CHAPTER 14

SIZING METHODOLOGY

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CHARACTERISTICS OF AIRBORNE PARTICLES

The most important single parameter useful in predicting or explaining the behavior of airborne particles is a description of their size. This fact can be appreciated more clearly when the wide range of sizes likely to be present is considered. Particle sizes may range from 10^{-7} cm. in diameter for condensation nuclei to 10^{-3} cm., the upper limit for respirable particles, thus covering four orders of magnitude. If the smallest size is visualized as a steel ball 1 mm. in diameter, then at the same scale, the largest size would be 10 meters in diameter. It would be surprising if these particles obeyed the same laws or indeed if they could be measured using the same instrument. If the relative masses of these two particles is considered, the comparison becomes truly astounding (10^{12}). With the same scale a molecule of air would be less than half a millimeter in diameter and the average distance between molecules of air would be approximately 10 cm. Thus, one could visualize particles smaller than 10 cm. on our scale, for example of the order of 0.1 micrometer (0.1 μm), floating about with only occasional contact with molecules of air. When contact did occur, however, the exchange of energy in the collision would be sufficient to alter the course of the particle. On the other hand, a large particle on this scale of perhaps a meter in diameter would be bombarded constantly by air molecules and its motion hindered considerably. In this case however, a collision with a single air molecule would probably go unnoticed. Thus, in attempting to describe the behavior of an airborne particle the most important description has to be its size; many characteristics of dust clouds such as rate of settling, agglomeration, Brownian motion, and diffusion must be primarily size-dependent.

On the other hand, if one wished to compare the behavior of two dust clouds having approximately the same size of particles, other factors could become important. The density of the particles might differ by a factor as high as two or three, and the shape could range from spherical for liquid droplets to needles for fibers or flat platelets in the case of mica or graphite. Certainly these differences would also alter the predicted behavior of the particles.

The hazard of airborne particles results from interaction with the tissue of the lung. In order to reach the deep lung, the particles must pass through the nasopharyngeal region, the trachea, and the bronchi. In each of these regions the airflow is quite turbulent and larger particles tend to be removed by impaction. These particles are transported to the mouth by the mucociliary flow, and therefore enter the gastrointestinal tract. Particles smaller than approximately ten micrometers in diameter, however, can penetrate into the deeper regions of the lung and be deposited where the mechanism for removal involves phagocytosis, a much slower process. Thus the size of particles of concern as a health hazard is generally considered to be below 10 micrometers in diameter. The lower size of the respirable range is less well defined. Particles smaller than a few tenths of a micrometer in diameter are subject to Brownian motion and are deposited in the lung by diffusion with reasonable efficiency. Since it would require millions of these small particles to equal the mass of one 10-micrometer particle the actual dose to the lung may be quite small. There are, of course, certain specific cases as radioactive materials where particles smaller than 0.1 μm in diameter are most important.

Quite apart from physiological considerations there are physical factors which affect the numbers and sizes of particles found in the air. These particles comprise a dynamic system which is constantly changing. Large particles tend to be removed rapidly by sedimentation while smaller ones are likely to agglomerate. In the production of small particles from a bulk material the amount of energy required to reduce relatively coarse material to extremely fine particles may be phenomenal and therefore many industrial processes such as grinding or crushing may be incapable of producing particles smaller than 0.1 micrometers in diameter. Welding operations, on the other hand, produce copious quantities of 0.01 micrometer fumes. Any given sample of airborne dust may therefore contain a wide variety of shapes as well as sizes of particulate matter.

This, of course, makes a description of particle distribution somewhat difficult. If all the particles were of one size, one would merely have to measure that size to define the distribution. If they were all spherical one could measure a sample of the particles and perhaps report an average size. If the shapes are irregular, however, one must first decide what dimension is to be considered as the particle diameter. Three possibilities are shown in Figure 14-1. Martin's diameter is the length of a line which divides the particle into two equal areas. This line could be drawn in any direction for the first particle to be measured, but all other particles should be measured in a direction parallel to the first. If the particles are randomly oriented and a large number

