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EVALUATION OF ELECTROSTATIC AUGMENTATION FOR FINE PARTICLE CONTROL

Industrial Environmental Research Laboratory
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EVALUATION OF ELECTROSTATIC AUGMENTATION FOR FINE PARTICLE CONTROL

by

D. W. Cooper and M. T. Rei

GCA Corporation
Burlington Road
Bedford, Massachusetts 01730

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EPA Project Officer: D. C. Drehmel

Industrial Environmental Research Laboratory
Office of Energy, Minerals, and Industry
Research Triangle Park, NC 27711

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ABSTRACT

This is a review of electrostatic augmentation of fine particulate control devices: the addition of electrical forces to scrubbing and filtration and the enhancement of electrostatic precipitation. The major electrostatic force equations are presented and evaluated for some reasonable values of particle and collector charge and geometry. A bibliography on electrostatic augmentation is given. The following programs in electrostatic augmentation of filters, scrubbers, electrostatic precipitators are analyzed: an investigation of fiber beds to capture particles electrostatically, research in the area of dust/fabric electrostatic effects, work done to assess the utility of electric fields applied across filters or generated within filters, research being undertaken to further the development of a collector using oppositely charged particles and droplets, investigation and development of a charged droplet scrubber (which accelerates droplets electrostatically and uses them to transfer charge to particles for electrostatic precipitation), an analysis of various polarities and configurations for charged droplet scrubbing of charged particles, experiments and analysis directed at the use of nuclear radiation to charge particles for electrostatic precipitation, study of various possible configurations and uses for the "electric curtain," and the improvement of particle charging by theoretical and experimental research in connection with precharging chambers. Other research in electrostatic augmentation, especially on filters, is discussed briefly. Analysis of two other possible systems is presented: an electrostatically augmented cyclone, and a foam scrubber which uses particle precharging. A cost/benefit method for setting research priorities is developed which takes into account the expected applicability of the results, their

expected probability of and time to fruition, and the estimated costs of implementation. The following areas of research are emphasized for consideration: ionic mobility and mean thermal speed determination; triboelectrification of droplets, fibers, and bed packings; use of electrostatic scattering to diminish aerosol concentration fluctuations in generation; detailed experimental determination of the efficiency of collection by charged droplets; the relations between charge and wettability and particle rebound and adhesion; charge transfer from droplet to particle; precharging as a means for improving collection efficiency of conventional collection devices; trade-offs in charged droplet scrubbing; the cleaning of open-structure electrified filters; wetted versus dry surfaces in various forms of electrostatic interaction and precipitation; difficult control problems and their electrical characteristics; cost/benefit analyses of charged droplet scrubbing and of the addition of particle charging devices to enhance conventional collection through electrostatic scattering. The appendices discuss the intrinsic power requirements for dust removal, the conditions under which insulator particles act as though conductive, some notes on exponential penetration formulas, and a simple method for calculating electrostatic collection efficiency of several geometries and several types of electrostatic interaction.

CONTENTS

FIGURES

FIGURES (continued)

FIGURES (continued)

FIGURES (continued)

TABLES

TABLES (continued).

ACKNOWLEDGMENTS

The authors appreciate the help of Eugene F. Mallove, who wrote most of the material on the gamma-ray precipitator, and of Benjamin Kincannon, who contributed substantially to the section on setting priorities.

SECTION I

CONCLUSIONS

Electrostatic forces can be appreciably stronger than other forces operating on fine particles within control devices under some feasible conditions. Electrical forces most likely to be useful are: Coulombic attraction or repulsion between charged particle and charged collector, attraction between uncharged particle and charged collector, repulsion among highly charged particles. The relatively high collection efficiencies of high porosity plastic fiber beds may be due to contact charging and charge buildup due to the deposition of charged particles. Superimposing an electric field across a filter medium will increase collection of charged particles; the use of electrets presents problems in cleaning, and the electrets become neutralized by the adhesion of charged particles in their vicinity; conductive fibers coated with nonconducting material would allow the use of electrical attraction without producing a current drain in neutralizing the particles and without requiring the formation of filter cake for high efficiencies. (The Japanese researchers have demonstrated the increase in collection efficiency which can be obtained with several different types of such electrified filters.) In some cases, cleaning electrostatic filters may remain a major problem. Scrubbers using droplets and particles charged oppositely have been shown to produce higher collection efficiencies than the same configurations without charging. Electrically accelerating spray droplets does not seem preferable to accelerating them hydraulically or pneumatically, but there may be advantages in charging particles via charged droplets. Charged droplet scrubbers probably would have power and size requirements between those for conventional scrubbers and those for electrostatic precipitators.

The times associated with particle collection and with droplet dissipation in a charged droplet scrubber, along with the residence time, can be useful for the analysis of such systems, as shown by the work at MIT by Melcher and Sachar; the residence time and the droplet dissipation time must be much larger than the characteristic collection time for nearly complete collection to occur. The work done on charging particles with radioactive materials by a reactor has produced an interesting electrostatic precipitator of doubtful practicality. The "electric curtain" has a number of possible control configurations, but its performance has yet to be tested and some of the proposed uses are questionable. Augmenting cyclones electrostatically does not seem promising, but precharging particles before they enter foam or packed bed scrubbers does. A rational methodology has been formulated for setting priorities for such electrostatic augmentation research.

SECTION II

RECOMMENDATIONS

In general, applications of electrostatics can be expected to increase collection efficiencies of control devices by adding another collection force to those already present. Continued investigation of electrostatic augmentation of control devices and of improved electrostatic precipitator operating conditions and parameters should lead to improvements in such particulate control methods.

SECTION III

INTRODUCTION

This is a review and compilation of information available on devices which utilize electrostatic augmentation for the collection of fine particles. Electrostatic augmentation is defined here as methods for increasing the role of electrical forces. The primary questions this document seeks to answer are:

- What has been done?
- What is planned?
- What has been omitted?
- What should be done to bring about practical new control technologies employing electrostatic augmentation?

What has been done has generally been published as reports or journal articles, and what is planned has generally been outlined in program projections. Recommendations for future work involve gauging the gap between where we are and where we wish to be. We have attempted to gauge this gap after having defined the current state of technology and its needs.

SIGNIFICANCE OF FINE PARTICLES

Fine particulates are those smaller than about 3 μm in diameter. They are of concern because they persist in the atmosphere without settling out rapidly and they penetrate man's natural defenses and lodge themselves in the lung.[1] They are much more harmful than their mass concentrations would suggest: "Total weight is an inadequate measure of particulate pollution and its effects. Particles in the 0.1 - 1 μm range generally have a much greater impact on public health, visibility, and cloud nucleation when compared with the same weight of larger particulates."[2] Particles in the 0.1 to 1 μm range also are the most difficult to collect. Their impact and the difficulty of controlling them have made fine particles the focus of intense pollution technology interest in recent years.

ATTRACTIVENESS OF ELECTROSTATICS

It is more than just a play on words to say that electrostatics are an attractive means for trying to control fine particle emissions. As Figure 1 shows, electrical forces are much stronger than gravitational forces, thermal forces, and adhesion forces in the 0.1 to 1 μm range. The electrical forces for particles in this size range are often greater than those which are readily obtainable through inertial methods, as well, such as cyclones or scrubbers. (Inertial acceleration would be on the order of the square of the gas velocity divided by the collector dimension, only ten times greater than gravity for a 10 cm/s velocity and a 10^{-2} cm collecting body.) As will be seen, there are various types of electrical interaction which can produce attractive or repulsive forces on particulate material. Moreover, these different types of forces can be used in very different kinds of control devices.

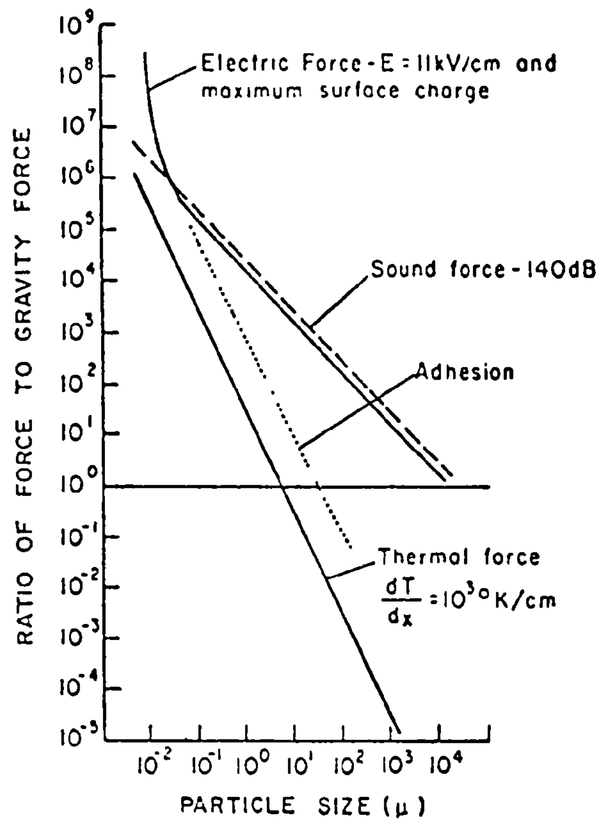

Figure 1. Some forces which can be exerted on aerosol particles[3]

The following projects have served as the principal objects of study for this review:

ELECTROSTATIC AUGMENTATION OF FABRIC OR BED FILTRATION

- Electrostatic fiber beds
- Electrostatic effects in fabric filtration
- Ambient fields across filter media

ELECTROSTATIC AUGMENTATION OF SCRUBBERS

- Electrically accelerated droplets
- Oppositely charged droplets and particles
- Systems of charged drops and particles

ELECTROSTATIC AUGMENTATION OF PRECIPITATION DEVICES

- Gamma-ray precipitator
- Electric curtain and AC fields
- Precharging chambers

Our report summarizes and analyzes these studies as well as others noted below. These summaries are intended to indicate where we are and to suggest where we should be headed with respect to the electrostatic augmentation of fine particle control devices. As indicated by the table of contents, the sequence in which we have presented this material is: first, a technical overview of the subject of electrostatic forces and aerosols; next, summary and evaluation of studies related to filtration, scrubbing, and electrostatic precipitator collection; a short discussion of the methods by which priorities for this kind of work might be set; finally, recommendations for further work.

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SECTION IV

TECHNICAL OVERVIEW

In this section we present a general model for particle collection devices, indicate some of the forces at work in collectors, emphasize and discuss electrostatic forces, and give a bibliography pertaining to the augmentation of particulate pollution control devices through the addition of electrostatic collection mechanisms.

BASIC CONCEPTS OF PARTICLE COLLECTION

Two basic types of collector flow geometry exist, and these are indicated in Figures 2a and 2b. Both rely on producing a component of aerosol particle motion perpendicular to the motion of the gas in which the particle is borne. In one type, the particles are collected on the walls of a channel. In the second, the particles are collected on an obstacle, such as a sphere or cylinder, around which the gas flows.

For laminar flow of an aerosol of initially uniform concentration having an average gas velocity $\bar{v}$ in a rectangular channel of length and width L and W, the efficiency of collection (the fraction of the entering particles which are captured) will be

$$\epsilon = w\, L/\bar{v}\, W \qquad (\epsilon \leq 1)$$

where w is the component of the particle velocity which is perpendicular to the gas velocity. In this case ϵ will have a maximum value of 1, complete particle collection. The penetration Pn is defined as 1 minus the efficiency. If several such channels were used in series and if they are so positioned, or if the particles so behave, as to produce a random

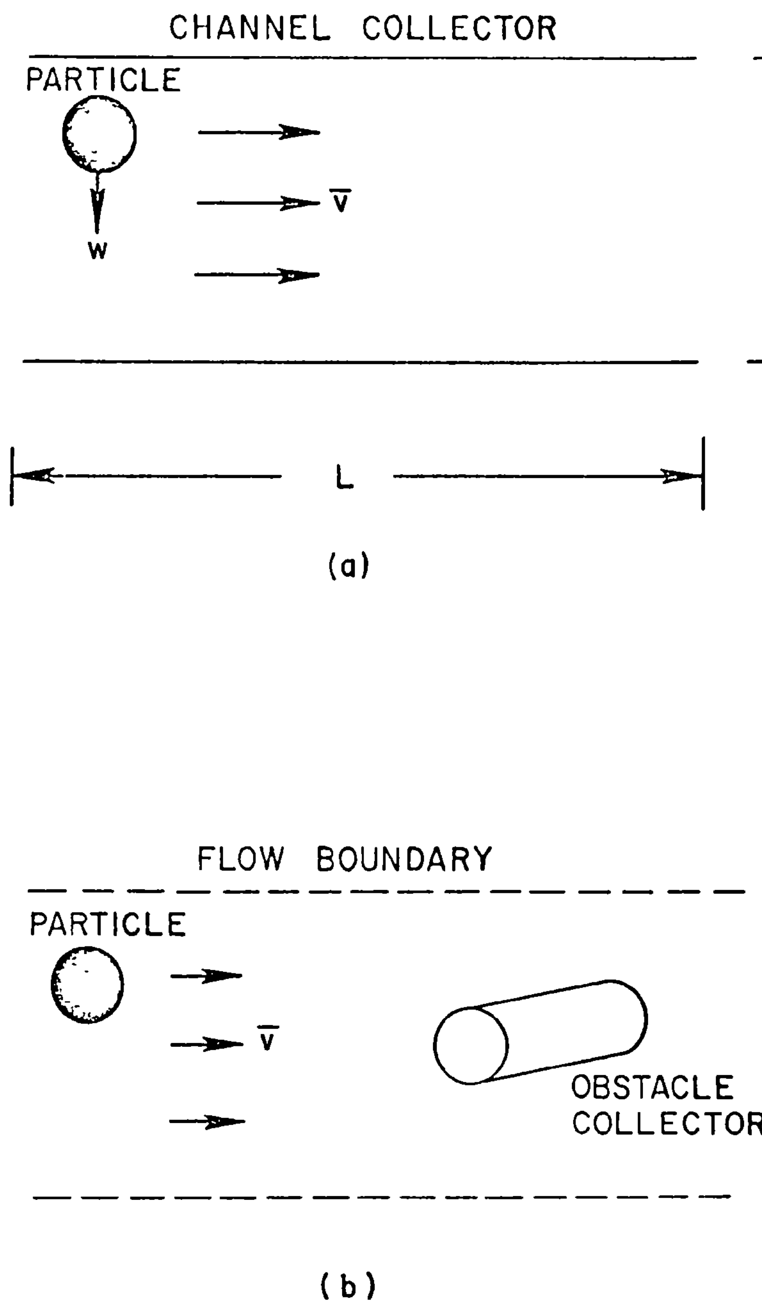

Figure 2. Particle collection in a channel and particle collection by an obstacle within a flow

distribution of particles after collection has occurred in each channel, then the penetration through N such channels would be

$$Pn = (1 - \epsilon_1)(1 - \epsilon_2) \cdots (1 - \epsilon_N)$$

where ϵ_1 is the collection efficiency of each channel. For identical channels this becomes

$$Pn = (1 - \epsilon)^N$$

and for an infinite number of channels, or for "completely turbulent" flow this is

$$Pn = \exp(-N\epsilon)$$

by the mathematical equality

$$\exp(-N\epsilon) = \lim_{N\to\infty} (1 - \epsilon)^N.$$

The exponential form is very significant. In the laminar flow case for a single element, $Pn = 1 - \epsilon$ can go to zero and does so as ϵ becomes 1. In the second case, many elements or turbulent flow, $Pn \ll 1$ only if $N\epsilon \gg 1$. For both situations, the following clearly aid collection: high particle collection velocity, low gas velocity (unless collection velocity is strongly increasing with gas velocity), long and narrow channels. This exponential relationship holds for the case where the collection occurs on an obstacle, too.

Usually, the collection efficiency of an obstacle in a stream is given by

$$\epsilon = \eta A_c/A_f$$

where η is the "single collector collection efficiency factor" (or a similar term), A_c is the collector cross-sectional area perpendicular to the flow of the gas and A_f is the cross-sectional area of the flow associated with the collector. (For one collector A_f would be the total area of the flow, for two collectors in a plane perpendicular to the flow each A_f would be half the flow cross section, etc.) For a series of such collectors, again the penetration would be

$$Pn = (1 - \epsilon_1)(1 - \epsilon_2) \ldots (1 - \epsilon_N)$$

if they acted independently. As the number of such collectors in series increases, this becomes the familiar exponential form for collection efficiency:

$$Pn = \exp\ (-N\ \eta\ A_c/A_f)$$

where N is the number of such collectors past which the gas flows, on the average. Collection of a uniform aerosol in laminar flow on an obstacle can be formulated similarly to collection in a channel by using

$$\epsilon = w\ L^*/\bar{v}\ W^*$$

where L* is the "effective length" of the obstacle in the direction parallel to the mean gas velocity v and W* similarly is the effective distance between collectors in planes perpendicular to the mean gas velocity. The analogy is imperfect (L* may well often be a function of v), but it is true that increasing w and decreasing W* are expected to improve collection. An equivalent common form is

$$\epsilon = w\ A/Q$$

where A is the collector area normal to the migration velocity w and Q is the volume rate of flow past the collector. Again, it may be that $w = w(Q)$.

An approximate but very general formula for the collection efficiencies of a great variety of control devices can be obtained as follows. Consider a volume V in which particles are approaching the collection surface A at a perpendicular velocity component w (deposition velocity) during the infinitesimal period dt. If the concentration is n, and uniform, then the number of particles hitting (assumed captured) the surface will be nAw dt and the change in concentration in this volume will be just this number of particles divided by the volume. This yields the following expression for the instantaneous change in concentration:

$$-\ dn = n\ w\ A\ dt/V\quad .$$

In turbulent flow the aerosol can be considered nearly uniform in many cases, although its concentration changes with time, so this equation can be integrated to give

$$n/n_o = \exp\ (-w\ At/V).$$

Here, n_o is the initial concentration. This expression can be recast into other forms by making some of the following substitutions:

$$t = V/Q$$

where Q is the volume flow rate of aerosol,

$$Q = A_o u_o$$

where A_o is the device inlet cross-sectional area and u_o is the inlet face velocity. The resulting forms are

$$n/n_o = \exp\ (-w\ A/Q)$$

$$n/n_o = \exp\ (-w\ A/u_o A_o)$$

This analysis can be linked to the usual analysis for scrubbers and filters by using for A the total cross-sectional area of the obstacles and for w the product of the single particle efficiency and the difference between the particle velocity (u_p) and velocity, if any, of the collecting object (u_c), so that

$$w\ A = \eta\ (u_p - u_c)A_c.$$

Collection systems will be highly efficient only if the argument of the exponential function above is much larger than 1 in magnitude.

Expressions of the type exp (-w A/Q) are widely used in electrostatic precipitation analyses (e.g., White[1]) and allow convenient and fairly accurate comparisons among control devices.

A more mathematical discussion of this is presented in Appendix C.

COLLECTION MECHANISMS

This work focuses on the role of electrical forces, of which there are a great number. In general, these forces will be effective when they produce a terminal velocity component perpendicular to the gas velocity which is large enough to make $w A/Q \gtrsim 1$. In general, these forces will be significant when they are larger than or of the same magnitude as other collection "forces." Electrical forces will be significant when the terminal particle velocities they produce (w) are larger than or comparable to the particle flux velocities (number of particles collected per unit area and unit time divided by concentration) produced by other collection mechanisms. The following mechanisms of particle collection may also be taking place while electrostatic mechanisms are at work:

- Impaction
- Interception
- Diffusion
- Sedimentation
- Diffusiophoresis
- Photophoresis
- Thermophoresis
- Acoustical migration

More information on them is available in the literature (e.g., Fuchs[2]). For control devices in which one or more of these is important, the electrostatic contribution should be compared with them.

ELECTRICAL FORCES

The total electrical force on a particle will be the vector sum of the various electrical forces which are acting. Strauss[3] listed the following:

- Coulombic force between charged particle and charged collector
- Image force between charged particle and uncharged collector
- Image force between uncharged particle and charged collector
- Coulombic repulsion of particles charged to the same polarity (space charge)

and to this list can be added:

- Charged or uncharged particle with charged or uncharged collector in a superimposed electric field (analyzed in depth by Zebel)
- Charged particle moving in a magnetic field (Lorentz force).

We reiterate that these forces are summed; thus the first three forces will be acting when a single charged particle is in the presence of a charged collector. Often, however, one force (such as the Coulombic) will be orders of magnitude larger than the others.

The two major types of electrostatic force significant in particle collection are the Coulomb force a charged particle is subjected to in an electric field and the induced charge (dipole) force, which operates in an inhomogeneous electric field. The Coulomb force is given by the equation

$$F = qE$$

where

q = particle charge, coul

E = electric field, $v - m^{-1}$, $N - coul^{-1}$.

The force due to induced polarization is[2]

$$F = x_E \, V_p \, \mathrm{grad} \, (E^2)$$

where

$x_E = (3\,\pi/8)(\epsilon_p - 1)/(\epsilon_p + 2)$ for a sphere

ϵ_p = dielectric constant of particle

V_p = particle volume.

Because the gradient of a homogeneous field is zero, this second force is only operative in inhomogeneous fields, such as those close to a charged collector. Image forces are a class of induced polarization force.

Electrostatic augmentation of collection efficiency of particulate control devices can be expected to rely primarily on either or both of these electrostatic forces, but we shall discuss a number of others as well.

As noted, the collection efficiency (or the penetration) can be calculated knowing the migration velocity for the particles and knowing the collection area and the volume flow rate. We shall calculate the migration velocities, w, for the particles under a variety of situations, but making the following assumptions:

- the particle has been charged to saturation in a corona discharge with a field of 10 kV/cm = 33.3 esu,
- the field is evaluated for its magnitude right at the collector surface,
- the particle is assumed to have reached its terminal velocity under the calculated force,
- the particle is in air at 20°C and 1 atm pressure,
- the fluid resistance is given by Stokes law with the Cunningham correction.[2]

From these calculations one should be able to make estimates of collection efficiency for various specific situations.

Charge Acquired By Particles

The charge, q_p, acquired by a particle of diameter d_p >0.5 μm in an electric field, E, in the presence of an ionic concentration, N_i, is:[1]

$$q_p = n_p e = \left[1 + 2\frac{\varepsilon_p - 1}{\varepsilon_p + 2}\right]\left[\frac{E d_p^2}{4}\right]\left[\frac{t/t_e}{1 + t/t_e}\right]$$

where n_p = number of charges

e = electronic charge

ε_p = particle dielectric constant

t_e = charging time constant.

The value for t_e depends upon the ion mobility and concentration as follows:[1]

$$t_e = 1/\pi e\ N\ Z_i$$

where e = electronic charge, 4.8×10^{-10} stat-coul

N_i = ion concentration, cm^{-3}

Z_i = ionic mobility

= 2.2 (cm/s)/(v/cm) = 660 esu

t_e = $1.0 \times 10^6/N$, seconds.

White[1] notes that Cochet extended the applicability of these two equations down to $d_p \geq 0.04$ μm by replacing the first bracket in the first equation with

$$\left[\left(1 + 2\lambda'/d_p\right)^2 + 2\left(1 + 2\lambda'/d_p\right)^{-1} \frac{\varepsilon_p - 1}{\varepsilon_p + 2}\right]$$

where $\lambda' = 0.1 \times 10^{-4}$ cm.

At $d_p = 0.25 \times 10^{-4}$ cm, $\varepsilon_p = 4$, the replacement changes the value in brackets from 2.0 to 4.5, a difference which may be significant for some applications. Cochet's equation seems to eliminate the need for a separate expression for the diffusive contribution to submicron particle charging.

Many particles behave as though they were conductors ($\varepsilon_p \to \infty$) during the time scales of interest (see Appendix A), so that for many calculations $(\varepsilon_p - 1)/(\varepsilon_p + 2) = 1$ is appropriate. Furthermore, control device designs usually assure sufficiently long residence times for $(t/t_e)/(1 + t/t_e) \doteq 1.0$. Under such conditions:

$$q_p = n_p e \doteq \left[(1 + 2\lambda'/d_p)^2 + 2(1 + 2\lambda'/d_p)^{-1}\right]\left[E\, d_p^{\,2}/4\right]$$

or, even ($d_p \gtrsim 1$ µm)

$$q_p = 3\, E\, d_p^{\,2}/4.$$

The above equations enable determination of the particle charge with several different degrees of sophistication. Table 1 has been calculated using the next-to-last equation above, based upon Cochet's.

Table 1. APPROXIMATE MAXIMUM CHARGE (COCHET EQUATION) (ε_p>>1, E = 10 kV/cm = 33.3 esu)

Particle diameter, d_p (μm)	Particle charge, q_p (esu)	Electrons, n_p
0.1	8.05×10^{-9}	16.8
0.3	2.80×10^{-8}	58.3
1.0	2.59×10^{-7}	539.6
3.0	2.26×10^{-6}	4.7×10^{3}
10.0	2.50×10^{-5}	5.2×10^{4}

Coulomb Force - Charged Particle In a Field

The force, F_c, on a charged particle in an electric field, E, is

$$F_c = q_p E.$$

The charge on a spherical, conducting sphere is approximately ($d_p \gtrsim 1$ μm)

$$q_p = 3 E d_p^2/4.$$

Assuming the charging field and the precipitating field are both near the field at which air breaks down E ~ 10,000 V/cm ~33 stat-volt/cm, then

$$F_c \doteq 3 E^2 d_p^2/4$$

can be evaluated, as it has in Table 2, to give approximate forces and migration velocities for conducting spheres. This table has these quantities calculated à la Cochet, too. Note the difference for $d_p \lesssim 1$ μm, for which the Cochet equation results should be used.

Table 2. FORCES, VELOCITIES FOR CONDUCTING SPHERE CHARGED AND PRECIPITATED AT E = 10 kV/cm

Particle diameter	Field Charging		Field Charging (Cochet)	
	Force (dynes)	Velocity (cm/s)	Force (dynes)	Velocity (cm/s)
0.1	8.17×10^{-8}	13.7	2.68×10^{-7}	45.0
0.3	7.35×10^{-7}	22.4	9.32×10^{-7}	28.4
1.0	8.17×10^{-6}	55.7	8.62×10^{-6}	58.8
3.0	7.35×10^{-5}	151.0	7.52×10^{-5}	155.0
10.0	8.17×10^{-4}	487.0	8.33×10^{-4}	496.0

The velocities are calculated here by

$$w = FB$$

where B = mobility, (cm/s)/dyne, s/g

$B = C/3\pi\mu d_p$

C = Cunningham slip correction

$C = 1 + 2 \frac{\lambda}{d_p} (1.257 + 0.400\, e^{-1.10\, d_p/2\lambda})$

$\lambda = 0.0653 \times 10^{-4}$ cm, mean free path of gas.

The equation comes from Davies (1945)[4] and values have been taken from a table by Gussman (1971).[5]

Charged Particle With Uncharged Collector

The charge on the particle, q_p, produces an altered charge distribution in the collector and a net attraction between the two, F_m, having a magnitude given by Kraemer and Johnstone (1955):[6]

$$F_m \doteq 4\, q_p^2/d_c^2$$

for a conducting spherical collector and (see Lundgren and Whitby[7]) by:

$$F_m = q_p^2/d_c^2$$

for a conducting cylinder. (F_m must be multiplied by $(\varepsilon_c - 1)/(\varepsilon_c + 1)$ for a dielectric cylinder.)

Assuming a particle charging field E = 10 kV/cm = 33 stat-volt/cm, and sufficient charging time, we obtain the force and terminal velocity values shown in Table 3 for conducting spherical collectors (e.g., water drops). (The Cochet charging equation has been used.)

This force is ~(q_p/q_c) times the value of the Coulomb force for a charged collector (q_c) and a charged particle, which means it is usually much less than the Coulomb force (usually $q_c >> q_p$).

Uncharged Particle, Charged Collector

The image force concept is really just a method for calculating the force on a body due to an inhomogeneous electrical field, given by

$$F = x_E\, V_p \operatorname{grad} (E^2)$$

as noted.

For a conducting sphere

$$F_I = \left(\frac{3\pi}{8}\right)\left(\frac{\epsilon_p - 1}{\varepsilon_p + 2}\right) \quad \frac{\pi}{6}\left(d_p^{\,3}\right)\vec{\nabla}\left((E^2)\right)$$

Table 3. FORCES AND TERMINAL VELOCITIES FOR PARTICLES CHARGED AT E = 33 esu, COLLECTED IN THE PRESENCE OF UNCHARGED CONDUCTING SPHERES[a]

Particle diameter d_p, μm	Forces (dynes) due to collector of diameter, d_c, μm				
	d_c = 0.1 μm	d_c = 1.0 μm	d_c = 10. μm	d_c = 100. μm	d_c = 300. μm
0.1	2.59×10^{-6}	2.59×10^{-8}	2.59×10^{-10}	2.59×10^{-12}	2.88×10^{-13}
0.3	2.8×10^{-5}	2.8×10^{-7}	2.8×10^{-9}	2.8×10^{-11}	3.11×10^{-12}
1.0	2.68×10^{-3}	2.68×10^{-5}	2.68×10^{-7}	2.68×10^{-9}	2.98×10^{-10}
3.0	0.204	2.04×10^{-3}	2.04×10^{-5}	2.04×10^{-7}	2.27×10^{-8}
10.0	25.0	0.250	2.50×10^{-3}	2.50×10^{-5}	2.78×10^{-6}
	Velocities (cm/s)				
0.1	435.	4.35	0.0435	4.35×10^{-4}	4.83×10^{-5}
0.3	855.	8.55	0.0855	8.55×10^{-4}	9.49×10^{-5}
1.0	1.83×10^{4}	183	1.83	0.0183	2.03×10^{-3}
3.0	$\sim 3 \times 10^{4}$ [b]	4.20×10^{3}	42.0	0.420	0.0467
10.0	$\sim 3 \times 10^{4}$ [b]	$\sim 3 \times 10^{4}$ [b]	1.49×10^{3}	14.9	1.66

[a] See text for assumptions.

[b] Derivations not applicable to sonic velocities.

becomes

$$F_I = \frac{\pi^2}{16} \, d_p^{\,3} \, \vec{\nabla} \, (E^2)$$

Generally, we are dealing with spherical or cylindrical collectors for which $\overline{\nabla}\,(E^2)$ has only a radial component, 2 EdE/dr. If E is ~33 statvolts/cm, an approximate upper limit, and if (as is also generally true) dE/dr ~ $2E/d_c$, where d_c is the collector diameter, then

$$F_I \doteq \frac{\pi^2}{16} \, d_p^{\,3} \; 2E(2E/d_c)$$

$$F_I \doteq (\pi/2)^2 \, E^2 \, d_p^{\,3}/d_c = 4\pi^2 \, q_c^{\,2} \, d_p^{\,3}/d_c^{\,5}$$

Table 4 gives the values of F_I for several particle sizes and for d_c = 100, 10, 1 μm, assuming E = 33 sv/cm. Given in Table 5 are the associated particle terminal velocities (migration velocities).

Table 4. FORCES (DYNES) FOR CHARGED COLLECTOR WITH UNCHARGED PARTICLE[a]

Particle size	Collector diameter		
	1 μm	10 μm	100 μm
0.1 μm	2.69×10^{-8}	2.69×10^{-9}	2.69×10^{-10}
0.3	7.25×10^{-7}	7.25×10^{-8}	7.25×10^{-9}
1.0	2.69×10^{-5}	2.69×10^{-6}	2.69×10^{-7}
3.0	7.25×10^{-4}	7.25×10^{-5}	7.25×10^{-6}
10.0	2.69×10^{-2}	2.69×10^{-3}	2.69×10^{-4}

[a]See text for assumptions.

Table 5. TERMINAL VELOCITIES (cm/s) FOR COMBINATIONS GIVEN IN TABLE 4

Particle size	Collector diameter		
	1 μm	10 μm	100 μm
0.1 μm	4.5	0.45	0.045
0.3	22.1	2.21	0.221
1.0	183.	18.3	1.83
3.0	1494	149.4	14.94
10.0	1.60×10^4	1.60×10^3	160.

This force can be conveniently compared with the Coulomb force, $F_c = q_pE$, by using the approximate equation for q_p for a conducting sphere.

$$q_p \doteq 3\ Ed_p^{\ 2}/4 \quad \text{for } d_p > 1\ \mu$$

so

$$F_c \doteq 3\ E^2d_p^{\ 2}/4$$

and

$$\frac{F_I}{F_c} \doteq \frac{4(\pi/2)^2}{3} \frac{d_p}{d_c} = \frac{\pi^2}{3} \frac{d_p}{d_c}$$

Thus, the image force becomes increasingly weak compared with the Coulomb force, as the particles become smaller with respect to the collectors.

The exact equations are available in the work by Kraemer and Johnstone (1955),[6] from which most treatments of this derive, but they require similar approximations to characterize a given situation, as the force is a function of distance and some "typical" distance must be chosen.

These analyses indicate image forces are weak compared to Coulomb forces in most practical situations.

Collection on a Cylinder in the Presence of an External Field

Two dimensionless parameters dominate the analysis of collection in an external field (Zebel, 1965;[8] Hochrainer et al., 1969[9]):

$$G = E_\infty q_p B / V_\infty,$$

the ratio of the velocity of the particles of charge q_p in the external field E to the free stream gas velocity V_∞, and

$$H = 2(Q_c/L)q_p B / V_\infty R_c,$$

a similar ratio based on the Coulomb force at the surface ($r = R_c$) of a cylindrical collector having charge Q_c and length L. The ratio H/2G indicates the relative strength of the Coulomb attraction to the force due to the external field. $H < 0$ indicates Coulomb attraction; $H > 0$ indicates repulsion. $G > 0$ indicates the field force and the flow are aligned for positively charged particles.

For uncharged particles, the dimensionless parameter

$$F = 2\left(\frac{\varepsilon_p - 1}{\varepsilon_p + 2}\right)\left(\frac{\varepsilon_c - 1}{\varepsilon_c + 1}\right)\frac{r_p^3}{R_c}\ \frac{E_\infty^2 B}{V_\infty}$$

takes the place of H and scales the particle-collector force due to induced charges.

A qualitative description of various field and attraction/repulsion combinations is presented in Table 6. The most efficient system is one with the particles and collectors oppositely charged and the electric field such that particles are impelled in the direction of flow. This is $G > 0$, $H < 0$, $|H| > |F|$, and for it, Zebel (1969)[10] calculated a single fiber efficiency:

$$\eta = -\pi H/(1 + G).$$

This assumes negligible diffusive flux. The same formula applies for $G < 0$, if $H < 0$ too. A problem with this efficiency formula is that it predicts better efficiency as $G \to 0$ in the case $G > 0$ which is described as the case where "field direction facilitates separation." If the field helps collection, it should help it more when strong than when weak.

Table 6. DESCRIPTION OF COLLECTION REGIMES FOR A SINGLE COLLECTOR, A CHARGED PARTICLE, AND AN EXTERNAL FIELD, BASED ON WORK OF HOCHRAINER ET AL.[9] AND ZEBEL[10]

	External field force parallel to flow	External field force antiparallel to flow
Particle-collector attraction ($H < 0$)	Highest efficiency, collection on whole collector (a)	Collection on rear of collector (d)
Neutral conditions ($H = 0$)	Collection on front of collector (b)	No collection (e)
Particle-collector repulsion ($H > 0$)	Little or no collection (c)	No collection (f)

Figure 3 is taken from Davies (1973),[11] based upon Zebel (1965).[8]

When $H = 0$, and both the particle and the collector are uncharged, the inductive force group F comes into play. Zebel (1965)[8] shows the efficiency η to be

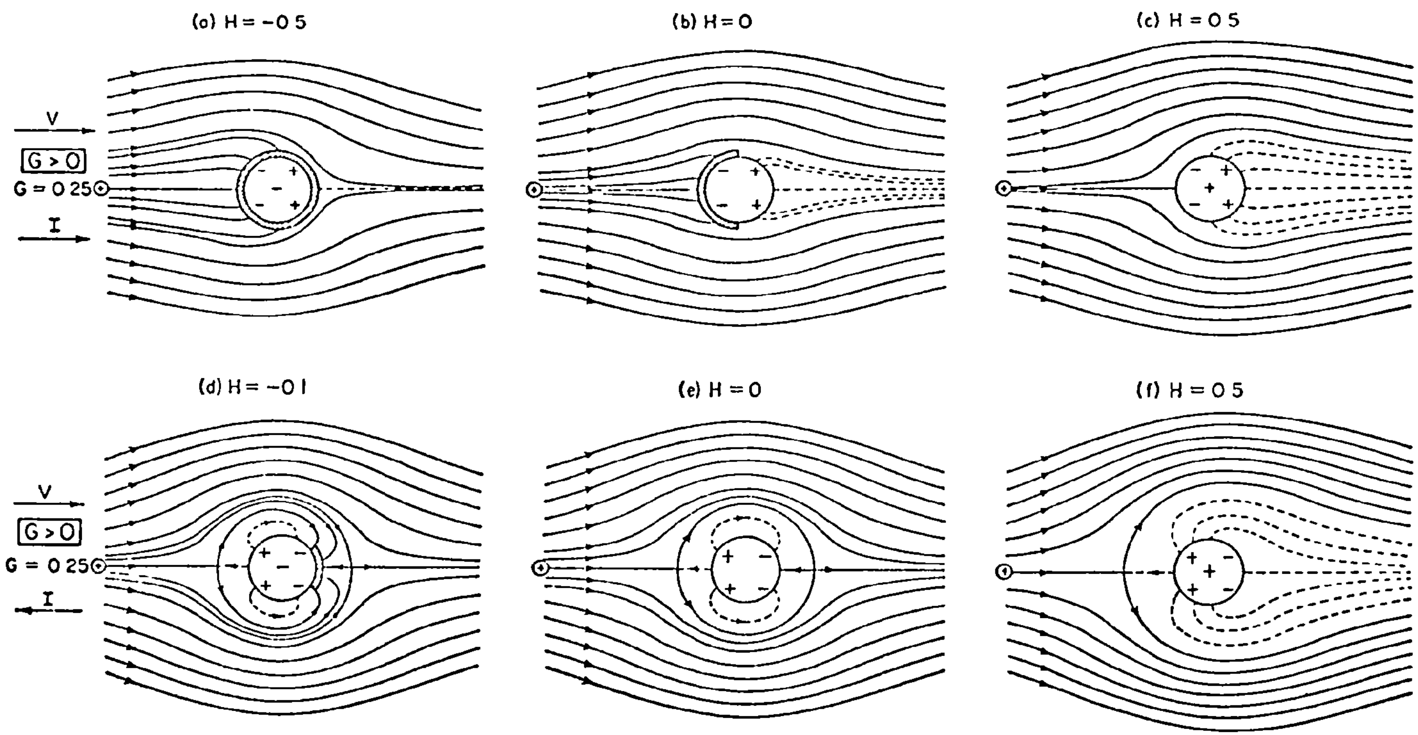

Figure 3. Trajectories of charged particles carried by viscous flow past an isolated, charged, dielectric cylinder in a polarizing field parallel to the flow direction (Zebel)[12]

$$\eta = F/2 \quad \text{for} \quad F \leq \sqrt{2}$$

for potential (ideal) flow, and

$$\eta \doteq F/2 \quad \text{for} \quad \tilde{F} << 1$$

for viscous flow, where

$$\tilde{F} = F(2.002 - \ln Re_f),$$

a group modified for low Reynolds number (Re_f) flow à la Lamb.

For an uncharged collector and a charged particle, Zebel (1965)[8] derived, for potential flow,

$$\eta = 1 + n' \qquad -1 \leq n' \leq 1$$

$$\eta = 2\sqrt{n'} \qquad n' \geq 1$$

where

$$n' = \frac{\left(\frac{\varepsilon_c - 1}{\varepsilon_c + 1}\right) + 1}{G + 1} G$$

The corresponding formula for viscous flow is $\eta = n$ $(G > 0)$.

The values for the single collector efficiency, η, can be connected with the effective migration velocities, w, by noting that the penetration expressions for the two approaches are

$$Pn = e^{-wA/Q} = e^{-\eta A_c/A_o}$$

where A = total collection area

A_c = total collector cross-sectional area perpendicular to flow

A_o = collection volume face area perpendicular to flow

Q = $V_o A_\infty$ = volume flow rate

V_∞ = free stream velocity upstream from collection volume.

Thus

$$\frac{w}{V_\infty} = \eta A_c / A$$

From these expressions for single element collection efficiency for cylindrical collectors, we can draw the following conclusions:

1. If neither the particles nor the collectors are charged, then the imposition of an external electric field will enhance collection.

2. If both the particles and the collectors are charged, then the imposition of an electric field will reduce collection if the external field produces a force which retards particle motion in the direction of the free stream velocity, and this field will enhance collection if it accelerates the particles in the direction of the free stream velocity.

3. If the particles are charged, but the collector uncharged, the collection efficiency increases with the applied field.

Lorentz Force

A charged body in motion transversely with respect to a magnetic field experiences a force, F_L, given by the vector cross product:

$$\vec{F}_L = q_p \vec{v} \times \vec{H}/c$$

where $\vec{v}$ = particle velocity, cm/s

$\vec{H}$ = magnetic field, oersted

c = speed of light, 3×10^{10} cm/s.

(This "Lorentz Force" is not, strictly, an electrostatic one.) Zebel (1968)[12] compared this force with the Coulomb force by noting that although magnetic fields of $H \sim 6 \times 10^3$ oersted are possible compared with electric fields $E \sim 60$ stat-volt/cm, the ratio of the Coulomb force, F_c, to the Lorentz force,

$$F_c/F_L = q_p E/q_p (v/c) H$$

is dominated by the ratio (v/c) so that

$$F_L = (H/E)\ (v/c)\ F_c$$

$$F_L \lesssim (6000/60)\ (3 \times 10^4 / 3 \times 10^{10})\ F_c$$

$$F_L \lesssim 10^{-4}\ F_c$$

Conclusion

$F_L << F_c$ even when the particles are moving at the velocity of sound. Thus the Lorentz force is an unlikely candidate for the enhancement of particulate collection efficiency because it is so much under then F_c.

Space Charge Precipitation (Electrostatic Scattering)

An aerosol containing charged particles will expand due to mutual particle repulsion if the particles are charged to the same polarity. If the particles have different polarities, expansion will be retarded but agglomeration will be enhanced. A simple analysis of this phenomenon is presented in the book by Fuchs (1964).[2] Either case results in a decrease of the number concentration, c, of the particulate matter.

Faith et al. (1967)[13] published results of their theoretical and experimental investigations into the use of the charge on an aerosol exposed to a corona as the driving force for deposition of the aerosol. Their calculations indicated that the expression given by Fuchs (1964)[2] and others for the decay with time of particle concentration in a stationary medium is almost exactly correct (to within 10 percent) for turbulent flow and plug flow. Wilson (1947)[14] had demonstrated that this expression is also correct for perfect stirring. The fraction of particle concentration at time t in comparison with that at t = 0 is:

$$Pn = c/c_o = 1/(1 + 4\pi B q_p^2 c_o t) = 1/(1 + \alpha)$$

where B = particle mobility (mechanical), cm/s-dyne

q_p = particle charge, stat-coul

c = particle concentration, cm^{-3}

t = residence time, s.

Two limiting cases are easily identified:

for $\alpha \ll 1$,

$$Pn \doteq (1 - 4\pi B q_p^2 c_o t)$$

for $\alpha \gg 1$,

$$Pn = 1/4\pi B q_p^2 c_o t.$$

The latter case is the one desired for efficient particle removal. From this last equation, it is clear that high charge and high concentrations favor electrostatic scattering. If the penetration is multiplied by the initial concentration, c_o, to obtain the final concentration, c, the c_o factor cancels out in this last expression, indicating that the outlet concentrations will be independent of the inlet concentrations, as long as the electrostatic scattering parameter, α, is much greater than one. Thus it could be designed to meet certain outlet concentration restrictions.

The residence time is just the length of the collector divided by the flow velocity, or the volume of the collector divided by the volume flow rate. Adapting an example given by Faith et al. (1967),[13] a smoke having a concentration of 2.3 g/m^3 (1 gr/ft^3) of 1 μm spherical particles of unit density charged in a corona at 5 kv/cm to an average of 261 electronic charges per particle would give a value of $\alpha = 4.6$, thus a penetration of $1/(1 + 4.6) = 0.18$, a collection efficiency of 82 percent. Figure 4 gives the fractional penetration, c/c_o, for values of α between 1 and 50. Values of α other than that calculated in this example can be approximated by noting that the charge will increase with approximately the square of the particle diameter, but the number concentration, c_o, will decrease with the cube of the particle radius, and the mobility is roughly proportional to the inverse of the particle diameter. From which, we can conclude that for particles having the same density and being $\geq$ 1 μm in diameter, it is nearly true that the penetration will be proportional to the mass concentration but independent of the mean particle size. (The Cochet correction for particle charging predicts somewhat of an increase in collection for particles with mean sizes much less than 1 μm.)

This analysis produces the rather surprising conclusion that 0.47 m^3/s (1000 cfm) of a fully charged aerosol having a concentration about

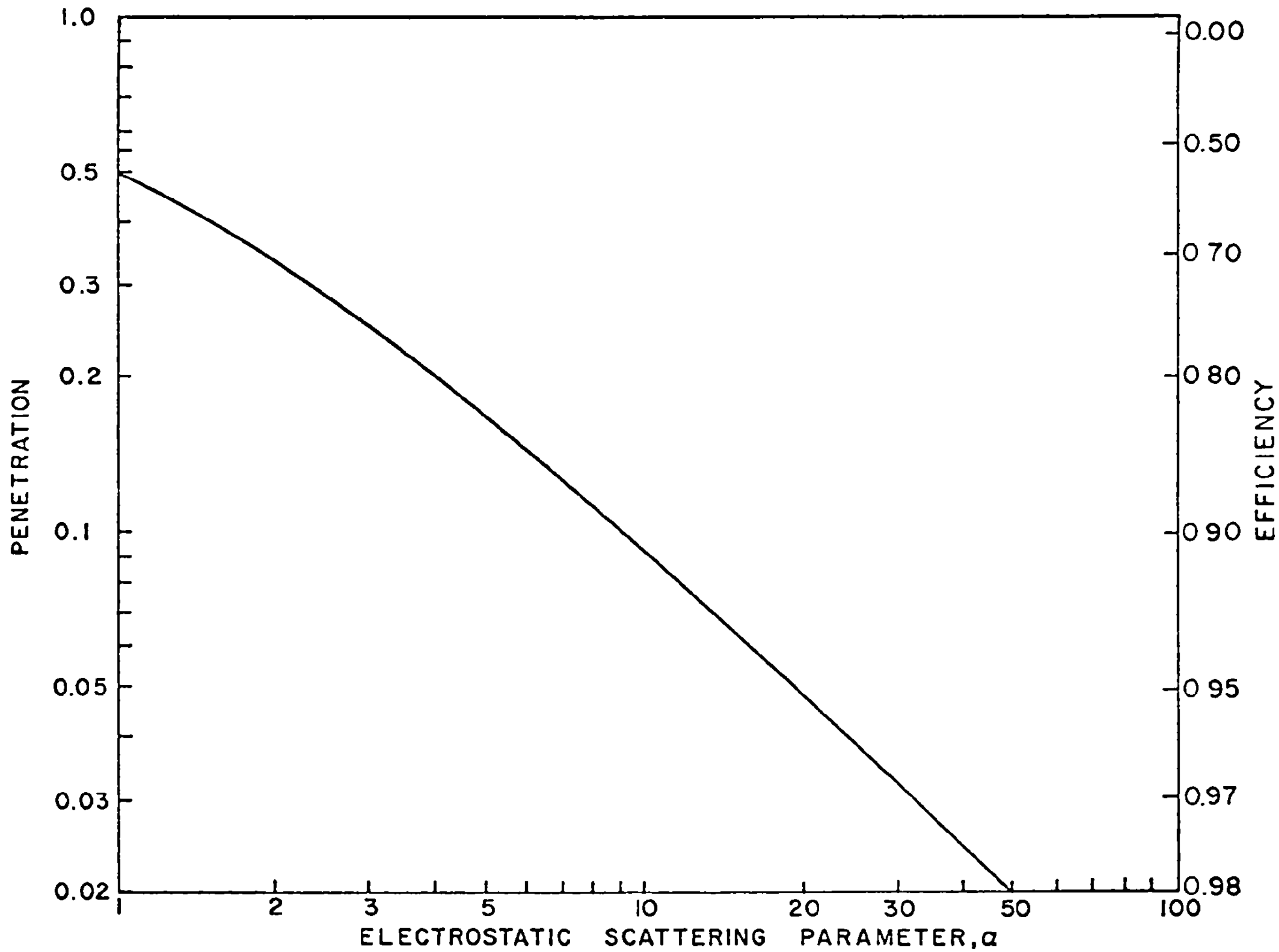

Figure 4. Penetration versus electrostatic scattering parameter

2.3 g/m^3 could be reduced in concentration by the factor 0.2 by passing through a duct 0.7 m (2.3 ft) square by 1 m (3.1 ft) long, as long as the material was not reentrained.

The tests made by Faith et al. were at only 3×10^3 cm^3/s (6.4 cfm), very low in comparison with commercial flow rates. The problems with such a device would be little different from those encountered with the conventional electrostatic precipitators, however. Three such problems are the achievement of complete particle charging, the prevention of particle reentrainment, and the periodic cleaning of the surfaces.

The main advantage such a space charge precollector would have would be ease of retro-fit; a secondary advantage would be that it could be arranged so that the major part of the collection (the major part of the residence time) occurs at the collector to which it is attached. Such a configuration might be attractive as a precollector used ahead of another control device or even as a complete control device itself.

Charged Particle in Space Charge Field

An aerosol which has all its particles of the same charge, q_p, can be collected on a conducting sphere due to the mutual repulsion of the particles, the force being (Kraemer and Johnstone, 1955):[6]

$$F_s = q_p^2 n_p (\pi/6) d_c^3/r^2$$

which is the same as the attractive force of that same aerosol concentration n_p having opposite polarity, $-q_p$, and filling the spherical collector volume $(\pi/6) d_c^3$.

Again approximating r by $d_c/2$ gives

$$F_s \doteq 4 q_p^2 n_p (\pi/6) d_c$$

An aerosol having a mass mean diameter of 3 μm, a particle density of 1 g/cm^3, and a mass concentration of 1 g/m^3 (0.44 gr/ft^3) has $n_p = 7.1 \times 10^4\ cm^{-3}$. Such an aerosol would have $F_s = 7.6 \times 10^{-9}$ dyn for d_c = 100 μm and a terminal velocity of 15.6×10^{-3} cm/s. This force is $\sim(q_p/q_c)(n_p\ d_c^{\ 3})$ times the Coulomb force. In some cases, it could contribute appreciably to collection.

Figure 5 is a graphical presentation of theoretically calculated migration velocities corresponding to the force which would be generated on each specific size particle, generated by various electrostatic mechanisms. These migration velocities vary between 10^{-4} and 10^2 cm/sec, with large variations due to both different electrostatic phenomena and the size of the particles for a given electrostatic phenomena.

The simplest case and the one producing the largest forces (highest migration velocities) is that of Coulomb force on a charged particle in an electric field. The charge on the particles was chosen to be the saturation charge obtained in a breakdown field, calculated using the Cochet equation, which considers the contribution of diffusion in particle charging. The initial migration velocity is higher for the 0.1 μm diameter particle than for the 0.3 μm diameter particle, and then increases steadily with increasing particle size. The dip in the curve at 0.3 μm corresponds roughly to a minimum, after which diffusional effects enhance particle charging to a greater extent as the particle diameter decreases. The migration velocities possible with Coulomb forces are by far the greatest of any considered for any given particle size.

