American Industrial Hygiene Association Journal

ISSN: 0002-8894 (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/aiha20

Technique for Assessing the Electrical Charge Levels of Aerosols

Frank B. Liebhaber , Arvydas Juozaitis , Klaus Willeke , Paul Baron , Glenn Talaska & Chih-Chieh Chen

Technique for Assessing the Electrical Charge Levels of Aerosols

Frank B. Liebhaber[a,c]
Arvydas Juozaitis[a,d]
Klaus Willeke[a,*]
Paul Baron[b]
Glenn Talaska[a]
Chih-Chieh Chen[b]

[a]Aerosol Research and Respiratory Protection Laboratory, Department of Environmental Health, University of Cincinnati, Cincinnati, OH 45267-0056; [b]Methods Research Branch, Division of Physical Sciences and Engineering, National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention, Public Health Service, U.S. Department of Health and Human Services, Cincinnati, OH 45226; [c]On leave from the Air Force University, Air Force Insitute of Technology, CIMI, Wright-Patterson Air Force Base, OH 45433-6583; [d]On leave from the Academy of Science, Vilnius, Lithuania

A relatively low-cost and easy-to-use method for estimating the charge level on aerosols has been developed. It uses the properties of an electrostatically enhanced (electret) filter combined with an optical particle counter to obtain size-dependent charge levels of workplace aerosols. The optical particle counter is calibrated to give a "filtration equivalent" particle size. For the size range of the present measurements, this is similar to geometric size. The aerosol concentration is measured before and after neutralization to determine a penetration ratio that can be approximately correlated with particle electrical mobility. For a particle of a given size, the penetration ratio increases with increasing particle charge level. The method was calibrated with monodisperse methylene blue particles charged to a known level. A polydisperse $CaCO_3$ aerosol, characterized as to size-dependent charge levels, also was measured. Finally, the charge level on a copy-machine toner dust was measured to simulate a highly charged workplace aerosol. The method is limited to the size range of 0.1 μm to 0.7 μm by the characteristics of the electret filter. Electrical mobilities ranging from 0.01 to 1 $cm^2/statV \cdot sec$ can be measured. The charge level on one particle size in a size distribution is proportional to the charge on other sizes, and can thus be an indicator of charge level of the overall aerosol. Although of limited size-range capability, the method can serve as an indicator of the importance of aerosol charge for sampling or for health effects.

Static electrification of aerosol particles can be of practical importance when considering the health impact of aerosols and aerosol sampling. This is especially true for small particles whose deposition in the alveolar region of the lung can be considerably amplified by charges. The experimental results of Melandri et al.[1] support Yu's[2] theoretical work showing that when the average charge per particle exceeds a threshold value (approximately 50 unit electrical charges (*e*) for a 1 μm particle) the electrical image forces on a particle would enhance deep lung deposition. Industrial hygienists may take note of electrostatic effects for several reasons. High levels of charge on particles can contribute to enhanced deposition on workplace surfaces and worker skin, potentially increasing exposure.

Particle loss due to electrical charge when sampling asbestos is familiar to many industrial hygienists. Baron and Deye[3] have described the trajectories of highly charged fibers entering a sampling cassette, noting resultant losses and nonuniformity of deposit at the filter surface. Liu et al.[4] calculated that sampler aspiration losses are small for the aerosol charge levels measured in several workplaces by Johnston et al.[5] However, sample loss through the sampling train can be substantially affected by particle charge, depending on the type of material and how the sampling train is handled. For example, tubing, cassettes, and cowls can be charged when they are flexed, twisted, or come in repeated contact with charged or easily charged materials, such as

*Author to whom correspondence should be addressed

Mention of product or company names does not constitute endorsement by the Centers for Disease Control and Prevention.

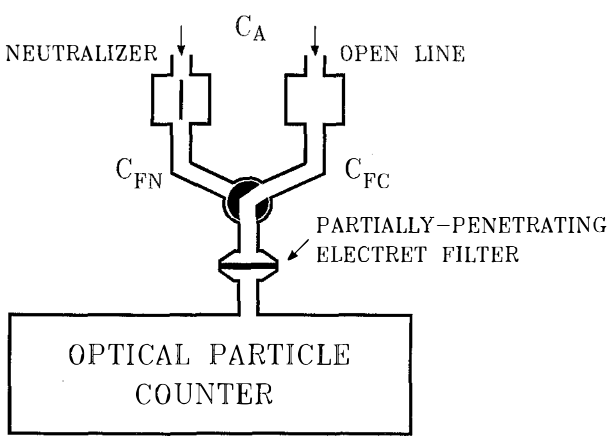

FIGURE 1. Basic apparatus for the filter charge-assessment method

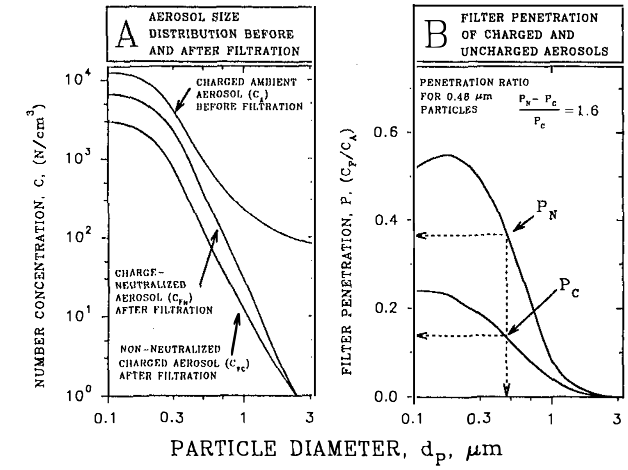

FIGURE 2. The principle of charge assessment using the aerosol penetration through partially penetrating filters

packing peanuts. Sampling filters made of plastic materials, e.g., polyvinyl chloride, polycarbonate, and polytetrafluoroethylene, can become charged through handling and during sampling. Thus, these materials can significantly increase particle deposition within the filter by attraction or repulsion of charged particles.

