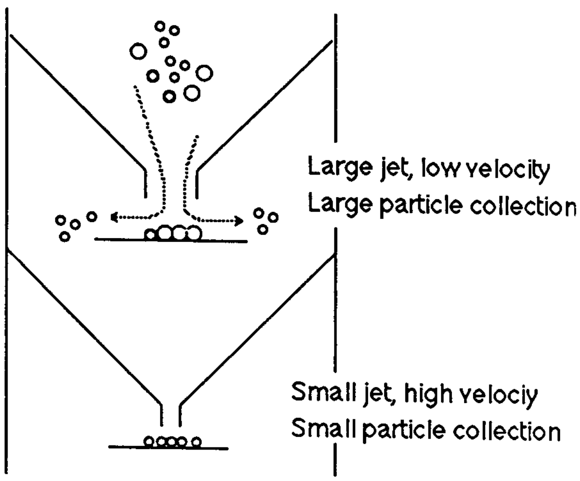

FIGURE 14-2. Schematic of two impactor stages showing large and small particle trajectories.(2)

For two particles of the same physical size but differing densities, the particle with the larger density will have the larger aerodynamic diameter. If the density of a particle is greater than 1 g/cm^3, then its aerodynamic diameter is larger than its Stokes diameter. Conversely, for particles of densities less than 1 g/cm^3, the aerodynamic diameter is smaller than the Stokes diameter.

For particles with diameters much greater than the mean free path, the aerodynamic diameter given by Equation 1 can be approximated by:

$$d_a = \sqrt{\frac{\rho}{\rho_0}}\, d_p \qquad (d_p >> \lambda) \tag{3}$$

In this approximation, the aerodynamic diameter is directly proportional to the square root of the particle density. This expression holds for large particles for which the slip factor equals one. It is often used for particles as small as 0.5 µm, which is acceptable if the particle density is at all close to 1 g/cm^3. For example, a density of 2 g/cm^3 and a Stokes diameter of 0.5 µm gives an aerodynamic diameter calculated from Equation 1 of 0.68 µm. The approximation of Equation 3 gives 0.71 µm, an error of only 4%.

For particles with diameters much smaller than the mean free path, the slip factor C is inversely proportional to particle diameter, which makes the aerodynamic diameter directly proportional to the particle density:

$$d_a = \frac{\rho}{\rho_0} d_p \qquad (d_p << \lambda) \tag{4}$$

This small particle limit is applicable for low-pressure systems, such as low-pressure or inertial devices used in stratospheric sampling.

Impactors

Description and Operational Principle

The term "impactor" encompasses a large category

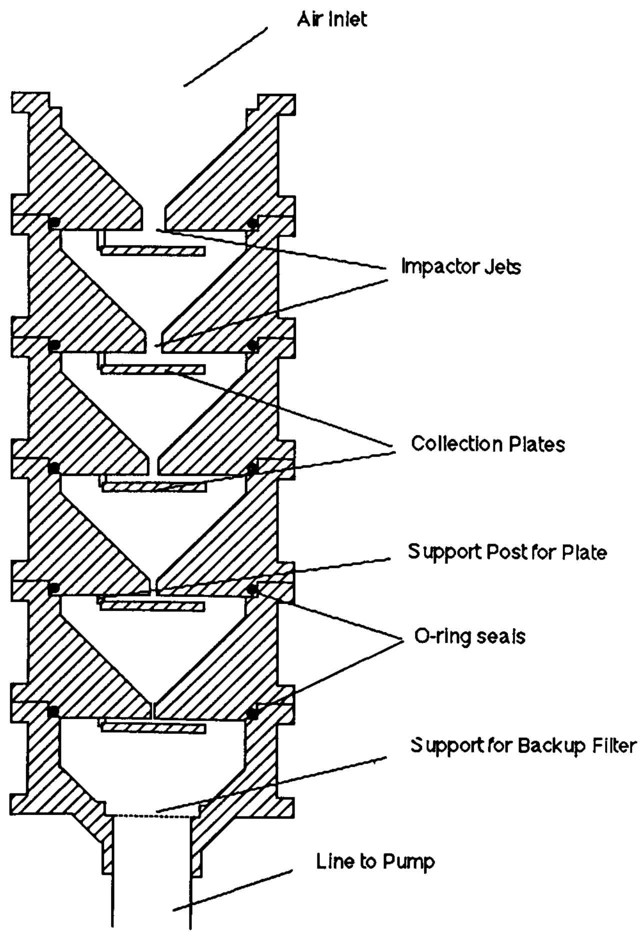

FIGURE 14-3. A single-jet, five-stage cascade impactor.

of aerosol collection instruments in which particle impaction in a nonrotating flow is the primary mechanism of particle capture. Particle impaction refers to the collection of particles that by virtue of their inertia deviate from the air flow streamlines. Impaction occurs when streamlines bend as the air flow bypasses a solid object.

Conventional flat-plate impactors employ a collection surface located internal to the device, as illustrated in Figure 14-2.[2] Particle-laden air passes through the nozzle and impinges on a collection plate oriented perpendicular to the nozzle axis. The air flow is laminar, and particles within the nozzle are accelerated to a nearly uniform velocity. At the nozzle exit, the streamlines of the gas are deflected sharply by the collection plate. Larger particles are propelled across the air streamlines and deposit on the plate. Smaller particles follow the streamlines more closely and remain suspended in the air.