The figure displays the migration velocities produced for charged particles in the presence of a 100 μm diameter uncharged spherical conductor. The particles are assumed to be charged as previously predicted using the Cochet equation, and the force is calculated as the force produced by the altered charge distribution in the collector, which was produced via

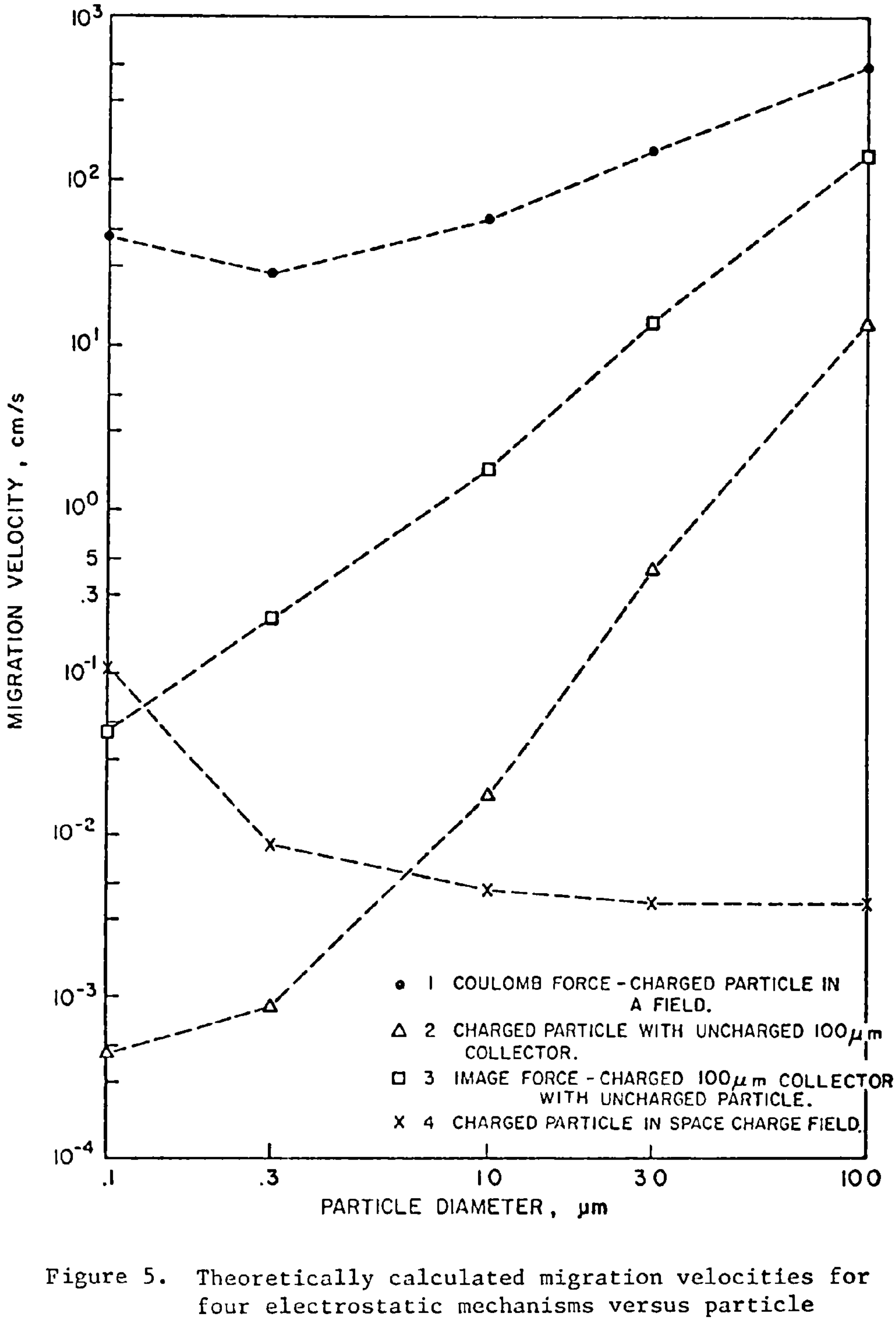

Figure 5. Theoretically calculated migration velocities for four electrostatic mechanisms versus particle diameter

the charges on the particle. The forces increase steadily with increasing particle diameter and display a tendency towards a minimum or leveling in the smaller particle size range for which calculations were made.

A third force is that which a charged collector (100 μm diameter collecting sphere) produces on an uncharged particle due to the inhomogeneous electric field away from the collector. These forces increase steadily with increasing particle diameter throughout the calculated range, and are second in magnitude only to the Coulomb force. These migration velocities are nearly equivalent to those produced via Coulomb attraction for the larger particles; however, they tend to decrease more rapidly than the Coulomb forces with decreasing particle size, making them much less desirable than Coulomb forces for very fine particles.

The fourth case corresponds to the migration velocity produced by the force exerted on a charged particle by an uncharged conducting 100 μm sphere, due to the space charge created by the other charged particles. Further explanation of this phenomena occurs earlier in the text. The assumptions utilized to make this calculation were that the aerosol had a mass mean diameter equivalent to that plotted on the curve, and that the particle density was 1 g/cm^3 and the particle mass concentration was 1 g/m^3. This, of course, means that each particle diameter corresponds to a different aerosol of different particle size distribution and number concentration. While these assumptions limit the applicability of the analysis somewhat more than in the previous cases, it is felt that the results are sufficiently valid for comparison with the other three cases. It can be noted that the migration velocity actually decreases with increasing particle size, showing a strong tendency to level out over 1 μm. The migration velocities are small overall, with the higher values for the very fine particles being somewhat biased by the assumptions used in the method of calculation.

We can summarize these calculations by noting the following relative ordering of the forces (for a 0.3 μm particle and the already noted assumptions), ranked from largest to smallest:

- Coulomb force between charged particle and charged collector
- Force between charged collector and uncharged particle
- Force due to mutual charged particle repulsion toward collector
- Force between charged particle and uncharged collector.

Increased collection efficiency can be expected by increasing any of these forces.

CONCLUSIONS

Electrostatic forces can be appreciable, especially in the particle size range of 0.1 to 1 μm, generally the most difficult particles to collect, yet particles which have health and visibility impacts out of proportion to their mass concentrations. Generally, the Coulombic forces (charged particle in an electric field) predominate over image forces (either particle or collector charged, but not both). Mutual repulsion of charged particles can also be significant for highly charged, highly concentrated aerosols. With the simple exponential equation used here and an estimate of the migration velocity w (calculated from the equations above), order-of-magnitude calculations of penetration should be relatively easy to make to judge the probable impact of various alternatives for electrostatically augmenting fine particle control equipment. We end this section with a bibliography concerning such electrostatic augmentation.

ELECTROSTATIC AUGMENTATION BIBLIOGRAPHY

Table 7 is a selected bibliography related to electrostatic augmentation. A few books on electrostatics and on aerosols in general have been listed, but primarily the bibliography is specific to the important aspects of electrostatic augmentation of control devices, aspects ranging from the charging of particles to their removal after collection. This bibliography should be useful to those who wish to study or apply electrostatics to the problem of particulate pollution control.

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SECTION V

ELECTROSTATIC AUGMENTATION OF FABRIC OR BED FILTRATION

FIBER BEDS TO CAPTURE PARTICLES ELECTROSTATICALLY[1]

The collection device consists of a loosely woven fiber bed used to filter previously charged fine particles. A relatively clean gas stream such as downstream from a conventional ESP, would have the particles positively charged by conventional saturation corona charging. The gas stream would then pass through a loosely woven fiber filter of polypropylene, teflon, or stainless steel, on which the particles are trapped. Cleaning would be achieved by use of water sprays. (See Figure 6.)

Goals of the Study

The long-range goal is to provide a reliable means for removing submicron particles from industrial waste gases. Short-term goals include fully defining the mechanism responsible for fine particle removal, and evaluation of the capacity of the mechanism for removal of very fine fly ash generated in the combustion of high ash, low sulfur coal.

Methods of Study

Theoretical — Definition of the envelope of conditions within which the fibers significantly remove submicron particles was to be determined. A mathematical model of the phenomena was to be developed as a follow-up to the proposed experimental work, and such a model has been developed. It is based upon the charging of the fiber bed by the fine particles

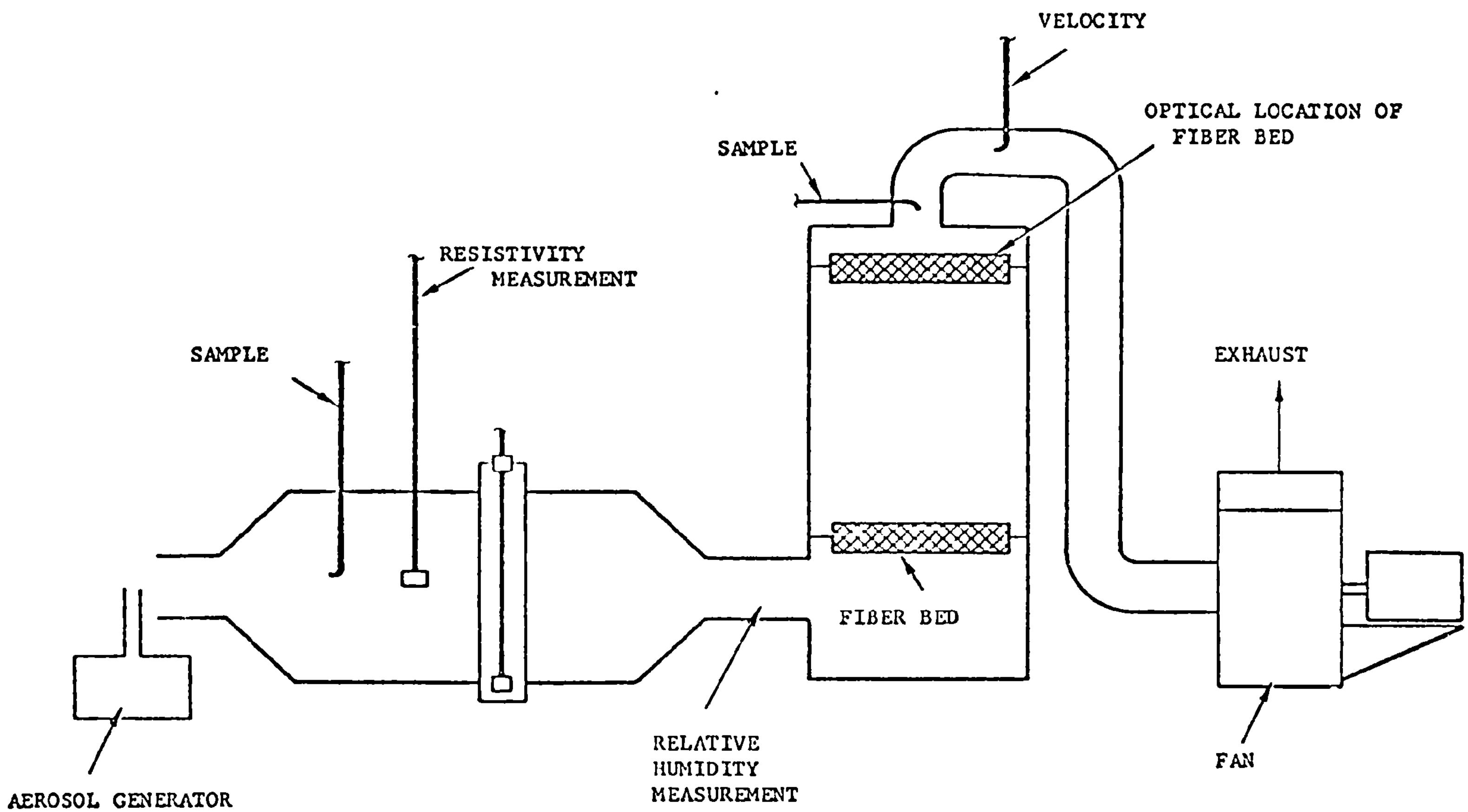

Figure 6. Schematic of test apparatus for study of removal of charged submicron particles by fiber beds [1]

collected thereon. Unequal collection within the fiber bed produces an electric field gradient, proposed as a significant collection mechanism. Self-consistent solutions to the equations of bed charging, electric field, and charge leakage were obtained. It is reported that the bed became charged even when no particles were being collected, suggesting contact charging (triboelectrification) is a major electrical phenomenon, which would cast doubt on the applicability of the theoretical model developed thus far.

It has been proposed that image forces may cause the observed removal of charged particles by the stainless steel fiber bed.[1] Using an equation for single fiber efficiency proposed by Natanson,[29] the overall efficiency was then computed, and they claimed that the calculated efficiencies agree well with the theoretical efficiency expected due to image forces. It was noted that the observed bed efficiency at 50 fpm was 18.6 percent and that the theoretically calculated efficiency for these conditions was 18 percent.

Although the hypothesis that image forces were at work is not crucial to the value of the investigation, it deserves closer scrutiny. As we will show, there were minor calculational errors and a significant error (neglect of the Cunningham slip correction) in the use of Natanson's equation for a charged particle and an uncharged sphere. Once these are corrected, the agreement with experimental results at 50 fpm (0.254 m/s) becomes worse. There is some question about the validity of the Natanson expression as well. It is actually derived for the case of a point charge approaching a plane, rather than for a sphere approaching a cylinder. It predicts an efficiency which depends upon an exponent containing the cube root of the ratio of the migration velocity to the free stream velocity, rather than an exponent with a linear dependence on this ratio. A linear dependence is predicted by Natanson's own equations for charged-particle-to-charged-cylinder efficiencies and uncharged-particle-to-charged-cylinder efficiencies. A linear, rather than cube root dependence, is also predicted by the form $e^{-wA/Q}$ we have used. The cube root expression leads to the anomalous result that small image forces produce much greater collection than larger image or Coulomb forces (the charged cylinder cases).

Our own calculations using the equations and data as appears in Table 8 reveals that the theoretical overall bed efficiency due to image forces at 50 fpm would be 59 percent.

It can readily be seen that the theoretically calculated efficiencies utilizing the equation as given[1] is different from their own calculated results and rather different from their measured efficiencies.

In the single fiber efficiency equation of Natanson, as used[1], the Cunningham slip correction factor was neglected. Recalculating the efficiencies, utilizing the Cunningham correction factor in the single fiber efficiency equation yields results in column 5, Table 9. We now have corrected the theoretical efficiency of the stainless steel fiber bed, according to Natanson's corrected (by addition of Cunningham slip correction factor) equation for single fiber collection efficiency for a charged particle and uncharged cylinder.

If it is correct to assume image forces to be the collection mechanism, and if Natanson's equation for single fiber efficiency is correct, then we would expect that the overall collection efficiency would vary with the cube root of the ratio of the face velocities. The experimental data for the stainless steel fiber pad indicates a drop in efficiency from 18 percent at 50 fpm, to zero at 350 fpm. If image forces were the dominant mechanism, then we would expect the efficiency to drop only to 9 percent, not zero. It would then appear that there is a discrepancy between experimentally observed efficiencies, calculated theoretical efficiencies, and results expected from theory. This leaves open the possibility that the theoretical efficiency equation is wrong, or the assumed particle capture mechanism is wrong, or both.

Table 8. INFORMATION UTILIZED TO CALCULATE THEORETICAL EFFICIENCY[1]

$$E = 1 - e^{-\alpha}$$

$$\alpha = (4/\pi)\epsilon_c \; \frac{1-\epsilon}{\epsilon} \frac{L}{d_f}$$

$$\epsilon_c = 2 \; \frac{K-1}{K+1} \left(\frac{e^2/4 \; \pi \; \epsilon_o}{V_o d_f^{\,2} \; \mu \; d_p} \right)^{1/3} \quad \text{(Reference 29)}$$

d_f = fiber diameter = 0.03 cm = 3×10^{-4} m

d_p = particle diameter = 0.22×10^{-4} cm

e = charge on a particle = 3.2×10^{-18} coul

ϵ_o = permitivity of free space = 8.85×10^{-12}

ϵ = bed porosity = 0.9

K = collector dielectric constant

V_o = fluid velocity = 0.25 m/sec (50 ft/min)

L = bed depth ~ 15 cm.

From this, one calculates an individual fiber collection efficiency of 0.0059 at 500 ft/min and an overall bed efficiency of 18 percent at 500 ft/min and 34 percent at 50 ft/min.

Table 9. EXPERIMENTALLY OBSERVED AND THEORETICAL FIBER BED EFFICIENCIES

Face velocity m/sec	Experimentally observed % efficiency[1]	Calculated % efficiency[1]	GCA calculated % efficiency with uncorrected equations	GCA calculated % efficiency with corrected equations
0.254	18.6	34	59	66
1.778	0	b	b	39
2.54	a	18	34	b

[a]Not measured.

[b]Not calculated.

Natanson's equation for single fiber collection efficiency is:

$$\eta = \left[2 \left(\frac{K-1}{K+1}\right) \left(\frac{q_p^{\,2}}{V_o d_f^{\,2} \mu \, d_p}\right) \right]^{1/3}$$

and is questionable due to the cube root. The analysis in Appendix D and the d_f^{-2} dependence for the image force[30] indicate a square root rather than a cube root. If we calculate the image force on a 0.22 micron particle in a conducting cylinder, we get $F_I = 4.1 \times 10^{-13}$ dynes, corresponding to a migration velocity of 2.05×10^{-5} cm/s. Using an equation for overall efficiency of the form:

$$E = 1 - e^{-w\,A/Q}$$

where A is the surface area of the collector (filter), Q is the volume throughput, and w is the particle migration velocity (force times particle mobility); we get an overall filter collection efficiency for the previously calculated migration velocity of less than 0.0002 at 50 fps (0.254 m/s). This is in close agreement with the efficiency calculated using the Natanson equation without the cube root factor (0.0003), but is much less than the square root (0.017), much less less than the cube root (0.067). If we use Natanson's equation for the single fiber collection efficiency for a charged particle and charged cylinder to determine the migration velocity required to achieve 66 percent overall collection efficiency (which the cube root form of the image force equation predicted) we get:

$$E = 1 - e^{-\alpha}$$

$$\alpha = 70.7\eta \quad \text{for the filter in question}$$

$$\eta = \pi w/V_o$$

$$1 - 0.66 = 0.34 = e^{-70.7\,\pi\,w/0.254}$$

$$w = 0.0012 \text{ m/sec} = 0.12 \text{ cm/sec.}$$

Thus Natanson's equations for Coulombic attraction require w = 0.12 cm/s to obtain 66 percent efficiency. Then if w = F B, the force required would be

$$F = 2.47 \times 10^{-9} \text{ dynes.}$$

If we use the similar, simple collection efficiency equation for the same conditions we get:

$$E = 1 - e^{-wA/Q}$$

$$0.34 = e^{-w\ 176/0.219}$$

$$w = 0.0013 \text{ m/sec} = 0.13 \text{ cm/sec.}$$

If w = F B, then the force required is

$$F = 2.68 \times 10^{-9} \text{ dynes.}$$

We calculated, using Natanson's image force equations, that F_I is 4.1×10^{-13} dynes. These forces, producing supposedly identical efficiencies are unreasonably different. A summary of the results appear in Table 10.

Natanson's efficiency equation (cube root form) for the charged particle/uncharged cylinder situation yields forces, and consequently migration velocities, which are far lower than those calculated for the same overall efficiency in the charged particle/charged cylinder case (Coulomb forces). It is this discrepancy that leads us to believe that Natanson's equation for the charged particle/uncharged cylinder is in error for the given conditions. It is further believed that the image forces have been shown to be insignificant, in that they are too small to cause any effective capture of particles in question.

Table 10. CALCULATED THEORETICAL EFFICIENCIES WITH SEVERAL COLLECTION MECHANISMS

Theory and equation utilized	Efficiency %	Force dynes	Migration velocity $\frac{cm}{sec}$
Charged particle and uncharged cylinder — Natanson Equation	66	4.1×10^{-13}	2.05×10^{-5}
Charged particle and uncharged cylinder — Deutsch Equation	0.0002	4.1×10^{-13}	2.05×10^{-5}
Charged particle and charged cylinder — Natanson Equation	66[a]	2.5×10^{-9}[b]	0.12[b]
Charged particle and charged cylinder — Deutsch Equation	66[a]	2.7×10^{-9}[b]	0.13[b]

[a]Assumed.

[b]Calculated from efficiency

Experimental - The envelope of conditions within which submicron particles are significantly removed is to be measured directly when possible. It is, however, anticipated that most of the electrical effects within the bed will have to be determined by inference, since direct measurement will normally not be possible.

Measurements will be taken of: particle resistivity, pad resistivity, air velocity, pad thickness, charge level on particles, dust loading, and particle size.

Utilizing information obtained in the first part of the study, an experimental rig will be sized for about 500 cfm (0.24 m^3/s) of gas at temperatures typical of both hot- and cold-side ESPs. Aerosol fly ash will be introduced with a plasma torch equipped with a solids feeder, with which particle size range is to be controlled at levels simulating loadings and particle size distributions typical of gases downstream from an ESP. Simulation of typical boiler off gas composition will be done synthetically via the addition of SO_2 and CO_2. See Figure 7 for a schematic of the apparatus. The parameters to be explored include the following (quoted from a document, Battelle Northwest Laboratories (BNWL)):[1]

"Particle size	- This will not be considered a prime variable. All tests will emphasize the removal of submicron particles in the 0.1-to-1.0-micron-size range as the larger particles are removed with reasonable effectiveness by existing electrostatic precipitators.
Air velocity	- Varied from 50 to 500 feet per minute.
Pad resistivity	- Will emphasize the use of pad materials of high resistivity which can tolerate temperatures greater than 240°F. At present, teflon is the prime candidate, but at least one other material will probably be investigated.
Pad thickness	- Will load on 6-, 12-, 18-inch beds.
Particle resistivity	- Coals will be examined that exhibit ash resistivities in the range of 10^9 to 10^{13} ohm-cm.
Ash loading	- Will be varied from 5 to 50 mg/m^3. Ash on pad will be calculated from gas sample data.
Charge level on the particles	- Will obtain saturation charge in existing charger. Mobility spectra will be measured, but charge level will not be a parameter to be studied.
SO_2 level	- SO_2 concentration in the gas will be varied from 500 to 3000 ppm independent of the sulfur content of the coal types investigated."

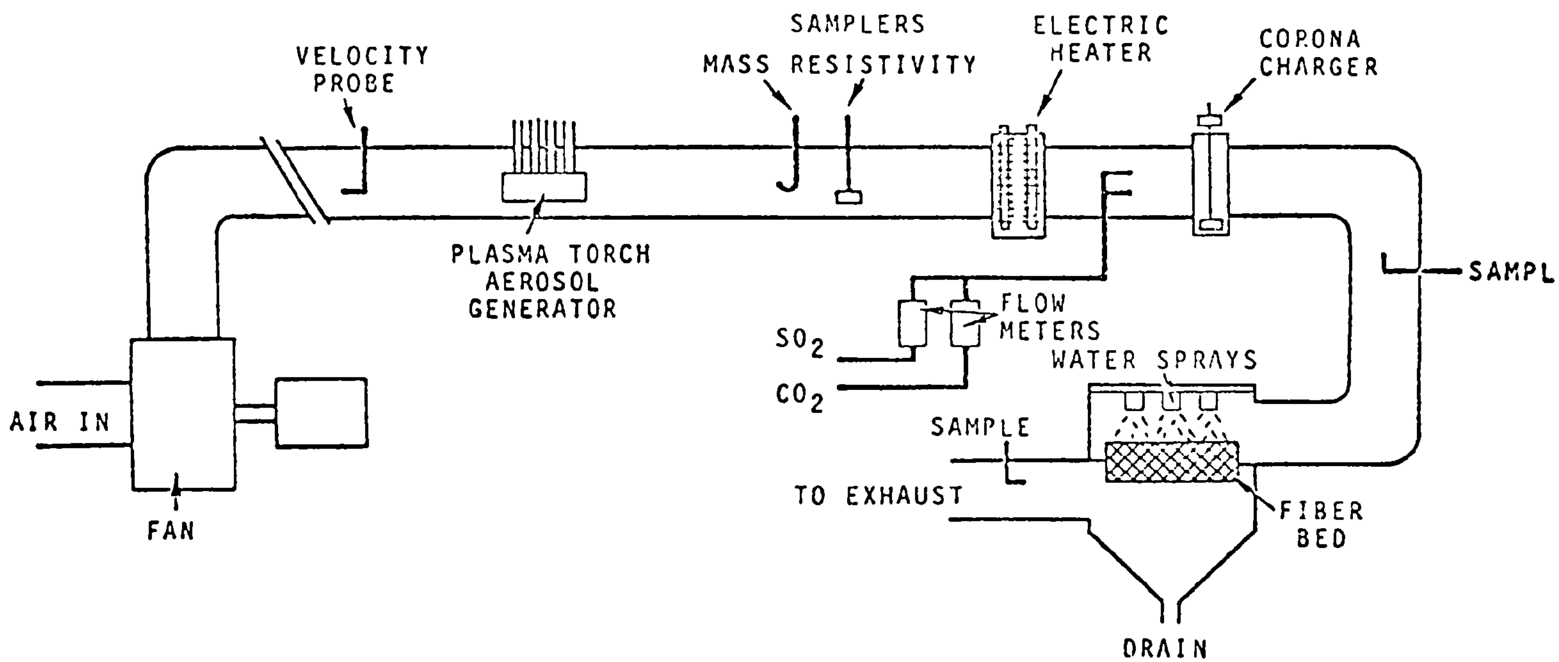

Figure 7. Schematic of experimental setup for study of removal of charged fly ash by fiber beds[1]

"It is planned that for each experiment the following data will be obtained

- Removal efficiency as a function of time
- Dust resistivity
- Air flow rate
- Total charge level of the fly ash
- Gas composition"

Experiments will also be conducted to determine pressure drop and removal efficiency as a function of the pad dust loading.

Results

It is expected that a process for economically removing submicron particles will be made available for plant designers. The pilot study is expected to lead to a feasible approach for removing submicron particles from power plant stack gases. A back-up device for use with presently installed ESPs will be designed to help meet more stringent emission regulations and to help control the more difficult to precipitate, high resistivity fly ash which is generated from low sulfur coal.

Experimental results are available from the progress report[1] (called there "Appendix A"), and from a previous privately funded study performed for Intalco Aluminum Corp. Results from the Intalco study led to the discovery that the loosely woven polymer fiber bed was an effective collector of charged fine particles. Extremely high efficiencies were determined for two different fine particulates at three different face velocities; see Figure 8 for results.

Results from the present study[1] (those in its Appendix A) indicate that 18 test runs have been completed in which, bed velocity, dust loading,

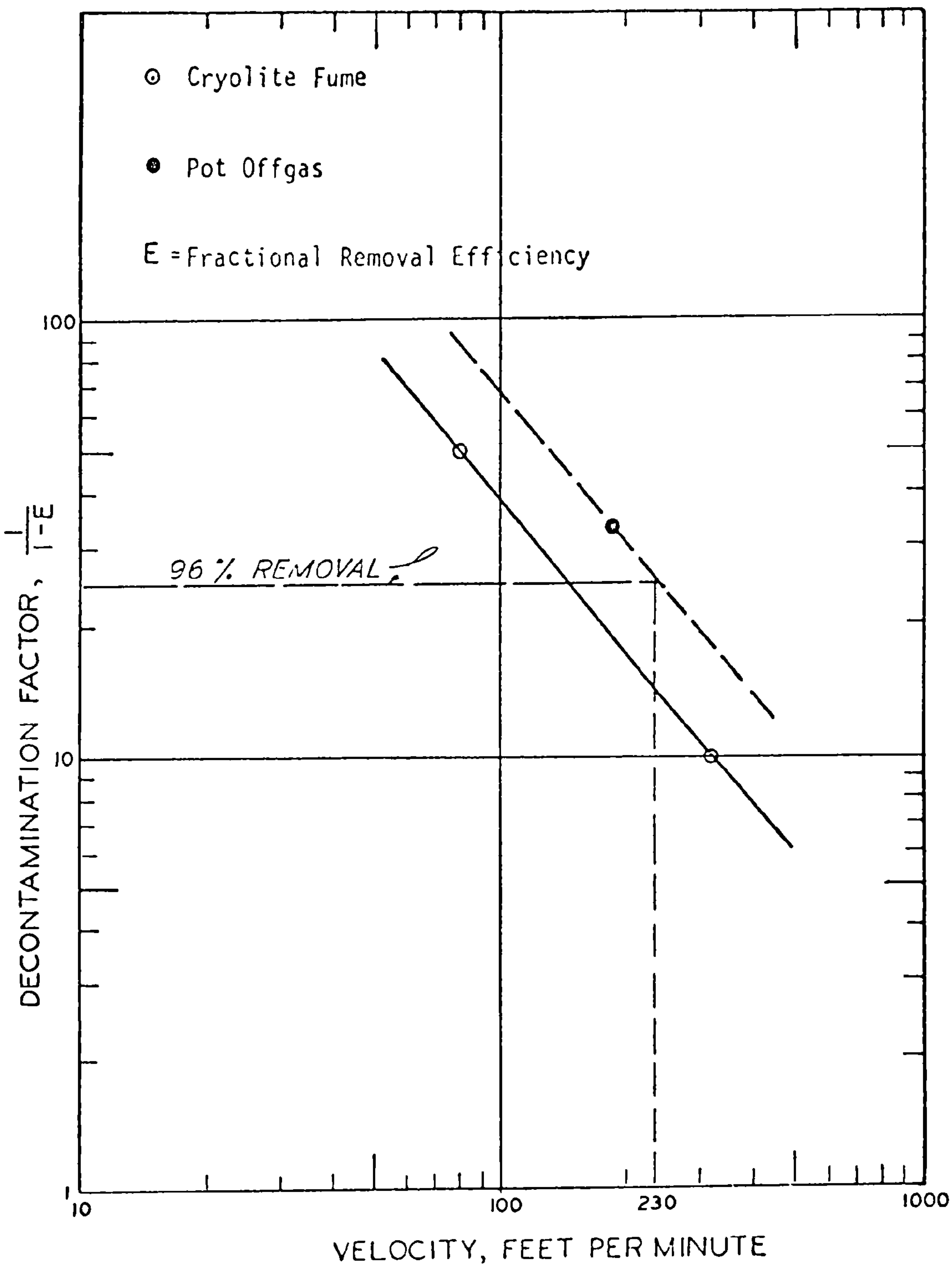

Figure 8. Electrostatic capture of particles by polypropylene fiber bed[10]

bed thickness, and bed chemical composition were variables. Results are shown graphically in Figures 9 and 10, and are tabulated in Tables 11, 12, and 13. It can be seen that bed efficiency is a function of: bed velocity, with a maximum occurring at 0.76 m/s (150 fpm); aerosol loading to a small extent; the bed thickness; and the chemical composition of the bed.

Conclusions

To date it has been concluded that it is likely that there were losses of initially deposited solids from the 3-inch beds, particularly at higher velocities. The possibility that a threshold velocity exists where shear forces predominate adhesive forces will be further evaluated.

Charge effects are concluded to be very important as determined via the difference in collection efficiency between the stainless steel bed and the polypropylene bed. It is believed that image forces are the only significant contributor to increased deposition of charged particles with the more highly conductive stainless steel bed. The efficiency of the stainless steel bed is "18 percent, which is approximately that anticipated for removal by image forces developed in conducting fibers by the charged particulates."[1]

Evaluation

Suitability of Goals - The goals of this research are particularly pertinent to present and future requirements for particulate removal equipment. Increasing attention toward collection of fine particles (< 3 μm diameter), due to increasing awareness of the more harmful health aspects associated with fine particles versus larger particles, has created a need for more efficient means of removal of this fine particulate. As presently available means of removal of fine particulate are high in both initial investment capital and operating costs, the

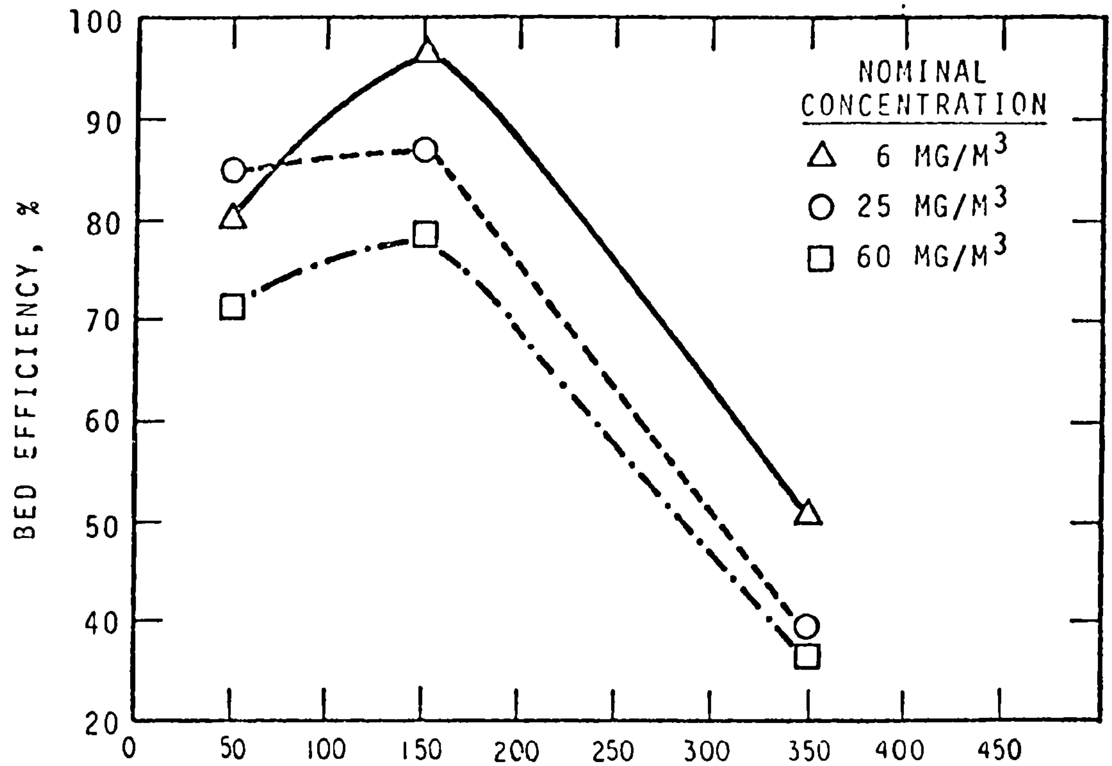

Figure 9. Aerosol removal by a 6-inch polypropylene bed[1]

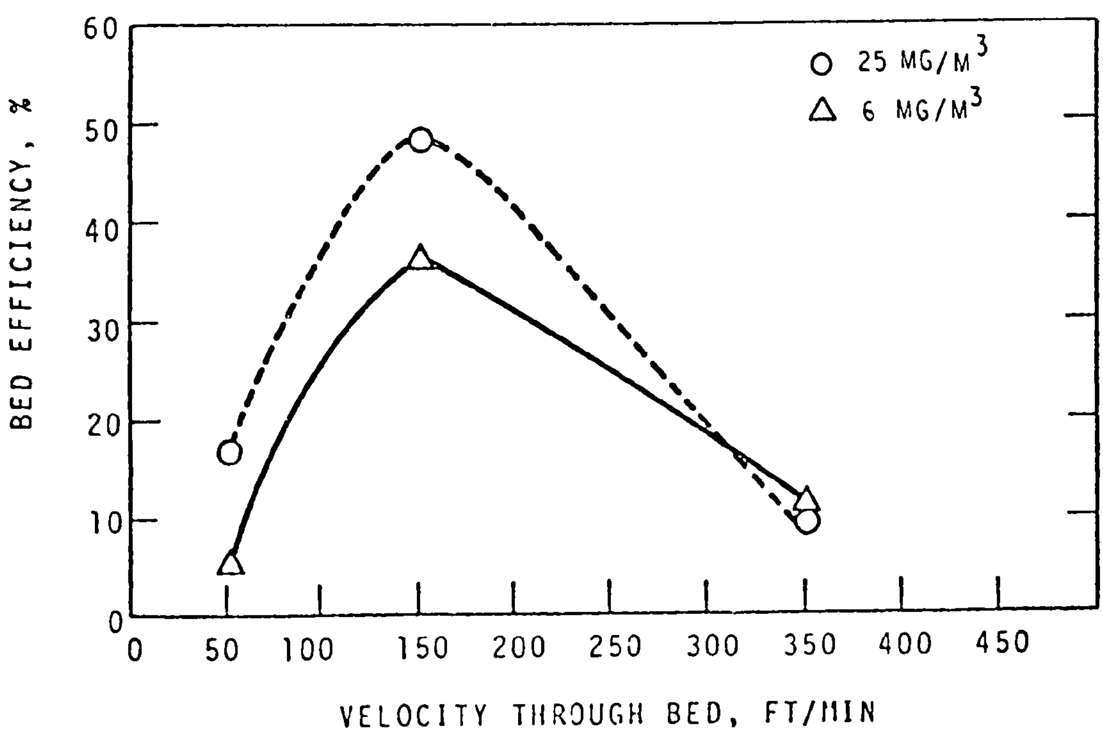

Figure 10. Aerosol removal by a 3-inch polypropylene bed[1]

Table 11. AEROSOL DEPOSITION IN A 6-INCH POLYPROPYLENE BED[1]

Bed velocity	Dust concentration	Overall efficiency	Bed efficiency
50 ft/min	9 mg/m^3	90.8%	79.7%
50	26	97.9	85.5
50	56	95.1	70.6
150	7	99.3	98.7
150	23	91.8	87.0
150	53	85.6	77.8
350	10	67.3	51.4
350	28	61.7	38.5
350	74	62.8	35.5

Table 12. AEROSOL DEPOSITION IN A 3-INCH POLYPROPYLENE BED[1]

Bed velocity	Dust concentration	Overall efficiency	Bed efficiency	ΔP bed
50 ft/min	14 mg/m^3	78.6%	5 %	0.01" H_2O
50	30	82.9	17.7	0.01"
150	10	76.3	36.7	0.11"
150	21	80	48	0.20"
350	6	24.3	11	0.33"
350	28	37.9	10.4	0.33"

Table 13. AEROSOL DEPOSITION IN A 6-INCH STAINLESS STEEL BED[1]

Bed velocity	Dust concentration	Overall efficiency	Bed efficiency
50 ft/min	14 mg/m^3	85.2%	18.6%
350	7	42	0
350	70	47	0

goals of producing a fine particle collector of low pressure drop and moderate cost, as a back-up on existing facilities, is certainly suitable for today's needs.

The alternate goal of producing a particulate control device which efficiently removes high resistivity fly ash is also very timely. Recent evaluations of the U.S. energy requirements have projected increased reliance on coal as a fuel for fossil-fueled power plants. Demands for more electricity, coupled with increasingly stringent environmental regulation at power plants, and high oil prices, will force these fossil-fueled plants to burn lower sulfur content coals. These lower sulfur content coals are normally associated with the sub-bituminous and lignite grades of coal of the West which suffer from high ash and low Btu content. One obvious effect of burning high-ash, low-Btu coal is the increased particulate generated per Btu fired; while a more subtle effect is the generation of a high resistivity fly ash which is not efficiently removed in present cold-side precipitators. In view of the projected future demand for low-sulfur coal, the goal of producing a back-up collection device which efficiently removes high resistivity fly ash is extremely important.

Suitability of methods for these goals - Next is discussed the suitability of the theoretical and experimental approach as proposed. Although a mathematical model is mentioned as part of the study, it has not been completed, and will therefore not appear in this section.

Analysis of theoretical approach - The majority of the experimental work to date has been with the polypropylene fiber beds, primarily the 6-inch thick fiber bed. The observed high efficiencies may be reasonably explained if we consider the polypropylene fiber bed to have a net negative charge, thereby exerting a Coulombic attraction on the positively charged particles.

Choosing the highest observed efficiency, 98.7 percent, for the 6-inch thick polypropylene fiber bed, we can calculate the particle migration velocity, for a 0.22 micron particle, required to achieve this high efficiency. Solving for migration velocity, w, in the equation:

$$E = 1 - e^{-w\,A/Q}$$

we get:

$$0.987 = 1 - e^{-w176/0.66}$$

$$0.013 = e^{-266.7\,w}$$

$$-4.34 = -266.7\,w$$

$$w = 0.0163 \text{ m/sec} = 1.63 \text{ cm/sec}$$

since $w = F\,B$,

$$F = 3.26 \times 10^{-8} \text{ dynes}$$

To determine the strength of the electric field at the surface of the polypropylene fiber required to generate the above calculated force, we solve the equation:

$$\bar{E} = F/q_p$$

which, for $q_p = 9.6 \times 10^{-9}$ stat-coulombs (saturation charge), is

$$\bar{E} = 3.4 \text{ statvolts/cm} = 1.02 \text{ kV/cm}$$

The electric field strength at the surface of the polymer fiber corresponds to a surface charge density of 3.4 stat-coulombs/cm^2. It seems, therefore, that if a charge density of 3.4 statcoulombs/cm^2 could be generated on the surface of the polypropylene fibers, the efficiency of removal of 0.22 micron particles under the aforementioned conditions would then be the observed efficiency of 98.7 percent. We must now consider a mechanism which is capable of generating a surface charge of 3.4 statcoulombs/cm^2, without any external application of electrical energy. Triboelectrification is one such mechanism. Charging of dielectric fiber filters by an air stream was observed by Van Orman and Endres[11] to be the principal collection mechanisms of filters composed of highly insulating polymers. Charge densities for polymeric materials quoted in the literature are: 1-10 statcoulombs/cm^2,[2] 1-20 statcoulombs/cm^2,[3] and 1.2-8.4 statcoulombs/cm^2.[4] (Both references 2 and 4 are referring specifically to charge densities produced by triboelectrification.) These charge densities would be sufficient.

Triboelectrification of polymers has been recognized by the plastics industry, classically due to its nuisance effect.[5] Plastics processing techniques often produce inherent static charges due to triboelectrification. Friction during calendering and contact during molding give rise to charge transfers between polymer materials and process equipment. The finished plastic product attracts dust due to its inherent static charge, degrading its appearance, or requiring frequent cleaning which often leads to greater charging. Charges built up during processing can lead to sparking which may pose a serious safety hazard. It is mostly for these reasons that interest in plastic triboelectrification exists.

Plastics, being highly resistive materials, appear to have the ability to hold charges of either sign at close proximity, without neutralizing each other.[11,4,5] Therefore, it is possible for a polymer surface to be highly charged, while exhibiting little or no net charge. This ability of polymers to hold different sign charges in close proximity makes it fiber beds includes tests with a 3000 cfm capacity control device as a polymer surface.

There is, however, a considerable tendency for polymers to show a bias towards a net overall charge of one sign. Numerous triboelectric series have appeared throughout the literature, which series contain polymers.[2,4,6,7,8] In all of the series containing Teflon, it was listed as the last material on the negative end, with polyethylene occurring just ahead of Teflon. This seems to indicate that these polymers, and polypropylene, since it has a very similar chemical structure, have a high propensity to acquire an overall negative charge (they are electronegative) due to triboelectrification. A similar statement by Frederick,[9] "those that are quite electronegative like the polyolefins, and especially, 'Teflon,'" indicates that the polyolefin in question, polypropylene, is highly electronegative.

In view of the evidence supporting the possibility of triboelectrification of polypropylene to the required sign and surface charge density to explain the observed experimental results, we suggest further investigation of the charging characteristics of the polymer fiber filter. Also since "Teflon" exhibits an even higher propensity towards negative charge acquisition, in theory, it would be interesting to compare the performance of the "Teflon" fiber bed with the polypropylene fiber bed, for identical conditions.

Analysis of experimental approach - The experimental work performed to determine the phenomena causing removal of charged fine particles in fiber beds includes tests with a 3000 cfm capacity control device as previously described here in the first section. Testing procedure involves the generation of a submicron particulate, charging the particles in a corona charger, determining the resistivity of the particles and the particle size distribution upstream of the corona charger, sampling the particulate material upstream and downstream of corona charger and downstream from the fiber bed filter, and measuring overall charge flux upstream and downstream of the bed.

Table 14a and 14b were formulated to assist in evaluation of the experimental approach. Important parameters which may affect the operation

Table 14a. PARAMETERS ASSOCIATED WITH THE STUDY OF ELECTROSTATIC CAPTURE OF PARTICLES BY FIBER BEDS [1]

Parameter	Magnitude, description, method of measurement or control, etc.
GAS	
Volume flow rate	up to 3000 cfm (1.4 m^3/s)
Face velocity	50-350 fpm (25 - 175 cm/s)
Reynolds number (Re_f)	?
Flow geometry	K (known)
Pressure drop (Δp)	M (to be measured)
Temperature	~ ambient
Pressure	ambient ?
Relative humidity	schematic indicates it will be measured, however no mention was made in the results or in the text
PARTICLES	
Size	measured with 8-stage Andersen impactor for submicron particles only
Shape	?
Chemical composition	NH_4Cl
Resistivity	M
Dielectric constant	K
Charge	particles are expected to receive a saturation charge — total charge flux of gas stream will be measured
Concentration	6-74 mg/m^3
CHARGING SECTION	
Type of charging	corona
Ion current	12.5 ma
Electric field	26 kV
Geometry	parallel plates and wires — three in a line
COLLECTOR	
Chemical composition	polypropylene, stainless steel, teflon

Table 14a (Continued). PARAMETERS ASSOCIATED WITH THE STUDY OF ELECTROSTATIC CAPTURE OF PARTICLES BY FIBER BEDS [1]

Parameter	Magnitude, description, method of measurement or control, etc.
Resistivity	K
Dielectric constant	K
Charge	M
Voltage	will not be measured, however it will be determined by inference from data
Particulate loading	M
Efficiency	M
Geometry	
Internal configuration	6-inch, 3-inch thick beds 4 ft x 2.33 ft; 3.0×10^{-4} m fiber diameter; 0.9 porosity
External configuration	6 ft diameter, 12 ft tall fiberglass chamber
CLEANING PROCESS	
Method	?
Effect on efficiency	?
COMMENTS	
STAGE OF DEVELOPMENT	Pilot scale apparatus

Table 14b. PARAMETERS ASSOCIATED WITH THE STUDY OF ELECTROSTATIC CAPTURE OF PARTICLES BY FIBER BEDS [1]

Parameter	Magnitude, description, method of measurement or control, etc.
GAS	
Volume flow rate	up to 500 cfm ($0.24\ m^3/s$)
Face velocity	50-500 fpm (25 - 250 cm/s)
Reynolds number (Re_f)	?

Table 14b (continued). PARAMETERS ASSOCIATED WITH THE STUDY OF ELECTROSTATIC CAPTURE OF PARTICLES BY FIBER BEDS[1]

Parameter	Magnitude, description, method of measurement or control, etc.
Flow geometry	N.A.
Pressure drop (Δp)	M
Temperature	typical of hot- or cold-side precipitators
Pressure	ambient ?
Relative humidity	we anticipate lower percent RH than in typical power plant off-gases due to combustion of lesser amounts of coal — BNWL indicates RH will be measured
PARTICLES	
Size	submicron particles only will be generated
Shape	particles will be formed in a plasma torch by burning coal; shape of particles is unspecified
Chemical composition	fly ash from various coals
Resistivity	10^9 to 10^{13} ohm
Dielectric constant	?
Charge	total charge level on fly ash will be measured
Concentration	5 to 50 mg/m^3
CHARGING SECTION	
Type of charging	corona
Ion concentration	?
Electric field	?
Geometry	parallel plates and wires — three in a line

Table 14b (Continued). PARAMETERS ASSOCIATED WITH THE STUDY OF ELECTROSTATIC CAPTURE OF PARTICLES BY FIBER BEDS[1]

Parameter	Magnitude, description, method of measurement or control, etc.
COLLECTOR	
Chemical composition	polypropylene, teflon, stainless steel
Resistivity	high – can be determined for each fiber bed material
Dielectric constant	K
Charge	M
Voltage E	inferred self-induced electric fields
Loading	M
Efficiency	M
Geometry	
Internal	6-inch, 12-inch, 18-inch bed filters 8 ft^2 or 4 ft^2
External	6 ft diameter; 12 ft tall fiberglass chamber
CLEANING PROCESS	
Method	liquid spray
Efficiency degradation	?
COMMENTS	CO_2 and SO_2 will be added to the gas stream, downstream from plasma torch. Addition of SO_2 downstream from coal combustion may not generate any SO_3 therefore conditioning of fly ash will not be at the same level as might be expected from the level of SO_2 in the gas stream.
STAGE OF DEVELOPMENT	proposal and lab scale

KEY: ? = Uncertain, unspecified
N.A. = Not applicable
M = To be measured
K = Known

of the collection device are listed under generalized headings for each of the important aspects of the control device under anticipated operating conditions.

Most important aspects of the gas have been adequately covered in the BNWL experimental design with the possible exception of relative humidity. Although Figure 6 indicates the provision for a measurement, there is no mention of such measurements in the texts.[1,10] It is anticipated that relative humidity may be an important factor, especially concerning the ability of the fiber bed to attract and hold a charge at elevated temperatures.

Although the measurement of static pressure was not considered in the text, it appears obvious from the total flow through the system and the size of the system that the static pressure will be very close to the ambient pressure. Since the static pressure is required for the correction of pitot readings, it would presumably have been measured during the velocity traverse, if it were found to be significant. Effects of pressure may have to be considered, however, if this device is ever proposed for installation in a significantly pressurized (positive or negative) gas stream, since charging levels of particles and the collector will be somewhat dependent upon this parameter.[12]

The particle size distribution is measured with 8-stage Andersen Impactors, upstream from the corona charger. It would appear that sampling downstream from the corona charger would be more likely to yield results corresponding to the actual particle size distribution of the particles which the fiber bed sees, providing that the charged particles do not alter the deposition mechanism in the impactor. Sampling upstream of the corona charger allows room for doubt about the size distribution of the particles after passing through the corona charger, where agglomeration may occur. The shape of the particles may be important, especially concerning maximum surface charge capacity; however, the shape of the particles will not be determined. Measurement of overall charge flux of the particles both upstream and downstream of the bed along with overall particle loading and size distribution does make it possible to determine the approximate charge on particles without knowing their actual shape.

Charging of the particles is accomplished with a conventional corona charger, where the voltage is set, and the subsequent current may be determined. The objective is to obtain a saturation charge on the particles.

The collector is a variable in this series of tests, where the chemical composition (and therefore resistivity, and dielectric constant), external geometry, and possibly internal geometry are parameters to be studied. Most important parameters relating to the collector have been given or will be measured but some exceptions are: dielectric constant, which was not mentioned in the text, but which will need to be known to solve the single fiber efficiency equation appearing in the text; the voltage at the collector, which will not be measured, but will be inferred from experimentally observed collection efficiencies; internal geometry of the bed, which is adequately described for only the stainless steel bed though it is likely that the fiber diameter and porosity of the two polymer beds are somewhat different. This missing information will be required to do a thorough theoretical analysis of the collection efficiency.

Cleaning of the filter bed has been considered, and tests will be made to determine the pressure drop across the filter, and consequently loading at which the filter should be cleaned. It was stated that, "relatively long duration runs will be made during which the pressure drop and removal efficiency will be obtained as a function of the pad dust loading." These runs will provide information about the efficiency degradation associated with the cleaning of the filter; however, runs spanning actual cleaning cycles will be required to define totally the problem of efficiency degradation with cleaning.

The proposed follow-up study, in which charged submicron fly ash removal is to be investigated, is similar to the initial experimental apparatus, see Figure 7, and the parameters to be investigated are handled similarly, with one significant difference: the study concerning the removal of charged fly ash by fiber beds seeks to determine the suitability of the proposed collection system for collection of very specific particulate matter in a very specific environment, offgas from a low-sulfur-coal-fired boiler. Fly ash from combustion of low sulfur coal usually has a resistivity above the critical level of 10^{10} ohms/cm, which causes back corona, and consequent poor precipitator performance. An average pulverized-coal-fired boiler generates 6 ppm SO_3 per each percentage point of sulfur in the coal.[13] Low-sulfur and or high-ash-content coal may require additional SO_3 to lower their resistivity to within the acceptable limits, 10^7-10^{10} ohms/cm, for electrostatic precipitation.