In a review of static electrification of workplace aerosols, John and Vincent[6] explain why moderately charged isometric dusts found in traditional workplaces pose little problem. In spite of this, they advocate charge measurement to ensure that fine-fiber dusts and new technology aerosols do not enhance inhalation hazards and sampling biases. Examples of workplaces where such problems may occur include charged-spray painting, the manufacture or use of new ceramic and composite fibers, and the manufacture or use of highly charged photocopy-machine toner dust.

The electrical mobility (Z, cm^2/statV·sec) of a particle is indicated by the final velocity reached by a particle in a unit electric field:

$$Z = \frac{neC_c}{3\pi\eta d_p} \qquad (1)$$

where n = number of unit charges, C_c = Cunningham slip correction factor, η = viscosity of air, and d_p = particle diameter. Thus, when a particle is placed in an electrical field, such as near the surface of a charged sampler or between the charged plates of an electrostatic elutriator, its velocity will be proportional to the charge on the particle and the strength of the electric field, and inversely proportional to its diameter. Measurements of particle charge are often made using the electrical mobility of a particle.[7]

Several such charge measurement methods are available.[7] However, measuring the charge of an aerosol is not easy, especially outside the laboratory, even though computer control and data management have somewhat streamlined data collection and analysis methods.[8] Aerosol researchers avoid the problems caused by highly charged particles and their assessment by using charge "neutralizers," which reduce the charge level on individual particles to the Boltzmann charge equilibrium, for which particles have low charge levels.[9] This is the same charge level acquired by particles that "age" naturally in the presence of background radiation. When sampling highly charged aerosols shortly after their generation, the typical industrial hygienist is not likely to measure the electrical charge level due to the size, cost, and complexity of the charge measurement methods. However, a simple method for determining the approximate aerosol charge level would allow the industrial hygienist to take appropriate action when needed.

FILTER CHARGE-ASSESSMENT METHOD

The basic principle utilized to develop a practical field charge measurement method uses the filtration differences between charged and charge-neutralized particles. These differences are caused by coulombic (charge to charge) and dielectrophoretic (charge to image charge) interactions between charged particles and bipolar-charged filter fibers. Artificially electrified filtering (electret) materials made of charged fibers, the type manufactured for some disposable respirators, are suited for this application.[10,11,12] Their electrostatic filtration enhancement amplifies their sensitivity to charged particles while their open structure avoids restrictive pressure drops. This material is used to filter an aerosol before and after neutralization. Size distributions of charged and neutralized aerosols are measured with an optical particle counter (OPC). The charge measurement procedure requires that a filter be attached to the sampling inlet of the OPC and that two measurements be made, one with and the other without connecting an aerosol charge neutralizer. The branched sampling inlet with a three-way valve shown in Figure 1 facilitates the measurement. In this method, charged ambient aerosol with number concentration C_A enters either branch of the apparatus and is filtered. The charged aerosol concentration after filtration is designated

C_{FC}, while the aerosol concentration after neutralization and filtration is designated C_{FN}.

The application of the method is illustrated in Figure 2, where the aerosol number concentrations are plotted as aerosol size distributions in Figure 2A. The charged ambient aerosol concentration C_A is shown here to demonstrate the principle of the method, but is not measured since it is canceled out in the calculation of results. First, the size distributions of C_{FN} and C_{FC} are measured with the OPC. These values are then used to calculate the filter penetration values versus particle diameter in Figure 2B. Filter penetration as a function of particle diameter ($P = C_F/C_A$) is either the neutralized C_{FN} or the non-neutralized C_{FC} divided by the ambient size distribution C_A. Next, the difference in penetration of the charged aerosol penetration P_C and the charge-neutralized aerosol penetration P_N over the penetration of the charged aerosol P_C is used to calculate the penetration ratio PR,

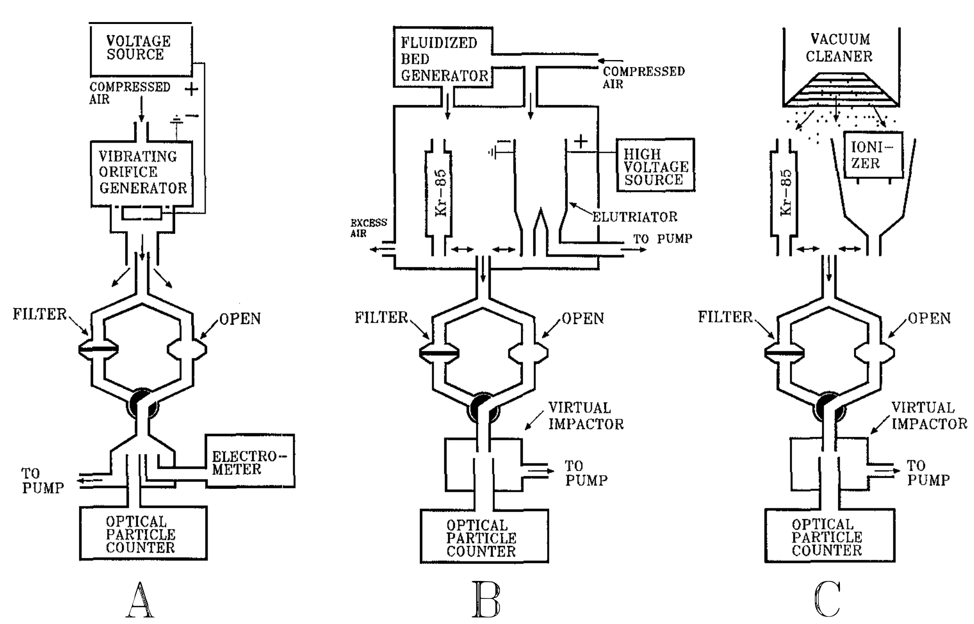

FIGURE 3. Experimental aerosol generation and filtering systems. (A) methylene blue system, (B) $CaCO_3$ system, (C) toner dust system

$$PR = \frac{P_N - P_C}{P_C} = \frac{\frac{C_{FN}}{C_A} - \frac{C_{FC}}{C_A}}{\frac{C_{FC}}{C_A}} = \frac{C_{FN} - C_{FC}}{C_{FC}}. \quad \textbf{(2)}$$

The magnitude of PR corresponds to the aerosol charge level. For example, the penetration ratio equals 1.6 at the particle size of 0.48 μm in Figure 2B and indicates a charged aerosol. The value, PR = 0, indicates a charge level equal to the Boltzmann level.