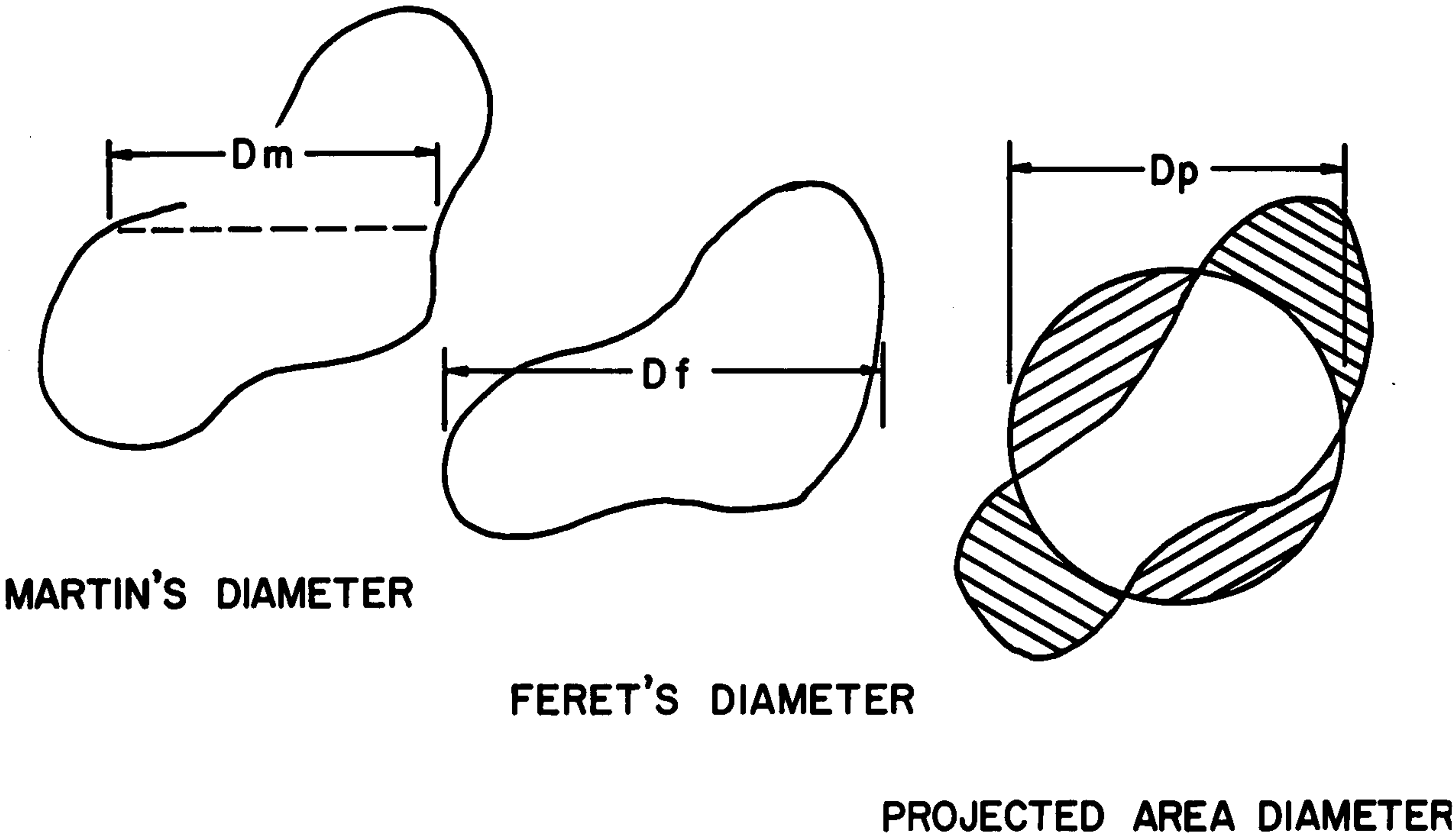

Figure 14-1. Geometric Diameters for Irregularly Shaped Particles

are measured, the direction of measurement is not important. Feret's diameter is the distance between the extreme boundaries of the particle. Again all measurements should be made in the same direction. The projected area diameter is the diameter of a circle having the same cross-sectional area as the particle. Other possibilities would be to measure the longest or shortest dimension of the particle. Estimates of the average size obtained by measuring the shortest diameter would yield the smallest value. Martin's diameter would be followed next by the projected area diameter and Feret's diameter. Measuring the longest dimensions would yield the greatest average diameter. Which then would be nearest to the correct or most useful estimate? Obviously neither the shortest nor the longest dimensions accurately describe the mass of the particles measured although recent work has indicated the smallest dimension may most nearly predict the aerodynamic behavior of fibrous particles. Martin's diameter would seem to underestimate the true size and Feret's diameter would appear to be an over-estimate. The projected area diameter therefore would seem to offer the best estimate of the true size. It is worth noting that for spherical particles all of these estimates would be the same. This statement may take on more significance when one realizes that as particle-size decreases all particles tend to approach the spherical or at least an isometric shape.

STATISTICAL CONSIDERATIONS

A sample of airborne dust will always yield particles of many different sizes and therefore can be called polydisperse. When we consider the behavior of airborne particles, the degree of this polydispersity is usually far more important than factors of shape and perhaps even density. Therefore a simple statement of the average diameter is not very useful in describing these particles. It would indeed be desirable to also be able to describe the degree of polydispersity. If we would assume that the sizes of the particles followed the normal or Gaussian distribution (bell shaped) we could use the powerful techniques of statistics to describe and analyze the distribution[1]. Thus we could say that 67% of all the particles had sizes falling between the limits of plus or minus 1 standard deviation from the mean, 95% between plus or minus 2 standard deviations and 99.7% between plus or minus 3 standard deviations. The average size of the distribution would be given simply by:

$$\bar{d} = \frac{\sum_{i=1}^{n} N_i d_i}{\sum_{i=1}^{n} N_i},$$

where $\bar{d}$ is the average size of the distribution, and N_i is the number of particles of size d_i; the stan-