The proposed addition of SO_2 to the test apparatus to simulate actual boiler offgases accounts for the effect that SO_2 undoubtedly will have on the particles and possibly the collector. Since the resistivity of the particles is largely determined by the SO_3 concentration in the off-gases, the particulate produced with the proposed plasma torch arrangement may have excessively high resistivity, not at all representative of fly ash generated from the same coal under normal firing conditions. The presence of SO_3 at natural levels may also have a noticeable effect upon particle collection mechanisms due to its effect upon the charge leakage from the filter pad. It appears that to simulate coal-fired boiler offgases, especially to study electrostatic effects, the addition of approximately 1/100 SO_3 per SO_2 is required.[13] The study apparatus also calls for the addition of representative amounts of CO_2 to help simulate boiler offgases, which appears to be sound. There is, however, no mention of the addition of water, which normally comprises approximately 10 percent of boiler off-gases. This water will have a significant effect on suppressing corona current and raising sparkover voltage. The effects of combined water and SO_3 may prove to have some synergistic effect far greater than expected from the mere addition of SO_2 and H_2O effects.

Applicability to Pollution Control - The applicability to pollution control of the proposed collection device is considered, with particular emphasis on the control of emissions from burning low sulfur coal.

Prospects of method - The proposed system of utilizing loosely woven fiber pads to capture submicron particles at a low pressure drop has thus shown very promising results. Efficiencies as high as 98.5 percent were reported during the initial Intalco study[10] and one 98.7 percent efficiency was reported during the initial phase of the present study.[1] Corresponding pressure drops appear to be below 1-inch of water, making this device truly remarkable when compared to the pressure drop required to attain similar levels of efficiency with conventional equipment.

Scrubbers, if designed to achieve similar efficiencies, would require a much higher pressure drop. The pressure drop required for a venturi scrubber which is 80 percent efficient on removal of 1 micron sized particles would range from 20 inches to over 50 inches of water,[14] and scrubber pressure drops increase much greater than linearly for increased efficiency. A precipitator designed to meet these high submicron efficiencies would result in a rather sizeable construction cost, due to the high size requirements of the collection surface. The high collection efficiency at low pressure drop of the present system looks very promising.

Status of the method - The original work done on a pilot plant sized scrubber of 3000 cfm (1.4 m^3/s) nominal capacity, attained high collection efficiencies for submicron particulate consisting of aluminum reduction pot off-gas. In this initial study there were reported efficiencies of greater than 95 percent with submicron particulate of one very specific type, at the rated throughput capacity of the unit, 3000 cfm (1.4 m^3/s). This volume flow rate corresponds to face velocity of approximately 320 fpm (1.6 m/s).

Results of subsequent experimental investigations associated with the present study, see Tables 11, 12, and 13, indicate lower efficiencies at the same face velocities utilizing NH_4Cl submicron aerosol. Data indicate a maximum collection efficiency occurring at some intermediate velocity, contrary to the expected inversely proportional relationship between velocity and efficiency. Also noted is the lack of collection by the stainless steel fiber bed; it exhibited nearly zero efficiency under nominal operating conditions, suggesting negligible impaction.

Further investigation of the relationship of face velocity and collection efficiency is scheduled, with the idea that there is some threshold velocity at which shear forces dominate over adhesion forces. This may explain the reason for the observed maximum efficiency at an intermediate velocity.

Work on the second phase of the task directed towards collection of high resistivity fly ash has not yet started. Work on this phase will likely not even begin until the initial phase of this study is completed.

Implications - Preliminary data from initial experimental work indicate that the fiber bed filters are capable of removing submicron particles from an industrial offgas, very efficiently, at low energy penalties, with reasonably priced equipment. If the fiber beds prove capable of handling various resistivity particles under conditions of temperature and gas compositions typical of industrial offgases, then a significant air pollution control device of unique capabilities will have been developed. Methods of cleaning must be developed which do not appreciably impair efficiency or the promise of this device will go unfulfilled.

ELECTROSTATIC EFFECTS IN FABRIC FILTRATION[31]

The study does not involve designing or evaluating any new specific device. A small lab scale fabric filter containing 0.124 m^2 (1.3 ft^2) of filter area will be used to study the effects of various parameters upon performance.

Goals of Study

The goals of the study are summarized in these statements quoted from the proposal,[31] "a comprehensive investigation of electrostatic effects in particulate filtration ... sufficiently broad to explain static parameters of filter media and particulate needed for establishing a reliable engineering approach to the design of commercial baghouses."

"In addition to the determination of the electrostatic properties of a variety of fabrics and particulates, the overall program would be expected to determine the electrostatic role in particle-to-particle and particle-to-fabric adhesion as well as electrostatic effects in the spatial relationship or arrangement of particles and fibers as the particles are deposited."

"The overall object of the project is to provide a clear understanding of the relationship existing between solid particulates and filter media as a function of such important parameters as solids – entrained gas flow rate, particulate loading, pressure drop, aerosol chemistry, air-to-cloth ratio, cloth permeability, fabric construction (including fiber surface chemistry, fiber type, fiber size, together with yarn and weave characteristics) and all other defineable fabric and particulate properties including, especially, the electrostatic properties of media and of particulates."

Methods of Study

The study will rely heavily upon the use of experimental results to corroborate theory. Both lab and field investigations will be employed using a small fabric filter.

Theoretical - The theoretical aspects of the study would appear to center on the idea that electrostatics play a major role in fabric filtration; however, the roles of various parameters affecting electrostatics are little understood. Again quoting from the text:

"The following statement (6) summarizes the current status of the information available on electrostatic involvement in the filtration process:

'While electrostatics undoubtedly plays a role in the capture and retention of dust particles by a fabric filter, the evidence is inadequate to evaluate this mechanism quantitatively. According to Frederick (1961), electrostatics not only may assist filtration by providing an attractive force between the dust and fabric, but also may affect particle agglomeration, fabric cleanability, and collection efficiency. He attributes the generation of charge to frictional effects, stating that the polarity, charge intensity, and charge dissipation rate of both the dust and filter media, and their relation to each other can enhance or hinder the filtering process. He cites qualitative differences only. For example, fabric A may be better than fabric B on dust X, while fabric B is better than A on dust Y. He gives a "triboelectric" series for a number of filter fabrics that may be useful as a guide to selecting fabrics with desirable electrostatic properties. This is a fertile field for further investigations.'"

The only very specific theory to be investigated is explained in the following quote from the proposal:

"One of the first studies of Part I will concern the theory that charged particles deposited in a 'nonionized' electrostatic field will produce a relatively porous dust layer. By 'nonionized': we mean a field having no molecular ions (i.e., no corona). Under these conditions, slight irregularities tend to concentrate the field. The charged particles follow the field lines so that particles tend to deposit onto these irregularities. This further concentrates the field. Thus particles tend to deposit on top of particles forming a porous deposit. In the absence of these electrical effects, particles are carried by the gas into the spaces between particles thus tending to plug any existing porosity. Preliminary tests indicate that this may be a very large effect and so this will be one of the first mechanisms to be studied. In addition to the usual measurements of gas flow and pressure drop, this will require measurement of the charge on particles and measurement of the electric field throughout the filter region. Also microscopic examinations of dust deposits will be made."

Experimental - The experimental work will involve two distinct phases, which are generally summarized by the following statements:

"Phase I will be a basic study of the various electrostatic mechanisms which can influence the filtration of dust. Initially the work will be directed to conditions which produce a dust layer that is permeable to gas flow but impermeable to particulates. Another important factor is the adhesion of the particulates to fabrics and the separation of the collected dust from the fabric during a cleaning cycle. Instrumentation will also be developed to make the necessary electrostatic measurements in Phase II.

"In Phase II, bag filters will be tested under both laboratory and industrial conditions. The work under these two phases will be closely coordinated so that each phase will take advantage of developments in the other phase."

"Phase II operations will involve practical filtration evaluations carried out in two distinct but complimentary methods. In Phase II-A a conventional laboratory or bench scale filter system would serve to relate the filtration characteristics of various media with selected redispersed dusts. In Phase II-B, a portable filter system similar in size to that used in Phase II-A would be designed and used to receive and study gas-entrained particulates at operating plant sites."

Results, Attained or Expected

To date there have been no results reported, as this study is apparently in its beginning stages. The expected results would obviously correspond to the objectives which have been set forth for this research work. It is expected that the significant parameters concerning the particulate, fabric, and operation, will be determined to the extent that they could be used in a systematic scheme for the design of a baghouse facility.

Conclusions

We have drawn no conclusions from the limited work to date. The experimental work thus far has not proceeded beyond the initial formulation and set-up of apparatus.

Evaluation

Suitability of Goals - The goals set forth in the proposal address legitimate shortcomings of fabric filtration technology. In view of the growing role of fabric filtration as an air pollution control device, it is obviously beneficial to generate any technical information which would contribute to the use of a more scientific approach to baghouse design.

The emphasis on the filter cake is quite appropriate, because the buildup of the cake provides the conditions for high efficiency filtration in industrial filtration, but is also responsible for much of the pressure drop, thus power consumption (Wilder and Dennis[17]). If the cake can be made to perform at high efficiency with lower pressure drop due to the intelligent application of electrostatics, this could be a major contribution to the technology of fabric filtration.

Suitability of Methods for These Goals - Utilizing available information, we will analyze the theoretical and experimental aspects of the proposed study.

Analysis of theoretical approach - Two basic fabric filter performance parameters will be investigated: filter pressure drop and collection efficiency. Addressing filter pressure drop, the proposal refers to an equation used to predict the resistance to flow of a granular bed and proposes that electrostatics will lead to particle agglomeration, thus changing the void fraction of the dust layer and decreasing the resistance. An equation describing the pressure drop is:[15]

$$\Delta p(t) = \frac{k\mu}{\rho_p} \left[\frac{A_p}{V_p}\right]^2 \frac{(1-\epsilon)}{\epsilon^3} C_i V^2 t$$

where:

k = Kozeny-Carman coefficient , 25/6

g = acceleration due to gravity, 980 cm/s^2

μ = air viscosity, g/cm-s

V = average filtration velocity, cm/s = total flow rate divided by effective filter area

$\frac{A_p}{V_p}$ = surface area to volume ratio of the dust particles, cm^{-1}

ϵ = porosity (void fraction) of the dust layer, dimensionless

ρ_p = true density of the dust, g/cm^3

C_i = dust loading to the filter, g/cm^3

t = elapsed time of filter operation at above loading,

Δp = pressure drop, $dynes/cm^2$.

If the electric fields have the effect of increasing the porosity only, then the equation predicts a decreased pressure drop. Table 15 shows values of the porosity factor $(1 - \epsilon)/\epsilon^3$ versus the porosity, from which it is clear that (on a percentage basis) a small change in porosity can produce a large change in pressure drop. If the electric field also effectively increased the average size of the particles as deposited (causing them to agglomerate), the ratio of the surface area to volume (A_p/V_p) would be expected to decrease, thus further lowering the pressure drop. Unfortunately, both factors which tend to lower the pressure drop are expected to lower efficiency, so that whether or not this is a fruitful approach will depend greatly on the details and magnitudes of these effects.

Table 15. PRESSURE DROP DEPENDENCE ON POROSITY FACTOR

Porosity ϵ	Porosity factor $(1 - \epsilon)/\epsilon^3$
0.3	25.9
0.4	9.38
0.5	4.00
0.6	1.85
0.7	0.875
0.8	0.391
0.9	0.137
0.95	0.058
0.99	0.010

There are several complicating factors in attempting to predict the pressure drop across a granular layer. One factor is that the particles are not monodispersed, and thus smaller particles may lodge between large particles, causing a high pressure drop. Another factor is that the particles may be stacked in different arrangements, and thus the granular structure could be altered by electrostatic forces.

An important factor that should be considered is that the pressure drop across a fabric filter is not simply a function of a granular deposit but is also effected by interactions with the fabric.

Since it is not possible to predict the value of the expression

$$K = \left[\frac{k\mu}{\rho_p} \left[\frac{A_p}{V_p}\right]^2 \frac{(1-\epsilon)}{\epsilon^3}\right]$$

referred to as the specific cake resistance, this value is usually determined experimentally by measuring C_i, V, t and Δp. Draemel[16] conducted an investigation with three dusts and 123 fabrics and reported the following results:

> "K values (specific cake resistance) with a given dust are dependent on the structure of the underlying fabric. The deep channel-like pores, formed by more rounder yarns, can lead to significant deposition of dust under velocity conditions of an order of magnitude or more greater than the average face velocity of the fabric. Deposition at local increased velocity would tend to increase dust packing density and thus increase K."

> "(Dusts subject to cake collapse phenomena imply pressure and/or velocity dependence on dust packing density.) Very shallow pores and a smooth fabric surface with no projecting fibers can be very efficient in particle retention but lead to a completely unsupported dust layer which has a characteristically high K value and is subject to cake collapse as pressure increase. Projecting fibers appear to support a more porous dust cake (lower K values), less subject to cake collapse. The dense projecting fibers

> found with napped fabrics may tend to produce nonlinear Δp versus t response, indicating a deviation from the cake law type of filtration behavior normally seen with a woven fabric. K values with a given dust may vary considerably as a function of fabric even though efficiency remains relatively constant for the same dust/fabric combinations."[16]

If the effect on filter pressure drop of electrostatics is to be determined, then this effect must be separated from the effects caused by any fabric variations, or else the effect of fabric variations must be demonstrated to be an indirect effect acting through electrostatic forces.

A second objective of the program appears to be to determine the effects of electrostatic forces on fabric filter efficiency. There have been a good number of investigations of the effects of electrostatics or single fiber efficiencies. Generally the collection efficiency of a single fiber has been shown to improve under the influence of electrostatic forces. However, fabric filters operate at much higher efficiency and the reasons for particle penetration may differ considerably from those involved in single fiber experiments. GCA and other investigators have found that a large part of the emissions from a fabric filter may occur during the cleaning process or immediately thereafter and that variations in pulse jet or mechanical shake cleaning can cause large changes in filter efficiency.[17] Particle penetration appears to be a combination of seepage (successive reentrainment), direct penetration, and dust that is loosened during cleaning. Electrostatics should affect seepage and direct penetration, although the magnitude of this effect on a high efficiency fabric filter has not been demonstrated. If electrostatic forces are used to decrease penetration during cleaning then quite likely the cleanability of the filter would suffer. Figure 11 is an analysis by Dennis[18] of data presented by Draemel.[16] This figure shows a single fabric-dust combination, Dacron-flyash, and the effect of free area (a function of yarn size, weave, average pore size) on the outlet concentration. Again as with filter pressure drop,

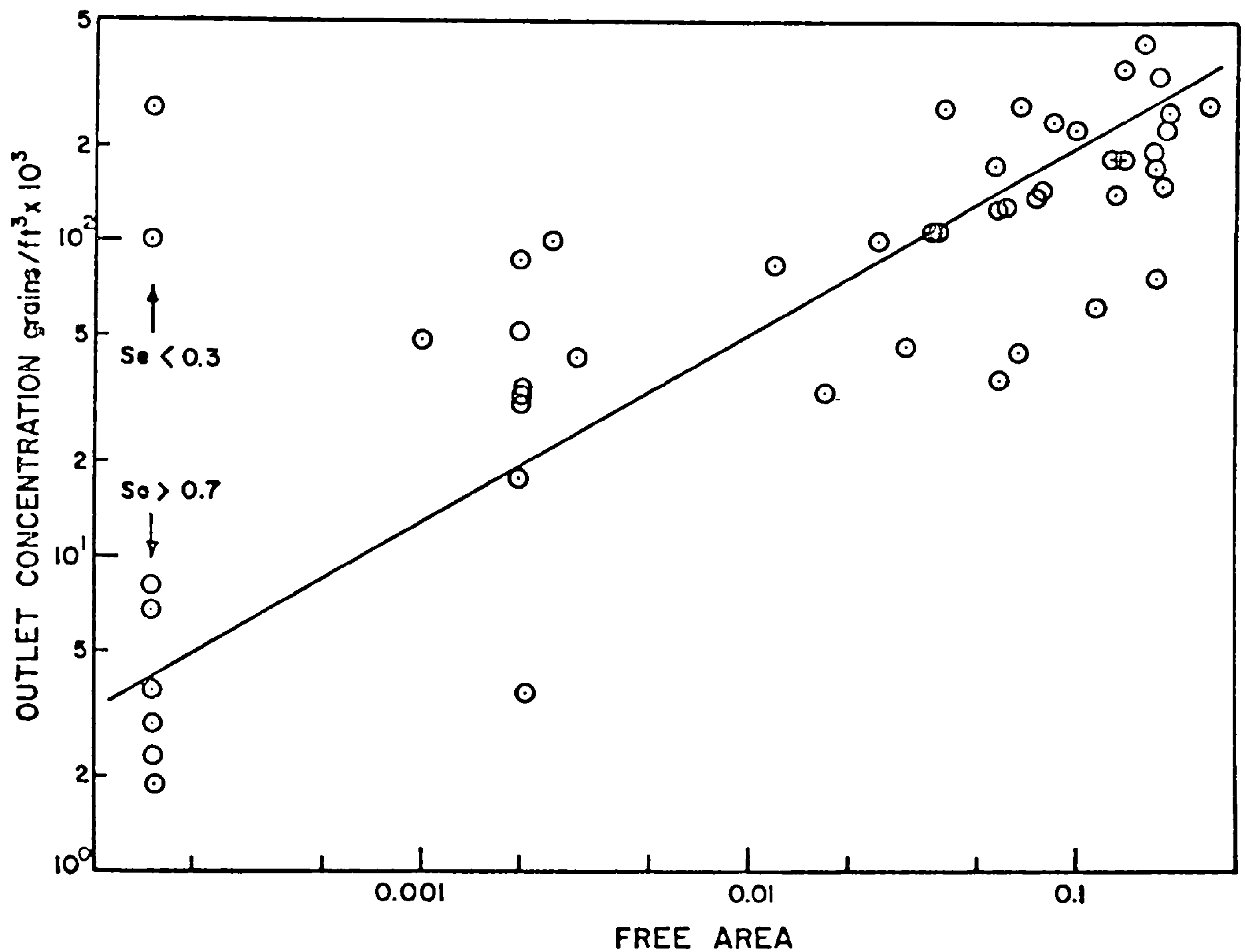

Figure 11. Outlet loading versus free area. Woven Dacron nylon bags, fly ash filtration at 3 grains/ft^3 and 3 fpm[18]

the question arises as to whether the result is a direct effect of fabric properties and cleaning parameters or an indirect effect acting through electrostatic forces or some combination of direct and indirect effects.

The above discussion is intended to point out some of the problems and pitfalls that may be encountered in an investigation of electrostatics and fabric filter performance. Electrostatics and fabric filtration is an area with large data deficiencies that should be investigated. Whether the proposed study shows that electrostatics are or are not an important factor, the results will be useful in that they should provide a functional understanding of the factors affecting fabric filter performance.

Analysis of experimental approach — The proposed experimental work to be performed[31] was lacking as to specifics of how various parameters will be measured or controlled. Table 16 contains all of the important parameters which pertain to the study, for each of the components and concepts. It appears that the parameters concerning the gas which are of importance in this study are either controlled or will be measured.

The same is not true for the particles however, where important parameter such as size and resistivity are not mentioned in the proposal. It may be that the apparently missing parameters will be determined as a matter of routine (they may well be known in advance) and were thus not mentioned in the text. Whatever the circumstances these parameters should be covered as they may be important concerning electrostatic effects.

Charging of the particles will be that charge that is naturally acquired via redispersing dust. There will be no direct application of electrical energy involved, as in corona charging, therefore the majority of the parameters do not apply.

Table 16. PARAMETERS ASSOCIATED WITH THE STUDY OF ELECTROSTATIC EFFECTS IN FABRIC FILTRATION[31]

Parameter	Magnitude, description, method of measurement or control, etc.
GAS	
Volume flow rate	controlled - will be varied
Face velocity	controlled - will be varied
Reynolds number (Re_f)	? (unspecified)
Flow geometry	N.A. (not applicable)
Pressure drop (Δp)	measured continuously and recorded
Temperature	controlled air stream which may be treated to simulate industrial off-gases
Pressure	ambient
Relative humidity	controlled
PARTICLES	
Size	?
Shape	?
Chemical composition	various types of particles will be used
Resistivity	probably to be measured
Dielectric constant	probably to be measured
Charge	assumed to contain natural charges of different polarity - will be measured as total charge of a specific volume of gas at known concentration
Concentration	uniform predetermined loadings will be employed
CHARGING SECTION	
Type of charging	only the charge formed naturally during the industrial generation or laboratory redispersal of particles
Ions	N.A.
Electric field	N.A.
Geometry	N.A.

Table 16 (continued). PARAMETERS ASSOCIATED WITH THE STUDY OF ELECTROSTATIC EFFECTS IN FABRIC FILTRATION[31]

Parameter	Magnitude, description, method of measurement or control, etc.
COLLECTOR	
Chemical composition	various bag materials will be used and the composition will be known
Resistivity	not mentioned specifically; however, it seems that the properties of the filter media will be known for any selected bag filter media.
Dielectric constant	not mentioned specifically; however, it seems that the properties of the filter media will be known for any selected bag filter media
Charge	inferred from field
Voltage, electric field	electric field due to particles will be measured - none will be otherwise induced in the bag
Particulate loading	M (to be measured)
Geometry	
Internal configuration	
External configuration	3-inch diameter bag with 1-1/3 square feet of surface area - 31 inches high
Collection efficiency	M
CLEANING PROCESS	
Method	shaking, pulse jet, reverse jet
Effect on efficiency	?
COMMENTS	effect of cleaning on Δp to be investigated
STAGE OF DEVELOPMENT	proposal for laboratory scale study

All of the parameters concerning the collector will be looked at in detail. Not mentioned specifically are the fabric resistivity and dielectric constant; however, it is likely to be determined under the statement, "all other properties including especially the electrostatic properties of media and of the particulates."

Conventional methods of cleaning fabric filters were discussed as was the effect of cleaning on the pressure drop. Both of these aspects are to be adequately covered; however, efficiency degradation with cleaning was not mentioned as a parameter to be studied. The efficiency degradation with cleaning may be important.

Applicability to Pollution Control - The objectives of this proposed study, to determine the electrostatic contribution to fabric filtration, would obviously be of great interest to designers of commercial baghouse facilities. Since current dèsign of fabric filter installations relies heavily upon past experience rather than laboratory data, formulation of a more systematic scientific approach to baghouse design would be an important tool for the designer.

AMBIENT FIELDS ACROSS FILTER MEDIA

The basic source for the material to follow is an evaluation and summary made by Midwest Research Institute (MRI),[19] based upon the literature and upon a document by Rao et al.[20]

Goals

The MRI study had as its goal "to evaluate the use of electric fields in fabric filters as a means of controlling fine particulate emissions from industrial sources." Systems MRI investigated involved combining with fabric filtration the following:

- external fields
- internal fields
- electrets

Methods

Theoretical - MRI summarizes one external field study: "Rao et al.,[20] extended Zebel's theory by including the effect of the closeness of fibers on the deposition of charged particles by the use of a three cylinder model. Rao et al. assumed potential flow in their model and corrected the velocity and electrostatic potentials by the method of images when the distances between the cylinders is small." The theory predicted decreased deposition on fibers as porosity decreased, which is in agreement with experimental data, for example those of Iinoya and Makino.[27] MRI noted that most filtration theories do not yet take into account most of the factors known from experience to be important: "The air-to-cloth ratio, cleaning mechanism, temperature, humidity, weave pattern, fabric weight, gas flow rate and filter fabric 'surface' characteristics appear to be the most important engineering parameters." MRI also discussed the theoretical work of Ziekman[21] with respect to electrets. Ziekman calculated the electric field in the vicinity of a cylinder in a square lattice array, using the field due to the cylindrical dipole and those of its eight nearest neighbors. His flow model was of the Kuwabara-Happel type. Efficiencies were calculated using computer modelling of trajectories by Ziekman, who found, as expected, higher efficiencies for highly charged particles and for low Reynolds numbers. MRI emphasized correctly that collection of charged particles would rapidly reduce the electret field and regeneration of the electrets would be difficult.

Experimental - MRI referenced work by Walkenhorst,[22] discussed separately here, and by Kirsch.[23] Kirsch used monodisperse aerosols and deliberately kept the filter loading very low. Figure 12, from the MRI report, shows the improvement measured by Kirsch, penetration decreasing as field intensity increased and as flow velocity decreased, as expected. MRI cited work by Dennis[24] and by Silverman[25] on commercial filters having electrostatic augmentation and concluded; "The general

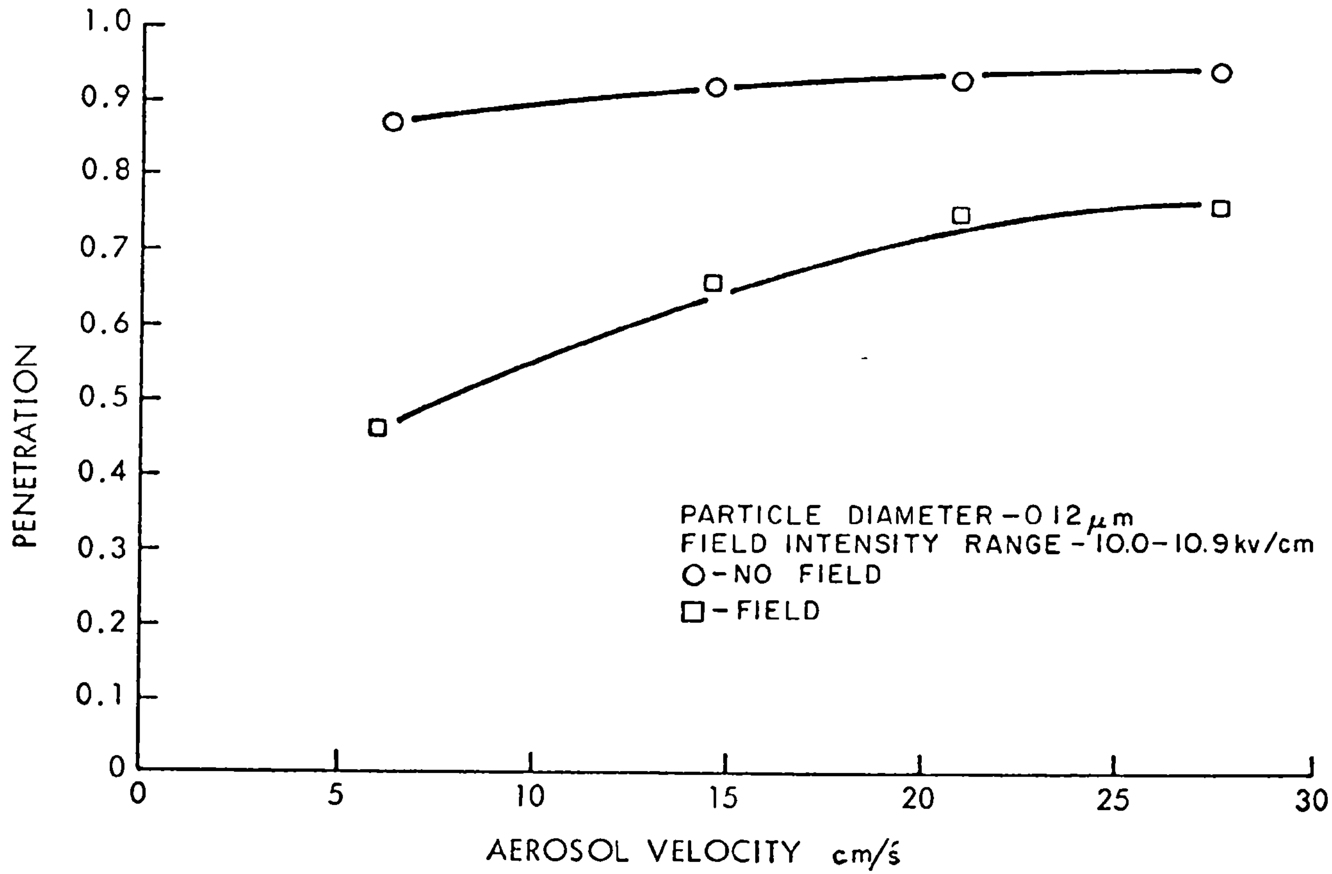

Figure 12. Performance of "real" filter in the absence and presence of external electric field (MRI)[14]

experiences reported in these references are (1) electrification improves collection efficiency for very light loadings of submicron aerosols; and (2) penetration of fine aerosols is relatively high (40 to 50 percent), depending on the flow velocities and porosity of the filter media."

As for electrets, Ziekman[21] also carried out experimental work with electret fibers about 23 μm in diameter for 0.7 μm dioctylphthalate aerosol particles and found, according to the MRI report, that penetration was initially 1 percent for filters made from electret fibers and about 80 to 90 percent for filters made from regular fibers. Unfortunately, penetration increases rapidly with loading as the electrets have their fields cancelled by the collected particles, as shown in Figure 15 from the MRI report (after Ziekman). MRI estimates that only 0.2 ft^3 of gas having a grain loading of 1 gr/ft^3 could pass through 1 ft^2 of area of such filter material before it needed regeneration (this means 6 cm of gas flow path length cleaned for a concentration of 2.3 g/m^3). Although, as Davies[26] notes, electret behavior has been extremely useful in the development of personnel respirator filters, the problem of regeneration seems overwhelming for their use as industrial source control devices.

Results

Figures 12 and 13 give the results from the experimental work of Kirsch[23] and Ziekman.[21] They have been described above.

Conclusions

External electric fields can increase the collection efficiency of filter media, as seen in Figure 12. The effect becomes less as porosity decreases, according to theory by Kao et al.[20] The use of electret material for fibers has the serious disadvantage that the captured particulate material, if charged, will deposit so as to cancel the electret fields, leading to a severe degradation of collection efficiency.

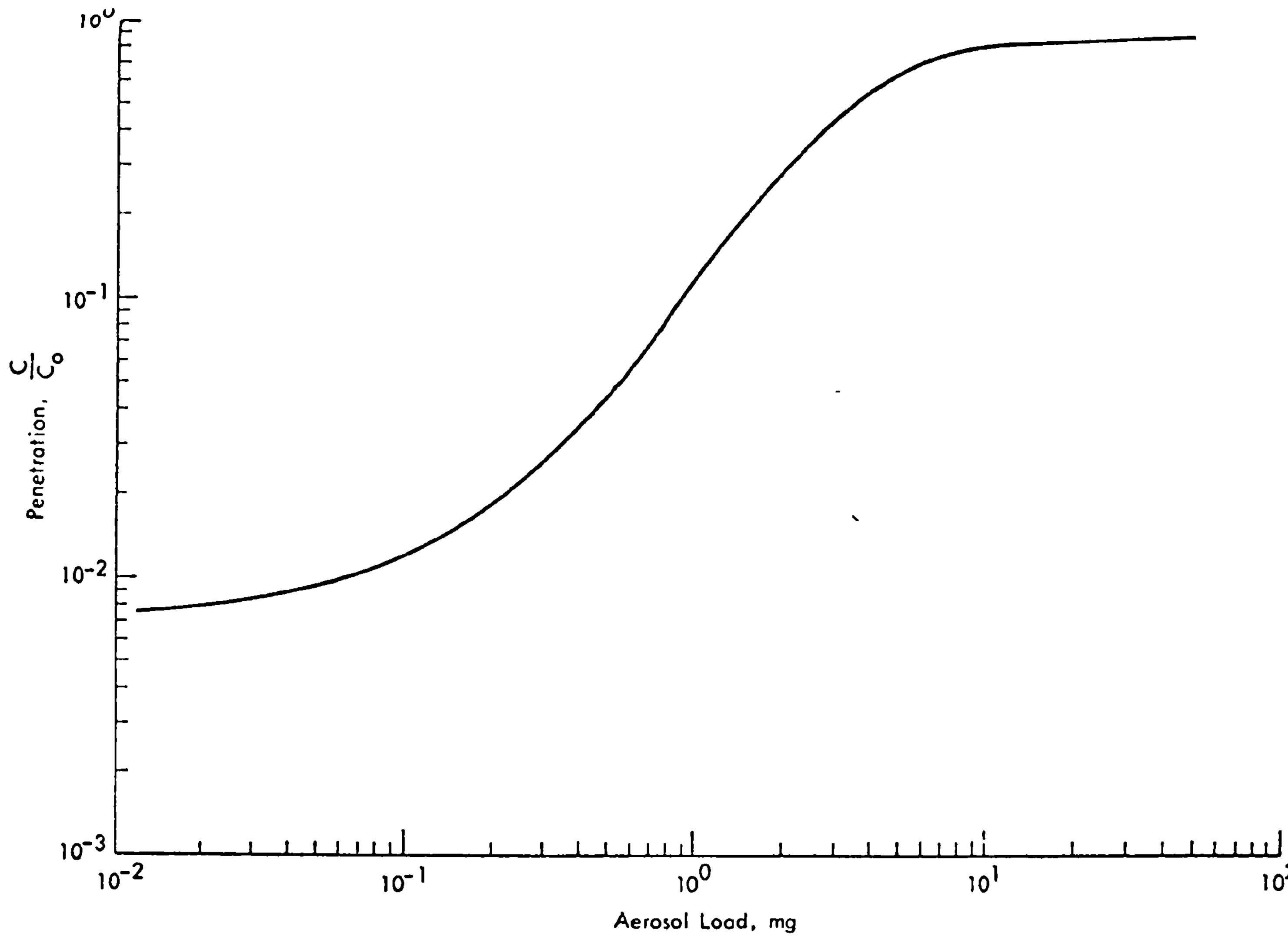

Figure 13. Penetration load curve for electret filter (MRI)[14]

Evaluation

The goal of augmentating filtration efficiencies electrostatically is suitable, clearly. The theory developed by Rao et al. of Notre Dame shows what experiments confirm: increased porosity increases the single fiber collection efficiency for electrified filter materials. Theories which are to handle practical problems in industrial filtration should deal with filters which are heavily loaded as well as with cleaning cycles and fabric surface characteristics. Porous filter media using electrostatics have bright prospects because of their lower pressure drop but there must be a way for these filters to be cleaned to prevent blockage and/or to maintain electrical fields.

Summary

A limited evaluation of the above research has been presented here. The Rao et al. theory seems to explain the effect of porosity on single fiber efficiency, as noted by Iinoya and Makino[27] in their experiments. External fields, internal fields, and electret fields all have similar possibilities and problems: the hope of efficiency collection at lower pressure drop and the problem of removing the collected material or the collected charge or both.

INSULATED WIRE FILTER BED

This work was reported by Walkenhorst,[22] whose description follows: "The construction of the filter is shown in Figure [14]. A frame measuring 5 x 5 cm^2 inside and 0.5 mm thick carries two windings of wire, insulated with varnish; the diameter of the wire is 0.08 mm and the spacing is 0.5 mm. ... the surface of the wire is rendered water repellent. The windings are indicated in the upper diagram of Figure [14], one of them being shown with broken lines. 600 V is applied between the windings and the polarity is reversed periodically. Very good insulation is necessary to avoid leakage at high relative humidities."

"To make the filter, 10 of the frames were mounted in series with a distance of 0.5 mm between each; this made the horizontal and vertical distances the same between all the wires. Each layer was opposite its neighbor. In the lower part of Figure [14], to make this clear, the positive and negative polarities, at a given moment, are shown by solid and open circles, respectively."[22]

Goals of the Study

This study was performed to determine the effect of inhomogeneous electric fields on the capture of particulate. Efficiencies were determined for the wire filter arrangement previously described, measured under varying electrical states to try to determine the best possible removal efficiency.

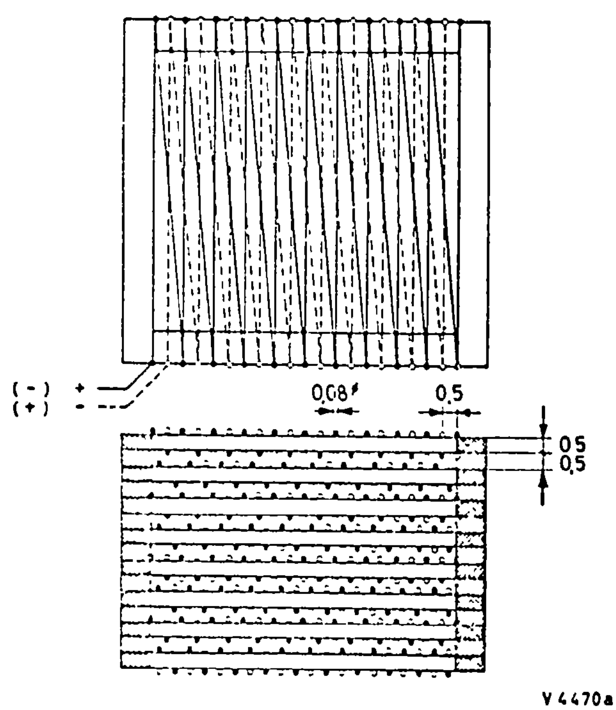

Figure 14. Diagram of filter construction[26]

Methods of Study

The study was performed by Walkenhorst in two parts, in which both theoretical and experimental analyses were utilized.

Theoretical — The theoretical method of study was closely linked with experimental results. Theories concerning the anticipated electric field strengths and direction were individually checked with a simple model to be described. Figure 15 illustrates the theoretical electric fields anticipated with the indicated arrangement of wires and collected charged particulate. The theories were then substantiated utilizing a simple experimental technique, the results of which are in good agreement with the theory.

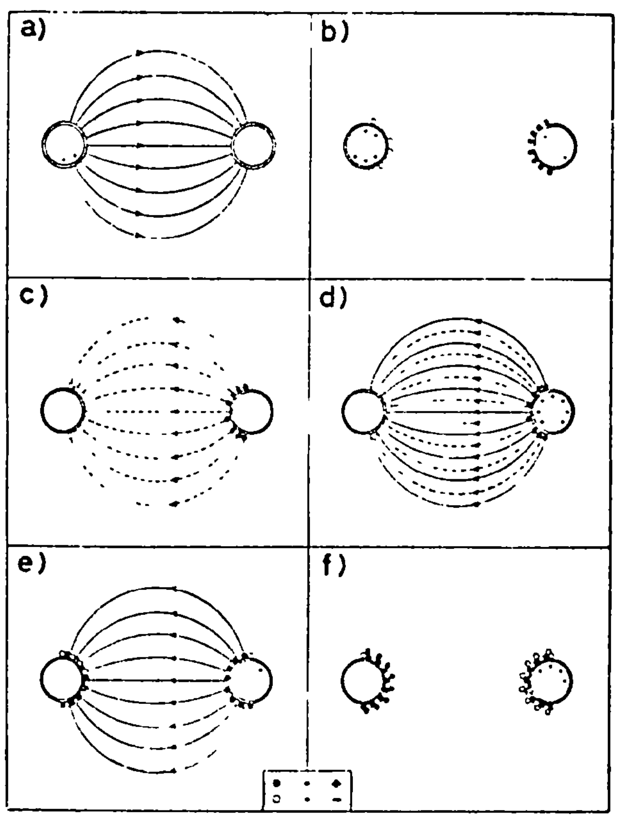

Figure 15. Changes in the electric field between a pair of insulated wires due to the deposition of charged particles (equal numbers of each polarity)[22]

Figure 15 illustrates the theoretical approach behind the first series of tests utilizing the simple model illustrated in Figure 16. Case (a) demonstrates the electric field generated between two insulated wires, across which an electric potential is applied. Since the wires have curved surfaces, and the distance between the wires is small, an inhomogeneous electric field is the result. In an inhomogeneous electric field, particle collection can occur in two ways, via coulomb attraction with charged particles, and via induced dipole attraction on charged and/or uncharged particles.

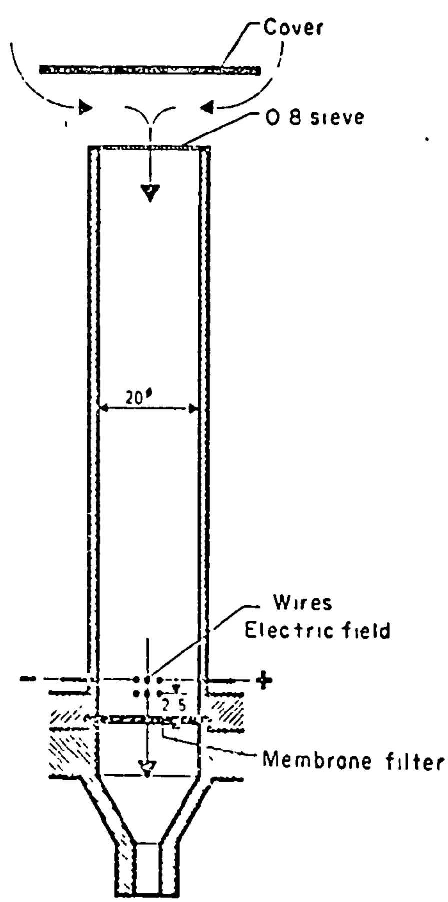

Figure 16. Experimental apparatus for studying the effect of an electric field on the trajectories of dust particles

Case (b) illustrates the complete neutralization of the electric field which could occur due to the deposition of charged particles of a particulate which contains no net charge, in other words an equal amount of positive and negative charged.

Case (c) illustrates the field resulting from removing the applied potential across the wires in case (b). The charged particles would now create a field equal and opposite in direction to the field in case (a). If we were now to apply a potential across the wires in the opposite direction as was previously applied we would have the result of doubling the strength of the field in case (c) corresponding to case (d).

If charged particles are again collected by the wires, they would eventually have the effect of neutralizing the previously oppositely charged particulate, at which point we would duplicate the field in case (c), illustrated in case (e). However, the source of the field in case (e) would be the potential applied across the wires, not the charge on the collected particles.

Finally, if more particles were collected by the wires, we would again neutralize the field generated by the applied potential and we would return to the case where the case of complete field neutralization, case (f), which corresponds to the original case (b). It was then postulated that an insulated wire filter could be operated under the aforementioned principles to remove naturally generated charged and/or uncharged aerosols, with parameters concerning applied potential, geometry, particle charges, and potential reversal frequency to be determined by experiment under given conditions.

It was recognized that the majority of naturally generated aerosols display a tendency towards an overall net charge and that the simplistic model discussed in Figure 15 would not as such strictly apply since at no time would the field be entirely neutralized due to the excess of charge of one sign over another. This does not however alter the basic mechanism from which such a filter would operate, only the voltage reversal frequency will require readjustment.

Experimental — The experimental approach consisted of two distinct phases. The first phase of the experimental work consisted of attempts to corroborate the theory put forth concerning electric field configurations anticipated with the wire arrangement shown in Figure 15. An experimental apparatus was constructed, shown schematically in Figure 16, which tested the field strength qualitatively via a photographic technique, described as follows:

"A suitable experimental method has been described previously (Walkenhorst, 1962). The present setup is shown in Figure [16]. The wire, or several wires which are insulated from one another and between which the electric field is established, are placed across a tube of 20-cm diameter. At a distance of 2.5 mm below the wires there is a membrane filter on which dust is collected in the same distribution of concentration as it has after passing the wire. A distance of 2.5 mm suffices to visualize undisturbed parallel flow, 2.5 mm being 25 times the wire diameter of 0.1 mm. A 'picture' of the obstacle in the flow is obtained on the filter which shows clearly what is going on and can be evaluated quantitatively. To prevent coarse dust from falling into the tube the upper end is covered above an entry zone and there is a wire gauze with 0.8 mm opening on top of the tube. This helps by preventing uncontrolled air currents in the tube and ensuring laminar flow. Using coal dust and a white membrane filter a visible 'picture' is obtained."[22]

The second phase of the experimental work consisted of the construction of the filter previously described, shown schematically in Figure 16. This filter was then tested for particulate collection efficiency while varying parameters of gas velocity, relative humidity, field strength and duration, and field reversal frequency. Details concerning the actual filter are given above. The experimental procedure is as follows in this quote from the text:

"The finished filter was mounced in a holder through which air could be blown. Some experiments were doen with a finely powdered bore dust (Ruhr sandstone, 95 percent < 5 μm). A tyndallometer was used to indicate concentration. In most experiments the dust was generated by a Wright apparatus, coal and quartz dust were used. To adjust the relative humidity an atomizer is used which may rise it up to saturation. A rotameter was used to measure the air flow through the filter, and the pressure drop across it was measured within 0.1 mm of water with an inclined manometer.

In order to determine the deposition, samples of air were taken with thermal precipitators up and downstream of the filter. Particle size and number were counted with a light microscope. The fractional deposition could thus be ascertained down to 0.5 μm." [22]

Results

The results of the initial experimental investigations with the apparatus in Figure 16 were a series of photographs illustrating bands of various widths associated with the distance surrounding the collecting wire pair in which particles were captured. The appearance of a wide fringe around the thin wire indicates that there were far fewer particles collected in that light area. The width of the fringe well beyond the wire width is a measure of the effectiveness of the electric field versus only the wire as an obstacle causing deposition. Thus by varying the field strength, duration, and direction, the theories previously discussed were corroborated.

The results of the second phase of the experimental work, that with the actual filter, were given in graphical form, illustrating the variations in filter efficiency with the parameters which were experimentally varied. Figures 17, 18, 19, 20, and 21 follow as they appeared in the original text. Figure 17 verifies the previous theoretical considerations, displaying the deposition efficiency with a tyndallometer under the different operating conditions listed. As expected, the very high porosity filter is not effective when used without any applied voltage. Following the operation of the filter without voltage for 10 minutes, the approximate theoretical maximum voltage of 600 volts was applied to the filter with the polarity reversed every 10 seconds to simulate the best possible collection conditions. Under these conditions the efficiency was measured at up to 97 percent for a time of 60 minutes; again the filter operated more efficiently with the applied voltage, as expected. The filter was again operated with no applied voltage, relying on the charge of the previously collected particles to generate some intermediate strength field, which would now mean efficiencies somewhere between the initial run without applied voltage and the subsequent run with applied voltage. As can be seen this is again the case, as the efficiency varied between 20 and 30 percent deposition. However, the increasing efficiency with time would not be the expected result; the existing field should be slowly neutralized as more particles are collected. The 600 volts are again applied across the fibers without reversing polarity, resulting in the overall high collection efficiency of about 95 percent for 24 minutes. The effect of running without polarity or field reversal would be a deposition of particles on the filter, strictly charge separated for the entire 24 minute run. This should have resulted in a strong residual electric field, due to the build up of charge strictly by sign. This appears to be the case when the external voltage is removed and the efficiency decreases from 83 percent to 70 percent in 15 minutes, as would be expected.

A significant parameter concerning the operation of their filter is the magnitude of the applied potential. A theoretical calculation, performed in the text, predicted that the maximum applied voltage before

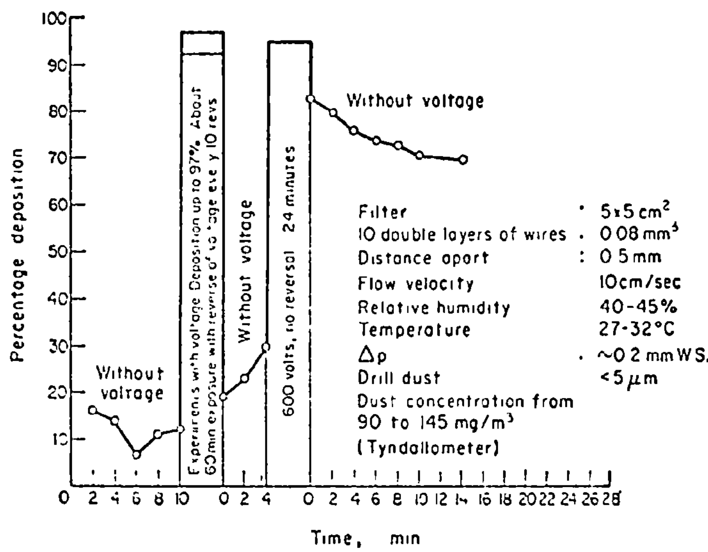

Figure 17. Deposition efficiency of a filter under different operational conditions[22]

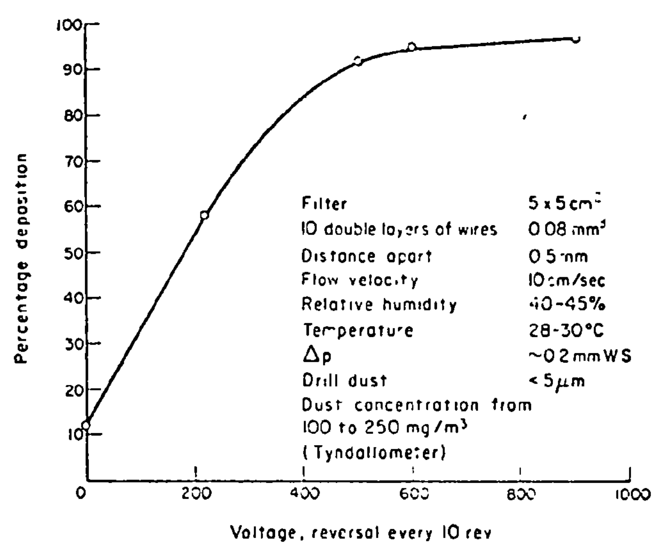

Figure 18. Dependence of deposition efficiency on applied voltage [22]

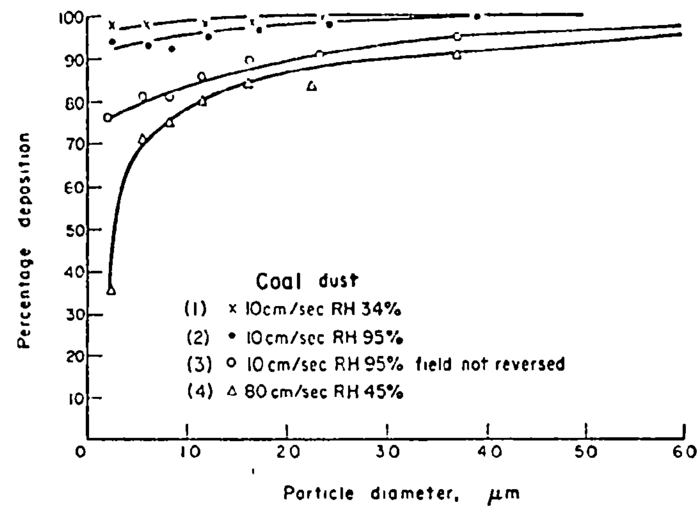

Figure 19. Experimental results with coal dust[22]

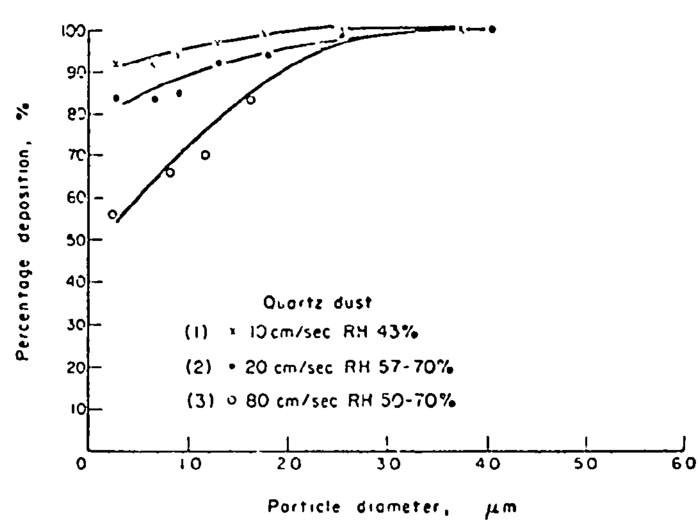

Figure 20. Experimental results with quartz dust[22]

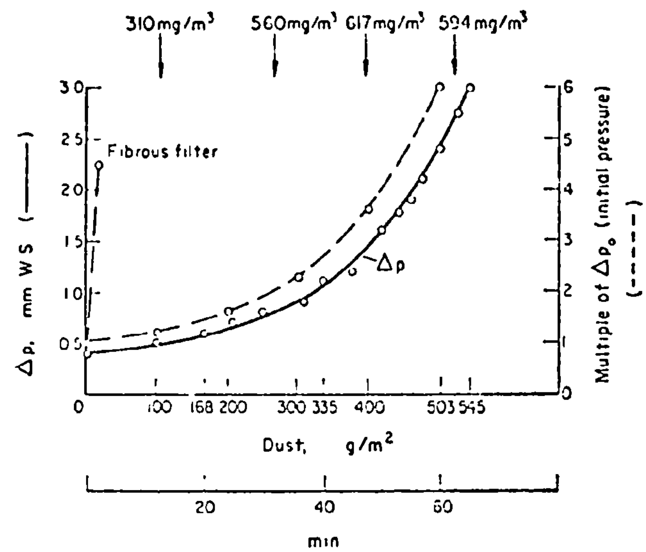

Figure 21. The increase of pressure drop at constant airflow in relation to the amount of dust on the filter[22]

corona onset was 577 volts. Figure 18, percentate deposition versus applied voltage, shows a leveling of the curve at about 600 volts, after which only a slight increase in deposition is observed. This is in excellent agreement with the theory, especially considering the allowable tolerances in the construction of the filter, and the likely resulting irregularities in the geometry and therefore electric field.

