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A NEW CHARGED FOG GENERATOR FOR INHALABLE PARTICLE CONTROL

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A NEW CHARGED FOG GENERATOR FOR INHALABLE PARTICLE CONTROL

by

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ABSTRACT

A review of the literature shows that control efficiency of inhalable particles using water droplets can be significantly improved if the droplets are electrically charged. A spinning cup fog thrower was developed initially to generate electrically charged water droplets. The poor performance of this device in wind tunnel tests was attributed to the short lifetime of the fine droplets generated, the ineffective ionizer ring method of charging the droplets, and the nonuniform charge distribution observed along different regions of the fog spray pattern.

A new charged fog generator (CFG) was then developed by modifying a commercial rotary atomizer. In this device, the droplets generated are contact charged to provide a high charge-to-mass ratio of 1.2 μC/g. The droplets have a number concentration median diameter of about 100 μm and a mass median diameter of about 200 μm. The water flow rate is variable (4 to 70 l/h) and the fog spray pattern can be easily changed from long and narrow to broad and short, with a typical spray coverage of 16-24 m^3. The device uses about 1 kW power (110 V ac) and is portable.

Extensive field tests of the CFG (at a bentonite ore unloading operation) were performed to determine the dependence of its inhalable particle control efficiency (PCE) on various instrument settings and field conditions. These tests show that the overall mean PCE is 78% higher than the corresponding value for uncharged fog. Individual PCEs as high as 88% were achieved. The lifetime of the droplets seems to be the dominant factor determining the PCE; and PCE values were higher for higher applied voltages and higher water flow rates. The data suggest that, under optimum instrument settings, PCE of water droplets could be doubled by charging the droplets.

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SECTION 1

INTRODUCTION

Since the National Ambient Air Quality Standards were established in 1971, significant progress has been made in the U.S. in controlling total suspended particulate matter (TSP) emitted from conventional industrial sources. However, various regulatory agencies are becoming increasingly concerned because ambient TSP standards are being exceeded at many urban and industrial areas, mainly because of the lack of appropriate control measures for particles from non-stack sources -- that is, fugitive emissions. Although the total particle mass loading from human activities is only about ten percent of that from natural sources, its effects are significant and largely detrimental. Recent reports (Cowherd, 1980; NRC, 1979; Friedlander, 1977; and Natusch, 1974) indicate that inhalable particles (10-15 μm and smaller in aerodynamic diameter), in general, and fine particles (2-3 μm and smaller), in particular, may be a human health hazard and degrade atmospheric visibility. Therefore, the U.S. Environmental Protection Agency (EPA) is emphasizing the importance of finding new methods of controlling inhalable particles, especially from fugitive emission sources.

Spraying fine water droplets is a well-known method to control dust. Various types of scrubbers rely on water droplets to sweep dust from gases. Although spraying water has been the most common dust control method used in material handling and mining, it has been marginally successful, with particle collection efficiencies of only 30-40% (Emmerling and Seibel, 1975; Courtney and Cheng, 1976). In addition, equipment to implement this method has drawbacks; water spray nozzles become clogged and large quantities of water are needed. The latter is critical, especially in the arid western United States and in applications where addition of large quantities of water is forbidden.

Studies by McCoy et al. (1983), Yung et al. (1980), Hoenig (1979 and 1977), Hassler (1978), Prem and Pilat (1978), Drehmel (1977), Lear (1976), and Pilat (1975) have shown that the collection of fine particles can be greatly enhanced using electrostatic forces in particle control devices. Hoenig (1979 and 1977), Hassler (1978), Suck et al. (1981), Walkenhorst (1971), and Schutz (1967) have shown that most industrial pollutants and naturally occurring dust particles acquire electrical charges as they are dispersed into the air. They have also shown that the polarity and magnitude of the charges depend on the size and origin (coal, soil, minerals, etc.) of the particles. Therefore, if oppositely charged water droplets are sprayed on the dust to be suppressed, the particles which collide with the droplets will agglomerate rapidly and settle out of the atmosphere. The particle collection efficiency of water sprays can thus be improved significantly if charged water droplets (fog) of appropriate sizes can be generated.

This report details the development and testing of a new Charged Fog Generator (CFG) under the sponsorship of the Industrial Environmental Research Laboratory (IERL) of the U.S. EPA. The objective of this research project was to develop a portable unit to control dust where conventional methods of dust control cannot be applied such as in

material handling areas with conveyor belt transfer points, front-end loaders, and material loading and unloading. This project consisted of two phases.

1. Phase I

The four objectives of this phase were:

a. Theoretical Calculations. To (1) define and identify the theory behind this new concept of controlling inhalable particles using electrostatically charged fog; (2) predict the control efficiency of the method based on the charge-to-mass ratio of the water droplets and the size distribution of the droplets, together with the mass collected and its size distribution -- both before and after the dust was treated with charged fog; and (3) estimate the power requirements as a function of fractional efficiency and the minimum power required to achieve 90% efficiency in control of inhalable particles.

b. Preliminary Experiments. To design a bench-scale prototype instrument to generate fog and to charge the water droplets to a high charge-to-mass ratio. The size distributions of the droplets were to be appropriate for controlling dust particles. The electrostatically charged fog was thus to be applied to inhalable dust particles in a controlled atmosphere (wind tunnel) to verify the fog's collection efficiency and this result compared with the predictions of the theoretical calculations.

c. Economic Analysis. To perform an economic analysis of the method for controlling inhalable particles with charged fog. Cost and power requirements were to be estimated for the new instrument and compared with the cost of any other instrument with the same capabilities.

d. Recommendations. To report on the work done under Tasks 1, 2, and 3 with recommendations for work to be done under Phase II.

2. Phase II

Based upon the Phase I report, AV was asked to proceed with Phase II of the program. The objectives of the second phase were:

a. To construct a working model of the instrument, applying the findings of Phase I;

b. To design an experiment to field test the instrument constructed;

c. To obtain data on the collection efficiency of the instrument and evaluate the instrument's effectiveness for controlling inhalable particles.

All field work under Phase II was completed by July 1981. This report presents the results of work done under the two phases. Section 2 gives the conclusions and Section 3, recommendations. Section 4 outlines the theoretical background, and Section 5 describes the development, test results and setbacks of the original spinning cup fog thrower. Section 6 summarizes the development of the CFG. Section 7 describes the extensive CFG field tests and relates the findings. Appendices A and B are reprints of two articles on work related to this report.

SECTION 2

CONCLUSIONS

Since most industrial pollutants and naturally occurring aerosol particles are electrically charged, theoretical studies have shown that inhalable particle control efficiency of water sprays can be improved significantly if well-charged water droplets of 100-200 μm in diameter are applied on these particles. Initially, charged fog was generated using a spinning cup fog thrower, developed in association with the University of Arizona in Tucson. This device created fog with a median droplet diameter of about 20 μm and a charge-to-mass ratio of about 1×10^{-11} C/g. Wind tunnel tests of this spinning cup fog thrower at Tuscon showed about 50% inhalable particle control efficiency. The poor performance of this device was attributed to the very short lifetime of the fine droplets generated, ineffective ionizer ring method of charging the droplets, and the nonuniform charge distribution observed along different regions of the fog pattern.

A new Charged Fog Generator (CFG) was then developed by modifying a commercial rotary atomizer. The CFG generates water droplets with a number concentration median diameter of about 90-100 μm and a mass median diameter of about 200 μm. These larger droplets will not evaporate as rapidly and will therefore remain in the air long enough to provide sufficient time for interaction between the droplets and particles. These droplets are electrically charged by the method of contact charging, wherein a 15-kV dc potential is connected to the inflowing water. This charging process provides a typical charge-to-mass ratio of 1.2×10^{-6} C/g. The water flow rate in the device can be varied from about 4 to 70 l/h. The total power required to operate the system is less than one kilowatt and, therefore, can be easily operated from a remote location with a small generator. The fog spray pattern covers a volume of 16 to 24 m^3 and the spray pattern can be varied from broad and short to long and narrow, thus adapting to the extent of the emission source to be controlled. This device uses no water-spray nozzles, thus eliminating nozzle clogging problems. The CFG, mounted on a small platform, is portable.

Extensive field tests of the CFG were performed to determine the dependence of its inhalable particle control efficiency under various instrument settings and field conditions. The field tests were conducted at a bentonite ore processing plant in Worland, Wyoming, during 1981. Bentonite was unloaded from front-end loaders into a semi-enclosed hopper and the dust generated in the hopper was treated with charged fog. Inhalable particle concentrations were measured as fine and coarse fractions using a combined cyclone preseparator/cascade impactor high-volume sampler. Ninety-six runs were made under three test scenarios: uncontrolled dust, uncharged fog applied to dust, and charged fog applied to dust. From these measurements, the CFG's inhalable particle control efficiencies were calculated for various combinations of instrument settings and field conditions. These test results show that:

1. Charged fog was shown to be an effective means of controlling fugitive dust emissions. The mean value of the inhalable particle (fine and coarse fractions combined) control efficiency of charged fog measured under all instrument settings and field conditions is 78% higher than the corresponding value for uncharged fog.

2. The relative humidity (in this particular experimental setup) seemed to play a significant role in determining the overall particle collection efficiency. It appears that the lifetime of the droplet is the dominant factor in determining particle control efficiency. The droplets should be large enough not to evaporate too quickly, yet small enough to yield a high particle control efficiency.

3. Under identical or nearly identical field conditions and instrument settings, negatively charged droplets gave higher values of particle control efficiency than did positively charged droplets, suggesting that inhalable bentonite particles carry a net excess positive charge.

4. Measured inhalable particle control efficiencies were higher for higher applied voltages in the 4-10 kV range. At the upper end of this range, the particle control efficiency seemed to attain a saturation value.

5. Measured inhalable particle control efficiencies were higher when charged droplets could cover more of the dust-laden air in the hopper. In the experimental setup used, higher water flow rates and a broad spray pattern generally resulted in higher collection efficiencies, although the key element appeared to be how many particles were treated by the droplets.

6. Because of the type of particle sampling method used and the field setup, the effect of wind speed and direction on particle control efficiency cannot be quantified with the available data.

7. The optimum CFG instrument settings are found to be 60 l/h water flow rate; a spray pattern which will cover maximum volume of the dust-laden air (broad or narrow spray depending on the extent of the source); an applied voltage of 8-10 kV; and positive or negative charge, depending on the charges on the dust particles. Ideal field conditions are high relative humidity (to ensure long droplet lifetime), and calm or low wind conditions.

Ordinary water sprays -- the closest technique to charged fog -- are inefficient in collecting fine particles. By the addition of electric charges on the droplets, it seems possible to at least double the inhalable particle control efficiency of water sprays. Other control methods using evacuation and hooding are roughly ten times more expensive than are charged-fog devices in capital cost and in operating cost. Charged-fog devices are currently available on the market and the Charged Fog Generator is expected to be commercially available soon.

SECTION 3

RECOMMENDATIONS

The capabilities of the Charged Fog Generator demonstrated in this report can be utilized in several applications, such as

- controlling dusts in material handling (loading, unloading, conveyor belt transfers of various materials, including coal and grain);
- controlling inhalable particles in the mining industry to reduce the fine fraction of particles inhaled and to recover, and subsequently recycle airborne particles of precious metals, such as gold;
- controlling particles generated by a mobile source (such as a road sweeper or construction equipment);
- decontamination or collection of biological organisms using charged droplets.

To facilitate the possible use of charged fog devices in areas listed above, the following studies need to be carried out.

1. Although some qualitative work on the electrical characterization of airborne particles has been done, quantitative information is needed on the polarity and magnitude of the electrical charges of airborne particles and their dependence on particle sizes and chemical composition. Also, the potential of the CFG to control particles of various origin is required. An instrument capable of measuring electrical charges and aerodynamic diameters of inhalable particles simultaneously has recently been reported by Mazumder et al. (1982) and Renninger et al. (1981).

2. The CFG and other commercially available charged fog devices use high voltages and their present designs are such that they could be a human safety hazard and a fire hazard in an inflammable, gaseous atmosphere. Therefore, additional work is needed to make the devices safe and explosion-proof before they can be used for inhalable particle control in mines.

3. Use of charged fog to collect airborne submicron- and micron-sized organisms should be of interest to the industrial hygienist. Control of germs and possible decontamination of an area using proper chemical additives in the water spray is of interest to the army. Preliminary investigation of this application could be coupled with 1. above.

4. The potential of the CFG to control dust from a mobile source is worth examining. No alternative method of control for such emissions is available, other than ordinary water sprays which do not efficiently control fine particles.

5. Possible application of charged fog in recovering airborne precious metals should be of great interest to the gold and other precious metal and mineral mining industries. Studies to evaluate the possibility of such a method could be undertaken.

SECTION 4

THEORETICAL BACKGROUND

Removing fine particles from a gas stream in an open area is difficult because of the particles' low mobility, unfavorable inertial properties and uncontrollable external factors. The use of electrostatics to control fine particles in a controlled atmosphere is well documented (White, 1963). However, only during the last few years have electrostatics been used to augment particle collection efficiency of water droplets (Yung et al., 1980; Hoenig, 1979; Prem and Pilat, 1978; Drehmel, 1977; Wang et al., 1978; Lear, 1976; Pilat, 1975). Hoenig (1977, 1979, 1980) and Hassler (1978) have shown that most industrial pollutants and naturally-occurring dust particles acquire electric charges as they are dispersed into the air. Therefore, particle collection can be enhanced via electrostatic attraction if the water droplets are charged to the opposite polarity. Unlike conventional water sprays, droplets in charged fog sprays carry electrostatic charges.

An electrostatically charged water droplet moving with reasonable speed in a medium containing aerosol particles sweeps out a volume equal to its pathlength times its projected area. Aerosol particles in this volume, which are not swept out by aerodynamic forces as the droplet moves along its trajectory, collide with the droplet. Figure 1 shows the definition of collision efficiency, E_o, which may be obtained from a knowledge of the particle's trajectory around the drop as

$$E_o = \frac{\pi y_c^2}{\pi (R+r)^2} \tag{1}$$

where y_c is the largest initial horizontal offset a particle can have and still collide with the droplet (Wang and Pruppacher, 1980). Further, we assume that once an aerosol particle and a droplet collide, they adhere to each other; in other words, the collision efficiency is identical to the collection efficiency. The agglomerated particles and the droplet then settle out of the air according to the Stokes relationship.

The collection of an aerosol particle by a charged droplet is the result of a number of simultaneous mechanisms of interaction between them such as inertial impaction; direct interception; Brownian diffusion; and electrostatic, diffusiophoretic and thermophoretic forces (Wang et al., 1978; Prem and Pilat, 1978; Grover et al., 1977; Nielsen and Hill, 1976a, 1976b). When an aerosol particle approaches a water droplet with a relative velocity, it may directly collide with the droplet, barely touch the droplet, or entirely miss the droplet. In this process, the first case is called an impaction and the second case is called an interception. The relative effect of the mechanisms of interaction between the droplet and the particle depends upon the size of the particle. For large particles (aerodynamic diameter greater than 2-3 μm), the dominant mechanisms of particle collection by droplets are impaction and interception. For particles smaller than 0.1 μm,

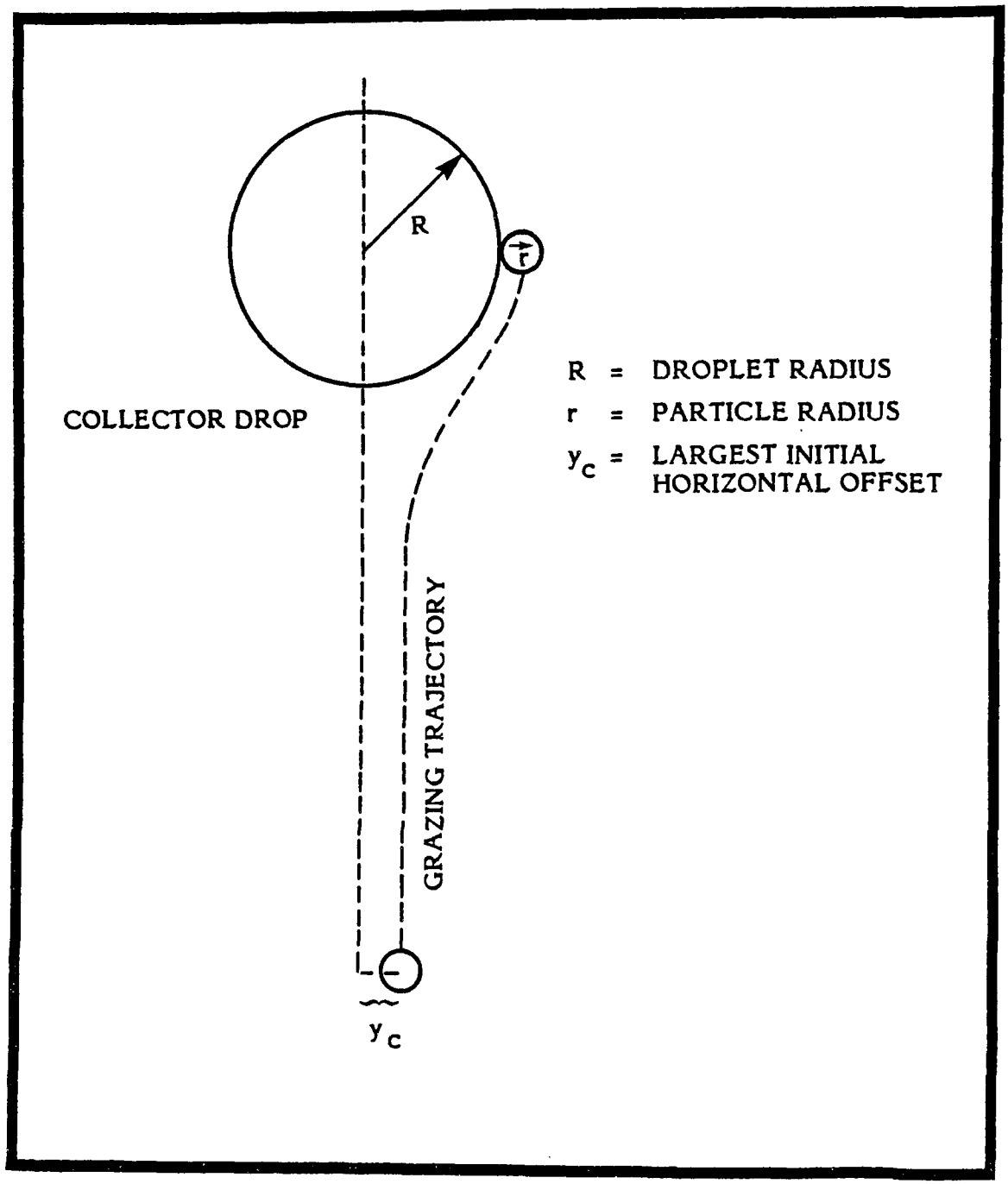


Figure 1. Definition of collision efficiency.

Brownian diffusion becomes very important, and for particles between these two ranges, electrostatic forces are the dominant interaction mechanism. Phoresis is the process by which particles move because they are subjected to a temperature gradient (thermophoresis) or vapor pressure (diffusiophoresis). These processes are significant only when the droplets are evaporating fast and when the particles are small.

The particle collection efficiency of uncharged water sprays (where inertial impaction is the major collection mechanism) is given by Cheng (1973) as,

$$E = 1 - \exp\left[-\frac{3}{2} \cdot \frac{Q_L}{Q_G} \cdot \frac{L}{D} \cdot \eta\right] \tag{2}$$

where Q_L and Q_G are the volume flow rates of the water and air component of the dust cloud, respectively, L is a characteristic length for the total capture process, D is the mean droplet diameter and η is the single droplet collection efficiency.

For a given particle size, single droplet collection efficiency due to inertial impaction is proportional to the relative velocity between the droplet and the particle and inversely proportional to the droplet diameter. Cheng (1973) also showed that for a given quantity of sprayed water and dust cloud, 300-μm droplets have the maximum collection efficiency for 3-μm particles, 200-μm droplets have the maximum collection efficiency for 2-μm particles, and 150-μm droplets have the maximum collection efficiency for 1-μm particles.

When particles are small or when the relative velocity between the particle and the droplet is very small, then the particle is considered to be inertialess. Electrostatic force is the dominant mechanism of interaction of particle collection for particles in this size domain. For the single droplet collection efficiency of a charged particle by an oppositely-charged droplet, Kramer and Johnstone (1955), Nielsen and Hill (1976a), and Prem and Pilat (1978), gave the following relation:

$$\eta = -4K_c = -4\, C\, Q_c\, Q_p \Big/ 24\pi^2\, \varepsilon r\, R^2\, \rho U_o \tag{3}$$

where

K_c = electrostatic parameter
C^c = Cunningham slip correction factor
Q_c = droplet charge
Q^c_p = particle charge
ε^p = dielectric constant
r = particle radius
R = droplet radius
ρ = viscosity
U_o = free-stream velocity.

This relation shows that for a given particle size the electrostatic forces are directly proportional to the magnitude of the charges on the droplet and particle, and

inversely proportional to the square of the droplet radius and its free-stream velocity. Physically, the last item indicates that when the droplet free-stream speed is slower, the particle spends a longer time near a droplet and thus the electrostatic forces between the droplet and particle act for a longer time thus enhancing particle collection.

Prem and Pilat (1978) showed that for a 200-μm and a 50-μm charged droplet and oppositely-charged particles in the size range 10-20 μm, the particle collection efficiency due to electrostatic forces and inertia are comparable. However, for particles less than 10 μm, and for the same droplet sizes, electrostatic forces progressively become the dominant collection mechanism, compared to particle inertia, as the particle sizes decrease.

The value of the single droplet collection efficiency given by Equation (3) may be substituted in Equation (2) and integrated over all droplet and particle sizes to obtain the total particle control efficiency of an electrostatically charged water spray system. Recall, however, that the relation thus obtained for E is an idealized version of the complex interactions between droplets and a moving dust cloud. Therefore, with a spectrum of droplet radii and a dust cloud of particles with various sizes, the particle control efficiency of a charged spray device becomes difficult to predict. Still, it is instructive to examine some of the details of the results of the theoretical studies on single droplet collection efficiency.

The mechanisms of interaction between water droplets and aerosol particles, and the collection efficiency of a single droplet falling under its terminal velocity have been topics of many detailed investigations (Yung et al., 1979; Wang et al., 1978; Grover et al., 1977; Beard and Grover, 1974; Beard, 1974; Slinn and Hales, 1971; Greenfield, 1957). In a series of papers, Pruppacher, Grover, Beard, and Wang at the University of California at Los Angeles have examined, both theoretically and experimentally, the single droplet collection efficiency, and some of their results are summarized graphically in Figures 2 through 5.

Figure 2 shows the theoretically computed, overall collection efficiency, E, of water droplets on aerosol particles of various radii for the case of 75% relative humidity, 900 mb pressure and 10° C temperature. Greenfield (1957) was the first to demonstrate that in the absence of an electric charge on either the droplets or the aerosol particles, the graph of the collection efficiency of water droplets plotted against the radii of the aerosol particles has a minimum for particles with radii near 1 μm. The minimum becomes more pronounced for progressively smaller droplets, and becomes a "gap" (i.e., the collection efficiency goes to infinitely low values) for droplets of radii approximately 55 μm and less. This gap, known as the "Greenfield Gap," and the minimum in the collection efficiency shifts to smaller particle radii as the radius of the collecting water droplet increases. This minimum (or gap) results from the fact that Brownian diffusion dominates particle scavenging for smaller particles (whose radii are less than the value corresponding to the minimum in collection efficiency), while inertial impaction dominates particle scavenging for particles with radii greater than the radius corresponding to the minimum in collection efficiency. For particles near 1-μm radii, neither of these two processes is very effective, thereby yielding the minimum; however, phoretic and electric forces play significant roles in the collection efficiency in this region, as will be shown shortly. The minimum in E and the Greenfield Gap, described above, is very clearly seen in this figure. Also, the collection efficiency of larger particles is greater

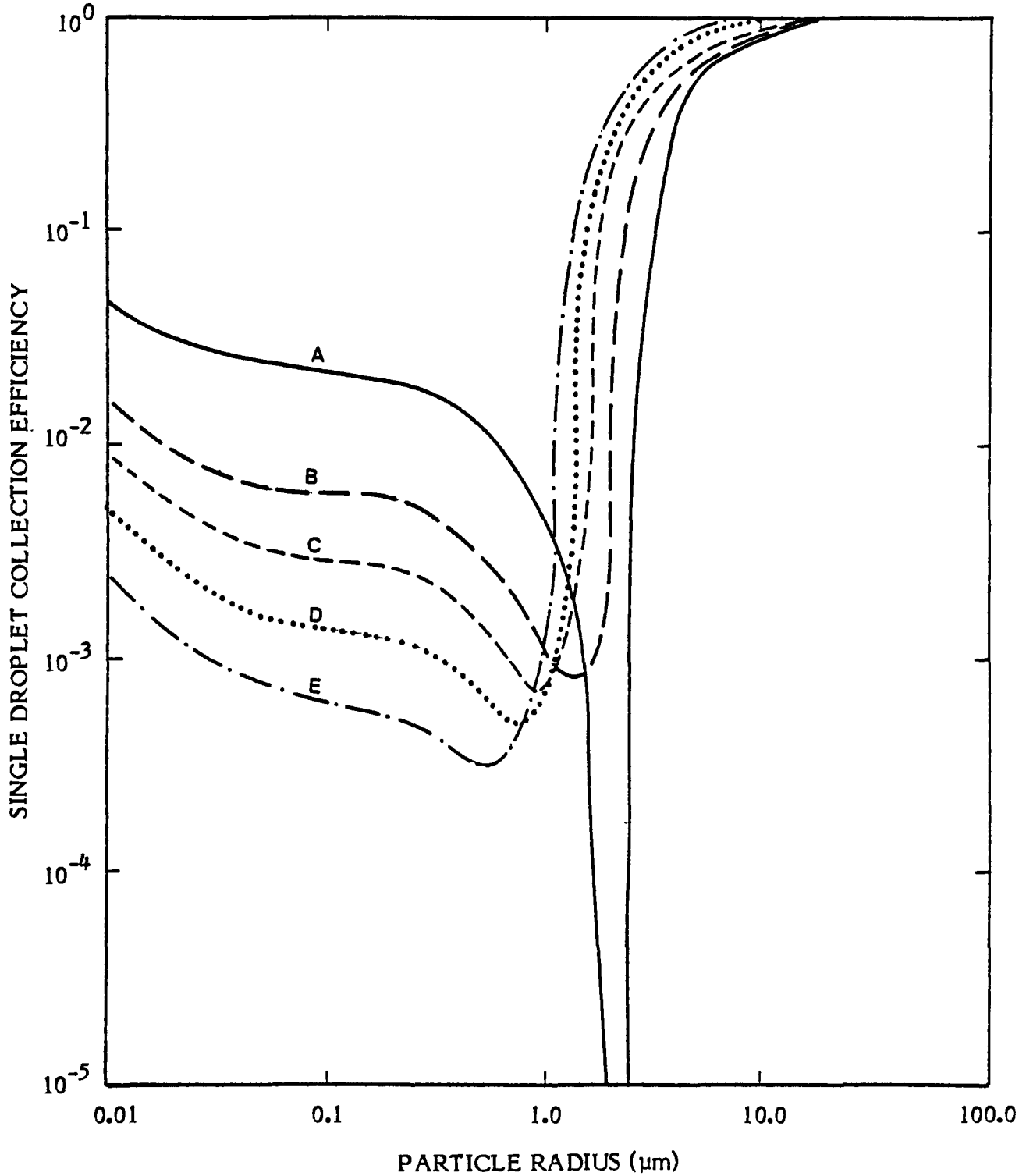


Figure 2. Calculated single droplet collection efficiency (adapted from Wang et al., 1978) in air of 10°C and 900 mb as a function of particle radius at a relative humidity of 75% with droplet radius as a varying parameter (A) 42 μm, (B) 72 μm, (C) 106 μm, (D) 173 μm, and (E) 310 μm.

for larger droplets, while the collection efficiency of smaller particles is greater for smaller droplets, and the minimum collection efficiency (Greenfield Gap) occurs for particle radius, ~1.0 μm.

Figure 3 plots the calculated collection efficiency versus aerosol particle radius for a water droplet of 72 μm radius, with relative humidity (RH) of the medium as a varying parameter. When the RH changes from 100% to 50%, the phoretic forces could raise E by an order of magnitude or more. As the figure also shows, for larger particles (>2-3 μm and larger in aerodynamic diameter) the collection efficiency is independent of RH. As noted previously, the evaporation rate increases as RH decreases which, in turn, reduces the lifetime of the droplet in the medium and consequently reduces the collection efficiency.

The discussion so far has not considered the effect of charging the droplets or the aerosol particles. Figure 4 shows three curves for the collection efficiency, E, versus particle radius for a droplet of radius, R = 106 μm, and 75% RH. Curve C at the bottom is similar to Figures 2 and 3 without any charges. Curve B gives collection efficiency as a function of particle radius, r, with droplets and aerosol particles both charged to the same magnitude of 2.0 esu cm^{-2}, but of opposite sign. And Curve A is similar to B, except the magnitude of the charge is 20.0 esu cm^{-2}; curve A is obtained by a less rigorous calculation method of George and Poehlein (1974). The charge of 2.0 esu cm^{-2} was chosen for Curve B because that is the mean charge found on water droplets during thunderstorms, as shown by Takahashi (1973).

Figure 4 shows that the introduction of electric charges on the droplets and the aerosol particles completely eliminates the Greenfield Gap and, depending upon the amount of charge, the collection efficiency of submicron particles is increased by more than an order of magnitude. This effect is the fundamental principle on which the charged fog technology is based. Figure 4 also shows that the addition of electric charges does not significantly affect the collection efficiency for particles larger than about 5 μm in aerodynamic diameter.

Figure 5 compares the theoretical prediction and the experimental data of Wang et al. (1978) for collection efficiency of charged water droplets of various radii for aerosol particles of radii, r = 0.25 μm, at about 20% relative humidity. The prediction agrees fairly well with the measured data. This agreement is also compatible with the conclusion of Walton and Woolcock (1960) that the overall collection efficiency of a given quantity of sprayed water should be fairly independent of droplet sizes, in the 100 to 500 μm radius range.

When sprayed into the air, the charged droplets will evaporate unless the air is saturated with water vapor. The droplet lifetime determines the effective contact time between the droplet and particles and thus strongly influences the overall particle control efficiency of the system. The lifetime of a water droplet depends upon the temperature and relative humidity of the medium into which it is introduced, as shown in Figure 6 (Daugherty and Coy, 1979).

The choice of droplet size is, at best, a compromise. On the one hand, 50- to 60-μm diameter droplets have a higher particle collection efficiency than do larger droplets; on the other hand, smaller droplets have a much shorter lifetime if they are introduced into a

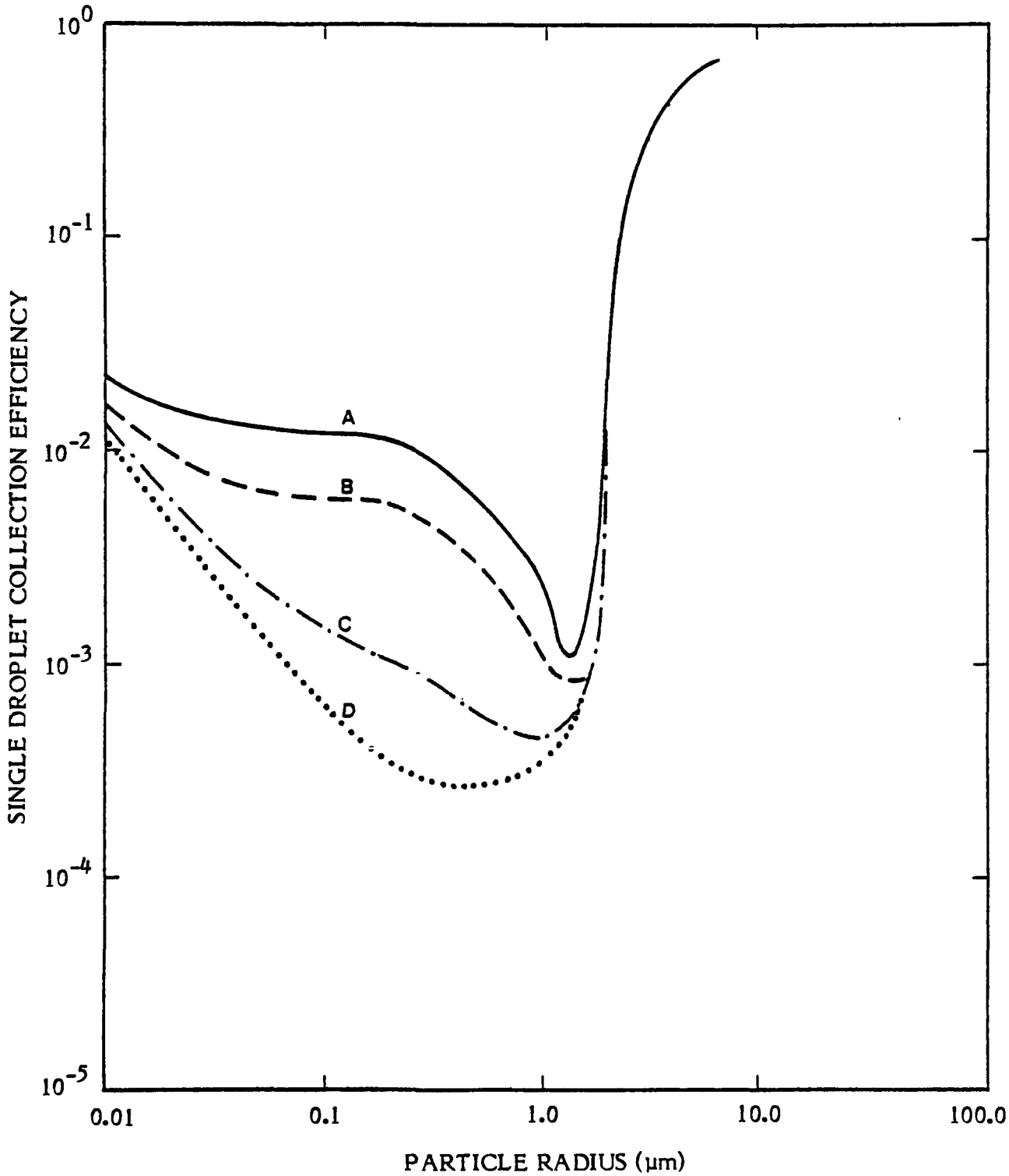


Figure 3. Calculated single droplet collection efficiency (adapted from Wang et al., 1978) in air of 10°C and 900 mb as a function of particle radius for 72 μm radius droplet with relative humidity as a varying parameter (A) 50%, (B) 75%, (C) 95%, and (D) 100%.