EXPERIMENTAL MATERIALS AND PROCEDURES

The experimental systems used to evaluate the charge assessment method are depicted in Figure 3. Test aerosols were sampled through branched sampling trains that allowed nearly instantaneous switching between the filtered line and an identical open line. Each line consisted of 1.9 cm i.d. diameter copper tubing terminating at a stainless steel filter holder (Model 2220, Gelman Sciences Inc., Ann Arbor, Mich.), which held a 39 mm diameter disk of filter material. The filter was cut from a disposable respirator consisting of electrostatically enhanced filter material (Model 8710, 3M Co., St. Paul, Minn.). The sections of filter material used in the various experiments were matched according to their penetration curves.

The two sampling rates used produced face velocities of 10 and 20 cm/sec at the filter face. To charge-neutralize the aerosol, a Krypton 85 (Kr-85) neutralizer (Model 3012, TSI Inc., St. Paul, Minn.) was used. A low-flow (0.06 L/min) OPC (Model LAS-X, Particle Measuring System Inc., Boulder, Colo.) calibrated with 0.15, 0.25, 0.55, 0.72, 0.91, 1.10, 2.01, 2.40, and 3.20 μm monodisperse polystyrene latex (PSL) particles (DOW Chemical Co., Indianapolis, Ind.) was used to count and size-classify the sampled aerosol. All the polydisperse aerosol samples were passed through a virtual impactor with a 2.5 μm cut point prior to entering the particle counter. This was done to augment the large-particle fraction of the sampled aerosol and increase the statistical precision of the large particle counts.[13] The aerosol size distribution data from the OPC was recorded with a personal computer. The filter penetration was determined by dividing the OPC counts per size interval downstream of the filter by those measured through the open line. Size-dependent penetration values were plotted as the mean of 10 tests with the error bars showing the 95% confidence interval.

The relationship of filter penetration to charge level on monodisperse particles was observed using the apparatus shown in Figure 3A. Methylene blue particles were generated from a 1/1 solution of distilled, deionized, and filtered (0.2 μm pore size filter) water and isopropyl alcohol (2-propanol, A416-4, Fisher Scientific, Pittsburgh, Penn.) with a vibrating-orifice monodisperse aerosol generator (VOMAG) (Model 50-A, TSI Inc., St. Paul, Minn.). The particle diameter (0.48 μm) was calculated from the VOMAG operating parameters and solution concentration. The VOMAG was modified to induce an equal charge on each particle generated according to the method described by Reischl et al.[14] To induce the desired unipolar charge on the generated aerosol particles, 1 to 55 volts were applied to the space between the generator's orifices. The VOMAG had inlet ports for introducing dry filtered laboratory air for

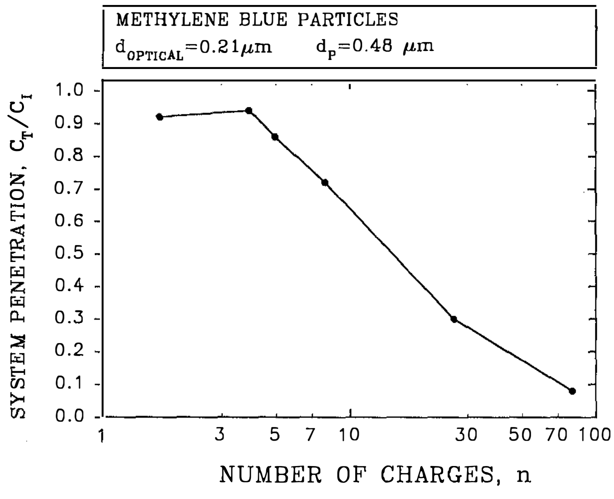

FIGURE 4. Effect of charge level carried by methylene blue particles on sampling and transport losses

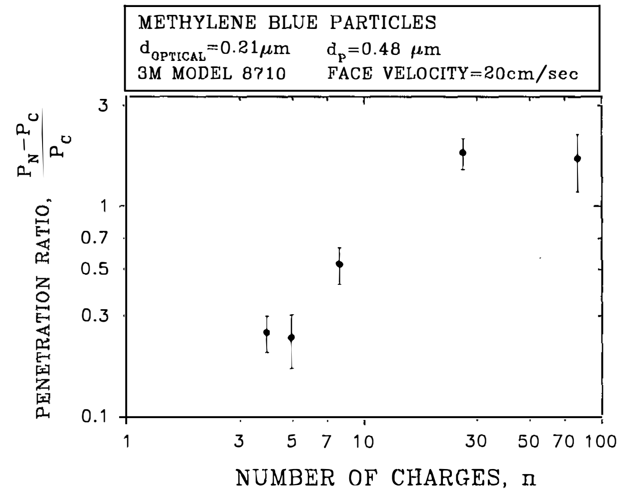

FIGURE 5. Effect of charge level carried by methylene blue particles on penetration through the filter

dispersion and dilution. A portion of the generator's monodisperse aerosol output was sampled for the optical particle counter and the electrometer measurements. The aerosol electrometer (Model 3068, TSI Inc., St. Paul, Minn.) readings were used in combination with the OPC particle concentrations to determine the charge per particle.