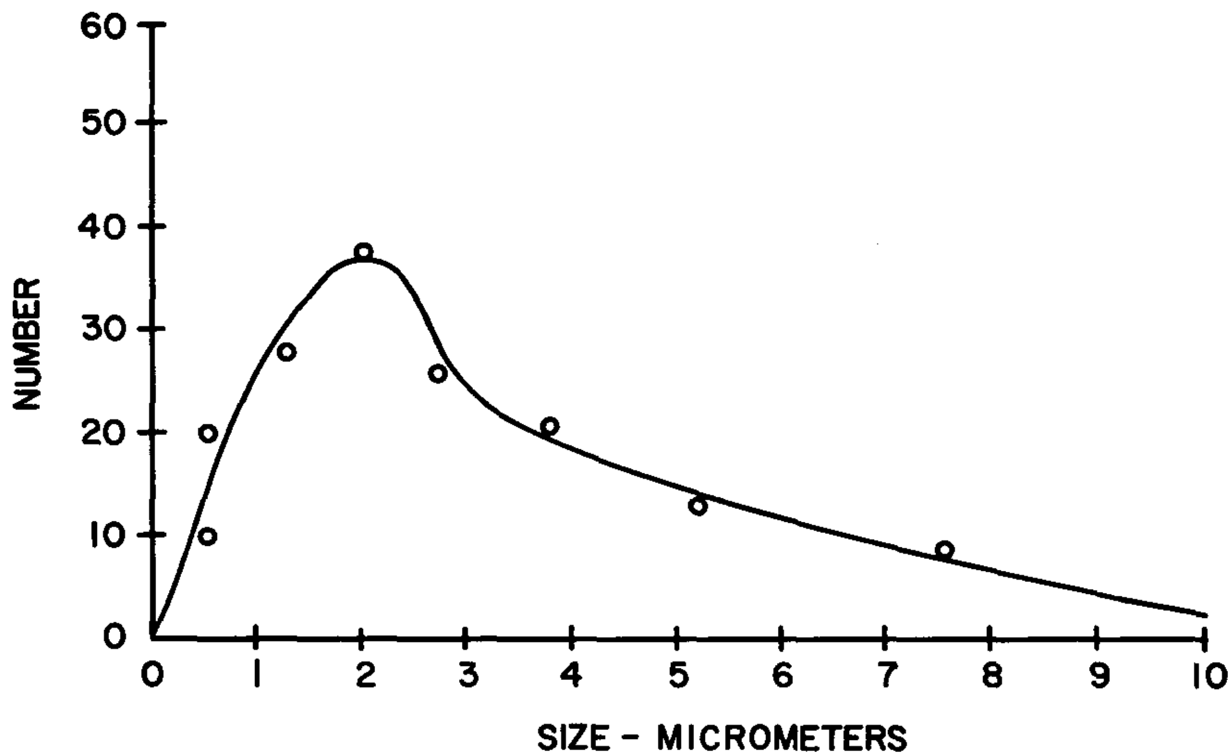

Figure 14-2. Log — Normal Size Distribution

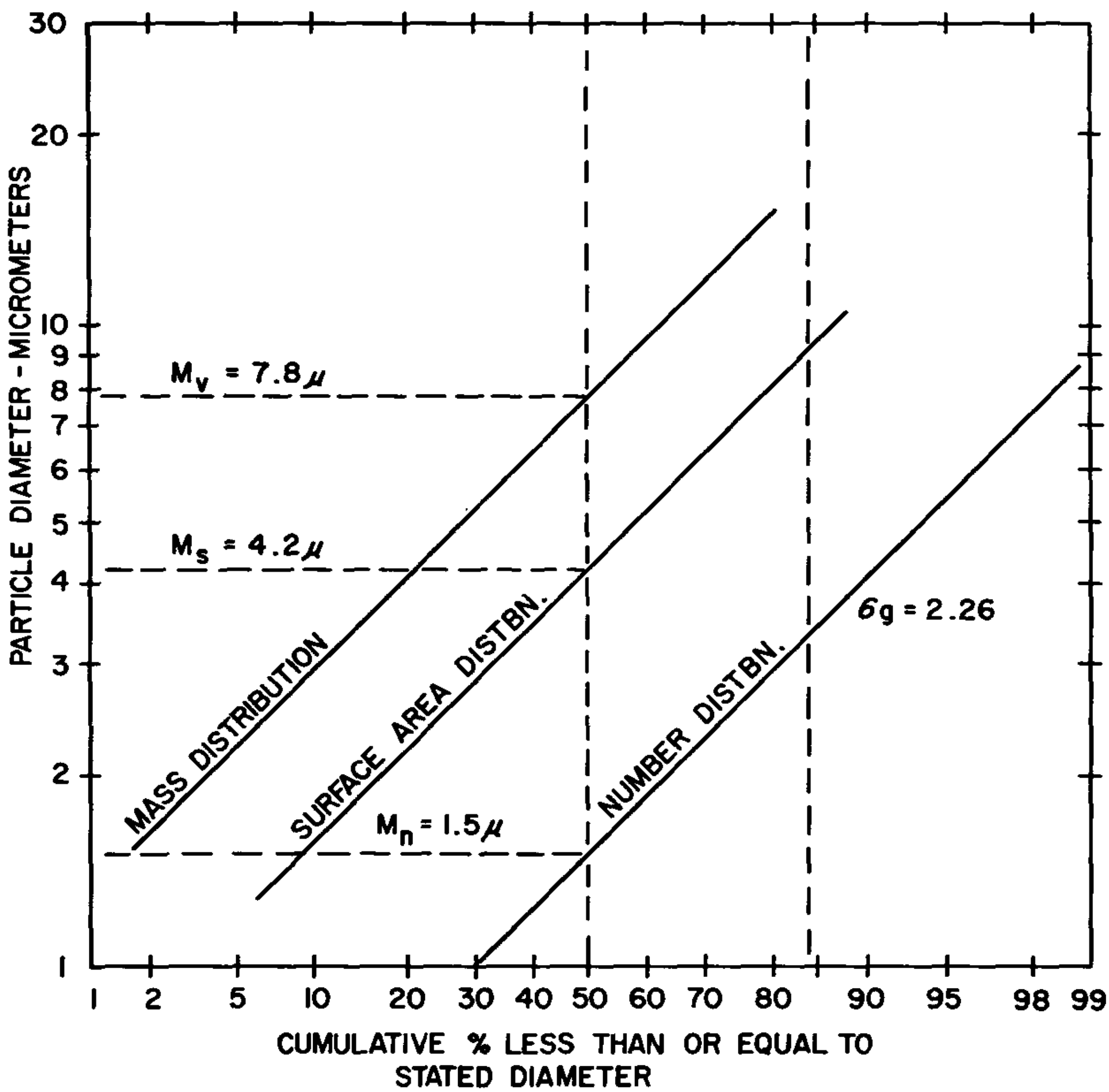

Figure 14-3. Summated Size-Number, Size-Surface and Size-Mass Distributions Plotted on Log-Probability Paper

dard deviation would be a measure of polydispersity:

$$\sigma = \left(\frac{\Sigma(d_i - \bar{d})^2 N_i}{\Sigma N_i - 1}\right)^{1/2}$$