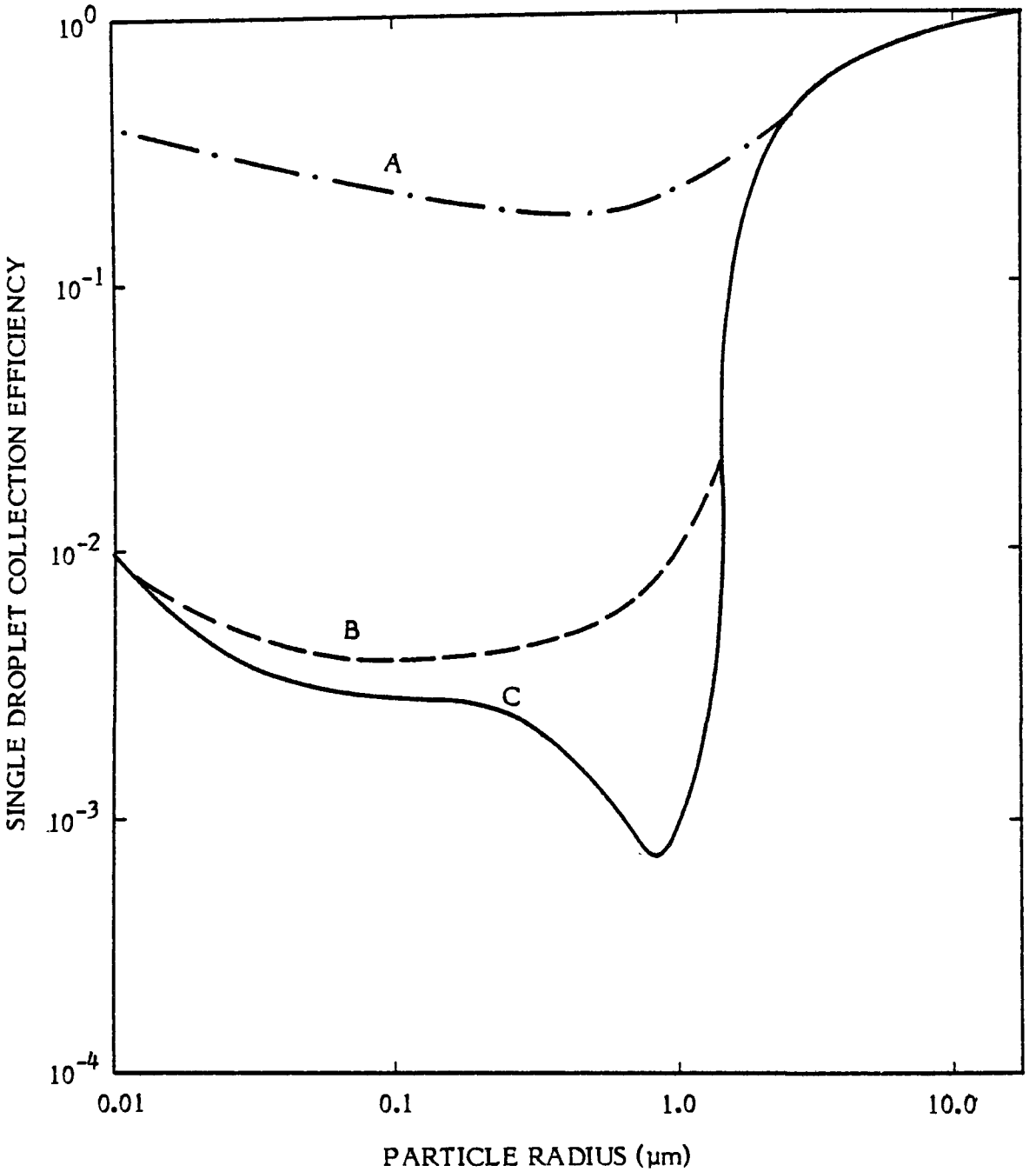


Figure 4. Calculated single droplet collection efficiency (adapted from Wang et al., 1978) in air of 10°C and 900 mb as a function of particle radius for 106 μm radius droplet at 75% relative humidity for droplet and particle charges of (A) ±20 esu cm^{-2}, (B) ±2 esu cm^{-2}, and (C) zero charge.

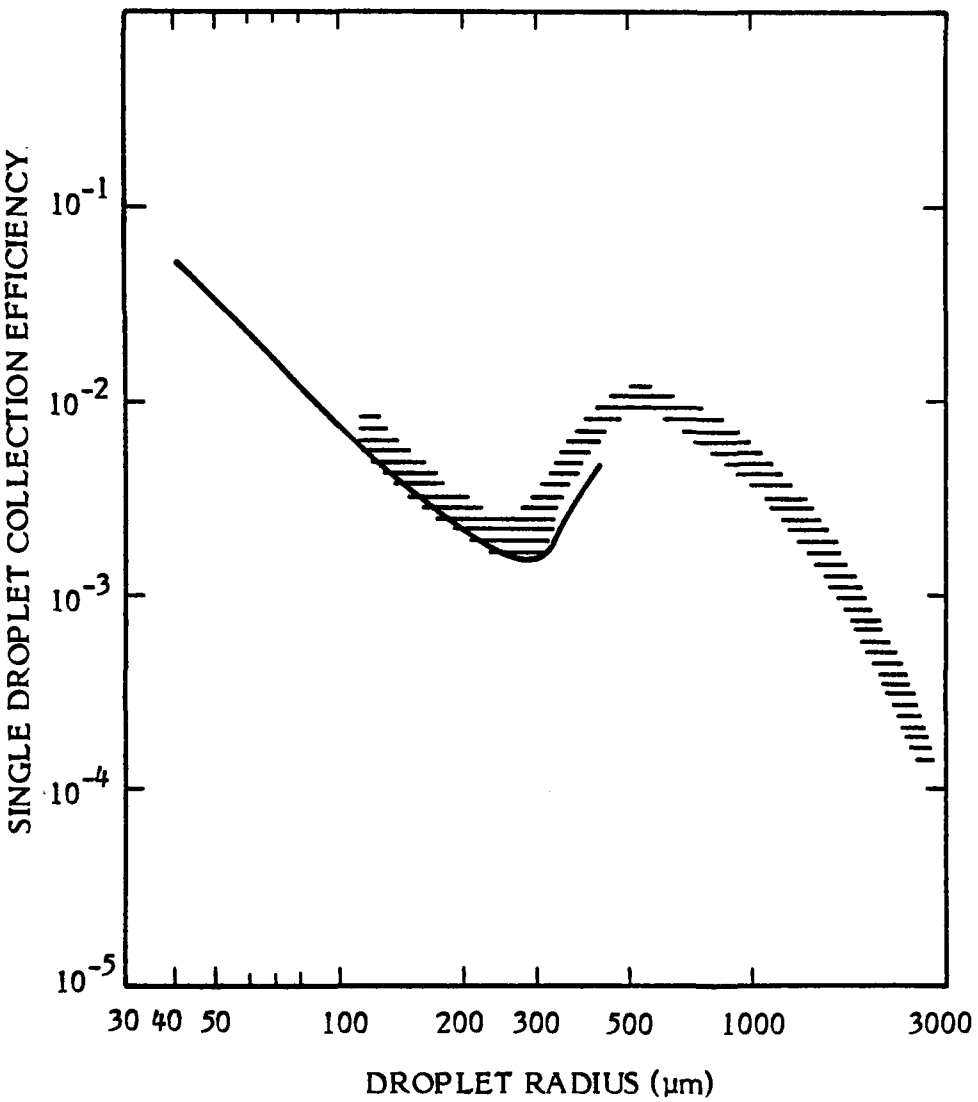


Figure 5. Comparison of calculated (smooth line) and experimentally measured (shaded) single droplet collection efficiency (Wang et al., 1978) as a function of droplet radius for uncharged aerosol particles of 0.25 μm radius in air of 22°C, 1000 mg, and a relative humidity of ~20%.

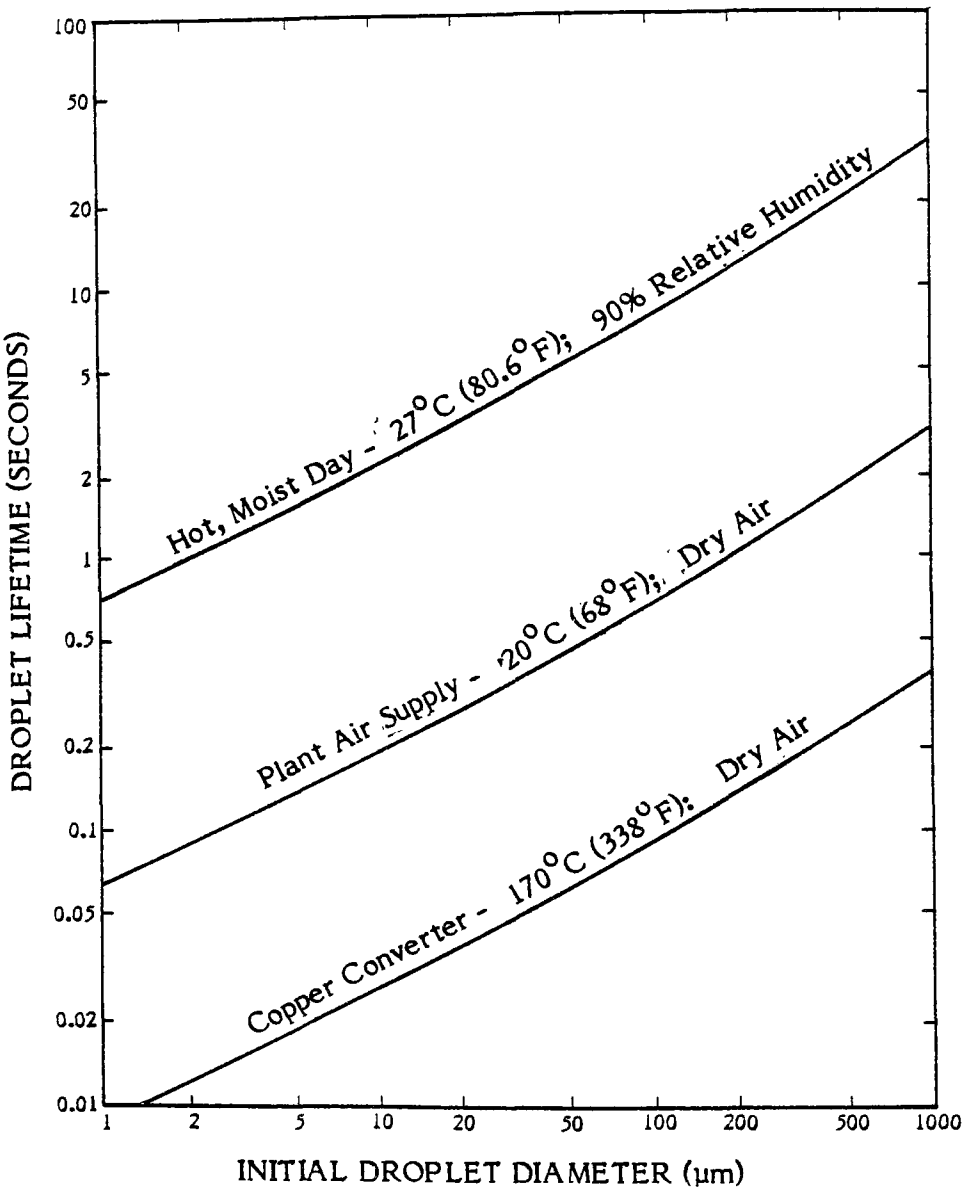


Figure 6. Lifetime of water droplets traveling at their terminal velocities (Daugherty and Coy, 1979).

fairly low RH and high temperature medium. Thus, to obtain the best collection efficiency, the droplets must be small enough to provide both an adequate spray rate per volume of gas treated and sufficient contact time, yet large enough not to evaporate too quickly. Droplets in the range 100-200 μm are expected to be a reasonable choice for ambient applications.

Another important consideration in charged fog technology is the limitation on the amount of charge on particles and droplets. As noted earlier, Hoenig (1979), Hassler (1978), and others, showed that aerosol particles in the air are generally charged. The maximum electric charge a particle or droplet can carry is limited by the physical properties of the particle or the droplet. Once these limits are reached, a particle will spontaneously emit some of the charge and a droplet will disintegrate into smaller droplets. For a spherical particle, the limiting charge is given by Whitby and Liu (1966) as

$$n_p = \frac{D_p^2 E_s}{4e} \tag{4}$$

where E_S is the surface field intensity at which charges are emitted, D_p is the particle diameter, e is the elementary unit of charge, and n_p is the number of elementary units of charge corresponding to the limit.

In the case of a water droplet, the maximum charge it can carry before it disintegrates is reached when the outward pressure produced by the electric field at the surface of the drop is equal to the inward pressure produced by the surface tension (Leong et al., 1982). This limiting charge is called the Rayleigh limit (after the physicist Lord Rayleigh) and is given by

$$Q_{Ray} = 8\pi\left(\varepsilon_o \sigma R^3\right)^{1/2} \tag{5}$$

where

Q_{Ray} = limiting charge on the droplet (Coulombs)
ε_o = permittivity of the medium in which the droplet is located
σ = surface tension of the liquid
R = droplet radius, in meters.

Assuming $\sigma = 7.2 \times 10^{-2}$ N/m, and using an ε_o value of a vacuum (8.85×10^{-12} $C^2/N\ m^2$), Equation (5) becomes

$$Q_{Ray} = (2 \times 10^{-5})\, R^{3/2} \tag{6}$$

where R is in meters and Q_{Ray} is in Coulombs. As the Rayleigh limit is reached, a droplet breaks up into smaller droplets. Figure 7 shows the relationship between droplet radius and Rayleigh limit of charges for water droplets.

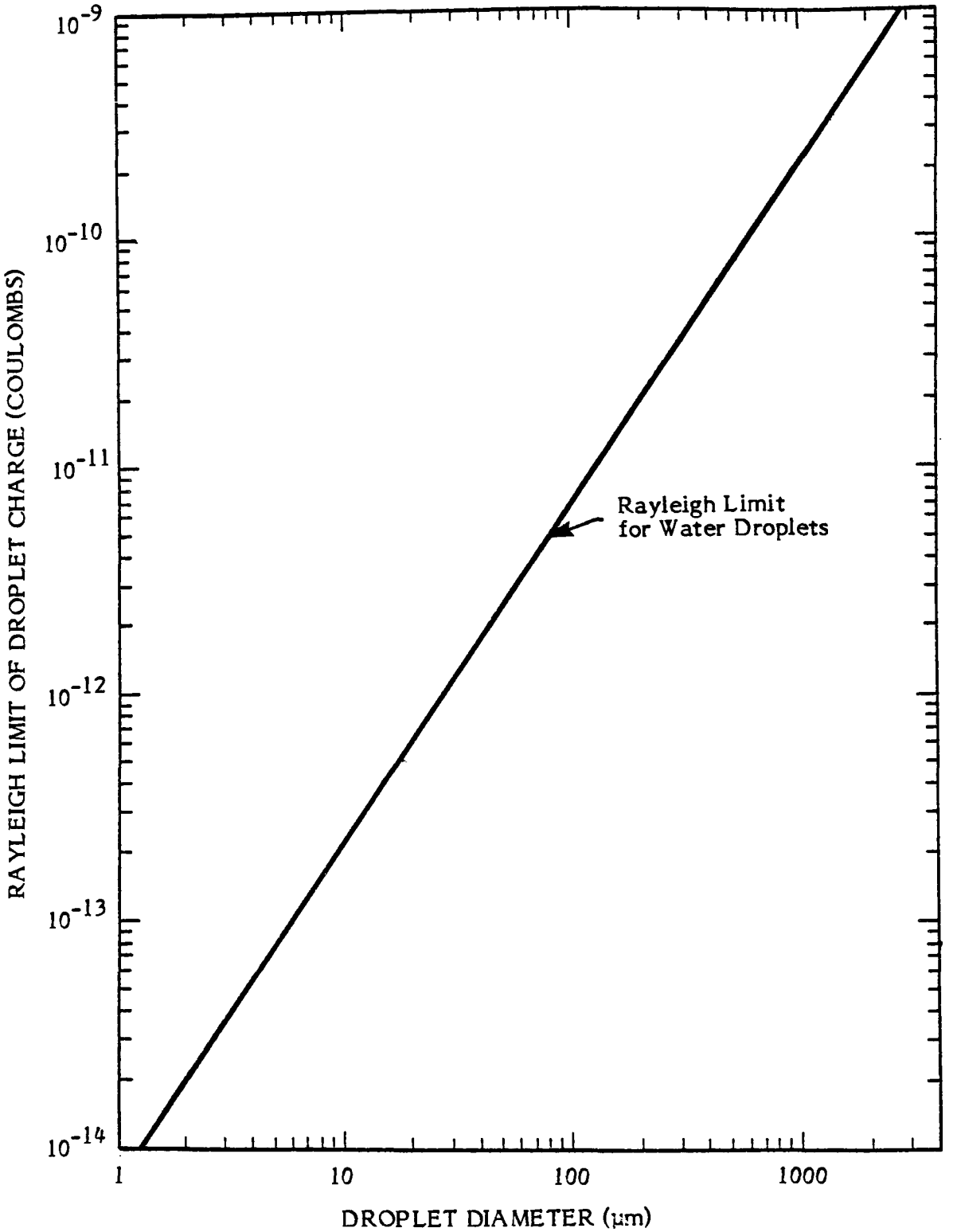


Figure 7. Calculated Rayleigh limit of water droplet charges as a function of droplet diameter.

In the studies outlined above, collision of a particle with the droplet was assumed to always result in the collection or removal of that particle from the air. Pemberton (1960) and McDonald (1963) argue that the particle collection efficiency should increase as the surface tension of the droplet decreases. Indeed, increased particle collection efficiency has been reported (Hesketh, 1974; Rabel et al., 1965) with the addition of surfactants to lower surface tension. Drees (1966) and others suggest quite the opposite result due to surfactants; yet others claim no effect at all.

Woffinden et al. (1978) suggested that the change in the droplet size distribution upon addition of surfactants, and the consequent effect on particle collection is a possible reason for the discrepancy in the observed results of the addition of surfactants. McCully et al. (1956) and Goldshmid and Calvert (1963) have shown that non-wettable particles are collected less efficiently by droplets than are wettable particles. Stulov et al. (1978) conclude that non-wettable particles adhere to the droplet surface upon impaction and, consequently, form a layer on the droplet surface causing particle bounce-off later. The Stulov et al. study was restricted to particles larger than 5 μm. In any case, data are lacking from any controlled experiment to study the effect of adding surfactants to water droplets used in collecting fine particles.

Finally, a comment on the possible enhancement of the particle collection efficiency by charging the droplets is appropriate. Although Figure 4 shows that the addition of electric charges on particles and droplets completely eliminates the minimum in particle collection efficiency (around r = 1 μm) and shows single particle collection efficiencies 5 to 10 times higher than for uncharged sprays, the overall collection efficiency of an operating system may not be that high. Increases in collection efficiencies of about 15% for 1-μm particles to over 45% for 0.3-μm particles compared to uncharged droplets were reported by Pilat (1975). Hoenig (1979) reported particle control efficiencies of 50 to 80% with charged droplets under controlled experimental conditions using a device called Fogger I, which he had patented. Under the sponsorship of the U.S. EPA, AV has developed a new charged fog device to control inhalable particles. This new device, called the Charged Fog Generator, was extensively field tested during 1981 to evaluate its particle control efficiency. These tests are described in Section 7 of this report. To our knowledge, this is the first attempt to examine the relationship of various parameters described earlier in this chapter and the actual measured particle control efficiency of an operating charged fog device in a field setup.

SECTION 5

DEVELOPMENT AND TEST RESULTS OF THE INITIAL SPINNING CUP FOG THROWER

INTRODUCTION

Many researchers have attempted to enhance dust agglomeration by wetting the dust, but have obtained limited success. Although as much as 60% collection efficiency has been claimed for this method, about 30 to 40% is the generally accepted value. The difficulties of generating small enough water droplets and inducing the dust particles to attach to the droplets are quite well known. These problems become more complicated when the dust to be controlled is in open areas with uncontrollable ambient conditions of temperature, pressure, relative humidity and, most significantly, wind speed and wind direction. Equations (2) and (3) (in Section 4) for the collection efficiency are for an ideally controlled situation. The actual control efficiency will depend on the ambient conditions, the electric charges on the droplets, the size distribution of the droplets and particles, and the lifetime of the droplets.

Devices to generate charged sprays have been used extensively in paint spray equipment for some time. Electrically charged sprays have been generated in applying agricultural pesticides, as reported by Law (1978) and Carlton and Bouse (1980). The use of charged sprays for dust control was initiated by Hoenig (1979) at the University of Arizona and Hassler (1978) at the Royal Institute of Technology, Stockholm, Sweden. All these devices use a pressure nozzle to atomize the water.

Water droplet charging is generally achieved by one of three principles: (a) electrostatic induction charging, (b) ionized field charging, (c) contact charging.

Hassler (1978) showed that the droplets may be charged by the water-to-metal frictional forces inside the nozzle during atomization. This method requires no high voltage supply; however, it requires very pure deionized water. The limitation to deionized water precludes the use of this method of charging for dust control in the field.

Figure 8 schematically shows these droplet charging mechanisms in conjunction with a spray nozzle. In the most frequently used method, electrostatic induction charging, a high voltage potential is maintained between the water spray nozzle and the induction ring, as shown in Figure 8a. Positive or negative charges are induced on the droplets due to the charges on the induction ring, depending on the polarity of the high voltage applied to the ring. A detailed analysis of the induction charging of droplets is given by Law (1978). In ionized field charging, as shown in Figure 8b, an electrode at a sufficiently high dc potential is placed near the water nozzle. This causes dielectric breakdown of the air immediately surrounding the electrode. Water droplets traveling through this ionized field region can acquire electric charges by ion attachment.

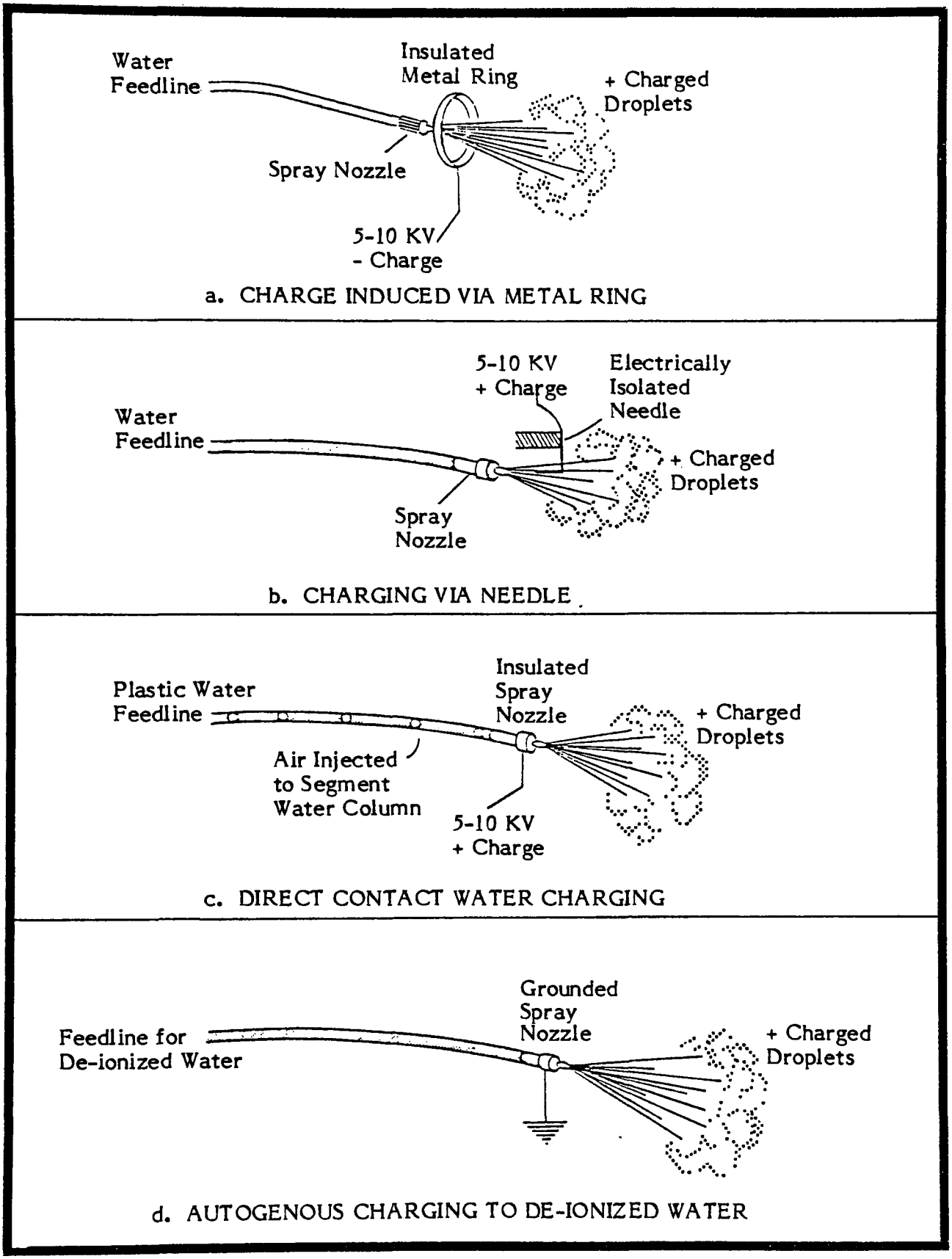


Figure 8. Means of producing a charged water spray (Source: Daugherty and Coy, 1979).

Charge transfer by conduction to the water and subsequently to the droplets at their instant of formation can be achieved by connecting a source of charges (high voltage supply) to the inflowing water. This method has been shown by many to be very effective in charging the droplets to a high degree. However, this method requires that the entire water supply and associated tubings be electrically isolated so that there is no current leakage. Injecting bubbles into the water tube, as shown in Figure 8c, was suggested by Hoenig (1979) as a possible solution for this problem.

The commercially available fog device ("Fogger") appropriate to our study was originally developed by Dr. Hoenig, primarily under sponsorship by the U.S. Environmental Protection Agency. The design of the Fogger had certain inherent problems, which not only limited its application to certain types of fugitive sources, but also limited the degree of control of fine particles. These problems are related to the need for high pressure air or water to properly atomize water, poor charge-to-mass ratio of droplets generated at reasonably acceptable waterflow rates, and the possibility of the nozzle clogging if the water supply contains high concentrations of dissolved salts and suspended solids. Thakur (1980) has reported dust and fog buildup on the induction ring and subsequent spark formation.

In order to overcome these difficultites, the U.S. EPA contracted with AeroVironment Inc. (AV), with Dr. Stuart Hoenig as AV's consultant, to design, develop, and field test a new charged fog device. During the beginning of the project, a prototype device, called a "spinning cup fog thrower" (SCFT) was built with Dr. Hoenig's assistance at the University of Arizona in Tucson. This device, described in this section, attempted ionized field charging of droplets. The SCFT was wind tunnel-tested in Tucson, and after a complete analysis of the data collected, the instrument was abandoned. Contact charging was thereafter used as the mechanism to charge the water droplets in the new charged fog device. This chapter discusses the development and early setbacks of the SCFT and gives its test results. The new charged fog device is discussed in detail in Sections 6 and 7.

THE SPINNING CUP FOG THROWER (SCFT)

Basic SCFT Design

Figure 9 is a schematic representation of the first prototype SCFT designed and built (with the assistance of Dr. Stuart Hoenig) at the University of Arizona. Figure 10 is a photograph of the SCFT. The SCFT has three main components: a rotary atomizer, an ionizer and a vane-axial blower. The rotary atomizer is composed of a small, hollow shaft motor and a spinning cup. Water from a low-pressure source is introduced into the hollow shaft and flows toward the other end where the spinning cup is mounted. Upon entering the rear of the cup, the water stream strikes a rotating spider which deflects the water to the sides. A sheet of water then flows toward the lip of the cup where droplets are formed by centrifugal force and by the air stream striking the thin water layer, normally leaving the edge of the cup tangentially. In an initial attempt, the droplets were passed through a screen mesh maintained at a high voltage. However, this method of charging the droplets had to be abandoned, because any mesh small enough to provide good charge on the droplets also seriously altered the fog pattern.

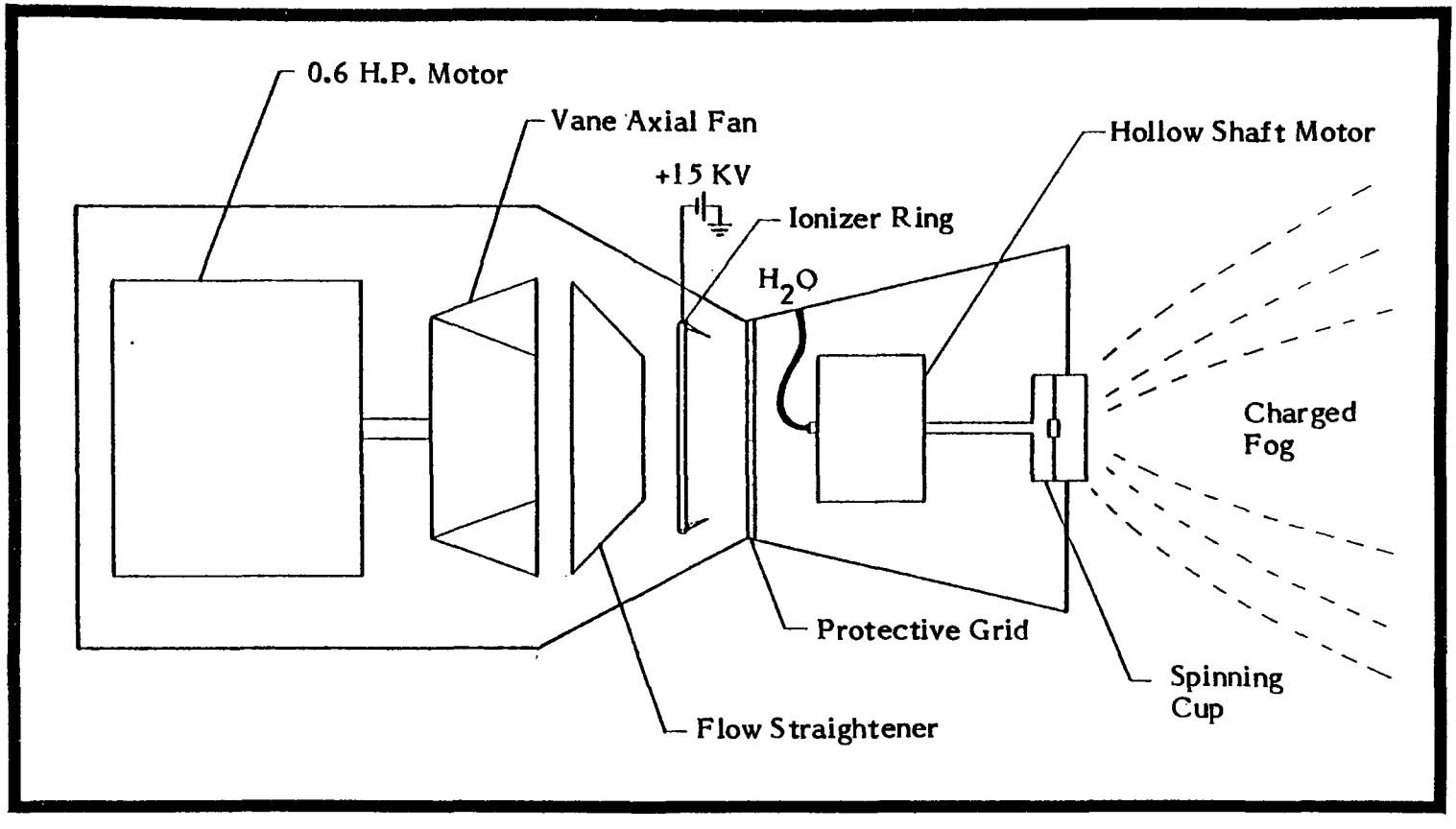


Figure 9. Schematic of the Spinning Cup Fog Thrower.