The cascade impactor shown in Figure 14-3 is a multistage device that fractionates the sample by particle size. Air enters at the top, passes through each of the impactor stages, and is exhausted through a back-up filter. Each impactor stage consists of one or more jets followed by a collection plate. Successive stages are designed to collect smaller particles. Those particles that penetrate the last impaction stage are collected by the back-up filter. Air flow is generated by means of a pump and controlled by a valve or critical orifice downstream of the back-up filter.

Particle trajectories in the single-jet cascade impactor are illustrated in Figure 14-2. The minimum size collected by an individual stage depends on the jet diameter and the air stream velocity in the jet. In low-pressure impactors, it also depends on the pressure at which the stage operates. Typically, the collection of smaller particles is achieved by using smaller diameter jets with higher jet velocities. Within limits, particle impaction is insensitive to the spacing between the collection plate and the jet exit, and to the geometry of the stage.

Size-fractionated samples from cascade impactors are used to determine the distribution of aerosol mass or chemical species with respect to particle size. When cascade impactor samples are analyzed chemically, they yield species size distributions as shown in Figure 14-4.[3] Alternatively, the impactor samples can be assayed gravimetrically to provide an aerosol mass distribution. Simultaneous data on particle size and mass or chemical composition are important for assessing health effects and particle transport in the atmosphere or in a room. Cascade impactors were introduced by May in 1945[4] and are widely used. A recent discussion of these instruments, their use, and data analysis procedures is given by Lodge and Chan.[5]

Commercially available impactors are listed in Table 14-I-1 of the "Instrument Descriptions" section at the end of this chapter. The impactor jets may be round or rectangular in cross section. Many use multiple jets per stage to permit larger collection of particles at larger

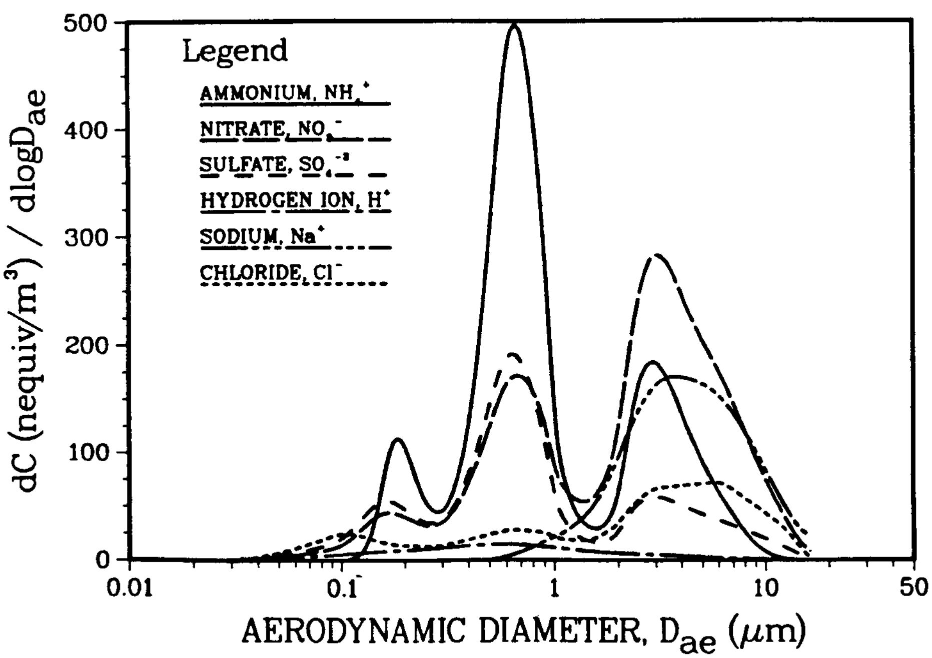

FIGURE 14-4. Inorganic ion particle size distributions collected with the Berner impactor in Claremont, CA.[3] Reprinted by permission of Elsevier Science Publishing Co., Inc.