Unfortunately, the particle sizes of most aerosols are not normally distributed due to the loss of larger particles by sedimentation and other factors mentioned above. Instead the curve is usually skewed toward the smaller sizes. A typical skewed distribution is shown in Figure 14-2; the data is given in Table 14-1. Hatch[2] showed, however, that if one plotted the logarithm of the particle size instead of the actual size the result closely approximated a normal distribution. Thus, we can say that:

TABLE 14-1: Particle-Size Distribution

size-μm	number	Σn	Σ%
0.5	10	10	5
0.7	22	32	16
1.0	26	58	29
1.4	29	87	43
2.0	37	124	62
2.7	28	152	76
3.8	22	174	87
5.4	14	188	94
7.7	8	196	98
10.9	4	200	100

$$\bar{d} = \log^{-1}\left(\frac{\Sigma N_i \log d_i}{\Sigma N_i}\right)$$

and

$$\sigma = \log^{-1}\left(\frac{\Sigma(\log d_i - \log \bar{d})^2 N_i}{\Sigma N_i - 1}\right)^{1/2}$$

We are saying that the log-normal distribution provides a reasonably good approximation of the particle-size distribution usually found in airborne dusts. It should be noted, however, that other possibilities do exist and such occurrences as bimodal distribution or the mixing of dusts from two entirely different sources (smoke and dust for instance) happen frequently.

If we accept the log-normal distribution as representing the actual size-distribution of airborne particles, we can simplify our calculations by resorting to a graphical solution. If we plot the summated size-distribution on logarithmic-probability paper, the result should be a straight line if the assumption of a log-normal distribution is correct. The lower line of Figure 14-3 is such a plot of the data from Figure 14-2. From this graph we can read directly the median or 50% size. In the illustration 50% of the particles are larger than 1.5 micrometers and 50% are smaller. We can also read any other points on the curve. 80% of the particles measured were smaller than 3.0 micrometers in diameter and 95% were smaller than 5.0 micrometers. As a measure of the polydispersity we can also find the standard deviation by dividing the 84.13% size by the 50% size, in this case 3.4 micrometers, divided by 1.5 micrometers gives a standard geometric deviation, σ_g, of 2.26, a dimensionless number. The same value for σ_g could, of course, be obtained from the other end of the curve by dividing the 50% size by the 15.87% size. The standard geometric deviation therefore represents the slope of the line and along with the median size is sufficient to describe the distribution.

The log-probability distribution described above is expressed mathematically as follows:

$$F(d) = \frac{\Sigma N}{\log \sigma_g \sqrt{2\pi}} \exp.\left[-\frac{(\log d - \log \bar{d}_g)^2}{2 \log^2 \pi_g}\right]$$

where F(d) is the frequency of occurrence of the diameter d, ΣN is the total number of particles, σ_g is the standard geometric deviation and d_g is the geometric mean diameter. This function predicts the existence of all sizes of particles from zero to infinity. Since the number of particles contributing to the extremes of the distribution is small, the confidence bands around the two ends of the line are wide and become narrowest at the 50% size. It can be shown that in order to estimate the median size within 10% of the true mean with 95% confidence, a minimum of 200 particles must be measured. If, on the other hand, we wished our estimate of the median size to be within 5% of the true mean with the same degree of confidence, we would have to measure at least 1000 particles. In the example given above we estimate the median size to be ±0.15 micrometers. For most purposes this is an adequate estimate and therefore the measurement of 200 particles is sufficient.

The number-size distribution of the particles having been established, other parameters of interest can also be determined. If we wished to examine the distribution of mass among these particles, assuming a constant density, we could multiply the frequency of occurrence of particles in each of our size ranges by the cube of the average diameter for that range and summate these weighted frequencies. This is shown in Table 14-2.

TABLE 14-2: Size-Mass Distribution Data

size	n	d	d^3	d^3n	Σd^3n	$\Sigma\% d^3n$
0.5	10	0.25	0.02	0.2	0.2	0.0
0.7	22	0.6	0.22	4.9	5.1	0.0
1.0	26	0.85	0.61	16.	21.1	0.3
1.4	29	1.2	1.7	46.	67.1	0.8
2.0	37	1.7	6.1	230.	297.1	3.0
2.7	28	2.3	10.2	290.	587.1	7.0
3.8	22	3.2	32.0	700.	1287.1	16.0
5.4	14	4.6	93.0	1300.	2587.1	33.0
7.7	8	6.5	260.	2100.	4687.1	59.0
10.9	4	9.3	790.	3200.	7887.1	100.0

Plotting these data as summated percentages on log-probability paper produces a curve which represents the mass distribution of the aerosol. This is plotted as the upper curve of Figure 14-3. From this curve we can obtain the mass-median diameter or the size below or above which half of the mass of the particles would occur. It should be noted that had the density of the particles been included in weighting each frequency range in the above calculation, the density factor would have cancelled when dividing through by the grand summation to reduce the data to percentages. It is also apparent that the standard geometric deviation of the size-mass distribution (the slope of the line) is identical to that of the number distribution. The size-mass distribution is often useful in predicting the actual dose to the lung resulting from the inhalation of a given amount of dust or the weight of material collected by a filter or other collection device which is efficient only for particles larger than a given size.

A similar technique can be used to describe the distribution of surface-area for the particles in question, assuming spherical symmetry of the particles. In this case the number-frequency of particles in each range is weighted by multiplying by the square of the average diameter of the range. This has been done in Table 14-3 and plotted as

TABLE 14-3: Size-Surface Distribution

size	n	d	d^2	d^2n	Σd^2n	$\Sigma\% d^2n$
0.5	10	0.25	0.06	0.6	0.6	0.04
0.7	22	0.6	0.36	7.9	8.5	0.6
1.0	26	0.85	0.72	19.	27.5	2.0
1.4	29	1.2	1.4	41.	68.5	6.8
2.0	37	1.7	3.6	140.	208.5	14.8
2.7	28	2.3	5.3	149.	357.5	25.3
3.8	22	3.2	10.0	220.	577.5	40.8
5.4	14	4.6	20.1	180.	757.5	53.5
7.7	8	6.5	40.2	320.	1077.5	76.0
10.9	4	9.3	83.0	332.	1409.5	100.0

the middle line of Figure 14-3. The surface-area distribution is sometimes useful in comparing or predicting surface related phenomena such as the scattering of light, adsorption of vapors or the reaction of insoluble particles with biological tissues. Hatch[2] has proposed equations which permit the direct calculation of the mass-median (M_g) and surface-median (S_g) diameters from the size-median diameter without the weighting procedures described above. The most important of these is given below:

$$\log M_g = \log d_g + 6.9078 \log^2 \sigma_g$$

Since σ_g is the same for the mass and number distributions, calculation of M_g permits the curve describing the entire mass distribution to be drawn immediately.