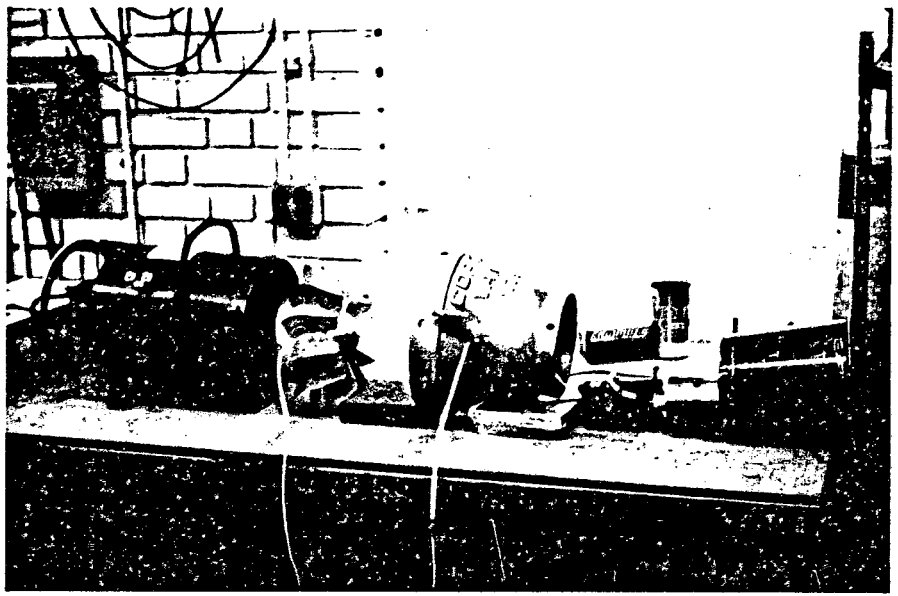


Figure 10. Original spinning cup fog thrower.

The droplets were then charged by a stream of positive ions produced by an ionizer containing numerous small discharge needles. It was expected that the ions produced in the region of the ionizer ring would follow the airflow from the vane-axial fan and mix with the droplets and charge them. Current to the ionizer ring was supplied by a vacuum tube high-voltage dc power supply. The charged droplets were then deflected and projected forward by a stream of air supplied by the vane-axial blower. However, this method of charging of the droplets was later found to be inefficient.

Initial Wind Tunnel Test Design

In order to evaluate the particle control efficiency of the SCFT, a series of tests was conducted in a 1.2 m x 1.2 m x 18 m wind tunnel provided by the University of Arizona. Figure 11 schematically represents the wind tunnel. A standard dust (AC coarse) of known particle size and density was pneumatically fed into the entrance of the tunnel by a vibra-screw feeder. Compressed air was homogeneously mixed with the incoming ambient air by a diffuser cone. The SCFT was mounted approximately 3 m downstream of the tunnel entrance with the fog and air in concurrent flow. Plexiglas viewing ports on both sides of the tunnel at the discharge end of the fogger allowed the wet/dry interface to be observed closely. Two sets of sampling ports were positioned in the front vertical wall of the tunnel; one set, approximately 2.5 m downstream of the discharge end of the SCFT was to determine charge-to-mass ratio and droplet size, and the other set at the far end of the tunnel was to determine particle mass concentration and size. An axial fan pulled approximately 12,000 dscf/min of air through the tunnel.

To determine the control efficiency of the SCFT under various experimental conditions, particle samples were collected according to the test plan shown in Table 1. The test runs were completed for each scenario of Table 1 at approximately 10-30% ambient relative humidity. An isokinetic sample was collected for each run. A sample train was made especially for this purpose to isokinetically extract a representative sample of particulate matter from the wind tunnel. Figure 12 is a photograph of the sampling train. This train consisted of a pitot tube and associated inclined manometer connected by a flexible sample line to a horizontal elutriator. The elutriator was designed to have a 15-μm particle diameter cut-point (50% efficiency) at a flow rate of 0.55 m^3/min (20 scfm). Behind the elutriator was mounted a standard Sierra Instruments five-stage cascade impactor which discharged to a silica gel trap to determine moisture content. The flow was measured by a National Bureau of Standards (NBS) traceable Laminar Flow Element manufactured by Merriam Instrument Company. The Laminar Flow Element (LFE) was located downstream of the silica gel trap and connected to a standard Dwyer magnahelic gauge for reading differential pressure. The flow rate was metered by a large capacity needle valve downstream of the LFE followed by a Cadillac centrifugal blower acting as prime mover. The particle sample collected was later analyzed gravimetrically to determine both the total mass concentration and particle size distribution for each test scenario.

For sample recovery, the front portion of the sample train and the horizontal elutriator were rinsed with deionized water and placed in separate plastic sample containers for transport back to the laboratory. There, the liquid/particle mixture was transferred to tared beakers and evaporated to dryness to determine the total mass collected. The samples were then resuspended in distilled water and deagglomerated ultrasonically. A Leeds & Northrup Microtrac Analyzer determined particle sizes using a

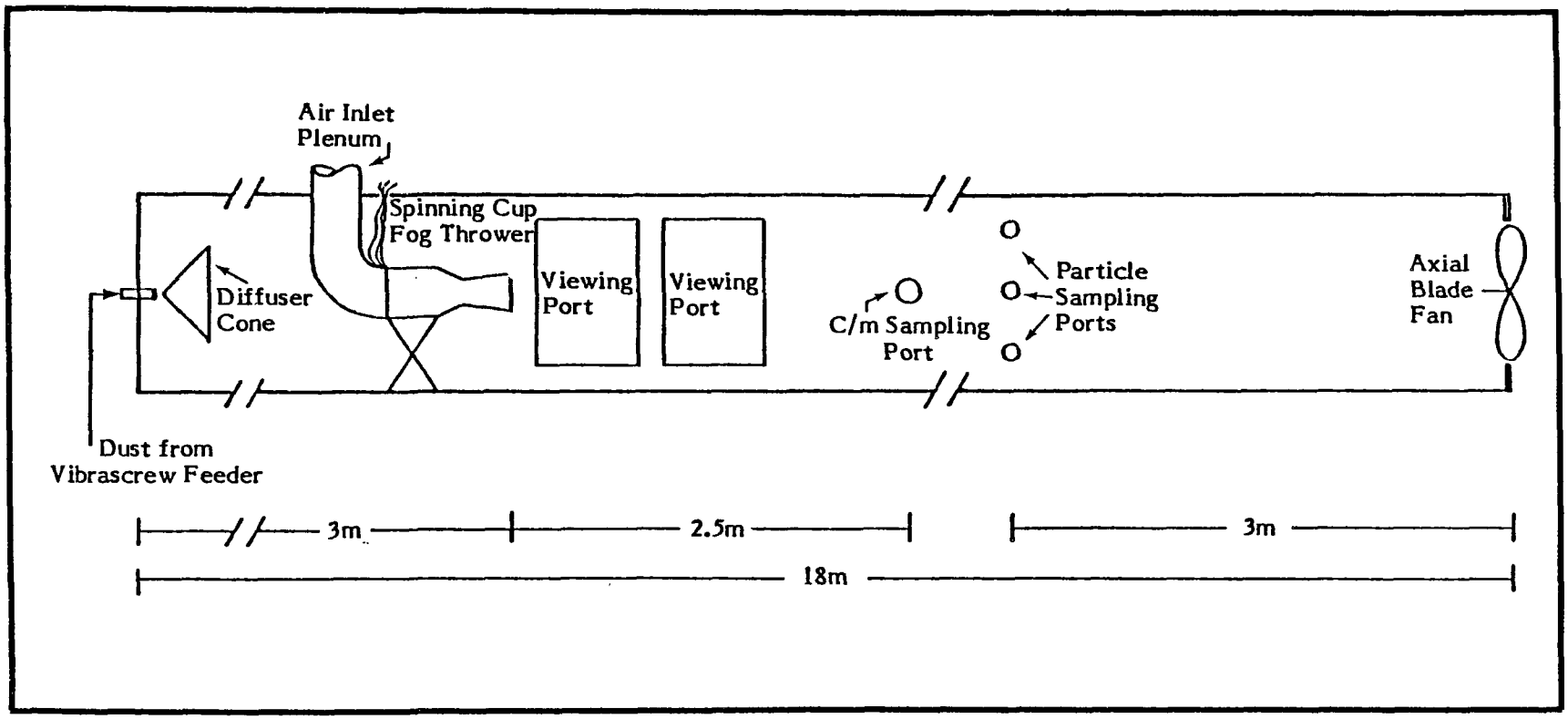
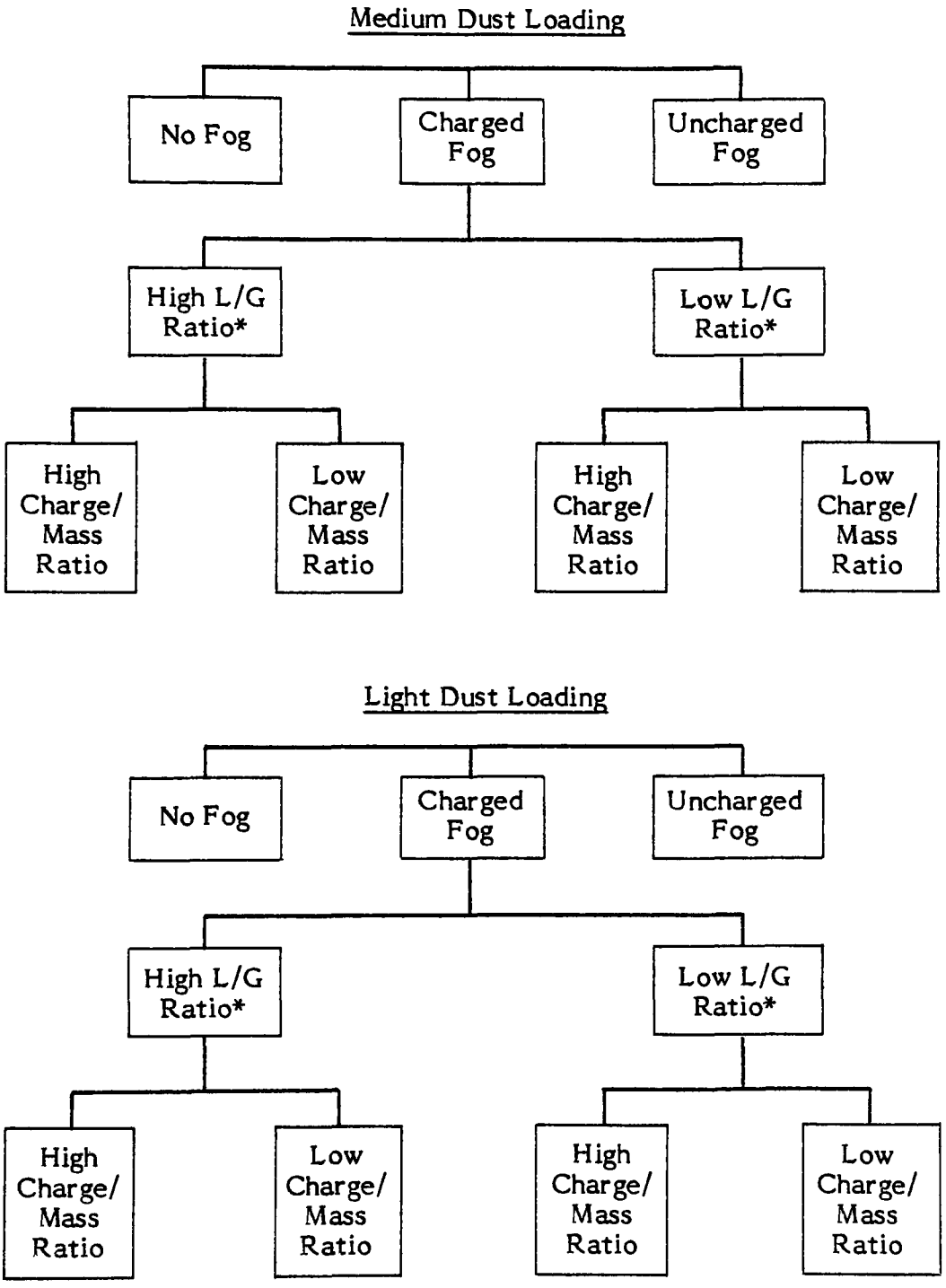


Figure 11. Schematic of University of Arizona wind tunnel.

TABLE 1. INITIAL SCFT WIND TUNNEL TEST PLAN



*High or low liquid-to-gas ratio.

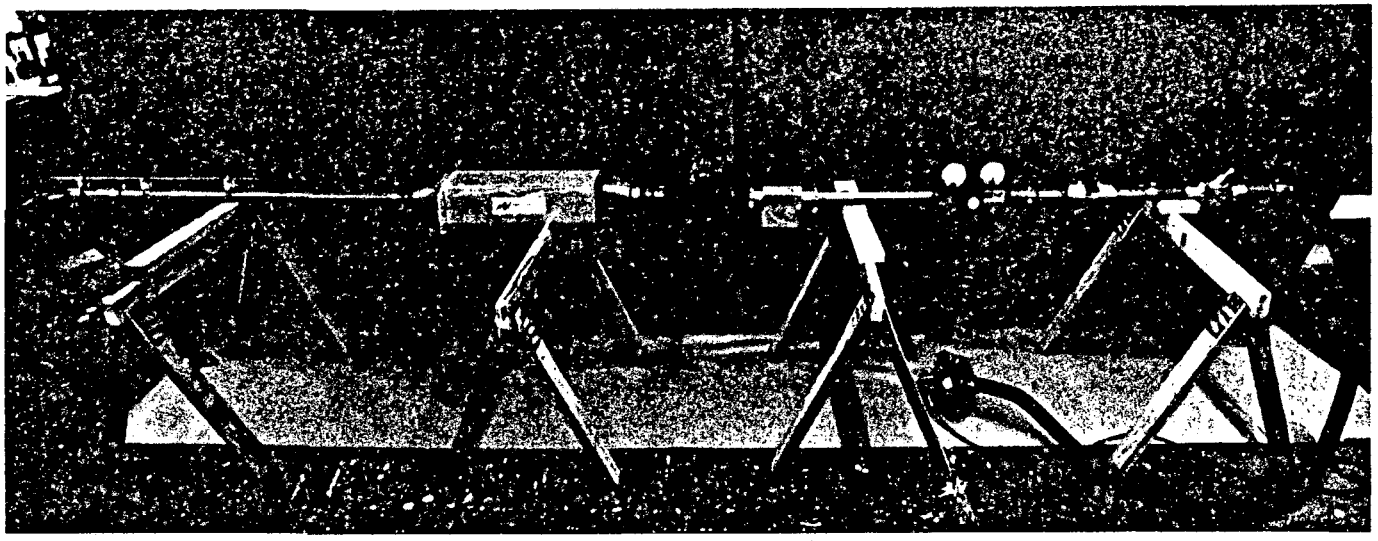


Figure 12. Particle sampling train used during the wind tunnel studies.

ruby laser and forward-scatter optical technique. The samples collected on the various cascade impactor stages were also weighed using a standard analytical balance.

The charge-to-mass ratio of the droplets was determined using a special sample train developed by AV, as shown in Figure 13. This train consisted of an insulated stainless steel probe tip mounted on a standard glass midget impinger. The probe was connected electrically to copper wool packing placed inside the midget impinger which was also connected by a shielded cable to an electrometer (Hewlett-Packard Model 425A) and associated strip chart recorder. The impinger was immersed in a Dewar flask containing dry ice. An isokinetic sample of droplets was then extracted from the tunnel. As the droplets moved through the impinger they were condensed out of the gas stream and frozen, thus transferring their charge to the copper wool packing. The charge was then measured by the electrometer and recorded by the chart recorder. Isokinetic conditions were maintained by a Hastings mass flowmeter and needle valve with a standard diaphragm pump acting as prime mover. A standard pitot tube and associated inclined manometer were mounted next to the impinger/Dewar flask assembly with adequate distance between them to avoid aerodynamic interference. The mass of water collected in the impinger was determined gravimetrically at the end of each test run using a portable triple-beam balance. Knowing the mass of droplets collected and the current produced by them, the charge-to-mass ratio was calculated.

The size distribution of the droplets was measured simultaneously with the charge-to-mass ratio by a KLD Model DC-2 droplet counter. This unit uses a hot-wire technique to measure the size of the droplets in 14 incremental ranges from 1 μm to greater than 450 μm. The hot-wire probe was mounted far enough from the impinger to avoid aerodynamic interference with it.

INITIAL WIND TUNNEL TEST RESULTS AND DISCUSSION

Data from the first series of tests, as described above, are presented in Table 2. The total mass concentration measured for various experimental conditions for a light dust feed rate to the tunnel is shown in Figure 14, and for a medium dust feed rate in Figure 15. It was found that the larger, agglomerated particles were being collected in the first bend of the sample probe and were not allowed to settle out of the gas stream due to the high velocity. For this reason, Figures 14 and 15 also show a second value, where available, for the total amount of particulate matter caught by the sample train less the larger particles collected in the probe.

The droplet size distribution measured using the KLD droplet counter showed a mean droplet diameter of about 5 μm. If this were indeed the case, the poor collection efficiency may be partly due to the very short lifetime of the droplets due to evaporation in the wind tunnel. The charge-to-mass ratio was observed to be only of the order of 10^{-11} C/g. It was also noticed that big satellite droplets of water, constituting as much as 70% of the SCFT water output, were too large for particle agglomeration and were just wetting down the wind tunnel.

A detailed analysis of the wind tunnel tests has demonstrated that a number of conditions were responsible for the poor collection efficiency of the SCFT. The first of these relates to the charging of the droplets. The charge on the droplets varied drastically across the cross-section of the spray cone. With a positive charge applied to

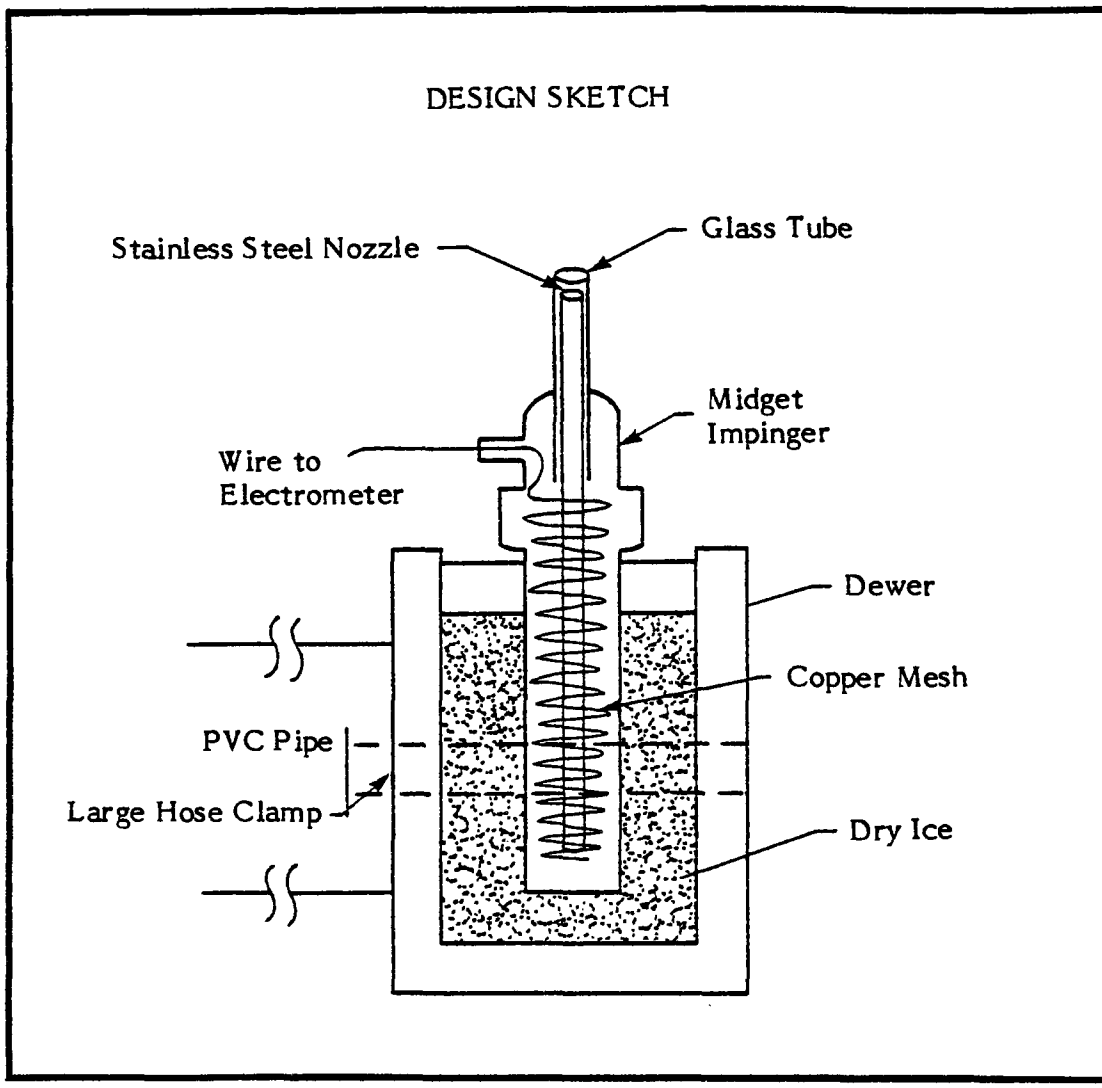


Figure 13. Sample train to determine the charge-to-mass ratio of water droplets.

TABLE 2. SUMMARY OF INITIAL SPINNING CUP FOG THROWER WIND TUNNEL TEST DATA.

Scenario	Run No.	Particle Mass Collected											Average Flowrate Through Sampling Train (dscf/min)	Grain Loading (gr/dscf)	Testing Date
		Mass of Washings			Mass Collected by Impactor Stages						Total Mass Collected		Sampling Time (min.)		
		A (gm)	B (gm)	Total (gm)	1 (gm)	2 (gm)	3 (gm)	4 (gm)	5 (gm)	Total (gm)	in grams	in grains			
Uncontrolled-Med. Dust	2	0.899	--	0.899	0.0062	0.0236	0.0282	0.0370	0.0249	0.1199	1.0189	15.7241	37	19.08	0.0221	11/14/79
Uncontrolled-Light Dust	3	0.055	0.770	0.826	0.0095	0.0368	0.0392	0.0442	0.0268	0.1565	0.9825	15.1623	60	17.23	0.0147	11/15/79
Uncontrolled-Light Dust	4	0.120	0.524	0.644	0.0062	0.0266	0.0298	0.0356	0.0228	0.1210	0.7656	11.8155	60	18.03	0.0109	11/15/79
Med. Dust; Fog; No Chg.	5	0.039	0.401	0.440	0.0078	0.0292	0.0342	0.0387	0.0236	0.1335	0.5735	8.8505	36	19.92	0.0123	11/15/79
Med. Dust; Fog No Chg.	6	0.595	--	0.595	0.0126	0.0392	0.0372	0.0410	0.0240	0.1540	0.7490	11.5589	36	16.62	0.0193	11/16/79
Light Dust; Fog; No Chg.	7	0.653	--	0.653	0.0094	0.0294	0.0350	0.0402	0.0244	0.1384	0.7914	12.2132	60	17.53	0.0116	11/16/79
Light Dust; Fog; No Chg.	8	0.602	--	0.602	0.0122	0.0376	0.0416	0.0470	0.0317	0.1701	0.7721	11.9154	60	18.18	0.0109	11/16/79
Med. Dust; High L/G; High C/m(-)	9	0.749	0.049	0.798	0.0134	0.0372	0.0377	0.0431	0.0271	0.1585	0.9565	14.7611	36	16.93	0.0242	11/17/79
Med. Dust; High L/G; High C/m(-)	10	0.585	--	0.585	0.0162	0.0410	0.0380	0.0399	0.0243	0.1594	0.7444	11.4879	36	17.60	0.0181	11/19/79
Med. Dust; High L/G; Low C/m(-)	11	0.473	--	0.473	0.0101	0.0294	0.0284	0.0320	0.0204	0.1203	0.5933	9.1560	36	20.01	0.0127	11/19/79
Med. Dust; High L/G; High C/m(+)	12	0.669	--	0.669	0.0106	0.0295	0.0280	0.0304	0.0178	0.1163	0.7853	12.1191	36	22.00	0.0153	11/19/79
Med. Dust; High L/G; High C/m(+)	13	0.739	--	0.739	0.0148	0.0434	0.0416	0.0441	0.0278	0.1717	0.9107	14.0543	36	18.55	0.0210	11/20/79
Med. Dust; High L/G; Low C/m(+)	14	0.675	0.085	0.760	0.0142	0.0404	0.0442	0.0448	0.0287	0.1723	0.9323	14.3876	36	20.92	0.0191	11/20/79
Med. Dust; High L/G; Low C/m(+)	15	0.611	--	0.611	0.0166	0.0419	0.0421	0.0464	0.0263	0.1733	0.7843	12.1036	36	19.83	0.0170	11/20/79

(continued)

TABLE 2. continued

Scenario	Run No.	Particle Mass Collected: Mass of Washings A (gm)	B (gm)	Total (gm)	Mass Collected by Impactor Stages: 1 (gm)	2 (gm)	3 (gm)	4 (gm)	5 (gm)	Total (gm)	Total Mass Collected: in grams	in grains	Average Flowrate Through Sampling Train: Sampling Time (min.)	(dscf/min)	Grain Loading (gr/dscf)	Testing Date
Uncontrolled-Med. Dust	16	0.858	--	0.858	0.0134	0.0386	0.0400	0.0435	0.0277	0.1632	1.0212	15.7596	36	16.63	0.0263	11/28/79
Med. Dust; Fog No Chg.	17	0.353	0.365	0.718	0.0197	0.0409	0.0392	0.0416	0.0269	0.1683	0.8863	13.6777	36	17.27	0.0220	11/28/79
Uncontrolled-Light Dust	18	0.781	--	0.781	0.0120	0.0353	0.0373	0.0416	0.0268	0.1530	0.9340	14.4139	60	17.38	0.0138	11/30/79
Light Dust; Fog; No Chg.	20	0.427	0.311	0.738	0.0120	0.0321	0.0360	0.0406	0.0274	0.1481	0.8861	13.6746	60	17.93	0.0127	12/03/79
Light Dust; High L/G; High C/m	21	0.421	0.434	0.855	0.0131	0.0362	0.0089	0.0440	0.0328	0.1350	0.9900	15.2781	60	25.14	0.0101	12/04/79
Light Dust; Low L/G; Low C/m	22	0.326	0.357	0.683	0.0111	0.0298	0.0342	0.0424	0.0270	0.1445	0.8275	12.7703	60	24.03	0.0089	12/04/79
Light Dust; High L/G; Low C/m	23	0.337	0.221	0.558	0.0101	0.0304	0.0342	0.0380	0.0267	0.1394	0.6974	10.7626	60	24.52	0.0073	12/05/79
Uncontrolled-Light Dust	24	0.724	--	0.724	0.01201	0.0288	0.0316	0.0409	0.0305	0.1438	0.8678	13.3922	60	23.59	0.0095	12/05/79
Light Dust; Low L/G; High C/m	25	0.363	0.233	0.596	0.0092	0.0304	0.0356	0.0388	0.0257	0.1397	0.7357	11.3536	60	26.03	0.0073	12/06/79
High Dust; Low L/G; High C/m	26	0.446	0.295	0.741	0.0094	0.0296	0.0310	0.0354	0.0250	0.1304	0.8714	13.4478	36	24.00	0.0156	12/06/79
Med. Dust; Low L/G; Low C/m	27	0.348	0.293	0.641	0.0089	0.0267	0.0292	0.0338	0.0251	0.1237	0.7647	11.8012	36	22.65	0.0145	12/06/79
Uncontrolled-Med. Dust.	28	0.849	--	0.849	0.0120	0.0252	0.0276	0.0352	0.0282	0.1282	0.9772	15.0805	36	23.90	0.0175	12/06/79

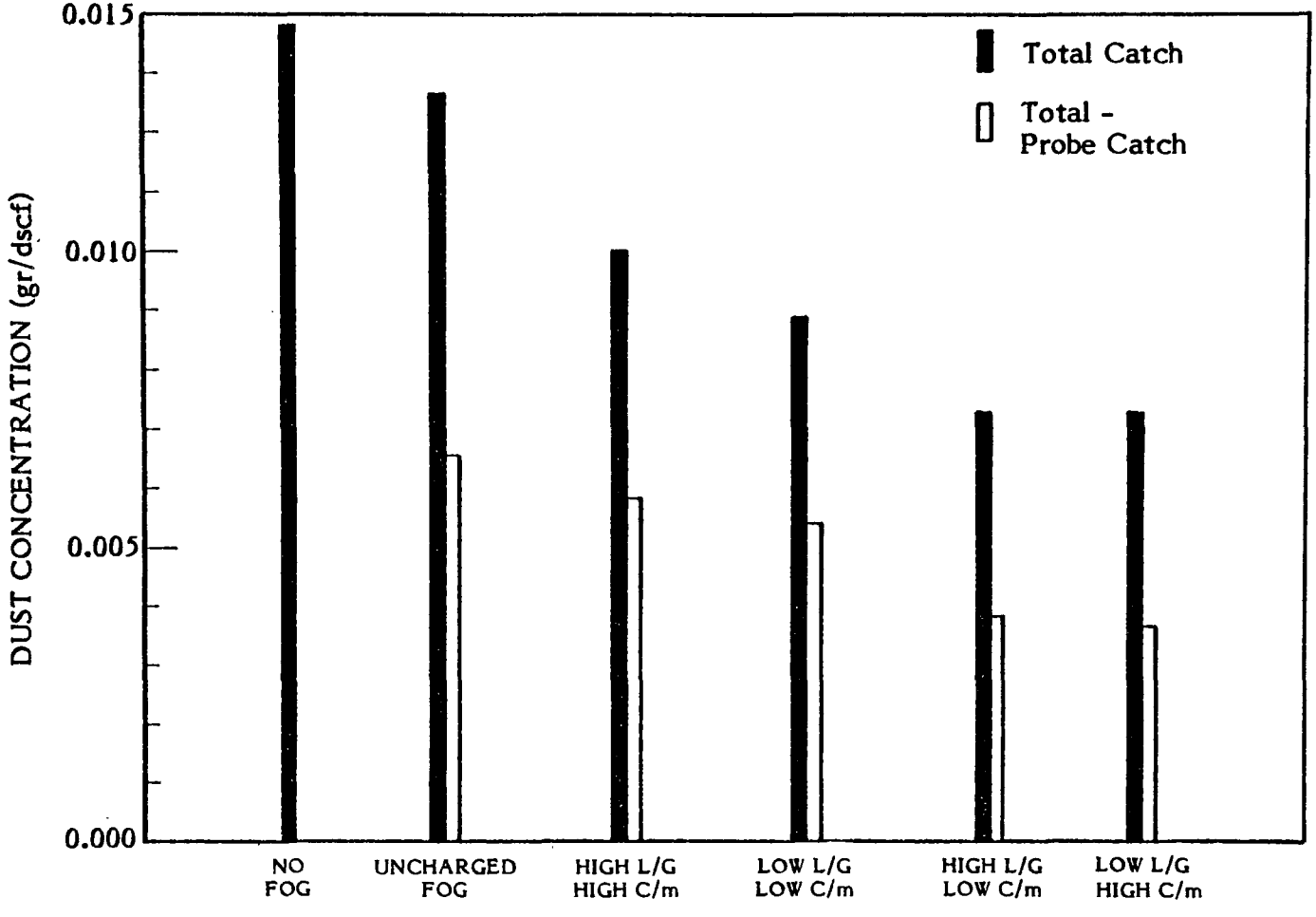


Figure 14. Summary of test data for light dust loading.