The experimental apparatus shown in Figure 3B was used to measure how the charge assessment method related filter penetration to both particle charge and size. A polydisperse calcium carbonate ($CaCO_3$) aerosol was generated from dry powder (C-63, Fisher Scientific Co., Pittsburgh, Penn.) with a fluidized bed generator (Model 3400, TSI Inc., St. Paul, Minn.), which produced aerosols having sufficient charge to significantly enhance deep-lung deposition.[15,16] This aerosol was introduced into a mixing chamber along with dry HEPA-filtered laboratory air. The average charge per particle in each size range was determined by using a split-flow electrostatic elutriator described by Johnston.[17] The elutriator penetration data and the electrical mobility distributions were calculated and smoothed according to Wake et al.[8]

The apparatus used in a field situation to measure aerosol charge is displayed in Figure 3C. Toner dust (styrene acrylate co-polymer and ammonium salt) from a photocopy machine toner-cartridge (Model SF-830NT1, Sharp Electronics Corp., Mahwah, N.J.) was sampled at the exhaust end of a shop vacuum cleaner (Model 3125-B, Eureka Co., Bloomington, Ill.) fitted with an unused dust-collection bag (Style C, Eureka Co., Bloomington, Ill.).

Samples were taken while the vacuum cleaner was actively engaged in dust collection. A Kr-85 neutralizer was first used to neutralize the sample. However, since this neutralizer is cumbersome for field use and requires a radioactivity permit, a 110 volt AC-powered bipolar ionizer (Model X-Static, Westward Electronics, Denver, Colo.) was used to neutralize samples as an alternative to the Kr-85 neutralizer. The bipolar ionizer produces large quantities of ions of both polarities, neutralizing particles in a manner similar to the Kr-85 radioactive source. The ionizer unit ($4 \times 10 \times 11$ cm^3) was placed, with the discharge needles facing toward the filter, at the mouth of a 25 cm tapered sheet-metal cone that acted as the sampling-train inlet. The ionizer was turned on and off to obtain the neutralized and non-neutralized samples, respectively.

Size measurements obtained with an optical particle counter are "optical-equivalent" diameters that are significantly smaller than the physical diameters when the particles are light absorbing.[18] Therefore, the measured optical diameters in this study were corrected to "filter-equivalent" diameters using the technique described by Liebhaber and Willeke.[19] The "filter-equivalent" diameter is the diameter of a unit density sphere having the same penetration value as the particle in question.

This correction was performed by replacing the 3M filter medium in the experimental apparatus (Figure 1) with filter media cut from a partially penetrating filter that employed much less electrostatic collection, but had mechanical collection characteristics similar to those of the 3M filter. A disposable respirator (Gerson model 1710, Gerson Inc., Middleboro, Mass.) utilizes filter material with the appropriate penetration characteristics for this application. By comparing the penetration values of the PSL calibration aerosol particles (0.1 to 3.0 μm) to the penetration values of the aerosol of interest, their respective diameters can be equated. In the supermicrometer size range the filter-equivalent diameter is predominantly an "aerodynamic-equivalent" diameter, while in the submicrometer size range it is mainly a "geometric-equivalent" diameter. Since the charge-determination method studied here deals mainly with submicrometer size particles, the diameters of the optically measured and then filter-corrected particles were described and plotted as "particle" diameter.

The temperature and relative humidity (RH) were monitored during all experiments and ranged between 24 °C and

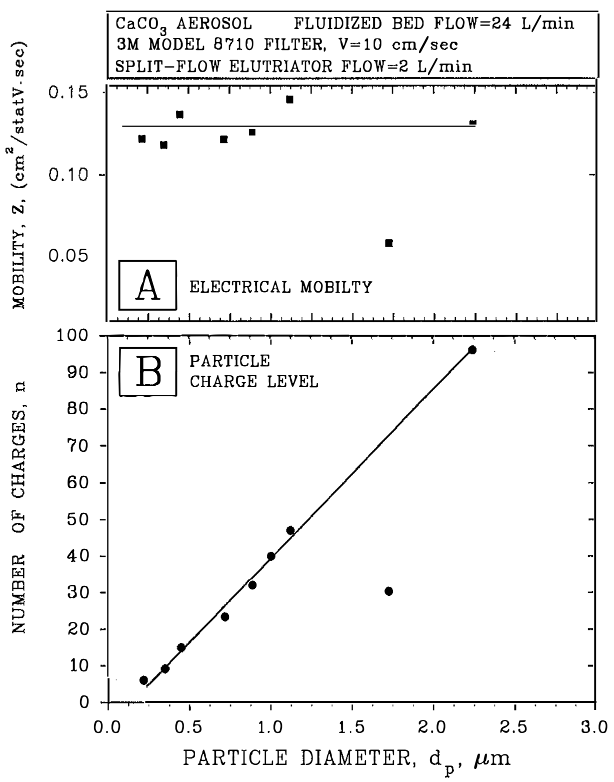

FIGURE 6. Particle electrical mobility and particle charge as a function of particle diameter for the $CaCO_3$ aerosol

28 °C, and 14% and 50% RH, respectively. RH is known to affect the static electrification of particles when they are generated from bulk materials that come into contact with other surfaces. The RH may alter the moisture content of the bulk material and the surface conductivity of an interacting surface.[5,16] The temperature and RH in these experiments were only expected to affect the charge level imparted onto the particles during generation. Once the charged particles were airborne, temperature and RH should not have altered the charge carried by particles, and therefore, were not expected to have any significant influence on the measurement of the charge levels.

RESULTS

Monodisperse methylene blue particles with a mean particle diameter of 0.48 μm were generated with various charge levels. The penetration of these particles through the aerosol generation and sampling system shown in Figure 3A was measured with the OPC. The final particle concentration C_T over the initially generated concentration C_I is the particle penetration (C_T/C_I) through the experimental system. For particles with less than 7 units of electrical charge (*e*), the system penetration was more than 0.85 (Figure 4). As the charge level carried by the particles increased, the losses within the system also increased. Over 90% of the generated aerosol was lost at the 80*e* charge level.