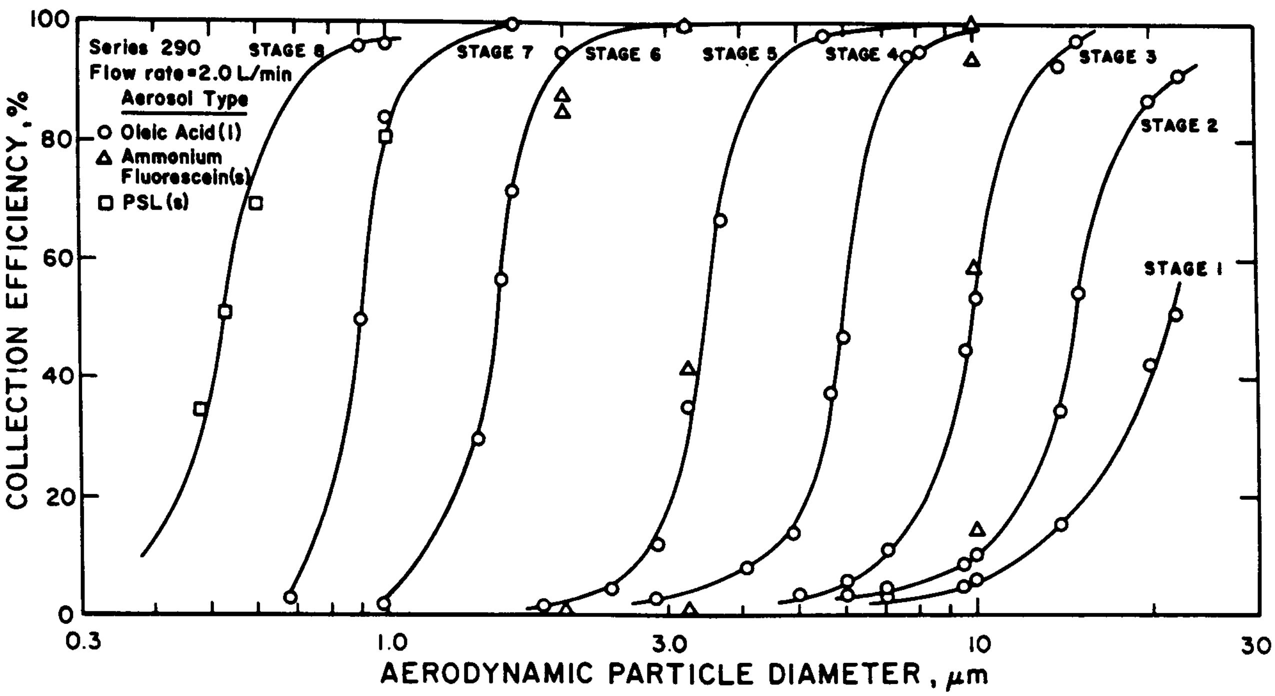

FIGURE 14-5. Collection efficiency curves for the Sierra/Andersen personal sampler.[16] Reprinted with permission, American Industrial Hygiene Association Journal.

flow rates. Large flow rate cascade impactors have been designed for use with Hi-Volume samplers.[6,7] Low flow rate impactors are used for personal and ambient sampling.[8–12] Impactors are also used for stack sampling[13,14] and viable particle sampling,[15] as discussed in Chapters 21 and 23.

The overall size range covered by an impactor depends on its design. Conventional cascade impactors can be designed to collect particles as small as 0.4 μm. Low-pressure and micro-orifice impactors can collect particles as small as 0.05 μm. Some impactors, such as the Andersen microbial sampler, are designed to collect very large particles, as much as 30 μm in diameter. Rotary impactors have been used with high efficiency to sample ambient air particles as large as 250 μm. In these, a rod moving through the ambient air impacts and collects particles larger than the characteristic cut-size for the sampler.

Impactors differ in the nature of the particle collection surface. Most collect particles on a solid plate located immediately downstream of the accelerating jet, as shown in Figure 14-2. However, unless the collection plate is greased, particles may bounce and be re-entrained in the flow. To avoid this problem, the virtual impactor uses a nearly stagnant airflow to transport the size-fractionated sample to a filter. Although it does not have an impaction surface, the air flow streamlines are similar to those in conventional impactors.

Impactor Theory

Impactor performance is characterized by a set of collection efficiency curves such as those shown in Figure 14-5.[16] Each curve shows the efficiency with which a particle entering the stage is collected. The point corresponding to a collection efficiency of 50% is referred to as the cut-size, or cutoff diameter, d_{50}. The curve shape indicates the sharpness of the size-segregation. For an infinitely steep collection efficiency curve, all particles above the cutoff diameter would be collected, and all below that size would pass onto the next stage. In practice, efficiency curves have a finite slope, which gives rise to crossover in particle size between neighboring stages.

Generally, impactors are designed such that the efficiency curves are as steep as possible. This is especially desirable because the most common data reduction methods use only the cutoff diameter to characterize stage performance. More sophisticated inversion methods for data reduction take into account the actual shape of the efficiency curves and produce a smoothed size distribution (e.g., see Figure 14-4).

Impactor theory can be used to predict the cutoff diameter and the shape of the collection efficiency curves. Theory does not account for nonideal effects such as particle rebound from the surface, but it is applicable for sticky particles. The first impactor theories were advanced by Ranz and Wong[17] and Davies and Aylward.[18] Currently used models include those of Marple and Liu[19,20] and Rader and Marple,[21] which use numerical solutions to the fluid dynamics and particle trajectory equations in impactors. Other models of note are those of Mercer and coworkers[22,23] and Ravenhall and Forney.[24] Results from these models are used as guidelines in the design of impactors.[25,26]

In an impactor, whether a particle impacts depends on the drag force on the particle, the particle momentum, and the effective transit time across the plate. Impactor theory combines these parameters into a dimensionless parameter called the Stokes number, given by:

$$St = \frac{\rho\, d_p^2\, C\, V}{9\, \mu\, W} \tag{5}$$

where: ρ = particle density
d_p = particle Stokes diameter
C = Cunningham slip factor, as defined in Equation 2
V = mean velocity in the jet
μ = air viscosity
W = jet diameter or width

Physically, the Stokes number is proportional to the ratio of the particle-stopping distance to half the jet diameter. (The stopping distance is the distance traveled by a particle before stopping when injected into still air.) Alternatively, it may be viewed as the ratio of particle relaxation time to the transit time of the air flow through the impaction region. (The relaxation time is the time for a particle initially at rest to accelerate within *1/e* of the velocity of the air stream, which is 63%, where *e* is the base of natural logarithms.) The larger the Stokes number, the greater the impaction efficiency.