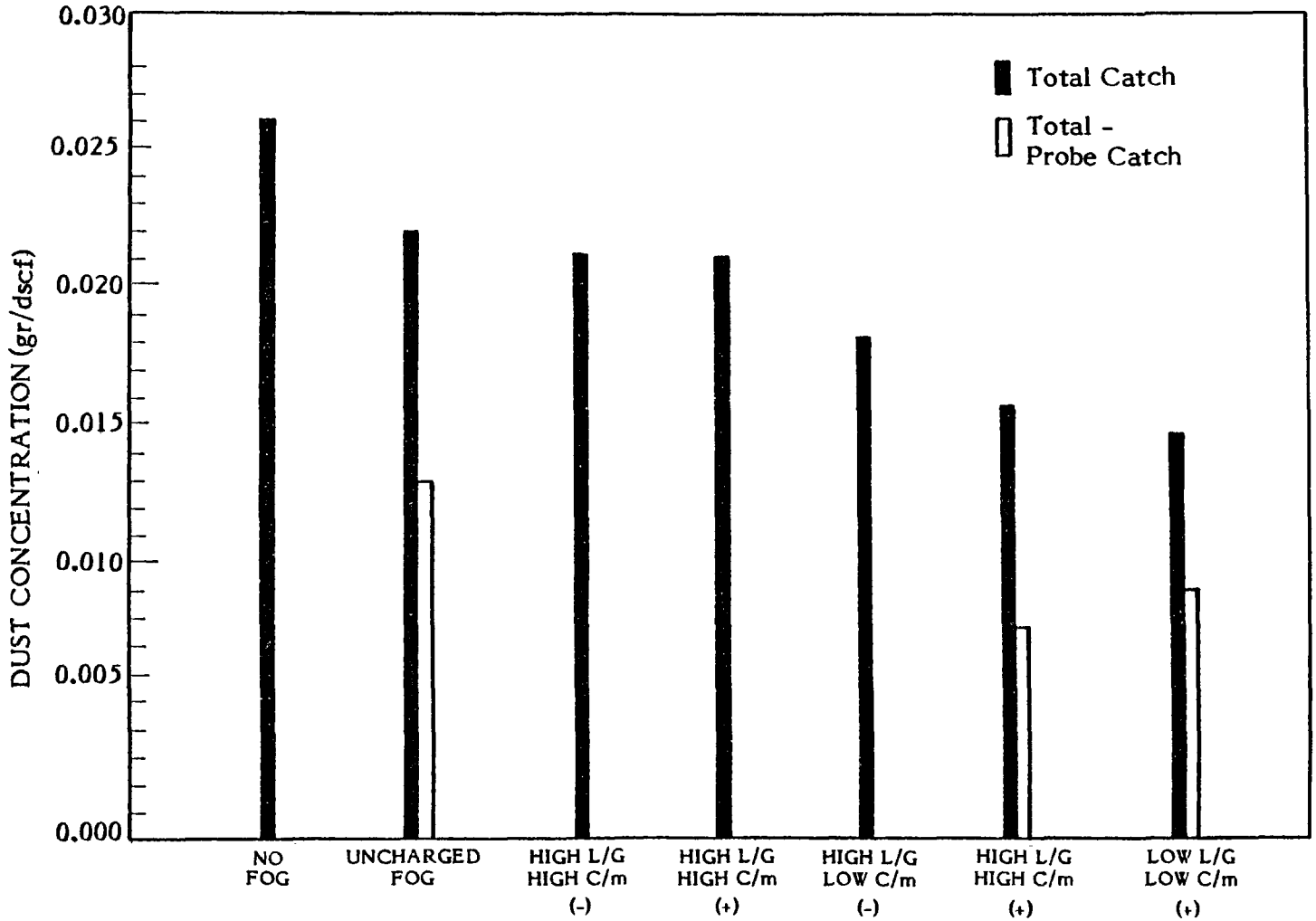


Figure 15. Summary of test data for medium dust loading.

the droplets, the outer edges of the spray seemed to exhibit a slight negative charge, whereas the droplets in the center of the cone exhibited a strongly positive charge.

The size of the droplets themselves also seemed to contribute to the poor collection efficiency of the SCFT. Given the size distribution measured by the KLD droplet counter, the median droplet diameter of approximately 5 μm, and the low relative humidity in the wind tunnel, the lifetime of the droplets was too short for effective control of inhalable dust particles. Several attempts were made to increase the relative humidity of the gas stream in the tunnel for the final series of runs. A header was constructed and mounted with a series of spray nozzles which produced fine droplets. The header was then supplied with high-temperature, high-pressure (200° F/800 psig) water from a spray cleaning device. Even placing the header in a specially constructed extension to the wind tunnel at its entrance did not give the water adequate time to vaporize and thus it wetted down the entire tunnel. A mist evaporator was constructed from four evaporative cooler pads to eliminate the water droplets and to allow more surface area for evaporation, and was placed downstream of the spray header in the tunnel extension. This setup yielded relative humidities of up to 80%; however, the increased pressure drop due to the mist evaporator caused the flow rate in the tunnel to drop to approximately 25% of normal.

WIND TUNNEL TEST MODIFICATIONS

The data in Figures 14 and 15 show only about 50% reduction in the dust, which is far short of the 90%+ targeted efficiency under controlled conditions. It was clear that the efficiency could be improved by

- increased charge-to-mass ratio of the droplets,
- decreased air velocity through tunnel allowing more time for interaction between the particles and droplets, and
- countercurrent flow of dust versus droplets.

Therefore, to facilitate the capture and removal of dust from the air stream, these changes were incorporated into the test setup. Several attempts were made to redesign the ionizer to increase the number of positive ions produced and thus increase the charge on the droplets. The first attempt was to install small wire brushes in addition to the needles on the ionizer ring. This arrangement did not significantly increase the charge on the droplets and was eventually discarded. The most successful method was to isolate the spinning cup itself at a high voltage and to supply water from a separate line into its center. The original ionizer ring, without brushes, was retained to produce a constant stream of positive ions, as before. Both the cup and the ionizer ring were to have separate high-voltage power supplies.

The velocity of the air moving through the tunnel was decreased from approximately 1200 fpm to approximately 475 fpm by a larger pulley on the fan in conjunction with the mist eliminator used for humidifying the gas stream. Further reductions in velocity were not practical due to limitations of the velocity-measuring instrumentation.

In the original experiment, the SCFT was installed inside the tunnel, projecting fog concurrently with the air/dust mixture. Arrangements were made to reverse the direction

of the fog 135° relative to the air stream, with the SCFT unit itself outside the wind tunnel. A complete 180° shift was not possible due to potential dust buildup on the insulators. In addition to these modifications, a new screw was installed in the Vibra-Screw Dust Feeder. Thus, more dust could be fed to the tunnel and the test run time decreased substantially.

After these modifications a number of new problems were encountered. The first was current leakage from the cup through the external water line. Several expedient methods to solve this problem were attempted, such as installing a pressure nozzle on the copper water line to break up the stream into coarse droplets, but measurements showed that significant current still followed the water flow depending on the distance from the pressure nozzle to the cup. The most effective method to reduce current leakage was to inject air bubbles into the water stream before atomization, using a large-bore hypodermic needle and compressed air. This technique did not completely eliminate the problem but did reduce the leakage to a tolerable level.

The second major problem concerned actually generating the fog. The rotary atomizer tended to produce large satellite drops which impinged on the tunnel walls and thus did not contribute to the capture of dust particles. In addition, the small droplets entrained in the airstream provided by the blower evaporated very quickly at ambient relative humidity (10% to 30%). Both these factors severely limited the effectiveness of the SCFT to control fine particles. To solve these problems and to provide droplets of an effective size and concentration, it was necessary to redesign the whole device. Associated with this new design would be a modified method for charging the droplets which would achieve a high charge-to-mass ratio, while remaining compatible with the new atomizer.

SECTION 6

THE CHARGED FOG GENERATOR (CFG)

INTRODUCTION

The wind tunnel tests of the spinning cup fog thrower at the University of Arizona revealed the need for a new system capable of producing well-charged fog. To assure the highest possible particle control efficiency with charged droplets, the new device had to achieve the following goals:

(1) It must be able to produce sufficient fog to control particles at typical material handling areas.

(2) The size distribution of the fog generated should be most suitable for inhalable particle control.

(3) It must incorporate an efficient method to charge the droplet so that the charge-to-mass ratio would be suitable for inhalable particle control.

(4) It must project the charged droplets to the dust particle-laden area and provide for sufficient residence and contact time between the droplets and the particles, and

(5) The unit should be somewhat small, preferably portable, and of fairly low power consumption for operation in areas where commercial power is not available and preferably operable from a mobile vehicle.

A commercially available device using a spinning cup and blower configuration for furnace oil atomization was determined to be adaptable to achieve the above goals. Thus, as the core of the new CFG, a Ray Oil Burner was chosen.

CHARGED FOG GENERATOR DESIGN

The type AG Ray Oil Burner is a horizontal, rotary atomizing unit consisting of only one movable part, a hollow steel shaft upon which are mounted the atomizing cup, the fan and the motor rotor. These parts comprise the shaft assembly which rotates as a unit on two ball bearings, as Figure 16 shows. Figure 17 is a schematic representation of the CFG. A stationary tube extending through the center of the hollow main shaft of the burner into the atomizing cup introduces the fuel -- in this case, water. The atomizing cup is long and tapered, which permits the water to form a thin film on the inside of the cup before reaching the rim, thus discharging evenly.

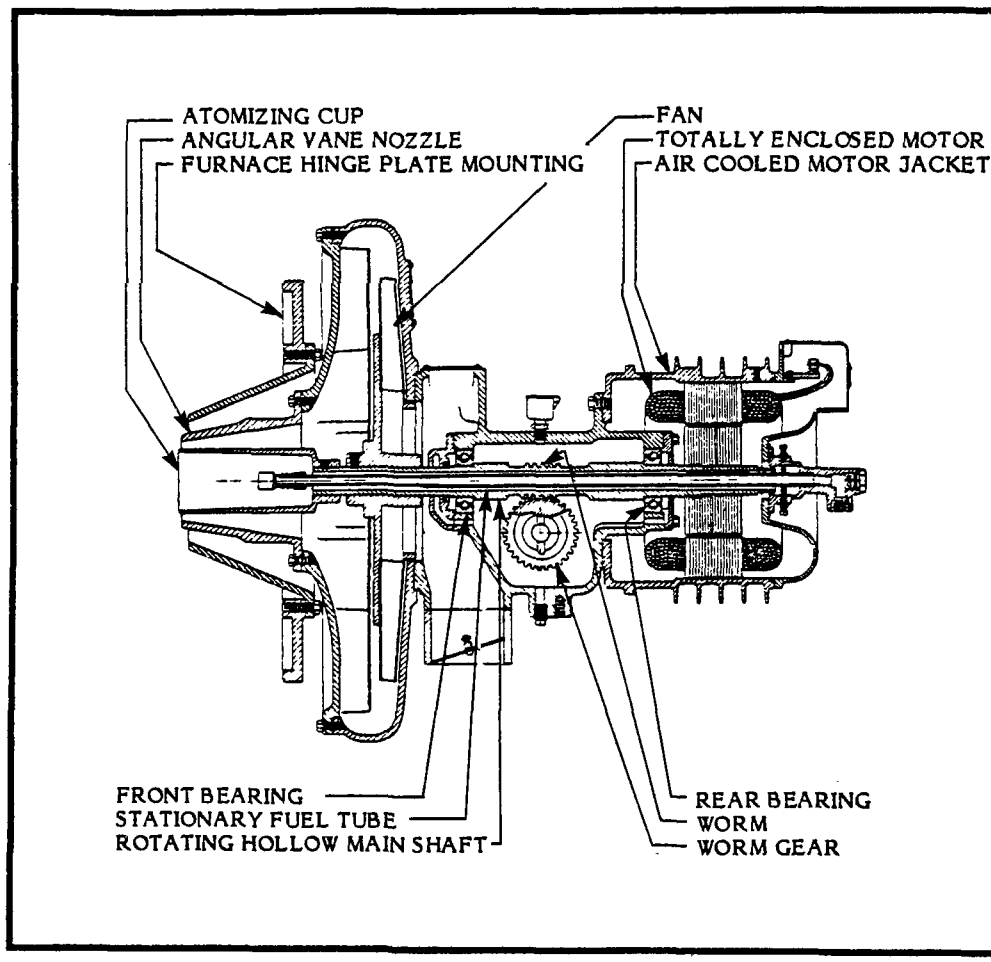


Figure 16. Cross-sectional diagram of a type "AG" Ray Oil Burner.

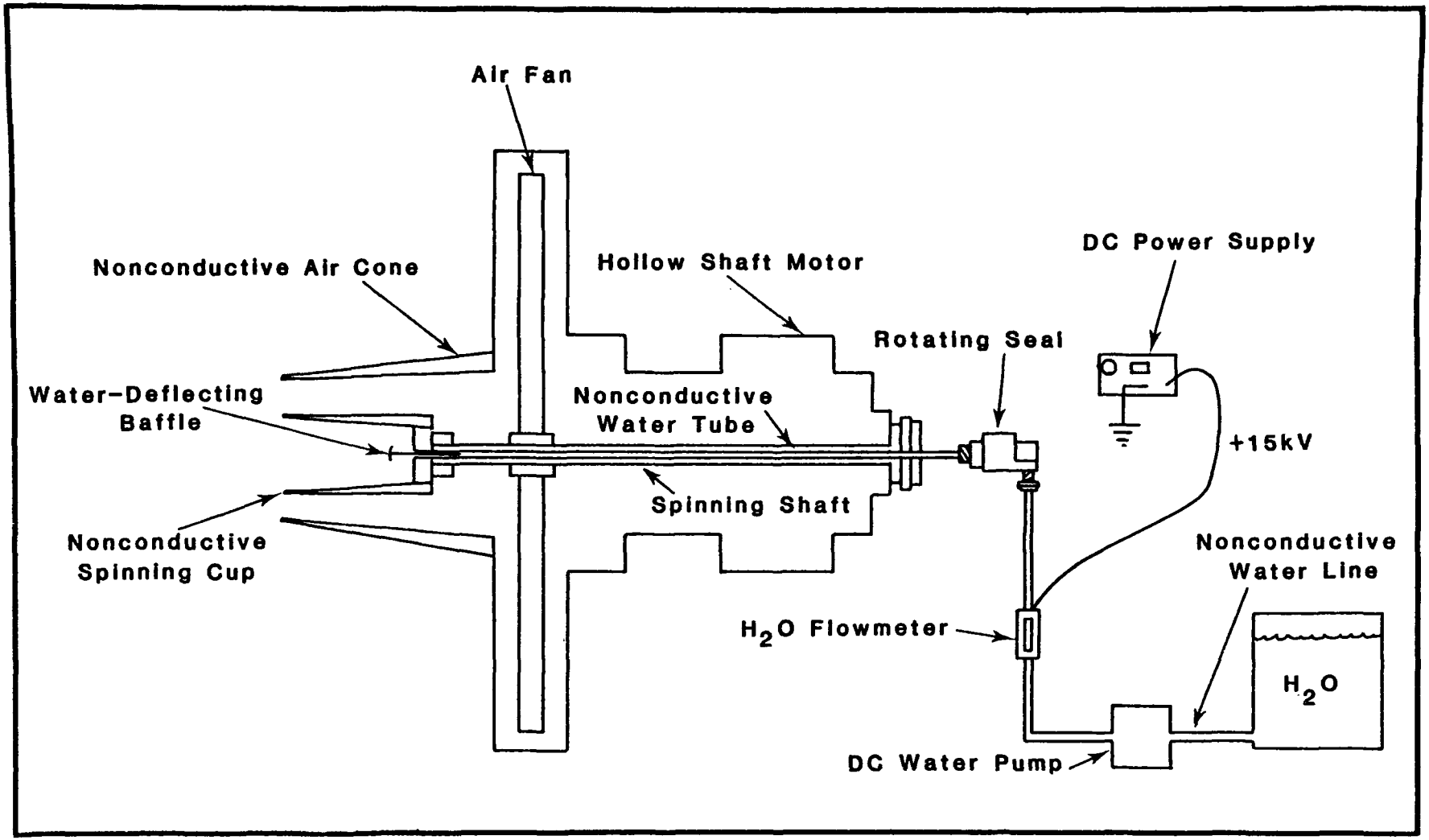


Figure 17. Schematic diagram of the Charged Fog Generator.

Water is introduced through the water tube into the 3600-rpm spinning cup, whose inside is fabricated to a gradual smooth taper (Figure 18). A small deflecting baffle is attached to the open end of the water tube so that the water will be deflected 90° and strike the rear end of the spinning cup. Because of the centrifugal forces, the water becomes a thin film and moves forward into a high velocity airstream from the axial fan. The impact of the high velocity air on the thin water film instantly breaks the water film into fine water droplets.

The fuel tube, air cone, and the rotating cup are made of nonconducting materials. The water tube is firmly attached to the rotating cup, thus rotating with the cup. The other end of the water tube is attached to the water supply through a rotating seal (see Figure 19). The water for atomization is stored in an electrically isolated reservoir (120-liter capacity) and a small pump is used to pump it to the inlet of the rotating seal. The water flow rate can be varied from about 4 liters to 70 liters per hour. The flow meter can be seen in Figure 20.

The oil burner is equipped with Ray adjustable angular vane nozzles which allow spray pattern adjustments. The vanes of the nozzle can be angled from 50 to 90°. The 50° nozzle produces a short, wide spray, while the 90° nozzle produces a long, narrow spray. The shape of the spray is also controlled by the airflow around the cup. The airstream from the fan can be controlled by an air butterfly setting (1 to 9 scale), and this airstream projects the fog forward. By adjusting this setting, the airflow speed can be controlled, thereby controlling the shape of the fog spray pattern. The spray pattern covers a volume of 16 to 24 cubic meters. Figures 21 and 22 show two possible spray patterns -- one long and narrow, and the other broad and short. Thus, the spray pattern can be easily adjusted to better conform to the shape and size of the source of dust where the charged fog is to be applied.

To achieve high charge-to-mass ratio for the droplets, this and other studies have shown that directly charging the inflowing water is the best alternative (Pilat, 1975; Kearns and Harmon, 1979). Thus, the water from the reservoir tank to the rotating cup (until it becomes fog) has to be electrically isolated and maintained at a high potential. A 15-kV dc power supply was directly connected to the inflowing water near the rotating seal. Although the voltage applied was very high, the current used was only fractions of milliamperes and therefore, in our experience, posed no significant safety hazard, even to someone accidentally touching the exposed high-voltage areas.

During the initial development stages of this method of droplet charging, the water tube was stationary, causing the water to leak to the casing of the oil burner and thereby the current to leak to the ground. This problem was solved by attaching the water tube to the rotating cup and connecting the rotating seal at the other end. Under the present configuration, the CFG is capable of producing well-charged fog (Mathai, 1983a), with a droplet size distribution suitable for inhalable particle collection (see discussion below on size distribution and charge-to-mass ratio).

SIZE DISTRIBUTIONS OF WATER DROPLETS

Initially, the size distribution of the droplets was determined by collecting the droplets on greased (silicon oil) glass slides and observing them under a microscope. As the spherical water droplets undergo a shape deformation when they are collected on slides, a conversion factor of 1.26 (as suggested by Pilat et al., 1974) was used to obtain

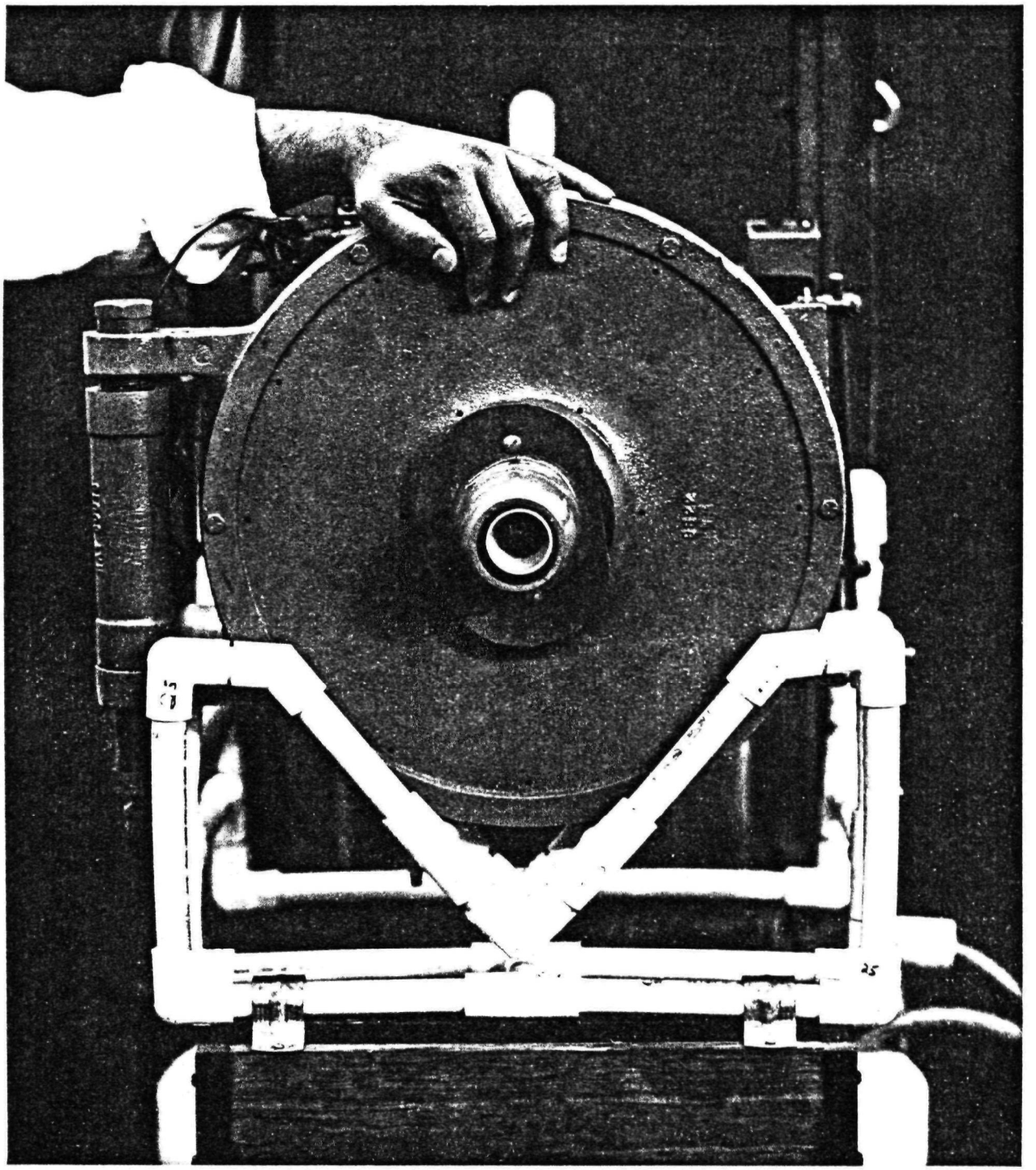


Figure 18. Rotating cup and air cone of the Charged Fog Generator.

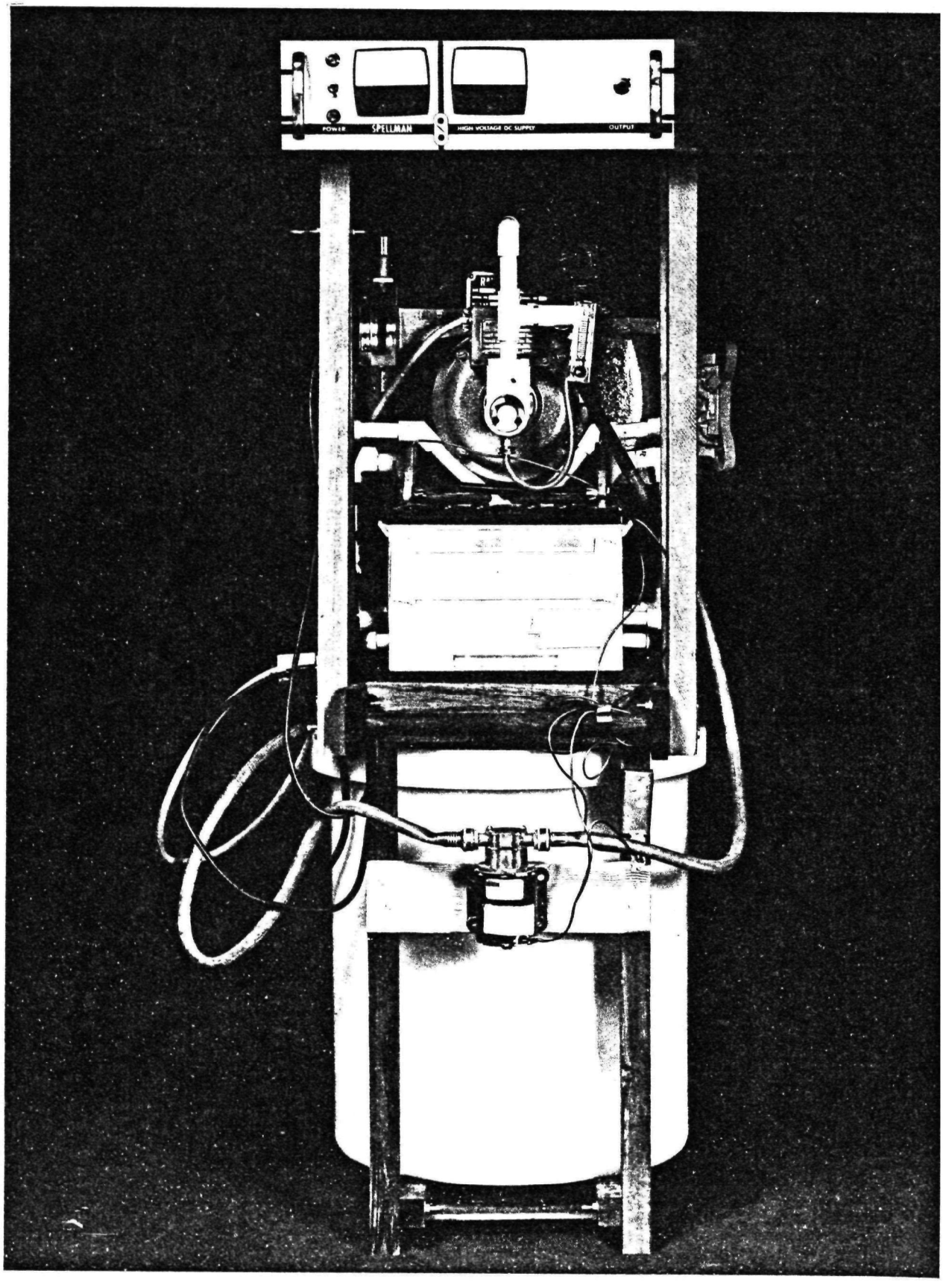


Figure 19. Rear of the Charged Fog Generator, showing rotating seal area.

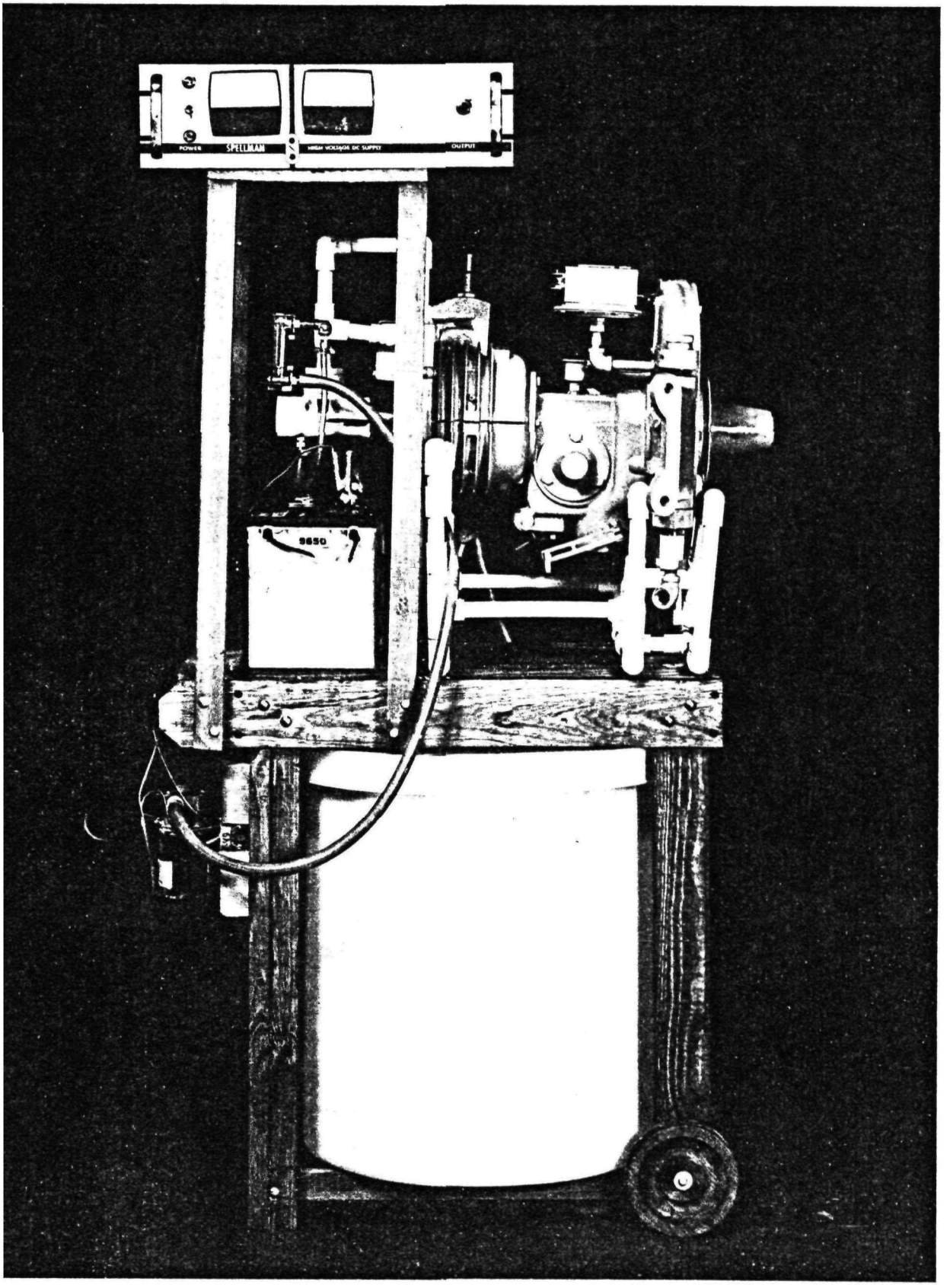


Figure 20. Side view of the Charged Fog Generator.

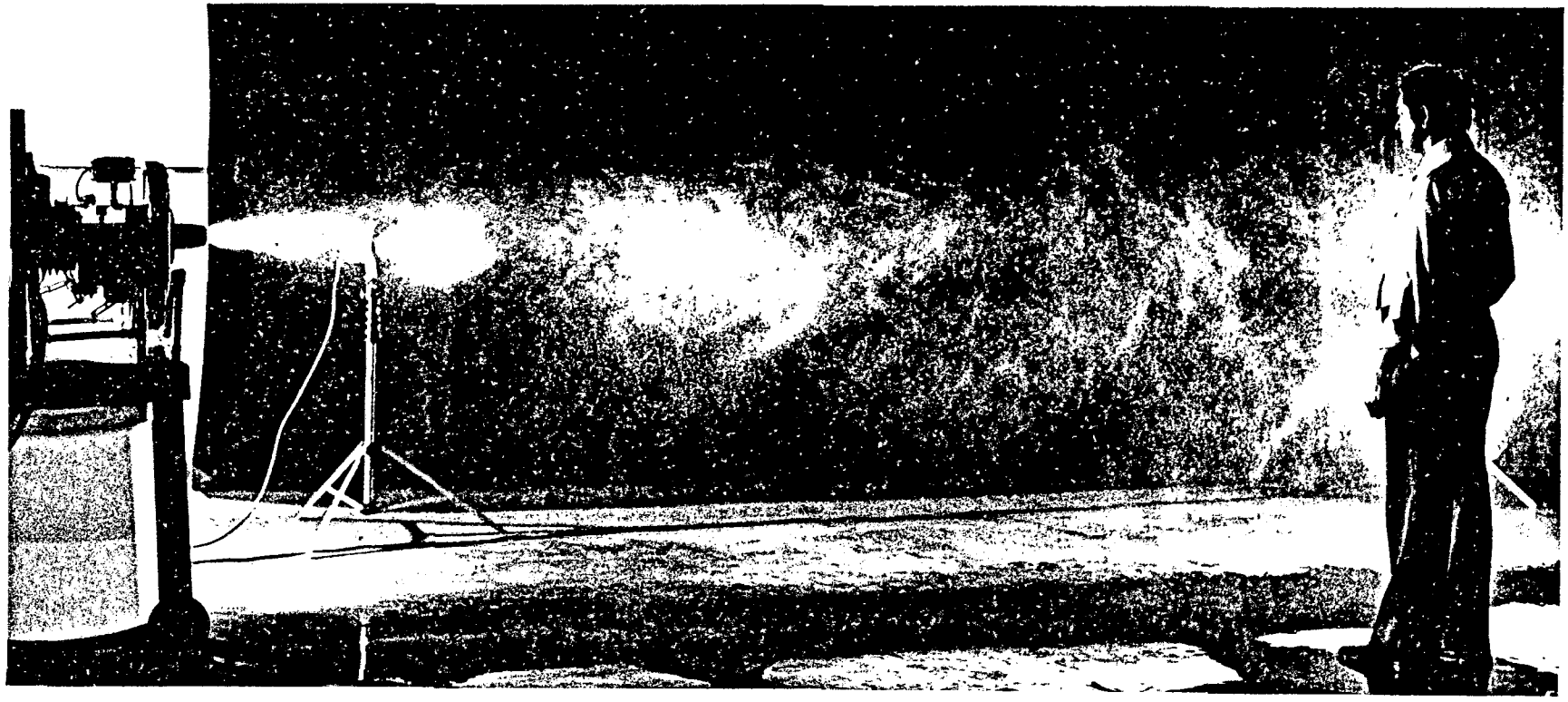


Figure 21. Typical long and narrow spray pattern from the Charged Fog Generator.

