

USE OF CASCADE IMPACTORS IN THE CHEMICAL AND PHYSICAL
CHARACTERIZATION OF COAL-COMBUSTION AEROSOL PARTICLES

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ABSTRACT

Aerosol particles from combustion of pulverized coal are typically distributed bimodally with respect to size, and contain particles ranging from about 0.01 μm to over 100 μm in diameter. Development of control technology, emissions testing, and prediction of health and environmental effects often require characterization of the size distributions of aerosol particulate mass or the various chemical components. Cascade impaction provides a relatively simple and fundamental measurement of the mass-vs-size distribution and can yield size-segregated material in quantities adequate for determining the distributions of chemical, physical, or biologically active constituents. This paper briefly reviews impactor theory, considers the merits and shortcomings of four cascade impactors, and reviews the principal problems involved in using cascade impactors to measure properties of coal combustion aerosols. These problems include errors in measuring narrow distributions, effects of particle bounce and reentrainment, diffusive deposition of fine particles, and deposition of condensable/adsorbable gases. Ambiguities in data reduction will also be discussed.

INTRODUCTION

Cascade impactors have been used extensively to provide size-segregated particulate samples for characterizing the distributions of mass and chemical constituents in both ambient and source aerosols. In principal, conventional inertial impactors can provide accurate data on particle distributions in the range of 0.2 to 50 μm (1,2). The lower size limit has been reduced to 0.05 μm with low-pressure impactors (3,4,5) and, more recently, to 0.026 μm with a microorifice impactor (6,7,8). Large errors in estimates of the distribution parameters can result, however, in cases where the size distribution is narrow (such as that for aerosols modified by highly efficient particulate-control devices), from the effects of particle bounce and reentrainment, and from the deposition of particles and gases from boundary streams onto impaction substrates. These problems are especially important in sampling the bimodal aerosols produced in the combustion of pulverized coal, which contain condensable gases, enormous concentrations of submicrometer particles, and predominantly dry, glassy aluminosilicate spheres that tend to stick poorly to impaction substrates. Because of particle bounce, contamination of submicrometer-particle fractions with larger particles is an especially important problem in sampling both source and ambient aerosols. These problems are reviewed below.

The Principle of Inertial Impaction

The underlying principle of inertial impaction is embodied in the concepts of relaxation time and stopping distance. When the velocity of a particle-containing gas is changed, for example, by accelerating the gas through a nozzle or by changing the direction of its flow, the suspended particle, with its greater inertia, lags behind the gas. The time required for equilibrium to become reestablished is known as the relaxation time, and the distance the particle travels while equilibrating is known as the stopping distance. In an impactor, placement of an obstruction (impaction plate) normal to the direction of flow forces the gas to change direction. A particle is deposited (i.e., collected) on the impaction plate if the size of the plate is large with respect to the stopping distance of the particle.

The stopping distance (S) of an aerosol particle is a function of the diameter (D_p), velocity (V_p), and density (ρ_p) of the particle, and the viscosity of the gas (μ), as shown in Equation 1 (9):

$$S = \frac{\rho_p V_p C D_p}{18\mu} \quad (1)$$

where C is the Cunningham slip correction factor, which accounts for discontinuity in the transfer of momentum to the particle (as a result of collisions with gas molecules at the particle surface) that occurs for particles of size near that of the mean free path of the gas molecules (9).

Typical cascade impactors consist of a series of nozzle plates, each followed by an impaction plate; each set of nozzle plate plus impaction plate is termed a stage. The sizing characteristics of an inertial impactor stage are determined by the efficiency with which the stage collects particles of various sizes. Collection efficiency is a function of three dimensionless parameters: the inertial parameter (Stokes number), the ratio of the jet-to-plate spacing to the jet width, and the jet Reynolds number. The most important of these is the inertial parameter, which is defined by Equation 2) as the ratio of the stopping distance to some characteristic dimension of the impaction stage (10), typically the radius of the nozzle or jet (D_j).