One of the most important uses of the Stokes number is to predict the cutoff diameter, d_{50}. Impactor stages with similar geometry but varying jet diameters or flow rates will have collection efficiencies that tend to fall on a common curve when plotted as a function of *St*. The cutoff diameter d_{50} corresponds to a single Stokes number, referred to as the critical Stokes number, St_{50}. The value of St_{50} is approximately the same for different impaction stages, and even for different impactors of similar geometry, and it can be used to predict impactor performance.

It is useful to express the cutoff diameter in terms of the critical Stokes number; the sampler volumetric flow rate, *Q*; and the number of jets per stage, *n*. This is accomplished by writing the jet velocity in Equation 5 as the ratio of the flow rate to the jet cross-sectional area. For round jet impactors, the expression is:

$$d_{50}^2\, C = \frac{9\, \mu\, \pi\, n\, W^3\, (St_{50,\,round})}{4\, \rho\, Q} \tag{6}$$

The Cunningham slip factor, *C*, depends on the particle diameter and thus has been placed on the left-hand side of the equation. For rectangular jet impactors, with jets of width *W* and length *L*, and with *n* jets (or slots) per stage, the cutoff diameter is given by:

$$d_{50}^2\, C = \frac{9\, \mu\, n\, L\, W^2\, (St_{50,rect.})}{\rho\, Q} \tag{7}$$

For most slotted impactors, the value of $St_{50,rect.}$ is close to 0.59. For round jet impactors, $St_{50,round}$ is about 0.24.

Equations 6 and 7 are used to calculate stage cutoff diameters for impactors operated at different flow rates, or at temperatures and pressures other than the design conditions. Changes in temperature affect μ; changes in pressure affect *C*. Impactor cutoff diameters decrease with increasing flow rate per jet and decrease with decreasing jet diameter. Because the cutoff diameter is relatively insensitive to the distance between the jet exit and the collection plate, this parameter does not appear in the Stokes number.

The shape of an impactor collection efficiency curve depends on the jet Reynolds number, defined as:

$$Re = \frac{\rho_{air} V W}{\mu} \tag{8}$$

Impactor collection efficiency curves tend to be steeper at higher Reynolds numbers, as shown in the model calculations of Figure 14-6.[19] The performance at $Re = 500$ is much better than at $Re = 100$. For very low Reynolds numbers, below 100, impactors are not very effective, and collection efficiencies may never reach 100%. Once the Reynolds number is above about 200, the impactor will perform well, and the effect of *Re* on the efficiency curves is relatively small.

The effect of the jet-to-plate spacing on impactor cutoff diameters is shown in Figure 14-7.[19] The jet-to-plate spacing is the distance between the outlet of the impactor nozzle and the impaction plate. Figure 14-7 plots the nondimensional cutoff diameter, expressed in terms of the critical Stokes number, against the ratio of the jet-to-plate spacing, *S*, to the jet diameter or width, *W*. For values of *S/W* between 1 and 5, the impactor stage d_{50} is almost unaffected. At much smaller jet-to-plate spacings, the cut-sizes are smaller and strongly affected by the spacing. At large *S*, greater than 5*W* or 10*W*, depending on the jet Reynolds number, the cut-sizes increase because of the expansion of the jet. The recommended jet-to-plate spacing corresponds to *S/W* values near 1 for round jet impactors and 1.5 for rectangular jets.

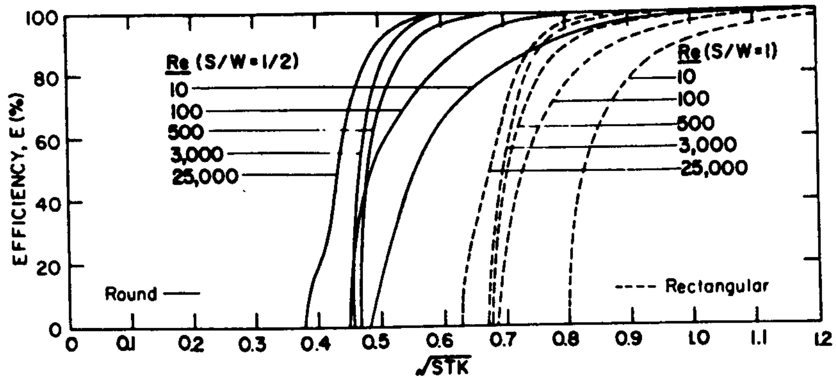

FIGURE 14-6. Model calculations of impactor collection efficiency curves for round and rectangular jet impactors at various jet Reynolds numbers.[19] Reprinted with permission from American Chemical Society.