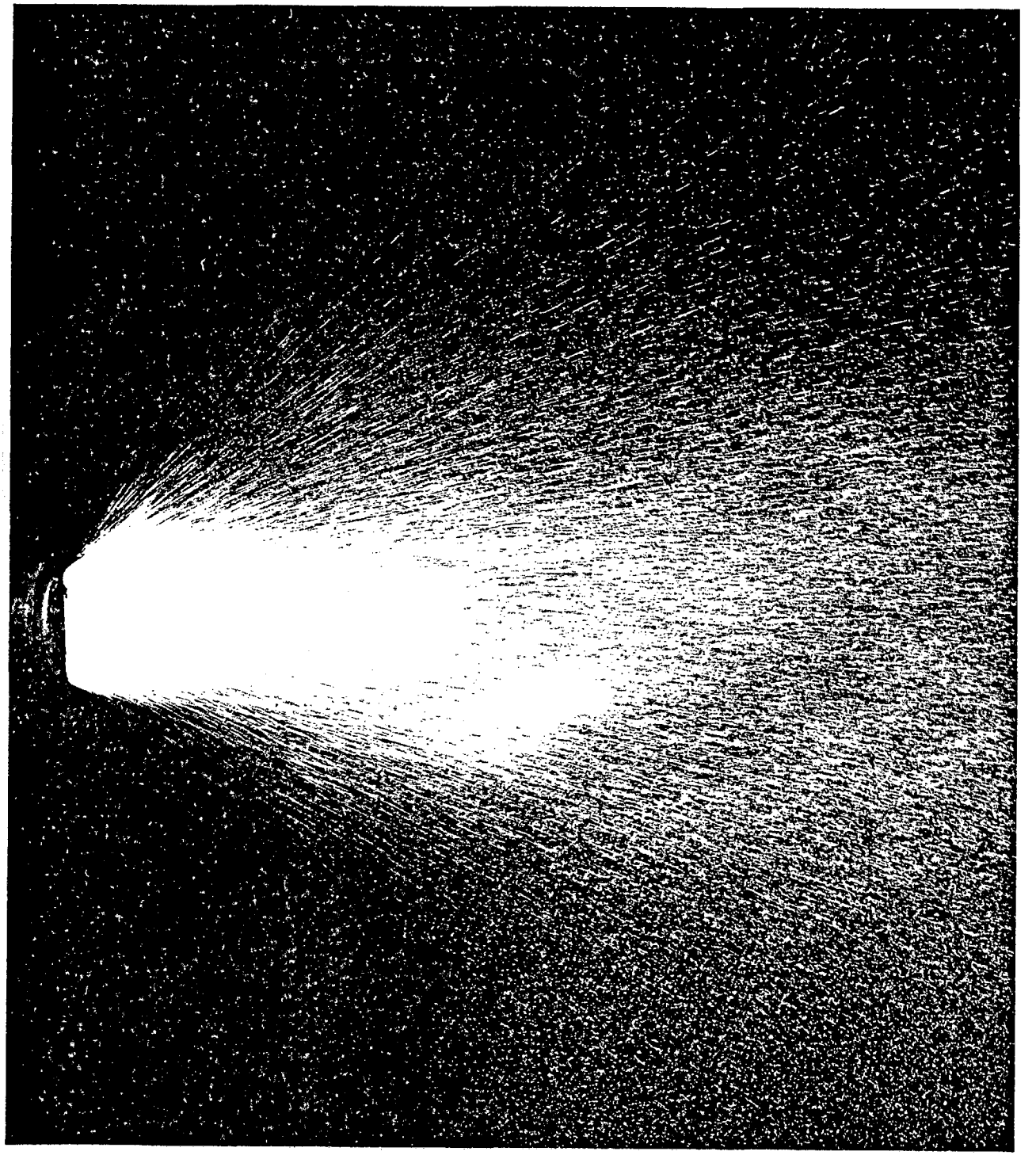


Figure 22. Typical short and broad spray pattern from the Charged Fog Generator.

the real droplet diameter. By repeating this method several times, a typical mean droplet diameter of about 90 μm was obtained.

Later, a KLD Model DC-2 droplet counter was used to measure the droplet diameters. The range of values given by this device was not in agreement with the above measurements. The droplet counter was sent to its manufacturer, KLD Associates, and they confirmed that the DC-2 counter was not operating properly. Therefore, Meteorology Research, Inc. (MRI), Altadena, California, was hired to accurately determine the droplet size distribution.

The droplet size measurements were made at AeroVironment using a cloud optical array probe (manufactured by Particle Measuring Systems Inc. (PMS), Boulder, Colorado) for droplets in the aerodynamic size range of 30 to 300 μm and using a precipitation optical array probe for droplets in the range of 125 to 1875 μm. The probes were calibrated with glass beads of known diameter just before data were taken.

In the PMS optical array probes, a collimated laser beam is projected at right angles to the air and fog flow (using mirror systems) and focused on a photo diode array. A droplet entering the light beam casts a shadow over part of the diode array, causing the recording system to register a count. The size of the droplet is determined from the number of elements in the diode array which are shadowed. The droplets are sized into 15 channels in both instruments.

From the probe measurements, droplet concentration in unit volume and unit micrometer intervals, and droplet mass median diameter were calculated. Figures 23 and 24 show the concentration and mass distributions (provided by MRI), respectively. Logarithmic scales are used for both figures since the values vary over an order of magnitude. These measurements gave a mass median diameter (MMD) of about 200 μm. This MMD is a good indicator of the central point in the distribution about which most of the mass is clustered. The concentration distribution gives a median droplet diameter of about 100 μm. This is an upper limit because the probe was not able to count droplets smaller than about 30 μm. This value is consistent with the value obtained using the microscope method.

It may also be possible to mechanically control the size distribution generated by the CFG to a certain degree. The best size distribution can be selected only after completing the actual field tests and optimizing different parameters for the best possible collection efficiency for the CFG.

CHARGE-TO-MASS RATIO OF THE DROPLETS

The charge-to-mass ratio of the water droplets generated by the CFG was determined using the method described earlier in Section 5. This study yielded a typical charge-to-mass ratio of 1.2×10^{-6} C/g, when the water was charged by direct contact at 15 kV. The Rayleigh limit of charges on a 200-μm droplet is about 4.2×10^{-6} C/g. This value may be compared with a typical value of 0.56×10^{-6} C/g obtained by Pilat et al. (1974) and Pilat (1975) when the droplets were charged with a 5000-volt inductance charging method, and a value of 0.1×10^{-6} C/g for the largest of the commercially available fogger devices, Fogger IV (Brookman et al., 1981, 1982).

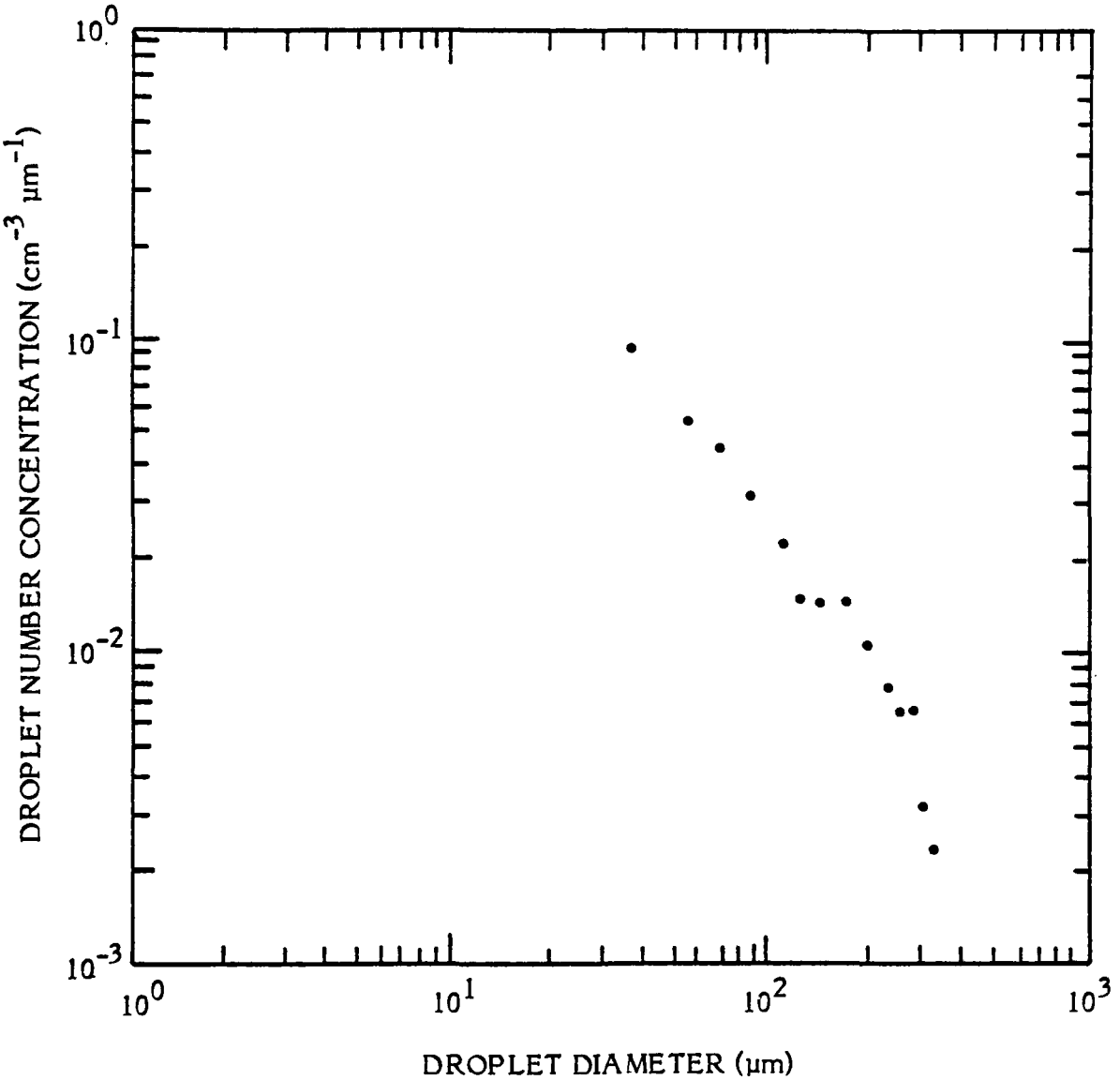


Figure 23. Water droplet number concentration as a function of droplet diameter measured using a cloud optical array probe and a precipitation optical array probe.

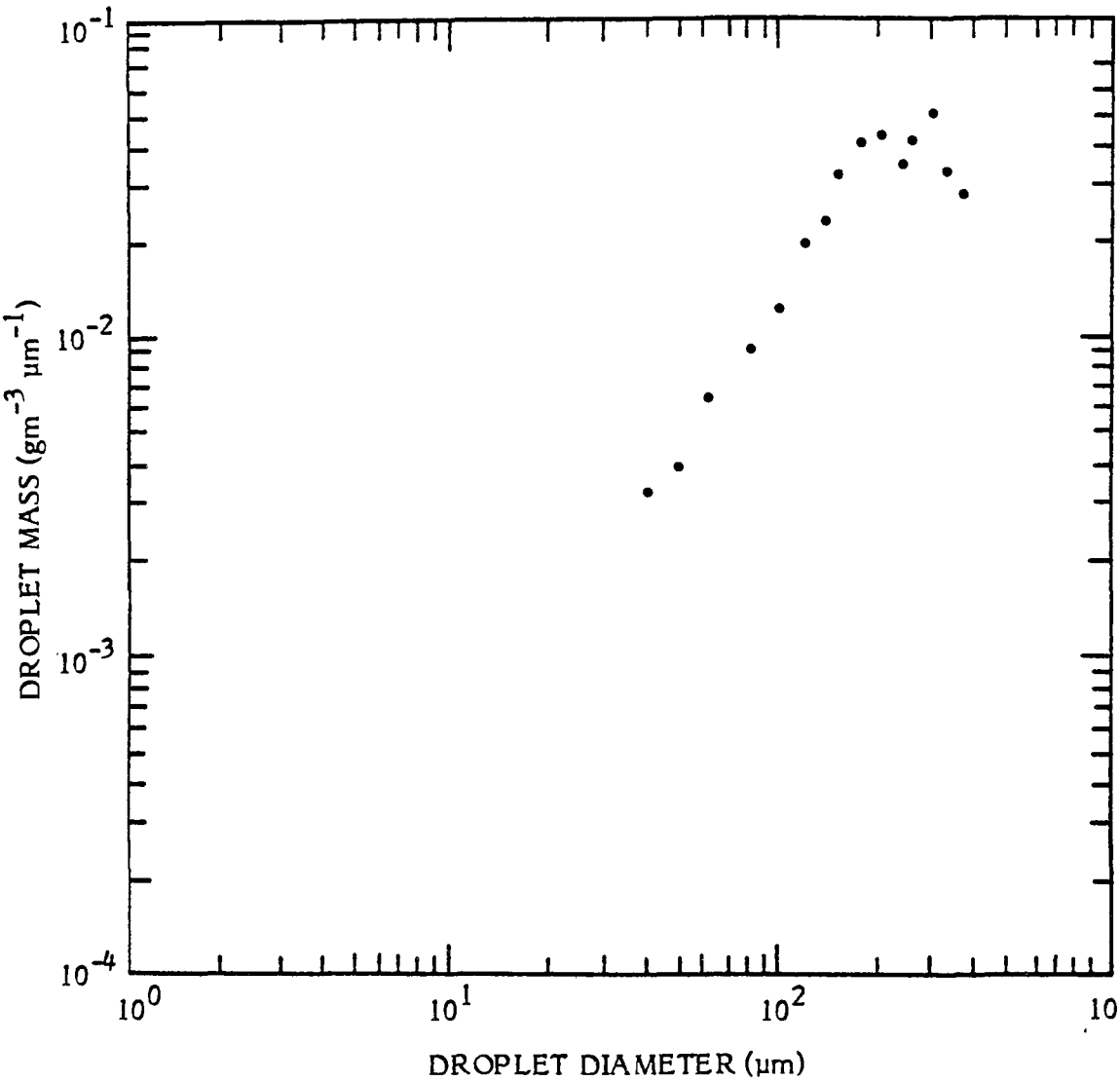


Figure 24. Water droplet mass as a function of droplet diameter measured using a cloud optical array probe and a precipitation optical array probe.

To estimate the charge-to-mass ratio of the droplets, another experiment was performed. A standard 8-inch diameter, No. 120 sieve (125-μm mesh size) was mounted in the path of the droplets. The electrical charges transferred to the mesh from the charged droplets are allowed to leak to the ground through a 1-megaohm resistor. The voltages generated across this resistor were measured with a Hewlett-Packard HP 419A dc null voltmeter.

With a water flow rate of about 60 l/h and an applied high voltage of 10-kV to the inflowing water, the current measured in the circuit described above was about 4 μA. It was determined, for this measurement setup, that about one-fourth of all droplets generated by the CFG were colliding with the 8-inch diameter sieve. Again, using the 200-μm mass median droplet diameter value, the charge-to-mass ratio for this particular arrangement was calculated to be about 1×10^{-6} C/g. The experiment was repeated for a different water flow rate and the result was consistent with the above value. However, when the applied voltage was reduced to 5 kV, the observed current was reduced to one-half the value obtained with 10 kV applied voltage. These values are quite consistent with the gravimetric method for determining the charge-to-mass ratio of the droplets of 1.2×10^{-6} C/g reported above with 15 kV applied voltage. It is clear that the charge-to-mass ratio increases with increases in the applied voltage (at least in the range used in this study).

It is interesting to estimate the number of elementary charges carried by a typical droplet. As explained above, 4 μA current was generated by 10^6 droplets (see below), which corresponds to 2.5×10^{13} elementary charge transfers. Therefore, assuming the typical mass median droplet diameter to be about 200 μm, the number of elementary charges carried by a typical droplet is 2.5×10^7 unit charges.

The following discussion illustrates the electric energy supplied to the droplets under various water flow rates and droplet charges.

At a water flow rate of 60 l/h flowing into the rotating cup of the CFG, and assuming the mass median diameter of the droplets to be about 200 μm, the number of droplets generated per second is approximately 4×10^6 droplets. Now, the maximum charge a droplet of radius R can carry (Rayleigh limit) is given by Equation (6)

$$Q_{Ray} = (2 \times 10^{-5}) R^{3/2} \tag{6}$$

where Q is in Coulombs and R is in meters.

Assuming no current leaks, therefore, the upper limit of current drawn from the high voltage power supply is given by

$$I_L = 4 \times 10^6 (2 \times 10^{-5}) R^{3/2} \tag{7}$$

where limiting current, I_L, is in amperes, and R is in meters.

For a 200-μm diameter droplet, this gives a limiting current of 80 μA. If the water flow rate is reduced to half (30 liters per hour), the corresponding value of this limiting current drawn will be half, or 40 μA.

If the droplet diameter is halved, eight times as many droplets will be generated per second i.e., 32×10^6 droplets at a water flow rate of 60 liters per hour. In this case, the corresponding limiting current will be 226 μA. Similarly, for 50-μm, 25-μm, and 12.5 μm mass median droplet diameter size distributions, the maximum possible currents will be 0.54 mA, 1.82 mA, and 4.2 mA, respectively. Again, these values are directly proportional to the water flow rates. Since 60 to 70 liters per hour is the upper limit of the CFG water flow rates, these values are the upper bound for various hypothetical mass median droplet diameters.

GENERAL REMARKS ON THE CFG

The CFG is fairly small, portable, and mounted on a movable platform. The total power requirement is about 1 kW (110 V ac power supply). It has no nozzle-clogging problems and does not require compressed air. With the use of a small inverter, the unit can be operated at a remote location where commercial power is not available. This feature may be important, because the system has high potential application at sources where commercial electric power is not available.

These measured droplet size distributions, charge-to-mass ratios, and droplet charge estimations indicate that the goals laid down for the new CFG at the beginning of this section were achieved. The physical characteristics of the charged fog droplets from the CFG are such that high inhalable particle control efficiency is expected. The inhalable particle control efficiency of the CFG in a field situation is described in the next section.

SECTION 7

EVALUATION OF THE INHALABLE PARTICLE CONTROL EFFICIENCY OF THE CFG

As indicated in Section 4, an exact theoretical analysis of the inhalable particle control efficiency of any charged fog device is very difficult because:

(1) Although the typical size distribution of the droplets is known, size variation of droplets and particles at various locations of the test volume may not be fully known.

(2) Concurrent with uncertainty about the size distribution of droplets and particles, as in (1) above, the magnitude of charges on the droplets and the magnitude and nature of charges on the particles may also not be fully known;

(3) Since charged fog technology is applied primarily in open areas containing a dust cloud, seldom are external variables, such as wind speed and direction, relative humidity, temperature and diffusive characteristics of the dust cloud, controllable or can they be accurately determined.

Therefore, in order to fully evaluate the particle control efficiency of a charged fog device, extended field tests under various combinations of possible field conditions and on dust clouds of various materials (coal, soil dust, mineral dust, etc.) need to be performed. As a first step toward this goal, a detailed field test plan for the project's second phase was prepared for the EPA project officer's approval.

Specifically, the objective of the Phase II field tests was to evaluate the particle control efficiency of the Charged Fog Generator on bentonite ore and under various instrument settings and meteorological conditions. From these results, one could assess the optimum instrument settings and field conditions. Ideally, this task would have been performed under a controlled experimental setup (wind tunnel study). However, because of financial and time constraints, it was decided to go ahead with the field program.

FIELD TEST SITE AND EXPERIMENTAL SETUP

The Charged Fog Generator was field tested at the Kaycee Bentonite Corporation's bentonite processing plant in Worland, Wyoming, during the first half of 1981 (Mathai, 1983b). Worland is about 250 km northwest of Casper, Wyoming. Bentonite is a highly water-absorbing material used mainly in sealing water leaks in oil wells. Bentonite ore is unloaded from front-end loaders onto the grill of a hopper which is attached to the west wall of the plant building (see Figure 25). From the bottom of the hopper (approximately 4 m below the hopper grill level, inside the plant) the ore is carried by conveyor belts to

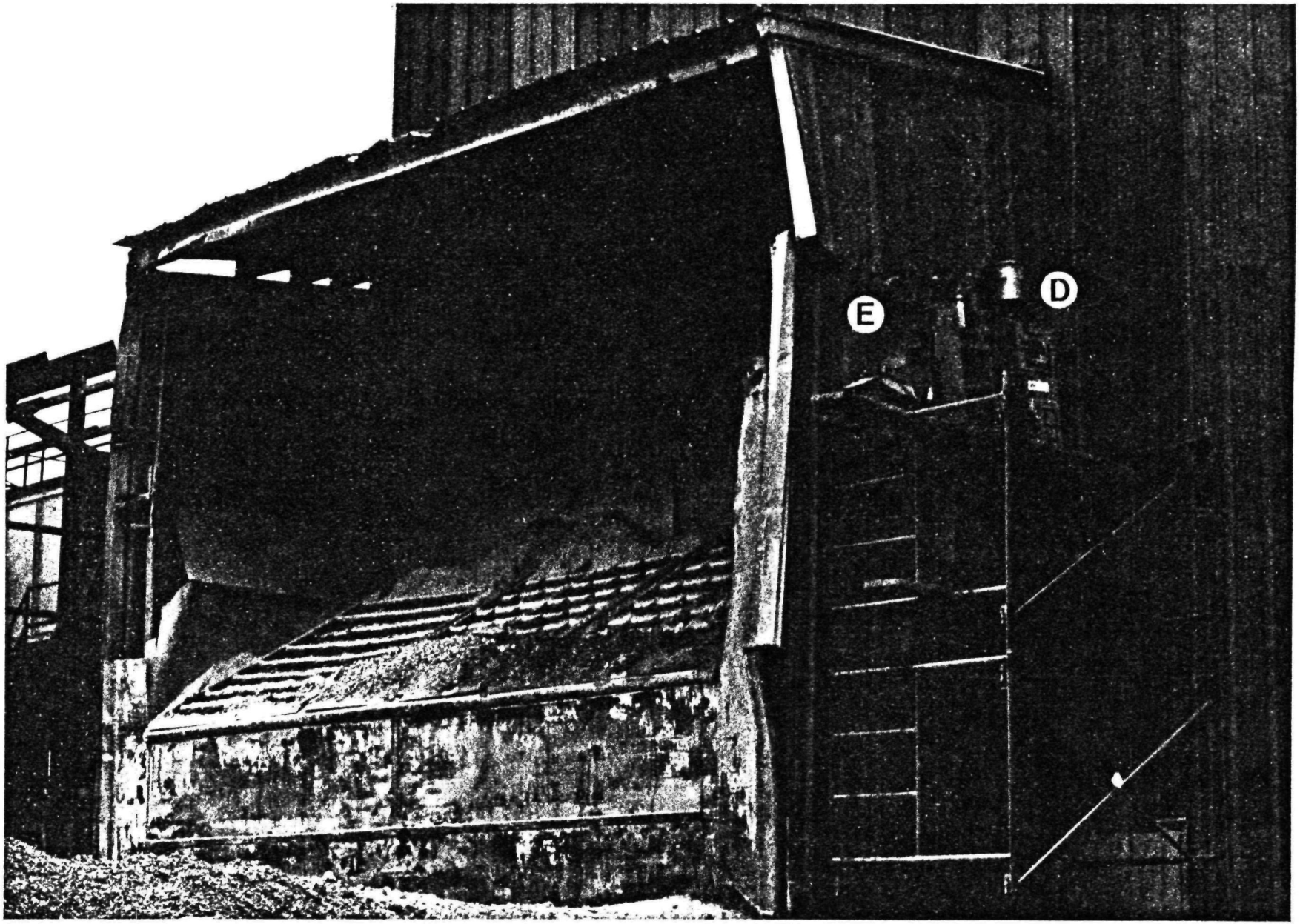


Figure 25. Experimental setup at the bentonite unloading operation at Worland, Wyoming. E is the location of the Charged Fog Generator and D, the particle sampler.

processing areas. The hopper is completely enclosed except on one side through which the front-end loaders unload. The hopper is 6.7 m wide, about 2 m deep and, from the grill level, about 3 m high. The grill is inclined about 30^{o} to the horizontal.

Bentonite ore from two large piles, approximately 100 m to northwest and southwest of the hopper, are carried to the hopper by front-end loaders and dropped on the grill (Figure 26). The bucket of the front-end loader is about 2.4 m wide and successive loads are unloaded uniformly over the 6.7-m wide hopper. It takes about ten front-end loader dumps to fill the hopper to the grill level. These ten dumps are accomplished in about 25 minutes. The bucket is removed from inside the hopper area in 20-25 seconds. One full hopper of ore will be carried away by the conveyor belt in about an hour.

Bentonite samples collected from the hopper area were resuspended to measure particle size distribution at IERL, EPA. This analysis showed that only 8% of the particles were smaller than 37 μm (Drehmel, 1981). The fraction of inhalable particles will, therefore, be even lower (maybe 3-5%). A source with a higher fraction of inhalable particles would have been preferable. It was hoped that this fraction would be higher for airborne bentonite samples than for the one collected from the hopper wall.

The land around the plant is fairly flat. A railroad track lies on the east side of the plant and a paved road (very little traffic) beyond that. Bottom-dump trucks filled with bentonite ore arrive near the storage piles from the south and, therefore, the dust in the hopper area due to transport of ore to the plant area is negligible compared to the dust generated in the hopper itself. In other words, the hopper can be considered as a fairly isolated source. The mean wind speed and direction in the area was estimated (using National Weather Service data) for the February-May period to be about 2.8-3.6 m/s. Daytime high temperatures during the test period varied from $9^{o}C$ to $35^{o}C$.

The Charged Fog Generator and the particle sampling instruments were mounted on the outside of the south wall of the hopper, marked as E and D in Figure 25, about 4 m above ground level. A platform was built to mount these instruments. Ideally, the particle sampler inlet should have been mounted on the east (rear) wall of the hopper, but for practical reasons could not be. The CFG sprayed water droplets across the hopper above the grill. The total volume to be treated by the charged fog was about (6.7 m x 2 m x 3 m) 40 cubic meters. This volume is somewhat larger than the maximum coverage of the CFG fog. Unfortunately, at that time only one prototype CFG was available for tests. To have had a second unit mounted on the north wall of the hopper and operated concurrently would have been ideal.

Because of the physical layout and the nature of the operation, a new particle sampler system, different from that described in Section 5, was installed. Particle samples were collected using a Sierra Model 230 CP cyclone preseparator followed by a Sierra two-stage cascade impactor. The cyclone's air inlet protruded 0.3 m into the hopper at location B in Figure 27. The CFG's spinning cup and aircone, marked as A in Figure 27, are 1 m away from cyclone's air inlet. This particular experimental setup was used because of practical limitations; this was done with the approval of the EPA project officer. The relative positions of A and B with respect to the hopper grill (C) can also be observed from this figure.

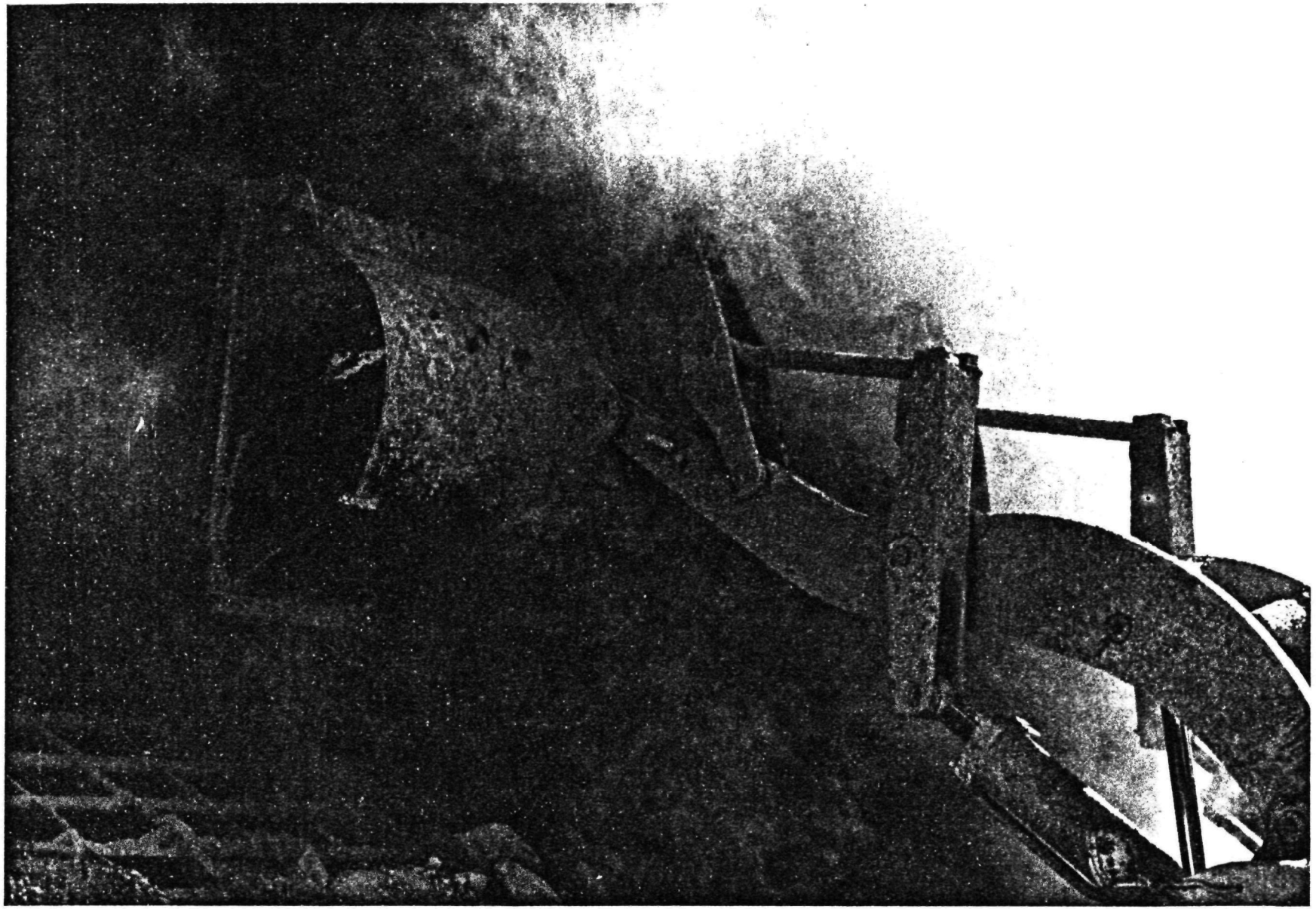


Figure 26. Typical dust plume generated when front-end loader unloads the bentonite on the hopper grill.