Figures 19 and 20 show the results of a series of tests run under the stated conditions, with the experimental approach previously discussed, for two different types of dust, coal and quartz. Variations in face velocity and relative humidity for coal and quartz dust yielded expected results of decreasing deposition with increasing face velocity and relative humidity. These curves of percentage deposition versus particle diameter display the usual decrease in deposition with decreasing particle size, however the dependence is not as pronounced as usual for this type of curve except for the highest velocity (80 cm/sec) case. Although the percent relative humidity adversely affects the percent deposition, the effect appears to be relatively small.

There are several aspects of a filter's operation which are important in determining its performance. The most important of these are the filter's collection efficiency and pressure drop. For most industrial applications the loading capability and cleanability are also very important. Figure 21 illustrates pressure drop, at a constant airflow, versus filter dust loading for the electrified insulated fiber filter and a fibrous filter. While both filters display the expected rise in pressure drop versus dust loading, the conventional type fibrous filter shows a dramatically higher rate of increase of pressure drop with dust loading. This indicates that the filter under study would be highly advantageous from an energy per unit volume of gas filtered basis.

Conclusions

The inhomogeneous electric field generated between the wires in the filter caused effective particulate removal in the filter. Operating the filter without any applied voltage resulted in efficiencies at or slightly greater than 10 percent, while an applied voltage raised the efficiency to as high as 97 percent.

It is necessary to reverse the field (current in the wires) periodically, to achieve the maximum removal efficiency, as can be noted by comparison of case (2) and (3) in Figure 19. It may also be noted by looking at case (1) and (2) in Figure 19, that relative humidity adversely affects particle removal efficiency. Figure 18 illustrates the proportional relationship between removal efficiency and applied voltage which reached a virtual maximum between 500 to 600 volts. Higher voltages did not result in increased particulate removal efficiency, in agreement with the theoretical corona onset potential of 577 volts.

The pressure drop for a given flow velocity was found to be very low, (see Figure 21), and increased slowly with filter loading. A conventional fiber filter displays a much larger increase in pressure drop with increased filter dust loading, giving the new filter an advantage.

Evaluation

Suitability of Goals – The practical goals of this study were to develop a fiber filter which would efficienctly remove particulate matter via an electrostatic capture mechanism. The filter was to be an efficient particle trap due mainly to the electrical capture mechanisms as opposed to mechanical capture mechanisms normally associated with filtration. This allows for the construction of a low pressure drop filter. Such a low pressure drop filter would not require large energy expenditures to force the gas through the filter, as is normally the case in filtration.

Fine particle control was not considered separately in the Walkenhorst study; however, it is implied that the filter in question would be more efficient capturing fine particles than a high pressure drop analog, if the filter were sufficiently deep to create a similar pressure drop to a conventional filter. In other words, increasing the size of the filter to the point where the low pressure drop advantage is lost would result in an efficient remover of particulate of all sizes when compared to a similar conventional filter.

The goal of developing a more energy-efficient particulate removal filter is obviously important, but there is a second aspect which will require study: cleaning and reusing such filters. The goals of Walkenhorst were limited in that this aspect was not studied in depth.

Suitability of Methods for These Goals - The methodology utilized to achieve the goals of this study will be analyzed, with particular emphasis upon the theoretical aspects of the study. (Detailed information concerning the experimental aspects were not published and the study was completed some years ago, making it of limited value to suggest improvements in experimental techniques).

Analysis of Theoretical Approach - The theoretical analysis, as previously outlined, concerning the generation of inhomogeneous electric fields and the use of these fields to capture particles appears to be sound, qualitatively. A quantitative theoretical analysis of the filter efficiency due to electrical forces was neglected. There was, however, an analysis of the field strength and field gradient for assumed conditions, which analysis bears upon the theoretical capacity of the type of filter in question.

The filter in question is expected to remove particulate from an air stream via two electrical mechanisms. The first mechanisms, thought to be the most important for uncharged or only slightly naturally charged aerosols, is the deposition of particles due to induced dipole attraction in an inhomogeneous electric field. The second mechanism, which could be important if sufficient natural charge exists on the particulate, is capture by coulombic attraction. Let us look more closely at the expected efficiency of the proposed filter for each of the two mechanisms.

If we examine the induced dipole mechanism, we can determine the electrical force (F_E) on a 1 micron diameter particle using the equation:

$$F_E = 2\, \chi_E\, V_p\, \bar{E} \text{ grad } E$$

where V_p = particle volume

E = electric field and

assuming a spherical particle,

$$\chi_E = (3\pi/8)\ \frac{\epsilon_K - 1}{\epsilon_K + 2}$$

which for a conductive particle is simply

$$\chi_E = 3\pi/8$$

because the dielectric constant, ϵ_K, tends to infinity. $\bar{E}$ is the average electric field, which in this case is the average of E_{max} and E_{min}, or 2.32×10^4 V/cm, and grad E is 10.26×10^5 V/cm^2. These become 77.3 stat volt/cm and 3.42×10^3 stat volt/cm^2. Both values are quoted from the text[22] for the 0.1 mm diameter wire and 0.5 mm space between the two wires.

(We were not able to verify the value for the average gradient due to an apparent error in equation (3) of the Walkenhorst[22] text for E_{min}, which generated a negative number in the natural log group, making it impossible to solve.) Solving the equation for the force acting on an uncharged 1 μm diameter particle in an inhomogeneous field we get:

$$F_E = 2\, \chi_E\, V_p\, E \text{ grad } E$$

$$F_E = 2\, (3\pi/8)\, (4\pi/3)\, (0.5 \times 10^{-4})^3\, (77.4)\, (3.42 \times 10^3)$$

$$F_E = 3.27 \times 10^{-7} \text{ dynes}$$

which corresponds to a migration velocity:

$$w = FB$$

$$w = 2.22 \text{ cm/s.}$$

In order to calculate the coulomb attraction on each size particle, it is necessary to make some assumptions concerning the naturally occurring charge on the particles. We have chosen the number of elemental charges on each particle by using the values quoted by Walkenhorst in the text, and extrapolating to obtain estimates for the 0.25 µm and 1.0 µm particles. In this way we had hoped to be consistent in our calculations with what Walkenhorst apparently expected the particulate charge distribution to be like. The actual values are tabulated in Table 17. (It must be noted, however, that our own lab experience with the Wright apparatus for redispersing dusts leads us to expect much more highly charged particles than indicated in Table 18. In view of the lack of any measurement of the charge on the particles in the study, we cannot make any accurate estimate of the charge concentration of the particles.)

Table 17. THEORETICAL AND EXPERIMENTAL EFFICIENCY FOR COAL DUST AND QUARTZ DUST AT 10 cm/s FACE VELOCITY

Particle diameter (microns)	Assumed number of elementary charges	Theoretical efficiency percent	Observed efficiency (coal dust) @ 34% R.H.	Observed efficiency (quartz dust) @ 43% R.H.
0.25	1	90.05	97	92
1.00	2	96.70	98	96
2.00	10	99.99	100	99
3.00	200	100.00	100	100
4.00	400	100.00	100	100

Table 18. THEORETICAL AND EXPERIMENTAL EFFICIENCY FOR COAL DUST AND QUARTZ DUST AT 80 cm/s FACE VELOCITY

Particle diameter (microns)	Assumed number of elementary charges	Theoretical efficiency percent	Observed efficiency (coal dust) @ 34% R.H.	Observed efficiency (quartz dust) @ 50-70% R.H.
0.25	1	25.10	35	56
1.00	2	34.80	78	70
2.00	10	77.70	86	91
3.00	200	99.50	90	99
4.00	400	99.98	92	100

If we assume a net charge on the 1.0 micron diameter particles to be equal to two elementary charges per particle, we can then solve for the Coulomb force on this particle. The coulomb force is given in the equation:

$$F = q\bar{E}$$

$$F = (9.6 \times 10^{-10} \text{ stat coulombs})\ (77.4 \text{ stat volts/cm})$$

$$F = 7.43 \times 10^{-8} \text{ dynes}$$

and the migration velocity is:

$$w = FB$$

$$w = (7.43 \times 10^{-8})\ (6.8 \times 10^{6})$$

$$w = 0.52 \text{ cm/s.}$$

The overall efficiency can be approximated from the sum of the forces, and thus migration velocities previously determined, using the equation;

$$E = 1 - \exp\ (-\ w_t\ A/Q)$$

we can solve for the efficiency (using MKS units):

$$E = 1 - \exp\left(-\ (2.2 + 0.5)\ (10^{-2})\ (3.17 \times 10^{-2})\ /\ 2.5 \times 10^{-4}\right)$$

$$E = 1 - \exp\ (-\ 3.4236)$$

$$E = 0.967.$$

This value for the efficiency of the filter is in excellent agreement with the experimental results. It was stated that "efficiency reached values up to 97 percent" for the previously stated conditions, also it can be seen in Figure 19, for case (1), that the collection efficiency at 1 micron is approximately 98 percent.

Table 17 contains the results of calculated theoretical efficiencies expected from the combination of induced dipole and Coulomb forces, and the corresponding experimental results obtained from Figures 19 and 20, case (1). It can be seen that the theory agrees very well with the experimental results; however, the values for efficiency taken from the curves are only approximations. Because we are looking at a very narrow portion of the curve, these approximate values are difficult to obtain with much accuracy. Table 18 is a comparison of theoretically calculated efficiency for coal and quartz dust at a face velocity of 80 cm/s, and the experimentally observed results for the tests at 80 cm/s. The assumed charge on the particles corresponds to those values given in Table 17.

It should be noted that the predicted efficiency for the 0.25 micron diameter particle (Tables 17 and 18) is lower than the observed experimental efficiency, especially with the coal dust. This may be due to the misplacement of the points on the curve which correspond to the 0.5 micron diameter particles, since in the text referring to measurement capability, it was stated that "fractional deposition could thus be ascertained down to 0.5 micron." Aside from this inconsistency, the theoretical efficiencies correspond well to the observed results.

Another possible source of conflicting results, especially at the lower particle size range, may have been the somewhat arbitrary value for the overall net charge which we assigned to the particles to determine the Coulomb force. It was assumed that the overall net charge on each particle would correspond to the values and ranges quoted in the text. It may well be, however, that these values are generally too low for the particulate used in the experimental procedure. The coal and quartz dust utilized in the experiment were redispersed aerosols which are typically highly charged. Because the smaller particles tend to have only a small amount of net charge (we used one elemental charge per each 0.25 micron particle and two elemental charges per 1.0 micron particle), the error in the predicted efficiencies would tend to be very great if the net charge were off by only one or two elemental charges.

Examination of Table 18, which corresponds to the conditions of Figures 19 and 20, case (4), reveals a more distinct tendency for the experimental results to be higher than the predicted theoretical results. This is as would be expected if the net charge assigned for each particle were indeed low, or if some collection mechanisms have incorrectly been assumed to be negligible.

It is important to note that in all of our theoretical calculations, we have been dealing with expressions which require the use of the equivalent aerodynamic particle diameter. While never clearly stated in the text, it would appear from the use of the optical microscope that the author is dealing with the optically measured particle diameter. Again, since we are dealing with small disagreements between theory and results, and since small differences in particle diameter have a large effect upon the theoretically calculated force, migration velocity, and ultimately efficiency, the discrepancy between theory and experimental results is within limits placed by observational errors.

Analysis of Experimental Approach — As mentioned, the analysis of the experimental approach will of necessity be brief. The first phase of the experimental work dealt with use of the apparatus displayed in Figure 16 to verify the proposed theoretical collection mechanisms. Results of these tests were previously covered, and may be summarized by stating that the theory is in very good agreement with the experimental results. The functioning of the test apparatus and the experimental procedures have little bearing upon the objectives of this evaluation, and thus will not be discussed further. Details of the experimental apparatus and procedure were not given in this article, and were referenced so that they could be studied by any interested persons.

The experimental techniques utilized were sound for their chosen use, with some reservations pertaining to details concerning the number of particles counted; however, without more detailed information we must assume the techniques were properly applied. The use of thermal precipitators, which are somewhat particle size dependent, may be questionable considering the altering of the particle size distribution expected after passage through the filter. Also, it has been our experience at GCA that the Wright apparatus produces a highly charged particulate, which may have seriously affected the collection on the charged filter. The charge on the particles was not measured and may have thus been underestimated.

Applicability to Pollution Control - The electrified insulated wire filter appears to have potential application as a pollution control device.

Prospects of the Method - The positive aspects of this device include its apparently high efficiency at very low pressure drop and the ability to function efficiently at high humidity. Possible negative aspects of the device deal with its capacity to handle efficiently aerosols of higher grain loadings. The experimental results were done at a relatively low, but not uncommon, grain loading of approximately 0.25 grains per cubic foot (approximately 0.5 g/m^3).

Status of the Method - The filter appears to be capable of efficiently removing particles at a high face velocity, when compared to a fabric filter, namely 10 to 20 cm/s (20 to 40 fpm) versus 1 to 1.5 cm/s (2 to 3 fpm). The filter also appears to be capable of accepting a somewhat higher loading than some fabric filters. The higher face velocity and loading capabilities would indicate that a smaller sized unit would be capable of handling a similar capacity of offgas, compared to conventional fabric filters. This would translate into an initial capital cost advantage due to the physically smaller facility, neglecting the probable cost difference of filter media. For a given grain loading and gas throughput, a smaller filter capacity would require more frequent cleaning. It is in the question of filter cleaning that the greatest potential problem for the insulated fiber filter arises. It is difficult to assess the filter cleanability since no effort was directed towards this goal; however, it is conceivable that increased costs associated with filter cleaning requirements could offset the previously mentioned potential savings.

Implications - If the filter could be demonstrated to operate efficiently at higher grain loadings, and is capable of being easily cleaned without serious efficiency degradation, then the device has many potential applications to pollution control.

RELATED STUDIES

Filter Electric Fields, Applied and Intrinsic

Recently, the Japanese scientists Iinoya and Makino (1974) [27] published a summary of their theoretical and experimental work concerning the following:

- Collection due to the natural charge existing on a fiber.
- Collection on conductive fibers with applied voltage.
- Collection on dielectric fibers with applied voltage.

Summary - In general they found higher efficiency could be achieved at lower pressure drops with electrified filters than with nonelectrified filters. The work was done with relatively light filter loadings, well below those for which a filter cake is formed. No work on cleaning was reported.

Naturally charged filters - Having shown earlier that collection by glass fiber filters was nearly equivalent to collection by synthetic fiber filters treated with anti-static coatings, Iinoya and Kimura[28] used the collection efficiency of the glass fiber filters as the reference point from which they measured the natural charge densities of synthetic filters. For cotton, nylon, teflon, and some other fibers they measured "characteristic numbers" ~ 10^6. The definition of the characteristic number, k_z, is

$$k_z = Pe\ Z/Z_G$$

where Pe is the Peclet number, (length)(velocity)/(diffusion coefficient), and Z is the ratio of the minimum experimental collection efficiency for a single fiber to the interception regime theoretical value; the subscript G is for glass. Their assumption is that the differences in disagreement with theory are due to a known factor (Pe) and the electrical "characteristic number." Values ~ 10^6 indicate these fibers are capturing material much more efficiently than comparable glass fibers. Iinoya and Kimura[28] used the formula for the capacitance (charge per unit voltage) of an isolated fiber to convert the q that they infer from the k_z into a "natural electrostatic potential." Increasing natural electrostatic potentials were found for the series: vinyl, cotton, nylon, teflon.

Electrically conductive fibers — Two different graphite-packed fibrous filters were constructed and tested by Iinoya and Makino,[27] a single-stage type and a double-stage type. (See Figure 22.) They were tested for collection efficiency as a function of applied voltage, and the data were presented in terms of the migration velocity, w, using the expression for penetration:

$$Pn = e^{-w\ A/Q}$$

in which A is the collector surface area and Q is the volume flow rate, as usual. For the single-stage device, they measured increasing efficiencies (greater migration velocities) with increasing voltages, regardless of voltage polarity. For the double-stage device, they measured greater migration velocities for smaller fiber volume fractions (presumably due to less electrostatic mutual interference), smaller distances between the two stages (more intense electrical fields), and lower face velocities, this latter perhaps indicating that other collection mechanisms (diffusion?) were important or that the complete mixing implicit in the exponential expression did not occur. For single fiber efficiency they calculated from their data the correlation for the increased efficiency due to voltage V:

$$\Delta\eta = 1.4 \times 10^{-14} V^2/(1 - \varepsilon)^{3/2} u^{1/2}$$

where $\Delta\eta$ = increase in efficiency of a single fiber

u = face velocity, m/s

ε = void fraction of filter

V = voltage, volts.

The correlation was obtained for particles from 0.8 μm to 1.4 μm in diameter and for fibers 7.0 μm and 9.0 μm in diameter. For filters with 99.5 percent open volume, the single fiber efficiency was 30 times that of a conventional fiber.

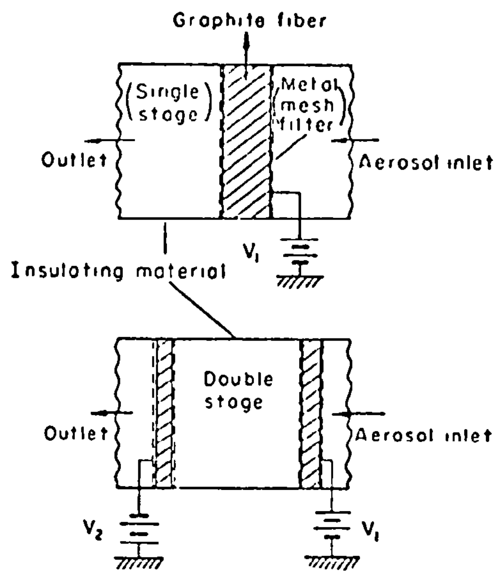

Figure 22. Methods of applying a d.c. voltage to electrically conductive fibrous filters[27]

Dielectric fibrous filter — The models for this type of filtration are shown in Figure 23. The voltage is zero at the wall. At the front and rear faces of the filter, metal grids allow the imposition of voltage by either putting the front face at one voltage and the rear at another (case I) or putting adjacent wires at alternate voltages. Figure 24 shows the dimensionless electric fields versus dimensionless distance for both cases. For case I, the field is nearly homogeneous across the filter, and for case II it is most heterogeneous at the faces and decays rapidly within the filter. The case II configuration is very similar to that studied by Walkenhorst[22] which we have described above. Iinoya and Makino give an equation based on the polarization of the fibers by the field that predicts the increase in collection efficiency due to the field, corresponding to case I. (They did not go into much detail about case II because they had noted that the collection efficiency would not be expected to be as great as for case I, but this may be offset by the greater ease of cleaning for a filter which causes most of the deposit on its face.) They evaluated an empirical constant for the equation, using data they obtained in the case I model. Again, much higher single particle efficiencies

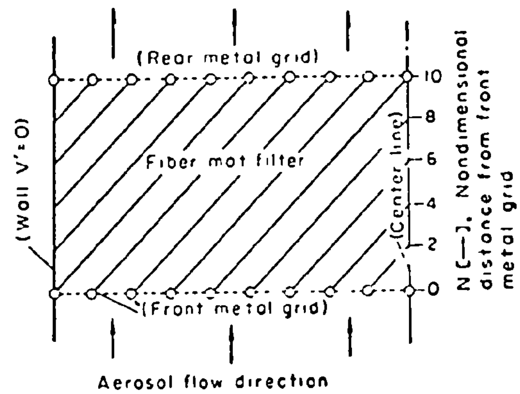

Figure 23. Analytical model of a dielectric fiber mat filter[27]

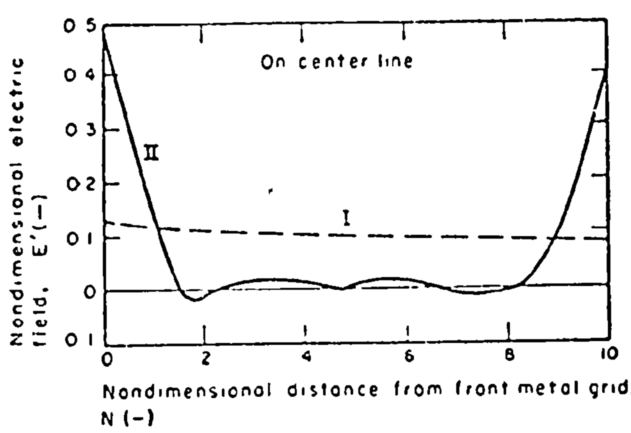

Figure 24. Effect of charged condition of metal grids on electric field distribution in a dielectric fiber mat filter[27]

are predicted with the addition of electrostatic forces. AC or DC fields could be used, as they pointed out.

Evaluation

The work by Iinoya and Makino[27] quantified several important collection enhancement methods employing electrostatics with filtration. If economical disposable fiber filters can be developed, then electrical effects could be used to improve the efficiency/pressure drop characteristics of a filter without worrying about the cleanability of such a filter. It may be possible to use electrostatic effects briefly at the beginning of a filtering cycle to accelerate the formation of the filter cake by increasing the "clean" collection efficiency of the filter. At present, however, such methods seem far from being ready for commercial application.

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SECTION VI

ELECTROSTATIC AUGMENTATION OF SCRUBBERS

OPPOSITELY CHARGED DROPLETS AND PARTICLES

This work is being done under Dr. Pilat of the University of Washington. The scrubber consists of two spray chambers, the first being counter-current flow and the second chamber cocurrent. The scrubber is electrostatically augmented by charging of the droplets and the particulates to opposite polarities using inductive charging and corona charging, respectively. The scrubber configuration, with aerosol charging chamber, is shown schematically in Figure 25. The study, to date, has utilized two different sized units, one of 6.61×10^{-2} m^3/s (140 cfm) capacity, and one of 0.472 m^3/s (1000 cfm) capacity, both constructed of 1/4-inch lucite to allow visual observation of the internal operation of the scrubber. More details concerning the physical dimensions and construction of the two scrubber units appear in Table 19.

Goals of the Study

This study is being performed to develop an efficient fine particle collection device, suitable for application to industrial sources. It is under development.

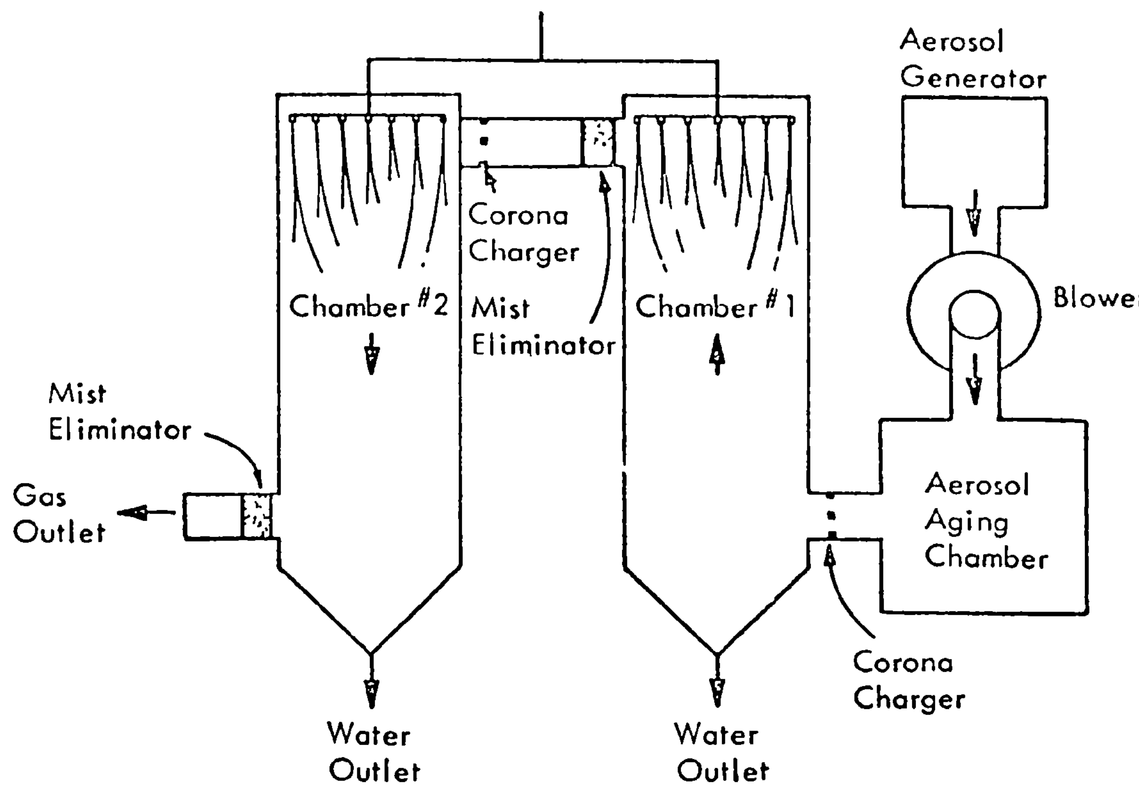

Figure 25. Schematic diagram of electrostatic droplet scrubber[6]

Table 19. PARAMETERS ASSOCIATED WITH THE STUDY OF THE ELECTROSTATIC SPRAY SCRUBBER

Parameter	Magnitude, description, method of measurement or control, etc.
GAS	
Volume flow rate	140 cfm (0.066 m^3/s)
Face velocity	measured
Reynolds number (Re_f)	?
Flow geometry	known (K)
Pressure drop (Δp)	measured
Temperature	ambient
Pressure	ambient
Relative humidity	controlled at 100%
PARTICLES	
Size	measured
Shape	spherical
Chemical composition	DOP
Resistivity	K
Dielectric constant	K
Charge	measured
Concentration	measured - 0.15 gr/acf (0.34 g/m^3)
CHARGING SECTION	
Particles	
Type of charging	corona
Ion current	2.2 mA
Electric field	27,000 volts of electric potential
Geometry	rectangular duct
Water Droplets	
Type of charging	induction
Ion current	2.2 mA
Electric field	5 kV power supply
Geometry	nozzle spray

Table 19 (continued). PARAMETERS ASSOCIATED WITH THE STUDY OF THE ELECTROSTATIC SPRAY SCRUBBER

Parameter	Magnitude, description, method of measurement or control, etc.
COLLECTOR	
Scrubber	
Chemical composition	lucite
Resistivity	K
Dielectric constant	K
Charge	
Voltage, $\vec{E}$	?
Efficiency	M
Internal geometry	13 spray nozzles, Fogjet 7N4
External geometry	45 inches high by 20 inches diameter cylinder, co-current
Water Droplets	
Chemical composition	water droplets
Resistivity	K
Dielectric constant	K
Charge	measured - 5.6×10^{-7} coul/gm
Voltage	?
Efficiency	DOP - 30% uncharged, 85% charged
Internal geometry	spherical drops
External geometry	See scrubber
CLEANING PROCESS	
Method	N.A.
Efficiency degradation	N.A.

Table 19 (continued). PARAMETERS ASSOCIATED WITH THE STUDY OF THE ELECTROSTATIC SPRAY SCRUBBER

Parameter	Magnitude, description, method of measurement or control, etc.
COMMENTS	The water consumption rate is 15.7 gallons/1000 acf (~ 2 liters/m^3) 1000 cfm unit had been constructed and some tests had been run.
STAGE OF DEVELOPMENT	Lab scale unit of 140 acfm constructed and tested. Larger 1000 acfm unit had been constructed and limited testing had been done at time of review.

Methods of Study

Theoretical - In the work reported thus far, Pilat et al.[1] used a simple exponential (Kleinschmidt or Deutsch-type) model to estimate the difference in collection efficiency due to the addition of charge effects. Figure 26 is from the paper by Pilat et al.,[1] based in turn on the work done by Sparks,[2] in which collection efficiency was gotten from particle trajectories calculated by numerical integration of the particle equations of motion, considering diffusion, electrostatics, and particle inertia. The droplets were assumed to be 200 μm in diameter, moving at 100 cm/s, and the particles were either uncharged or carried charge equivalent to that induced by corona charging in an electric field of 1 kV/cm. This figure indicates that the minimum collection efficiency for the charged aerosol should be the maximum efficiency for the uncharged aerosol under the conditions considered, which was confirmed experimentally, but the measured efficiencies were much less than predicted by the simple model for both cases, especially for the smaller particle sizes. The model for the charged aerosol predicts that collection efficiency should increase as particle size decreases, and exactly the opposite was measured.

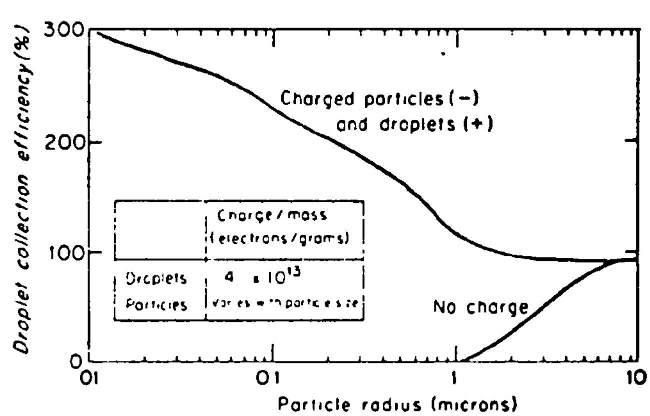

Figure 26. Calculated particle collection efficiencies for a single 200-μ diameter droplet with a 100-cm/sec undisturbed fluid velocity[1]

Experimental - The experiments involved two different capacity lucite scrubbers, the smaller unit having been used first in several preliminary investigations, the larger unit being built for subsequent analysis.

The smaller 0.066 m^3/s (140 cfm) unit was equipped with a corona charger for the particles, and an inductive charger for the droplets. A fine aerosol of DOP was generated by injecting it into an electrically heated aluminum tube, and by exposing it to negative corona charging in the inlet duct. The particulate was sampled at the inlet and outlet simultaneously, with Mark III University of Washington Source Test Cascade Impactors.

The water droplets were charged positively by induction, and experiments were run both with and without this charging. The spray nozzles were Spraying Systems Fogjet 7N4 nozzle tips with an overall water flow of 6×10^{-5} m^3/s (1.0 gal/min). The liquid to gas volume ratio was 21×10^{-4} m^3/m^3 (15.7 gal/1000 acf). This overall water flow was varied to determine the most effective rate.

The size distribution of the water droplets was measured optically with a Zeiss particle size counter, after collection on glass slides smeared with petroleum jelly. (A correction factor of 1.26 was used to correct the flattened diameter to the actual droplet diameter.) The distribution was determined for both charged and uncharged droplets.

The overall electrostatic charge on the particulate was measured with a glass fiber filter held in a glass holder, which collected the particles or droplets isokinetically, and a charge measuring circuit.

The droplet charge was measured with a droplet collector that was packed with aluminum shavings and connected to a microammeter. Charge on the droplets was determined by monitoring the current and sampling time and weighing the amount of water collected. This yielded charge per unit mass for the water.

Table 19 contains the majority of the information we considered to be useful in evaluating an electrically augmented particulate collection device. Properties and parameters concerning the various components of the particulate laden gas and the collecting device are listed under their respective headings.

The majority of the parameters that are important were determined by Sparks et al.,[2] either by being known beforehand or by direct measurement. The gas velocity is not stated; however, the references to isokinetic sampling indicate that the velocity was measured. The gas Reynolds number was not given in the original text, but could likely be determined with the information available to the researchers.

The parameters concerning the particulate are measured or can be determined from available information in the literature concerning DOP. All of the pertinent parameters concerning particle charging are covered, with the exception of specific dimensions of the duct in which the charging occurs.

The collector parameters are well covered, with the complication that the collector in a scrubber is really the water droplets. Table 19 contains available information for the collector as water droplets, and as the lucite scrubber unit itself. "Methods of Cleaning" does not really apply to the scrubber as it does in a precipitation or filtration device.

Results

The charge on the particles was measured at 5.3×10^{-5} coulombs per gram in the first scrubber chamber. The droplets were found to contain, typically, 5.6×10^{-7} coulombs per gram of water.

Figure 27 is a log-probability plot of the spray droplet size distribution, for both charged and uncharged droplets, at the same nozzle pressure. The geometric mean diameter (or number median diameter) droplet is approximately 50 microns, with a range from under 20 microns to nearly 150 microns, and a geometric standard deviation ~ 1.8.

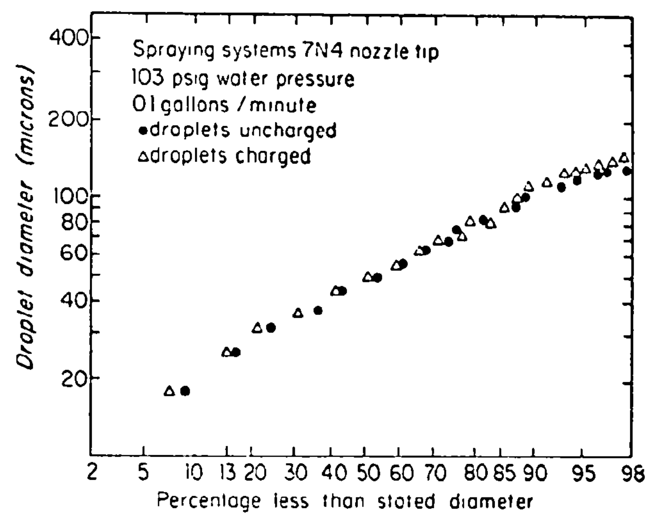

Figure 27. Size distribution of water spray droplets[1]

The size distributions of the particulate DOP were measured at the inlet and the outlet of the scrubber with Mark III University of Washington Source Test Cascade Impactors. The results are given graphically in Figure 28.

The collection efficiency for each particle size was measured using simultaneous impactor runs. Curves representing these runs are given in Figure 31 for the charged and uncharged modes of operation, at the stated water consumption.

The inlet mass concentration was measured at 0.34 g/m^3 (0.15 gr/acf), and was not substantially different in any of the runs.

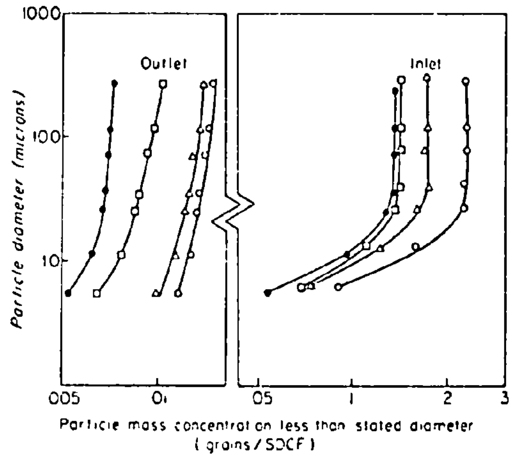

Figure 28. Size distributions of dioctylphthalate aerosol particles at electrostatic droplet spray scrubber inlet and outlet[1]

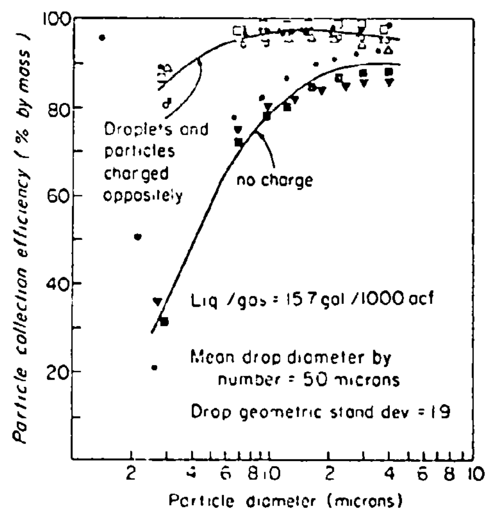

Figure 29. Particle collection efficiency of electrostatic spray droplet scrubber as function of particle size[1]

Conclusions

The particles were not necessarily charged to the theoretical saturation charge. If we calculate the charge on the observed mass median diameter particle of 0.4 micron, using the results of the particle charge measuring data, we get a charge of 5.25×10^{-9} statcoulombs (11 electrons) per 0.4 micron diameter particle. This is even less than the saturation charge calculated for a 0.3 micron diameter particle in a 10 kV/cm field, 2.8×10^{-8} stat-coul (958 electrons).

The average charge on the water droplets was calculated in a similar manner to that used for the particles and was found to be 1.1×10^{-4} stat-coul (2.3×10^{5} electrons) per 50 μm diameter droplet.

The particle size distribution is altered after passing through the scrubber, due to the dependence of collection efficiency on particle size. The particle size distribution was measured with an impactor, the performance of which may be affected by the charge on the particles. The charge on the particles has not normally been considered to interfere with impactor performance, and we have assumed that the results are valid, but we have some reservations concerning electrostatic effects. The electrostatic spray droplet scrubber was found to have significantly greater particle collection efficiency, especially at the lower particle sizes, when operated with particles charged versus uncharged. From this we could conclude that the electrostatic augmentation does increase particle collection efficiency; we also conclude that the electrostatic spray scrubber is a more efficient particle collector per unit of energy expended than another type of scrubber, as we shall discuss.

The power requirements have been determined for the electrostatic spray scrubber. The scrubber consumes energy due to: pressure drop across the scrubber, pressurizing the water for spraying, and charging the aerosol and droplets. The total energy demand of the system is 1.27 kW/(m^3/s) (0.80 hp/1000 cfm), of which nearly 70 percent is for pressurizing the water for spraying. This level of power consumption is considerably lower than that calculated for a conventional Venturi scrubber of similar efficiency. Using values for pressure drop given by Calvert[3] for two Venturi scrubbers with f values of 0.25 and 0.5, we calculated a power consumption 39.4 kW/(m^3/s) and 9.8 kW/(m^3/s) respectively (24.9 and 6.2 hp/1000 acfm). Even this calculation is conservative, since the conventional scrubbers chosen are only 50 percent efficient at 0.4 μm diameter particle collection versus over 90 percent efficiency for these particles with the electrostatic spray scrubber. The overall energy consumption is extremely low for the stated efficiency.

Evaluation

Suitability of Goals - Efficient fine particle collection is becoming increasingly important. Many industries with existing particulate controls are not effectively collecting the fine particles, which are usually the most objectional, considering health. As this study is seeking to produce a device that is generally applicable to industrial particulate control, this goal is very appropriate. Scrubbers can be used on liquid aerosols (where filters are not suitable) and on high-resistivity materials (where electrostatic precipitators may not work).

Suitability of Methods for These Goals - The suitability of both the experimental and theoretical approach utilized in this study will be analyzed, utilizing the available information at this time.

Analysis of theoretical approach - Pilat cited theoretical calculations done by Sparks,[2] who solved numerically the particle equations of motion for charged and uncharged particles. Figure 26 is taken from Pilat's paper, and it shows the theoretical single droplet collection efficiency for a 200 μm droplet and the particle size range shown. The flow velocity was assumed 100 cm/s and both charged and uncharged particles. The Sparks calculations were done for charge levels of 6.6 x 10^{-6} coul/g on the droplets, an order of magnitude larger than the charge noted in the experiment by Pilat.

In general the measured increase in the scrubber overall particle collection efficiency due to electrostatic charges agrees with the trend of the theoretically calculated single droplet collection efficiencies shown in Figure 26. Pilat's analysis[1] and that of George and Poehlein[4] follow.

For a 1 μm diameter particle, theoretical calculations indicate target efficiency of 0.01 for the uncharged condition and 1.6 for the charged condition. Pilat applied the equation for efficiency:

$$E = 1 - e^{-f\eta}$$

where $f = \frac{4}{3} \frac{HL}{RG}$ and

H = the distance the droplets travel with respect to the gas, cm

L/G = the liquid to gas volume ratio

R = the droplet radius, cm

Pilat assumed H was 1 ft, L/G was 15.7 gal/1000 ft^3 and R was 25 μm. This gave overall particle collection efficiency increasing from 17.4 percent for uncharged particles to near 100 percent when charged, which differs from the measured results of 80 percent for uncharged particles and 97 percent for charged particles.

George and Poehlein's[4] analysis was done as follows. Trajectories of spherical particles approaching a spherical collector were solved by numerical methods for various collection mechanisms. The target efficiency,

$$\eta = \frac{\pi \, Y_{lim}^2}{\frac{1}{4} \pi \, D_c^2} = \frac{4 \, Y_{lim}^2}{D_c^2}$$

is the ratio of the area containing all captured particles to the cross-sectional area of the collectors. Y_{lim}, is the greatest streamline offset distance for which the particle trajectory intersects the collector surface. D_c is the collector diameter. Figure 30 shows the geometry and coordinates of the two sphere system.

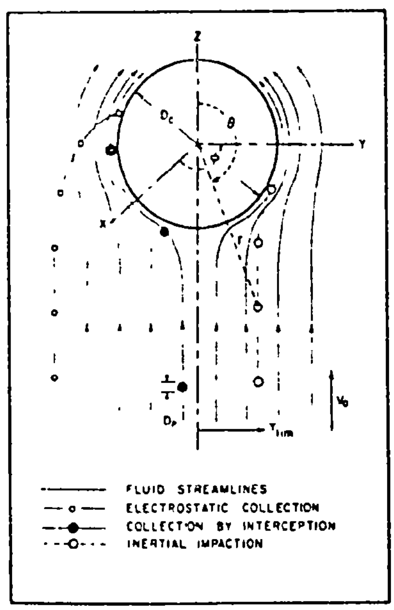

Figure 30. Geometry and coordinates of the two sphere system[4]

The equation of motion is expressed in vector form as

$$\vec{F}_g + \vec{F}_e + \vec{F}_s = m \frac{d\vec{v}}{dt}$$

where $\vec{F}_g$ = the gravity force

$\vec{F}_e$ = the electrostatic force

$\vec{F}_s$ = the fluid resistance force

the assumptions for this system are sticking efficiency of 1.0, particle and collector are conductors, and $d_p << D_c$.

The target efficiency, η, versus inertial impaction parameter ψ is graphically presented at various electrostatic parameters (ES) in Figure 31,

where $$\psi = \frac{C \rho_p V_c d_p^2}{18 \mu D_c}$$

$$ES = \frac{C Q_1 Q_2}{3\pi^2 \varepsilon_o \mu V_o D_p (D_c + d_p)^2}$$.

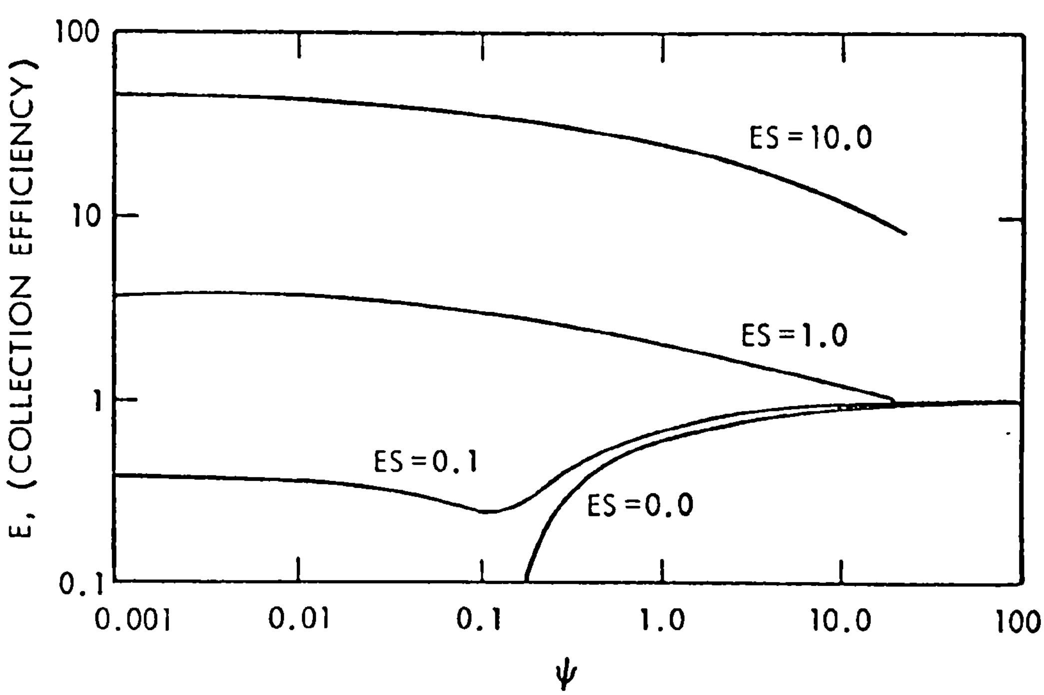

Figure 31. Single particle collection efficiency - inertial and electrostatic effects[4]

A similar computation of the η, ψ relation done by Nielsen,[5] does not wholly agree with that of George and Poehlein.[4] Figure 33 is the comparison of the two computer results.

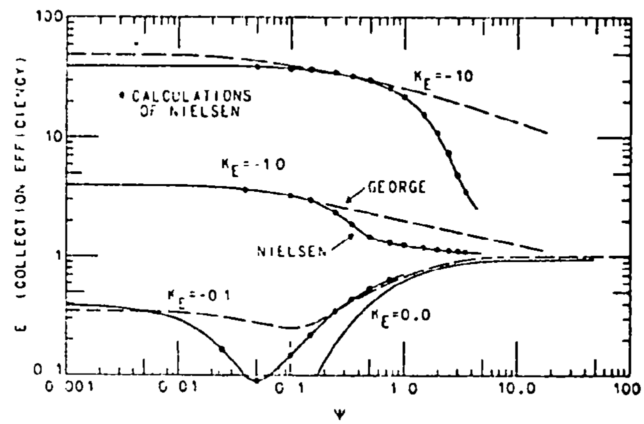

Figure 32. Collection efficiency in potential flow as function of ψ for various K_E, computed by Nielsen (solid lines) and by George (dashed lines)[5]

Note that

$$K_E = \frac{C\, Q_1\, Q_2}{3\pi^2\, \varepsilon_c \mu\, V_o D_c^2\, d_p}$$

is nearly identical to ES, and Nielsen indicated that George and Poehlein actually used K_E rather than ES.

Although Nielsen's results do not agree with those of George and Poehlein, there are few substantial discrepancies between them. The work done by Nielsen seems to have been the carrying out of the goals of George and Poehlein in somewhat more detail. Both will clearly be somewhat incorrect for Reynolds flow numbers greater than about 10 because of the formation of eddies in the wake of the droplets, giving a very different flow profile in the lee of the drop than that used by either set of calculations. This is a general problem: for Reynolds numbers of interest, between 1 and 100, neither viscous flow nor potential flow really suits, and almost all theoretical work has assumed, for understandable reasons, that one or both of these flow models is appropriate. This problem of flow model makes Nielsen's improvements on the work of George and Poehlein less significant than they seem at first.

MRI's evaluation[6] was based on George and Poehlein's report; together with Pilat's experimental conditions, it is used as the groundwork of the following analysis.

In Figure 31, $\eta = 1.0$ represents target efficiency when inertial forces are large. Pilat's measurement of overall particle collection efficiency in Figure 29 shows E approaches 95 percent when particle size increases. From the exponential relation

$$E = 1 - e^{-f\eta}$$

we can express

$$f = \frac{\ln (1 - E)}{-\eta} .$$

For $\eta \doteq 1$, $E \doteq 0.95$ and $f = 3.0$.

This value differs greatly from that calculated from $f = \frac{4\ HL}{3\ RG}$, assuming H = 1 ft, L/G = 15.7 gal/1000 ft, and R = 25 μm, which yields f = 37. The difference may arise from other parameters in the experimental system.

The overall collection efficiency at different electrostatic parameters versus $\sqrt{\psi}$ calculated from η in Figure 31 and in Table 20 are graphically shown in Figures 33, 34, and 35. We have predicted efficiencies using 3.0 rather than 37 for f for the unknown factors of this specific system. We have used $\sqrt{\psi}$ because it is almost proportional to particle diameter. The electrostatic effect becomes distinct as particle size decreases.

The electrostatic parameter, ES, George and Poehlein introduced is a function of electrostatic charges, particle size, and velocity of the bulk gas stream toward the collector. It plays an important role in affecting target efficiency for particle diameter less than 5 μm.

Using the operating parameters from Pilat's experiment, we calculate the ES and d_p relation at different V_o. For CGS system of units

$$ES = \frac{4\ C\ Q_p\ Q_c}{3\ \pi\ \mu\ d_p\ (D_c + d_p)^2\ V_o}$$

where d_p = aerosol particle diameter (cm)

D_c = collector diameter (cm). (50×10^{-4} cm is assumed in Pilat's report for water droplet.)

C = Cunningham correction factor $1 + 0.17 \times 10^{-4}/d_p$

Q_c = electrostatic charge on water droplet (Pilat's report gives 5.6×10^{-7} coul/g)

$Q_c = 5.6 \times 10^{-7} \times \frac{4}{3}\pi\ (25 \times 10^{-4})^3 \times 3 \times 10^9$ stat-coul

Q_p = electrostatic charge on aerosol particle

$$Q_p = (1 + \frac{2\lambda'}{d_p})^2 + \frac{2}{(1 + \frac{2\lambda'}{d_p})}\ E\ \frac{d_p^2}{4}$$

E = charging field, assumed 33.3 esu

$\lambda' = 0.1 \times 10^{-4}$ cm

μ = gas viscosity, 1.8×10^{-4} poise.

Table 20. EFFICIENCIES CALCULATED FOR VARIOUS ELECTROSTATIC AND INERTIAL PARAMETERS[a]

Inertial parameter		ES = 0		ES = 0.1		ES = 1.0		ES = 10	
ψ	$\sqrt{\psi}$	η	E %	η	E %	η	E %	η	E %
0.001	0.032		0	0.36	66.04	4	100	50	100
0.01	0.1		0	0.35	65.01	4	100	50	100
0.04	0.2		0			3.8	99.999	45	100
0.05	0.224		0	0.28	56.83	3.6	99.998	44	100
0.09	0.3		0			3.4	99.996	41	100
0.1	0.316		0	0.25	52.76	3.2	99.993	40	100
0.18	0.426	0.1	25.92						
0.19	0.436			0.3	59.34				
0.2	0.45	0.13	32.29						
0.3	0.548	0.23	49.84	0.38	68.02	2.7	99.97	34	100
0.4	0.63	0.33	62.84						
0.5	0.707	0.4	69.88	0.5	77.69	2.4	99.93	30	100
0.6	0.77	0.46	74.84	0.55	80.80				
0.7	0.837	0.5	77.69	0.6	83.47	2.2	99.86	28.5	100
0.8	0.89	0.56	81.36						
1.0	1.0	0.65	85.77	0.7	87.75	2.0	99.75	27	100
1.5	1.225					1.9	99.665	20	100
1.7	1.3	0.75	89.46	0.8	90.93				
2.0	1.414	0.79	90.65			1.8	99.548		
3.0	1.732	0.85	92.19	0.9	93.28	1.7	99.39		
5.0	2.236	0.9	93.28			1.5	98.89	15	100
7.0	2.645					1.4	98.50		
10.0	3.162					1.3	97.98		

[a]From $E = 1.00 - e^{-f\eta}$, $f = 3.0$.