At each of the charge levels, the methylene blue particle penetration through the filter was measured at a face velocity of 20 cm/sec. This filter face velocity was selected because at the initially selected lower velocity, 10 cm/sec, there was insufficient particle penetration of the highest charged particles through the filter to give a statistically significant particle count at the detector. Low counts also were due to particle losses within the experimental system, making the filter penetration measurement more difficult and less certain, especially at charge levels of 80*e* and higher.

The relationship between penetration ratio and charge level in Figure 5 indicates that the penetration ratio of the electret filters was a function of particle charge level, and, hence, particle electrical mobility. The methylene blue particles used for the neutralized aerosol were given a fixed level unipolar charge with the VOMAG at the value predicted for a particle at Boltzmann charge equilibrium (1.7*e*).[18] Use of a radioactive source to neutralize this aerosol may have been more appropriate but probably would not have given significantly different results. The penetration ratio for the methylene blue particles increased from 0.25 at 3.9*e* to 1.69 at 80*e*. The penetration ratio at 80*e* did not appear to follow the increasing trend with charge and may have been low due to errors induced by low particle counts.

$CaCO_3$ particle electrical mobility (Equation 1) was calculated from measurements with the split-flow electrostatic elutriator (Figure 3B) and was approximately constant (Figure 6A). The average charge level at each size calculated from the mobility data was shown to be directly proportional to particle diameter (Figure 6B). The elutriator data point for a 1.7 μm particle with 30*e* (Figure 6B) was apparently an outlier and was not included in the calculated average value of 0.13 cm^2/statV·sec.

The aerosol penetration differences between electrically charged and uncharged filters were noticed by Chen et al.[20] during a study of loading and filtration characteristics of disposable respirators. The data and filter performance parameters reported in that study (effective fiber diameter [d_{FIBER}], filter packing density [α], fiber charge density [δ]) were used in a modified semi-empirical single fiber model[18,20] to predict the filter penetration for charged and neutralized aerosol for the filter material used in this study. The aerosol penetration curves in Figure 7A depict the model penetration values at three filter face velocities. The calculated penetration ratios for the three face velocities are plotted in Figure 7B.

These modeled values are compared with the experimental data for the $CaCO_3$ aerosol at a face velocity of 10 cm/sec in Figure 7. As previously shown in Figure 6A, the $CaCO_3$ particles had an average electrical mobility of 0.13 cm^2/statV·sec independent of size between 0.2 to 2.24 μm. Therefore, this mobility was used to obtain modeled values. The average charge per particle calculated from the data in Figure 6A using Equation 1 increases with particle size (Figure 6B).

The electrical mobility of the charge-neutralized aerosols was Z_N, as calculated for Boltzmann equilibrium. The filter penetrations were measured as a function of the particle diameters of the charged airborne dust (Figure 7A).

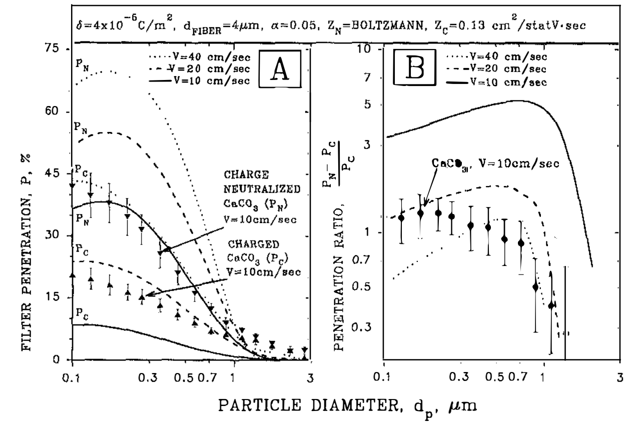

FIGURE 7. Filter penetration relationship with particle size and filter flow for single-fiber efficiency model and the $CaCO_3$ data

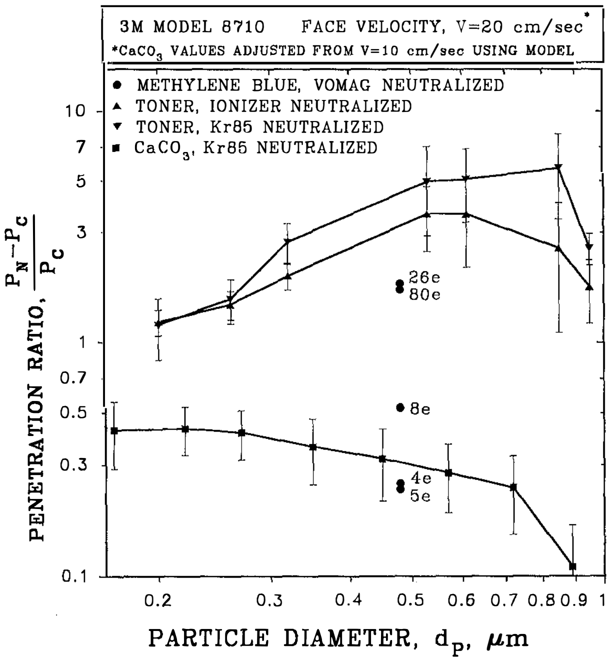

FIGURE 8. Comparison of filter penetrations for toner, monodisperse methylene blue, and $CaCO_3$ aerosols

The penetration values of the charge-neutralized aerosol, P_N, were more than twice those of the charged aerosol, P_C, at the smaller sizes, but converged at the largest sizes. When the penetration ratios of the measured penetration values are plotted, Figure 7B, they show a relatively constant value (in this case, about 1) in the submicrometer sizes, but decreasing values for sizes larger than approximately 0.7 μm.