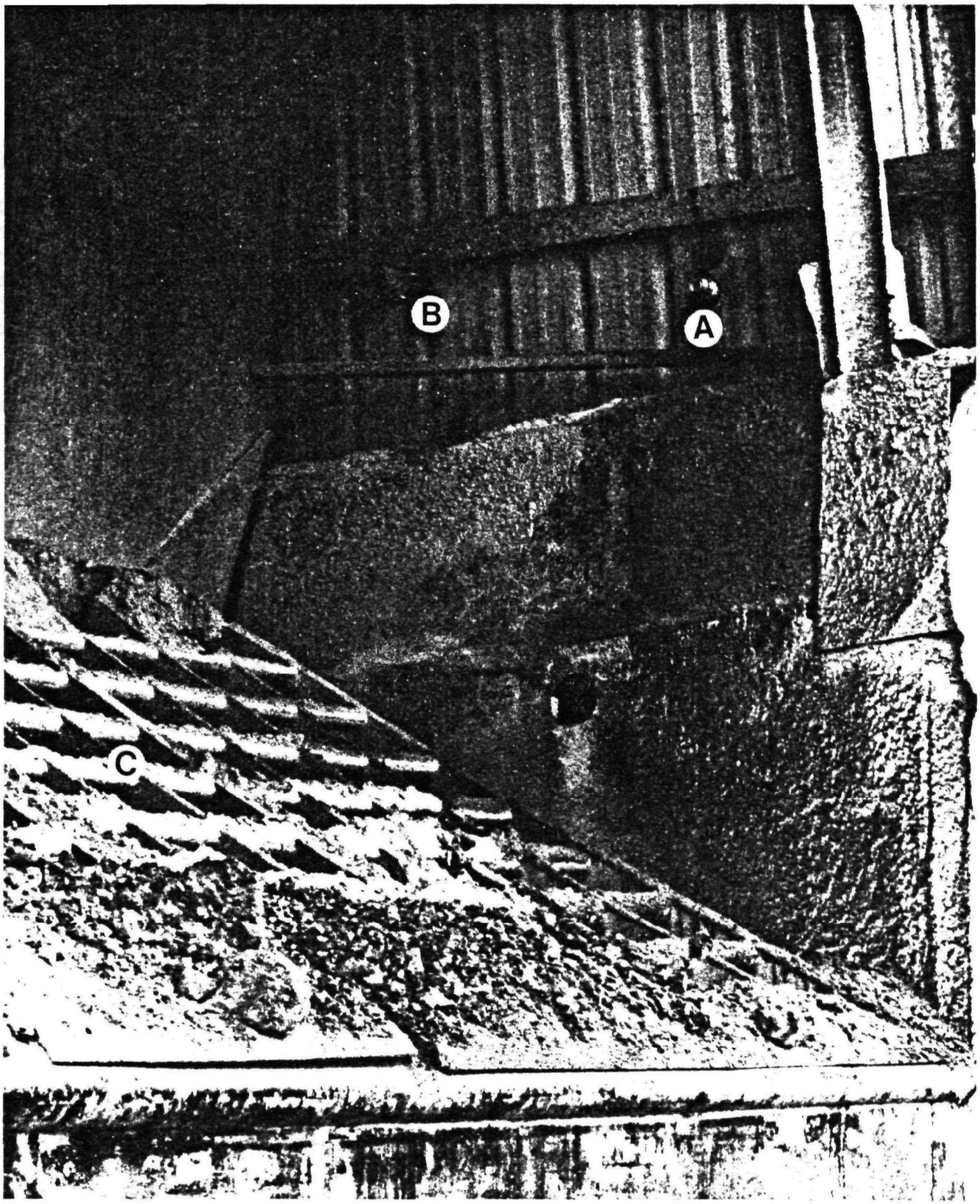


Figure 27. View of the rotating cup (A) of the Charged Fog Generator, inlet of the Cyclone preseparator (B) and the hopper grill (C) from inside the hopper.

The particle sampling system was operated at a flow rate of 0.85 m^3/min (30 CFM). At this flow rate, the cyclone has a particle cut-point of about 7.3 µm. The impaction plates of the cascade impactor were chosen so that the upper filter would collect particles larger than 1.8 µm. According to the manufacturer, because the collection efficiency curves of the cyclone and impactor are not perfectly sharp, and because approximately 30% of the particles larger than the cyclone's cut-point of 7.3 µm will pass through the cyclone to the impactor, the size range of particles collected on the upper slotted filter will be from 1.8 µm to somewhat larger than 7.3 µm (Sierra Instruments, 1981). The lower back-up filter collects all particles smaller than 1.8 µm. For the purpose of this report, particles collected on the back-up filter will be characterized as the fine particle fraction and those on the upper filter will be characterized as the coarse fraction. The mass of coarse fraction collected was often an order of magnitude smaller than the fine fraction, possibly indicating a severe particle bounce problem, with particles larger than the cut-point of 1.8 µm reaching the back-up filter. Subdividing the samples into more size ranges would have required either much longer sampling time or much higher flow rates to obtain acceptable filter loadings. Neither of these alternatives was desirable. The sampler flow rates were calibrated at regular intervals during the entire test program.

ESTIMATION OF PARTICULATE MATTER MEASUREMENT ACCURACY AND PRECISION

All the particle control efficiency evaluations were derived from particulate matter concentration measurements made during various test runs. Particulate matter concentrations were determined by dividing the mass of particulates collected on the filter media by the volume of air sampled. Therefore, the uncertainty in mass concentration values involves the uncertainties introduced by the filter weighing process and sampling volume measurements. At the mass concentrations encountered in this experiment, the uncertainty due to the filter weighing process was negligible compared to the corresponding value due to sample volume measurements.

If we define the precision to be given by the relative standard deviation, precision of volume measurement is given by Mueller and Hidy (1983) as,

$$\frac{\sigma_V}{V} = \left[\frac{\sigma_{F_1}^2 + \sigma_{F_2}^2}{(F_1 + F_2)^2} + \left(\frac{\sigma_T}{T}\right)^2 \right]^{1/2} \qquad (8)$$

where F_1 and F_2 are the initial and final sample flow rates, V is the sample volume, T is the sampling duration, and σ's refer to the corresponding standard deviations. Assuming that the flow rates remain constant throughout the sampling period (i.e. $F_1 = F_2 = F$), and that T can be measured precisely, we get,

$$\frac{\sigma_V}{V} = \frac{1}{\sqrt{2}} \quad \frac{\sigma_F}{F}. \tag{9}$$

It is reasonable to assume that the precision of the flow rate values during flow calibrations is representative of the precision of the actual sample flow rate measurements; one can then calculate σ_V/V using the above equation and the flow calibration records. From our experience in various mass concentration measurement projects, it is estimated that the precision of sampling volume measurements reported here is in the 3-5% range (Mathai, 1983c; Mathai, et al., 1983). Therefore, it is estimated that the precision of particulate matter data presented in this report is in the range of 3-5%.

The accuracy of the mass concentration measurements can be estimated from the accuracies in filter weighing and sample volume measurements. Again, at mass concentrations encountered in this experiment, the overall accuracy is dominated by that of sample volume measurement. The latter value can be estimated using the calibration records. Again, from our prior experience, we estimate that the accuracy of particulate matter mass concentrations reported are in the 1-3% range.

Particle size cut-point data given earlier in this section were based on information provided by the instrument manufacturer. No attempt was made during this experiment to verify these cut-points independently, mainly due to financial and time constraints of the project.

FIELD TEST DESIGN

To determine the particle control efficiency of the Charged Fog Generator, three test scenarios were designed. In the first scenario, no attempt was made to control the dust inside the hopper, except that the CFG's fan blew continuously. This test scenario was necessary to ensure that the mixing of the dust cloud was nearly identical among various runs in order to make direct comparison of tests with and without charged fog. In the second scenario, uncharged fog was applied on the dust clouds; and in the third scenario, charged fog was applied. Other governing parameters were varied under each scenario to yield a statistically acceptable set of test data.

The parameters varied were water flow rates, fog pattern (short or long), applied high voltage, wind conditions, and relative humidity. In addition, a group of test runs was performed with the polarity of charges on the droplets reversed. Table 3 shows the planned test program.

An alternate combination of field conditions was given by:

- Low wind/Low humidity/Broad spray
- Low wind/High humidity/Long spray
- Medium wind/Low humidity/Long spray
- Medium wind/High humidity/Broad spray

as the column headings in Table 3, with the same water flow rates and charge conditions. Either of these test protocols called for a total of 32 test runs.

TABLE 3. PROPOSED CFG FIELD TEST PLAN.

Run No.	Medium Wind, High Humidity, Narrow Spray		Medium Wind, Low Humidity, Broad Spray		Low Wind, High Humidity, Broad Spray		Low Wind, Low Humidity, Narrow Spray	
	Water Flow (l/h)	Charge*	Water Flow (l/h)	Charge*	Water Flow (l/h)	Charge*	Water Flow (l/h)	Charge*
1-4	No water		No water		No water		No water	
5-8	30	none	30	none	30	none	30	none
9-12	60	none	60	none	60	none	60	none
13-16	30	V_1	30	V_1	30	V_1	30	V_1
17-20	30	V_2	30	V_2	30	V_2	30	V_2
21-24	60	V_1	60	V_1	60	V_1	60	V_1
25-28	60	V_2	60	V_2	60	V_2	60	V_2
29			30	V_1				
30			30	V_2				
31			60	V_1				
32			60	V_2				

*V_1 and V_2 are two voltages.

However, in actual practice, data had to be collected under prevailing field conditions and, therefore, more test runs were performed under some columns of Table 3, and fewer runs were performed under others. Also, because of fluctuations in the dust level observed from day to day, several times more than the four planned 'no water' runs had to be recorded. In total, 96 runs were performed instead of the planned 32.

Particle samples were collected on preconditioned and preweighed glass fiber filters. Each particle sample was collected during 12 to 15 front-end loader dumps (roughly 30-40 minutes). Simultaneously, wind speed and direction and relative humidity were also recorded. After each sample was collected, the filters were transferred to special envelopes and brought to AV's laboratory for analysis.

DATA PROCESSING

Particle samples collected on glass fiber filters were returned to the laboratory on a weekly basis along with the field logs. These filters were conditioned in a constant temperature and humidity chamber for at least 24 hours before final weighing The sampling time, the number of front-end loader dumps, and the sampling flow rates, as well as meteorological data were obtained from the field log. As discussed in the previous section, particle samples were collected as two fractions, fine and coarse. The mass of each fraction and sum of the two were obtained from the final and initial weights of the filters. Using known values of the sample time, number of dumps, and flow rate, particle mass concentration for a single dump is calculated from:

$$C_i = \frac{M_i \times 10^6}{N \cdot T \cdot F} \quad \mu g/m^3 \tag{10}$$

where

C_i = particle concentrations; i = 1, 2, or 3 for fine and coarse fraction and the sum of these, respectively

M_i = particle mass collected on filter media, in grams

N = number of front-end loader dumps in each sample

T = sample time in minutes

F = sample flow rate in m^3/min.

Particle concentrations were calculated for all the 96 test runs (fine and coarse fractions separately and their sum) and they are presented in Table 4.

As we indicated earlier, the amount of dust generated in the hopper fluctuated from dump to dump. To overcome this variation, each sample was collected during a total of 12 to 15 dumps and the mean value for each dump was calculated. The amount of dust generated also varied from day to day. This variation was caused by factors such as changes in ambient conditions and the moisture content of the bentonite ore itself. The

TABLE 4. MEASURED PARTICLE CONCENTRATIONS ($\mu g/m^3$) INSIDE THE BENTONITE UNLOADING HOPPER DURING CFG FIELD TESTS.

Test Date	Run No.	Particle Concentrations ($\mu g/m^3$)								
		Fan Only			Uncharged Fog			Charged Fog		
		Fine	Coarse	Total	Fine	Coarse	Total	Fine	Coarse	Total
4/22/81	1							341	55	396
	2				426	59	485			
	3	1198	120	1318						
4/23/81	4							988	196	1184
	5	1940	208	2148						
	6				1702	107	1809			
4/24/81	7				1936	119	2055			
	8	2382	123	2505						
	9				980	72	1052			
	10							923	94	1017
4/25/81	11							713	165	878
	12				997	122	1119			
	13	1323	133	1456						
4/28/81	14							113	131	244
	15							562	230	792
	16				1704	163	1867			
	17	1936	126	2062						
	18				1904	148	2052			
4/29/81	19							1523	197	1720
	20				1622	190	1812			
	21							1556	116	1672
	22	3435	205	3640						

(continued)

TABLE 4 (continued)

Test Date	Run No.	Particle Concentrations (μg/m^3)								
		Fan Only			Uncharged Fog			Charged Fog		
		Fine	Coarse	Total	Fine	Coarse	Total	Fine	Coarse	Total
5/20/81	23							544	167	711
	24	1186	197	1383						
	25				658	143	801			
	26							506	125	631
5/21/81	27				707	193	900			
	28	1491	102	1593						
	29							469	178	647
	30				507	355	862			
	31							294	199	493
5/22/81	32							133	122	255
	33	1825	298	2123						
6/2/81	34	2225	133	2358						
	35				1481	111	1592			
	36				1506	104	1610			
	37	1783	151	1934						
6/3/81	38	588	96	684						
	39				711	75	786			
	40							405	58	463
6/4/81	41							74	130	204
	42							149	220	369
	43	1345	174	1519						
	44				1462	101	1563			
	45							1210	73	1283
	46	1579	116	1695						
	47							1277	72	1349

(continued)

TABLE 4 (continued)

Test Date	Run No.	Particle Concentrations ($\mu g/m^3$)								
		Fan Only			Uncharged Fog			Charged Fog		
		Fine	Coarse	Total	Fine	Coarse	Total	Fine	Coarse	Total
6/5/81	48							619	96	715
	49	1291	84	1375						
	50							640	55	695
6/8/81	51	3097	285	3382						
	52				987	67	1054			
	53							1079	96	1175
	54							648	146	794
6/9/81	55							492	111	603
	56				1197	156	1353			
	57							920	71	991
	58	1091	50	1141						
	59							943	68	1011
	60				930	260	1190			
6/10/81	61							1207	245	1452
	62	2196	207	2403						
	63				1469	107	1576			
	64	2384	111	2495						
6/11/81	65							1140	271	1411
	66				1035	128	1163			
	67							1134	103	1237
	68	1672	105	1777						
	69							1111	74	1185

(continued)

TABLE 4 (continued)

Test Date	Run No.	Particle Concentrations ($\mu g/m^3$)								
		Fan Only			Uncharged Fog			Charged Fog		
		Fine	Coarse	Total	Fine	Coarse	Total	Fine	Coarse	Total
6/12/81	70							901	275	1176
	71				1393	174	1567			
	72							731	85	816
	73	1256	166	1422						
6/15/81	74							197	119	316
	75	546	238	784						
7/7/81	76							862	145	1007
	77	1144	105	1249						
	78				894	42	936			
	79							832	101	933
	80	6918	284	7202						
	81							2655	190	2845
	82							2920	185	3105
7/8/81	83	2537	305	2842						
	84							1977	143	2120
	85							2013	260	2273
7/9/81	86							1916	94	2010
	87	2896	197	3093						
	88				1566	133	1699			
	89							1761	123	1884
	90	2689	139	2828						
	91							2210	144	2354
	92							1570	109	1679

(continued)

TABLE 4 (continued)

Test Date	Run No.	Particle Concentrations ($\mu g/m^3$)								
		Fan Only			Uncharged Fog			Charged Fog		
		Fine	Coarse	Total	Fine	Coarse	Total	Fine	Coarse	Total
7/10/81	93							1724	264	1988
	94	2253	152	2405						
	95				1862	117	1979			
	96							1784	129	1913

effect of the latter is not too significant since the ore stored in each pile comes from the same mine and a pile is completely processed before a new pile is started. To overcome the day-to-day dust level fluctuations, sample concentrations were normalized for each day with respect to the background value (the "fan only" value) and a percentage particle collection (control) efficiency was calculated. Percentage particle control efficiency is obtained from:

$$E_j = \frac{C_o - C_j}{C_o} \times 100 \qquad (11)$$

where

E_j = particle control efficiency (percentage); j = 1 for uncharged fog and j = 2 for charged fog;

C_o = particle concentration when no fog is applied (fan only -- dry run); and

C_j = particle concentration when the fog (charged or uncharged) is applied.

Values of E_j are calculated, as before, for the fine fraction, the coarse fraction and the sum of fine and coarse. Table 5 gives these percentage particle control efficiencies and the corresponding field condition data, water flow rate, applied high voltage, and comments, if any, for the whole field test program.

DATA ANALYSIS, DISCUSSION, AND RESULTS

As indicated earlier, data were collected under prevailing field conditions and various combinations of instrument settings. This resulted in a data base with a large number of variable parameters making data analysis very difficult.

Comparison Between Charged and Uncharged Fog

Figure 28 shows the mean values of the measured percentage fine particle control efficiency and total particle control efficiency for charged (striped bars) and uncharged (solid bars) fog. For this comparison, all test runs under all instrument settings and field conditions are included. The mean and standard deviations of the fine particle control efficiency are 48.1% and 23.0%, respectively, for the charged fog and 27.8% and 25.3%, respectively, for the uncharged fog. The corresponding values for all the particles (fine and coarse together) are 44.5%, 21.8%, 25.0%, and 24.4%, respectively. These numbers show that, even under average field conditions and instrument settings, inhalable particle control efficiency can be almost doubled by electrically charging the water droplets. However, under optimum instrument settings and favorable field conditions, the improvement in inhalable particle control efficiency can be expected to be higher. It may also be pointed out that the volume of the dust cloud treated was somewhat larger than the maximum coverage of the CFG; therefore, the observed improvement in particle control efficiency is encouraging.

TABLE 5. MEASURED INHALABLE PARTICLE CONTROL EFFICIENCY (PERCENTAGE), METEOROLOGICAL CONDITIONS AND CFG SETTINGS DURING THE FIELD TESTS ON BENTONITE ORE.

Test Date	Uncharged Fog			Charged Fog			Meterological Conditions				CFG Settings		
	Fine	Coarse	Total	Fine	Coarse	Total	Temp. °C	Wind & Direction (kmph)		R.H. %	Water Flow Rate (lph)	Spray Patterns	Applied Voltage (kV)
4/22/81				72	54	70	9	N&NW	13	64	60	B	4
	64	51	63				12	W	19	60	60	B	0
4/23/81				49	6	45	9	S	5-8	60	60	N	4
	12	49	16				23	NE	0-3	45	60	N	0
4/24/81	19	3	18				25	SW	3-8	32	60	B	0
				61	24	59	24	SW	8-16	35	60	B	4
	60	42	58				26	NNE	8	30	60	B	0
4/25/81				46	-24	40	17°	W	5-16	64	60	N	4
	25	9	15				18	NNE	16-25	48	60	N	0
4/28/81				94	-4	88	6	Calm		84	60	B	4
				71	-83	62	14	Calm		67	60	B	4
	12	-30	10				15	S	3	60	60	B	0
	2	-18	1				23	NE	3-8	33	60	B	0
4/29/81				56	4	53	17	Calm		60	60	N	4
	53	7	50				19	NE	3-15	63	60	N	0
				55	43	54	25	N	5	44	60	N	4
5/20/81				54	15	49	18	Calm		37	60	N	4
	45	27	42				17	SSW	8-25	53	60	N	0
				57	37	54	17	SW	8	69	60	N	4
5/21/81	53	-89	44				14	E	8	63	60	B	0
				69	-75	59	14	W	5	63	60	B	4
	66	-248	46				16	E	8	64	60	B	0
				80	-95	69	15	E	8-15	65	60	B	4
5/22/81				93	59	88	13	W	3	90	60	B	4
6/2/81	26	23	26				24	NE	5	39	60	B	0
	25	28	25				25	E	5	31	60	B	0

(continued)

TABLE 5 (continued)

Test Date	Uncharged Fog			Charged Fog			Meterological Conditions				CFG Settings		
	Fine	Coarse	Total	Fine	Coarse	Total	Temp. °C	Wind & Direction	(kmph)	R.H. %	Water Flow Rate (lph)	Spray Patterns	Applied Voltage (kV)
6/3/81	-21	22	-15				24	N	16	45	30	B	0
				31	40	32	20	N	32	72	30	B	-7
6/4/81				95	25	87	7	W	3	95	30	B	-7
				89	-26	76	10	SW	8	89	30	B	-7
	7	13	8				22	S	3	44	30	B	0
				23	37	24	23	S	3	32	30	B	-10
				19	38	19	24	Variable	1-2	30	30	B	-10
6/5/81				52	-14	48	27	Variable	1-12	37	30	B	-10
				50	35	50	28	Calm		34	30	B	-10
6/8/81	68	77	69				21	NE	5-8	35	30	B	0
				65	77	65	27	NE	8	31	30	B	-10
				79	49	77	24	N	20	46	30	B	-10
6/9/81				55	-120	47	16	NE	8	74	30	B	8
	-10	-212	-19				21	NW	16	39	30	B	0
				16	-42	13	22	NW	8-11	37	30	B	8
				14	-36	11	21	N	19	27	30	B	8
	15	-420	-4				19	N	5	28	30	B	0
6/10/81				47	-54	41	17	S	2	60	30	N	8
	36	33	36				26	Calm		25	30	N	0
6/11/81				32	-158	21	11	Calm		73	60	N	8
	38	-22	35				15	N	3	60	60	N	0
				32	2	30	20	NW	16	61	60	N	-7
				34	30	33	28	Calm		27	60	N	-9
6/12/81				28	-66	17	11	Calm		73	60	B	-5
	-11	-5	-10				26	E	3	48	60	B	0
				42	49	43	28	E	3	43	60	B	+8

(continued)

TABLE 5 (concluded)

Test Date	Uncharged Fog			Charged Fog			Meterological Conditions				CFG Settings		
	Fine	Coarse	Total	Fine	Coarse	Total	Temp. °C	Wind & Direction (kmph)		R.H. %	Water Flow Rate (lph)	Spray Patterns	Applied Voltage (kV)
6/13/81				64	50	60	13	E	3	86	60	B	8
7/7/81				25	-38	19	24	S	5	50	30	B	4
	22	60	25				33	N	16	29	30	B	0
				27	4	25	33	S	16	29	30	B	8
				62	33	61	33	S	16-25	20	30	N	4
				58	35	57	33	S	30	21	30	N	8
7/8/81				22	53	25	29	N	13	22	60	B	-8
				21	15	20	28	N	8	29	60	B	-8
7/9/81				31	44	32	15	SW	3	49	60	N	8
	44	21	43				30	Calm		23	60	N	0
				37	27	36	34	Calm		21	60	N	8
				21	14	17	36	Calm		27	60	B	4
				44	39	43	33	S	8	33	60	B	8
7/10/81				24	-74	17	21	Calm		65	60	N	4
	17	23	18				29	Calm		36	60	N	0
				21	22	21	33	Calm		29	60	N	8

*B - Broad; *N - Narrow.

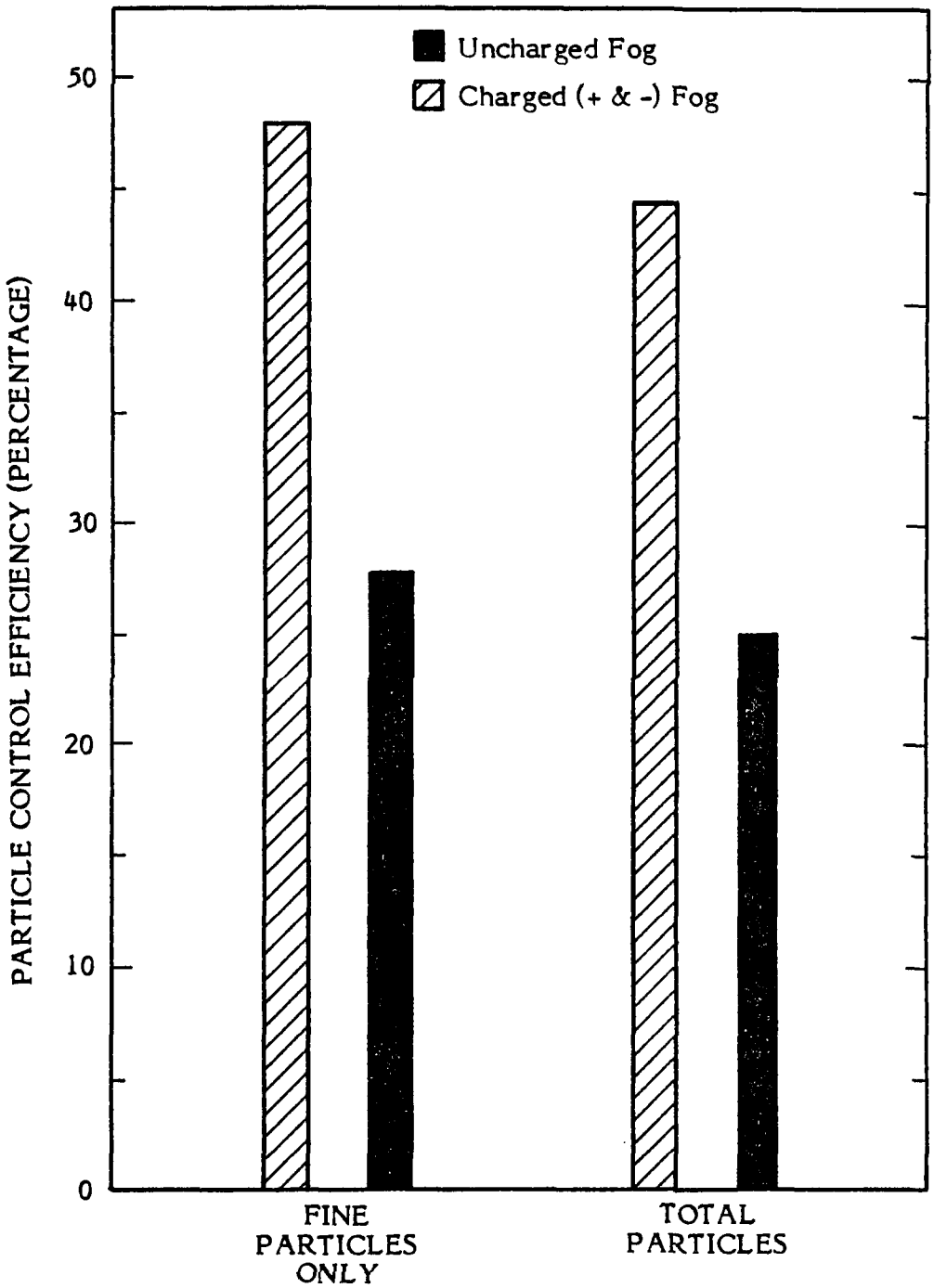


Figure 28. Mean inhalable particle control efficiency of all the test runs (for various CFG settings and field conditions) for charged fog and uncharged fog.

Although the effect is not as strong as for the fine fraction, the mean value of the particle control efficiency of coarse particles increased modestly when the droplets were charged. This result is in good agreement with the theoretical predictions. However, the size range of particles collected in the coarse mode was fairly narrow, and the mass collected was often an order of magnitude smaller than the fine fraction. Another problem which may have inhibited coarse particle collection is the particle bounce effect, by which some of the larger particles pass the upper impaction plate and settle on the back-up filter with the fine particles. Therefore, this particular experiment could not demonstrate the full effect of charged fog on these particles. Consequently, most of the ensuing discussion will concentrate on the sum of fine and coarse fractions of the particles collected, and the subscript on E will be dropped hereafter.

For further detailed analysis, the data base was divided into four groups on the basis of water flow rate (60 l/h or 30 l/h) and the spray pattern (broad or narrow). Each group contained particle control efficiencies (percentages) measured for two or more applied voltages, and existing meteorological conditions. Data in each one of these four groups were examined to determine the dominant variable parameters affecting the value of the particle control efficiency, while other variable parameters are constant or nearly identical. Findings of these analyses are presented below.

Spray Pattern and Relative Humidity

Figure 29 shows particle control efficiency, E (for all particles -- fine and coarse), plotted as a function of ambient relative humidity for two sets of instrument settings for an applied high voltage of 4 kV (positive charges) and a water flow rate of 60 l/h. The circles represent a broad spray pattern and squares represent a narrow spray pattern. The method of least squares was used to fit a straight line to the data sets, shown in the figure, yielding a correlation coefficient of 0.93 for the broad spray and -0.19 for the narrow spray. The corresponding slopes are 0.99 and -0.09, respectively. Although the wind conditions were not identical for the data points, it can be seen that the particle control efficiency increases with increases in ambient relative humidity for a broad spray, while it is fairly independent of RH for a narrow spray.

Figure 30 compares the total particle control efficiencies for broad spray (A, B, and C) and the corresponding values for narrow spray (A', B', and C') with identical or nearly identical field conditions and an applied voltage of 4 kV at a water flow rate of 60 l/h. The broad spray pattern provides higher particle control efficiencies.

The difference in the dependence of E on RH for the broad spray and narrow spray can be explained as follows. For a narrow spray, most of the droplets occupy a volume away from the open side of the hopper, and when fog is continuously applied, this area becomes more saturated with water droplets and water vapor than outside the hopper or near the hopper opening, if the wind is not too strong. Thus, there is less droplet evaporation and, consequently, fairly steady particle collection efficiency. However, in the case of a broad spray, the droplets are distributed from the rear wall of the hopper to outside the open side of the hopper. Thus, if the ambient relative humidity is high, a smaller number of droplets will evaporate leaving more droplets to collect dust particles; on the other hand, when the ambient relative humidity is low, more droplets are lost due to evaporation near the open side of the hopper and outside the hopper.

The increase in particle control efficiency with increased relative humidity may appear to contradict the theoretical predictions shown in Figure 3. In practice, however,

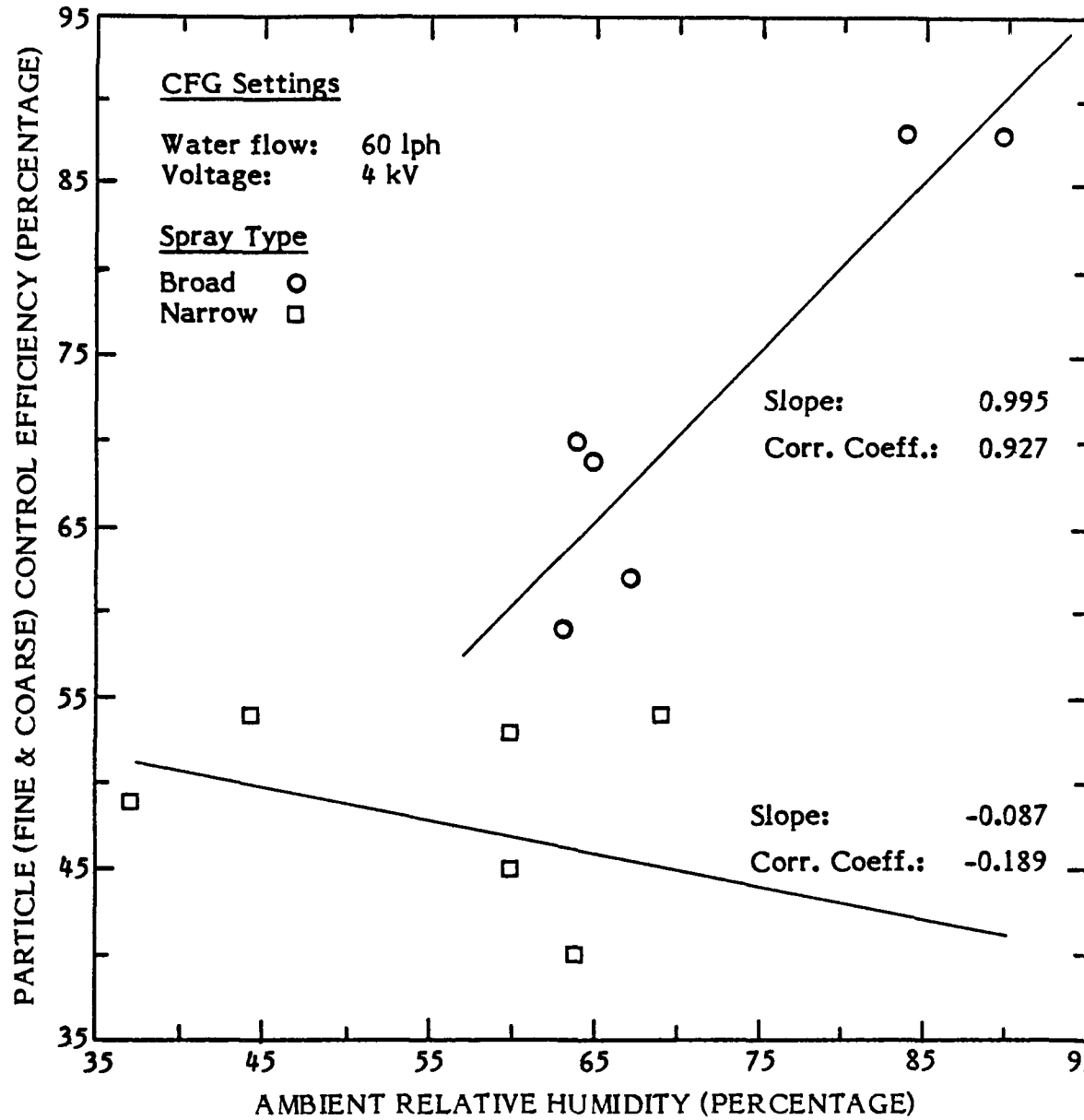


Figure 29. Particle control efficiency of the CFG plotted as a function of ambient relative humidity for broad (O) and narrow (□) spray patterns.