Particle Bounce

Impactor theory assumes that all particles striking the collection surface adhere to it. In practice, this criterion is not always met. Dry, solid particles may bounce from the surface on impaction and be re-entrained in the air stream. If collected on a subsequent stage, the size distribution will be further distorted. This problem is perhaps the greatest limitation in the use of impactors. It was recognized in 1945 by May[4] in the initial development of the impactor and has been raised by many others since.[27–41] Examples of solid particle collection on different impaction surfaces are shown in Figure 14-8.[33]

The theory of particle interactions with surfaces shows there is a critical approach velocity below which the particle will stick on a clean surface, and above which it will bounce.[42–44] This velocity depends on the coefficient of restitution, which is a measure of the particle's tendency to rebound. Cheng and Yeh[45] proposed a criterion for impactor design that would maintain jet velocities below typical critical approach velocities, thereby minimizing particle bounce. However, obtaining the desired cut-sizes at low jet velocities requires small orifices, which often is not a practical option. Generally, case substrate coatings must be used.

Submicrometer as well as supermicrometer particles are subject to particle bounce. Particles as small as 0.2

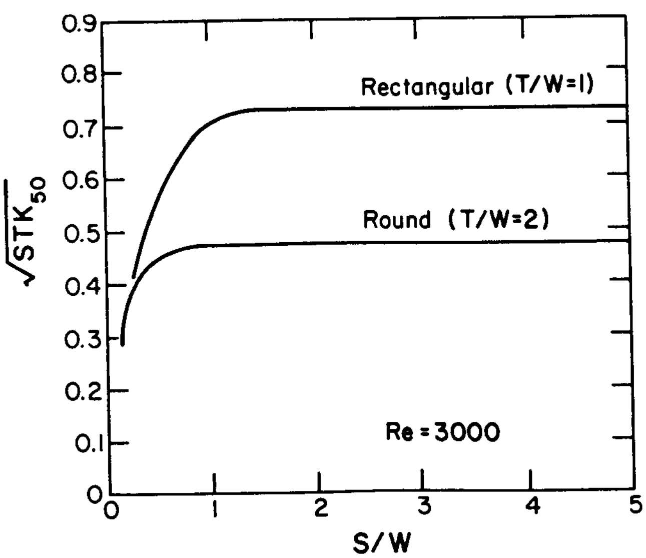

FIGURE 14-7. Impactor 50% cutoff size as a function of the jet-to-plate spacing, S, expressed as a fraction of the jet diameter, W. Curves are shown for round and rectangular jets with a throat length T and diameter or width W.[19] Reprinted with permission from American Chemical Society.

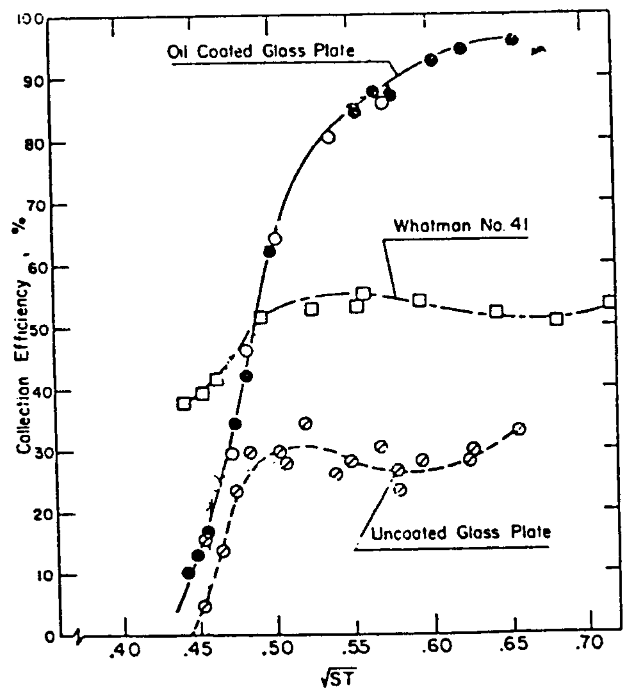

FIGURE 14-8. Collection characteristics of a single jet impactor for solid, polystyrene latex particles with uncoated, coated, and fiber filter impaction surfaces (adapted from Reference 33). Reprinted with kind permission from Pergamon Press, Ltd, Headington Hill Hall, Oxford OX3 0BW, UK.

TABLE 14-1. Adhesive Coatings Used for Impaction Surfaces

	Source*	Author (Ref. No.)
A. Recommended Coatings:		
Apiezon L grease	1.	Wesolowski *et al.*,[31] Lawson,[37] Vanderpool *et al.*,[49] and Pak *et al.*[46]
Dow Corning Antifoam A silicone adhesive	2.	Mercer and Chow[22]
Dow Corning oil (200 & 600 cst)	2.	Rao and Whitby,[32,33] Mercer and Stafford,[23] Vanderpool *et al.*,[49] and Pak *et al.*[46]
Dow Corning silicone grease	2.	Cushing *et al.*,[29] Wesolowski *et al.*,[31] and Vanderpool *et al.*[49]
Flypaper mixture: one part rosin to three parts castor oil	—	May[4]
Halocarbon	3.	Wang and John[3]
One part methylated starch to three parts tricresyl phosphate	—	May[4]
Polyisobutene	—	May[4]
Petroleum jelly (Vaseline)	—	May,[4] Hering *et al.*,[58] Rao and Whitby,[32,33] Lawson,[37] Cushing *et al.*,[29] and Vanderpool *et al.*[49]
Oil-sintered metal	—	Reischl and John[41]
Oil Teflon® membrane filters	—	Turner and Hering[47]
B. Ineffective Coatings:		
Sticky tape		Wesolowski *et al.*[31]
Paraffin		Lawson[37] and Wesolowski *et al.*[37]

*Source: 1. Apiezon Products Ltd., England; available through most scientific supply houses.
2. Dow Corning Co., Midland, Michigan 48686; available through most scientific supply houses.
3. Halocarbon Products Co., 82 Burlews Court, Hackensack, New Jersey 07601.