MEASUREMENT TECHNIQUES

The technique of measuring the size of airborne particles has to begin with the selection of the sampling instrument. The factors which must be considered to prevent bias of the sample in favor of either larger or smaller particles have been described in Chapter 13. Once a representative sample has been obtained a specimen of this must be prepared for observation and measurement using a standardized technique. Care must be taken that the preparation of this specimen and the measurement technique itself does not introduce bias and destroy the representative nature of the specimen.

Optical Microscopy

In order to serve as a standard method in the field of Industrial Hygiene, a technique should be suitable for use generally in laboratories across the nation. This may preclude the use of certain exotic instruments that are so expensive or complicated that they are found only in a few highly specialized laboratories. For the counting and sizing of airborne dust particles, the optical microscope is usually available and can be operated by a trained technician. For particle-size analysis any good quality clinical microscope is adequate. Because the size of the smallest particles to be measured will approach the theoretical limit of resolution of the optical system, the illumination either built into the microscope or provided by the operator should meet the requirements of either Kohler or critical illumination. Thus the operator must have some knowledge of the optical system that he will use.

The optical microscope[3] is comprised of five basic components: (1) the light source, (2) the condenser lens which focuses the light on the specimen, (3) the specimen stage which holds and makes possible movement of the specimen, (4) the objective lens which produces an intermediate and magnified image of the object and (5) the ocular which further magnifies the intermediate image and presents it as a virtual image to the eye. The heart of the instrument is the objective lens, for the quality of the final image can be no better than that of the intermediate image produced by this lens. The quality of the image is better described as the resolution or fineness of detail that is preserved by this lens. The limit of resolution is given by the Abbé equation:

$$d = \frac{0.61\lambda}{\eta \sin \alpha}$$

where d is the shortest distance separating two fine lines at which the two lines can still be distinguished; λ is the wave-length of the light used; η is the index of refraction of the medium between the specimen and the lens; and α is the half angle subtended between the axis of the optical system, the periphery of the lens and the specimen. It is, therefore, the maximum angle through which the lens can receive light from the specimen. This angle, of course, can not exceed 90° or the specimen would have to be inside of the lens. The sine of α can approach 1.0 as a limit and is usually 0.94 for a high magnification lens. The index of refraction of the medium is also limited, being 1.0 for air, 1.33 for water and 1.515 for the usual immersion oils. The product of the index of refraction and the sine of α is called the numerical aperture (N.A.) of the lens. This will range from 1.25 for a high magnification (97x) oil immersion lens to less than 1.00 for a low power lens. The wavelength of the light used is limited to the visible spectrum. Thus the shortest visible wavelength will be at the violet end of the spectrum and of the order of 400 millimicrons. Substituting these values in the Abbé equation shows that the theoretical limit of resolution for any optical lens must be approximately 200mμ (0.2 μm). In order to attain this, however, the full numerical aperture of the lens must be utilized, and this is possible only with a condenser lens having a high numerical aperture and either Kohler or critical illumination. In addition to this the objective lens must be of high quality and corrected for chromatic abberations for three colors. Such a lens is called an apochromatic objective.

The quality of the ocular is somewhat less important. The limit of resolution of the eye is usually taken to be approximately 0.1 mm. If the finest detail in the specimen is magnified to 0.1 mm, it will be discernible to the eye. Therefore, the finest detail resolvable by the objective lens (0.2 μm) has to be magnified only 500 times in order to be visible. If the high-dry objective (usually 46x) were used, a 10x ocular would accomplish this since the overall magnification would be 46x10 or 460. Certain refinements which are available in oculars such as wide field, flat field (for photographic purposes), high eyepoint (for people who wear glasses) and higher magnifications (15-20x) may be desirable and convenient even though they may contribute little to actual improvement of the image.

Preparation of Specimens

Given a satisfactory optical system, the specimen must be suitably prepared for observation and measurement. The sample may have been obtained in the same manner as described in Chapter 13 for dust counting, with either the midget impinger or a membrane-filter. In either case the sample would be prepared in the same manner in the Dunn cell or the haemocytometer or by using the proper immersion fluid to render the membrane-filter transparent. There is no need to relate the sample used for size analysis to any particular volume of air, and it is often convenient, therefore, to collect separate samples for size analysis in order to obtain a greater number of particles. Occasionally, one may be working with a bulk sample of material, and in this case great care must be taken to spread a representative sample uniformly on a microscope slide in such a manner that bias is not introduced by selectively retaining the small particles on the glass surface. It must be remembered that the collection of the sample resulted in the concentration of the particles either on a surface or in a liquid and thus may have resulted in agglomeration or other change from the airborne state. It may, therefore, be necessary to subject the particles to a deagglomeration procedure such as insonation in an ultrasonic generator prior to the preparation of the final specimen. In general it is felt that collection on the membrane filter causes less change from the airborne state than other methods.