The filter charge-assessment technique was applied to a field situation by measuring aerosolized photocopy machine toner-dust while the dust was being collected with a vacuum cleaner. Professional copier maintenance personnel generally use vacuum cleaners equipped with more efficient HEPA-filters, preventing the aerosol formation observed here. The two upper curves in Figure 8 indicate the penetration ratios of toner dust in the submicrometer size range. Two charge neutralization devices were tested: a Kr-85 neutralizer traditionally used for laboratory experimentation and a commercial bi-polar ionizer. For comparison with the methylene blue experiment described above, the penetration ratio of a 0.48 μm diameter toner-dust particle (optically sized as 0.21 μm diameter; approximately 1.5 g/cm^3 density) was 4.5 for the Kr-85 neutralizer and 3.4 for the bipolar ionizer.

DISCUSSION

The method described here can be used for estimating the charge level on aerosols. The method depends on the collection characteristics of an electret filter and these characteristics are compared to a semi-empirical filtration model. The following discussion presents some of the features, experimental difficulties, and limitations of the method as well as of the calibration procedures.

Monodisperse methylene blue particles with several selected levels of charge were used to characterize the charge dependence of filter penetration. As also noted by Reischl et al.,[14] the increase in charge level on the methylene blue particles produced a decline in the measured aerosol concentration (Figure 4). Though this decline in concentration is not as noticeable for the 0.48-μm diameter particles carrying charges of 7*e* or less, it is attributed to electrostatic losses within the aerosol generation and, to a lesser extent, within the sampling system. Several mechanisms can produce losses of charged particles within a closed system: repulsion of charged unipolar particles from one another (space charge) and onto the enclosure walls; coulombic attraction or repulsion from the walls; and induced image charge attraction to the walls.[18] Space charge deposition is calculated to be the primary deposition mechanism that occurred almost wholly in the generation system.[21] The apparatus was made of conductive material; hence, there should have been little coulombic interaction of the particles with the walls. Some induced charge losses (10%) were predicted in the OPC inlet for the highest charge level due to the low sampling flow rate and small inlet diameter.[22] Other OPCs with larger inlet flow rates and diameters would have lower losses.

Although the losses in the generation system caused poor counting statistics at the high charge levels, the relatively low losses expected in the measurement system should not invalidate the measured penetration ratio at electrical mobility levels an order of magnitude higher than those observed in these experiments. However, very high mobility particles can be lost at the inlet and within the measurement system and limit the range of the measurement.

The aerosol penetration through an electrostatically enhanced (electret) filter can be used as an indicator of particle electrical mobility and, hence, particle charge (Figure 5). The semi-empirical filter model predicts that if the filter penetration of an aerosol is measured in its ambient state of charge and after it is passed through an aerosol neutralizer, the difference between those two charge states (ambient and Boltzmann equilibrium) will be indicated by the filter penetration ratio. Thus, for a given particle size, filter penetration ratio increases with increasing charge on an aerosol particle of a given size.

The use of Equation 2 assumes that the losses of charged and uncharged aerosols through the measuring system, apart from the filter deposition, are the same. If additional losses occur due to charged particle deposition, i.e., C_{FC} decreases, Equation 2 indicates that the penetration ratio will increase. This might be the case for particles with mobilities higher than those measured in this study.

The data in Figure 5 indicate that for the methylene blue particles tested, the measured filter penetration ratio for the electrostatically enhanced filter increases with particle charge, and, hence, the particles' electrical mobility. At the highest charge level in Figure 5, the penetration ratio appears to level off at a value of about 2.5. Part of this leveling may be due to the increased losses of particles in the experimental apparatus. However, it may also be close to the upper limit of the penetration ratio measurable with this filter, though it is not apparent why this should happen. Further investigation of this phenomenon needs to be carried out, since it may represent an important limitation to the method.

The filter penetration data for the $CaCO_3$ aerosol are more likely to be representative of a workplace aerosol in terms of particle size distribution and charge. Johnston et al.[5] found a variety of mobility relationships with size for different types of laboratory-generated and workplace aerosols. Theory predicts and experiments have confirmed a most penetrating size for most fibrous filters in the range of 0.1 to 0.3 μm.[20] The drop-off of penetration ratio with particle size at about 0.7 μm in Figure 7B may be explained by the increasing influence of inertial impaction and interception, which become the principal filtration mechanisms in the large-particle size range.[18] As also noted in Figure 7, the filtration model predicts this behavior. The characteristics of the filter, i.e., the sizes at which mechanical collection overshadows electrostatic collection, determine the size range for which relative particle charge can be estimated by this method. Figure 7B indicates that this maximum size is approximately 0.7 μm. The measurements do not extend to a small enough particle size to demonstrate a similar limit due to diffusional collection. Increasing the flow rate through the filter shifts the penetration range to smaller particle size.

The model used in Figure 7 for comparison with the measured penetration values and the penetration ratios is a semi-empirical model that adds up all single fiber efficiencies and does not include interactions between the several collection mechanisms. Thus, the shape of the calculated penetration and penetration ratio curves give an indication of the behavior of the filter, but the absolute values predicted by the model do not exactly fit the data.

Between 0.1 and 0.7 μm, the measured particle mobility (Figure 6A) for the $CaCO_3$ aerosol and its penetration ratios (Figure 7B) are both essentially constant with particle size. This supports the proportionality of penetration ratio to particle mobility indicated in Figure 5, but only within the limited size range. This relationship appears reasonable since the principle mechanism of electrostatic deposition in the electret filter is due to the coulombic interaction between the charged particles and the charged filter fibers. However, this measurement was made for only one type of aerosol under a single set of generation conditions and further experiments need to be carried out to verify this relationship.