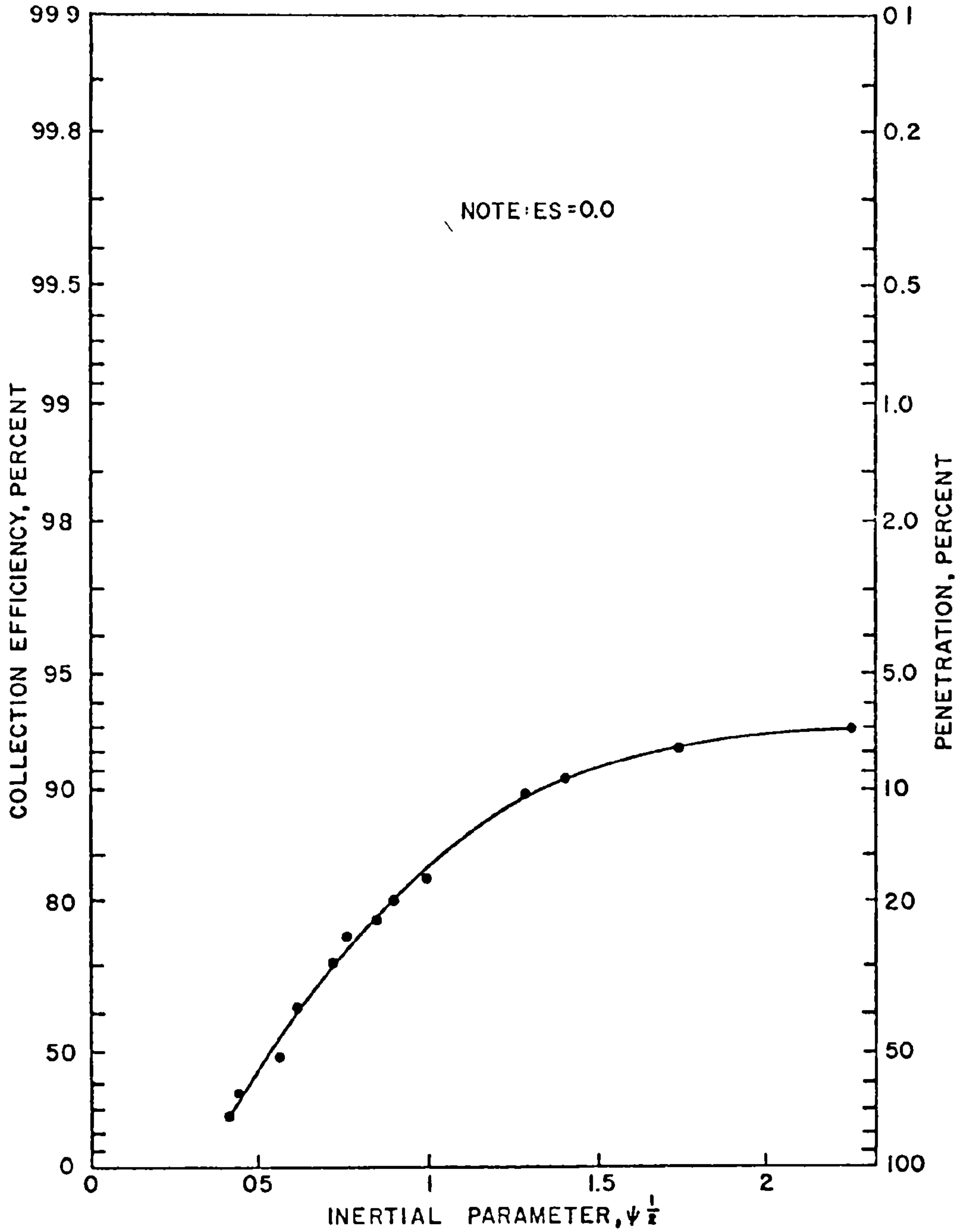

Figure 33. Theoretical overall collection efficiency for scrubber as a function of inertial parameter, $\psi^{\frac{1}{2}}$; ES = 0.0

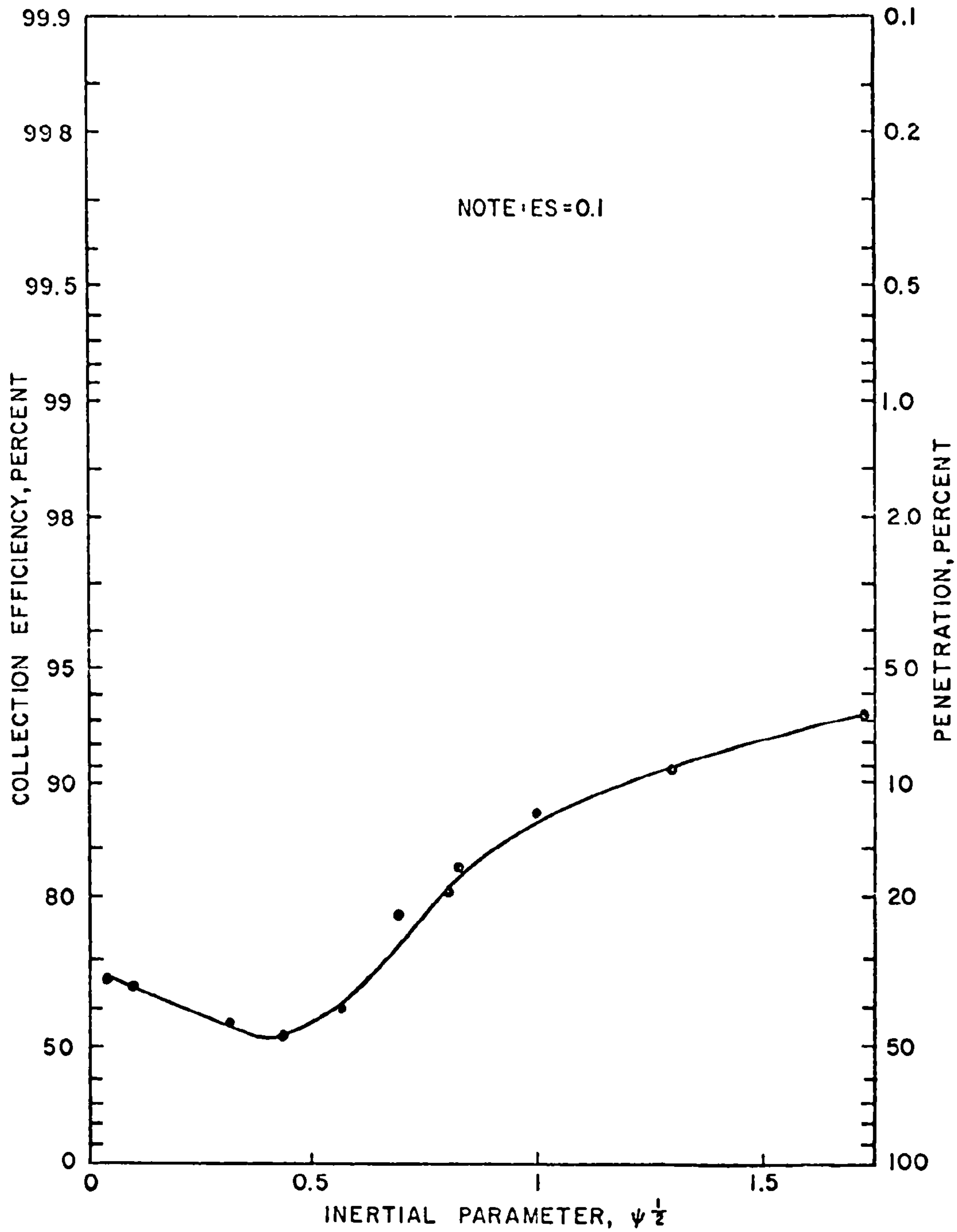

Figure 34. Collection efficiency versus $\psi^{\frac{1}{2}}$ for ES = 0.1

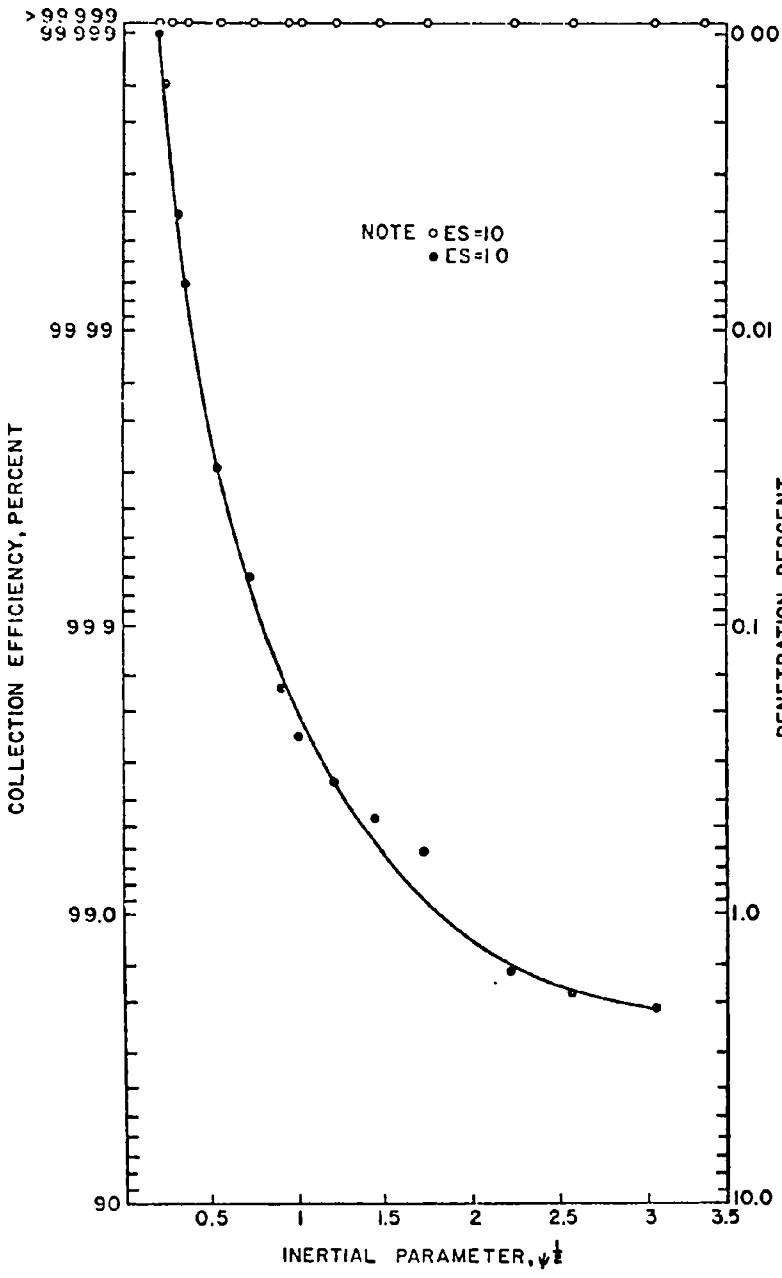

Figure 35. Collection efficiency versus $\psi^{\frac{1}{2}}$ for ES = 1.0, 10.0

Figure 36 reveals that ES increases sharply as the particle size becomes smaller than a certain value, d_z, which is about 0.2 μm in this case.

We may also solve for f by calculating H for the system that Pilat developed. The nozzle pressure was 7.1×10^5 N/m^2 (103 psi); by applying $\Delta p = 0.5 \rho v_o^2$ for ideal flow to estimate the droplet velocity v_o,

$$v_o = \sqrt{\frac{2 \times 7.1 \times 10^5}{1000}} = 37.7 \text{ m/s} = 3770 \text{ cm/s} \quad .$$

The mean gas velocity in chamber 1 was 17.8 cm/s and in chamber 2, 58 cm/s. The droplet settling velocity was about 8 cm/s. The distance travelled by the droplet with respect to the gas flow has as its upper limit the particle stopping distance (initial velocity times particle relaxation time, $v_o\tau^*$) plus the product of the settling velocity and the residence time. The particle relaxation time can be approximated by $(24/55)\tau$, where τ is the usual value from Stokes law calculations and the (24/55) factor comes from Ingebo's work[8] with accelerating droplets at Reynolds numbers greater than 1. The initial droplet velocity (ignoring the small correction for mean gas flow rate) gives a stopping distance of 12.7 cm. The total residence time was 10.53 s, thus the settling distance was 85.64 cm. Recall the assumed value of 30.5 cm (1 ft) in the Pilat analysis. Considering the assumptions involved, this difference in the value assigned to H is not large.

Analysis of experimental approach - The experimental work with the two-stage lucite scrubbers was done in a similar fashion for the two units, using 0.006 m^3/s (140 cfm) and 0.33 m^3/s (700 cfm) capacity. The

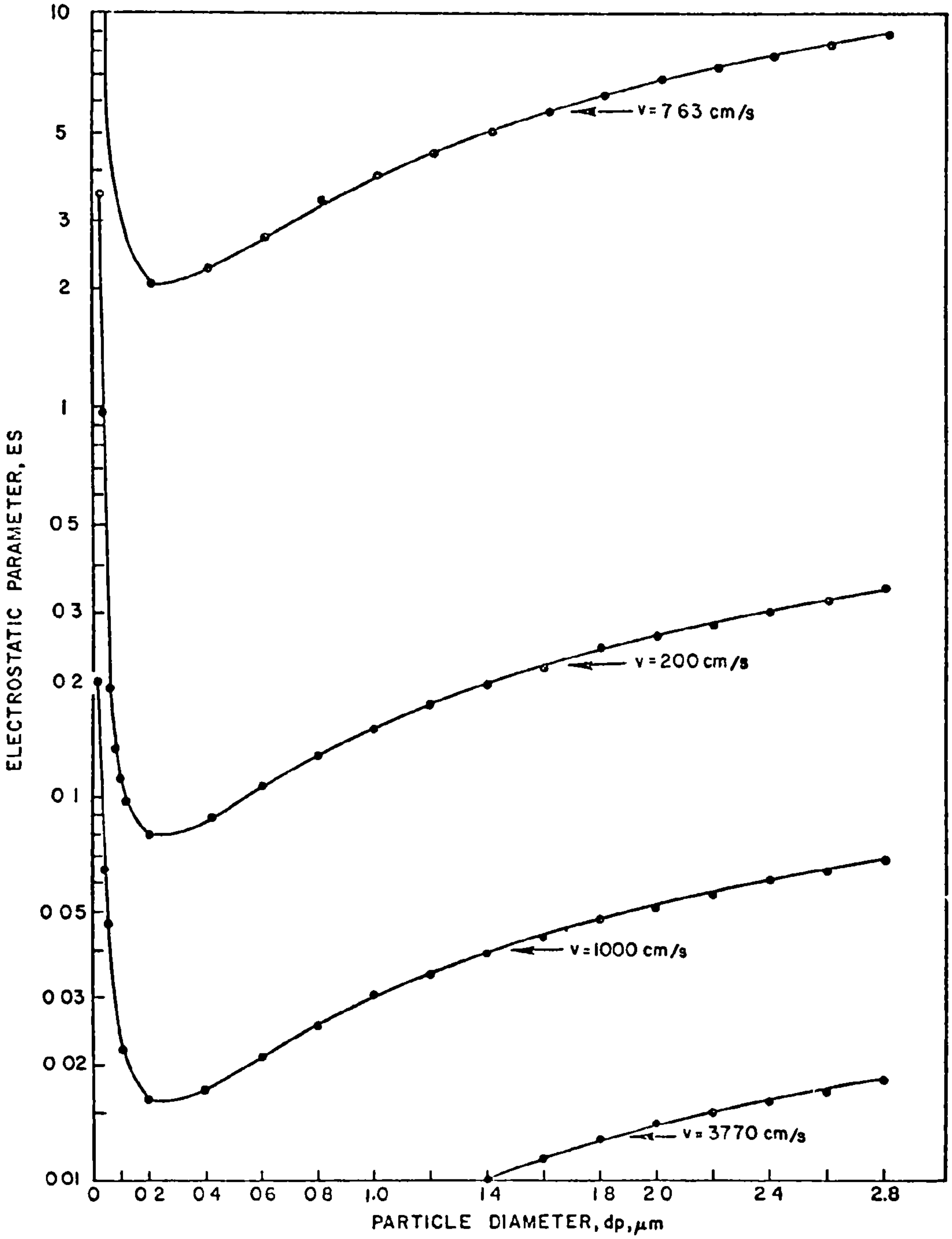

Figure 36. Electrostatic parameter versus particle size for several flow velocities from 7.63 cm/s to 3770 cm/s

measurements of the particle and droplet size distributions with the cascade impactors and the Zeiss particle counter appear to be adequate. As previously mentioned, there remains open the question of the effect of particle charge on impactor data.

The use of 1/4-inch lucite (polymethylmethacrylate), a highly insulating polymer, for the construction of the entire scrubber assembly may have biased the overall results by collecting charged particles on the dry plastic previous to the scrubber chamber. It is not unusual for polymer surfaces to acquire a static charge which remains immobile, which could have aided in precipitating the aerosol after the inlet sampling port. Although the effect may be minimal, insufficient data concerning geometry and size of the inlet ducting and sampling location are available to rule out this possibility. Dry plastic has been shown to collect aerosol in localized areas having voltages as high as 10 kV (Stein et al.).[7]

Applicability to Pollution Control - The electrostatic spray scrubbers is being studied for its eventual use as an industrial air pollution control device, and as such should have broad applicability, especially where scrubbers would be suitable if their efficiencies were sufficiently high.

Prospects of method - The measured efficiencies obtained for small particles were very high, making the prospects of the method look encouraging. An overall power consumption of 600 watts (0.8 hp) per 1000 cfm (0.47 m^3/s) is rather low when the fina particle collection efficiency is considered. The higher than usual water consumption rate of approximately 66×10^{-3} m^3 (15 gallons) per 28.3 m^3 (1000 ft^3), is somewhat more than used by conventional scrubbers, which use approximately 33×10^{-3} m^3 (8.4 gallons) per 28.3 m^3 (1000 ft^3). The potential high efficiency for small particles makes this device attractive, but somewhat high water consumption, with its resulting treatment costs, would be a disadvantage in industrial application.

Status of method - The scrubber was, at the time of this review, in its early stages, having been successfully scaled up from a 0.066 m^3/s (140 cfm) unit to a 0.33 m^3/s (700 cfm) unit with no noticeable drop in efficiency. We understand that there are plans for further scaling-up of the unit and for testing.

Implications - If similar fine particle collection efficiencies can be achieved with larger units treating industrial offgases, then the electrostatic spray scrubber would be an attractive air pollution control alternative. Industries presently utilizing scrubbers, because their emissions are not amenable to collection with other devices, might find the electrostatic spray scrubber a cost-effective option that meets increasingly stringent emission standards.

ELECTRICALLY ACCELERATED DROPLETS

The material presented here was derived from progress reports by Lear and Krieve[8] and from a paper by Lear, Krieve and Cohen.[9] The "charged droplet scrubber" (CDS) they are developing is designed to use electrostatic forces to accelerate droplets from a spray and to produce increased collection efficiency either from electrostatic capture by the droplets or from electrostatic capture after the droplets have transferred electric charge to the particles.

Goals

The goal of the work was to investigate the collection mechanisms involved in the charged droplet scrubber and to test the collection efficiency of a CDS.

Methods of Study

Both theoretical and experimental investigations were carried out.

Theoretical - Lear et al.[9] presented a concise description of their theoretical approach in their recent paper, which we quote:

> "The model assumed is one in which a relatively large droplet is introduced into the carrier gas within which a small particle is at rest. The droplet moves at a drift velocity U which is assumed constant for purposes of the derivation. As the droplet moves within the gas, a "wake" flow field is generated which gives rise to accelerations on the particle, and which, if sufficiently strong, can sweep the particle out of the direct path of the droplet.
>
> "As the droplet moves through the gas, it sweeps out a volume equal to its path length times it projected area. Particles within this volume which are not swept out by aerodynamic forces as the droplet moves along its trajectory are collected on the droplet by agglomeration.
>
> "Particles within a concentric cylinder of radius S + D may remain within this cylinder as the droplet passes. If a particle passes with its center within a distance D of the droplet surface, it is assumed to have interacted with the droplet strongly enough to be collected by induced charging. Particles originally residing within a concentric cylinder of radius Z ... will remain in the interaction cylinder. A particle starting from radius Z will follow a grazing trajectory ... and this radius defines an interaction boundary.
>
> "The analysis given in the present work is in terms of a collection efficiency which is consistent with common usage. The basis of its definition is the cross section of the complete interaction cylinder.
>
> $$P = \left(\frac{Z}{S + D}\right)^2$$
>
> "The portion of this efficiency due to induced charging depends on an impact parameter defined by
>
> $$A = \frac{D}{S}$$
>
> "Induced charging impact parameters were calculated in two ways ... The dashed line shows values of A for which corona breakdown will occur at the surface of a spherical particle. The droplet is assumed to be spherical and charged to the Rayleigh limit. The surrounding medium is air at standard conditions. The electric field enhancement is caused by the induced polarization of the particle.

"If the droplet surface charge is at the Rayleigh limit, then a field perturbation at the surface may cause a Rayleigh-type or corona breakdown. A quantity of charge is transferred to the particle, neutralizing the field perturbation. The particle charge was calculated, and the resulting drift velocity of the particle in a field of 5 kv/cm was calculated assuming Stokes law drag. ... Larger impact parameters result in smaller particle charges, thus longer drift times.

"Droplet collection efficiencies were obtained by solving the full equations of motion of a particle in a Stokes flow field surrounding the droplet. Again, Stokes law drag was assumed on the particle. The analysis was programmed for a computer. The collision effectiveness probability was found to depend on three parameters, physically corresponding to droplet velocity, droplet surface charge, and induced charging impact parameter."

More details on the theoretical work will be presented in a subsequent discussion section.

Experimental - Although some work was done to characterize the spray size and charge parameters, the major focus of the experimental work was testing the collection efficiency of the device. Table 21 contains most of the major parameters which we felt were pertinent. The CDS, as all scrubbers considered, did not fit the format of the table particularly well. The concept of the droplets being the collectors in the case of a scrubber, and the droplets having been charged rather than the particles should be kept in mind when reviewing this table. Figure 37 is from the article by Lear et al.,[9] and it describes the experimental apparatus. The scrubbing water flowed through a long insulated tube to a nozzle which was kept at a potential of about 40 kV. The spray is propelled from the nozzle toward the walls by electrostatic forces, achieving velocities $\lesssim$ 30 m/s. Table 22 is based on the same publication and gives some operating conditions for the CDS. Photographic analysis indicated the spray had droplets in the range from 120 to 180 μm number modal diameter and 300 to 400 μm mass mean diameter. The number concentration was reported to be about $42/cm^3$ with a standard

Table 21. PARAMETERS ASSOCIATED WITH THE STUDY OF THE CHARGED DROPLET SCRUBBER

Parameter	Magnitude, description, method of measurement or control, etc.
GAS	
Volume flow rate	0.47 m^3/s (1000 acfm)
Face velocity	1.5 m/s (300 fpm)
Reynolds number (Re_f)	?
Flow geometry	Duct with a cross-sectional area of 0.33 m^2
Pressure drop	Negligible?
Temperature	24-81 °C
Pressure	Ambient
Relative humidity	Saturated
PARTICLES	
Size	1.8 μm "mean size"
Shape	Assumed spherical
Chemical composition	Talc
Resistivity	K (known)
Dielectric constant	K
Charge	No charge was placed on the particles
Concentration	0.002-0.2 g/m^3 (0.001-0.01 grains/scf)
CHARGING SECTION	
Type of charging	Particles are thought to be charged by corona breakdown at the droplet surface
Ions	N.A.
Electric field	N.A.
Geometry	N.A.
COLLECTOR	
Chemical composition	Water
Resistivity	Conductivity of 400-700 μmho/cm
Dielectric constant	80

Table 21 (continued). PARAMETERS ASSOCIATED WITH THE STUDY OF THE CHARGED DROPLET SCRUBBER

Parameter	Magnitude, description, method of measurement or control, etc.
Charge	Theoretically the water droplets are charged to the Rayleigh or corona limit
Voltage, $\bar{E}$ field	5.6 kV/cm between the wall and electrode - applied voltage of 40 kV at 6 milliamps
Particulate loading	N.A.
Efficiency	96.4-99.94 percent
Geometry	
Internal configuration	8 cm electrode to wall spacing
External configuration	300-400 μm mass mean diameter, 120-180 μm modal diameter droplets
CLEANING PROCESS	
Method	N.A.
Effect on efficiency	N.A.
COMMENTS	Scrubbing water flow of 1.5 liter/min Wall wash flow of 4.5 liters/min
STAGE OF DEVELOPMENT	A 0.47 m^3/s (1000 acfm) model has been built and tested. A 14 m^3/s (30,000 acfm) pilot scale scrubber has been built

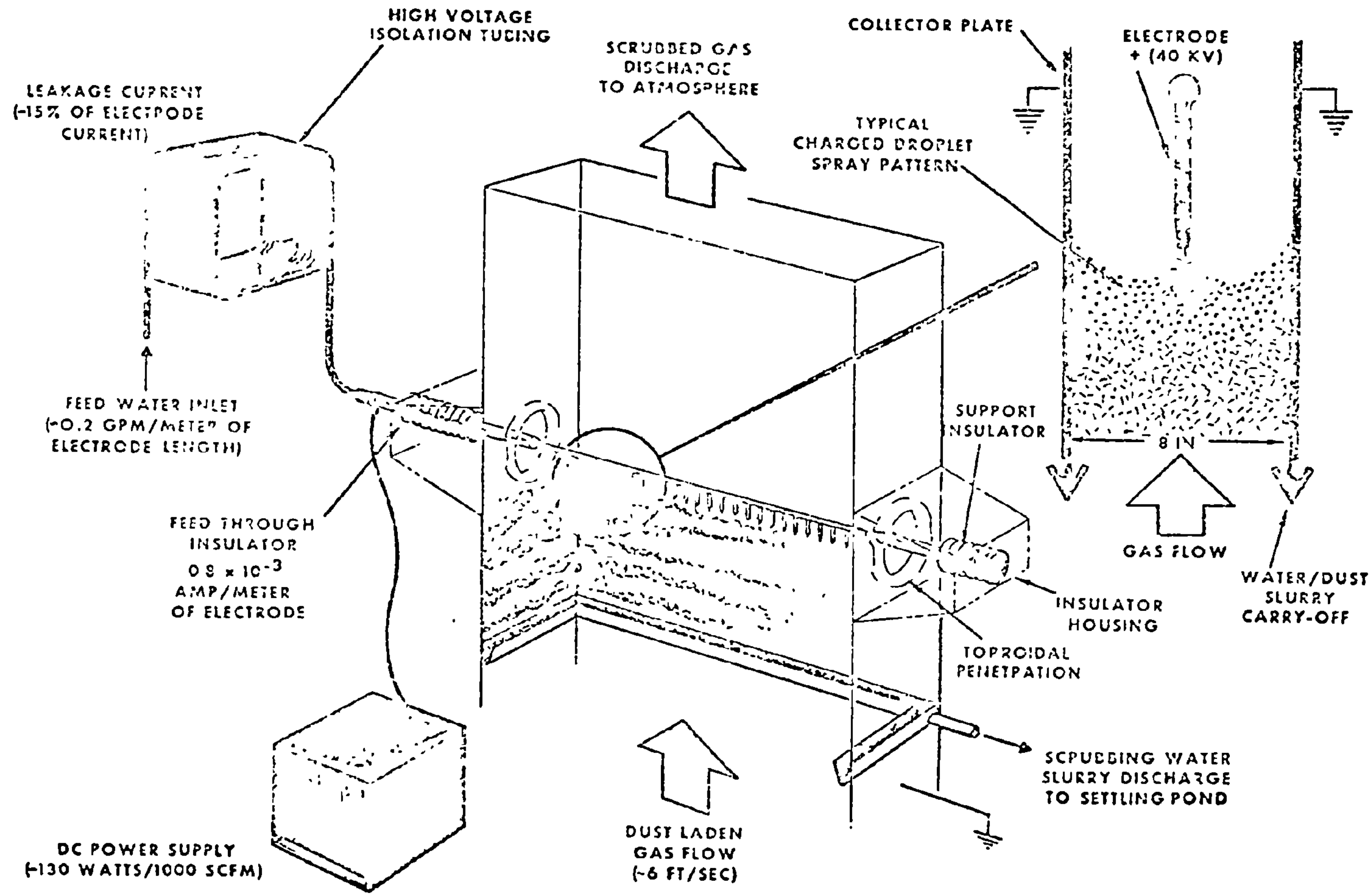

Figure 37. Charged droplet scrubber[9]

Table 22. THREE STAGE CDS PERFORMANCE DATA—UNITED SIERRA TALC – 1.8 μm MEAN SIZE

Test no.	Gas temp. ^{o}C	Gas velocity m/sec	Collector spacing, m	Spray nozzle voltage, kV	Collector current, ma	Inlet loading, g/m^3	Specific power $W/m^3/hr$	Specific water flow, ℓ/m^3	Scrubbing efficiency, (percent)
1	61	1.22	0.15	41	3.0	0.796	0.147	0.093	97.6
2	61	1.22	0.15	41	3.1	0.796	0.153	0.093	98.7
3	61	1.22	0.15	41	3.1	0.796	0.153	0.093	99.5
4	61	1.22	0.15	-50	6.0	0.796	0.365	0.093	99.7
5	61	1.22	0.15	-50.5	6.3	0.796	0.388	0.093	99.8
6	21	1.22	0.10	42.5	6.0	1.60	0.470	0.150	99.91
7	21	1.22	0.10	42.5	6.0	1.60	0.470	0.150	99.93
8	24.3	1.22	0.10	20	1.0	2.69	0.037	0.158	99.59
9	24.3	1.22	0.10	30	2.5	2.69	0.139	0.158	99.94
10	23.8	2.13	0.10	30	2.3	0.40	0.072	0.088	97.63
11	81.5	1.22	0.15	43	3.5	0.704	0.182	0.111	97.38
12	81.5	1.22	0.15	50	4.8	0.704	0.294	0.108	96.40

deviation of $30/cm^3$. The efficiency of the three-stage model of the CDS was tested using a "1.8 μm mean size" talc, 40 percent of which by weight was less than 2 μm diameter. The results as reported by Lear, et al.,[9] are shown in Table 22. It is not clear what fraction of this collection is done by droplet-particle contact and what fraction is done by charge transfer to the particles and their eventual collection on the plates by electrostatic forces. Lear, et al.[9] reported that the ratio of plate area to volume flow was significant in affecting efficiency, as was the ratio of water flow rate to air flow rate. More information would have been obtained if their work incorporated a factorial design and an analysis of variance. The power consumption values of ~ $0.1\ W/m^3/hr = 360\ W/m^3/s$ = 0.2 hp/1000 cfm are attractive, considering the collection efficiencies obtained.

Conclusions

The investigators concluded that[9] "charged droplet scrubbers are important devices for control of particulates in the 0.1 to 1.0 μm range," and that "scrubbing efficiencies of 30 to 70 percent per stage have been demonstrated in the submicron particulate size range." It is clear from their data that they have obtained at least 99 percent collection efficiency for 2 μm particles during their tests on talc under some of their conditions. Whether this CDS is a more economical alternative than electrostatic precipitators or fabric filters or conventional high energy scrubbers remains to be ascertained.

Evaluation

Suitability of Goals - It is generally recognized that a major drawback of scrubbers is their power consumption when high efficiencies are desired on fine particulates. It is also recognized that a major drawback of electrostatic precipitators is their size and associate construction costs when high efficiencies are desired on fine particulates. The goal of using charged droplets for particle control make sense from both perspectives: the electrostatic forces between particle and droplet can reduce the velocity required of the droplets to collect fine particles and thus, perhaps, reduce power consumption; the relatively high surface area to volume achieved by using droplets (rather than walls) as collection sites makes charged droplets an attractive possibility for electrostatic precipitation. On the other hand, as indicated below and in the appendix on power consumption, there seems to be no power advantage to accelerating the droplets electrically rather than with fluid pressure.

Suitability of Methods - We discuss here somewhat more than the "suitability" of the experimental and theoretical methods.

There are several ways by which, in principle, the charged droplet scrubber might prove advantageous:

1. The droplets might be accelerated to unusually high speeds or be accelerated more efficiently in terms of power.

2. The droplets might capture particles with substantially greater efficiency than is usual.

3. The charged droplets might impart more charge to particles or might impart the same charge more efficiently.

4. The charged droplet device might be more readily cleanable than either a typical scrubber or an electrostatic precipitator or both.

Using the material available to us, we have tried to analyze each of these potential advantages.

Change transfer in the CDS - The sequence of events for charging of particles by the charged droplets would be as follows:

1. The droplets leave the spray nozzle initially with a charge which corresponds to a voltage on the droplet that matches the nozzle voltage, as both are conductors. (This is an idealization.)

2. The droplets may lose charge due to ionization of the air (corona discharge) and perhaps due to the break-up of the drops due to electrostatic repulsion at the surface. The final charge will be near the lesser of two limits: the corona breakdown field or the Rayleigh limit. (This is assuming it started above the lesser of one of these limits.)

3. When a particle comes sufficiently close (a distance D between their surfaces, in the TRW notation) to the droplet, some of the charge from the droplet will be transferred to the particle. If the droplet and particle were connected by a conducting wire, this would bring both to the same potential; this would seem a reasonable upper limit to assume for the charge acquired by the particle.

4. The particle thus charged would then migrate to the walls of the collector. (D is chosen so that the charge transferred is sufficient to cause collection.)

The CDS droplet size distribution was determined to be approximately log normal, with a number median diameter of 173 μm and a geometric standard deviation of $\sigma_g = 1.86$. The modal value was 118 μm. The number mean diameter was 210 μm. We will use a value of 200 μm here to characterize the droplets.

One test with the CDS was performed with a nozzle voltage of 46 kV and another at 31 kV, so we have chosen 40 kV as an approximate value to characterize the CDS. The formula for the voltage V of a sphere having charge Q_d and radius R_d is

$$V = Q_d/R_d$$

where

V = voltage, statvolts (1 sV = 300 volts)

Q_d = charge, stat-coul (1 electron = 4.8×10^{-10} stat-coul or esu)

R_d = diameter, cm.

The charge acquired by the spherical droplet is expected to be 1.33 esu or 2.78×10^9 elementary charges, if it reaches the voltage of the nozzle.

The Rayleigh limit is the maximum amount of charge a sphere can hold before the charge repulsion overcomes surface tension (γ) and disrupts the sphere. This charge Q_R is given by

$$Q_R = (2\pi\ \gamma)^{1/2}\ D_d^{\ 3/2}$$

where

Q_R = charge, esu

γ = surface tension, dynes/cm

D_d = drop diameter, cm.

The surface tension for water is 73 dynes/cm. For 200 µm diameter, the predicted maximum charge is thus 6.1×10^{-2} esu or 1.26×10^8 elementary charges.

Air will break down and produce a corona discharge when the voltage gradient (electric field) between two parallel plates reaches 30 kV/cm. It is noted[8] that for spheres a correction factor, Peek's, should be used, which increases this field by a factor of $(1 + 0.54/(R_d)^{1/2})$, where R_d is the droplet radius in centimeters. Peek's correction becomes 6.4 for a 200 µm diameter droplet; this would mean a corona discharge field of 1.9×10^5 volts/cm or 640 sV/cm. The field at the surface E_s (stat volts/cm) is

$$E_s = Q_d/R_d^{\ 2}$$

which means that the upper limit on Q_d becomes 6.4×10^{-2} esu or 1.33×10^8 elementary charges. This limit is very close to the Rayleigh limit just calculated, so that the 200 µm diameter is just about the size for which the two limits (Rayleigh, corona) are equal. Larger droplets will have their charge limit set by the Rayleigh criterion. Smaller droplets will have it set by the corona discharge criterion. For $R_d \ll 0.3$ cm, the two limits are very close to each other.

Having obtained an upper limit on the droplet charge, we calculated the amount a droplet might transfer to a particle, if the particle is brought to the same voltage as the droplet. Using the subscript p to denote particle (and d to denote droplet), and equating the voltages after the passage of charge:

$$V_p = V_d$$

$$Q_p = Q_d \ (R_p/R_d),$$

which means a 1 μm diameter particle would be charged to about 1/200 the level of the 200 μm droplets or about 1.3×10^6 elementary charges. Such a charge would then produce a field of about 6.4×10^4 stat V/cm or 19.2×10^3 kV/cm. If Peek's correction is still applicable for particles as small as 1 μm, then the air breakdown field for a 1 μm particle becomes 55 times the usual 30 kV/cm, or 5.5×10^3 stat V/cm and no corona discharge would occur. The charge would then be 1.38×10^{-5} esu or 2.86×10^4 electronic units, an unusually large charge. The saturation charge acquired by a particle in a corona discharge is such that the field at the particle surface matches the field in which it is being charged, thus the droplet would have charged the particle to 55 times (at maximum) what it might be charged in a corona of 30 kV/cm. The problem with this analysis is that the droplet may just act as a typical corona discharge source and charge the particle so that their fields are equal rather than their potentials, in which case the factor by which the droplet charging improved upon the usual corona charging would only be the droplet Peek correction, a factor of 6.4 or less for 200 μm droplets. The process may also have a significant rate limitation, unless the charge transfer is nearly instantaneous.

This approximate analysis indicates that the charged droplet method may be able to increase the particle charge an order of magnitude. This was not done in as elaborate a manner as by Lear and Krieve,[8] but the assumptions are more readily seen and the results are presentable as equations of closed form.

Droplet velocity production in the CDS - Is there an energy advantage to producing high velocity droplets with electrostatic forces rather than using fluid pressure? If the droplets start with the same velocity from each type of nozzle, then the answer is simple: the kinetic energy per droplet is the same in each case, and if the number of droplets produced per unit time is the same, then the power used is identical. Actually, the droplet steadily decelerates after it leaves a pressure nozzle, but from the electrostatic nozzle the droplet tends toward an equilibrium velocity given by electrical forces and fluid forces, this equilibrium velocity itself changing as the field decreases away from the electrostatic nozzle. The average velocity $\bar{v}$ over the distance L traveled by the drop is given by the integration along the path length, of which ds is the infinitessimal:

$$\bar{v} = (1/L)\int_0^L v(s)\, ds$$

This will be true for both types of nozzles.

The work energy expended, W, by the droplet must come from the nozzle in both cases and is just the integral of the resistance force over the distance:

$$W = \int_0^L F(s)\, ds$$

For accelerating drops with Reynolds numbers, Re, in the general range unity to a hundred, Ingebo[10] found that the resistance force term is approximately (55/24) that of Stokes law, giving for the work energy

$$W = (55/24)\ 3\pi\ \mu\ D_d \int_0^L v(s)\ ds.$$

By comparing the two integrals, we can see that the same average velocity is going to require the same energy; thus, there is no inherent advantage from energy considerations to the charged nozzle compared with the pressurized nozzle.

Capture by droplets in the CDS - Most of the mechanisms for particle capture by drops will be the same for the CDS as for conventional scrubbers: impaction, interception, diffusion, diffusiophoresis (under some conditions). No claims have been made by the developers of the CDS that the droplet size distribution is especially good for scrubbing efficiently by such mechanisms, and we have shown that there is no inherent advantage to producing the droplet velocities by electrostatic forces rather than by pressurized spraying. This leaves only electrical phenomena as possible sources of enhanced collection efficiency. The reports[8] on the charged droplet scrubber have emphasized the mechanism of collection which involves the transfer of charge to the particles by the droplets followed by the electrostatic precipitation of the particles onto the walls of the CDS. Their analysis has also included Coulomb and dipole forces between droplets and particles. We will discuss these briefly.

Central to their analysis is the concept of "distance of closest approach," labeled D, which is the farthest distance from the droplet surface to the particle center which still achieves particle collection, either on the drop or by electrostatic precipitation on the scrubber walls. Another concept used is the "collision effectiveness probability," labeled p, which is the ratio of the cross-sectional area of the flow (assumed parallel and directed at the droplet at a great distance from the droplet) cleaned to the cross-sectional area of the sphere having a radius equal to the droplet radius plus the distance of closest approach (R_d + D). Figure 38 shows the various distance dimensions.

These definitions are analogous to those used in the usual treatments of other capture mechanisms: for impaction, as an example, the distance of closest approach is D = 0 and the term "single target efficiency" (η) is used instead of "collision effectiveness parameter." The volume of gas cleaned by each particle will be the integrated product

$$\int_o^L p\pi \, (R_d + D)^2 \, ds$$

which is just the volume swept out by the effective collecting area.

If the mechanism of cleaning were only impaction, then the volume cleaned by the droplets would be:

$$\int_o^L \eta \, \pi \, R_d^2 \, ds$$

Because impaction is often the predominant mechanism for collecting particles larger than about 1 μm, it is worthwhile to compare these volumes. It is clear that for the CDS to be substantially better as a practical collector, the product of its augmented cross-sectional area, $(R_d + D)^2$, and its collision effectiveness parameter, p, should be substantially greater than $\eta \pi R_d^2$ for conventional scrubbers.

The distance of closest approach augments the geometrical radius of the droplet with respect to collection. If this increased size is appreciable, and if the collision probability parameter is no less

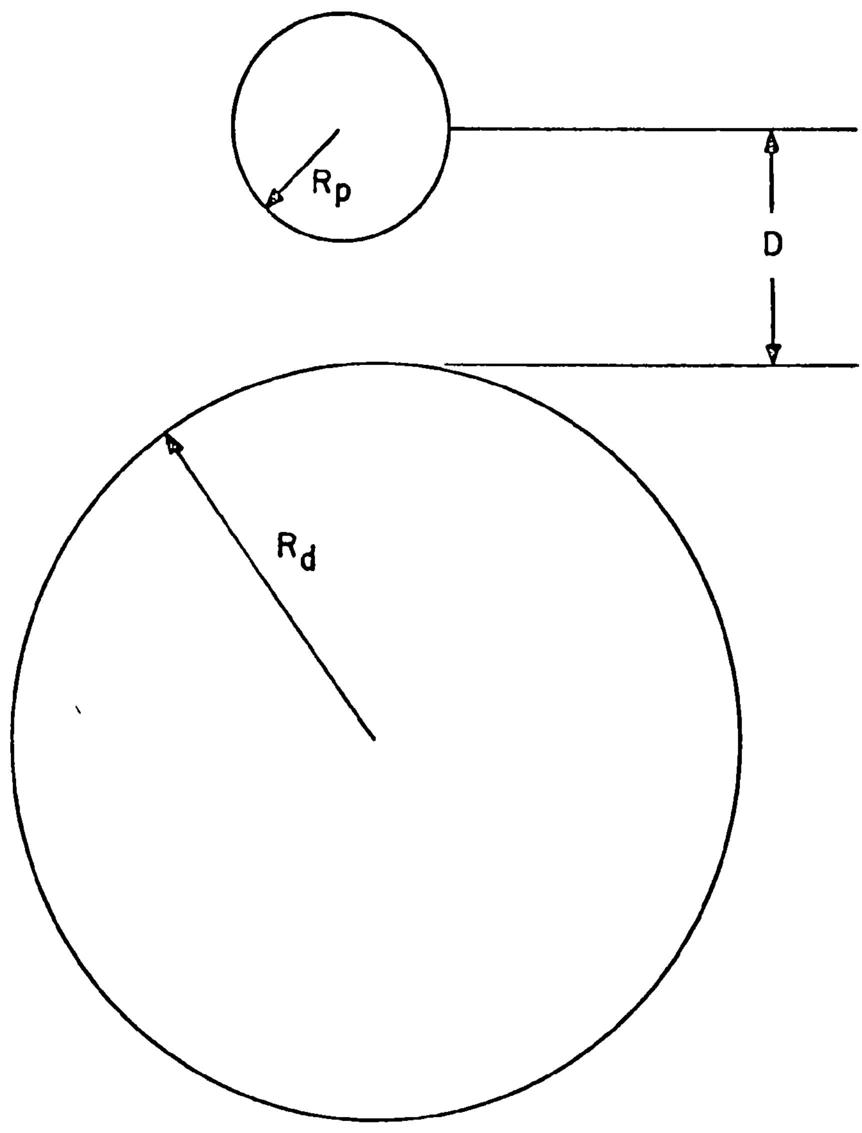

Figure 38. Droplet and particle dimensions at distance of closest approach

than it is due to conventional collection mechanisms, then increased collection should take place, roughly in proportion to the square of the ratio of the augmented radius to the geometrical radius, in comparison to the conventional situation.

Their analysis[8] obtains D as follows. A dimensionless drift time function, T, is defined as:

$$T = 0.164\ E_o\ (R_p^{\ 2}/R_d)\ t_D$$

where: E_o = droplet field at surface, V/cm
R_p = particle radius, cm
R_d = droplet radius, cm
t_D = drift time, sec

derived for a conducting particle in an average field of 5 kV/cm and a 10 cm drift distance to the collecting plates. Having calculated a value for T, one substitutes it into an equation relating T and a

$$T = G(a)$$
$$T \doteq a + 2.5\ a^2,\ a \ll 1$$

where: $a = D/R_d$.

The function G(a), shown in Figure 39, was derived[8] by assuming that the particle accepts just enough charge to produce a coulombic field at the droplet surface which just cancels the dipole field produced by the droplet image in the particle. Given a T, one can obtain D, using:

$$a \doteq (-1 + \sqrt{1 + 10T})/5,\ a \ll 1.$$

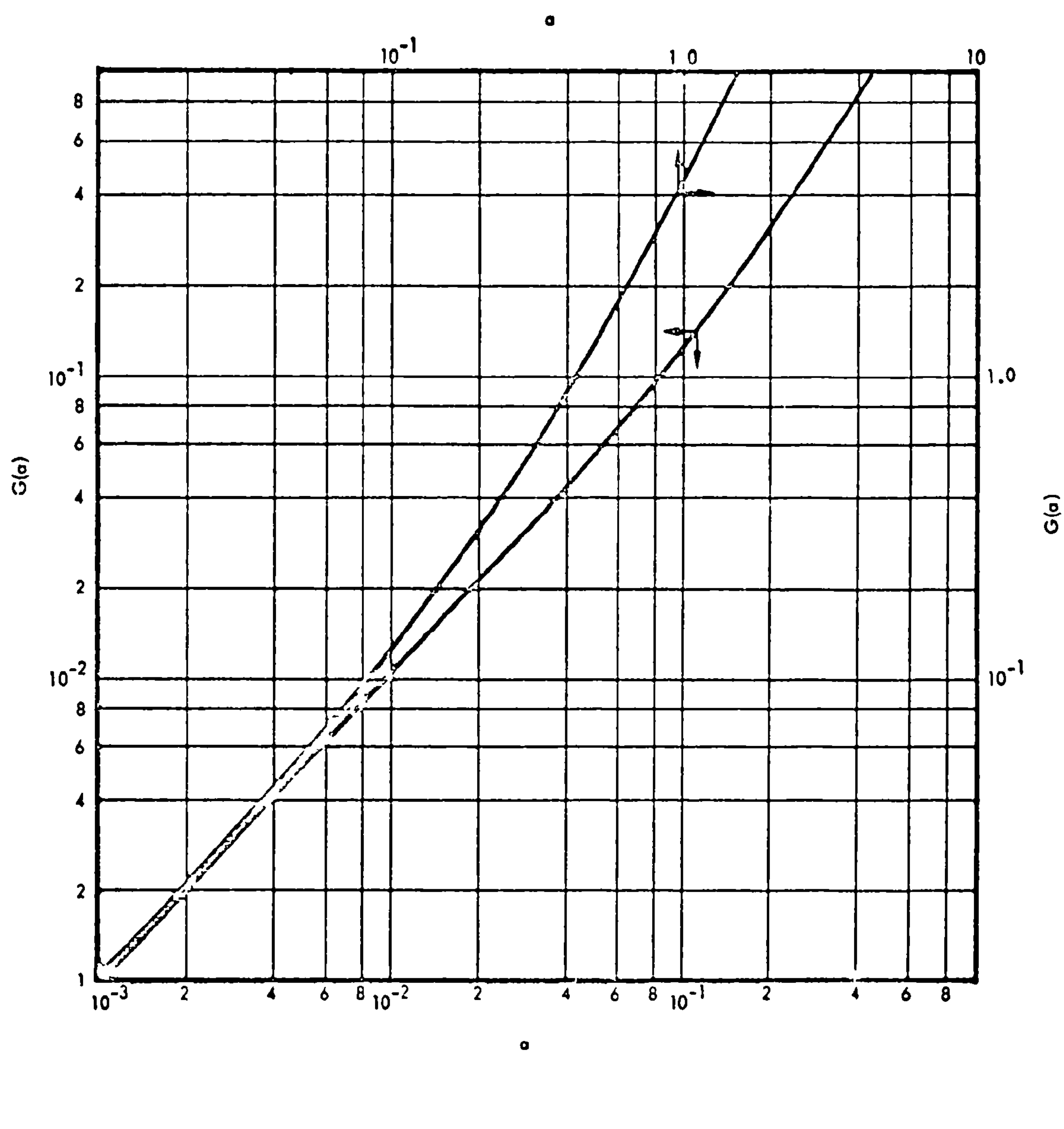

Figure 39. Plot of function G(a) related to particle drift time[8]

Figure 39 comes from reference 8 and shows G(a) versus a.

We have derived Table 23 from the material above for various particle diameters ($2R_p$) assuming, $R_d = 60$ μm, $E_o = 2.3 \times 10^5$ V/cm, $t_D = 15$. From this table, it is clear that for fine particles ($D_p \leq 3$ μm) the droplet effective size ($R_d + D$) has not been made substantially greater than its geometric radius.

Table 23. DISTANCES OF CLOSEST APPROACH, D, FOR PARTICLES AND DROPLETS UNDER ASSUMPTIONS STATED IN TEXT

D_p (μm)	T	a	R_d (μm)	D (μm)	$R_d + D$ (μm)
0.5	0.0039	0.0039	60	0.234	60.23
1	0.0157	0.0151	60	0.906	60.906
3	0.141	0.110	60	6.6	66.6
10	1.57	0.617	60	37.02	97.02

An earlier set of computations for D made[8] under somewhat different assumptions also supports the conclusion that the effective size of the droplets is not substantially increased with respect to the capture of particles smaller than a few microns. We quote here the description of that calculation (note that their system of units is MKS rather than cgs):

"A model for the induced, or corona, charging of particulate by charged water droplets has been analyzed. The premise of the model is that the surface electrostatic field on a particle can exceed the breakdown strength of the medium in which the particle and droplet reside. When breakdown occurs, charge will be transferred between the particle and droplet. The particle will assume charge of the same sign as the droplet.

"The condition for induced charging of spherical particulate with charged water droplet is:

$$E_p = \left(\frac{3\epsilon_D}{\epsilon_D + 2}\right) E_s \left(\frac{S}{S + D}\right)^2 \geq E_o \left(1 + \frac{C}{\sqrt{R}}\right) \quad \cdots\cdots\cdots \quad (1)$$

where: E_p = surface electrostatic field on the particle

ϵ_D = dielectric constant of the particle material

E_s = surface electrostatic field on the droplet

S = radius of the droplet

D = separation distance between the droplet surface and the center of the particle

E_o = breakdown strength of the medium for planar electrodes

R = radius of the particle

C = Peek's correction constant

C = 0.054 for R in meters

"The geometric model for Equation (1) is shown in Figure [38] and a solution to the equation is shown in Figure [40]. It was assumed in the analysis that the electrostatic field on the droplet surface, E_s, corresponds to the Rayleigh Limit and the dielectric constant of the particle material, ϵ_D, was 5."

"The quantity, D - R, is the maximum distance between the droplet and particle surfaces at which charge exchange can occur. The values of the separation distance as a function of particle radius for the various droplet sizes to the right of the peak value are only approximate because of the deviation from uniform induced field on the particle from geometric effect. The curves will decay to zero at a faster rate in this region because of this effect."