$$\text{Stokes} = \frac{\rho_p V_p C D_p / 18\mu}{D_j / 2} \quad (2)$$

Particle collection efficiency is a monotonically increasing function of the inertial parameter and has been determined experimentally (1,11,12). Customarily, this function is represented by a single value, that is, the value of the Stokes number that corresponds to a collection efficiency of 50%. Thus by rearranging Equation 2), the diameter of the particle collected with 50% efficiency (D_{50}) is expressed in terms of the Stokes number for 50% collection (Stk_{50}) as follows:

$$D_{50} = \sqrt{\text{Stk}_{50}} \times \sqrt{\frac{D_j^2 9\mu}{\rho_p V_p C}} \quad (3)$$

Particles with large enough stopping distances will be deposited on the first impaction plate; those with somewhat smaller stopping dis-

tances will be carried to the next stage; and so on. By increasing the velocity of the aerosol in successive stages, the stopping distance of the particle is likewise increased, and progressively smaller particles are collected. The jet velocity can be increased either by reducing the number or size of the jets or by increasing the overall flow rate of the aerosol.

Data Reduction

In typical aerosols, particle size is distributed lognormally. The distribution parameters (median and the geometric standard deviation) may be estimated graphically from cumulative plots of mass vs particle size, or mathematically, by fitting the data to a lognormal distribution function.

Gravimetric or chemical analysis of the individual impaction plates is used to determine the aerosol mass or the amount of some chemical constituent associated with the range of particle sizes collected on the plate. The size distribution of the measured variable can then be deduced by plotting the data against the appropriate impactor stage parameter, usually the D_{50} as determined by Equation 3). The D_{50} , however, is a measure of the diameter of a particle collected with 50% efficiency, and not the size of the particle collected on the impactor stage. The true distribution of particles actually collected on the stage is a function of the distribution of the aerosol sampled and the efficiency-vs-size curves for the individual stages; only by chance would the D_{50} be equal to the median diameter of particles on the stage. The use of D_{50} s in determining actual distributions therefore contains an intrinsic error. If efficiency curves are available, this intrinsic error can be reduced by using data-inversion techniques (13,14). These techniques determine the distribution that, after multiplication by the appropriate sets of calibration curves, best reproduces the amounts of particulate mass collected on each impactor stage.

In general, if the aerosol distribution is wide enough and the mass median diameter (MMD) is within the range of the device, D_{50} s can provide reasonably accurate estimates of the aerosol-distribution parameters. Efficiency curves for impactors are sigmoidal, however, and collection efficiency for particles of all sizes is non-zero. Thus, when the size distribution is narrow, as in aerosols modified by particulate-control devices, the amount of mass attributed to the larger particles may be incorrect. As a rule, the size of the largest particle collected on the first stage of the impactor should be determined by microscopy or by inference from other measurements. Additional sizing errors, resulting from nonideal behavior, are discussed below.

Nonideal Behavior

The principal problems in determining size distribution parameters with cascade impactors are wall losses, inefficient collection due to particle bounce, deposition of gas-phase species on impaction substrates, and deposition of fine particles from boundary layers. As discussed above, an intrinsic error can result from using D_{50} s to infer size distributions from the impactor data. Depending on the sampling conditions and on the chemical and physical properties of the aerosol sampled, each of the other errors can also be significant, and generally must be considered in sampling coal combustion aerosols.

Wall losses. Ideally, all of the aerosol sampled in an impactor should be deposited on the collection plates or be captured by the after-filter. In practice, some of the particles collect on other interior surfaces and are typically excluded from the analysis. Wall losses result from diffusion of particles in turbulent eddies, from sedimentation of large particles (especially in large-particle stages with large internal volume and corresponding low gas velocities), from electrostatic effects, and from particle bounce. Wall losses appear to depend on size and hence on stage. Therefore, if they are significant, both the total mass concentration of the aerosol and its inferred size distribution will contain an error. Experience has shown that wall losses are greater for large, hard, dry particles, typically composed of aluminosilicate materials, than for small (submicrometer) carbonaceous or sulfate particles.