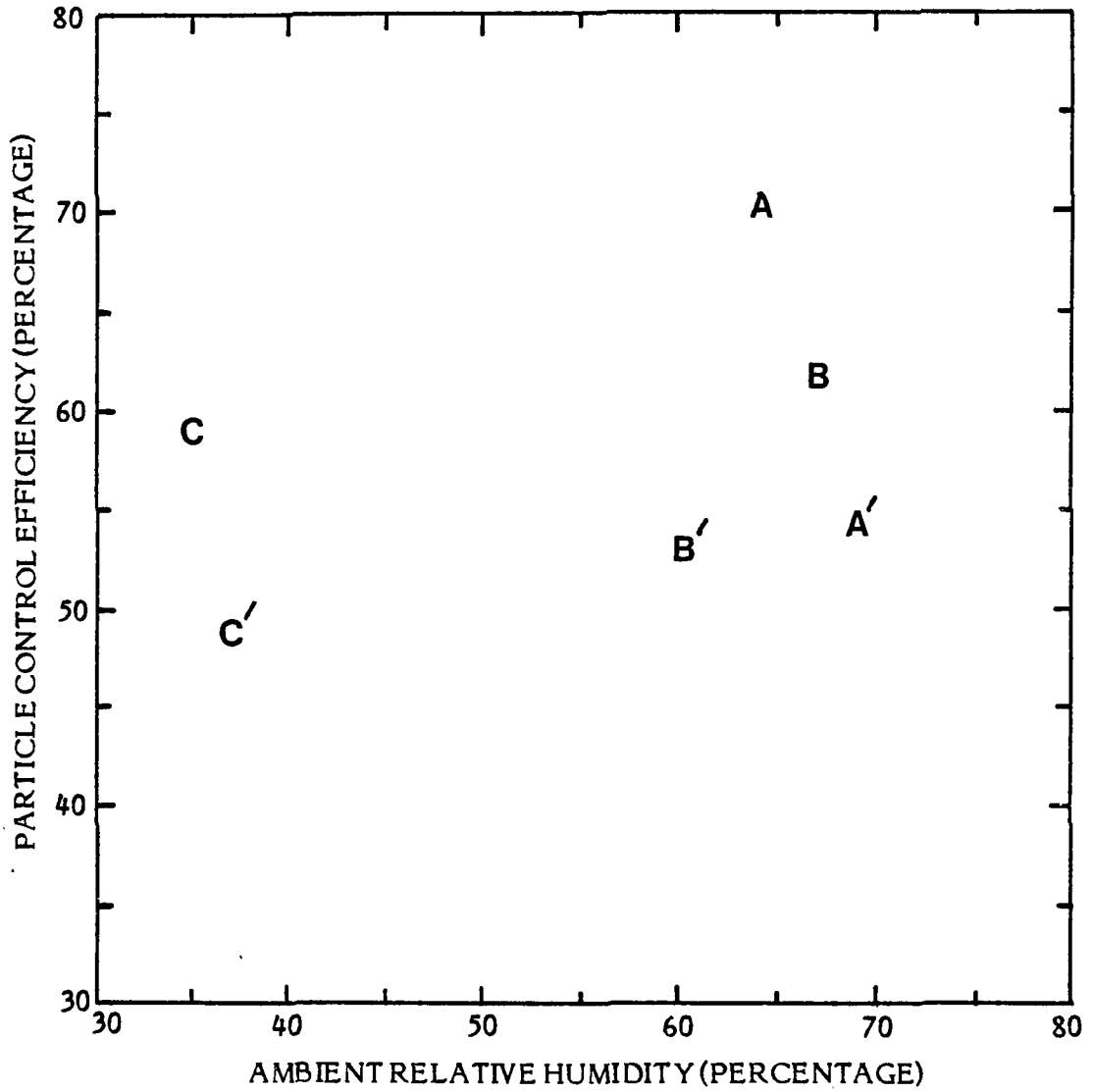


Figure 30. Comparison of total particle control efficiency of the CFG for a broad spray (A, B, and C) and narrow spray (A', B', and C') under identical or nearly identical conditions.

the effect of the longer droplet lifetime in a higher relative humidity atmosphere increases the particle control efficiency. Our test observations are thus consistent with the conclusion that the droplets should be small enough to provide high particle collection efficiency, yet large enough not to evaporate too quickly.

Particle Control Efficiency and Applied Voltage

Hoenig (1977) and Hassler (1978) have shown that most mineral particles, especially those in the fine fraction, are negatively charged. It was observed, however, that the particle control efficiency of charged fog, when applied on bentonite ore, was higher when the fog was charged negatively than when the fog was charged positively, with all other parameters being identical. Figure 31 shows particle control efficiencies for negatively charged fog (stripes tilted to the left) and positively charged fog (stripes tilted to the right) for the fine fraction, and for both fine and coarse particles, with the same water flow rate, same applied voltage, and nearly identical field conditions.

Table 6 compares the effect of applied high voltages on the observed particle control efficiency, with all other variable parameters identical or nearly identical. It is evident that a higher applied voltage results in a higher value of E. As we have shown in the last section, an increase in the applied voltage generated droplets with more charges (and charge-to-mass ratio). Consequently, the electrostatic forces of attraction between the droplet and particles were increased, resulting in higher values of E.

Table 6 also shows the particle control efficiency when two negative voltages are applied to the inflowing water. These data show only a slight increase in particle collection efficiency when the applied voltage was increased from -7 kV to -9 kV. This result may be because, with either of the voltages applied, the droplets reach their Rayleigh limit of charges and they begin to evaporate. Therefore, increased high voltage above about 8 kV does not significantly increase the particle collection. It should also be recalled that the absolute value of the particle control efficiency in this particular case is low because of the effect of other variable parameters, such as water flow rate and unfavorable meteorological conditions.

Effect of Water Flow Rate on Particle Control Efficiency

Figure 32 is a good example of the effect of water flow rate in the CFG on its ability to control particles. The percentage particle control efficiency in this case decreased by 42% when the water flow rate was reduced from 60 l/h to 30 l/h, with all other instrument settings and field conditions nearly identical. This effect is expected as increased water flow rate increases the number of charged droplets available for particle collection. Water flow rate was particularly significant in our experiment because the CFG was being applied to control dust in a volume larger than its maximum coverage; therefore, a decrease in the water flow rate decreased its particle control efficiency.

Effect of Wind Conditions on Particle Collection

Under a controlled experimental setup one would expect the particle control efficiency of charged droplets to decrease if the wind speed in the volume being treated were increased. The increased wind would reduce the time available for the droplet and particle to interact. However, in our experimental situation, because of the location and method of particle sampling, this effect cannot be quantified.

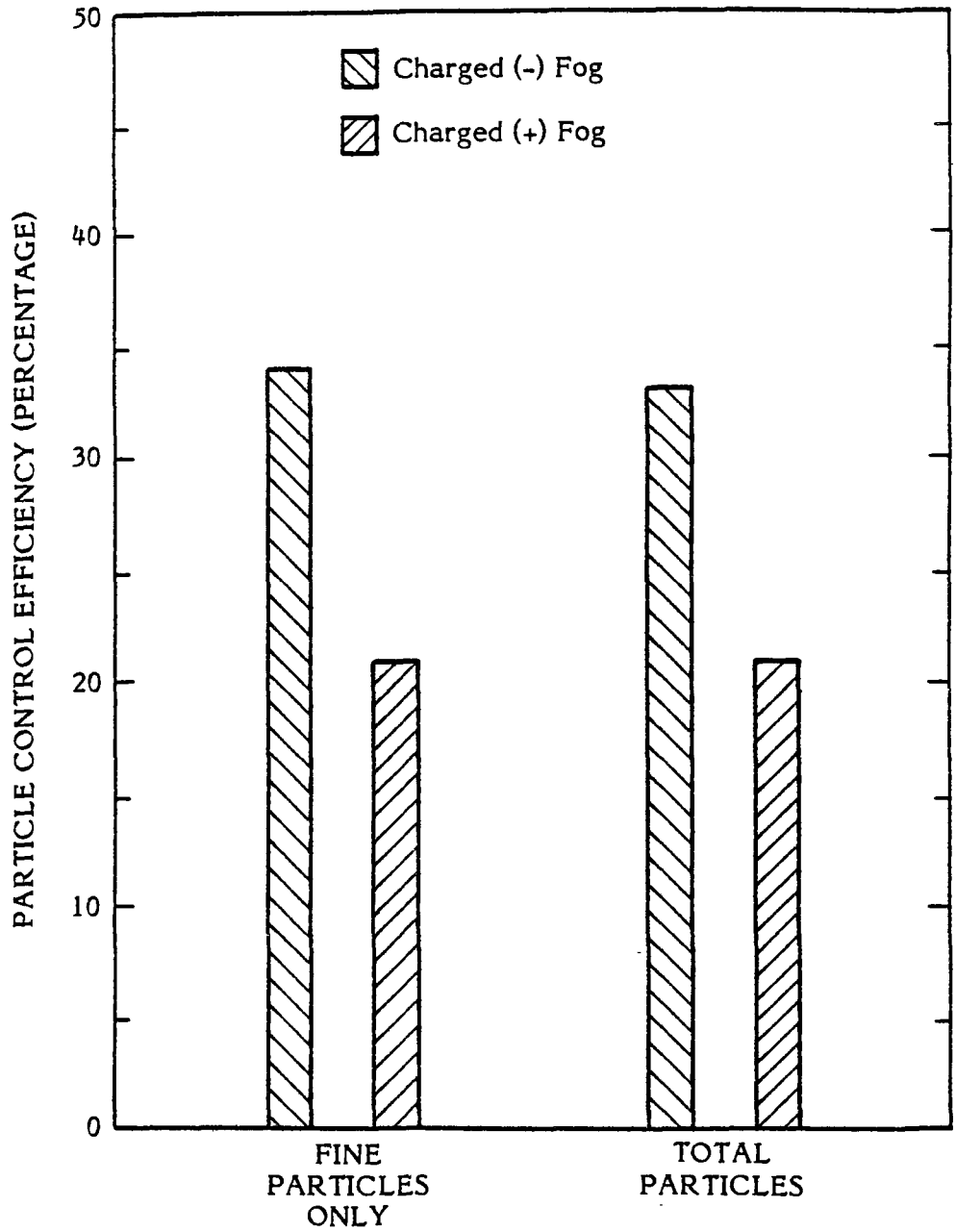


Figure 31. Comparison of particle control efficiency of the CFG for positively charged fog and negatively charged fog, with all other parameters nearly identical (Run Numbers 69 and 96).

TABLE 6. COMPARISON OF TOTAL PARTICLE CONTROL EFFICIENCIES OF CFG FOR THE TWO PAIRS OF APPLIED VOLTAGES, WITH ALL OTHER PARAMETERS NEARLY IDENTICAL.

Applied High Voltage	CFG Particle Control Efficiency (%)
4 kV	17
8 kV	21
-7 kV	30
-9 kV	31

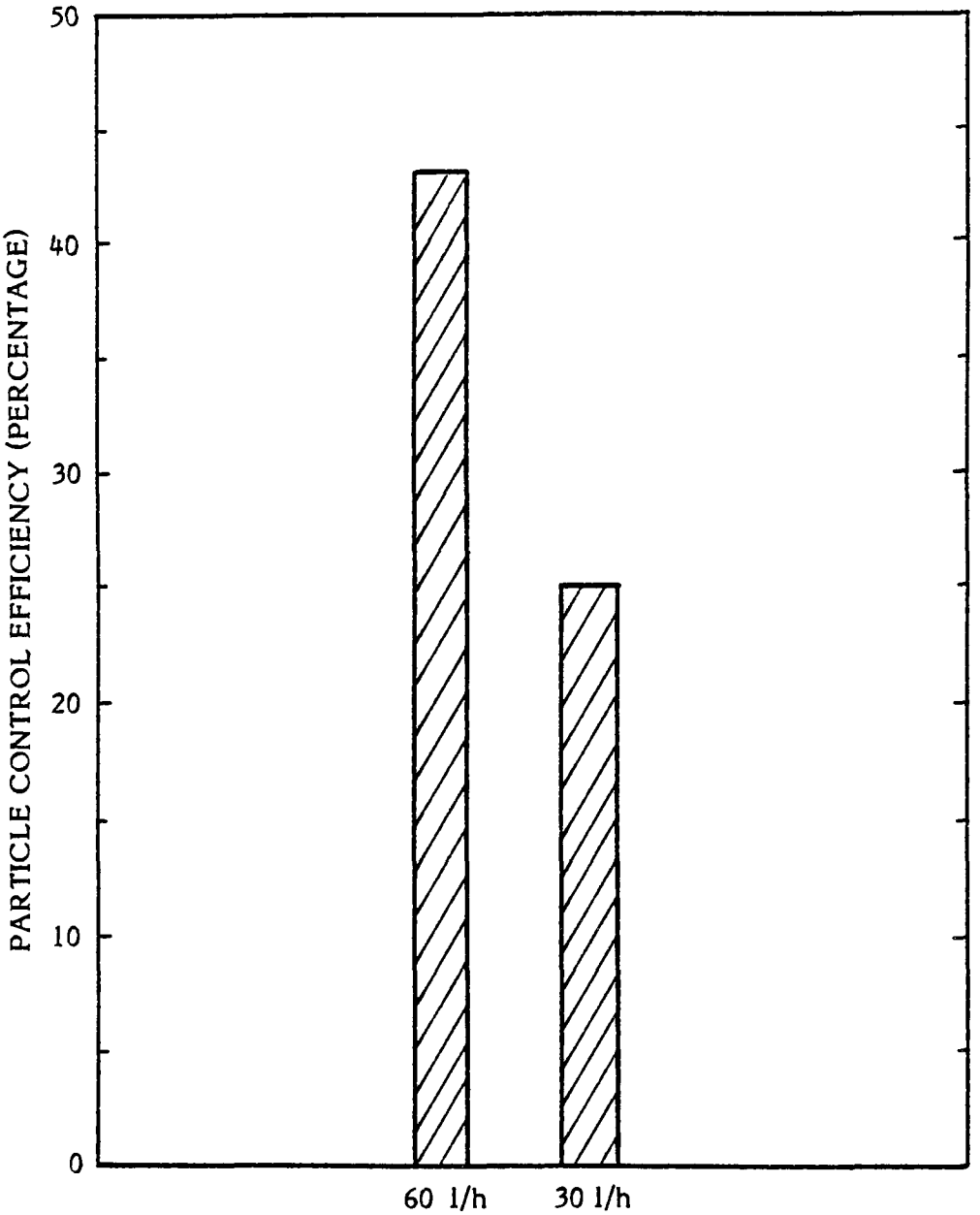


Figure 32. Comparison of particle control efficiency of the CFG for two water flow rates, with all other parameters nearly identical.

Because the hopper is completely enclosed except on the side through which the bentonite ore is dumped and because the particle sampler inlet is located near the southeast corner of the hopper, slow winds from the southeast, east, and northeast will not significantly affect the particle concentration measured. If the wind is from the north and northwest, more dust will be blown toward the sampler inlet, and the sampler may record a higher concentration than when there are no such winds. This wind condition enables the dust to remain in the hopper area longer, giving more time for the droplets to interact with the particles.

CONCLUSIONS OF THE CFG FIELD TESTS ON BENTONITE

As was indicated at the beginning of this chapter, the experiment to evaluate the particle control efficiency of the CFG and to determine the optimum instrument settings and meteorological conditions ideally would have been done under controlled conditions -- or a much larger data base obtained. Nevertheless, the following conclusions can be drawn from the available data.

1. Charged fog was shown to be an effective means of controlling fugitive dust emissions. The mean value of the particle control efficiency of charged fog measured under all instrument settings and field conditions showed a 78% increase when compared with the corresponding value for uncharged fog.

2. The relative humidity (in this particular experimental setup) seemed to play a significant role in determining the overall particle collection efficiency. It appears that the lifetime of the droplet is the dominant factor in determining what the particle control efficiency will be. Therefore, the droplets should be large enough not to evaporate too quickly, yet small enough to yield a high particle control efficiency.

3. Under identical or nearly identical field conditions and instrument settings, negatively charged droplets gave higher values of particle control efficiency than did positively charged fog, suggesting that inhalable bentonite particles carry a net excess positive charge.

4. Measured inhalable particle control efficiencies were higher for higher applied voltages in the 4 to 10 kV range. At the upper end of this range, the particle control efficiency seemed to attain a saturation value.

5. Measured inhalable particle control efficiency was higher when charged droplets could cover more of the dust-laden air in the hopper. In the experimental setup used, higher water flow rates and broad spray patterns resulted generally in higher collection efficiencies, although the key element appeared to be how many particles were treated by the droplets.

6. Because of the type of particle sampling method used and the field setup, the effect of wind speed and direction on particle control efficiency cannot be quantified with the available data.

7. The optimum CFG instrumental settings are found to be 60 l/h water flow rate, a spray pattern which will cover a maximum volume of dust-laden air (broad or narrow spray depending on the extent of the source), an applied voltage of 8-10 kV, and positive or negative charge depending on the charges of the dust particles. Ideal field conditions are high relative humidity (to ensure long droplet lifetime), and calm or low wind conditions.

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APPENDIX A

Charged Fog Technology. Part I: Theoretical Background and Instrumentation Development

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Charged Fog Technology Part I: Theoretical Background and Instrumentation Development

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Water sprays, the most common method of controlling dust in mines and from fugitive emission sources, do not control inhalable particles very effectively. Since most industrial pollutants and naturally occurring fugitive dust particles acquire electric charges as they are dispersed into the air, the inhalable particle control efficiency of water sprays can be significantly improved if the water droplets are also electrically charged to the opposite polarity. Commercially available charged fog devices have several disadvantages. They require high pressure air and/or water, their nozzles are prone to clogging, and they generate charged droplets which are poorly suited for good inhalable particle control. This paper reviews the basic principles of charged fog technology and describes a new charged fog generator which overcomes the problems of commercial charged fog devices.

In the charged fog generator (CFG), water from a reservoir is introduced into a rotating cup where the water forms a thin layer due to centrifugal forces. As the water moves towards the lip of the cup, high speed air from an axial fan strikes the thin water film, breaks it into fine droplets and projects the droplets forward. The droplets thus generated have a typical mass median diameter of about 200 μm and a concentration median diameter of about 100 μm. The droplets are electrically charged by contact charging the inflowing water, providing a typical charge to mass ratio of 1.2×10^{-6} C/g with an applied voltage of about 15 kV. The water flow rate in the CFG can be varied from 4–70 L/h and the spray pattern can be easily adjusted to conform to the size and shape of the dust source to be treated. Other advantages of this device are that it uses only about 1 kW power, it is portable, and it is easily adaptable for use at remote areas where commercial electrical power supply is not available.

Recent reports[1–3] indicate that inhalable particles (particles smaller than 15 μm in aerodynamic diameter), in general, and fine particles (particles smaller than 2–3 μm in aerodynamic diameter), in particular, are a human health hazard, contribute to the formation of acid rain, and degrade atmospheric visibility. Although significant progress has been made in controlling emissions from conventional industrial stack sources, effective and economically feasible methods are lacking for controlling inhalable particles from nonstack sources (fugitive emissions). Recognizing this situation, EPA has been encouraging the development of new methods, such as charged fog technology, to control fugitive emissions.

Removing fine particles from a gas stream in an open area is difficult because of the particles' low mobility and unfavorable inertial properties, and because of uncontrollable external factors (meteorological parameters). The most commonly used dust control method (ordinary water sprays) in mining and other material handling areas is only 30–40% efficient in controlling inhalable particles.[4] Only during the last few years have electrostatics been used to augment particle collection efficiency of water droplets.[5–10] Numerous studies[8–18] have shown that most industrial pollutants and naturally occurring dust particles acquire electric charges as they are dispersed into the air. Walkenhorst,[11] Schutz,[12] Hoenig,[8,9] and Hassler,[10] have also shown that the polarity and magnitude of the charges on these particles depend upon their size and origin (coal, soil, mineral, etc.). Therefore, particle collection efficiency of water droplets can be significantly enhanced via electrostatic forces of attraction if the droplets are charged to the opposite polarity.

In this paper the theoretical concepts of charged fog technology are outlined and currently available charged fog devices are discussed, with special emphasis on a prototype charged fog generator developed under the sponsorship of the Industrial Environmental Research Laboratory of the EPA. Tests of this prototype device for fugitive emission control are described in a subsequent paper.[19]

Theoretical Background

The collection of an aerosol particle by a charged droplet is the result of a number of simultaneous mechanisms of interaction between them, such as inertial impaction, direct interception, Brownian diffusion, and electrostatic, diffusiophoretic and thermophoretic forces.[20–24] When an aerosol particle approaches a water droplet with a relative velocity, it may directly collide with the droplet (impaction), barely touch the droplet (interception), or entirely miss the droplet. The relative effect of the mechanisms of interaction between the droplet and the particle depends upon the size of the particle. For large particles (aerodynamic diameter greater than 2–3 μm), the dominant mechanisms of particle collection by droplets are impaction and interception. For particles

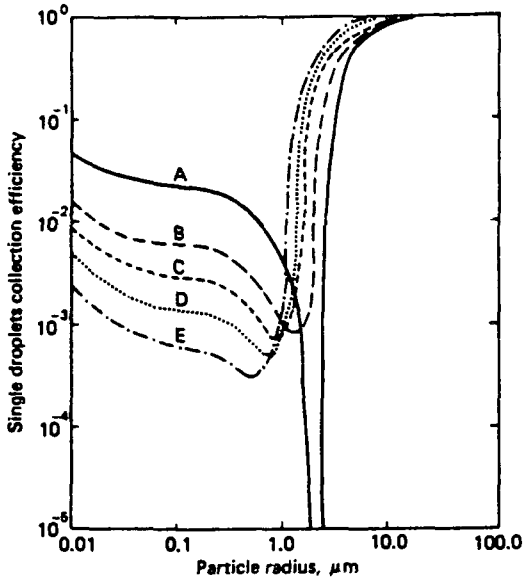

Figure 1. Calculated single droplet collection efficiency in air of 10°C and 900 mb as a function of particle radius at a relative humidity of 75% with droplet radius as a varying parameter (A) 42 μm, (B) 72 μm, (C) 106 μm, (D) 173 μm, and (E) 310 μm.

smaller than 0.1 μm, Brownian diffusion becomes very important, and for particles between these two ranges, electrostatic forces are the dominant interaction mechanism.

The particle collection efficiency of uncharged water sprays (where inertial impaction is the major collection mechanism) is given by,[25]

$$E = 1 - \exp\left[-\frac{3}{2} \times \frac{Q_L}{Q_G} \times \frac{L}{D} \times \eta\right] \quad (1)$$

where Q_L and Q_G are the volume flow rates of the water and air component of the dust cloud, respectively; L is a characteristic length for the total capture process; D is the mean droplet diameter; and η is the single droplet collection efficiency (assumed to be identical to collision efficiency).

For a given particle size, single droplet collection efficiency due to inertial impaction is proportional to the relative velocity between the droplet and the particle and inversely

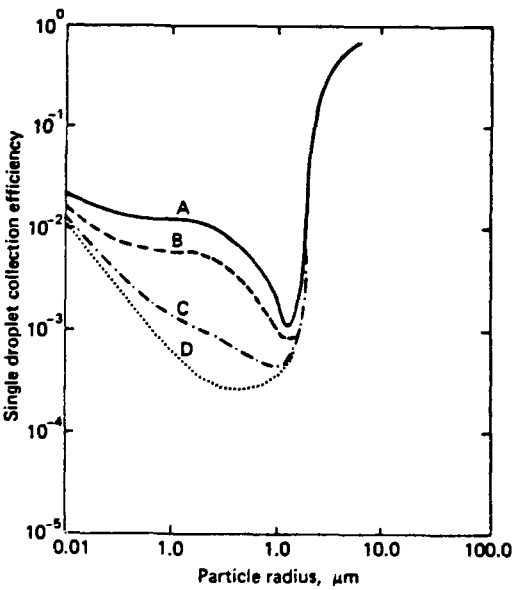

Figure 2. Calculated single droplet collection efficiency in air of 10°C and 900 mb as a function of particle radius for a 72 μm radius droplet with relative humidity as a varying parameter (A) 50%, (B) 75%, (C) 95%, and (D) 100%.

proportional to the droplet diameter. The single droplet collection efficiency of a charged particle by an oppositely charged droplet is given by[20]

$$\eta = -Cq_c q_p / 6\pi^2 K r R^2 \mu U_o \quad (2)$$

where C is the Cunningham slip correction factor; q_c is the droplet charge; q_p is the particle charge; K is the dielectric constant; r is the particle radius; R is the droplet radius; μ is the viscosity; and U_o is the droplet free stream velocity.

Single droplet collection efficiency has been investigated by many.[20-25] Figures 1 and 2 (adapted from Wang *et al.*[21]) show calculated single droplet collection efficiency (E) plotted (for uncharged particles and droplets) as a function of particle radius, with droplet radius and relative humidity (RH) as a varying parameter, respectively.

From Figure 1, it may be noticed that the collection efficiency of larger particles is greater for larger droplets, while the collection efficiency of smaller particles is greater for smaller droplets. The minimum in E occurs near a particle radius of ~1 μm (due to the ineffectiveness of different in-

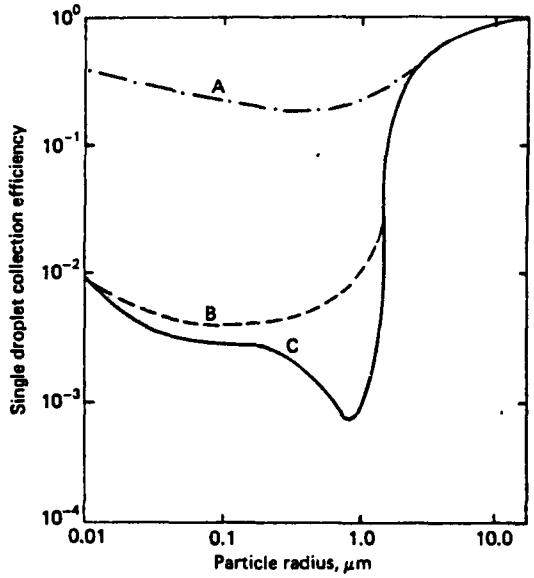

Figure 3. Calculated single droplet collection efficiency in air of 10°C and 900 mb as a function of particle radius for a 106 μm radius droplet at 75% relative humidity for droplet and particle charges of (A) ±20 ESU cm^{-2}, (B) ±2 ESU cm^{-2}, and (C) zero charge.

teraction mechanisms), and for droplets less than ~55 μm radius, E becomes infinitely low, giving rise to the so called "Greenfield gap." Figure 2 shows that the collection efficiency increases with decreasing relative humidity for smaller particles and E is independent of relative humidity for larger particles.

Turning our attention to charged particles and charged droplets, Figure 3 (adapted from Wang *et al.*[21]) shows calculated single droplet collection efficiency plotted as a function of particle radius for a droplet of radius, R = 106 μm, and 75% RH. Curve C at the bottom is for the case when the droplet and particles carry no charges. Curve B gives collection efficiency with droplets and aerosol particles both charged to the same magnitude of 2 ESU cm^{-2}, but of opposite sign. Curve A is similar to B, except the magnitude of the charge is 20 ESU cm^{-2}; Curve A is obtained by a less rigorous calculation method.[26] Figure 3 shows that the introduction of electric charges on the droplets and the aerosol particles completely eliminates the minimum in E, and depending upon the amount of charge, the collection efficiency of fine particles is increased by more than an order of magnitude. This effect is the fundamental principle on which the charged fog tech-

nology is based. Figure 3 also shows that the addition of electric charges does not significantly affect the collection efficiency for large particles.

Prem and Pilat[20] showed that for 200-μm and 50-μm charged droplets and oppositely charged particles in the size range 10–20 μm, the particle collection efficiency due to electrostatic forces and inertia are comparable. However, for particles smaller than 10 μm, and for the same droplet sizes, the collection efficiencies due to the electrostatic forces progressively become the dominant collection mechanism (compared to inertial impaction) as the particle sizes are decreased.

When sprayed into the air, the charged droplets will evaporate unless the air is saturated with water vapor. The droplet lifetime determines the effective contact time between the droplet and particles and thus strongly influences the overall particle control efficiency of a charged fog device. The lifetime of a water droplet depends upon the temperature and relative humidity of the medium into which it is introduced. To obtain the best collection efficiency, the droplets must be small enough to provide both an adequate spray rate per volume of gas treated and sufficient contact time, yet large enough to not evaporate too quickly.

The maximum electrical charge that can be carried by a particle is limited by the physical properties of the particle. Three such limits, the electron limit, the ion limit, and the Rayleigh limit are discussed by Cohen.[27] The maximum charge a droplet can carry before it disintegrates is reached when the outward pressure produced by the electric field at the surface of the drop is equal to the inward pressure produced by the surface tension. This limiting charge (Rayleigh limit) is given by[28,29]

$$Q_{Ray} = 8\pi(\epsilon_o \sigma R^3)^{1/2} \quad (3)$$

where Q_{Ray} is the limiting charge on the droplet, ϵ_o is the permittivity of the medium in which the droplet is located, σ is the surface tension of the liquid, and R is the droplet radius.

Although Figure 3 shows that the addition of electric charges on particles and droplets completely eliminates the minimum in particle collection efficiency (around $r = 1\ \mu$m), and shows single particle collection efficiencies 5–10 times higher than for uncharged sprays, the overall collection efficiency of the system may not be that high. In laboratory experiments, investigators[6] have reported increases in the collection of efficiencies of charged droplets over uncharged droplets of about 15% for 1-μm particles to over 45% for 0.3-μm particles. Hoenig[8,9] reported particle control efficiencies of 50–80% with charged droplets under controlled experimental conditions. Brookman *et al.*[30] have reported inhalable particle control efficiencies of about 60% from measurements at a sand and gravel operation using the largest commercially available charged fog device.

Charged Fog Devices

Charged droplet devices are used in fugitive emission control and in agricultural spraying.[31,32] Here we will restrict our discussion to those devices used in fugitive emission control.

Water droplets can be generated using a pressure nozzle or a rotating cup. Droplets may be charged by electrostatic induction charging, ionized field charging, or contact charging methods. Hassler[10] showed that droplets may be charged by the water to metal frictional forces inside the nozzle during atomization. This method requires no high voltage supply; however, it requires very pure deionized water. This limitation precludes using this method of charging water droplets for dust control in the field.

In the most frequently used method, electrostatic induction charging, a high voltage potential is maintained between the water spray nozzle and the induction ring. Positive or negative charges are induced on the droplets by the charges on the induction ring, depending on the polarity of the high voltage applied to the ring. In ionized field charging, an electrode at sufficiently high DC potential is placed near the water nozzle, causing dielectric breakdown of the air immediately surrounding the electrode. Water droplets traveling through this ionized field can acquire electric charges by ion attachment.

In contact charging, charges are transferred by conduction to the water, and subsequently, to the droplets at their instant of formation by connecting a source of charge (high voltage supply) to the inflowing water. This method has been shown to be very effective in charging the droplets to a high degree.[33] However, this method requires that the entire water supply and associated plumbing be electrically isolated to avoid current leakage.

Charged fog devices are commercially available from Keystone Dynamics Inc., Villanova, PA ("Dustron"), and Sonic

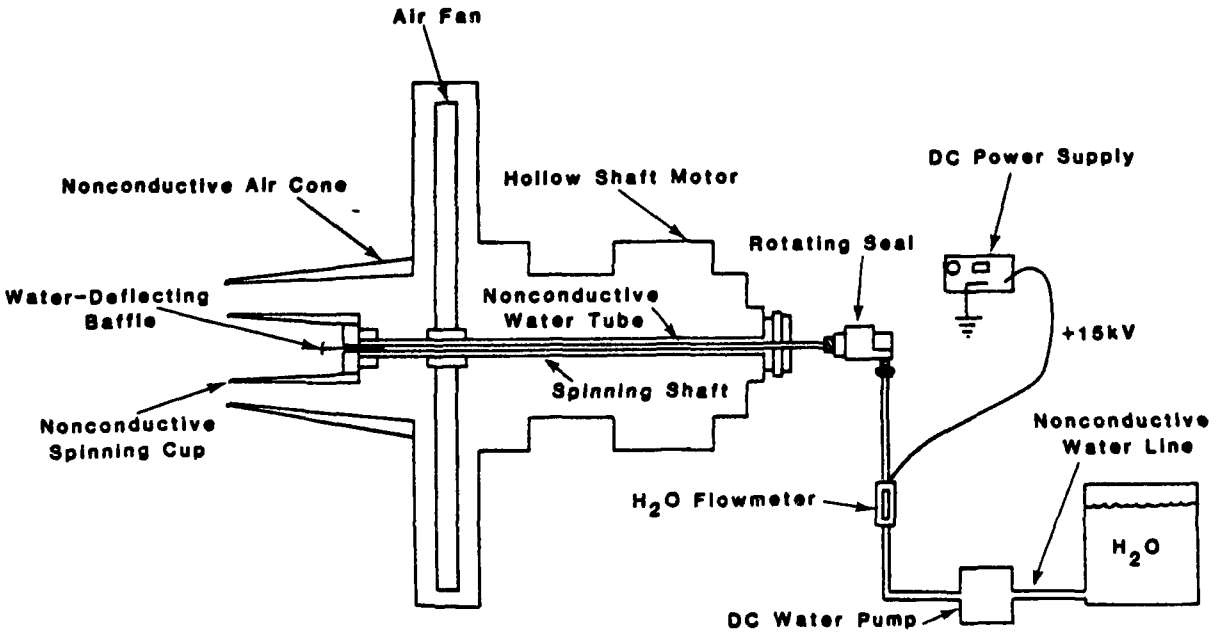

Figure 4. Schematic diagram of the charged fog generator.