Reticles and Calibration

When the specimen has been properly prepared on the microscope slide it must be focused in the field of the microscope. Actual measurement then consists of superimposing on the field a suitable scale, reticle or measuring device. The first device that was used intensively for this purpose was the Filar micrometer. It is, in fact, a substitute eye piece which superimposes on the field a scale comprised of 100 units. Part of this scale is a movable verticle cross-hair which is controlled by a micrometer screw thread connected to a drum dial. The circumference of the drum dial is divided into 100 units and can be read to 0.1 unit by means of a vernier. One complete rotation of the drum dial (100 units) moves the cross-hair one division of the field scale. In practice the cross-hair must be moved in one direction until it just touches one boundary of the particle to be measured. A reading of the drum dial is taken and the traverse continued until the other side of the particle is reached. The difference between the two drum dial readings gives the Feret's diameter of the particle in units. A minimum of 200 particles are measured in this manner.

The Filar micrometer, however, is a tedious instrument to use. The measurement of Feret's diameter obtained with this instrument is less representative as the particles depart from isometric. For these reasons reticles which are more easily used have come into favor.

The most common of these is the Porton reticle which is named after the research group in England that was responsible for its design. It consists of a photographically reduced and reproduced transparent grid which is mounted exactly in the focal plane of either the Hygens or the Ramsden ocular. The grid is thus superimposed on the field of the microscope. A picture of this grid superimposed on a dust specimen is shown in Figure 14-4. It consists of a large rectangle one half of which is divided into six smaller rectangles. Along the top and bottom of the rectangle are a series of circles or dots of increasing size. The diameter of each dot is larger than the previous one by the square-root of two. Thus the diameter of any circle in Porton-units is given by:

$$d = \sqrt{2^n}$$

where n is the number of the circle. The height of the large rectangle is 100 units and its length is 200 units. Either the length or height can be calibrated against a stage micrometer to determine the value of one Porton unit in micrometers. Measurements are made by comparing the size of the particles with the circles to find the circle that would completely enclose the particle. This can be done visually and without superimposing the circle on the particle by moving the stage of the microscope. Therefore, all particles contained in the area defined by the six smaller rectangles can be sized before moving on to a new field. This tends to minimize the possible bias of sizing only the larger particles. There is, of course, a natural tendency to equate projected areas of the particles

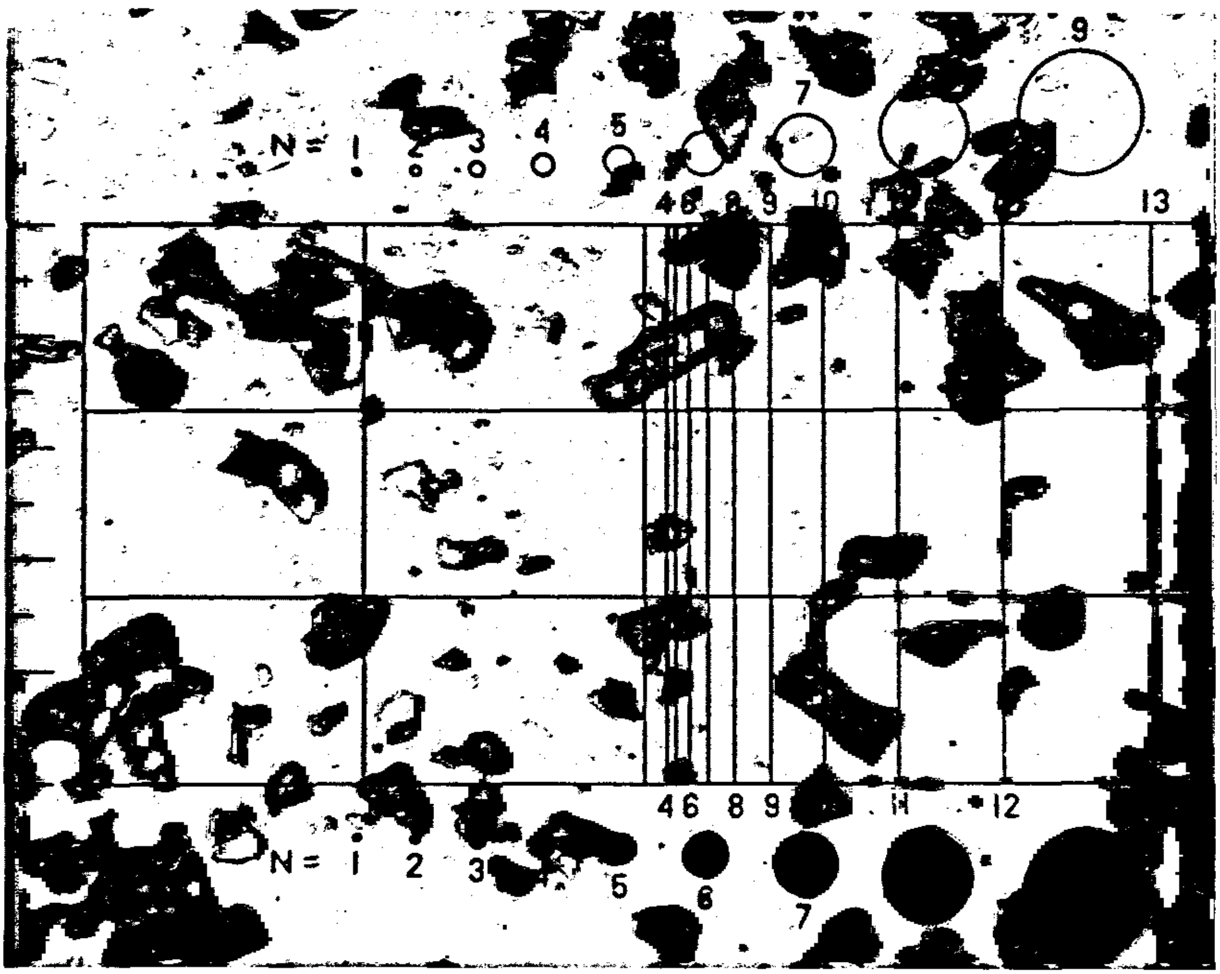

Figure 14-4. The Porton Reticle Superimposed on a Dust Field

and circles. In many cases this projected area diameter is more desirable than Feret's diameter. The entire analysis can be done by one operator and only one reading is required for each measurement.