Particle bounce. When particles bounce off the collection surface, they may be carried to subsequent stages, where they may stick or again bounce off. The result is that subsequent stages collect more mass than is appropriate, and the inferred particle-size distribution is biased towards the smaller particles. Apparently, because of increasing velocity, particles that bounce off an earlier stage of the impactor quite often continue to bounce off the subsequent stages and are finally collected on the afterfilter. As discussed below, such collection can severely limit the utility of afterfilter data. Typically, sticky substances are applied to impaction surfaces to reduce particle bounce. Compounds that can be "wicked" by the collected particles tend to be the most effective.

The significance of these and other real-world difficulties are discussed below for sampling coal combustion aerosols.

Problems in Measuring Coal Combustion Aerosols

In an earlier study (15) we addressed some of the problems in obtaining accurate concentration-vs-particle-size distributions for elements in stack aerosols collected downstream of an electrostatic precipitator and a Venturi wet scrubber at a coal-fired power plant. The problems investigated were error associated with the use of the D₅₀s, wall losses, and contamination of afterfilters by particle bounce. In a later study, we observed the artifactual deposition of gas-phase components during sampling (16). In both studies we used the University of Washington Mark III and Mark V Source Test Cascade Impactors (17). Our specific objectives were to verify the sizes of particles collected on impaction stages and afterfilters and to estimate impactor efficiency relative to collection on filters. The ultimate goal was to determine elemental emission rates as a function of particle size.

The Mark III and Mark V impactors used in these studies are, respectively, 7- and 11-stage multicircular jet units with integral backup filters. These were operated isokinetically, in-stack, with Nuclepore™ polycarbonate impaction substrates coated with vacuum grease. Elemental constituents of the particles collected were determined by neutron activation analysis, and number-size distributions (for each stage) were determined by counting particles in discrete size ranges after sonic dispersion in hexane. Particle sizes were determined from scanning electron microscope (SEM) photographs or by use of a Quantimet image analyzer with an interface to the SEM.

In Figure 1 are plotted both the cumulative mass distributions of Al in fly-ash particles as determined from stage D₅₀s and the distribution parameters for each stage as determined from SEM analyses. The SEM number-distribution (nmd) parameters for each stage were transformed to the corresponding volume parameters and adjusted for the measured particle density (2.44 g/cm³) and slip correction factor to obtain estimates of the mass median aerodynamic diameters (mmad) for the stage. Neither the nmds nor the mmads determined from the microscopy analysis are directly comparable to the D₅₀ stage parameters. Values corresponding to the D₅₀s can, however, be interpolated from the cumulative curves (Fig. 1) and are listed in Table 1. Comparison of these data shows that use of the D₅₀s supplied with the impactor (these are calculated values, and generally agree well with calibrations) results in serious overestimation of the amount of mass associated with large particles. As indicated in Fig. 1, aerosol MMAD was overestimated by a factor of two when the D₅₀s were used, and the estimated geometric standard deviation was 40% too large. In this case, the aerosol contained relatively few particles with diameters comparable to the D₅₀s of the first impactor stages. The presence of particles with diameters much smaller than the D₅₀s is attributed to their low, but significant, collection efficiency.

Wall losses were estimated by comparing the mass concentrations of various elemental constituents of aerosols collected with a series of alternately collected filter and impactor samplers. For samples collected downstream of an electrostatic precipitator (ESP), where the aerosol MMAD was 11.5 μm, the average amount of mass collected in the impactors was about 60% of that collected by the filters (Table 2). When fine (MMAD < 2 μm), wet particles were collected downstream of a Venturi wet scrubber, the impactor and filter data typically agreed to within 20%, which was well within the uncertainty of the comparison. We concluded, therefore, that wall losses were lower for small, wet particles than for larger, dry fly-ash particles.

Afterfilter data. As indicated in Table 1, the minimum D₅₀ in this study was about 0.5 μm, and particles smaller than this were collected on an afterfilter. Aerosols from combustion of pulverized coal typically are distributed bimodally, with a fine-particle mode at about 0.1 μm and a large-particle mode at supermicrometer sizes; the modal diameter of the latter depends strongly on the efficiency characteristics of the control device. The elemental concentrations in the fine-particle mode are of interest in health-impact and source-apportionment studies because of the typically high enrichment of the concentrations of many potentially toxic elements and useful tracer elements in particles in this size range. Large-particle contamination of the afterfilter due to particle bounce can, however, limit the value of these data.