In order to give optimal results for a selected particle size range, the electret filter method must be optimized with respect to filter face velocity. For a particle with a given electrical mobility, the velocity through the filter determines the time that the particle can interact with the charged fibers within the filter. Hence, as the face velocity through the filter increases, there is less collection of charged particles within the electret filter (Figure 7B). While lower face velocities allow measurement of larger particle sizes and increase the penetration ratio, an experimental limitation to low face velocities exists. At very low face velocities, the enhanced collection efficiency of the filter decreases the number of particles penetrating the filter, resulting in poor statistical precision. In addition, the model predicts that the penetration ratio is approximately proportional to the inverse of face velocity. Since this relationship is only an approximate one, the measurements should normally be done only at the calibration face velocity.

Johnston et al. made many measurements of the dust generated in the laboratory[16] and in industrial workplaces[5] and found a consistent relationship between particle charge and size. Thus, if the charge level for the 0.5 μm particles is determined and found to be significant for lung deposition or sampling effects, then these electrostatic effects are likely to be important for the larger and smaller particles as well. Thus, the limited measurement range of the method presented here is not likely to be a drawback in assessing workplace aerosols as long as the small and large particles are from the same source. If the small particles come from a different source than the large particles, their charge will not be indicative of large particle charge.

The penetration ratio data from the various experiments are compared in Figure 8. The methylene blue data are replotted from Figure 5. The $CaCO_3$ data (Figure 7B) are also plotted, but since these data were taken at a face velocity of 10 cm/sec, they were adjusted using the theoretical model to estimate the change in penetration ratio between 10 cm/sec and 20 cm/sec. Two sets of toner data are plotted; one set was taken using a Kr-85 radioactive source, and the other set was taken while using a commercial ionizer to neutralize the aerosol. The ionizer produces consistently lower penetration ratios, suggesting slightly less effectiveness in neutralizing the aerosol. However, for most of the particle sizes the difference is not statistically significant. This indicates that the ionizer can be used for the electret filter measurement, making the filter charge-assessment method more amenable to field use.

The charge level on several aerosols has been estimated using the filter method. The purpose of making these measurements is to allow estimation of the importance of these charge levels both from the health standpoint and from the sampling standpoint. Electrostatically induced dust deposition in the lung has been found to have a charge threshold value, above which deposition is enhanced and dose is increased.[1,2] The threshold value for particle charge over the range of particle sizes relevant to deposition in the deep lung of human subjects under typical breathing conditions can be described by the equation[16]

$$|n| \cong 54\sqrt{\frac{\rho_P}{\rho_w}}d_V^3 \quad (3)$$

where ρ_p = density of particle, ρ_w = density of water, d_v = equivalent volume diameter with units of μm, and $d_v = 0.8d_P$ for a cubic or tetrahedral-shaped mineral-dust particle. As an example, the threshold value for 0.48 μm methylene blue particles (ρ_p = 1.26 g/cm^3) with a charge of 18.7*e* corresponds to a penetration ratio value of 1 − 1.5. The threshold calculated for the $CaCO_3$ particles of the same size agrees with the methylene blue threshold. Based on this threshold, enhanced lung deposition of the toner dust appears likely, while enhanced deposition of the $CaCO_3$ powder, which is comparable to dusts typically found in the workplace, appears less likely.

When coal, quartz, and mica dusts were generated in a study performed by Johnston et al.[16] with the same type of fluidized bed used in this study, the resulting aerosol had charge levels slightly below, but not significantly different from the threshold levels for particles ranging between 0.6 and 7.5 μm diameters. When another form of mechanical dispersion, a glass venturi, was used by Kousaka et al.[23] to generate calcium carbonate dust, it resulted in an aerosol with a geometric mean diameter of 2.06 μm and a measured average charge of 35*e*.[16] The charges measured on the $CaCO_3$ in the present study agree with the Johnston study for small sizes, but not for larger sizes. However, the lower charge level measured on the larger sizes in this study agree with the levels found in the Kousaka study.

To estimate the effect of the charge levels on sampling efficiency, as characterized by the penetration values measured in this study, a value for charged particle sampling efficiency was taken from Baron and Deye.[3] Twenty-three percent of the charged asbestos fibers sampled at 1 L/min were lost to the conductive cassette cowl, which had a voltage potential of −1000V. For the same asbestos fiber mobility (−0.5 cm^2/statV·sec), higher cassette potentials exhibited greater losses, while higher airflow rates exhibited lesser losses. In this example, the electrical mobility is higher than expected for most workplace isometric aerosols; the charge on the sampler tends to be less for humid environments, but can be greater for low humidity environments. For comparison with the data in this study, the $CaCO_3$ had a mobility of 0.13 cm^2/statV·sec, considerably less than the fibers in the above example. Thus, sampling problems would not generally be expected for an aerosol with this charge level. However, if the hypothesis that the penetration ratio is proportional to mobility is correct, then the toner dust has a 3–10 times greater mobility than that of the $CaCO_3$. The toner dust is therefore more likely to exhibit significant sampling biases. This finding is consistent with the design of toner dust, which carries high electrostatic charge levels so it can bind to photo-electrified images on copy paper.

The particle size-dependent limitations of the electret filter method have been discussed above. The lower limit is determined by the detection threshold of the optical particle counter (approximately 0.1 μm), while the upper size limit is due to inertial and interceptional losses in the filter (approximately 0.7 μm). The measurable range of particle mobilities can be estimated. The lower limit approaches the Boltzmann charge, since this is the reference charge level for the measurement. The lowest penetration ratio observed in these studies was about 0.25 for the 0.48 μm diameter methylene blue particles. This corresponds to a particle charge of 4*e*–5*e*, while the average Boltzmann charge for a particle of this size is predicted to be 1.7*e*. Statistical variability determines how close the Boltzmann level can be approached by the charged aerosol. It appears that penetration ratios below 0.25 will be difficult to measure precisely.

Another limitation of the method is the requirement of aerosol stability over the sampling period. Since the charge measurement requires at least two measurements of the aerosol, the aerosol must be stable in concentration, size distribution, and charge during that period. This stability may be achievable under relatively controlled generation conditions, such as in a toxicology chamber, but is difficult to achieve in workplace situations. The toner dust measurements were carried out by taking 10 pairs of 30-second samples and averaging the results. Each measurement provided on the order of 1000 particles per channel. Thus, the total sampling time was on the order of 15 minutes; the resulting charge measurement is an average over this time period.