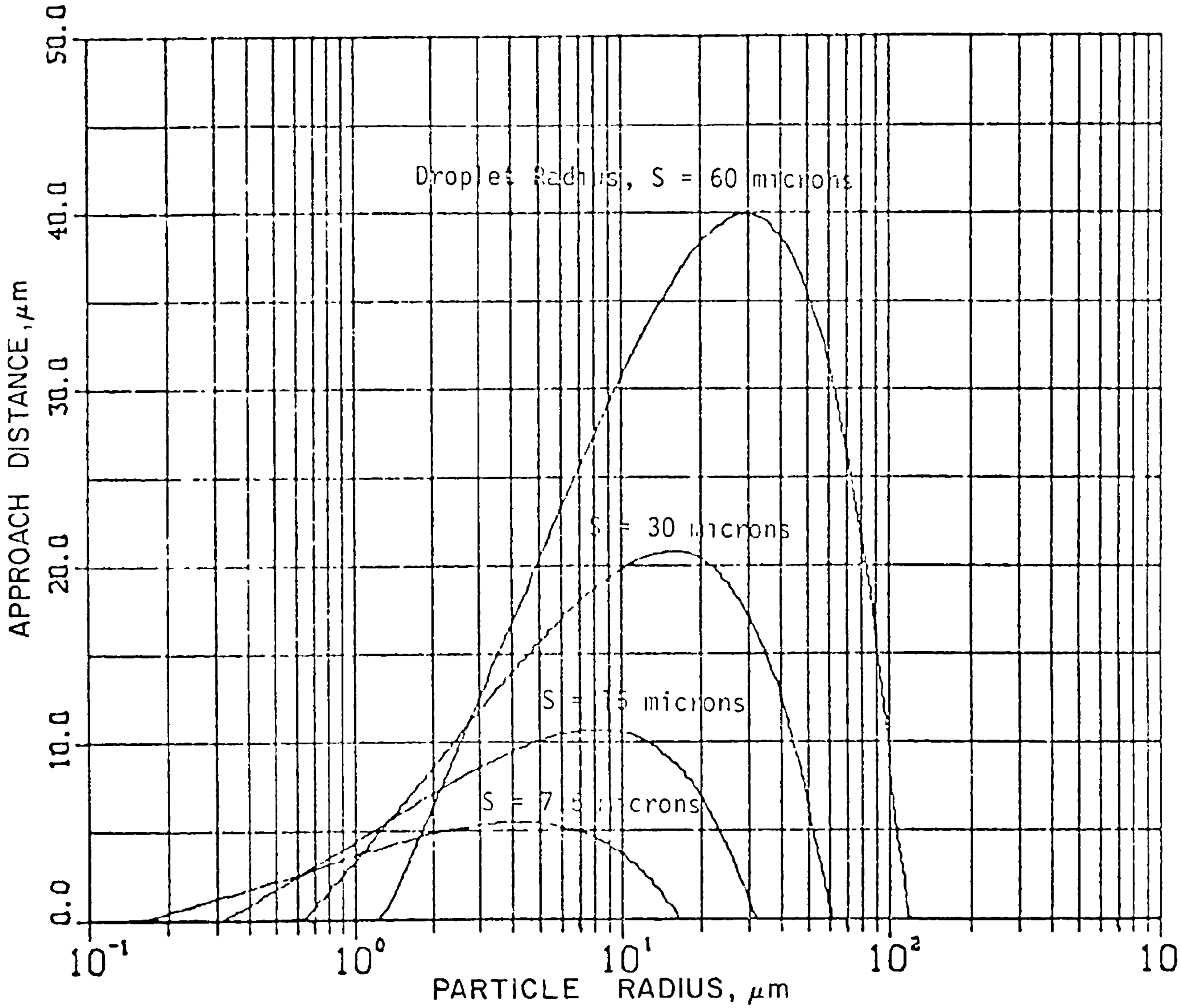

Figure 40. Induced charging of spherical particles

The effective size increase of the 120 μm droplet is negligible for $R_p < 1$ μm.

To compare the collision effectiveness probability (p) with the target efficiency expected from impaction, we have added an impaction efficiency curve to a figure presented by TRW as part of their parametric computer study of the charged droplet collection process. Figure 41 is taken from their work with the exception of the circles and triangles which we have added. The ordinates have the particle radius, a characteristic charge parameter, and the ratio $A = a = D/R_d$; the abscissa is both the collision effectiveness probability, p, for the combined set of forces studied by TRW and single target efficiency, η, for impaction alone (estimated by from the curves of May and Clifford[11] for impaction on spheres, neglecting the D contribution to the droplet radius). The nominal values used here were: drift time of 1 second, droplet diameter of 120 μm, electric field of 5 kV/cm, initial droplet field of 230 kV/cm, particle density 2.15 g/cm^3 and air at STP. To calculate the impaction parameter, we took both 1 m/s and 10 m/s as droplet velocities, as indicated. The calculations show that the collision effectiveness probability is not much different from the impaction efficiency for droplets traveling at 10 m/s (triangles) but considerably better than from droplets traveling at 1 m/s (circles).

A problem with their calculation is that they have a calculated velocity for the droplet at the high end of the range of the measured velocities. The parameter which characterizes droplet velocity is:[8]

$$U = 2\,\epsilon_o\,E_o\,E\,R_d/3\mu \quad \text{(MKS)}$$

or

$$U = E_o\,E\,R_d/6\pi\mu \qquad \text{(cgs)}$$

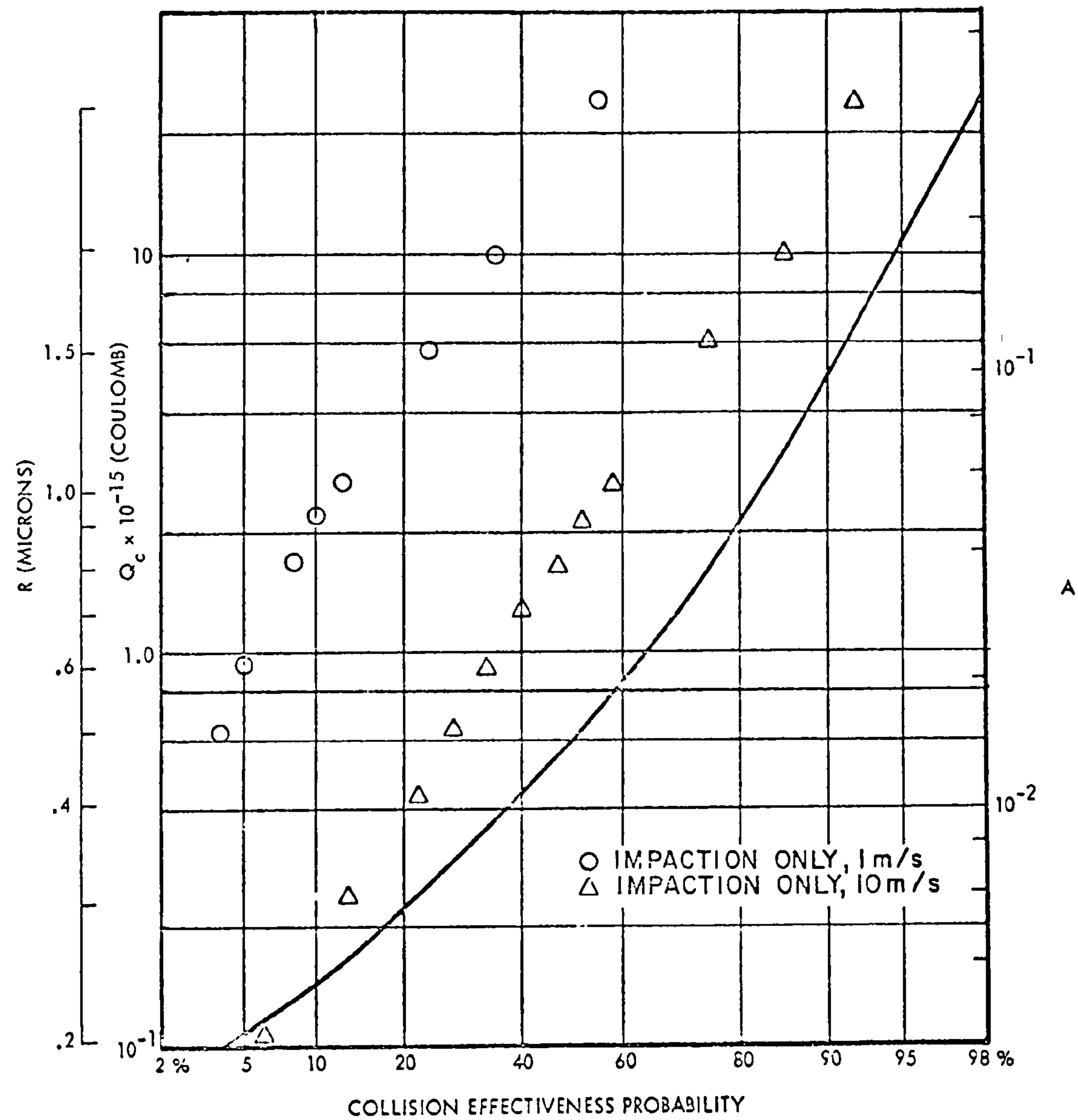

Figure 41. Functional dependence of collision effectiveness probability on characteristic charge, Q_c

which assumes Stokes law drag on the droplets. Their equations imply velocities of 2.24×10^2 m/s for the droplets, more than 10 times greater than those they measured.

If the velocity used in our calculation for impaction is made to be 2×10^2 m/s to match that implied by the theoretical parameters, then the 10 m/s impaction curve shifts parallel to the radius axis (the ordinate) by nearly a factor of $(20)^{1/2}$, making the impaction efficiencies higher than the collision probabilities. In comparison, a nozzle at a pressure of 6.9×10^5 N/m^2 (100 psig) produces a flow with approximate (potential flow) initial velocity for the droplets of 37 m/s, the collection efficiency curve for which would nearly match the curves given for collision probability by their analysis.

Estimates of the collection efficiency of the CDS can be made using the formula for penetration (one minus efficiency):

$$Pn = \exp\left(- \frac{3}{2} \eta \frac{Q_d}{Q_g} \frac{L}{D_d^*}\right)$$

where: η = single target efficiency

Q_d = volume rate of flow of droplet material

Q_g = volume rate of flow for gas

L = droplet path length

D_d^* = ratio of mean cube diameter to mean square diameter.

The efficiency will be high only when the argument of the exponent is large compared with one. Typical values for the volume flow ratio were $Q_d/Q_g \sim 10^{-4}$; the D_d^* can be estimated by D_d which was 200 μm, and the path length of the droplets for the prototype CDS was ~10 cm. The product of the factors other than target efficiency (collision effectiveness parameter) becomes:

$$\left(\frac{3}{2} \frac{Q_d}{Q_g} \frac{L}{D_d^*}\right) \sim 0.1$$

In order for the argument of the exponent to be one or greater, the single target efficiency must be greater than or on the order of 10.

The experimental collection efficiencies correspond to an exponential function with an argument substantially greater than one. This calculation would suggest that the droplets had single target efficiencies of 1000 percent, much greater than they would have had due to impaction alone. In a sense, this is true, but in another sense it is as misleading as it would be to ascribe a very high collection efficiency to a few drops injected into a conventional electrostatic precipitator. Collection would primarily occur on the walls, not on the drops.

To summarize, we conclude the following:

1. There is no intrinsic power advantage to accelerating the droplets electrostatically rather than by the use of pressurized liquid.

2. Theoretical analysis does not indicate why this charged droplet scrubber should capture significantly more fine particles than an uncharged droplet scrubber of the same power consumption. On the other hand, the experimental results corresponded to exceptionally high droplet-particle interaction efficiencies, casting doubt on modeling the system as a scrubber rather than as an electrostatic precipitator.

3. The use of droplets to transfer charge to particles may produce as much as an order of magnitude increase in particle charging as does conventional corona charging methods, because the field in the immediate vicinity of the droplets is higher (Peek's correction) than the typical breakdown field. The kinetics of the charge transfer and probability of approach still could negate the possible charge increase.

4. Wetted-wall precipitation has certain advantages with respect to cleaning, preventing reentrainment and overcoming high resistivity in comparison to drywall precipitation. Liquid waste disposal, however, is more difficult than dry waste disposal.

Applicability to Pollution Control - The charged droplet scrubber studied has shown[9] that it can produce 99 percent collection efficiencies at about 2 μm particle diameter. These results suggest it could be an important method of fine particle control.

Propects of method - If the promise of such a device were fulfilled, it would be a hybrid of scrubbing and electrostatic precipitation which would have lower power usage than a scrubber of identical efficiency and smaller size than electrostatic precipitators with the same efficiency. It presents problems in the handling of the water-borne solids, as do other scrubbers, and in the safety of dealing with tens of thousands of volts of electricity in the presence of water spray.

Status of method - A pilot plant unit has been constructed and tested at 0.47 m^3/s (1000 cfm) and plans are under way to test a full-scale model.

Implications - This could lower the cost of control of fine particles, and it will place added emphasis on the successful handling of scrubber waste water.

Summary

A charged droplet scrubber has been investigated which uses electrostatic forces to accelerate charged droplets and uses these droplets to collect particles either directly on the droplets or indirectly by transferring charge to the particles and collecting them on the walls of the scrubber, which act as electrodes. It is not clear from theoretical analysis why this should be substantially superior to either high-energy scrubbing or electrostatic precipitation, but it is plausible that charged droplet scrubbing would tend to be less energy-consuming than high energy Venturi scrubbers and smaller in volume than electrostatic precipitators, at the same efficiency. The next steps in the development of the device should be tests which allow direct comparison between the charged droplet scrubber and the other control devices named; data from full-scale operation would also be very useful.

SYSTEMS OF CHARGED DROPLETS AND PARTICULATES

The basis for the discussion which follows is a report[16] by Melcher and Sachar entitled "Charged Droplet Scrubbing of Submicron Particulate," portions of which are included in a Ph.D. thesis in electrical engineering for MIT by Sachar. The report describes characteristic times for various droplet and particle behavior; reviews the literature, including patents, related to the concept of charged droplet scrubbing broadly defined; gives theory and experimental confirmation of the theory for the behavior of charged submicron particle aerosols, charged sprays much larger than a micron, and the interactions between the two when present together. The implications of the research are also discussed.

Goals

Objectives delineated in their report were: to analyze what was "unique in the use of drops and electric fields in collecting fine particles by providing a classification based upon the fundamental mechanisms for the electrically induced collection of particles on drops," to complete a literature review on this topic, to perform "experiments that can be used to test knowledge of the electromechanical dynamics of (a) systems of charged submicron particles; (b) charged supermicron systems of droplets and (c) systems involving both charged droplets and charged fine particles in charged droplet scrubbing configurations," these experiments to be done (by implication from their being contrasted with earlier work) with (a) "sufficiently high charged-drop densities to be of industrial interest and (b) experimental parameters carefully enough controlled so that comparisons could be made between theoretical models and experimental results."

Methods of Study

Theoretical - Although in a number of instances the relevant equations are solved in detail and evaluated, much of the work hinges on the technique of investigating characteristic times, a variety of analysis of scale. This kind of analysis allows one to draw conclusions based on models which attempt to incorporate the physical mechanisms involved and to obtain approximate values for their magnitudes using characteristic dimensions, velocities, etc. Thus, for example, without specifying the shape of a control device, the gas residence time, t_{res}, is just the ratio of the device volume (V) to the gas volume flow rate (Q_g), in consistent units. The following times are important to the Melcher and Sacher analysis:

- Precipitator collection time, t_{pc}, the electrostatic precipitator plate spacing divided by the charged particle migration velocity;

- "Particle self-discharge or self-precipitation time," t_a, roughly the average interparticle distance divided by the particle velocity produced by the Coulomb force between the particles at that distance (velocity being force times particle mobility);

- "Drop-particle collection time or time for precipitation of particles due to space-charge of drops," t_c, roughly the average distance between droplets divided by the particle velocity produced by the Coulomb force between particles and droplets at that distance;

- "Drop self-discharge or self-precipitation time," t_R, roughly the average distance between drops divided by the drop velocity produced by the Coulomb force between drops at that distance.

In our notation, these times are given by the following formulas:

$$t_a = 1/4\pi \, q_p^2 \, B_p N_p$$

$$t_c = 1/4\pi \, q_p \, q_d \, B_p \, N_d$$

$$t_R = 1/4\pi \, q_d^2 \, B_d \, N_d$$

where the subscripts d and p stand for droplet and particle and the quantities q, B, N are charge (esu), mobility (cm/dyne-s), and number concentration (cm^{-3}).

It is interesting to note, as Melcher and Sachar do, that these times are characteristic for the rates of change of number concentration of particles (t_a,t_c) or droplets (t_R) whether the Coulomb force is attractive or repulsive for particle-particle, particle-droplet or droplet-droplet interactions. This idea can be overstated however, because there is a significant difference between a particle number or droplet concentration which decreases due to mutual repulsion to the walls of the control device and to the decrease accompanying agglomeration...one mechanism removes mass from the air stream while the other does not.

The use of characteristic times has an advantage in allowing easy comparison with "reasonable" system residence times and the disadvantage that it is not the way most of the practitioners in air pollution control, especially those using electrostatics, have formulated the problem. For scrubbers and electrostatic precipitators, the formulation for penetration of a control system with turbulent flow is:

$$Pn = \frac{(N_p)}{(N_p)_o} = \exp\left(-w \, A/Q_g\right)$$

in which formula the first ratio is that of the outlet particle concentration to the inlet, and the argument of the exponential function is a particle collection velocity times the collection area divided by the volume flow rate of the gas. This argument can be made to be the ratio of a characteristic time for cleaning, t_c, and the residence time in which case we have

$$Pn = \exp\,(-\, t_{res}/t_c)$$

and

$$wA/Q_g = (V/Q_g)/t_c$$

in which V is the device volume. For a device of fixed volume and volume flow rate, a decrease in t_c corresponds to an increase in the product of the effective migration velocity and the effective collection area, hence is desirable. Where drops are used as collectors they must stay in the collection region long enough to do the cleaning, meaning $t_R > t_c$ is required; achieving this can become a problem, because the highly charged droplets which produce the highest individual drop collection efficiencies are also those which are most rapidly lost to the walls of the control device, for unipolar drops, or which coalesce with other highly charged droplets and become neutralized and less effective, where bipolar drops are used.

An overview of the results of the Melcher and Sachar analysis is presented in Table 24, which is an adaptation of one of theirs. It contains a descriptive designation of the system, details about particle and drop charge, whether there is a substantial net electric field due to the particles or drops or imposed upon them, and the characteristic time important in the analysis of its collection efficiency.

Experimental Methods

The experimental work was subdivided to study the behavior of submicron particles, then "supermicron" drops, then the two together.

Table 24. SUMMARY OF BASIC CONFIGURATIONS FOR COLLECTING SUBMICRON PARTICLES. (BASED UPON TABLE BY MELCHER AND SACHAR).

System	Particle charge	Drop charge	Ambient field	Characteristic times
Inertial scrubber	None	None	None	(deleted)
Electrostatic precipitator	Unipolar	-	Imposed	t_{pc}
Space-charge precipitator	Unipolar	-	Self	t_a
Self-agglomerator	Bipolar	-	None	t_a
Charged droplet scrubber	Unipolar (+ or -)	Unipolar (- or +)	Self ($N_p q_p < N_d q_d$)	t_c, t_R
Charged droplet scrubber	Unipolar (+ or -)	Unipolar (- or +)	None ($N_p q_p = N_d q_d$)	$t_c = t_a$
Charged droplet scrubber	Unipolar (+ or -)	Bipolar	None	t_c, t_R
Charged drop precipitator	Unipolar	Unipolar	Self ($N_p q_p < N_d q_d$)	t_c, t_R
Electric inertial scrubber	None None	a) unipolar b) bipolar	Imposed or "self" imposed	(deleted)
Electro-fluidized and electro-packed beds	Unipolar or bipolar	None or bipolar	Imposed	t_c (q_d based on "half-charge" induced on spherical collector's hemispheres)

In the submicron particle study, the particles were generated with a condensation generator: an atomizer followed by a heating and condensing section, with the central core of nearly monodisperse dioctylphthalate (DOP) particles used for experimentation. Their particle size was measured with the optical owl to find high order Tyndall spectra and with a polarizer/analyzer to size the smallest particles by their polarization ratio at 90^o scattering angle. Concentration was measured by extinction measurements. The particles were charged with a corona discharge and the charge was measured by using the method of tangents on data from a parallel-walled precipitator (see Fuchs's[12] book for details). The calculated values of the characteristic time for self-precipitation, t_a, were calculated from the measurements and then were used in the solutions of the equations for penetration obtained by assuming slug flow and Poiseuille flow profiles. Where the penetration was roughly one-half, the computed solutions differed from each other by about 20 percent and the data were about 20 percent outside the range of the two calculations, for laminar flow. Three experiments with turbulent flow gave even better agreement with the turbulent flow, perfect mixing, version of the penetration equations. Experiments were also conducted with an aerosol made bipolar by the mixture of two unipolar aerosols. As with the other experiments, penetration was inferred from measurements of current due to particle transport versus distance traversed. The bipolar aerosols were reported to confirm the t_a analysis, although the agreement was not as good as had been obtained between theory and experiment for the unipolar case.

For the droplet-droplet studies, vibrating multiple orifices were used, as done by Berglund and Liu[13] for example. The droplets were charged by induction by having this generator attached to high voltage sources operated at the same or opposite polarities. Useful discussion is given concerning this and other types of charged droplet generators. Droplet velocity in a long tube was measured, as was gas velocity. The charge could be calculated. Predictions using droplet characteristic time t_R

agreed fairly well with experimental results. For self-discharge, the charge of the drops was inferred by their deflection by electrodes; the results were 6 to 8 times different from the predictions made by their model, the droplets discharging each other more slowly than expected.

The droplet-particle studies focused on three systems: charged particles collected by oppositely charged droplets, charged particles collected by bipolar droplets, charged particles repelled to the walls by charged droplets with the same polarity. The model used to compare with tests predicted droplet collection efficiency in a manner similar to that for which charge acquired in corona discharges is calculated (as done recently by Smith and McDonald),[14] assuming a uniform external electric field and a viscous flow model. This flow was reported to give results little different from those for other flow models.

Results

In general, the measured collection efficiencies of the various configurations verified the time scaling approach and the efficiency equations associated with that approach. Figures 42 and 43 from the work of Melcher and Sachar[16] shows the agreement between the theoretical ratio of outlet concentration to inlet concentration (n_{out}/n_{in}) for their test aerosol. The measured values are graphed against the drop charging voltage, the specific configuration being the precipitation of positive particles by negative drops and, in Figure 43, by positive drops. Table 25 adapted from one of their tables. For three different kinds of precipitator it gives the measured efficiencies with no charging, with charging only the particles and with charging both particles and droplets.

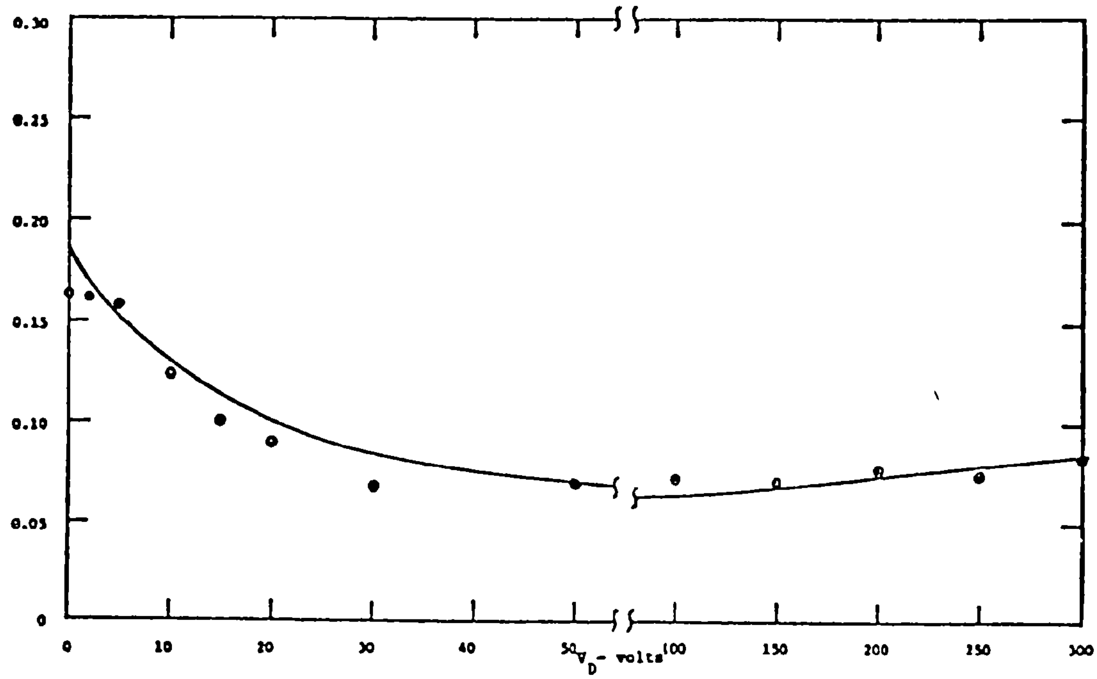

Figure 42. Theoretical and measured collection of positively charged aerosol particles upon negatively charged drops as a function of drop charging voltage[16]

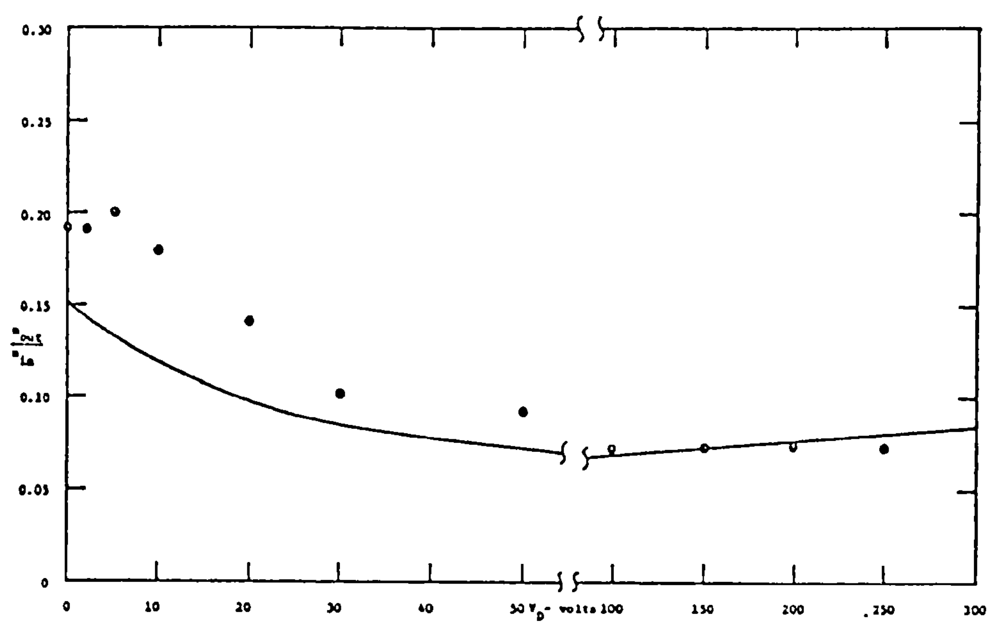

Figure 43. Theoretical and measured particle collection for precipitation of positively charged aerosol particles by positively charged drops as a function of drop charging voltage[16]

Table 25. EXPERIMENTALLY DETERMINED EFFICIENCIES FOR THREE CHARGED DROPLET SCRUBBER CONFIGURATIONS[16]

Conditions	Scrubber configuration used: Unipolar drops and unipolar aerosol, oppositely charged	Bipolar drops and unipolar aerosol	Unipolar drops and unipolar aerosol, same sign charge
No charge on drops or aerosol	25%	25%	25%
Charge on aerosol only	87%	86.5%	85%
Charged drops, charged aerosol	95%	92%	95%

Conclusions

Based on their experimental and theoretical work, Melcher and Sachar concluded that the various possible types of charged droplet scrubbers would not have residence times (thus volumes, thus capital costs) smaller than electrostatic precipitators with the same efficiency. They concluded that electrostatic augmentation would increase the collection efficiency of spray scrubbers. Charged droplet scrubbers thus form "a class of devices with the capital investment and operating cost profile of the wet scrubber but a particle removal efficiency approaching that of the electrostatic precipitator."

Evaluation

Suitability of Goals - As noted elsewhere, the idea of using electrical forces to enhance collection efficiencies of spray scrubbers is one which seems promising. The work done by Melcher and Sachar aimed at defining the various combinations of droplet and aerosol charge, determining the efficiencies which could result and looking for the underlying similarities. This rather fundamental approach is quite useful for unifying the analysis of control device ideas which seem quite dissimilar.

Suitability of Methods

Theoretical Approach - The emphasis on dimensionless groups (the ratios of characteristic times) is particularly appropriate for work which seeks to be applicable to a wide variety of device configurations which differ appreciably from simple models, and for which the would-be analyst has only sketchy information. A minor problem is that the use of characteristic times differs from the usual methods of analysis: those who work with electrostatic precipitators are used to a similar approach in terms of migration velocity and those who work with scrubbers are more familiar with droplet collection efficiency. In general, Melcher and Sachar have used equations describing droplet and particle charging and motion which are at or near the state-of-the-art and have used them at a level of detail appropriate to the degree of information available about the parameters which enter into the equations.

Experimental Approach - As can be seen from the information in Table 26, Melcher and Sachar have measured or defined the important variables in their experimental systems. The methods used to measure particle and droplet size and charge showed an understanding of the problems of such measurements and an awareness of the current methods in aerosol technology.

Applicability to Pollution Control - Because the work done was an academic investigation rather than the testing of a specific control device, we will not try to evaluate the applicability to pollution control of the devices except to paraphrase the authors' conclusions that

Table 26. PARAMETERS ASSOCIATED WITH THE STUDY OF SYSTEMS OF CHARGED DROPLETS AND PARTICULATE

Parameter	Magnitude, description, method of measurement or control, etc.
GAS	
Volume flow rate	Variable
Face velocity	(1) 0.5 m/s (see comments)
	(2) M
	(3) 10-50 m/s
Reynolds number (Re_f)	K
Flow geometry	K
Pressure drop (Δp)	?
Temperature	ambient
Pressure	ambient
Relative humidity	?
PARTICLES	
Size	(1) 1-1.0 micron
	(2) monodisperse
Shape	spherical
Chemical composition	(1) DOP
	(2) ?
	(3) ?
Resistivity	K
Dielectric constant	K
Charge	(1) unipolar measured
	(2) bipolar
	(3) A - no charging
	B - bipolar charging
Concentration	M
CHARGING SECTION	
Type of charging	impact charger
Ion concentration	Variable, M
Electric field	Variable, M
Geometry	K

Table 26 (continued). PARAMETERS ASSOCIATED WITH THE STUDY OF SYSTEMS OF CHARGED DROPLETS AND PARTICULATE

Parameter	Magnitude, description, method of measurement or control, etc.
COLLECTOR	
Chemical composition	water
Resistivity	K
Dielectric constant	K
Charge	(1) unipolar using induction charging variable
	(2) bipolar-charged and re-charged by induction charging
	(3) induction charging - measured
Voltage, electric field	(1) no ambient
	(2) no ambient field utilized
	(3) ambient field
Particulate loading	?
Geometry	
Internal configuration	(1) 5-25 μm
	(2) 5-25 μm
	(3) 2.5-10 μm
External configuration	
Collection efficiency	M
CLEANING PROCESS	
Method	N.A.
Effect on efficiency	?

COMMENTS: Three types of systems are covered:

(1) Unipolar particles and oppositely charged unipolar particulate.

(2) Bipolar particles and particulate and ambient electric field.

(3) Electrically driven impact scrubbing and agglomeration through particle polarization.

STAGE OF DEVELOPMENT: Final Report - Phase I the operating characteristics of the charged droplet scrubbers can be expected to fall between those of electrostatic precipitators and conventional high-energy scrubbers in terms of efficiency, power consumption, and capitalization.

Summary

The MIT researchers have categorized the configurations for charged droplet scrubbing, shown the similarity of the time constants involved for the various configurations, measured particle and droplet concentration changes under well-defined conditions and verified that these time constants can be used in mathematical models which predict measured collection efficiencies rather well. They concluded that charged droplet scrubbers have performances which lie between those typical of electrostatic precipitators and spray scrubbers, which may mean they will be optimal for certain control problems.

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SECTION VII

ELECTROSTATIC AUGMENTATION OF PRECIPITATION DEVICES

GAMMA-RAY PRECIPITATOR

The gamma-ray precipitator prototype differs fundamentally from a conventional electrostatic precipitator only in its mechanism of charge production. The experimental gamma-ray precipitator[1] employed a Co^{60} γ-ray source rather than a corona discharge. Any advantages as an air cleaning device for the γ-ray precipitator must involve an advantage in the charging of the particulates. In both the conventional electrostatic precipitator and the γ-ray device the mechanism of particulate deposition by electrostatic field removal is the same. Furthermore, the primary charging mechanisms of diffusion charging and field charging are at work in both devices.

Goals

The Pennsylvania State University (PSU) Department of Nuclear Engineering undertook both an experimental and theoretical study of the gamma-ray precipitator. Their goals were to measure the prototype device's collection efficiency with respect to particulate size and to explain the performance by a theoretical model. Midwest Research Institute (MRI) undertook an evaluation of the PSU group's work which amounted to a recheck of calculations and a general discussion of the practical utility or lack thereof of the γ-ray precipitator. The overall conclusions of the two groups were at variance: MRI was negative in its draft final report; PSU found the concept promising.

Methods of Study

Experimental - The PSU group performed an experimental study of the collection efficiency of the γ-ray precipitator in a pilot plant operation. The basic precipitator flow system consisted of two concentric stove pipes, 20.32 cm i.d. and 12.7 cm i.d. (8 inches and 5 inches), which served as collection electrodes. The vertically-oriented assembly (see Figure 44) directed incoming ash-laden gases from a coal-fired furnace down the central pipe. At the bottom of the assembly in the irradiation zone the gases were forced to make a 180° turn to enter the annular space between the two pipe electrodes. The annular space near the turn-around was strongly irradiated by γ-rays from surrounding pencils of Co^{60}. This was the basic site of air ionization and much of the deposition. To a decreasing extent the remaining length of annular space above the irradiation zone served to collect electrostatically the charged particulates.

The basic experimental data collected in the studies were six-stage impactor samples taken of the inlet and outlet gases. The weight-percent impactor data was adjusted to a number-percent scale by assumption of 2 gm/cm^3 as a reasonable particulate material density. Particle collection efficiencies were obtained from these adjusted results.

Experimentally variable parameters included the annular space air velocity (generally 152 cm/s, or 5 ft/sec), irradiation dose rate, electrode potential, and electrode polarity. Total weight-percent collection efficiencies were taken at varying electrode potentials, dose rates, and alternate changes in electrode polarity. Weight of ash deposited on test patches along the annular collection zone indicated the anticipated fall-off in collection along the precipitator length.

Theoretical - Schultz et al.[1] predicted the collection efficiency variation with particle size. The basic model input was the assumed ion

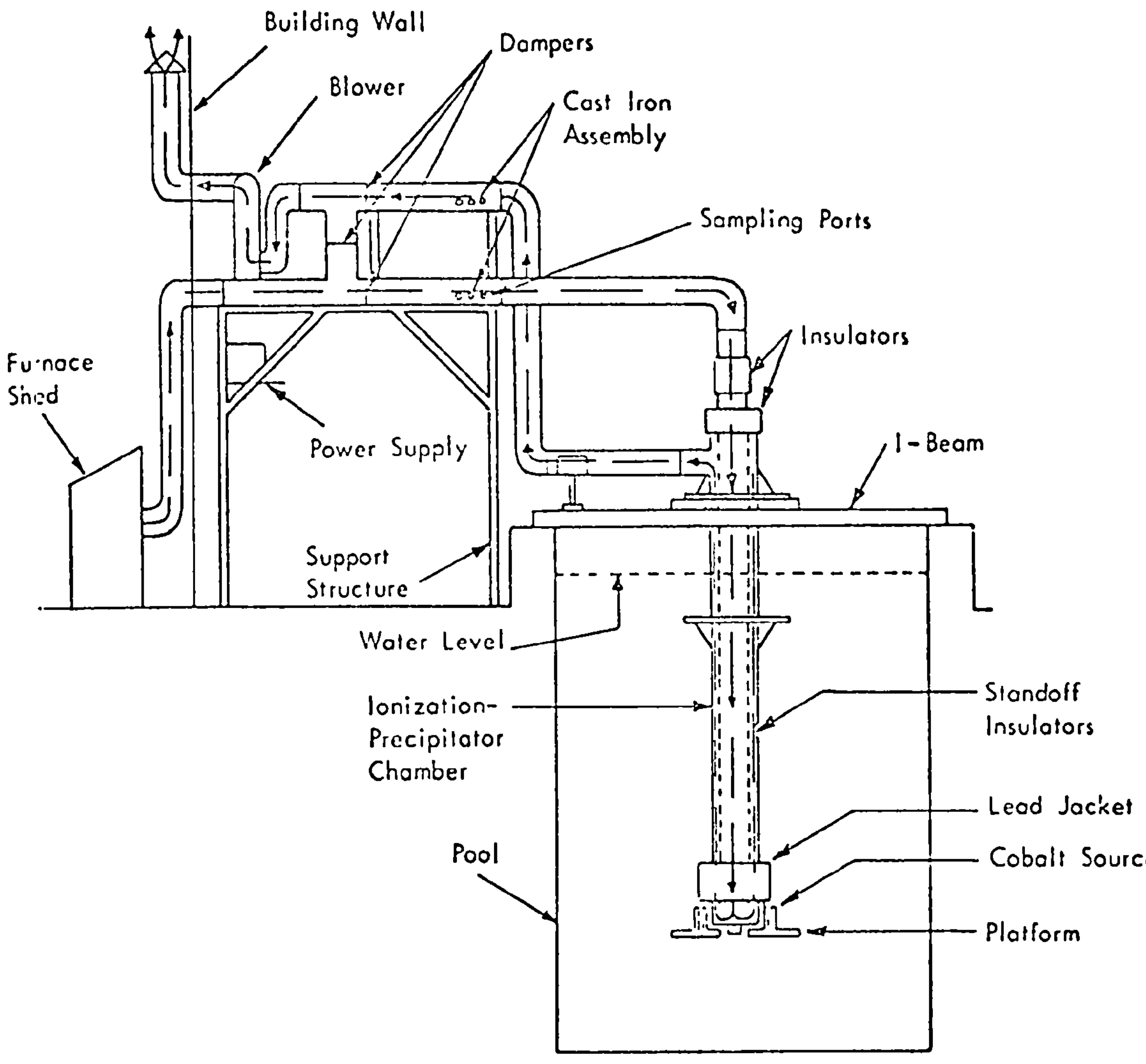

Figure 44. Schematic diagram of gamma ray precipitator and auxiliary equipment[1]

concentration which they claimed by "crude measurement" to be as high as 10^{10} ions/cm^3 near the electrodes. Their unpublished theoretical ionization calculations indicated that at least 10^7 ions/cm^3 would be achieved in the irradiated zone. The particle drift velocity is linearly related to the saturation charge of individual particles due to field charging and the attainable diffusion charge. Theoretical efficiencies were computed directly from the Deutsch equation by combining drift velocity and the collection area to volume flow ratio (A/V) in the exponent.

Schultz et al.[1] also discussed mechanisms of unipolar ion production which may be involved in the γ-ray precipitator. The γ-rays interacting with the electrode walls and the air molecules ultimately produce both positively and negatively charged ions. In the view of the authors, photoemission of electrons at the walls combined with high ion concentration produces space charge separation between the electrodes sufficient to inhibit recombination and strongly charge the particles.

The MRI evaluation accepted the validity of the Deutsch equation efficiency approach but focused its attention on two difficult particle sizes, 0.01 and 0.1 μm. The evaluation was seriously flawed in that it made the mistaken assumption of Cunningham slip correction approximately equal to 1.0 for these very fine particles.

Results and Conclusions

In their paper, Schultz et al.[1] compared their experimental data with the efficiencies they would predict for an electrostatic precipitator under comparable but not identical conditions. Although this comparison was favorable for the GRP, it is not conclusive because the two cases were not identical and because the comparison is between experimental data for one system and theory for the other. In addition, as indicated below, our calculations of the particle charge achieved, using these data, indicates inferior rather than superior charging by the GRP compared with the ESP.

The MRI analysis indicated only marginal advantages in charging for the GRP. Our recomputations still support this conclusion. Furthermore, MRI concluded that the special problems connected with the handling of radioactive materials probably outweigh any advantages under present circumstances.

Evaluation

Certain shortcomings in the theoretical analysis of the GRP are corrected in the material which follows and a short analysis of the experimental data is presented, both of which support the conclusion that the GRP has no substantial inherent advantages for particle charging compared with the conventional corona discharge method now in use. The economics of obtaining and handling radioactive material will vary greatly from installation to installation and would have to be analyzed by each potential user. For those without special access and expertise, we believe the problems and cost to be more substantial than those encountered with corona charging. The studies done thus far by Dicter and Schultz in 1971[2] and Schultz, et al.[1] in 1973 have not demonstrated how the collected material could be removed from the collector economically, a major drawback.

Suitability of Goals - The major problems in electrostatic precipitation technology can be inferred from the focus of most of the recent work (e.g., Symposium on Electrostatic Precipitators, Pensacola Beach, Florida, October 1974, sponsored by EPA): adhesion, high resistivity, high temperature, sneakage, reliability, gas flow distribution, electrostatic augmentation of control devices. Still, the possibility that radioactive wastes could be put to good use was one worth investigating. Because the primary difference between the GRP and the ESP is the method of particle charging, this should have been studied in detail, although the experiments do allow some conclusions to be drawn concerning particle charging. There is value in demonstrating, as has been done, that a technique does work; what remains is a determination of its practicality.

Suitability of Methods - Experimental and theoretical methods are discussed here.

Theoretical - Leipunskii et al.[3] point out that there are more than 10 types of elementary processes of interaction of γ-rays with matter. For the 1.17 Mev and 1.33 Mev γ-rays emitted by Co^{60}, only three processes occur with significant probability:

(1) Photo-electric absorption - γ-ray completely absorbed by K shell electron

(2) Compton scattering

(3) Pair production - minimum of 1.022 Mev γ-ray required to produce pair

Either the entire energy of the γ-ray or partial energy is transmitted to electrons in each of the three processes. These primary electrons are called:

(1) Photo-electrons

(2) Compton electrons

(3) Electron-positron pairs

Part of the energy lost to electrons in these primary events may ultimately be recovered as radiation in the form of Bremsstrahlung (radiation due to acceleration of charged particles) and annihilation radiation (positron-electron combination). The secondary radiation is of negligible importance compared to the primary γ-ray flux.

It is of great importance to the efficiency calculations to determine an average theoretical ion concentration in the annular space of the irradiation zone. Precise analysis is difficult because primary electrons emitted at the electrodes may be heavily involved. However, a lower bound on the average ion concentration can be obtained from the published range of dose rates to the annulus.

Dose (as contrasted with the term absorbed dose for biological systems) describes the ionizing effect of γ-rays on air. Dose is in units of Roentgens. One Roentgen (R) is the dose required to produce one CGS unit of charge (of either sign) in 1 cm^3 of air at 0^oC, 760 mm Hg. So 1.0 R = 2.08×10^9 ion pairs/cm^3. Since mechanisms of energy absorption of γ-rays depend on the energy of the γ-rays, different fluxes are required to produce the same dose for different γ energies.

Schultz et al.[1] indicate the dose rate range employed in the experiments was 10^3 R/hr to 1.5×10^5 R/hr. Using the conversion factor for Roentgens to ion pairs, the ion pair production rate is calculated.

Dose rate (R/hr)	Dose rate (R/sec)	Q, production rate of ions (ions/cm-s)
10^3	2.78×10^{-1}	5.78×10^8
10^4	2.78	5.78×10^9
1.5×10^5	41.7	8.67×10^{10}

An equilibrium ion concentration, n_∞, can be obtained from the relation given by Cooper and Reist:[4]

$$n_\infty = 2 \left[\frac{Q}{\alpha}\right]^{1/2} .$$

Where $\alpha = 3.6 \times 10^{-6}$ cm^3/s, the recombination coefficient.

The results for the various dose rates are:

Dose rate (R/hr)	n_∞ ion pairs/cm^3
10^3	2.53×10^7
10^4	8.01×10^7
1.5×10^5	3.10×10^8

The calculated n_∞ values compare favorably with the theoretical result of a minimum of 10^7 ion pairs/cm^3 mentioned by the PSU group. However, the figures fall short of their approximate measurement of 10^{10} ion pairs/cm^3.

Table 2 and Figure 2 of the MRI draft report have been redone (Table 27, Figure 45) with the sole alteration of use of proper slip corrections. That investigation assumed $C_c \approx 1.0$ for both 0.01 μm and 0.1 μm particles whereas the proper figures are approximately 17 and 2.6. The correct drift velocities were thus 17 and 2.6 times those calculated. The increased drift velocities yield substantially increased calculated efficiencies for both GRP and ESP. Efficiencies for 0.01 μm particles are now shown to be greater than for 0.1 μm particles for both devices.

A further adjustment of the table and chart is made in Table 28 and Figure 46, based on somewhat different assumptions. First, a higher stack temperature of 400^oK instead of 300^oK was used throughout - this change increases diffusion charge achieved in the nominal 1-second charging period. Second, instead of MRI's assumed 10^7 ion pairs/cm^3, a typical value of $n_\infty = 5 \times 10^8$ ion pairs/cm^3 for a corona discharge ESP is assumed. White[5] states that this is a typical ESP value. Even though our theoretical calculations indicate a maximum of 3.10×10^8 ion pairs/cm^3 for the GRP, we assume here $n_\infty \doteq 10^9$, roughly the logarithmic mean of 3.10×10^8 and the experimental result of $\sim 10^{10}$ ions/cm^3. The assumption of 10^9 ions/cm^3 was also made in the MRI report.

The results obtained using more generous assumptions for the ESP-GRP comparison show very marginal collection efficiency superiority for the GRP. The theoretical model for calculating collection efficiencies is sound, but there is still the uncertainty about attainable unipolar ion concentration in the γ-ray precipitator. PSU's impactor measurements lack sufficient resolution in the sub-micron region to indicate what collection efficiencies were achieved for 0.1 μm particles.

Table 27. CORRECTED VERSION OF MRI's TABLE

Particle radius (μm)	Charge per particle (elementary charges)		Drift velocity (cm/sec)		A/V (sec/cm)	Collection efficiency (%)	
	ESP	GRP	ESP	GRP		ESP	GRP
0.1	4.11	12.2	1.54	4.57	0.08	11.6	30.6
	4.11	12.2	1.54	4.57	0.39	45.2	83.2
	4.11	12.2	1.54	4.57	0.59	59.7	93.3
	4.11	12.2	1.54	4.57	0.79	70.4	97.3
0.01	0.11	0.81	2.71	20.0	0.08	19.5	79.8
	0.11	0.81	2.71	20.0	0.39	65.2	99.96
	0.11	0.81	2.71	20.0	0.59	79.8	99.99
	0.11	0.81	2.71	20.0	0.79	88.2	≈ 100.0

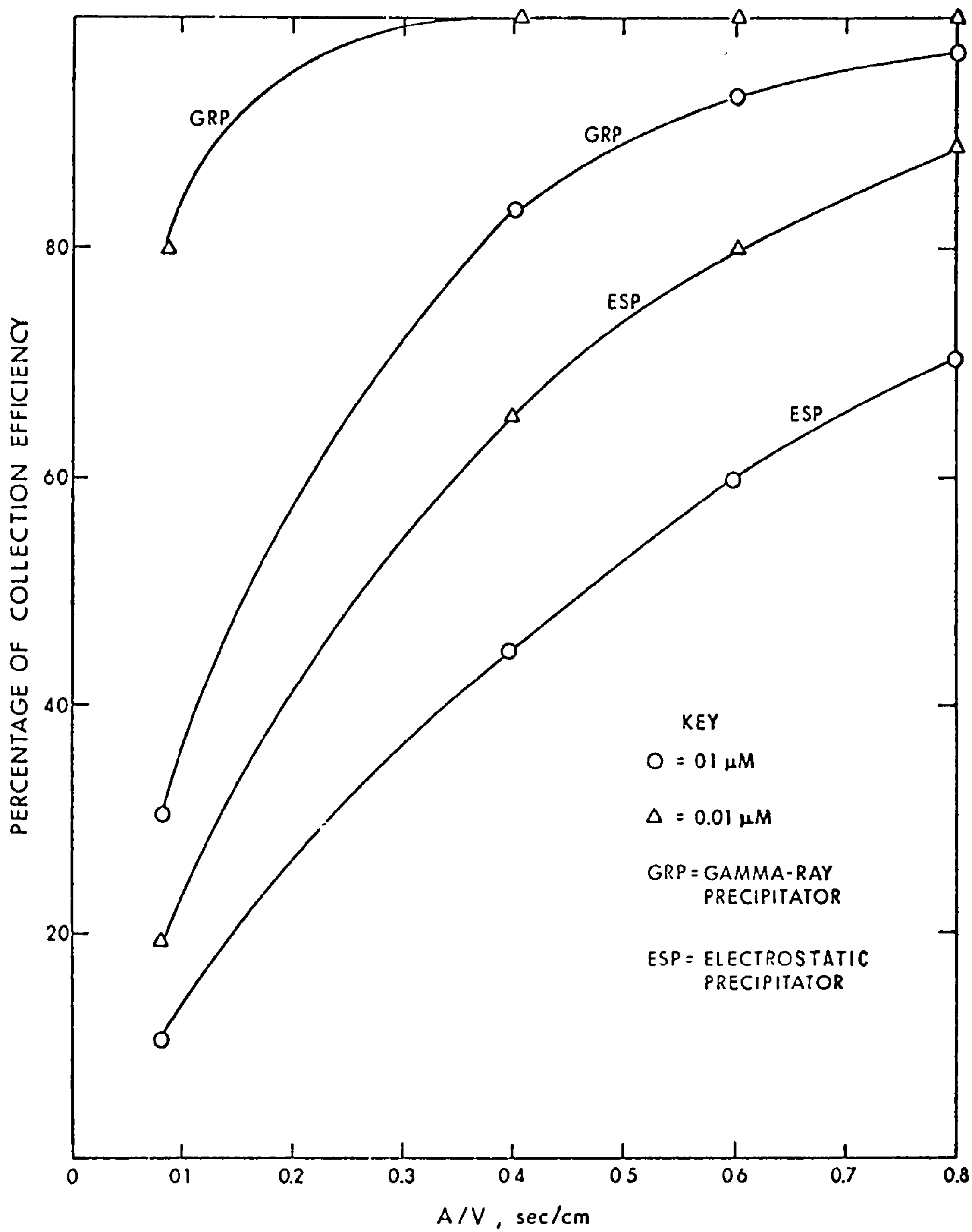

Figure 45. Estimated collection efficiencies for gamma ray precipitator and electrostatic precipitator

Table 28. RESULTS FOR ALTERED ASSUMPTIONS

Particle radius (um)	Charge per particle (elementary charges)		Drift velocity (cm/sec)		A/V sec/cm)	Collection efficiency (%)	
	ESP	GRP	ESP	GRP		ESP	GRP
0.1	6.13	6.96	2.30	2.61	0.08	16.8	18.8
	6.13	6.96	2.30	2.61	0.39	59.2	63.9
	6.13	6.96	2.30	2.61	0.59	74.3	78.6
	6.13	6.96	2.30	2.61	0.79	83.7	87.3
0.01	0.343	0.423	8.46	10.5	0.08	49.2	56.8
	0.343	0.423	8.46	10.5	0.39	96.3	98.3
	0.343	0.423	8.46	10.5	0.59	99.3	99.8
	0.343	0.423	8.46	10.5	0.79	99.9	≈ 100.0

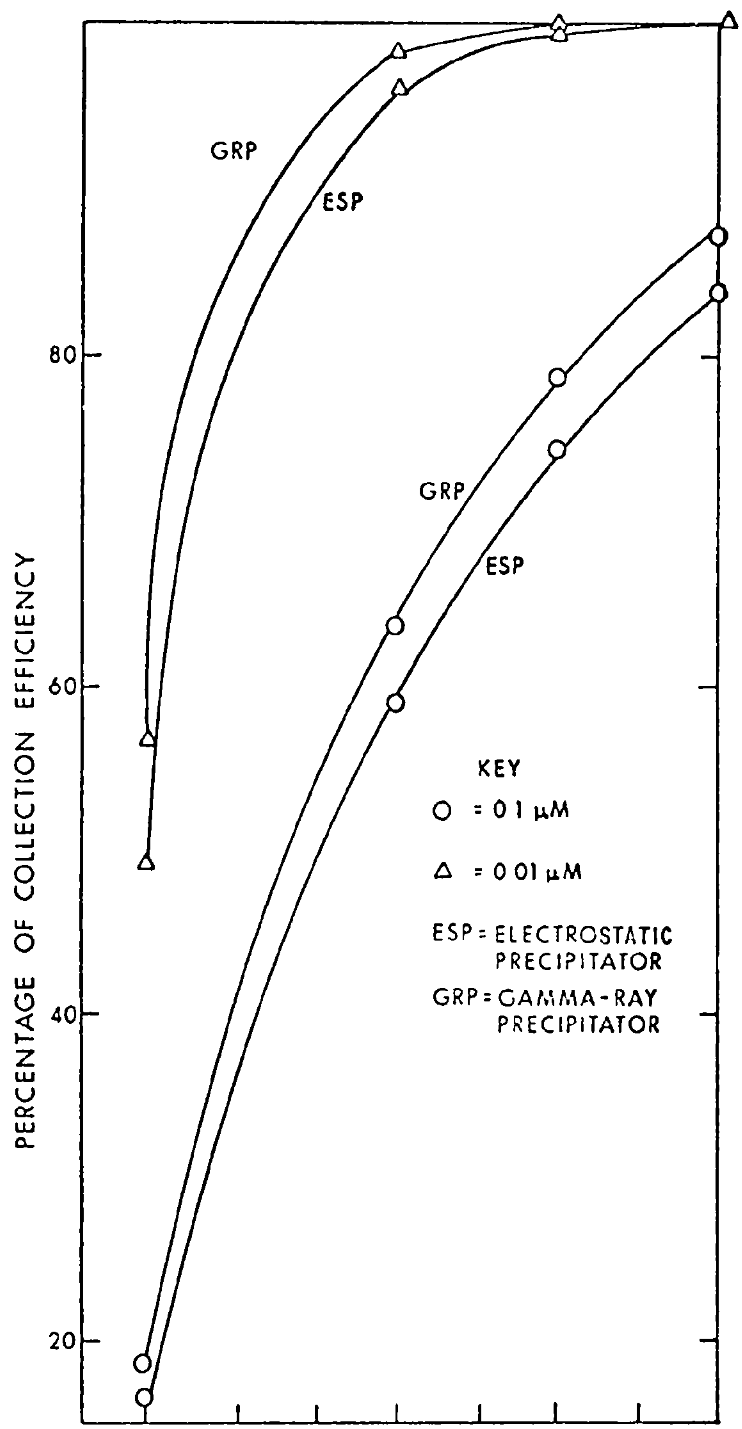

Figure 46. Estimated collection efficiencies for gamma ray precipitator and electrostatic precipitator utilizing altered assumptions

One possible mode of particle charging not explored in the published reports of either PSU or MRI is direct γ-ray charging of the particles. The prospect of direct γ-ray particle charging might have altered the ESP-GRP comparison favorably toward the new device. Our calculations showed that direct γ-ray charging will be unimportant and will not alter the conclusions of the diffusion and field charging calculations.