To investigate the importance of afterfilter contamination by particle bounce, particle-size distributions were determined by SEM techniques for afterfilters from three impactors (15). With a final-stage D₅₀ of 0.5 μm, we would expect to see particles as large as about 0.94 μm on the afterfilters; however, the afterfilters actually contained particles as large as 4 μm. Cumulative mass distributions for the observed particles are plotted in Fig. 2. Curves a and b represent data for samples collected downstream of an ESP. Impactor stages were coated with vacuum grease (curve a) or not coated (curve b). Curve c represents afterfilter data for a coated impactor run downstream of a Venturi wet scrubber. As indicated in Fig. 2, large particles accounted

for about 96% of the particulate mass on the afterfilter from the coated ESP impactor and 98% of that from the uncoated ESP impactor. A somewhat lower value (87%) for large-particle mass on the third afterfilter indicates that particle bounce and reentrainment were only slightly reduced for the small ($<2 \mu\text{m}$), wet particles collected downstream of the Venturi scrubber.

The mmads for the distribution of particles on these afterfilters, which ranged from about 1.4 to 3 μm , were far larger than the D_{50} for the final impactor stage and could not have been inferred without SEM measurement. Since neither the correct mass nor the correct particle size can be determined without SEM measurements, afterfilter data should usually be excluded from the analysis when SEM analyses are not made. However, there are some exceptions. For example, the concentrations of certain trace elements are typically much higher in submicrometer particles than in supermicrometer particles. In this study, the concentrations of Mo, Sb, As, and Se in the large particles were so low that a high degree of large-particle contamination could be tolerated. As shown in Table 3, we used the microscopy data and chemical analyses to estimate the true concentrations of elements in the fine-particle component of one of the afterfilters. Except for Mo, Sb, As, Se, and Ba, the elemental concentrations determined in particles on the afterfilter (which would normally be assigned a size less than the final-stage D_{50}) ranged from 40% to over 200% higher than our estimates of their bounce-off-corrected concentrations.

Although we have not formally investigated the deposition of condensable gases, the overall concentrations of Br and Se in impactor samples collected downstream of a hot-side ESP at a large western coal-fired power plant far exceeded their concentrations as determined by filter sampling (16). In addition, the concentrations of Br and Se were nearly uniform on all stages of an impactor (16). Both of these elements tend to be distributed inversely with respect to particle size, and concentrations typically differ by a factor of 10 between particles of 0.1 μm and 1 μm diameter. The surface area available for vapor adsorption is dominated by the substrate rather than by the particles collected on the substrates. Therefore we concluded that the flat concentration-vs-size distributions for Br and Se resulted from the adsorption of vapor-phase components of these elements.

Another phenomenon that we have observed in sampling coal-combustion aerosols is the collection of numerous fine particles on large-particle impaction stages. Figure 3 is an SEM photograph of the third stage of an impactor located downstream of an ESP at a large western coal-utility boiler. Although the D_{50} was 6 μm , hundreds of tenth-micrometer particles are visible. In treated off-gas streams from combustion of pulverized coal, concentrations of submicrometer particles are typically about $10^7/\text{cm}^3$, while supermicrometer particle concentrations typically are three or four orders of magnitude lower. We attribute the collection of these fine particles to diffusive deposition from flow streams passing near the collection surface. Since these fine particles typically contain much higher concentrations of many trace elements, their collection may significantly bias the reported size distributions of these elements towards large particles.

Submicrometer Aerosol Measurements

Impactors that size-segregate particles via a series of stages operating at successively higher nozzle velocities have been designed by

numerous investigators (11,17,18,19). There is a practical upper limit to jet velocity (3,000-4,000 cm/s), above which particles tend to rebound from the collection plate and no longer stick to it (3). Further, given conventional drilling techniques, it is difficult to make jets with diameters less than about 0.025 cm. As a result, the lower limit of sizing by these impactors is about 0.4 μm (3). Particles below this size are typically collected on a backup filter, but are not size-segregated. Fresh aerosols from high-temperature combustion sources typically contain accumulation modes with modal diameters of about 0.1 μm . Thus the distribution characteristics of these aerosols cannot be determined with conventional cascade impactors operated at near-atmospheric pressure.