µm have been observed to bounce from uncoated surfaces. Particles that bounce are often lost to the walls of the impactor.[35,45] Thus, bounce can underestimate mass loadings, as well as distort size distributions. Some have tried to correct for bounce errors in the data analysis. However, bounce-off errors do not affect all types of particles equally. For the same operating conditions, liquid particles adhere, whereas solid particles may not. Therefore, the stage collection efficiency becomes dependent on an unknown and uncontrollable factor, namely the composition of the aerosol being sampled.

To obtain reliable data, it is best to use an adhesive coating on the impaction stage to ensure that all sampled particles will stick. In some cases, the sampled aerosol itself will be sticky and no coating will be needed, but this must be evaluated on a case-by-case basis. In practice, only collection surfaces that show good retention of solid particles are considered "bounce-free."

The effectiveness of different impaction surfaces has been evaluated in several laboratory[28,31–33,35–37] and field[27,30,34,37] studies, as given in Table 14-1. In general, greases and oils are quite effective in reducing particle bounce. It is important that the coating be sufficiently thick and that substrates not be overloaded with particles. A laboratory study of the effect of coating thickness showed that Apiezon L (Apiezon Products Ltd., England; available through most scientific supply houses) coatings less than 0.7 µm thick were not as effective as 9-µm-thick coatings of the same grease for capturing 0.56- and 1-µm latex particles.[46] These same investigators found that for silicone oil, the coating thickness did not have as large an effect on capture efficiencies.

When sampling solid particles, it is important not to overload the substrate. John and coworkers[40,41] found that greased surfaces become ineffective after becoming partially coated with particles. As shown in Figure 14-9, the effect is noticeable at submonolayer loadings, with sticking efficiencies dropping below 50% at less than one monolayer substrate loadings. With half of the grease coating covered with particles, the incoming particle is equally likely to impact on top of a deposited particle as on the greased surface.

To eliminate the effect of substrate loading, Reischl and John[41] used an oil-soaked sintered metal disk. This surface is bounce-free even for high substrate

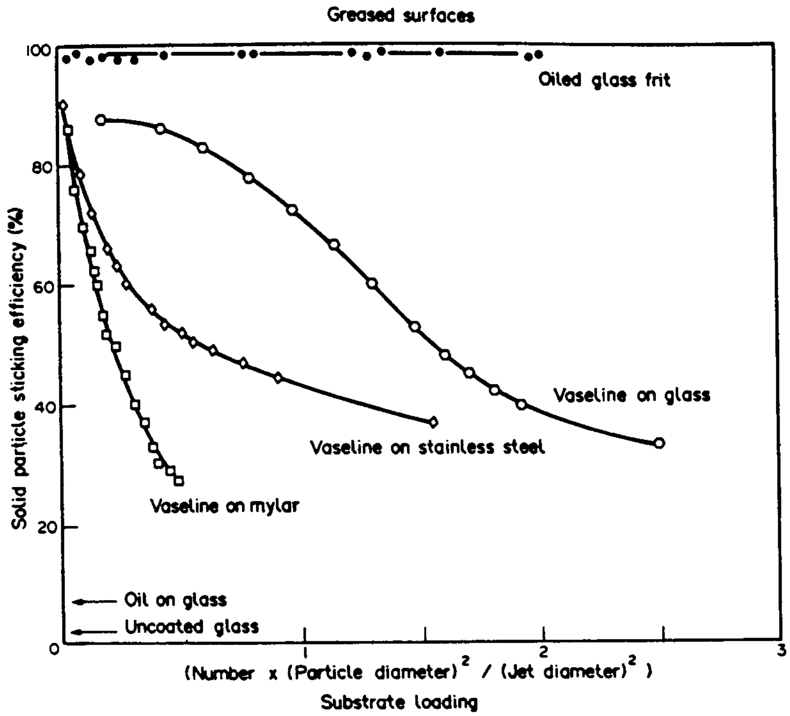

FIGURE 14-9. Dependence of solid particle sticking efficiency on substrate loading for greased and oiled surfaces.[47] Reprinted with kind permission from Pergamon Press, Ltd, Headington Hill Hall, Oxford, OX3 0BW, UK.

loadings. The oil is drawn up onto the depositing particles by capillary action; thus, incoming particles are always presented with an oily surface. The porous metal serves to hold the oil in place under the impactor jet. Sticking efficiencies do not drop even for large accumulations of deposited aerosol. This concept has been used in some commercial devices such as the Wedding PM_{10} particle inlet for Hi-Volume samplers, and it is analogous to the oiled glass frit data shown in Figure 14-9.[47] The disadvantage for some applications is that the surface is not amenable to chemical analysis. Turner and Hering[47] evaluated oil-impregnated membrane filters, which are more readily analyzed chemically, and found that oil-impregnated 10-μm pore size Nuclepore and Teflon filters gave solid particle sticking efficiencies above 90% for substrate loadings up to several monolayers.