The calibration of any reticle placed in the optical system consists of comparing that reticle to a stage micrometer substituted for the actual specimen and using exactly the same optics that are used for measurement. Thus one cannot calibrate the optical system using the 10x objective and then switch to the 46x or oil immersion objective to size the particles. Nor can a calibration be transferred from one microscope to another even if similar lenses are used. The tube length of the microscope on older models can sometimes be adjusted to make the calibration result in even numbers. It is good practice, therefore, to include the calibration data with each size analysis and also, if possible, a photo-micrograph superimposing the reticle directly on the image of the stage micrometer so that the reader can see for himself that the calibration is at least approximately correct.

RELATED TECHNIQUES

Although the standard method for particle-size analysis with the optical microscope is usually adequate to describe the implication to health of airborne particles, there may be special situations which require the application of more sophisticated techniques. Smoke and fume particles may well lie below the limit of resolution of the optical system. Continuous monitoring using automated instrumentation and an immediate readout may be desired. It is appropriate therefore to describe a few of the techniques which may be useful in research or specialized field application.

The Electron Microscope[4]

Because of the short wavelength associated with a beam of electrons, the theoretical limit of resolution of the electron microscope is extremely small. In practice resolution between 10 and 20 angstrom units is readily attainable. Physically the electron microscope is quite analogous to the optical microscope. It consists of a heated filament which is the source of electrons, a condenser lens, a mechanical stage, an objective lens, a projector lens and a fluorescent screen which converts the electron image into visible light. Electrons, having both mass and charge, have a short path length or penetrating power through any medium, and a high vacuum is necessary if they are to travel the length of the microscope column. Since the specimen must be placed in the vacuum, only dry nonvolatile materials can be examined. These must be extremely thin (0.1μ or less) and be supported on a thin film of low density material. Classically, films of collodion or Formvar (R) approximately 100 A° thick are used to support the specimen. These films in turn are supported on 200 mesh grids of copper or stainless steel ⅛ in. in diameter.

Preparation of the specimen consists of transferring the airborne particles which may have been collected by a technique described in Chapter 13 to a previously prepared film and grid. Because of the high magnification of the electron microscope and consequently the small field to be observed, the preparation of the specimen without introducing bias is more critical than in the case of optical microscopy. The particular technique will depend on the method that was used to collect the sample. If the dust sample was collected in water by impingement, a drop of the particulate suspension may be placed on the grid and allowed to evaporate to dryness. If a bulk sample of insoluble dust is to be examined, a dilute suspension of the particles in distilled water may be prepared. Insonation by ultrasonic energy is often useful to deagglomerate the particles. If the sample has been collected on the membrane filter, it may be transferred to a grid by placing a small piece of the filter face down on a Formvar (R) grid and removing the filter media by solution in ethyl acetate as described by Fraser.[5] Airborne dusts or fumes may be deposited directly on the filmed grids by electrostatic or thermal precipitation. In each case, however, the size distribution may be altered.[6] Shadow-casting, the technique of evaporating a thin film of metal on the specimen from a low angle, can be used effectively to enhance the detail and increase the contrast of any of the above preparations.

Impaction Devices

Impingement implies the collection of particles in a liquid medium. Impaction, on the other hand, describes the deposition of particles on a dry (or adhesive coated) surface. If air moving at high velocity is forced to change direction abruptly by an obstacle, particles entrained in the air may be unable to follow the air stream and, due to their momentum, may collide with the barrier. If in a single instrument air is drawn through a series of orifices of decreasing size, the velocities attained will increase as the cross-sectional area of the orifice decreases. With increasing velocity, smaller particles will be forced to collide with an obstacle such as a microscope slide placed in the path of the jet. Only large particles will be deposited on the first stage of this device while smaller particles will deposit on subsequent stages. Such a device is called a "cascade impactor" and is used to collect particles in various size fractions. It should be noted that the range of sizes collected on each stage depends on the density and shape of the particles as well as the diameter and therefore represents the aerodynamic behavior of the particles. The number or weight of particles collected on each stage can be determined by counting, using an optical microscope, by weighing or by chemical analysis. If the density of the dust is known and a size-distribution is obtained for each stage, a relationship can be calculated which will permit one to predict what size of particles will be deposited on each stage for dusts of different densities. For subsequent analyses it is only necessary to determine the mass of material collected on each stage in order to describe the particle-size distribution. The volume flow of air through the device must of course, be kept constant. Because of the varieties of sizes, shapes and densities of airborne particulates inertial impactors are usually calibrated with reference to a standard material. If this standard consists of spherical particles having a density of 1 gm/cc (polystyrene latex balls), then in subsequent analyses particles of irregular shapes and varying densities will be classified according to their aerodynamic equivalence to these unit density spherical particles.

A recent innovation has been the Anderson sampler which is a multi-orifice cascade impactor. A number of orifices of the same size are arranged in concentric circles on each stage. Orifice diameters decrease for each succeeding stage and the diameters of the circles in which they are arranged are staggered on alternating plates; thus the orifice plate serves as the collecting plate for the preceding stage. This design has a number of advantages over single jet impactors. The multiple jets permit large air flows and the collection of larger samples. The plate construction can be quite thin and light-weight permitting more sensitive weighing. The instrument has fewer parts and each time the plates are cleaned the jets are also cleaned. The orifices are circular and therefore the machining can be more precise and the calculations simpler. There is a minimum size of particle which can be collected by inertial impaction. This is the smallest particle that can be collected when the air passing through the jet reaches sonic velocity. This maximum velocity limits the collection of particles by this technique to those larger than a few tenths of a micrometer in diameter. It may be desirable to follow the cascade impactor with a membrane filter or an electrostatic precipitator to collect smaller particles.