From Equation 3), it is clear that the size of particles collected on an impaction stage can also be reduced by increasing the value of the slip correction factor (C) or by reducing the diameter of the jets. The value of C is increased by reducing the gas pressure, and such an increase is the basis for low-pressure and high pressure-drop impactors such as those designed by McFarland et al. (3), Hering et al. (4), and Pilat et al. (5). The McFarland and Hering impactors use commercially available preimpactors for supermicrometer sizing and have three and four additional stages, respectively, for sizing submicrometer particles. The submicrometer sizing stages operate at a final stage pressure of 24.3 mm Hg (McFarland impactor) or 8 mm Hg (Hering impactor). The lower limit diameter for both impactors is 0.05 μm . The McFarland impactor samples at a rate of 28 μpm and, by using multiple jets (600 or 1,762), achieves jet velocities within the range required for acceptable particle bounce. Unfortunately, however, the unit requires a vacuum pump weighing between 400 and 500 lb to support the 28- μpm sampling rate at the low final-stage pressure. Because of its large size and power requirements, the unit has not been adopted for routine field use and has never been fully evaluated.

The Hering impactor is more portable and has been used to study the distribution of submicrometer sulfate aerosols (20). In this impactor a critical orifice separates the atmospheric and low-pressure stages and determines the 1- μpm sampling rate. The low-pressure stages each use a single jet, which even at the relatively low sampling rate produces jet velocities ranging from 9,300 to 30,000 cm/s. These jet velocities are so high that particle bounce is severe for the submicrometer particles (21). The single-jet design is not conducive to analysis by x-ray fluorescence, and the low flow-rate hampers the collection of sufficient material for analyses of trace constituents in ambient air.

In another study (22), we used a University of Washington Mark V impactor to determine the distributions of trace elements in submicrometer combustion aerosols from a 430-MW(e) coal-fired power plant. The Mark V is similar in design to the Mark III, but it has 11 impactor stages and may be operated as a high pressure-drop impactor. The orifice plates of the last four stages of the Mark V are quite similar to those of the University of Washington Mark IV, which was designed specifically for low-pressure operation. The unit can provide up to six submicrometer particle-size fractions. The Mark V was operated at flow rates of about 7 μpm at final-stage pressures no lower than 345 mm Hg.

Theoretical values of stage cutoff diameters can be calculated for the impactor if the gas pressures can be accurately estimated or measured. Pilat et al. (23) have extensively measured the pressures on each stage of the Mark IV and have prepared theoretical curves giving stage cutoff diameters as a function of gas temperature and sampling rate for a speci-

fic final-stage pressure. Because of the constraints of isokinetic sampling and the somewhat high pressure-drop filter required for our chemical analyses, and possibly because the amount of gas leakage around the jet stages in our study may have differed from that in the study of Pilat et al. (23), we were unable to obtain the final-stage pressures and sample flow rates called for by the theoretical curves. Because the degree of leakage between stages was unknown, and because the effects of particle bounce are not accounted for by theory, we relied on SEM techniques to determine the size distributions of particles collected on individual stages. The mmds for individual stages that collected sub-micrometer particles ranged from 0.77 to 0.11 μm . In this study we used Teflon[®]-fiber afterfilters to achieve the desired flow rate, but these could not be analyzed by SEM. The size distributions observed for the last four stages (Fig. 4) were generally "well behaved"--i.e., they fit well the lognormal distribution function, and tended to be free of the large particles that should have been collected on previous stages. We believe that the use of coated substrates and the numerous impactor stages helped to minimize the effects of particle bounce.