Experimental - The experimental data obtained by the PSU group can be used to estimate the charge levels actually achieved by the GRP, and these turn out to be no better than the usual ESP charge levels. To obtain the charge levels, one first calculates the effective migration velocity (w, cm/s) from data on the penetration (Pn = 1 - efficiency) and collection area (A, cm^2) and volume flow rate (V), using the Deutsch equation:

$$Pn = e^{-wA/V}$$

$$-\ln Pn = w(A/V)$$

$$w = -(V/A) \ln Pn$$

From Figure 13 of Schultz et al.,[1] E = 1 - Pn was 0.997 at 5.4 μm, 0.965 at 1.8 μm, 0.90 at 1.1 μm, and 0.78 at $\leq$ 0.4 μm. The volume flow can be estimated from the statement that most of the tests were done at 5 ft/s and were in the 4 to 15 ft/s range; the pipes used were 8 inches i.d. (20.3 cm) and 5 inches i.d. (12.7 cm), which is a cross-sectional area of about $(\pi/4)(413 - 161)\ cm^2 = 198\ cm^2$, thus a volume flow of $(152\ cm/s)(198\ cm^2) = 3.02 \times 10^4\ cm^3/s$ [$64.0\ ft^3/min$]. The collector length seems to have been 12 ft (3.6 m). Collector area was thus $A \doteq \pi(20.3 + 12.7)(360)\ cm^2 = 3.73 \times 10^4\ cm^2$. This means:

$$V/A \doteq 0.81\ cm/s = 0.027\ ft/s.$$

The ratio A/V was about 1.2 sec/cm $\doteq$ 37 sec/ft. The tests were done with a much larger A/V than usually used with ESP's, values close to those here in Tables 27 and 28.

From the penetration value we obtain the effective migration velocities given in Table 29.

The migration velocities can, in turn, be used to calculate approximate particle charge, using for the electric field E ~ 20 kV/1.5 inches or 5.2 kV/cm or 17 stat-volt/cm. Then

$$W \doteq q_p E\, B$$

Table 29. APPROXIMATE GRP EFFECTIVE MIGRATION VELOCITIES (EXPERIMENTAL)

Particle size (μm)	Migration velocities (cm/s)	(ft/s)
5.4	4.70	0.155
1.8	2.72	0.089
1.1	1.85	0.061
~ 0.4	1.22	0.041

where q_p is particle charge (elementary charge = 4.8×10^{-10} esu) and B is particle mobility ($C/3\pi\mu d$). This gives the experimental average charges shown in Table 30.

These charge values are somewhat lower (2-1/2 x) than the corona charging done by Penney and Lynch at 2.3 kV/cm and by Hewitt at 0.6 kV/cm, as reported by Whitby and Peterson (1965).[6] Thus, the charging produced by the γ-ray precipitator does not seem to have been superior to that achieved by conventional corona charging methods, even at the low end of their electric field range.

Table 30. EXPERIMENTAL CALCULATED AVERAGE CHARGE FOR GRP

Particle diameter	Particle charge (esu)	Particle charge (elementary charges)
0.4 μm	3.40×10^{-9}	7.1
1.1 μm	17.7×10^{-9}	36.8
1.8 μm	4.47×10^{-8}	93.2
5.4 μm	25.0×10^{-8}	528.

In summary, the experimental evidence does not demonstrate that the gamma-ray precipitator produced superior particle charging in comparison with the usual electrostatic precipitator method of corona discharge electrification. The theory for the charge production and equilibrium for the device is still incomplete, but the available theory indicates particle charging only marginally superior to that of the corona technique. Table 31 summarizes advantages and disadvantages of the GRP, from the MRI draft. Because there are no substantial inherent advantages with respect to particle charging and particle collection, economic considerations will determine the relative utility of the GRP with respect to the ESP. At present, the problems of shielding and safety seem to outweigh the advantages of reduced electrical power consumption and no maintenance of corona discharge wires. Particularly problematic would seem the removal from the GRP of the particulate material collected therein. The GRP is not at present a practical replacement for the ESP.

Applicability to Pollution Control - Prospects, status, implications are treated next.

Prospects of method - At best, the method would give collection efficiencies comparable to those of electrostatic precipitators. Energy consumption would be less than that of ESP technology, but special material handling techniques would be needed for the radioactive sources and for removal of the collected material.

Table 31. GAMMA-RAY PRECIPITATOR ADVANTAGES AND DISADVANTAGES

Advantages	Disadvantages
1. Possibly greater collection efficiency for < 0.2 μm particles	1. Little efficiency improvement with added technical and economic problems
2. Low power consumption	2. Expensive on a per ft^3 treated basis
3. Eliminates fragile corona wires - rapping easy	3. Radiation hazards, licensing problems
4. Useful storage for utility-produced radioactive wastes	4. Massive shielding required
	5. Complex maintenance and operation

Status of method - Collection efficiencies have been demonstrated at a nuclear reactor site using a small home-type coal furnace.

Implications of method - If practical, it would provide a use for radioactive wastes and reduce the energy consumption of the particle charging aspect of electrostatic precipitation. It would increase radiation hazards, especially if used in numerous small applications.

Summary

The gamma-ray precipitator does not charge particles to appreciably higher charge levels than normally achieved by electrostatic precipitators. The collection mechanisms in the two types of devices are the same. The only advantage of the gamma-ray precipitator is that it charges particles with radioactive sources rather than with a corona discharge, saving electrical energy, but this is also its primary disadvantage, as the handling of radioactive materials poses formidable problems. Only if it can be shown to be prospectively a more economical alternative than electrostatic precipitator would there be a rationale from an air pollution control perspective to investigate if further.

AC FIELD "ELECTRIC CURTAIN"

This discussion is based on information from C.D. Hendricks (Illinois University), who has had extensive experience in a related field, mass spectroscopy, and some of the concepts were germinated by that experience.

Goals

Dr. Hendricks's work involves theoretical and experimental research on four related devices:

1. An electrostatic curtain to be used downstream from an electrostatic precipitator to use electrical repulsion of the particles that penetrated the precipitator to keep these particles from flowing through a charged planar assembly of rods. See Figure 47.

2. A planar assembly of rods used instead of the collecting plates of an electrostatic precipitator, with a travelling wave electric field parallel to the surface of the assembly to move the particles into a collecting zone. See Figure 48.

3. An electric curtain placed so as to keep scrubber droplets in the flow longer than they would if the curtain were not there, to enhance scrubbing. See Figure 49.

4. A device for sampling which would use the size-selective aspects of the electric curtain field to collect size-fractionated particle samples. (Because of the very limited information about this idea, it will not be considered here further.)

Methods of Study

Theoretical Methods - The equations studied are those for a particle under electrical and other forces, such as gravity, in a medium which is

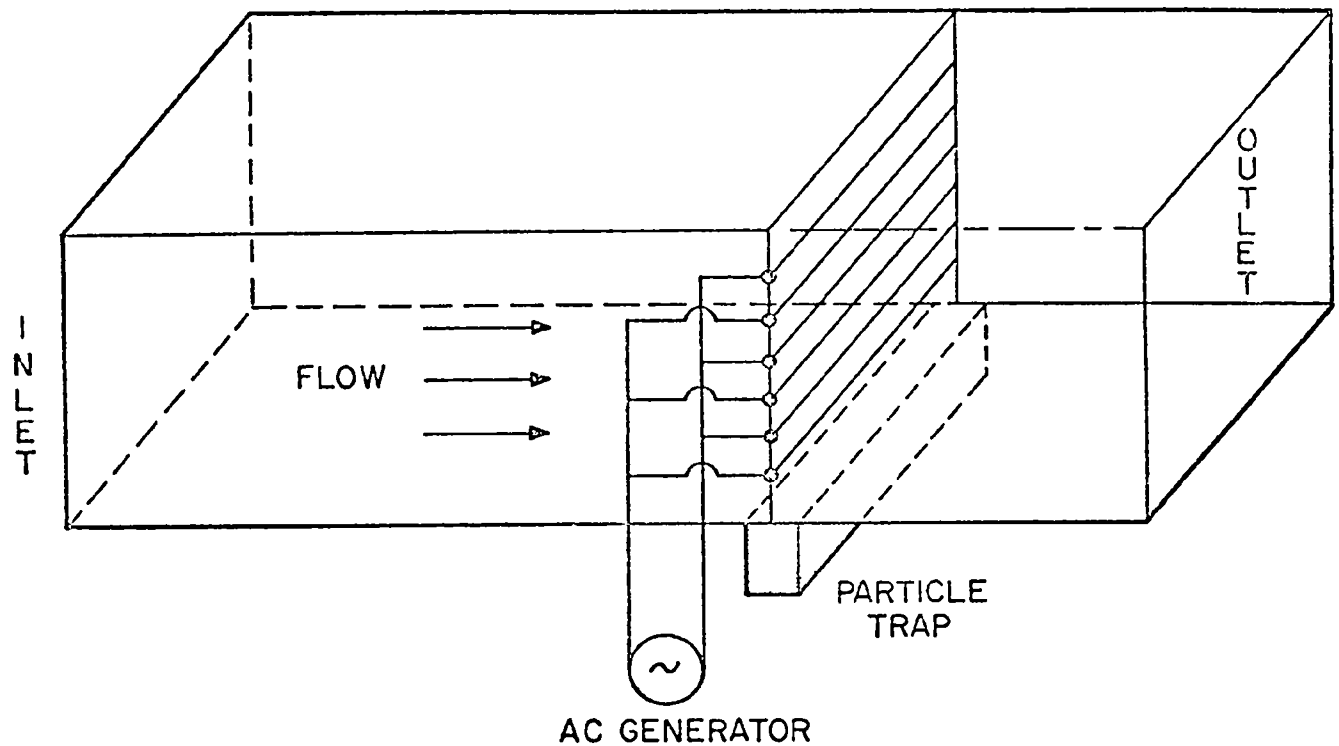

Figure 47. Electric curtain

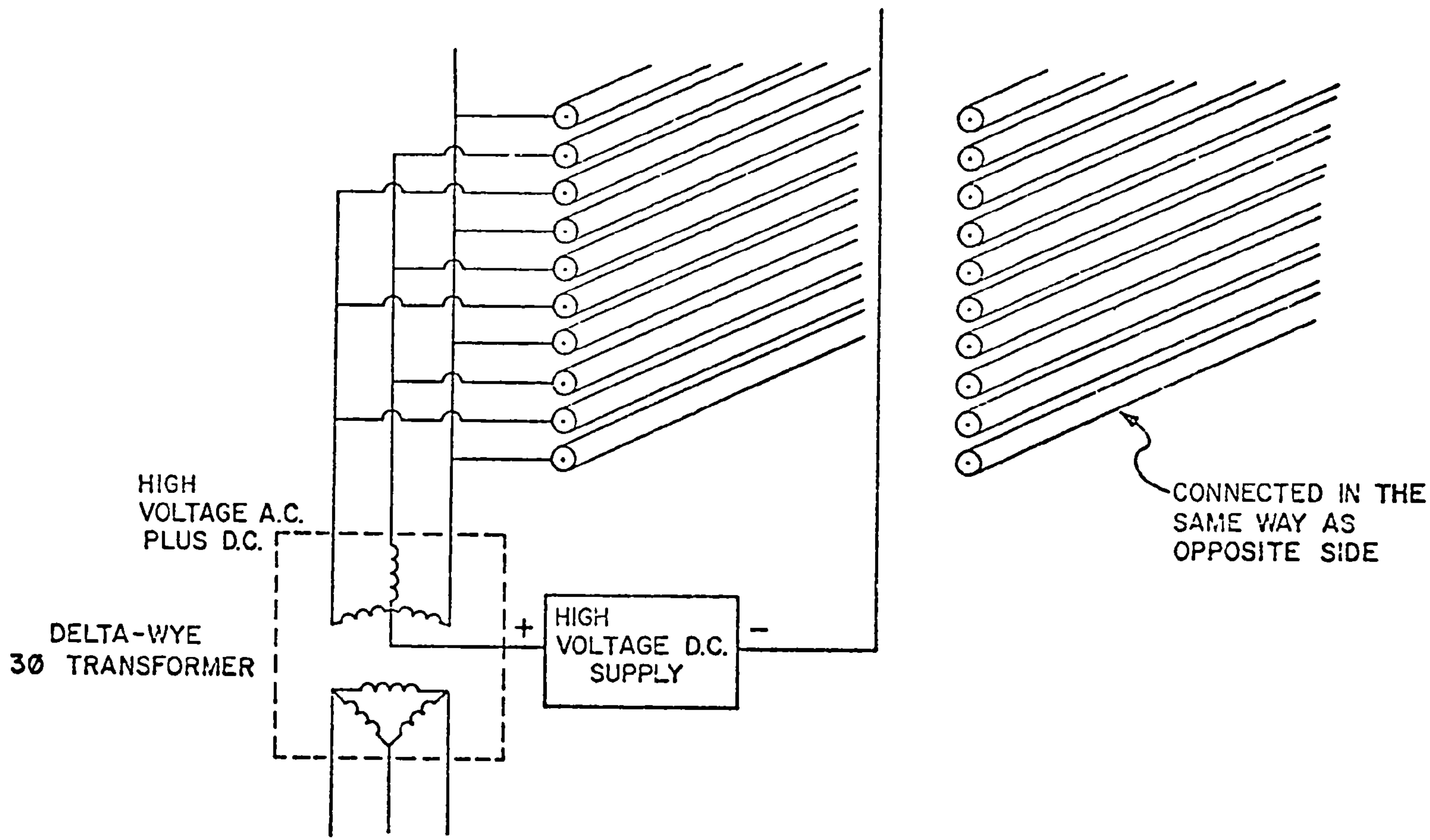

Figure 48. Electric curtain connected so as to provide a traveling wave electric field moving toward bottom of rods (after Hendricks)

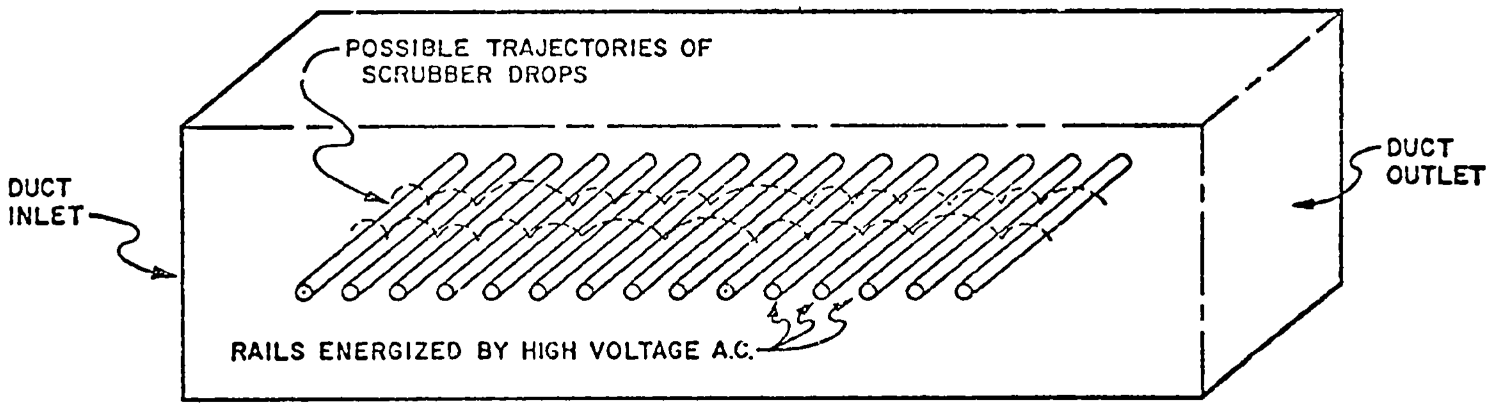

Figure 49. "Horizontal rail structure to support liquid scrubber drops to increase interaction time with gas flow from which it is necessary to remove gases such as SO_2 by absorption or chemical interaction with scrubber drops" (Hendricks)

resisting the particle motion according to Stokes law of fluid resistance. This is a second order ordinary differential equation for position as a function of time. Using dots to indicate derivatives with respect to time, these equations would be:

$$m \ddot{x} = F_x + q_p E_x \cos \omega t - 3\pi\mu\dot{x}d_p$$

for one-dimensional motion of a particle having diameter d_p with an external force F_x and electrical field $E_x \cos \omega t$. Details of the approach to solving such equations to be used by Hendricks and co-workers were not presented, but computer solutions seem straightforward and they will use "computer simulation." Features to be studied, presumably theoretically as well as experimentally, included the effect of the following on efficiency:

- Particle size
- Particle charge
- Gas flow velocities
- Voltage
- Geometry

Theoretical analysis very similar to that described in the preceding paragraph will be done for the case where the rods are used as the plates of an electrostatic precipitator. Results already obtained by Masuda[11] may prove useful, although it is expected that for the problem of many particles rather than one, such analysis may not be applicable. A similar type of analysis seems planned for the scrubber geometry, as well.

<u>Experimental Methods</u> - Each of the three applications for the electric curtain are to be tried out in test models. The following variables were explicitly listed to be tested for their effect on efficiency:

- Particle size
- Particle charge
- Gas flow velocity
- Gas composition
- Voltages, AC and DC
- Geometry
- Scrubber droplet sizes
- Flow patterns
- Power consumption
- Laminar and turbulent flow
- Methods of reentrainment elimination

This is a very complete list. The group is experienced in the generation of uniformly sized particles and in charge measurement, two areas in which expertise is very useful. The actual methods to be used to accomplish the above were not elaborated in their proposal.

Results

If the program is successful, the effects of the various parameters listed in the Methods sections will be quantified by computer simulation and by experiment. The experimental set-up would involve an electric curtain of about 25 m^2, so that the results would be nearer a pilot scale device than a bench top or laboratory scale, and if any of the applications studied appeared feasible, it would be possible to scale up to a demonstration unit much more readily than if a lab scale device were being used.

Conclusions

The results would probably be sufficient evidence to remove from consideration those configurations which did not prove feasible. As there are no results yet, no conclusions can be drawn.

Evaluation

Suitability of Goals - Each of the proposed electric curtain applications has a goal which is suitable to air pollution control:

1. The elimination of the particles which escape electrostatic precipitators.

2. The reduction or elimination of particle reentrainment due to rapping used to clean solid surface electrostatic precipitator electrodes.

3. The formation of something analogous to a fluidized bed using water droplets for scrubbers. Water is about the cheapest material imaginable for such applications. (Arcing may turn out to be a serious hazard and drawback, however.)

Suitability of Methods - As presented, we find nothing to object to in the proposed methods of study of the possible applications of the electric curtain. As Table 32 shows, there are a number of unspecified aspects with regard to the particles and with regard to their charging. The particle characteristics will probably be known or measured, however, and the particle charging, though of interest, is of less concern than the particle charge, which is to be measured.

Applicability to Pollution Control - There are several aspects which make its applicability questionable.

Prospects - Although the study is to be a very thorough one, one which should generate a substantial amount of useful information, each of the proposed applications has drawbacks which make it a doubtful prospect

Table 32. PARAMETERS ASSOCIATED WITH THE STUDY OF THE ELECTRIC CURTAIN AS A DEVICE FOR THE CONTROL AND REMOVAL OF PARTICULATE MATERIALS

Parameter	Magnitude, description, method of measurement or control, etc.
GAS	
Volume flow rate	M (to be measured)
Face velocity	M (will be one of the variables in testing the curtain)
Reynolds number (Re_f)	laminar and turbulent flows will be measured
Flow geometry	several types
Pressure drop (Δp)	it is noted that Δp is to be minimized utilizing expanded ducting
Temperature	M
Pressure	approximately ambient
Relative humidity	gas composition is to be controlled; no specific gases mentioned
PARTICLES	
Size	M
Shape	?
Chemical composition	?
Resistivity	?
Dielectric constant	?
Charge	M
Concentration	M
CHARGING SECTION	
Type of charging	charging of particles is by corona-type in the preceding ESP
Ions	?
Electric field	?
Geometry	?

Table 32 (continued). PARAMETERS ASSOCIATED WITH THE STUDY OF ELECTRIC CURTAIN AS A DEVICE FOR THE CONTROL AND REMOVAL OF PARTICULATE MATERIALS

Parameter	Magnitude, description, method of measurement or control, etc.
COLLECTOR	
Chemical composition	metal rods
Resistivity	low
Dielectric constant	∞
Charge	detailed information is given for a small sized unit
Voltage electric field	varied loadings will be employed-AC + DC
Particulate loading	M
Geometry	
Internal configuration	planar structure, composed of cylindrical rods placed at different angles to flow in the duct
CLEANING PROCESS	
Method	trapping; electrically induced flow
Effect on efficiency	will be measured in the form of reentrainment study

COMMENTS: Proposed device would have three possible applications:

(1) supplemental device to follow a conventional ESP

(2) replacement for the collection plates in a conventional ESP

(3) support and containment system for liquid drops in a scrubber

STAGE OF DEVELOPMENT: Bench-scale testing for pollution control. The electrostatic curtain may be prohibitively large and expensive as an add-on to a precipitator. The replacement of the flat electrodes in the electrostatic precipitator with a bank of rods may well not prevent very substantial reentrainment, and the use of electric fields to support scrubbing droplets against a gas flow is problematic. We shall elaborate on each of these points next.

Using Figure 50, we can set down the equations governing the field from an electric curtain and gain some insight into its operation. We obtain the field by taking the gradient of the electrical potential function ($\vec{E} = \vec{\nabla} \phi$) once the potential function ϕ has been obtained from the appropriate differential equation.

The electrical field distribution can be obtained from the solution of Laplace's equation for the electrical potential:[7]

$$\nabla^2 \phi = 0$$

$$(\partial^2/\partial x^2 + \partial^2/\partial y^2 + \partial^2/\partial z^2) \phi = 0$$

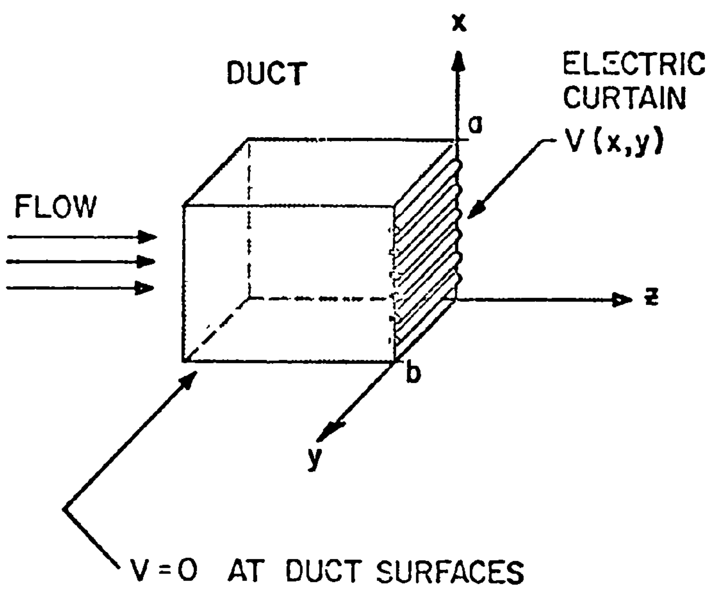

Figure 50. Electric curtain schematic with coordinates

Let Φ be a separable function:

$$\Phi = X(x)\ Y(y)\ Z(z)$$

and use primes (′) to indicate differentiation.

Then:

$$X''/X = -\alpha^2$$

$$Y''/Y = -\beta^2$$

$$Z''/Z = \gamma^2 = \alpha^2 + \beta^2.$$

Choosing α^2 and β^2 to be positive gives:

$$\Phi \propto e^{\pm i\alpha x}\ e^{\pm i\beta y}\ e^{\pm\sqrt{\alpha^2+\beta^2}\,z}$$

where α and β are arbitrary.

If we assume that we have a potential V on a plane surface, V(x,y), which surface is at z = 0 and if we assume that the walls are at zero potential at x = 0, x = a and y = 0, y = b, as in Figure 50, then for z < 0 (upstream):

$$X \propto \sin \alpha x$$
$$Y \propto \sin \beta y$$
$$Z \propto e^{+\gamma z}$$

satisfy the boundary conditions (including $Z \to 0$ as $z \ll 0$). The full solution will be:

$$\Phi(x,y,z) = \sum_{n,m=1}^{\infty} A_{nm} \sin(\alpha_n x) \sin(\beta_m Y) e^{-z\gamma_{nm}}$$

where $\alpha_n = n\pi/a$

$\beta_m = m\pi/b$

$\gamma_{nm} = \pi\sqrt{n^2/a^2 + m^2/b^2}$

and the A_{nm} are obtained by solving:

$$V(x,y) = \sum_{n,m=1}^{\infty} A_{nm} \sin(\alpha_n x) \sin(\beta_m y),$$

a double Fourier series for V(x,y). (For the electric curtain, V(x,y) might be approximated by adjacent strips at $\pm$V.)

The spatial derivative of the potential in z direction is our major interest, because this is the z-component of $\vec{E}$:

$$E_z = -\partial\Phi/\partial z$$

and here it is exactly,

$$E_z = \sum_{n,m=1}^{\infty} (-\gamma_{nm}) A_{nm} \sin(\alpha_n x) \sin(\beta_m y) e^{-z\gamma_{nm}}$$

The first term of this series gives a contribution to the field of

$$E_z \propto \pi\sqrt{1/a^2 + 1/b^2} \exp(-\pi\sqrt{1/a^2 + 1/b^2}\, z)$$

which (for a = b) is a field that falls off as $e^{-\sqrt{2}\,\pi z/a}$ from a maximum at z = 0. (The other components fall off more rapidly in the same $e^{-\gamma z}$ manner.) Thus the field will extend out upstream to distances on the order of a or b.

If the whole curtain were at one voltage V, then the equation for ϕ becomes:

$$\phi\,(x,y,z) = \sum_{n,m=1}^{\infty} \frac{4V}{nm\pi^2} \sin(n\pi)\ \sin(m\pi)\ \sin(\alpha_n x)\ \sin(\beta_m y) \exp\left(-\gamma_{mn} z\right)$$

and the z-component of the field would be the same series with $(-\gamma_{mn})$ multiplying each term. The major component of this field would be:

$$E_z \doteq \frac{4V}{\pi} \sqrt{1/a^2 + 1/b^2}\ \ \exp\left(-\pi \sqrt{1/a^2 + 1/b^2}\ z\right)$$

i.e., a field on the order of the voltage divided by the smaller dimension, a or b. By using closely spaced rods at alternate potentials, one achieves fields on the order of the voltage divided by the larger of the two dimensions, the rod spacing or the rod diameter. Thus the rod configuration with different voltages will generally give more intense fields than a curtain with each of its elements at the same voltage. Having different voltages would produce a net motion toward one of the rods for a given charged particle, if the voltages were not chosen to be alternating, as they have been.

It is not intuitively clear, however, that the net result of alternating fields would be a force away from the electric curtain, which is needed if the device is to produce a particle motion opposing the gas flow, or opposing gravity (where scrubbing drops are to be suspended). To sum up: the DC field would have an approximate magnitude equal to the voltage divided by the smallest curtain dimension (the rod diameter in the immediate vicinity of the rods, the curtain width or height at distances comparable to either) and the AC field does not seem able to produce a net force on a charged particle to push it away from the curtain.

The goal of the electric curtain is to hold up those particles which have not been caught in an electrostatic precipitator. This means that the curtain must give the particles a migration velocity w^* ($w^* = q_p EB$) which is greater than the mean velocity of the gas in the vicinity of the electric curtain:

$$w^* > v^* = Q/A^*$$

where Q = volume rate of flow,

A^* = cross-sectional area at electric curtain.

The formula for penetration of an electrostatic precipitator has been given as:

$$Pn = e^{-w\ A/Q}$$

where w = particle migration velocity,

A = collecting surface area.

Particles which penetrate the precipitator with a one percent penetration or greater, targets of the electric curtain, are characterized by:

$$w\ A/Q < 4.6.$$

We can combine the inequalities to form the following two relationships:

$$(Q/A^*) < w^* < 4.6\ (Q/A)$$

$$A/4.6 < A^*$$

where we have made the assumption that the field at the electric curtain is as strong as it is in the precipitator (and it may well be less, as the designers want to prevent corona in the electric curtain). Thus the cross-sectional area at the curtain must be at least a fifth as large as the total surface area of the electrostatic precipitator plates. A major cost for electrostatic precipitators is construction cost because of their size. Even if the electric curtain can produce fields comparable in intensity to those of an electrostatic precipitator, it would seem to require a fairly large additional section in which the flow is subjected to an expansion so that the gas flow velocities reach the particle migration velocities. Precisely for those particles for which the electrostatic precipitator is least efficient will the electric curtain also have the most difficulty. If the migration velocity is 10 cm/s (20 ft/min), the curtain will have an open area of about 10 m^2 (109 ft^2) for every m^3/s (2120 cfm) volume flow rate. This is a relatively large structure for such flows, and its cost would be expected to be relatively high.

We consider next its application as a scrubber. If, as proposed, the curtain uses rods 2.5 cm in diameter at a voltage of 30 kV, then the maximum field will be 24 kV/cm at the surface (80 stat-volt/cm) which would be above the breakdown field for corona discharge, generally. Assuming a field of 10 kV/cm and water droplets 100 μm in diameter we can calculate the droplet charge necessary to have the electric field offset gravity for d = 100 μm:

$$\begin{aligned} q_p &= mg/E \\ &= (10^3\ kg/m^3)\ (\pi/6)\ (10^{-4}\ m)^3\ (9.8\ m/s^2)/(10^4\ V/cm) \\ &= 5.1 \times 10^{-13}\ coul \\ &= 3.2 \times 10^6\ \text{elementary charges.} \end{aligned}$$

This charge could easily be put on the droplets using a corona or an inductive nozzle method. The sedimentation velocity in the absence of the field would be about 25 cm/s. Equivalently, the droplets could be supported against a flow velocity $\sim$ 25 cm/s.

Another consideration is whether the electrical force will be sufficient to stop the droplets, assuming they start with the velocity of 25 cm/s. Using a Stokes law approximation to the drag force and assuming an electric field which is homogenous over the distance of interest, it will take 0.75 cm to stop 100 μm diameter water drops. This distance will vary inversely with the force, linearly with the velocity and with the square of the droplet size. The electric field, even if strong right near the curtain, will have to extend for at least such a distance upstream into the flow, if the curtain is used across the flow. If the curtain is used parallel, the force field would have to extend most of the way through the duct, and, as we show, it is expected to fall off more rapidly than $e^{-z/a}$, where z is distance perpendicular to the curtain and a is a dimension characteristic of the curtain.

What is the magnitude of the force parallel to the curtain in the traveling wave mode? This is crucial to the analysis of its use in both situations in which the surface is to be placed parallel to the flow. At least a dimensionless group for this electric force and the fluid resistance should be derived and evaluated.

If the curtain is used perpendicular to the flow, then it may well present an appreciable pressure resistance, especially in a scrubber mode, where it will be desired to get relatively large velocities between air and held-up droplets in order to give them appreciable efficiency for capturing the particulate material by impaction, usually the predominant capture mechanism in such cases. This resistance may be a significant power drain.

If the droplets are to be repelled by the rods, then these two will have the same polarity. Then a choice must be made: if the particles also are charged to the same sign, droplet capture efficiency will be reduced; if the particles have the opposite sign, then they will collect on the rods as well as on the drops and this may create cleaning, arcing problems. The decision is not trivial. In general, it seems quite difficult to work with high voltages in a spray environment without getting short-circuiting.

The idea of making something like a fluidized bed using electrical forces rather than gravitation and water rather than solid collectors is an interesting one and deserves to be explored.

Finally, let us look at the idea of using the curtain in place of the collection plates of an electrostatic precipitator. The major advantage would be to overcome the difficulty of cleaning the precipitator plates once they have collected appreciable particulate material. This is reflected in such problems as back-corona and reentrainment, often especially problematic in the collection of high resistivity dusts.

Where will the dust actually collect? The high potential at the corona wires will produce a field toward the curtain and toward the walls behind the curtain. Although it is conceivable that the fields can be arranged to make the dust collection bin the lowest potential surface, there can be expected to be particle capture by the rods and the walls behind the rods due to particle inertia, local fields, etc. The traveling wave cannot be made to have an amplitude which overwhelms the DC level or there will be no net motion from the corona to the curtain. Once again, an important question will be the magnitude of the electric force produced by the traveling wave in comparison with fluid forces. The method may be feasible, but there are evidently several aspects which will pose problems. Once the particles reach the collection area they will tend to repel other particles unless the charge is conducted away, which is precisely the same problem as the precipitator plates usually have. The curtain will present an aerodynamically rough surface to the flow, inducing turbulence which will be especially strong in the vicinity of the collection zone (the rods). The space between the rods and the walls of the device will have to be kept much smaller than the distance between the two curtains, or a substantial amount of "sneakage" will occur, the flow of particulate material in areas without significant collecting fields.

Status - Although the electric curtain has been fabricated, no experimental results have been reported in any formal publication.

Implications - If the electric curtain placed immediately downstream from an electrostatic precipitator is shown to have promise, it could be implemented as a retro-fit, although a bulky one. If either the scrubber configuration or the electrode configuration were successful, they would probably be made part of new installations rather than existing ones.

Summary

There are three proposed control uses of the planar assembly of charged rods referred to as the electric curtain:

- A screen to remove particles downstream from an electrostatic precipitator.
- A support to keep scrubber droplets retarded with respect to particle-laden air flow.
- A replacement for the flat collecting electrodes now used in electrostatic precipitators.

The proposed theoretical and experimental work will consider the major relevant aspects of the problems: particle size, charge, composition; gas flow, temperature, and composition; collector geometry voltages and electrical characteristics.

The electrostatic curtain's prospects are modest. Used downstream from a precipitator, it will be trying to control particles by electrical forces in competition with viscous forces, and the particles will be those for which a similar process in the electrostatic precipitator has been insufficient. As a scrubber modification, it should be able to retard droplet motion and thus improve collection efficiency, but the droplets and the curtain will produce a greater pressure drop than did the droplets without this modification; electrical insulation may prove very difficult. As a collecting electrode for a precipitator, it may reduce reentrainment and sneakage, although it may do just the opposite, depending upon the details of the geometry, the electrical field and the ratio of the fluid resistance forces to the electrical force parallel to the curtain, and the induced turbulence.

It will be worthwhile to test the various possible uses, however, and such tests will be more informative if theoretical analyses are carried out as well and used to guide the testing.

FINE PARTICLE CHARGING DEVELOPMENT

A paper detailing the theoretical methods and results has just been published by Smith and McDonald (1975).[8] We have been informed that the literature review, the development of a new charging theory, its comparison with work by other investigators, and the assembling of experimental test equipment have been completed at Southern Research Institute (SRI).

Goals

The aim is to increase understanding of particle charging and to improve particle collection in electrostatic precipitators by raising the average charge per particle and thus raising the migration velocity. Quoting from a summary of the SRI work:

"This joint theoretical-experimental study has three important objectives: (1) to develop an adequate theory for charging of fine particles in a unipolar ion field with an applied electric field; (2) to supplement the existing experimental data on fine particle charging; and (3) to design and build a pilot scale charging device to investigate the technical and economic feasibility of improved collection of high resistivity dust by using a precharging section in conjunction with a high field, low current density, precipitator.

"Aerosols will be generated having diameters from 0.01 to 10 μm, and the charging rate measured for a variety of charging conditions. Variables are: particle diameter and dielectric constant, electric field intensity, ion polarity, and gas constituency and temperature. Theoretical studies will be performed in an effort to adequately describe the experimental results."

Methods

Theoretical - The SRI scientists began by reviewing the literature in which two major types of charging theory have evolved: diffusion charging, for which the driving mechanism is the ion gradient between the particle surface and the gas, and field charging, for which the driving force is the applied electric field. (In Section IV we presented the results of a field charging equation due to Cochet.) Figure 51 shows the electronic charges picked up by particles due to the two mechanisms, based upon White's book,[5] cited by them. (The product of the ion concentration and the time was assumed to be 10^7 s/cm^3 and the particles were assumed conductive.) For particles with diameters c. 10^{-1} μm, the contribution of diffusion charging can rival that of field charging in typical coronas. Moreover, there is an interaction between the two mechanisms, so the resulting rate of charging is not just the sum of the two. Improved equations for charging were the goal of the theoretical analysis. Figure 52 is from the work of Smith and McDonald.[8] For a specific particle size (0.92 μm diameter) and applied electric field

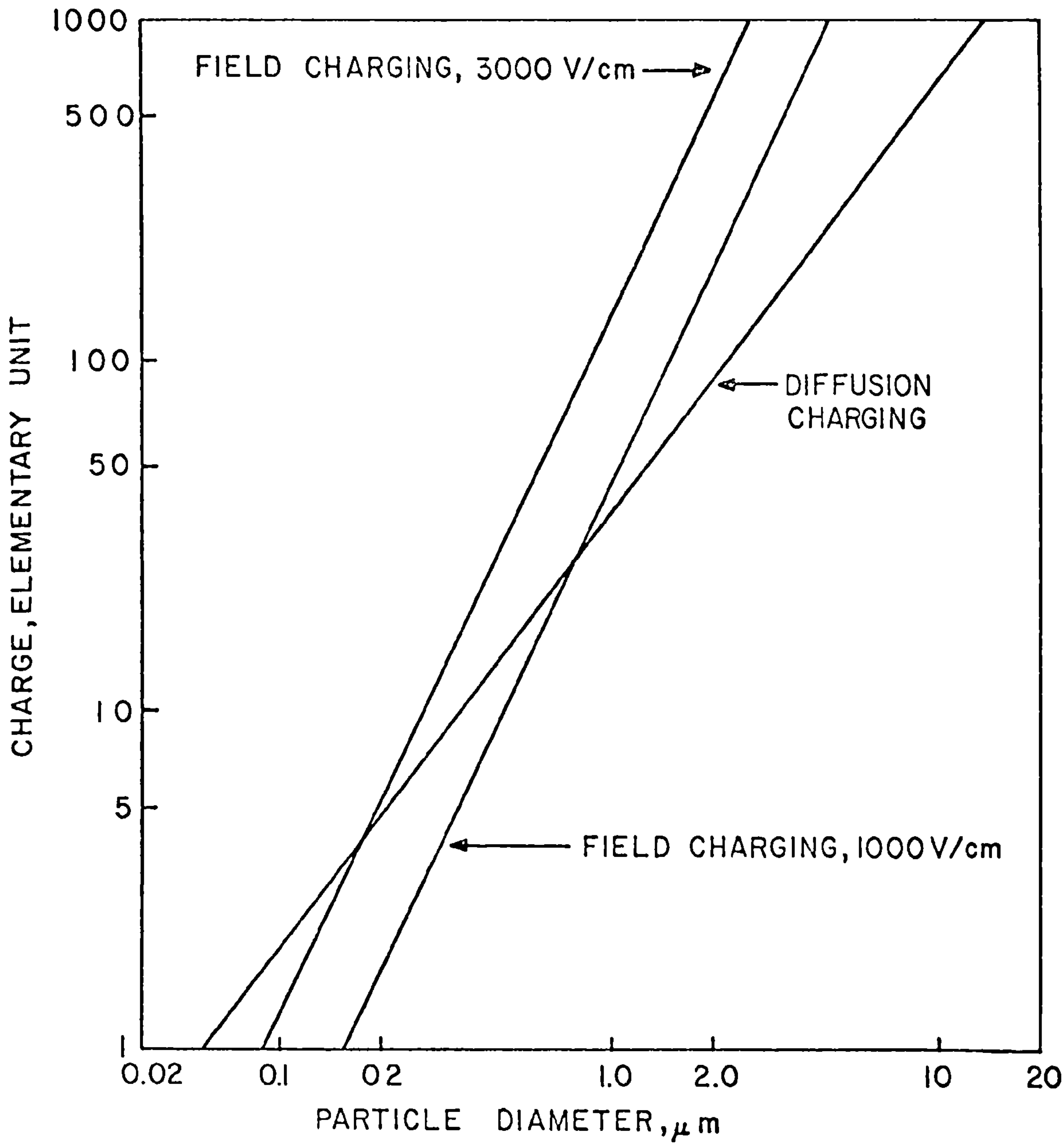

Figure 51. Field and diffusional charging of small particles[5]

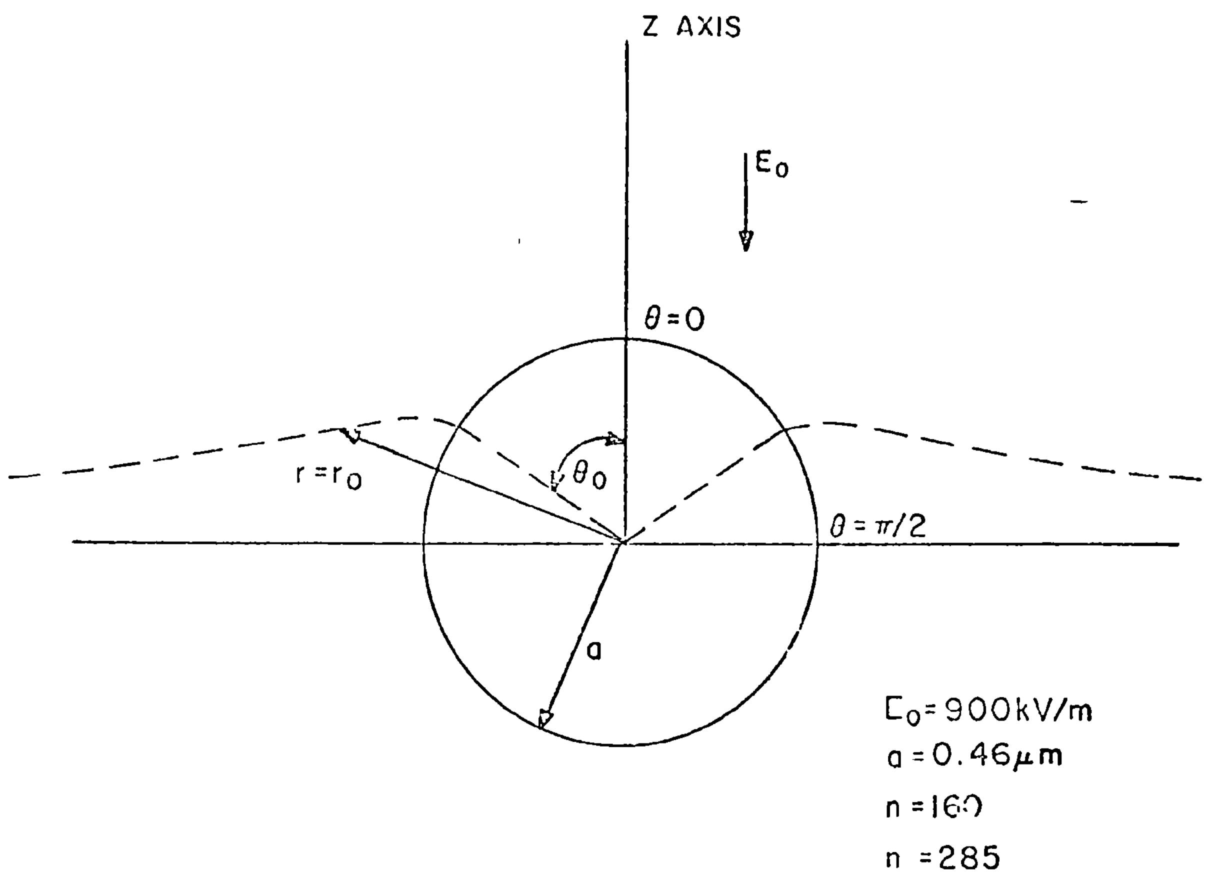

Figure 52. Model for mathematical treatment of charging rate

(9 kV/cm), they have calculated the field surrounding the conductive particle after while it is acquiring charge (here, 160 electronic units of a saturation value of 285 units). The dotted line is the locus of points for which the resultant electric field has a zero radial component. Their analysis breaks the charging process up into three regions one ($\theta < \theta_o$) for which a field charging equation applies, one ($\theta < \pi/2$) for which diffusion charging applies and one of which a hybrid equation applies. They used a computer program to calculate the number of charges as a function of time for a given ambient ion concentration.

Experimental - The material available to us at this time do not indicate details of the work, but clearly particle charging is to be measured as a function of particle size, which means using aerosol sizing techniques with, possibly, the generation of monodisperse aerosols in the size range of interest. The particle dielectric constant is to be varied; it would be known from the chemical composition of the material (for example, dioctylphthalate, DOP, with a dielectric constant of 5.1 and metal fumes with infinite dielectric constants). Knowing the electric field intensity involves the knowledge of corona voltage and geometry; the ion polarity will be known from the corona current. Finally, they will measure gas composition (suggesting the addition of water and perhaps SO_2), gas temperature, and presumably, pressure.

Table 33 contains what we infer about the experimental plans. N.A. is used for "not applicable."

Results

Theoretical - Figure 53 comes from the publication by Smith and McDonald[8] of SRI. It compares the model they developed with various theories and with the experimental data obtained by Hewitt.[9] The data are closer to the SRI theory than they are either to a theory proposed by Liu and Yeh[12] or field charging or diffusion charging or the sum of field and diffusion charging. In general, though, the difference between this SRI theory

Table 33. PARAMETERS ASSOCIATED WITH THE STUDY OF PRECHARGING CHAMBERS

Parameter	Magnitude, description, method of measurement or control, etc.
GAS	
Volume rate	M (to be measured)
Velocities	K (to be known)
Reynolds number	K
Geometry	K
Pressure drop	N.A.
Temperature	M
Pressure	M
Relative humidity	M
PARTICLES	
Size	0.01 to 10 μm
Shape	K
Chemical composition	K
Dielectric constant	K
Charge	M
Concentration	M
CHARGING SECTION	
Type	Corona
Ion current	M
Voltage	M
Geometry	K
COLLECTOR	
Chemical composition	N.A.
Resistivity	N.A.
Dielectric constant	N.A.

Table 33 (continued). PARAMETERS ASSOCIATED WITH THE STUDY OF PRECHARGING CHAMBERS

Parameter	Magnitude, description, method of measurement or control, etc.
CHARGE	
Voltage, electric field	M
Loading	N.A.
Geometry	N.A.
Internal	N.A.
External	N.A.
Efficiency	N.A.
CLEANING	
Method	N.A.
Efficiency degradation	N.A.

COMMENTS: Study of charging rates.

STAGE OF DEVELOPMENT: Theory complete, experimental set-up in progress.

and the theory which sums diffusion and field charging was less than about 25 percent in the amount of predicted charge at any time. A number of other comparisons were made by the investigators, besides that shown in Figure 53. The SRI analysis was generally better than all those to which it was compared, for Hewitt's data.