CONCLUSIONS

A technique for assessment of the electrical charge of an aerosol by measuring particle penetration through an electret filter has been proposed. By comparing the filter penetration of an aerosol to the penetration of the same aerosol after it has been passed through a charge neutralizer, a penetration ratio can be determined. The penetration ratio of an electrostatically sensitive, submicrometer particle (e.g., 0.5 μm) can be used to indicate if the aerosol has a charge level too low to be of concern, or sufficiently high to warrant attention and controls. With further investigation and development, this technique may be incorporated in a system capable of rapid field assessment of aerosol charge levels.

Several limitations of the method have been noted. The data suggest that very highly charged particles may be difficult to measure accurately due to losses in the measurement system. The limited size range of the technique (0.1 μm–0.7 μm) may cause uncertainty in assessing supermicrometer particle charge levels when several sources of small particles are present. Since the method of measurement is a function of particle mobility, the results may depend on particle size as well as charge. Improved electret filters with better theoretical understanding of their performance may allow the improvement of the electret filter method. Field studies with different types of aerosols also need to be carried out to validate the utility of this technique.

ACKNOWLEDGMENT

The authors thank Gregory J. Deye of NIOSH for providing the electrical mobility computer program.

REFERENCES

1. **Melandri, C., G. Tarroni, V. Prodi, T. DeZaiacomo, M. Formignani, and C.C. Lombardi:** Deposition of charged particles in the human airways. *J. Aerosol Sci. 14*:657–669 (1983).
2. **Yu, C.P.:** Theories of electrostatic lung deposition of inhaled aerosols. *Ann. Occup. Hyg. 29:*219–227 (1985).
3. **Baron, P.A. and G.J. Deye:** Electrostatic effects in asbestos sampling ii: comparison of theory and experiment. *Am. Ind. Hyg. Assoc. J. 51*:63–69 (1990).
4. **Liu, B.Y.H., D.Y.H. Pui, K.L. Rubow, and W.W. Szymanski:** Electrostatic effects in aerosol sampling and filtration. *Ann. Occup. Hyg. 29(2):*251–269 (1985).
5. **Johnston, A.M., J.H. Vincent, and A.D. Jones:** Measurement of electrical charge for workplace aerosols. *Ann. Occup. Hyg. 29:*271–284 (1985).
6. **John, W. and J.H. Vincent:** Static electrification of workplace aerosols: a perspective. *Ann. Occup. Hyg. 29:*285–288 (1985).
7. **Hochrainer, D.:** Measurement methods for electrical charges on aerosols. *Ann. Occup. Hyg. J. 29:*241–249 (1985).
8. **Wake, D., A. Thorpe, G.J. Bostock, J.K. Davies, and R.C. Brown:** Apparatus for measurement of the electrical mobility of aerosol particles: computer control and data analysis. *J. Aerosol Sci. 22:*901–916 (1991).
9. **Liu, B.Y.H. and D.Y.H. Pui:** Electrical neutralization of aerosols. *J. Aerosol Sci. 5:*465–472 (1974).
10. **Baugartner, H.-P. and F. Löffler:** The Collection performance of electret filters in the particle size range 10 nm to 10 μm. *J. Aerosol Sci. 17:*438–445 (1986).
11. **Lathrache, R. and H. S. Fissan, and S. Neumann:** Deposition of submicron particles on electrically charged fibers. *J. Aerosol Sci. 17:*446–449 (1986).
12. **Kanaoka, C., H. Emi, Y. Otani, and T. Iiyama:** Effect of charging state of particles on electret filtration. *Aerosol Sci. Technol. 7:*1–13 (1987).
13. **Liebhaber, F.B., M. Lehtimäki, and K. Willeke:** Low-cost virtual impactor for large-particle amplification in optical particle counters. *Aerosol Sci. Technol. 15:*208–213 (1991).
14. **Reischl, G., W. John, and W. Devor:** Uniform electrical charging of monodispersed aerosols. *J. Aerosol Sci. 8:*55–65 (1977).
15. **Yeh, H.C., R.L. Carpenter, and Y.S. Cheng:** Electrostatic charge of aerosol particles from a fluidized bed aerosol generator. *J. Aerosol Sci. 18:*147–151 (1987).
16. **Johnston, A.M., J.H. Vincent, and A.D. Jones:** Electrical charge characteristics of dry aerosols produced by a number of laboratory mechanical dispensers. *Aerosol Sci. Technol. 6:*115–127 (1987).
17. **Johnston, A.M.:** A semi-automatic method for the assessment of electrical charge carried by airborne dust. *J. Aerosol Sci. 14*:643–655 (1983).
18. **Hinds. W. C.:** *Aerosol Technology Properties, Behavior, and Measurement of Airborne Particles.* New York: John Wiley and Sons, 1982.
19. **Liebhaber, F., and K. Willeke:** Optical particle sizing: filtering out refractive index effects. *Ann. Occup. Hyg. 37*: 377–394 (1993).
20. **Chen, C.C., M. Lehtimäki, and K. Willeke:** Loading and filtration characteristics of filtering facepieces. *Am. Ind. Hyg. Assoc. J. 54:*51–60 (1993).
21. **Fuchs, N. A.:** *The Mechanics of Aerosol.* Oxford: Pergamon, 1964.
22. **Yu, C. P. and K. Chandra:** Deposition of charged particles from laminar flows in rectangular and cylindrical channels by image force. J. Aerosol Sci. 9:175–180 (1978).
23. **Kousaka, Y., K. Okuyama, M. Adachi, and K. Ebie:** Measurement of electric charge of aerosol particles generated by various methods. *J. Chem. Eng. Japan. 14*:54–58 (1981).