More recently, Kuhlmeier et al. (6) developed a uniform-deposit micro-orifice impactor in which nozzles with diameters of 100 μm were made in 50- μm -thick plates by a photochemical etching process. The original impactor used 200 jets per stage and could collect 0.1- μm particles at a flow rate of 10 μpm with an overall pressure drop of only a few inches of Hg. Because of the large number of nozzles, the relatively high flow rate is achieved at quite low jet velocities. The nozzles were placed in a spiral pattern and the collection plate was rotated to achieve uniform deposition. The advantages of uniform deposition are that particles do not pile up under the nozzles and alter the jet-to-plate spacing, thus changing the cutoff diameter; and that x-ray fluorescence can be used for analysis. A later, horizontally configured five-stage design with up to 2,000 jets per stage permitted sampling at 30 μpm with a minimum cutoff size of 0.06 μm . Marple (8) has recently built two vertically configured microorifice impactors having a final cutoff size of 0.026 μm . These vertically configured units use four-stage conventional atmospheric-pressure preimpactors to remove supermicrometer particles, and they also operate at 30 μpm . All of these microorifice impactors can be used with standard low-volume rotary carbon-vane vacuum pumps.

We have used both the horizontally and vertically configured impactors to sample coal-combustion aerosols in elevated plumes and in plumes at ground level near Deep Creek Lake in western Maryland. Aside from the usual difficulty with the effects of particle bounce, few problems were encountered. Particle bounce could not be evaluated for ambient samples because the individual submicrometer particles could not be discerned. Marple and Rubow (8) have performed extensive calibrations with monodisperse aerosols; these show that impaction plates covered with aluminum foil have slightly larger D_{50} s than plates covered with Teflon-fiber filters.

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Table 1. Comparisons of D_{50} values for a University of Washington Mark III in-stack impactor and observed particle sizes in a sample collected downstream from the electrostatic precipitator of a 750-MW coal-fired electrical power unit (15)

Stage	mg Al	nmd ^a	σ_g	mmad	Interpolated ^b D_{50}	D_{50}
1	2.01	8.14	1.88	34.4	18.5	38.3
2	1.75	2.91	2.10	11.7	8.06	16.7
3	0.985	2.21	1.71	6.72	4.70	6.40
4	0.586	1.39	1.65	4.24	3.01	3.17
5	0.428	1.00	1.35	2.24	1.70	1.77
6	0.179	0.64	1.38	1.37	0.99	0.94
7	0.0837	0.34	1.35	0.73	d	0.50

^aNumber median diameters (nmd) determined from SEM observation. ^bDiameter taken from mmad curve (Fig. 1) corresponding to cumulative mass points of impactor D_{50} values. ^c50% cutoff diameters taken from calibration curves provided with the impactor and adjuster to reflect a particle density of 2.44 g·cm⁻³. ^dValue not determined.

Table 2. Comparisons of selected elemental concentrations in samples collected on filters and on impactors located downstream from the electrostatic precipitator of a 750-MW coal-fired electrical power unit

	Average impactor ($\mu\text{g}/\text{m}^3$)	Average filter ($\mu\text{g}/\text{m}^3$)	Collection efficiency (impactor/filter)
Al	230,000 \pm 21,000	402,000 \pm 46,000	0.57 \pm 0.08
As	72.3 \pm 4.9	118 \pm 8	0.61 \pm 0.06
Ba	3,640 \pm 490	5,990 \pm 420	0.62 \pm 0.09
Br	10.2 \pm 0.7	81 \pm 34	0.13 \pm 0.05
Ce	210 \mp 29	381 \pm 28	0.55 \pm 0.09
Co	25.4 \mp 3.9	43.1 \pm 3.5	0.59 \pm 0.10
Sb	12.4 \pm 0.7	19.5 \pm 1.2	0.63 \pm 0.05
Sc	24.7 \pm 2.7	45.9 \pm 3.2	0.54 \pm 0.07
Se	55 \pm 18	44 \pm 22	1.27 \pm 0.75
Sr	738 \pm 28	1,320 \pm 20	0.56 \pm 0.02
Ta	3.74 \pm 0.14	7.73 \pm 0.57	0.48 \pm 0.04
Th	45.9 \pm 5.7	86.5 \pm 8.5	0.53 \pm 0.08
Ti	10,500 \pm 900	17,500 \pm 2,300	0.60 \pm 0.09
U	25.5 \pm 2.4	42.0 \pm 3.5	0.61 \pm 0.08
V	268 \pm 18	498 \pm 28	0.54 \pm 0.05
	Average collection efficiency ^a ($\pm\sigma$)(excluding Br and Se)		0.60 \pm 0.05
	Range		0.47 - 0.71