Figure 5. Typical long and narrow spray pattern from the charged fog generator.

Development Corp., Mawah, NJ ("Foggers I, II and IV"). The charged fog generator developed by AeroVironment Inc. currently exists in prototype form. The Dustron and Foggers operate on the same principle—atomizing water in a nozzle with high pressure air and/or water and passing the droplets through an induction charging ring. On the other hand, the charged fog generator uses rotary atomization and direct contact charging of the inflowing water.

In the Fogger IV[30] (the largest commercially available charged fog device), water at a variable flow rate of 0–151 L/h is atomized as it is ejected from a nozzle by a compressed (5.6–8.8 kg/cm^2) air supply. The droplets pass through an induction ring maintained at 12.5 kV, where the droplets acquire electric charges by induction. A flow of air around the nozzle provided by a 79 m^3/min centrifugal fan projects the fog towards the dust source. The droplets generated by this device are estimated to have an average diameter of 60 μm and a charge to mass ratio of 0.11×10^{-6} C/g at a water flow rate of 75 L/h. The Fogger IV requires 230 V (AC) and a maximum power of 8 kW. Foggers I and II are similar to Fogger IV, except they do not use fans to blow the fog forward toward the dust source and their water handling capabilities are lower: 0–60 L/h for Fogger I and 0–120 L/h for Fogger II.

Charged fog devices using pressure nozzles require a substantial supply of high pressure water and/or air for proper atomization and have a tendency to clog if the water supply contains high concentrations of dissolved salts and suspended solids. As indicated earlier, the induction ring method of charging the droplets provides a lower droplet charge to mass ratio than is needed for a high degree of inhalable particle control. Most of the problems associated with pressure nozzles can be eliminated by using rotary atomizers. Rotary atomizers using either a spinning disc or cup have been used for many years for generating fine droplets.[34,35] The charged fog generator described below uses a spinning cup.

Charged Fog Generator

Figure 4 is a schematic representation of the charged fog generator (CFG). Water is introduced through the water tube into the 3,600 rpm rotating cup, whose inside is configured with a gradual linear taper. A small deflecting baffle is attached to the open end of the water tube so that the water will be deflected 90° and strike the inner rear surface of the rotating cup. Because of the centrifugal forces, the water spreads into a thin film and moves forward into a high velocity airstream generated by the axial fan. The impact of the high velocity air on the thin water film breaks the water film into fine water droplets.

The water tube, air cone, and the rotating cup are made of nonconducting materials. The water tube is firmly attached to the rotating cup, thus rotating with the cup. The other end of the water tube is attached to the water supply through a rotating seal. The water for atomization is stored in an electrically isolated reservoir (130-L capacity) and a low pressure pump is used to pump it to the inlet of the rotating seal. The water flow rate can be varied from about 4–70 L/h. The airstream from the fan can be controlled by a butterfly valve

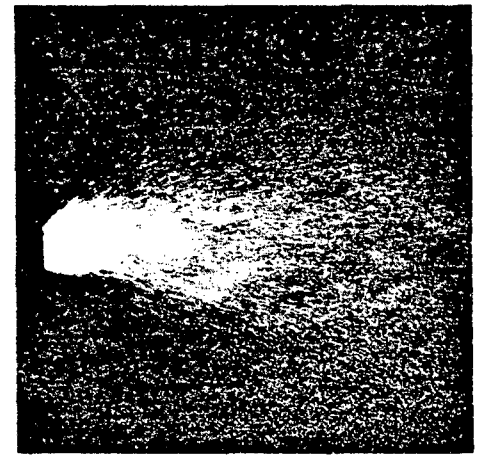

Figure 6. Typical short and broad spray pattern from the charged fog generator.

setting and this airstream projects the fog forward. By adjusting this valve, the airflow speed can be controlled, thereby controlling the shape of the fog spray pattern to conform to the shape and size of the source of dust upon which the charged fog is to be applied (see Figures 5 and 6). The spray pattern covers a volume of 16–24 m^3.

To achieve the preferred high charge to mass ratio for the droplets, contact charging by directly connecting a high voltage source to the inflowing water was found to be the most efficient method. However, this method requires that the entire water supply (reservoir) and associated tubing be electrically isolated to prevent current leakage.

Droplet Size Distribution

The size distribution of the droplets was determined using a cloud optical array probe and a precipitation optical array probe manufactured by Particle Measuring Systems of Boulder, CO (for droplets in the size range of 30–1875 μm). These measurements gave a mass median droplet diameter of about 200 μm (Figure 7) and a concentration median diameter of about 100 μm (Figure 8). Collecting the droplets on greased glass slides and observing them under a microscope also yielded values consistent with the above result.

Droplet Charge to Mass Ratio

The charge to mass ratio of the droplets was determined using a special sampling train. This train consisted of an insulated stainless steel probe tip mounted on a standard glass midget impinger. The probe was connected electrically to

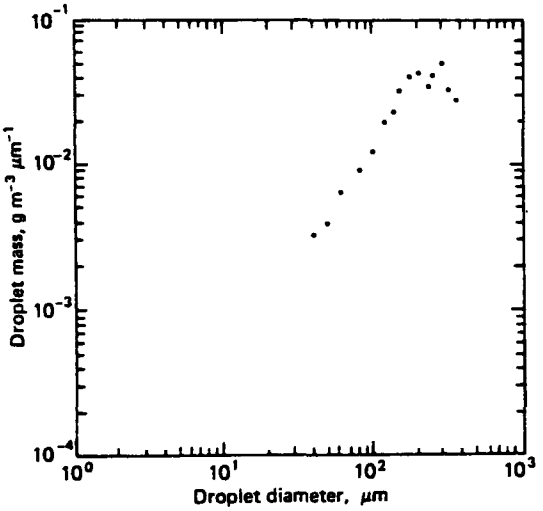

Figure 7. Droplet mass as a function of droplet diameter measured using a cloud optical array probe and a precipitation optical array probe.

copper wool packing placed inside the midget impinger which was also connected by a shielded cable to an electrometer. The impinger was immersed in a Dewar flask containing dry ice. An isokinetic sample of droplets was then extracted from the fog spray. As the droplets moved through the impinger they were condensed and frozen, thus transferring their charge to the copper wool packing. The charge was then measured by the electrometer. Knowing the mass of droplets collected and the current produced by them, the charge to mass ratio was calculated. This method gave a typical value of 1.2×10^{-6} C/g with an applied voltage of 15 kV. This value is about one fourth of the maximum allowed droplet charge value (Rayleigh limit) for 200 μm droplets.

The charge to mass ratio was also estimated using another experimental setup. In this case, the droplets were allowed to transfer their charges to a 125 μm mesh size standard sieve placed in the path of the fog spray and measuring the current generated through the mesh. Knowing the mass median droplet size and the total number of droplets generated per second by the CFG, the charge-to-mass ratio was estimated. This method, though less reliable, gave values consistent with that reported above for the gravimetric method. In a similar manner, the charge per unit area of the droplets can be calculated using the measured current generated in the mesh and the surface area of the droplet with the median concentration diameter. In terms of electrostatic units used in Figure 3, the charges on the droplets generated by the CFG will fall approximately midway between cases A and B.

Summary and Conclusions

Since inhalable particles in the air are known to be electrostatically charged, their control by water sprays can be significantly enhanced if the water droplets are also electrostatically charged to the opposite polarity. Commercially available charged fog devices require high pressure air and/or water and their nozzles are prone to clogging if the water supply contains dissolved salts and a high concentration of suspended solids. Moreover, their induction ring method of droplet charging provides a lower droplet charge to mass ratio than is needed for a high degree of inhalable particle control.

The new charged fog generator uses rotary atomization, eliminating both fine nozzle and high pressure air requirements. Contact charging of droplets provides a high charge to mass ratio for the droplets generated. The CFG's spray pattern can be easily adjusted to conform to the extent of the dust source upon which the charged fog is to be applied. The size distribution of the droplets gives a mass median diameter of about 200 μm and a concentration median diameter of about 100 μm. The contact charging method provides a high charge to mass ratio of 1.2×10^{-6} C/g. The CFG is small, portable and requires only about 1 kW (ordinary 110 V AC line voltage). With the use of small inverter the unit can be operated on battery power. This feature may be important, because the system has potential applications where commercial electric power is not readily available.

For certain fugitive dust sources in open areas, charged fog technology seems to be the most practical and cost-effective method of dust control, and probably the only method for controlling fine particles (<2.5 μm in aerodynamic diameter) efficiently.

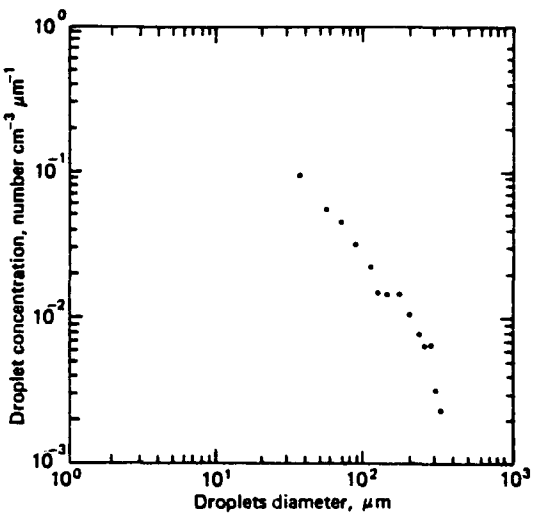

Figure 8. Droplet concentration as a function of droplet diameter measured using a cloud optical array probe and a precipitation optical array probe.

Further research is required in two areas: 1) quantitative information is needed on electrical charges (both polarity and magnitude) carried by aerosols in the size range 0.5 μm to 10 or 15 μm; and 2) further improvements are needed in the instrumentation, especially to make it explosion proof, before it can be used to control inhalable particles in gassy underground mines.

Acknowledgments

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APPENDIX B

Charged Fog Technology. Part II: Prototype Tests of
A New Charged Fog Generator for Fugitive Emission Control

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Charged Fog Technology
Part II: Prototype Tests of a New Charged Fog Generator for Fugitive Emission Control

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The prototype charged fog generator described in a preceding paper[1] was field tested on a fugitive emission source at a bentonite ore processing plant in Worland, Wyoming, during 1981. Particulate matter samples were collected as fine and coarse fractions under three different test scenarios: with no control, with partial control (uncharged fog), and with full control (charged fog). Measured particulate matter sample concentrations were normalized for each test day with respect to the background values so that particle control efficiency of the device could be evaluated without any bias during the entire test program.

These tests have shown that mean value of the inhalable particle control efficiency of charged fog measured under all instrument settings and field conditions is increased by 78% when compared with uncharged fog. In particular, fine particle control efficiencies of over 90% were recorded under optimum instrument settings and ideal field conditions. The bentonite particles seemed to carry a net positive charge. The optimum instrument settings were found to be: 60 L/h water flow rate, an applied voltage of 10–15 kV and a spray pattern which covers maximum volume of dust-laden air. Ideal field conditions are high relative humidity and calm or low winds.

Charged fog technology appears to be an effective and economically feasible method to control sources of fugitive particle emission in the inhalable size range. Further research is needed to evaluate the inhalable particle control efficiency of the device for emissions of various chemical compositions.

The prototype charged fog generator (CFG) described in a preceding paper[1] was field tested at the Kaycee Bentonite Corporation's bentonite ore processing plant in Worland, Wyoming, during 1981. The plant is located in a remote area in a fairly flat terrain. A railroad track and a paved road lie on the east side of the plant. Bottom-dump trucks filled with bentonite ore from mines, about 15 miles away, arrive from the south and unload bentonite on two piles, approximately 100 m to the northwest and southwest of the plant building. Front-end loaders carry bentonite from these piles and unload onto the grill of a hopper which is attached to the west wall of the plant building. The hopper is completely enclosed except on one side through which the front-end loaders unload. From the bottom of the hopper (approximately 4 m below the hopper grill level) the ore is carried inside the plant by conveyor belts to processing areas. When the front-end loaders dump the ore on the hopper grill, clouds of fugitive dust fill the hopper and spread to outside the hopper. The hopper was selected as the source of fugitive dust emission on which the CFG would be tested.

The objectives of the field tests were to evaluate:

1. Optimum instrument settings for maximum value of inhalable particle control under various combinations of meteorological parameters in the field; and
2. Optimum field conditions for maximum value of inhalable particle control efficiency of the device.

A secondary objective was to determine whether positively or negatively charged fog would control particles more efficiently.

Experimental Arrangements

The hopper is 6.7 m wide, about 2 m deep and about 3 m high from the grill level. The bucket of the front-end loader is about 2.4 m wide and successive loads are unloaded uniformly over the 6.7 m wide hopper. About 10 front-end loader dumps fill the hopper to the grill level, and take about 25 minutes to complete. The bucket is removed from inside the hopper area in 20–25 seconds. One full hopper of ore is carried away by the conveyor belt in about an hour.

The CFG and the particle sampling instruments were mounted on the outside of the south wall of the hopper, about 4 m above ground level. A platform was built to mount these instruments. Ideally, the particle sampler inlet should have been mounted on the east (rear) wall of the hopper, but for practical reasons could not be done. The CFG sprayed water droplets across the hopper above the grill. The total volume to be treated by the charged fog was about 40 m^3 (6.7 m × 2 m × 3 m). This volume is somewhat larger than the maximum coverage of the CFG fog. Unfortunately, at that time only one prototype CFG was available for tests. To have had a second unit mounted on the north wall of the hopper and operated concurrently would have been ideal.

Particle samples were collected using a Sierra Instruments Model 230 CP cyclone preseparator followed by a Sierra Instruments two-stage cascade impactor.[2] The cyclone's air inlet protruded 0.3 m into the hopper. The particle sampling system was operated at a flow rate of 0.85 m^3/min (30 cfm). The

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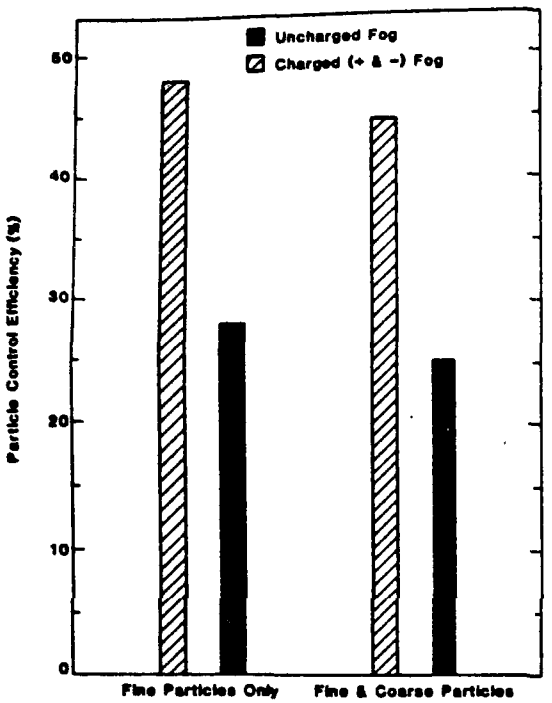

Figure 1. Mean inhalable particle control efficiency of all the test runs (for various CFG settings and field conditions) for charged fog (both positive and negative) and uncharged fog.

sampler flow rates were calibrated at regular intervals during the entire test program. The cyclone has a particle cut-point of about 7.3 μm at this flow rate. The impaction plates of the cascade impactor were chosen so that the upper filter would collect particles larger than 1.8 μm. The lower backup filter collects all particles smaller than 1.8 μm. For the purpose of this report, particles collected on the backup filter will be characterized as the fine particle fraction and those on the upper filter will be characterized as the coarse fraction. The mass of coarse fraction collected was often an order of magnitude smaller than the fine fraction, possibly indicating a particle bounce problem, with particles larger than the cut-point of 1.8 μm reaching the backup filter. Subdividing the samples into more size ranges would have required either much longer sampling time or much higher flow rates to obtain acceptable filter loadings. Neither of these alternatives was desirable.

Field Test Design

To determine the particle control efficiency of the CFG, three test scenarios were designed. In the first scenario, no attempt was made to control the dust inside the hopper, except that the CFG's fan blew continuously. This test scenario was necessary to ensure that the mixing of the dust cloud was nearly identical among various runs in order to make direct comparison of tests with and without charged fog. In the second scenario, uncharged fog was applied on the dust cloud, and in the third scenario, charged fog was applied. Other governing parameters were varied under each scenario to yield a statistically acceptable set of test data.

The parameters varied were water flow rates, fog pattern (short or long), applied high voltage, wind conditions, and relative humidity. In addition, a group of test runs were performed with the polarity of charges on the droplets reversed. This test protocol called for a total of 32 test runs. However, in actual practice, data had to be collected under prevailing field conditions; hence, a total of 96 runs were performed.

Particle samples were collected on preconditioned and preweighed glass fiber filters. Each particle sample was collected during 12–15 front-end loader dumps (roughly 30–40 min). Simultaneously, wind speed and direction and relative humidity were also recorded. After each sample was collected, the filters were transferred to special envelopes and brought to AeroVironment's laboratory for analysis. Further details of the experimental program are described elsewhere.[3]

Data Processing

The mass of the fine and coarse fraction and sum of the two were obtained from the final and initial weights of the filters. Using known values of the sample time, number of dumps, and flow rate, particle mass concentration for each dump was calculated.

The amount of dust generated in the hopper fluctuated from dump to dump. To overcome this variation, each sample was collected during a total of 10–15 dumps and the mean value for each dump was calculated. The amount of dust generated also varied from day to day. This variation was caused by factors such as changes in ambient conditions and the moisture content of the bentonite ore itself. The effect of the latter is not very significant since the ore stored in each pile comes from the same mine and a pile is completely processed before a new pile is started. To overcome the day to day dust level fluctuations, sample concentrations were normalized for each day with respect to the background value (the fan only value) and a percentage particle collection (control) efficiency was calculated. Percentage particle control efficiency E is obtained from:

$$E = \frac{C_o - C}{C_o} \times 100$$

where C_o and C are the particle concentrations corresponding to fan only and fog test scenarios, respectively.

Values of E are calculated for the fine fraction, the coarse fraction and the sum of fine and coarse. Percentage particle control efficiencies and the corresponding field condition data, water flow rate, and applied high voltage for the whole field test program are available from the author.

Results and Discussion

Figure 1 shows the mean values of the measured percentage fine particle control efficiency and total particle control efficiency for charged (striped bars)—both positive and negative—and uncharged (solid bars) fog. For this comparison, all test runs under all instrument settings and field conditions are included. The mean particle control efficiencies and standard deviations for these tests are shown in Table I.

These numbers show that, even under average field conditions and instrument settings, inhalable particle control efficiency can be almost doubled by electrically charging the water droplets. However, under optimum instrument settings and favorable field conditions, the improvement in inhalable particle control efficiency can be expected to be much higher. It may also be pointed out that the volume of the dust cloud treated was somewhat larger than the maximum coverage of the CFG; therefore, the observed improvement in particle control efficiency is remarkable.

Although the effect is not as strong as for the fine fraction, the mean value of the particle control efficiency of coarse particles increased modestly when the droplets were charged.

Table I. Mean particle control efficiencies of all test runs.

	Particle Control Efficiency (%)	
	Charged Fog	Uncharged Fog
Fine particles only		
Mean	48.1	27.8
Standard deviation	23	25.3
Fine and coarse particles together		
Mean	44.5	25
Standard deviation	21.8	24.4

This result is in good agreement with the theoretical predictions. However, the size range of particles collected in the coarse mode was fairly narrow, and the mass collected was often an order of magnitude smaller than the fine fraction. Therefore, this particular experiment could not demonstrate the full effect of charged fog on these particles. Another problem which may have inhibited coarse particle collection is the postulated particle bounce effect, by which some of the larger particles pass the upper impaction plate and settle on the backup filter with the fine particles. Consequently, most of the ensuing discussion will concentrate on the fine fraction of the particles collected.

Figure 2 shows fine particle control efficiency E plotted as a function of ambient relative humidity (RH) for two sets of instrument settings for an applied high voltage of 4 kV (positive charges) and a water flow rate of 60 L/h. The method of least squares was used to fit a straight line to the data sets, shown in the figure, yielding a correlation coefficient of 0.91 for the broad spray and −0.19 for the narrow spray. The corresponding slopes are 0.64 and −0.07, respectively. Although the wind conditions were not identical for all the data points, it can be seen that the fine particle control efficiency increases with increases in ambient RH for a broad spray, while it is fairly independent of RH for a narrow spray. The generally lower values of E for the narrow spray can be easily explained. A broad spray will cover most of the dust cloud in the hopper while the narrow spray will cover a smaller portion, resulting in slightly lower E values.

The difference in the dependence of E on RH for the broad spray and narrow spray can be explained as follows. For a narrow spray, most of the droplets occupy a volume away from the open side of the hopper, and when fog is continuously applied, this area becomes more humid than outside the hopper or near the hopper opening, if the wind is not too strong. Thus there is less droplet evaporation, and consequently, fairly steady particle collection efficiency. However, in the case of a broad spray, the droplets are distributed from the rear wall of the hopper to outside the open side of the hopper. Thus, as the ambient RH increases, a smaller number of droplets evaporate, leaving more droplets to collect dust particles; on the other hand, when the ambient RH decreases, more droplets are lost due to evaporation near the open side of the hopper and outside the hopper.

The effect of the longer droplet lifetime in a higher RH atmosphere increases the particle control efficiency. This result

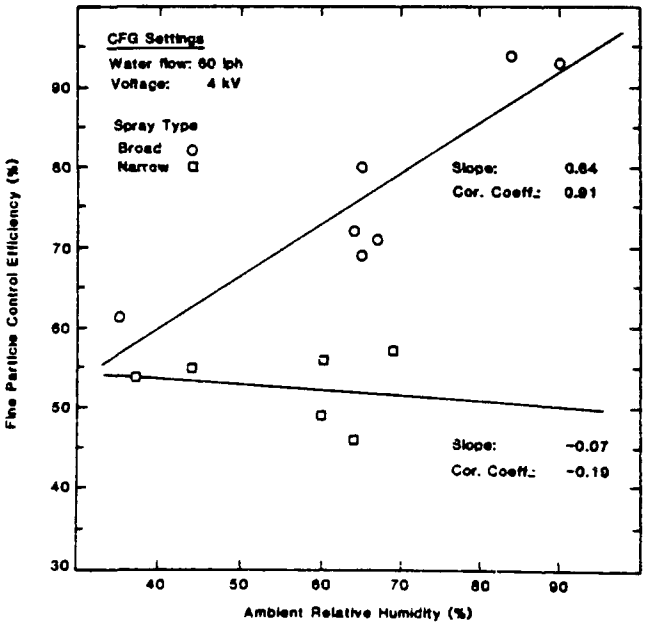

Figure 2. Fine particle control efficiency of the CFG plotted as a function of ambient relative humidity for broad (○) and narrow (□) spray patterns.

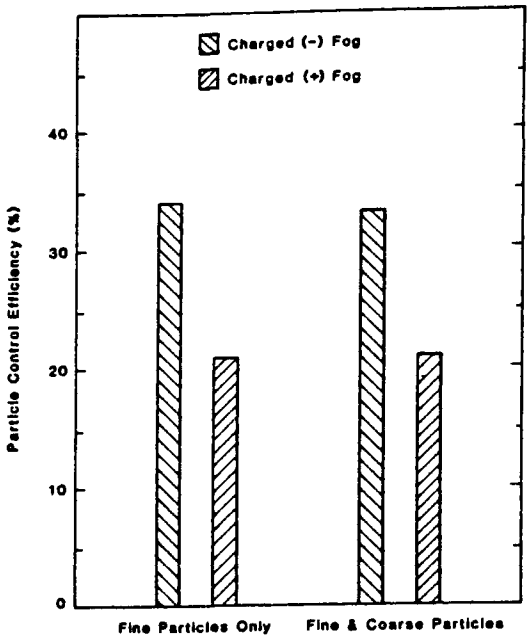

Figure 3. Comparison of particle control efficiency of the CFG for positively charged fog and negatively charged fog, with all other parameters nearly identical.

may appear to contradict the results shown in Figure 2 of the preceding paper.[1] In practice, the lifetime of the droplet, which is dictated by the ambient conditions of temperature and RH, overwhelms the effect of RH alone on particle control efficiency, providing the observed results. These test observations are thus consistent with the assertion that the droplets should be small enough to provide high particle collection efficiency, yet large enough not to evaporate too quickly.

Figure 3 shows particle control efficiencies for negatively charged fog and positively charged fog for the fine fraction, and for both fine and coarse particles, with the same water flow rate, the same applied voltage, and nearly identical field conditions. The higher value of E for negatively charged fog suggests that inhalable bentonite particles carry a net positive charge.

Figure 4 is a good example of the effect of water flow rate in the CFG on its ability to control particles. The percentage fine particle control efficiency in this case decreased by 36% when the water flow rate was reduced from 60 L/h to 30 L/h, with all other instrument settings and field conditions nearly identical. This effect is expected as increased water flow rate increases the number of charged droplets available for particle collection. Water flow rate was particularly significant in this experiment because the CFG was being applied to control dust in a volume larger than its maximum coverage; therefore, a decrease in the water flow rate decreased its particle control efficiency.

Figure 5 compares the effect of applied high voltage on the observed fine particle control efficiency, with all other variable parameters identical or nearly identical. It is evident that a higher applied voltage results in a higher value of E. An increase in the applied voltage generates droplets with more charges and consequently, the electrostatic forces of attraction between the droplet and particles increase, resulting in higher value of E.

Under a controlled experimental setup one would expect the particle control efficiency of charged droplets to decrease if the wind speed in the volume being treated were increased. The increased wind would reduce the time available for the droplet and particle to interact. However, in this experimental situation, because of the location and method of particle sampling, this effect is not evident, and therefore the effect of wind speed on inhalable particle control efficiency could not be quantified.

Conclusions

Extensive field tests of the prototype CFG at a bentonite ore unloading operation show that:

1) The mean inhalable particle control efficiency of charged fog measured under all instrument settings and field conditions shows a 78% increase when compared with the corresponding value for uncharged fog.
2) Individual tests with charged fog show a particle control efficiency (absolute value) as high as 87% over uncharged fog. Overall fine particle control efficiencies of over 90% were achieved under optimum instrument settings and favorable field conditions.
3) The enhancement in particle control efficiency is significant for the fine particles, and that for the coarse particles is moderate, in agreement with theory.
4) The relative humidity (in this particular experimental setup) seemed to play a significant role in determining the overall particle collection efficiency. The lifetime of the droplet is believed to be the dominant factor in determining what the particle control efficiency will be. Therefore, the droplets need to be large enough not to evaporate too quickly, yet small enough to yield a high particle control efficiency. Mean droplet diameters ranging from 100–200 μm appear to be reasonable for charged fog devices.
5) Negatively charged droplets gave higher values of particle control efficiency than did positively charged fog, suggesting that inhalable bentonite particles carry a net positive charge.
6) Measured inhalable particle control efficiencies were higher for higher applied voltages. An optimum voltage for good particle control seems to be 10–15 kV.
7) Measured inhalable particle control efficiency was higher when charged droplets could cover more of the dust-laden air in the hopper. It thus appears that if the source is large, multiple units of CFG will have to be used. In this experimental setup, higher water flow rate resulted generally in higher collection efficiencies, although the key element was how many particles were treated by the droplets. This quantity depended, to a certain extent, on the spray pattern for this experiment.

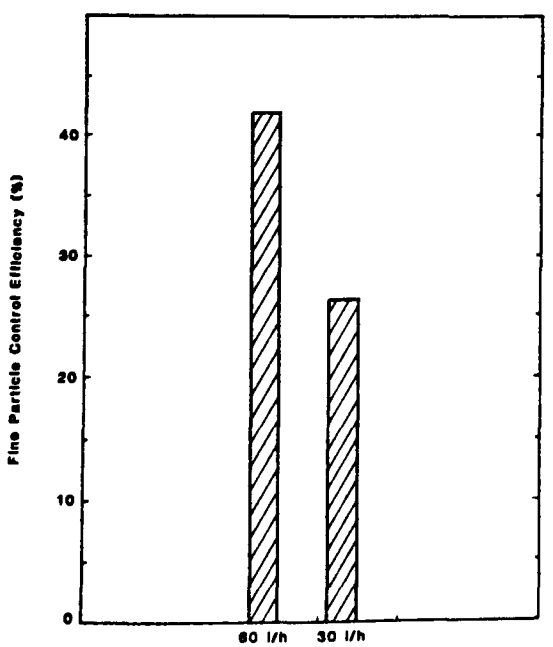

Figure 4. Comparison of fine particle control efficiency of the CFG for two water flow rates, with all other parameters nearly identical.

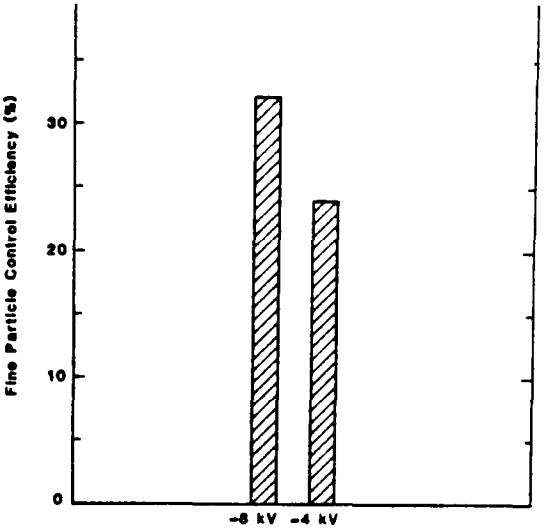

Figure 5. Comparison of fine particle control efficiency of the CFG for two applied high voltages, with all other parameters nearly identical.

8) Because of the type of particle sampling method used and the field setup, the effect of wind speed and direction on particle control efficiency could not be quantified with the available data.
9) The optimum CFG instrument settings are found to be 60 L/h water flow rate, a spray pattern which will cover a maximum volume of dust-laden air (broad or narrow spray depending on the extent of the source), an applied voltage of 10–15 kV, and positive or negative charge of opposite polarity to the charges on the dust particles. Ideal field conditions are high relative humidity (to ensure long droplet lifetime), and calm or low winds.

Although the charged fog method of dust suppression is only a temporary form of inhalable particle control, there is no other practical alternative method to control inhalable particles effectively under certain material handling situations and for other moveable emission sources like road sweepers, front-end loaders, and construction activities. Thus, in those cases where any other form of dust control is not economically feasible and at locations where personnel exposure is hazardous, charged fog technology appears to be the ideal dust control method. Additional research work is required to evaluate the inhalable particle control efficiency of the charged fog generator on emission sources of different chemical composition.

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16. ABSTRACT The report discusses the development of a new charged fog generator (CFG) by modifying a commercial rotary atomizer. In this device, the droplets generated are contact-charged to provide a high charge-to-mass ratio of 1.2 microcoulombs/g. The droplets have a number concentration median diameter of about 100 micrometers and a mass median diameter of about 200 micrometers. The water flow rate is variable (4-70 l/h) and the fog spray pattern can be changed easily from long and narrow to broad and short, with a typical spray coverage of 16-24 cu m. The device uses about 1 kW of power (110 VAC) and is portable. Extensive field tests of the CFG (at a bentonite ore unloading operation) were performed to determine the dependence of its inhalable particle control efficiency (PCE) on various instrument settings and field conditions. These tests show that the overall mean PCE is 78% higher than the corresponding value for uncharged fog. Individual PCEs as high as 88% were achieved. The lifetime of the droplets seems to be the dominant factor determining the PCE; and PCE values were higher for higher applied voltages and higher water flow rates. The data suggest that, under optimum instrument settings, the PCE of water droplets could be doubled by charging the droplets.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Pollution	Dust	Pollution Control	13B	11G
Fogging	Aerosols	Stationary Sources	14G	07D
Aerosol Generators	Drops (Liquids)	Fog Generators	13D	
Atomizers		Charged Fog	13K, 07A	
Charging		Inhalable Particles		
Particles		Particulate		

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