Fiber filters are not effective impactor collection substrates for solid particles. Rao and Whitby[33] found that while fiber filters reduce particle bounce, they do not eliminate it (Figure 14-8). Furthermore, the filter has the effect of shifting and flattening the efficiency curve because a fraction of the air stream penetrates the filter mat and is, in effect, filtered. These curves no longer follow impactor theory. The ineffectiveness of filters has been confirmed by several investigators including Dzubay *et al.*,[30] Walsh *et al.*,[34] Willeke,[48] Vanderpool *et al.*,[49] and Newton *et al.*[35]

An alternative approach to eliminating particle bounce is exemplified by the grooved surface[50] once used in the Sierra/Andersen 246 PM_{10} sampler. Grease and oil coatings minimize particle bounce by absorbing the kinetic energy of the incoming particle. The grooved surface uses multiple collisions to dissipate the particle kinetic energy. This design proved effective in laboratory tests with glass beads. It has the disadvantage that the machining requirements render the approach infeasible for smaller cutpoint stages.

Impactor Operation: Guidelines for Use

The mechanical and theoretical simplicity of impactors has made them popular instruments for particle sampling; however, they are easily misused, leading to the generation of erroneous data. Correct operation requires 1) proper preparation and loading of the collection substrates, 2) leak-tight assembly of the instrument, 3) measurement and regulation of the flow rate, 4) appropriate choice of sample time, 5) a suitable inlet system, and 6) a precut device, where appropriate.

Substrate Coatings and Preparation

One of the most critical factors in impactor operation is the preparation of the collection surface. Except for virtual impactors, sampling of solid aerosols requires an adhesive coating to prevent errors from particle bounce. Although many manufacturers supply fibrous filter substrates, these substrates degrade impactor performance and do not eliminate bounce-off, as discussed above.

The choice of the adhesive surface depends on the application. Greases work well for chemical or elemental analyses of nonorganic species. They have also been used for determining the size distributions of specific organic species. The size distributions of polycyclic aromatic hydrocarbon compounds presented in Chapter 6 were collected using Vaseline-coated substrates. Other commonly used adhesive greases are Apiezon L and M, Halocarbon (Halocarbon Products Co., 82 Burlews Court, Hackensack, New Jersey 07601), and Dow silicone (Dow Corning Co., Midland, Michigan 48686). Although these vacuum greases have the advantage that they do not volatilize during sampling, Vaseline has the advantage of lower blank values for sulfur and trace metals.[37] Various types of oils and greases that have been used in impactor applications are listed in Table 14-1.

Analyses for total organic carbon remain a problem because there are no noncarbon greases or oils. To date, these samples are collected on uncoated substrates, which are suspect except in cases such as the sampling of cigarette smoke, where the aerosol particles may be self adhesive. In some cases, investigators have operated parallel, single-stage impactors with different cutpoints and analyzed only the after-filters. The impactor stages can then be coated without interfering with the analyses, provided suitable precautions are taken to prevent any transfer of the grease to the after-filter.

Installation of Collection Substrates

In using any impactor, the operator must be careful to ensure that the impaction stages are installed correctly. Jet-to-plate spacings often equal the diameter of the jet and can be quite small. An improperly installed collection surface that is too close to the jet or, worse yet, one that partially blocks the flow, can sharply affect the cutoff diameter. Impactor cutoffs are significantly affected when jet-to-plate spacings are less than 0.4 jet diameters. It is generally a good idea to inspect each stage before sampling to ensure proper installation.

Flow Rate Regulation

As with most inertial samplers, the particle cut-sizes depend on the sampler flow rate. Thus, proper operation requires a steady flow at a known rate. Simply knowing the sampled volume is not sufficient. Pumps that produce pulsating flows, such as some of the small diaphragm pumps, should not be used for impactor sampling because the cut-sizes will fluctuate. Likewise, a large drop in the flow rate during the course of sampling will affect the sharpness of the size fractionation. It is recommended that the operator measure the flow rate at the beginning and end of sampling. This can be done using a low pressure-drop device such as a rotometer or a dry-test meter placed at the inlet. Rotameter response depends on pressure, and readings will be different if the rotometer is placed downstream of the flow-regulating valve or orifice. If a rotometer is used on the low-pressure side, its pressure must be noted and the appropriate calibration applied.

Sample Duration

With impactors, it is possible to sample for too long a period as well as too short. Minimum sample durations are chosen on the basis of expected particle concentrations, analytical requirements, and substrate blanks. Maximum sample times are limited by the buildup of particle deposits on the collection surface. For sampling solid particles, greases can become ineffective at substrate loadings of a fraction of a monolayer (see Figure 14-9), and particle bounce errors can reappear if sampling times are excessive. If a porous oiled substrate is used, the particle deposit can grow to be quite high, and jet-to-plate distances can decrease enough to lower the particle size cutoff. In some applications, the first impactor stage may become overloaded prior to collection of enough sample on subsequent stages. This problem can be avoided by use of a precutter, as discussed below.