^a Includes additional data reported in reference 15

Table 3. Ratios of observed elemental masses on a typical afterfilter to those adjusted for particle bounce

Element	Ratios
Mo, Sb, As, Ba	1.0 \pm 0.3; 1.18 \pm 0.08; 1.19 \pm 0.08; 1.3 \pm 0.1
Se, W, V, In	1.3 \pm 0.1; 1.4 \pm 0.2; 1.5 \pm 0.2; 1.9 \pm 0.3
Zn, Fe, U, Sr	2.1 \pm 1.1; 2.9 \pm 1.0; 2.5 \pm 1.2; 2.9 \pm 1.4
Mn	3.8 \pm 2.6
Ca, Ce, Co, Cr Hf, K, Lu, Sc Sm, Ta, Yb	>1.0
Ga, Ti, Eu, Al Dy, Th, La, Na	>1.4, >1.7, >2.0, >2.1 >2.2, >2.6, >2.7, >3.3

Adapted from reference 15

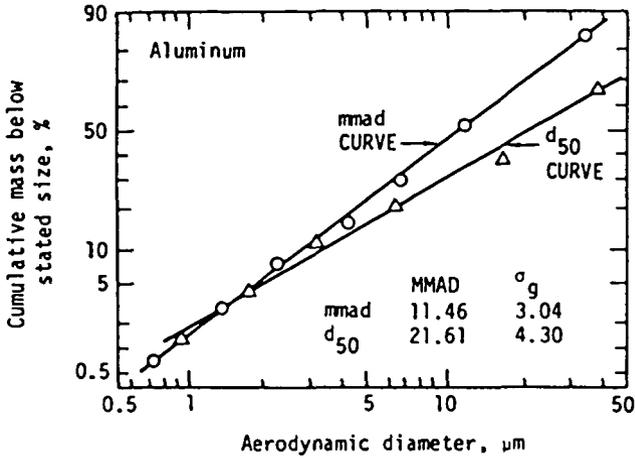


Figure 1. Cumulative mass distributions of the element Al plotted using impactor D_{50} values and mmads derived from SEM analyses. The impactor was run downstream from an ESP with uncoated impaction stages.

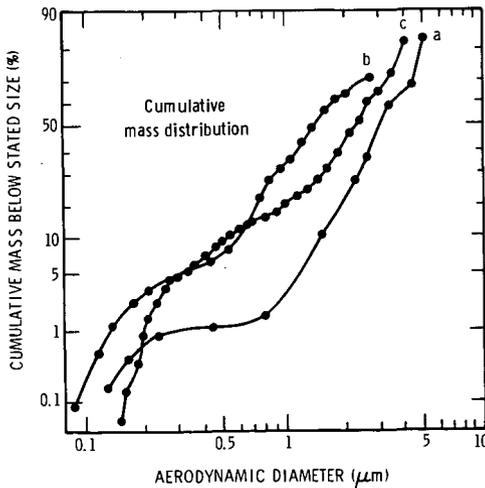


Figure 2. Curve a - cumulative mass distribution for coal combustion particles collected on an afterfilter of a coated impactor. Curve b - cumulative mass distribution for particles collected on an afterfilter of an uncoated impactor. Curve c - cumulative mass distribution for particles collected on an afterfilter at the outlet of a wet scrubber.