Centrifugal Collectors

Centrifugal classifiers or cyclone separators have been used commercially for many years to provide aerodynamically sized fractions of bulk materials. In sampling technology they are generally used as pre-filters to eliminate particles larger than the respirable size. In a few instances the technique has been used to provide information concerning the size of airborne particles.

When an air stream containing dust is forced to follow a circular path, the particles experience a centrifugal force which tends to move them across the stream lines toward the outer wall of the vessel or duct. The centrifugal force increases as the radius of curvature decreases. In the cyclone collector the air stream is introduced tangentially into the widest section of a cone and forced to follow a spiral path of decreasing radius of curvature to the apex of the cone. Thus the centrifugal force increases to a maximum at which point all particles larger than a minimum size will intersect the wall of the cone and be collected. The minimum size that will be collected depends on the dimensions of the cone, the inlet velocity of the air and the distance that the particle must travel perpendicular to the direction of the air flow in order to reach the side. The greatest efficiency will be provided by a long narrow cone operating at high air velocity.[7] For any given cyclone the minimum size can be increased or decreased by varying the air velocity. Goetz designed an aerosol spectrometer which passed the air in a narrow channel between two concentric rotating cones so that the larger particles were eliminated at the larger end and smaller ones were deposited near the apex. By examining the surface of the outer cone and measuring the distance between the point of inlet and point of deposition, and knowing the speed of rotation and therefore the centrifugal force, he was able to calculate the aerodynamic size of the particle. This instrument was particularly useful in investigating the effect of air, temperature and humidity on the size of particles.

Light Scattering

In the search for automated techniques, instruments which can detect light reflected or scattered from the surface of airborne particles have been developed. A major advantage of such a technique is that the particles need not be collected but are examined in their airborne state. These instruments may respond to light scattered by all particles contained in a fixed volume or the light from individual particles. While the former are sensitive to changes in the number of particles, they are of little use in determining the size of the particles since many small particles may scatter the same amount of light as a few larger ones. Since the light from a discrete particle is reflected from its surface, it can be related to its size. This, however, is not a simple relationship since light may also be diffracted by the edge of the particle or adsorbed a specific wavelength by colored particles. This is further complicated when the particle-size approaches the wavelength of the light. Thus the intensity of light scattered depends on the angle of observation relative to the direction of the incident beam, the greatest intensity usually being observed in the forward direction or looking back toward the light source. The original theory of light scattering was described by Rayleigh for large particles and by Mie for small particles approaching the wavelength of light.[8] Mathematical functions and tables have been constructed to describe the light scattered at various angles by transparent isotropic spheres. This is, of course, most useful, but one has only to consider the effect of particle shape ranging from flat platelets to long fibers to imagine the complexity of the practical situation. In spite of this, light-scattering devices can be calibrated empirically for a particular dust with a standard chemical or optical method and can be extremely useful for routine monitoring of clean rooms, animal inhalation chambers, certain industrial processes and testing of filter penetration.

Measurement of Electrical Charge

Airborne particles undergo a continuous bombardment of approximately 10^9 collisions per second by the molecules which comprise the air. If a portion of these molecules are electrically charged ions, this charge will be transferred to the particles and if the ions are unipolar the particles assume this polarity. Due to the coulombic force of repulsion between like charges this charge will be distributed on the surface of the particles. The first ions which approach the neutral surface experience no repulsive force but as the total charge on the particle increases additional ions approaching the surface must overcome a force of repulsion if contact is to be made with the surface. It is apparent that there will be a maximum number of charges that a particle can accept for a given concentration and energy of the ions in its environment. This maximum will be a function of the surface area of the particle.

A charged particle which finds itself in an electrostatic field between two plates will migrate toward the plate of opposite polarity. The velocity that it attains will depend on the field strength as well as the charge to mass ratio of the particle. Since the ratio of the surface to the mass is greatest for small particles, this will also be true for the charge to mass ratio. Small particles will therefore have a greater mobility in the electrical field than larger ones.

In recent years instruments have been developed to take advantage of the phenomena to classifiy particles according to their size.[9] The airborne particles are first subjected to a dense concentration of unipolar ions. Maximum charging of the particles can usually be attained in a few milliseconds. They are then passed between a series of plates each of which subjects the particles to an electrostatic field of increasing strength. Thus the free ions will be eliminated by the first field while small charged particles will be collected by the next, and larger particles by subsequent plates. A sensitive electrometer connected to each of the plates can measure the electrical current collected at each stage. Thus the fraction of the current flowing in each stage becomes a measure of the number of particles of each size that comprise the overall particle-size distribution.

The major advantage of the charge measuring technique is its ability to cope with the total range of particle sizes from air ions to large dust particles and its great sensitivity for the smallest particles. The equipment, however, is extremely complicated and expensive, and it is not now feasible to use it as a field instrument.

SUMMARY

Information concerning the distribution of airborne particles can be obtained by means of a variety of methods and techniques which measure any one of several physical properties of the particles. The interpretation of the results from measuring different physical properties may be quite different and not necessarily comparable.

It is most important, therefore, that the sampling device, the measurement technique, and the parameter measured be chosen with careful consideration of the application to be made of the data. It is often true that as the sophistication of the instrumentation increases, the actual parameters measured become more obscure. The industrial hygienist should be thoroughly familiar with the basic concepts and the relatively simple techniques that can be used for estimating the size of airborne particles, since these provide a basis for standardization of automated equipment and a solution to problems when such equipment is not available.

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3. Staub
4. British J. Applied Physics
5. Environmental Science and Technology
6. Review of Scientific Instruments
7. Health Physics
8. British Journal of Industrial Medicine
9. Annals of Occupational Hygiene
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