Inlets

If impactor size distributions are to be representative, the sampler placement and inlet configuration must not exclude particles of the size range of interest. This can be quite significant for sampling large particles (greater than about 5 μm). Long stretches of tubing on the impactor inlet can cause unaccounted-for losses. If the impactor inlet is a small tube oriented perpendicular to the air currents in the room or atmosphere being sampled, larger particles will not follow the streamlines into the impactor. The problem is lessened by using a wider inlet with a lower intake velocity, or pointing the probe inlet into the flow. The accurate collection of coarse particles requires isokinetic sampling, as discussed in Chapter 4.

Precutters

In many applications, it is necessary to prevent very large particles from entering the impactor. This is accomplished by means of a precut device such as a cyclone or size-selective inlet. Precutters exclude large particles that would otherwise bounce or overload the first impactor stage and thereby distort the impactor size distribution measurement. They are appropriate for applications that call for size distributions below a specified particle diameter, such as in respirable or thoracic sampling.

Data Reporting

Impactors provide data on aerosol mass or chemical composition in one or more size ranges. To obtain mass or chemical species size distributions, one of several data reduction procedures can be employed. The approaches include 1) histogram and cumulative plots based on stage cutoff diameters, 2) data inversion methods that take into account the shape of the collection efficiency curves, and 3) extraction of mass median diameters and distribution widths.

Histograms, such as those shown in Chapter 6, are a straightforward means of presenting impactor data. In this approach, each impactor stage is characterized by its cutoff diameter, and crossover between neighboring stages is neglected. This is the same as assuming infinitely steep collection efficiency curves. These graphs plot the quantity $\Delta M_i/\Delta \log d_a$ against $\log d_a$, where ΔM_i is the mass collected on the i^{th} stage, d_a is aerodynamic diameter, and $\Delta \log d_a = \log (d_{50,i-1} / d_{50,i})$ is the difference between logarithms of the aerodynamic cutoff diameters, $d_{50,i-1}$ and $d_{50,i}$ for the stage immediately preceding stage i (labeled i–1) and stage i itself. The denominator $\Delta \log d_a$ is a normalizing factor, such that the area under the histogram is proportional to the mass collected. It also accounts for whatever nonuniformity may exist in the spacing of the impactor cut-sizes, so that the shape of the histogram reflects the mass distribution. The data reduction procedures are described in Chapter 6 and will not be repeated here.

The histogram presentations do not account for cross-sensitivity in the impactor calibration curves. They assume infinitely sharp collection efficiencies such that the impactor stage collects all particles at or above the cutoff and no particles below that size. Actual efficiency curves have a finite slope, and particles of equal size will collect on several stages. When the impactor calibration efficiency curves are known, it may be desirable to take them into account in the data reduction. These procedures are known as data inversion methods.

Data inversion techniques have been applied to a variety of problems for which instrument responses are multivalued. There is no unique solution to the inversion problem. Mathematically it is possible to have several mass distributions yielding the same loadings on the impactor stages. The inversion methods that have been developed are constrained to produce physically reasonable solutions. Inversion results are to be considered "best estimates" and will vary somewhat depending on the algorithm used.

One of the more widely used inversion methods for aerosol instruments is that of Twomey.(51) The data of Figure 14-4 were reduced using this method, and they show a smooth curve for the chemical species size distributions. Another method with similar output is that of Wolfenbarger and Seinfeld.(52) Hasan and Dzubay(53) developed an inversion method that assumes a lognormal form for the aerosol size distribution. The accuracy of these methods depends on how well the efficiency curves are known.

Sometimes the investigator is not interested in the details of the aerosol size distribution but simply wishes to extract certain parameters, such as the mass median diameter or the fraction of aerosol in the respirable size range. These calculations are facilitated by presenting the data in terms of a cumulative distribution, as shown in Chapter 6. Cumulative distributions display the percentage of the aerosol in particles with diameters equal to or smaller than the diameter indicated.

Aerosol size distributions can often be approximated by lognormal distributions, which have a Gaussian shape when displayed against the logarithm of the particle diameter. When the cumulative distribution is plotted on a log-probability graph, the result is a straight line. These plots are useful for evaluating whether a distribution is lognormal, and for extracting the median diameter and the geometric standard deviation, which is the measure of the width of the distribution. For lognormal distributions, the mass median and count median diameters are related through the geometric standard deviation. For a detailed treatment of this approach to the analysis of impactor data, refer to Hinds(54) and Chapter 6.

Special Types of Impactors

Micro-orifice and Low-Pressure Cascade Impactors

Traditional impactors do not offer much size resolution for submicrometer particles; typically, their finest cut-size size is around 0.4 µm. Yet for many aerosol applications, it is useful to be able to size-segregate smaller particles. Diesel emissions, welding fumes, cigarette smokes, and photochemically generated smog aerosols typically exhibit mass median diameters between 0.1 and 0.6 µm. When sampling these aerosols with a conventional impactor, 50% or more of the aerosol mass can penetrate the final impactor stage. Although the material can still be collected on a back-up filter, the filter gives no size resolution; as a result, the investigator has no size information on a substantial portion of the sample. Often a lower cutoff diameter of 0.1 µm or less is needed to size-segregate the majority of the aerosol mass.

Two types of impactors have been developed to obtain smaller cutoff diameters: low-pressure impactors and micro-orifice impactors. Both instruments can provide