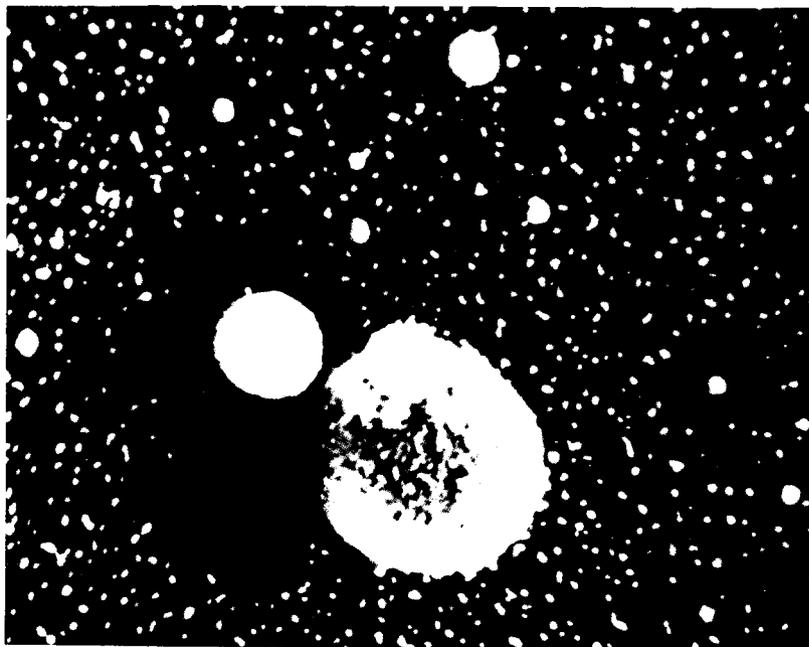


Figure 3. Particles collected on an impactor stage with a D_{50} of $6.4 \mu\text{m}$; 4000X magnification.

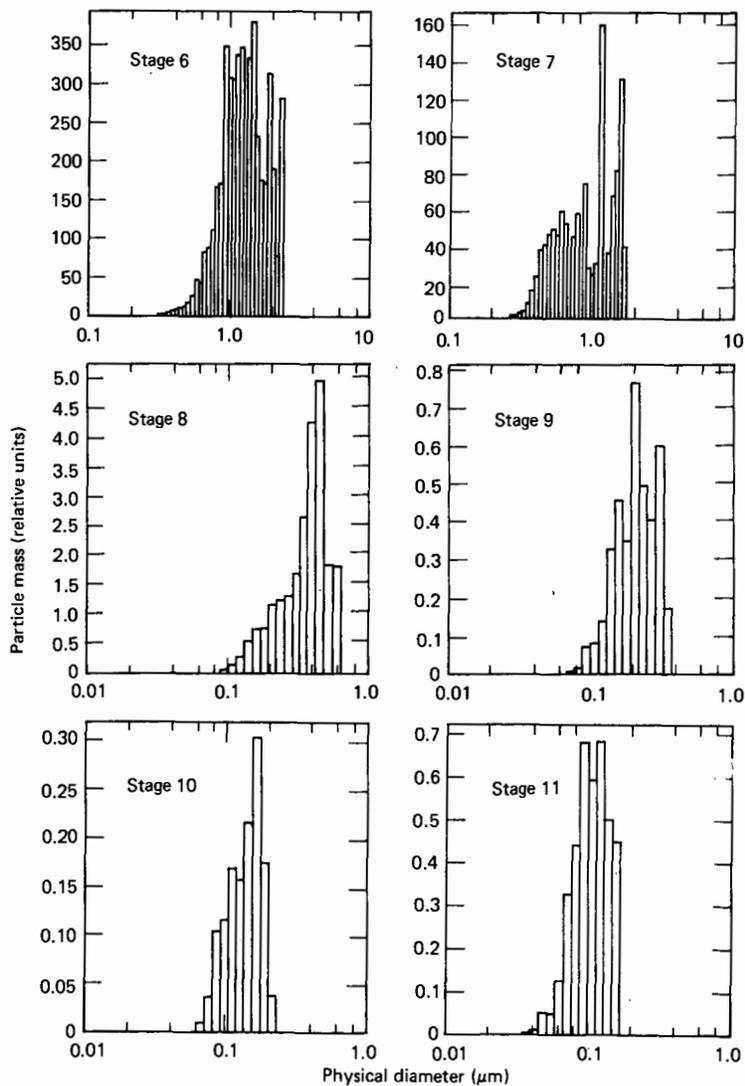


Figure 4. Distribution of particles on stages of a high pressure-drop impactor with submicrometer cut off diameters.