Experimental - When the experimental part of this program is completed. rates of charging for particles will have been measured and compared with theory, with the following treated as variables:

- Particle diameter
- Particle dielectric constant
- Electric field intensity
- Ion polarity
- Gas composition
- Gas temperature

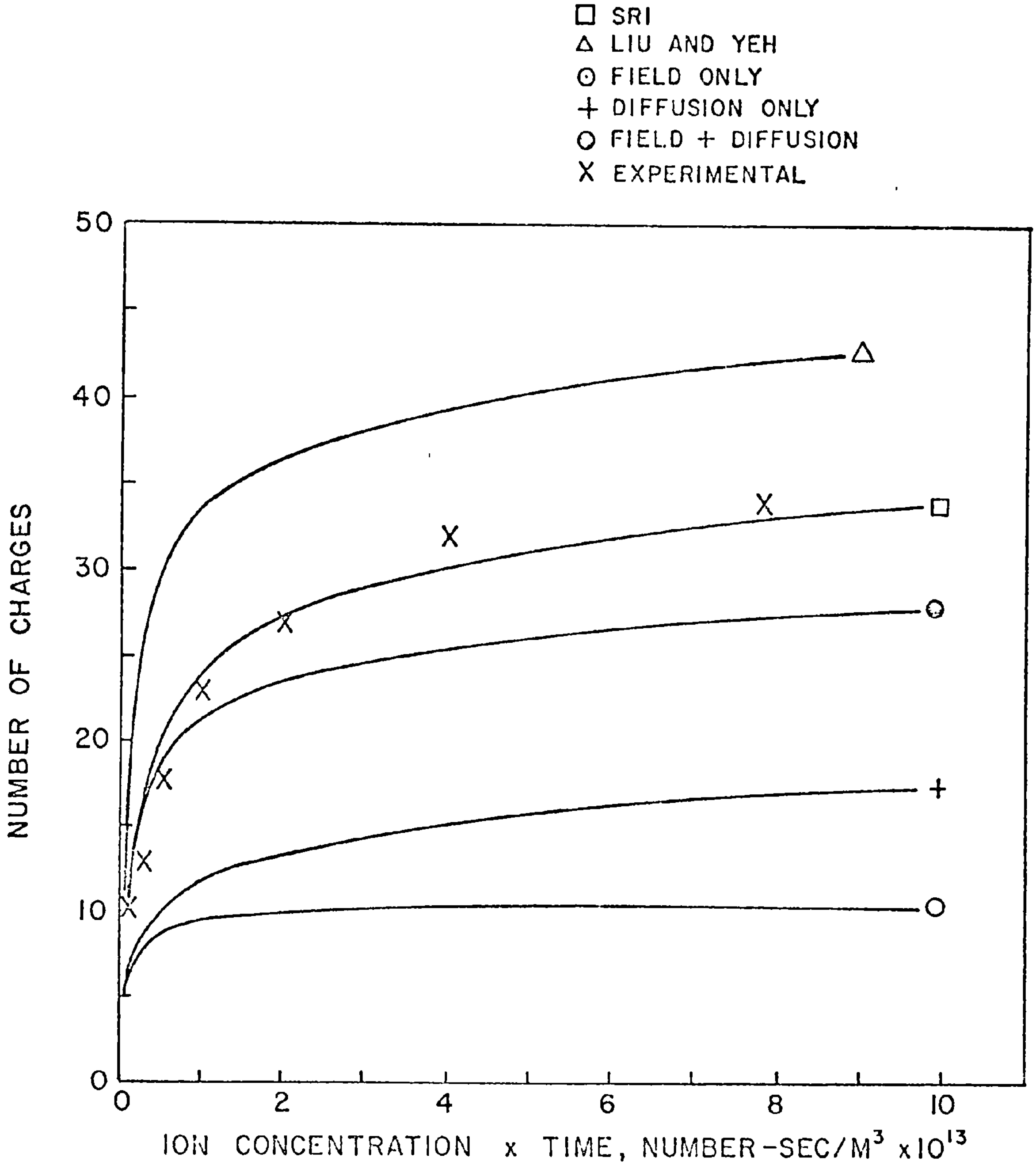

Figure 53. Comparison of theories and Hewitt's experimental data for 0.28 micron diameter particles and medium electric field intensity, E = 3.6 kV/cm

Conclusions

The work by Smith and McDonald on charging theory produced results within 25 percent of Hewitt's data over the range for which it was available and was generally the most accurate theory of those compared. The theory was roughly 25 percent higher than the combination of diffusion and field charging, which calculations can be done without a computer; this is an improvement, although often the combining of field and diffusion equations will be sufficiently accurate for design purposes, we believe. The experimental work will serve to check the charging theory against a new set of data and may also lead to the development of improved corona charging section which could be used upstream from a high field, low-current electrostatic precipitator.

Evaluation

Suitability of Goals - The collection efficiency of an electrostatic precipitator for a given particle size can be modeled by using an exponential expression with the negative product of the migration velocity and surface area divided by volume rate of flow as its argument. As the particle charge increases, the migration velocity will increase, and the efficiency would be expected to increase. Two other factors influence the collection efficiency appreciably: the reentrainment of material which has been captured and the sneakage of some of the flow through regions of low electric field. A detailed model is presented by Gooch and Francis (1975)[10] which incorporates these effects. If the sneakage and reentrainment effects are predominant in the penetration of a given precipitator, then increasing the effective migration velocity may not be much help. In general, increasing the particle charge would seem advantageous.

If the corona power is used more efficiently in charging particles in some precharging chamber, then power savings might be expected beyond any savings due to lowered penetration for existing devices or lower construction costs for new operations with such a precharging chamber. As noted in Appendix C, however, the work per particle precipitated increases with the magnitude of the applied force, so that high-intensity field methods will inherently require more power per volume of gas treated, other things being equal; this may not be much of a practical problem, however, because a power consumption in electrostatic precipitators is low compared with scrubbers.

Suitability of Methods - We analyze next the methods used and proposed.

Theoretical Approach - It remains to be seen whether or not the improved theory of particle charging will improve corona charging technology. For the relatively strong fields near a corona, the field charging aspect of the new theory predominates and this is the same as existing theory. Still, one of the terms in the rate equation is new and may offer insights, and much can be said in behalf of more accurate theories even when they do not change, qualitatively, our understanding of the processes involved. The new theory clearly improved upon the existing ones.

Experimental Approach - From what we infer about the experimentation to be done, the important variables seem to be measured, controlled, or known. There is a value to having Hewitt's data confirmed. Furthermore, innovations in the design of the charging chamber may have control impact.

Applicability to Pollution Control - The theoretical analysis will allow a more accurate prediction of the particle charging. The experimental work may lead to improved charging. These would both be applicable to pollution control by electrostatic precipitation or the electrostatic augmentation of other types of control device.

Prospects - A new type of charging chamber might be suitable for retrofit as well as for use in new installations. Where insufficient charging is a problem, this could be a solution.

Status - The theoretical framework for particle charging is completed and the experimental equipment is being assembled.

Implications - Improved charging could decrease installation size at the same collection efficiency thus realizing construction cost savings for the electrostatic precipitator, for which construction costs are major.

Summary

The theory developed in this project seems more accurate than previous theories. In practice, the use of a simpler theory, field charging plus diffusion charging, may be as accurate as the accuracy of the various parameters needed to calculate it justifies. The correct values for mean ionic mobility and thermal speed seem subject to dispute, although those used here are the conventional ones. The experimental work is aimed at investigating the variables relevent to particle charging and may lead to an improved charging device as well as a confirmation of the data obtained by Hewitt with which the theory was compared.

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SECTION VIII

OTHER ELECTROSTATIC DEVICES

ELECTROSTATIC CYCLONE

To extend the work done by Molyneux[1] on his proposed combination of electrostatic and centrifugal collecting mechanisms, a high efficiency cyclone was designed by us to handle 0.472 m^3/s (1000 cfm) at an efficiency of 50 percent removal of 3 μm size particles. This basic design was then modified by the addition of corona charging wires, making the body of the cyclone the equivalent of the collector plates in a conventional electrostatic precipitator. The proposed electrostatically augmented cyclone is shown schematically in Figure 54, with the actual dimensions given in Table 34.

Goals of the Study

The high efficiency cyclone was designed for the purpose of determining the potential for improvement in collection efficiencies versus particle aerodynamic diameter when electrostatic forces are applied within the cyclone.

Methods of Study

Theoretical - The use of electrostatic forces in a cyclone was demonstrated by Molyneux[1] in which the particles were charged by corona discharge as in a conventional electrostatic precipitator, and the cyclone body itself acted as the collecting electrode. The proposed cyclone was

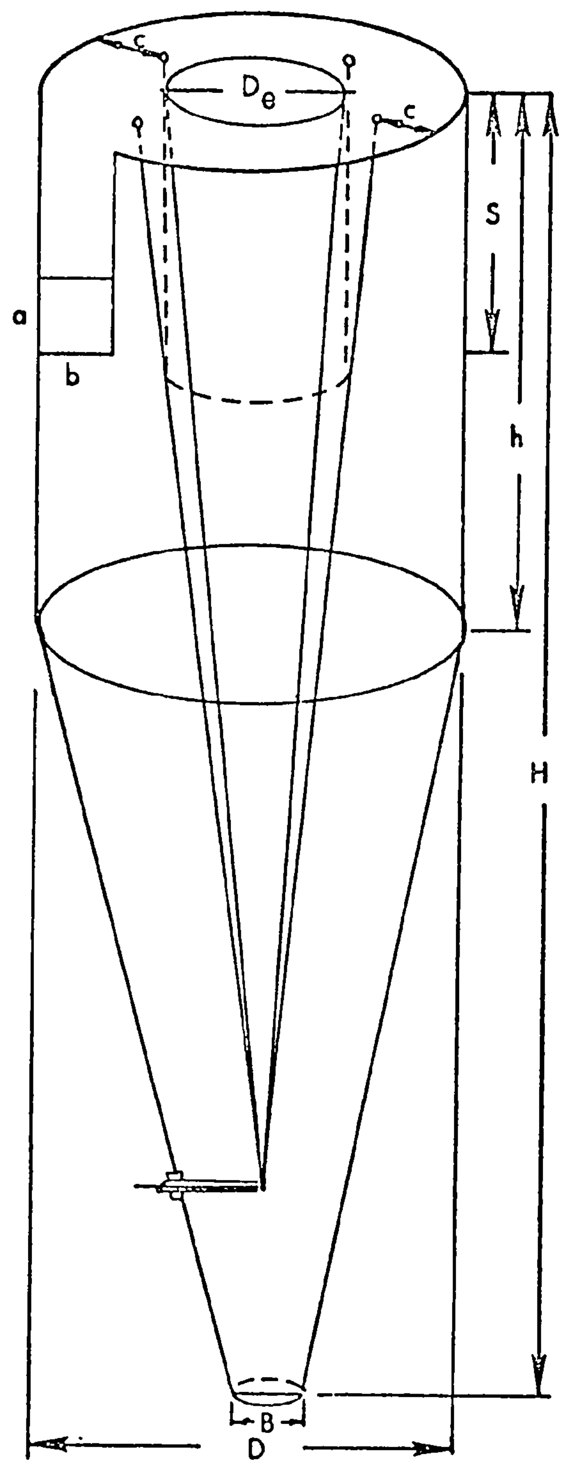

Figure 54. Schematically drawn electrostatically-augmented cyclone

Table 34. DESIGN PARAMETERS FOR A HIGH EFFICIENCY CYCLONE OF 0.472 m^3/sec (1000 cfm)

d_{pc}	= 3 μm
a	= 17.3 cm
b	= 6.9 cm
D	= 34.5 cm
D_e	= 17.3 cm
S	= 17.3 cm
h	= 51.8 cm
H	= 138.0 cm
B	= 12.9 cm
ΔH	= 6.38
ΔP	= 5.98×10^4 dynes/cm^2 or 24 in. H_2O
A_c	= Area = 8237.9 cm^2
Volume	= 81538 cm^3
V_I	= 3954 cm/sec
t_{ret}	= 0.173 sec
Q_g	= 4.72×10^5 cm^3/sec

designed for 0.47 m^3/sec (1000 cfm) using the parameters suggested by Stairmand[2] for a high efficiency cyclone. The actual dimensions were derived from Lapple's[2] equation for the cyclone particle cut size:

$$d_{pc} = 3\left(\frac{\mu_g b}{2\pi\rho_p V_g Ne}\right)^{1/2}$$

where:

d_{pc} = 50 percent cut diameter
μ_g = viscosity of gas
b = cyclone inlet dimension

ρ_p = density of the particle

V_g = velocity of gas

Ne = effective number of turns the gas makes in the cyclone,

using a 3 micron particle diameter cut size the equation was solved for b, the width of the gas inlet. This value of b was then used with Stairmand's suggested ratios to determine the remaining cyclone dimensions. Pressure drop was calculated from the Shepherd and Lapple equation:[2]

$$\Delta H = K \frac{ab}{D_e^2}$$

where K = 16 for a cyclone with a standard tangential inlet, which gives pressure drop in inlet velocity heads, ΔH. This ΔH was converted to pressure drop using the equation:

$$\Delta P = \frac{V_g^2 \rho_g \Delta H}{2}$$

where ΔP = pressure drop

V_g = velocity of gas

ρ_g = density of the gas.

The interior collecting surface of the cyclone was determined using the equation:

$$A_c = \pi Dh + \frac{\pi}{2} (D + B) \left[(H - h)^2 + \left(\frac{D - B}{2}\right)^2 \right]^{1/2}$$

and the volume of the cyclone was determined using traditional formulas of solid geometry. The residence time was calculated by dividing the cyclone volume by the volume throughput. All of the aforementioned parameters are listed in Table 34. The efficiency of the cyclone was determined using Sproull's equation:[2]

$$\eta = 1 - \exp\left(- \frac{wA_c}{Q_g}\right) .$$

The migration velocity, w, was calculated from Sproull's equation:

$$w_r = \frac{d_p^{\ 2} \rho_p V_L^{\ 2}}{18 \mu_g D}$$

for the migration velocity of the particles due to the motion of the carrier gas. The velocity of the particles due to electrostatic attraction was determined using the equation:

$$w_e = \frac{3 E^2 d_p^{\ 2}}{4} \quad \frac{C}{3\pi \mu_g d_p}$$

where:

E = electric field strength

d_p = diameter of the particle

C = Cunningham slip correction factor

μ_g = viscosity of the gas.

Utilizing this cyclone design, the addition of four corona wires within the cyclone was investigated to determine the necessary parameters: wire diameter, corona starting voltage, initial field strength, corona current, corona voltage, field at cyclone wall, and power consumption.

The corona wire diameter 0.2 cm, was chosen as a likely wire size from information given by White.[3] The critical voltage gradient at the wire surface for corona onset in air (the initial field strength) was determined from White's equation for E_o in kV/cm:

$$E_o = 30 \text{ f } \delta \ (1 + 0.30 \ \sqrt{\delta}/a)$$

where f is the roughness factor, chosen to be 0.5, and δ is the relative air density, chosen to be 1.0. The corona starting voltage, the minimum voltage at which corona will occur, is determined by the equation:

$$V_o = a\ E_o \ln \frac{c}{a}$$

where a is the corona wire diameter, and c is the cylinder diameter, 0.1 cm and 5 cm, respectively. The current density, j was determined using equation:

$$j = N_o\ e\ Z\ E_o$$

where:

N_o = number density of ions
e = unit electron charge
Z = ion mobility, 660 esu.

The factor N_o, ion density adjacent to the cyclone surface, was determined utilizing a time charging constant, t_o, which was chosen to be one-tenth of the particle residence time. If $t_o = \frac{t_{res}}{10}$, then substituting into the equation:

$$t_o = \frac{1}{N_o\ e\ Z\ \pi}$$

yields:

$$N_o = \frac{10}{t_{res}\ e\ Z\ \pi} \quad .$$

Multiplying the current density at the surface of the cyclone by the area of the cyclone, A_c, yields the total corona current i_t. Dividing the total corona current by the total length of the four corona wires gives the current per unit of length for the corona wires, i.

The applied potential across the wires was then determined using the equation:[3]

$$V = V_o + a E_o \times \left[\sqrt{1 + (2i/Z)\left(c^2/E_o^{\,2}\, d^2\right)} - 1 - \ln \frac{1 + \sqrt{1 + (2i/Z)\left(c^2/E_o^{\,2}\, d^2\right)}}{2} \right] .$$

The electric field at the cyclone wall was determined utilizing the equation:[3]

$$E_{cw} = 2i/Z$$

and the anticipated electrical power consumption of the electrostatic augmentation was determined by:

$$P = E\, i_t \quad .$$

All of the equations utilized are for the geometry associated with a concentric corona wire within a cylinder. While the geometry of the cyclone is not strictly a cylinder, it was felt that these equations would give reasonable estimates of the corona parameters with the chosen corona wire arrangement, shown schematically in Figure 54.

Experimental - Since this was strictly a feasibility analysis, it involved only a theoretical evaluation with no experimental work.

Results

The resulting parameters concerning the electrostatic augmentation of the proposed cyclone are as follows:

$d = 0.1$ cm

$c = 5.0$ cm

$E_o = 29$ kV/cm

$V_o = 11$ kV

$j = 1.8 \times 10^4$ statamps/cm^2

$i_t = 49$ mA

$L_w = 414$ cm

$i = 3.5$ statamps/cm

$V = 51$ kV

$E_{cw} = 10$ kV/cm

$P = 2.5$ kW.

The resulting applied voltage of 51 kV is much greater than the corona starting voltage of 11 kV therefore assuring corona production. There is an upper limit on applied voltage to produce corona, beyond which sparkover occurs. It would appear from information presented by White[3] that the upper limit for the cyclone in question is approximately 50 kV or nearly equal to the calculated applied voltage. Since sparkover is a function of voltage waveform as well as applied voltage, and is also often tolerated to a controlled extent in practice to take advantage of using a higher voltage, it was felt that the calculated applied voltage would be very near the actual voltage used in practice.

The efficiencies of the cyclone, both with and without electrostatic augmentation, for various sized particles and their associated migration velocities are listed in Table 35, and depicted graphically in Figure 55. w_r is the migration velocity due to inertia, w_e is the migration velocity due to electrical forces, and w_t is the sum of these two migration velocities.

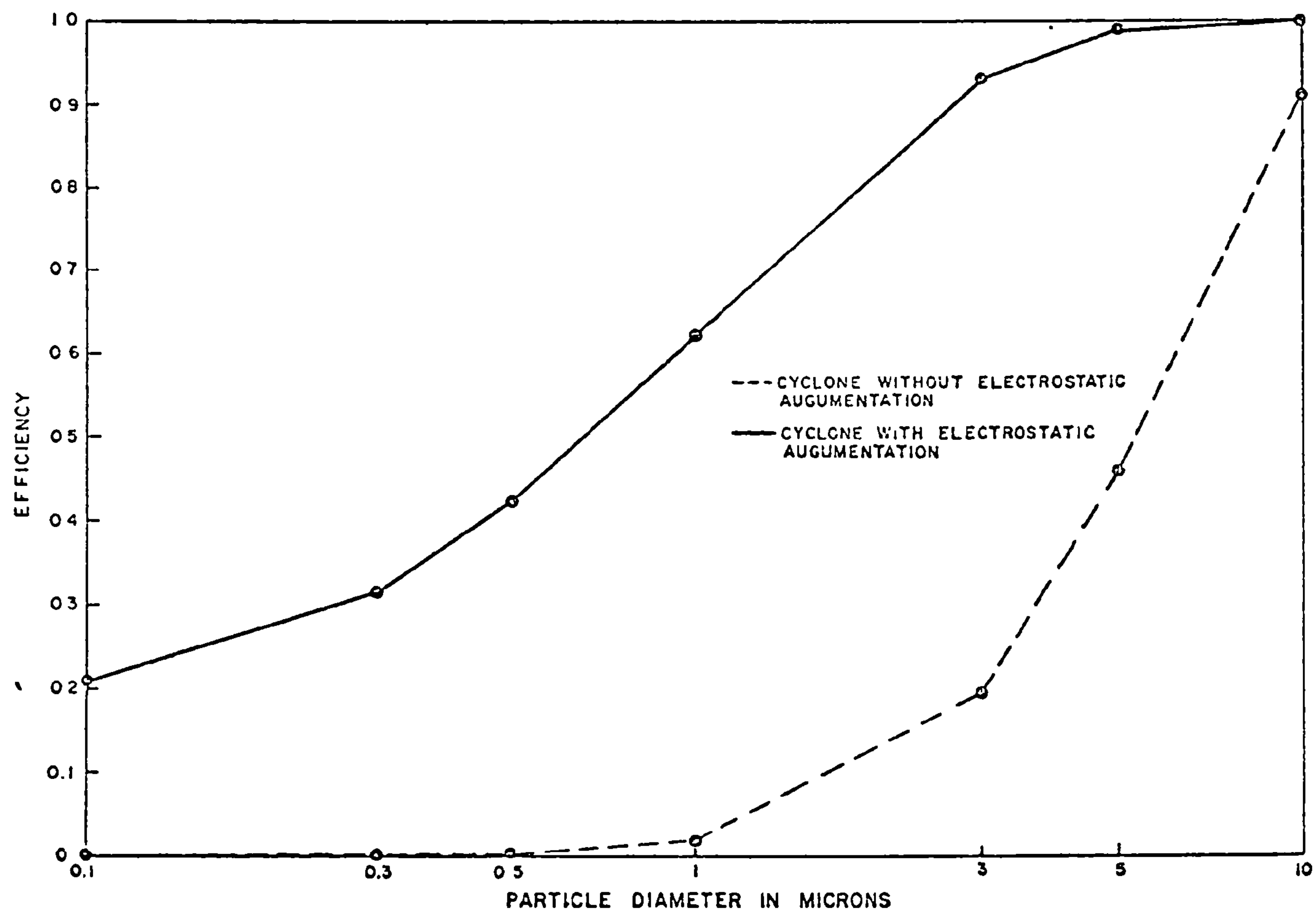

Figure 55. Efficiency versus particle diameter for cyclone with and without electrostatic augmentation

Table 35. CALCULATED THEORETICAL MIGRATION VELOCITY AND CORRESPONDING EFFICIENCY FOR THE HIGH EFFICIENCY CYCLONE WITH AND WITHOUT ELECTROSTATIC AUGMENTATION

Particle diameter in microns	Migration velocity cm/sec			Efficiency % due to	
	w_r	w_e	w_t	Inertial forces	Inertial & electrical forces
0.1	0.014	13.72	13.74	0.02	21.26
0.3	0.126	22.42	22.55	0.22	32.45
0.5	0.350	31.85	32.19	0.61	42.88
1.0	1.40	55.74	57.14	2.41	62.99
3.0	12.6	151.12	163.70	19.74	94.21
5.0	35.0	247.3	282.3	45.61	99.26
10.0	140.0	487.0	627.0	91.25	99.99

The total energy consumption of the cyclone was calculated from the flow rate times the pressure drop and the electrical energy consumption of the corona charging. It was found that the energy consumption due to mechanical losses, the pressure drop, was 2.8 kilowatts, and the electrical charging required 2.5 kilowatts. Therefore, the total energy consumption would be 5.3 kilowatts for an electrically augmented cyclone with a 50 percent cut diameter of 0.7 μm.

Conclusions

The increase in efficiency expected from the addition of electrostatic augmentation is substantial, and as such may seem attractive. However, the energy requirements are fairly high to achieve the efficiencies stated in Table 35. The energy requirements for a venturi type scrubber of efficiency similar to the cyclone with electrostatic augmentation yielded an energy consumption of 2.45 kilowatts per 1000 cfm (0.47 m^3/sec), considerably lower than that for the electrostatically augmented cyclone.

A similar comparison between the same capacity commercial cyclone rated as a high efficiency unit, reveals a much lower pressure drop, as expected, with a correspondingly higher 50 percent cut diameter particle.

It would appear that the cyclone is simply not an inherently efficient device for removing small particles, because it relies upon the movement of the entire gas stream to be cleaned at high velocities. The acceleration of the entire gas stream, compared to the normally small fraction of the particles which need to be accelerated, obviously entails a much higher energy expenditure. It can be noted from the results in Table 35 that the efficiency attributable to the electrostatic augmentation alone is greater than that attributable strictly to mechanical forces, with the exception of the 10 μm particles. Since the mechanical energy requirements are actually somewhat higher than the electrical energy requirements, it is obvious that the electrostatic mechanism is a more energy-efficient removal mechanism.

It should also be noted that there is a basic conflict between the cyclonic inertial removal mechanism and the electrostatic attraction removal mechanism. Increased gas stream velocity tends to increase the efficiency of cyclones due to the higher inertia of the particles, which are removed by impaction. Increased gas stream velocity in electrostatic precipitation means a decrease in residence time, which decreases both particle charging and removal efficiency. Obviously, then, there is a basic conflict between the two mechanisms described which would lead to poor overall energy efficient particulate removal.

It is interesting to note that the pressure drop across a cyclone is related to the 50 percent cut diameter by the relationship:

$$\Delta p \propto \frac{1}{d_{pc}^{4}}$$

and as such rises dramatically as the particle diameter decreases and vice versa. (Particle cut diameter is related to the square root of the gas velocity, and pressure drop to the square of the velocity.) We also have the relationship between the particle migration velocity due to inertial forces and the diameter of the cyclone which is, - assuming the other dimensions change proportionately:

$$\left(\frac{w_1}{w_2}\right) = \left(\frac{D_2}{D_1}\right)^5$$

from which we may deduce that the migration velocity decreases dramatically with an increase in the cyclone's physical dimensions. This is especially important when dealing with fine particles. It should be further noted that the relationship between migration velocity due to electrical forces and the cyclone diameter is:

$$\frac{w_1}{w_2} = \frac{D_2}{D_1}$$

that is, as the cyclone diameter increases, the migration velocity decreases linearly. The equation for efficiency is

$$E = 1 - e^{-wA/Q} .$$

The area increases with increasing cyclone diameter squared if all dimensions change proportionately and the expression relating the two is:

$$\frac{A_1}{A_2} = \left(\frac{D_1}{D_2}\right)^2 ,$$

therefore the parameter wA/Q changes in proportion to inverse cubed diameter for geometrically similar cyclones operated at the same flow rate, using inertial forces, and linearly with diameter, using electrostatic forces. The efficiency of the cyclone increases substantially due to the electrostatic augmentation as the dimensions are increased, and the efficiency due to inertial forces decreases dramatically with an increase in cyclone dimensions. For fine particles the migration velocity due to inertial forces is negligible, so the overall electrostatic cyclone efficiency increases with increasing dimensions.

Table 36 contains the results of the migration velocity due to both mechanical and electrical forces, and the efficiency, for a cyclone of double the dimensions of that in Table 35. These values can be compared to those in Table 35, to note the decrease in migration velocity and the overall increase in collection efficiency. In theory, as we increase the size of the cyclone and hold the volume throughput constant, the cyclone approaches a conventional electrostatic precipitator. There is a basic conflict between efficient cyclone design and efficient electrostatic precipitator design; we conclude it does not seem promising to try to augment a cyclone electrostatically, in the above fashion. Use of space charge repulsion due to having the particles highly charged (to the same polarity) has not been ruled out, however.

Table 36. CALCULATED THEORETICAL MIGRATION VELOCITY FOR INERTIAL AND ELECTRICAL FORCES AND PREDICTED EFFICIENCY DUE TO THE COMBINATION OF FORCES FOR A CYCLONE OF TWICE THE ORIGINAL CYCLONE DIMENSIONS

Particle diameter in microns	w_r (cm/sec)	w_e (cm/sec)	w_t (cm/sec)	Efficiency (%)
0.1	4.4×10^{-4}	6.86	6.86	38.00
0.3	3.9×10^{-3}	11.21	11.25	54.40
0.5	1.1×10^{-2}	15.93	15.94	67.10
1.0	4.4×10^{-2}	27.87	27.91	85.80
3.0	0.394	75.56	75.95	99.50
5.0	1.090	123.65	124.74	99.98
10.0	4.375	247.88	247.88	99.99

Evaluation

Analysis of Theoretical Approach - The initial phase of the study involved designing a cyclone in sufficient detail to yield results close to those expected if the cyclone were built and tested.

The second phase of the analysis, the addition of corona charging wires within the main body of the cyclone involved a less precise or more approximate approach than that utilized in designing the cyclone. A major source of possible error in the analysis would occur from the use of the wire in a cylinder model from which the equations utilized were derived. Since the cyclone as proposed, with four wires increasing in proximity to themselves and the cyclone walls to follow the taper of the cyclone, is not strictly a wire in a cylinder we would not expect the estimates concerning corona currents, voltages, etc. to be highly accurate. It seems probable that the approximations which were made with respect to cyclone geometry are well within the limits of uncertainties of the overall analysis, and that the results as presented here would approximate the results which would have been obtained with a much more rigorous analysis.

Analysis of Experimental Approach - As previously stated, there was no experimental work done.

Prospects of Method - In view of the conclusions drawn from the analysis, it would appear that there is little or no prospect in pursuing the above electrostatic augmentation of cyclones. It is highly unlikely that existing cyclones would be readily amenable to the economical retrofitting of the necessary electrical equipment. Secondly, it has been shown that it would be more advantageous to go directly to a precipitator design if higher efficiencies than those readily attainable with a cyclone are required. It appears that the prospects of the method are severely limited, although space charge precipitation may aid in collection (see next evaluation).

Status of the Method - The idea of electrostatically augmenting a cyclone has not received widespread acceptance as an emission control device. The article by Molyneaux[1] describes an electrostatically augmented cyclone for use on diesel truck exhausts, and beyond this reference and possible application we have not found significant mention of this type of device. It would appear that this is a novel device having very little if any experimental work done to evaluate its performance.

Implications - The electrostatically augmented cyclone suffers from the combination of two competing collection mechanisms, and does not have any clearly advantageous area of application. As such, it seems that there is little likelihood of the further pursuit of this device by people seeking improved particulate control devices.

ELECTROSTATICALLY AUGMENTED SIEVE PLATE SCRUBBER

The Scrubber Handbook[4] contains calculations for the collection efficiency to be expected for a sieve plate scrubber used to control highly charged particulate emissions, such as those which would result if the particulate material passed through a particle charging section upstream from the scrubber. A schematic of such a system is shown in Figure 56.

Goals

We will estimate the collection efficiency of such a system due to the electrostatic factor and compare this with the collection efficiency due to inertial impaction, as calculated in the Scrubber Handbook.[4]

Methods and Results

The charge per particle is calculated by the equation for q_p given in Section IV. The charging field is 3 kV/cm to coincide with one used in the Scrubber Handbook[4] analysis. The number concentrations are functions of time; the initial concentration is a parameter. As noted this means that the penetration, Pn, is given by:

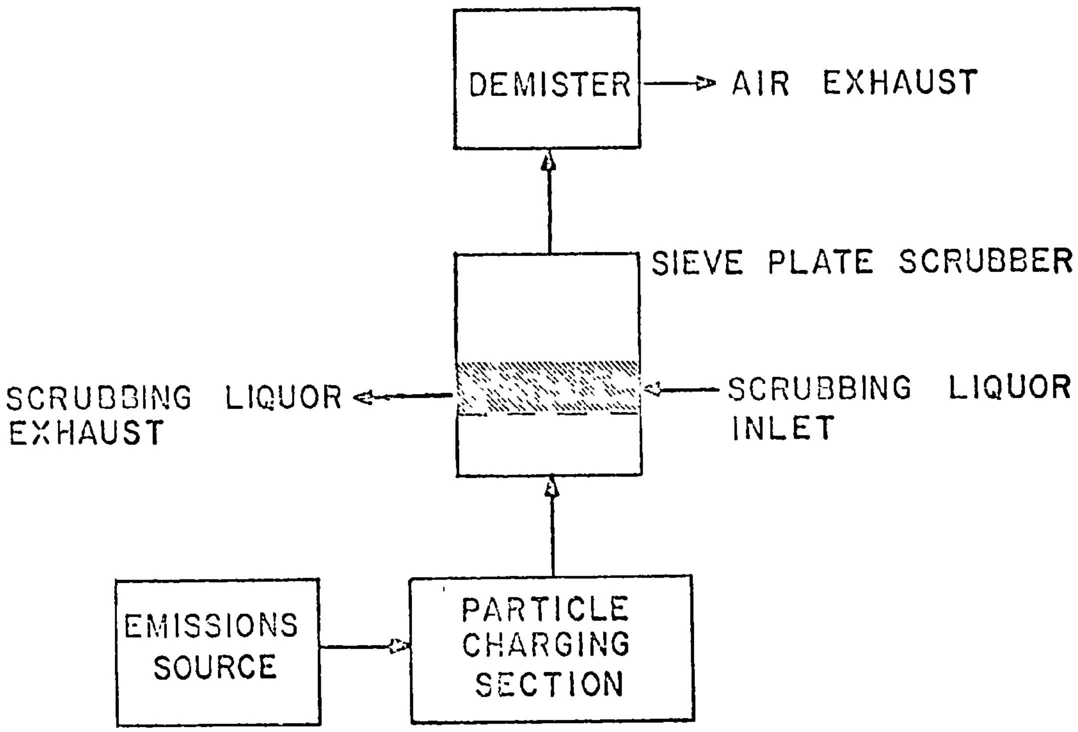

Figure 56. Schematic of possible electrostatically-augmented sieve plate scrubber

$$Pn = n/n_o = 1/(1 + 4\pi B q_p^2 n_o t) \quad .$$

For large values of the denominator, the penetration becomes, effectively, inversely proportional to the initial number concentration, the residence time in the bubble and the square of the particle charge. Note that the only factor which relates to the bubble from the sieve plate is the residence time, the height of the foam divided by the mean bubble velocity.

It is worth noting that the use of electrostatic scattering (space charge repulsion) tends to produce an emission concentration which is independent of the inlet concentration. As the denominator becomes large (thus small penetration) the preceding expression can be re-written as

$$n \doteq 1/4\pi B q_p^2 t$$

showing that the outlet concentration will just be a function of particle charge and mobility and the residence time in the system.

The Scrubber Handbook indicates that a typical bubble velocity is about 20 cm/s and a typical foam layer height is 10 cm, so the residence time, t, would be about 1/2 second. Table 37 has the factor $4\pi\ Bq_p^{\ 2}$ calculated from the particle charge and mobility. This factor has the units which are the inverse of the number concentration; $1/4\pi Bq_p^{\ 2}$ is the initial concentration which gives a penetration of 0.33 in 0.5 second, the bubble residence time.

In Table 38 we list the penetrations calculated from the above for number concentrations from 10^8 to 10^5 in decade steps. This is also the space charge effect penetration expected for other scrubbers with 0.5 sec residence time.

A substantial collection efficiency is achieved for, say, 1 μm particles at 10^7 cm^{-3} concentration, but it should be noted that for unit density particles this would be a mass concentration of 5.2 g/m^3 (2.3 gr/ft^3), higher than industrial emissions often are.

The penetration values can be compared with the penetration or (efficiency) expected for particle collection in the bubble by diffusion and by impaction, obtaining the following parameters from the Scrubber Handbook as appropriate for such a scrubber:

Diffusional collection was calculated using the Scrubber Handbook[4] equation

$$n/n_o = e^{-\left[\frac{6}{\pi}\ h \left(3D/\pi\ r_b^{\ 3}\ v_b\right)^{1/2}\right]} \quad .$$

Table 37. PARTICLE PARAMETERS USED TO ESTIMATE SPACE CHARGE DEPOSITION IN BUBBLES

Particle diameter, d_p (μm)	Particle mobility[a], B (cm/dyne-s)	Particle charge[b], q_p (esu)	Factor $4\pi Bq_p^2$ (cm^3/s)
.1	1.68×10^8	2.41×10^{-9}	1.23×10^{-8}
.3	1.95×10^7	0.84×10^{-8}	1.13×10^{-8}
1.0	5.86×10^6	0.77×10^{-7}	4.37×10^{-7}
3.0	1.95×10^6	0.68×10^{-6}	1.13×10^{-5}
10.0	5.86×10^5	0.75×10^{-5}	4.14×10^{-4}

[a]From tables by R. A. Gussman, BGI, Inc., Waltham, Mass.

[b]See Table 1. Here, the charging field is 3 kV/cm = 10 esu.

Table 38. PENETRATION OF SPACE CHARGE SCRUBBER (ASSUMING 0.5 sec RESIDENCE TIME, 3 kV/cm CHARGING FIELD)

Particle diameter (μm)	$n_o = 10^5/cm^3$	$10^6/cm^3$	$10^7/cm^3$	$10^8/cm^3$
0.1	0.999	0.994	0.942	0.619
0.3	0.999	0.994	0.946	0.639
1.0	0.979	0.821	0.314	0.044
3.0	0.639	0.150	0.017	0.0018
10.0	0.046	0.0048	0.0005	5×10^{-5}

where h = foam thickness = 10 cm

D = particle diffusivity, cm^2/s

r_b = bubble diameter, 0.33 cm

v_b = bubble velocity, 20 cm/s .

The calculated penetrations were 0.944, 0.976 and 0.988 for 0.1, 0.3, and 1.0 μm particles, respectively, all too high to show conveniently on Figure 57.

Impactive collection was calculated using the Scrubber Handbook equation

$$n/n_o = e^{-a\Psi/2}$$

where $a = 40\ F^2 = 10$

F = foam volume concentration, 0.5

Ψ = impaction parameter, based upon orifice velocity (1220 cm/s) and bubble diameter

The results of the calculation of penetration for impactive collection alone are also shown in Figure 57.

Conclusions

From the foregoing analysis, there are realistic levels of particle concentration, charge and mobility for which the mechanism of space charge repulsion (also called electrostatic scattering) is more effective than impaction, typically the predominant mechanism for scrubbing. At high concentrations and fine particle sizes this difference increases, and these are conditions for which improved scrubbing would be advantageous.

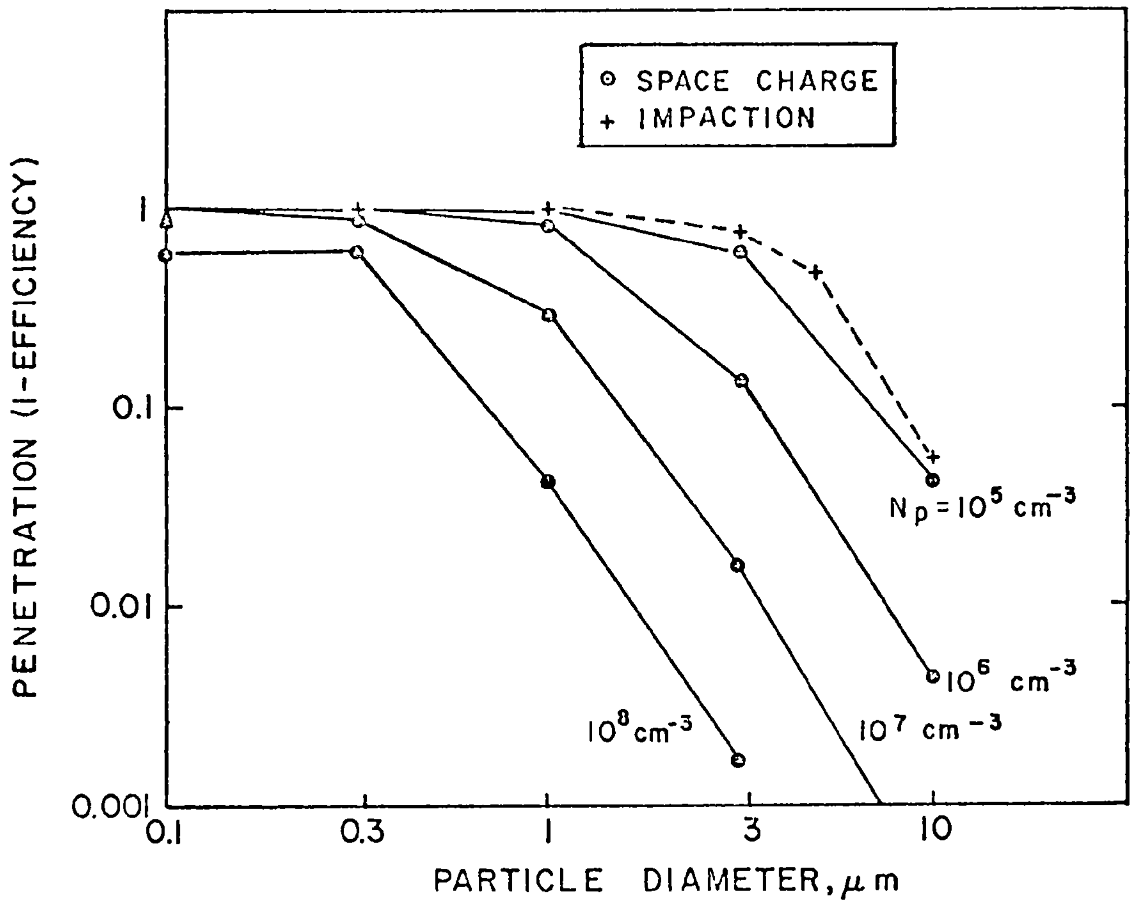

Figure 57. Calculated penetrations at 0.1, 0.3, 1.0, 3.0, 10 μm and linear interpolations

Evaluation

Electrostatic augmentation of seive-plate scrubbers is of possible utility because it would improve collection efficiency for fine particles and would do so most when the concentrations are high. If a simple and reliable means for charging the particles upstream from the scrubber can be employed, this might be an attractive way to augment scrubber collection efficiency with relatively small/power input. It would seem worthwhile to test this at the bench scale and the pilot scale.

Summary

Charging the emissions before they enter a sieve-plate scrubber can be expected to increase their collectibility, due to space charge repulsion, and under some reasonable circumstances this effect could outweigh impaction. Experimental investigation of this would seem worthwhile. (This should also be true of a packed bed scrubber.)

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SECTION IX

SETTING PRIORITIES

This section presents a model for setting priorities concerning future work in the area of electrostatic augmentation. We have attempted to incorporate essential elements necessary for rational decision-making into the model formulation, even though not all the information required by the model is available.

ASSUMPTION

One basic assumption is made. The model seeks solutions which have the minimum cost in comparison to benefits. Factors such as uncertainty are introduced through the application of probability or discount factors to costs or benefits.

DEFINITIONS

Advantage

The advantage of electrostatic augmentation is defined as the difference between the mass of fine particulates removed with the use of an augmented control device and the mass of fine particulates removed by use of a particulate control device with no electrostatic augmentation, both having the same mass input. Both of these removal factors are expressed in the common removal efficiency fashion - in terms of percentage reduction. For each application of a given device, the advantage factor is expressed as follows:

$$A_{ij} = (P_{ac} - P_{nc})_{ij}$$

where A_{ij} = advantage of augmentation device i for application j

P = removal efficiency factor expressed as a percentage

ac = augmented control

nc = nonaugmented control.

It is assumed that where $P_{nc} \geq P_{ac}$ $(A \leq o)$, the augmentation technique is rejected with no further consideration.

Cost

Two types of cost are considered, capital cost and annualized cost. Capital cost is defined as the amount of monetary outlay required for the purchase and installation of a given augmentation device. Capital costs are significant in that they represent the significance of commitment on the part of the purchaser.

Annualized costs are the yearly expenses associated with operating a given augmentation device. Included in the annualized cost are fixed costs (depreciation, insurance, finance charges) and variable costs (maintenance, power requirements, etc.). Annualized costs are important since they increase the users' costs of production and thereby influence the price charged for the good or service produced.

k_i = capital cost of augmentation device i

o_i = annualized cost of augmentation device i

Applicability

The costs of the various electrostatic augmentation devices are not directly comparable for two main reasons. First, the devices vary as to their likelihood of reaching commercial application. Secondly, they differ in the scope of their potential applications. Thus, factors which take account of these two areas must be derived if objective comparisons among the various devices are to be made.

Likelihood of Application - The likelihood of commercial application is related to the stage of development of the augmentation device. It is assumed that there are four stages of development. For each development stage the probability of success, the chance that the device will become commercially available, and the number of years until commercial availability are estimated. It should be noted that these two items are assumed to be independent of one another. For example, a given device may have a high likelihood of becoming commercially available because it is based on sound theoretical and practical grounds yet the time needed to work out production kinks and the like may lengthen its development time.

The four development stages, from the least to the most advance stage, are listed below.

- Research
- Pilot
- Demonstration
- Commercially available

The probability, or likelihood, of success is designated as follows:

ℓ_i = probability of augmentation device i becoming commercially available.

The number of years until an augmentation device becomes commercially available is taken into consideration by the application of the standard discounting technique to the advantage factor A_i.

$$P.V. \text{ of } A_i = A_i/(1 + r)^t$$

where P.V. of A_i = present value of the advantage factor

A_i = advantage factor of augmented device i

t = number of years until the augmentation device becomes commercially available

r = rate of discount reflecting the opportunity cost involved in waiting for augmentation device i to become commercially available. (The inflation-corrected interest rate can can be used as an approximation of the "true" discount rate).

Potential Applicability - The potential applicability of a given electrostatic augmentation device must also be taken into consideration. It is assumed that devices with a widespread potential applicability are preferable to those devices with a limited number of possible applications. The potential applicability is expressed as follows:

$$a_i = g_i M_i$$

where a_i = mass emissions for which augmentation device i would apply.

g_i = likelihood that device i would have its assumed application.

M_i = mass emissions from all control devices for which device i is applicable.

Cost Normalized for Benefits

The information previously discussed is used to normalize costs in order to make possible objective comparisons among the various electrostatic augmentation devices. Costs are normalized as follows:

$$K_i = \left(\frac{1}{\ell_i}\right) k_i \left(\frac{1}{A_i/(1 + r)^t}\right) \left(\frac{1}{a_i}\right)$$

where K_i = normalized capital cost of augmentation device i

$\frac{1}{\ell_i}$ = reciprocal of likelihood factor

k_i = nominal capital cost of augmentation device i

$\left(\frac{1}{A_i/(1 + r)^t}\right)$ = reciprocal of discounted advantage factor for augmentation device i

$\frac{1}{a_i}$ = reciprocal of the applicability factor for device i .

As probability, applicability, and the advantage factor increase, normalized capital cost declines. Increases in normalized capital cost are caused by increases in the nominal capital cost, the time until commercial availability and the discount rate.

Treatment of Annualized Costs

Once the normalized capital cost has been calculated, annualized cost can be determined. This is accomplished as follows:

Fixed Costs - Fixed costs include depreciation, insurance, and finance charges. Once the lifetime of the augmentation device is known, the straight line depreciation technique can be applied to determine annual depreciation charges. Finance charges, if any, can be amortized in the same manner. Insurance charges are computed as a percentage of total capital investment.

Variable Costs - Variable costs include labor, power requirements, and maintenance. For these costs, estimates from the manufacturer may be the best source of information.

Summation - The summation of fixed and variable costs is the annualized cost, o_i. This can be expressed in terms of per unit benefit, just as was done for the capital cost k_i, by replacing k_i with o_i in the preceding equation.

CONCLUSIONS

A method for setting priorities for research and development with respect to control device technologies such as electrostatic augmentation has been formulated. The devices with the lowest annualized cost per benefit should be given highest priority. This model requires the following inputs:

- Efficiency of the augmented device and the unaugmented device, if any.
- Capital cost of the augmented device.
- Annualized cost of the augmented device.
- Likelihood the device will ever become commercially available.
- Estimated time until commercially available (related to stage of development).
- Mass emissions of sources for which the device would be applicable.
- Likelihood it would be applied to such sources once available.
- Inflation-adjusted interest rate.

This model is an attempt to build a methodology for setting priorities for investing in research and development. It can be no better than its assumptions and its data, and some of the information it requires is not readily available or may always be a matter of judgment. The fact that such a model exists may provide impetus for the collection of the kind of information it requires. Even with incomplete information, it may allow order-of-magnitude cost/benefit estimates, which will show certain investments to be clearly more advantageous than others.

SECTION X

SOME RESEARCH POSSIBILITIES

INTRODUCTION

In this section, we will point out some areas relating to electrostatics and aerosols which might fruitfully be investigated further.

RESEARCH POSSIBILITIES BY RESEARCH CATEGORY

One categorization of research in air pollution control is:

- Fundamentals
- Unit mechanisms
- Control systems
- Control systems applications
- Comparison of control systems

In reviewing the work done with respect to electrostatic augmentation, we have found possible research topics in each of these categories.

Fundamentals

- What values are correct for mean ionic thermal speed and mobility?
- How do these vary as functions of gas composition?
- What factors govern rate of charging and equilibrium charge level on:
  - scrubber droplets,

- filter materials such as teflon, polypropylene, and others at the extremes of the triboelectric series,

- bed packing materials?

Unit Mechanisms

- Can a constant-concentration aerosol generator be built using the space charge effect to dampen concentration variations? Recall:

$$Pn = n/n_o = 1/(1 + 4\pi q_p^2 B n_o t)$$

$$n = 1/4\pi q_p^2 B t,$$

$$\text{for} \quad 4\pi q_p^2 B n_o t >> 1 .$$

- What is the experimental collection efficiency of charged drops when inertial forces are negligible? (Recall that the electrostatic droplet scrubber collection efficiency decreased with particle size even though the predicted collection efficiencies increased.)

- How does particle charge interact with wettability in scrubbing? (It has been argued that particle charge completely dominates poor wettability.)

- Can particles be more readily charged through contact with or close approach to charged droplets than in a comparable conventional corona discharge?

- How can one design a trouble-free pre-charging section to be used to enhance collection in scrubbers, cyclones, packed beds, etc., through space charge repulsion (electrostatic scattering)? Must field charging be used or would diffusion charging suffice to increase the collection of the fine particle fraction?

Control Systems

- Can precharging the particles produce marked improvements in fine particle collection in foam scrubbers or packed beds?

- What are the operating differences between charged droplet scrubbers of the same polarity and of opposite polarity with respect to the aerosol to be collected?

- What are the trade-offs between efficiency (as function of particle size), power consumption, and residence time (thus capital costs) for charged droplet scrubbers?

- How can open-structure filters be cleaned once their efficiency has been enchanced electrostatically?

- Can disposable filters have their fine particle collection efficiency substantially enhanced by superimposing an electric field parallel to the air flow?

- How does the use of wetted surfaces affect cleaning and dust resistance problems in electrostatic precipitators?

- How can sneakage and reentrainment be minimized in electrostatic precipitators?

Applications

- Which applications areas (such as acid mist) are most difficult to achieving high efficiency control? What are the electrical characteristics of the aerosols and gases involved? How might electrostatic augmentation be achieved?

Comparisons

- What are the cost/benefit factors in the use of charged droplet scrubbers?
- What would be the cost/benefit comparison for adding precharging sections to augment control devices by adding to the particle collection through space charge repulsion? (This will depend upon the cost of such a system, the aerosol concentration and size distribution, precharger design, and the system residence time, including the time spent in ducting after the precharger.)

CONTROL SYSTEMS

The particle pollution control systems all have the following features: some expenditure of resources (materials, labor, power) is used to remove particulate material from a gas stream and transport this material elsewhere. The studies discussed in this document have had the following general approaches to electrostatic augmentation as a means to lessen resource expenditures:

- improve particle charging (raise levels, charge inexpensively)
- add electrostatic forces to augment collection by impaction, interception, diffusion, sedimentation, diffusiophoresis, etc.
- use electrostatic forces to change system geometry (increased porosity in filter cake through electrostatic repulsion, increased residence time for scrubbing droplets with the electrostatic curtain).

By comparing such approaches with the mechanisms operating in the conventional control methods, one can note some attractive possibilities.

Table 39 lists widely-used particle collection devices and the primary and secondary mechanisms they employ to achieve gas/particle separation. We will discuss some possible applications of electrostatics device-by-device.

Settling chambers are normally used for the coarsest aerosols, producing gas/particle separation by the settling of particles under the force of gravity. This is favored by large particles and long residence times. Because large particles will take high charges and because the residence times are long, precharging the particles before they enter the settling chamber may appreciably increase collection efficiency, due to the space charge (electrostatic scattering) effect. The chamber should be grounded in any such application.

Table 39. WIDELY-USED CONTROL DEVICES AND PARTICLE REMOVAL MECHANISMS

Removal mechanisms	Control devices												
	Settling chamber	Cyclone	Impinger	Seive	Packed bed	Filter	Electrostatic precipitator	Spray scrubber	Incinerator	Foam scrubber			
sedimentation	P							S		P			
centrifugation		P					S	P					
impaction			P	S	P	P		P		S			
interception				P	P	P		P					
diffusion			S		P	P		P		P			
electrostatic						S	P						
diffusio-phoresis								S					
thermophoresis								S					
photophoresis													
vaporization									P				
combustion									P				
turbulent deposition													
sonic migration, oscillation													

P - Primary mechanism.
S - Secondary mechanism

Cyclones use high velocities and relatively short residence times. We have analyzed one possible method of adding electrostatics to enhance collection (Section VI). The relative influence of electrostatic forces would increase for cyclones with slower gas velocities, other things being equal, so that electrostatic augmentation, through the use of an applied electric field within the cyclone or through space charge precipitation, would have a greater impact on cyclones with fairly large cut diameters rather than those with substantial efficiencies in the fine particle range.

Impingers also use relatively large gas velocities, velocities it is difficult to match with electrostatic forces.

Packed beds generally use face velocities substantially slower than those in venturi scrubbers or cyclones, so that the addition of electrostatic collection through space charge precipitation might be quite advantageous. A conductive system (water-washed, for example) would allow collection of precharged particles without the build-up of a field opposing such deposition. It is hard to superimpose a strong external field across the bed, however. because of the typical dimensions involved.

Filters which build up a charge may achieve enhanced collection by Coulomb attraction of oppositely charged particles. Even uncharged particles, as shown, will be appreciably attracted by the charged fibers (see Section III discussion on image force between charged collector and uncharged particle.) Penney and Frederick at Carnegie-Mellon are, as discussed, also following up the intriguing possibility that particle charge may be used to lower filter cake resistance without lessening collection efficiency. The low face velocities ($\sim$ 1 cm/s) suggest electrostatic forces can have important contributions to collection. The large structures and long residence times in fabric filtration also suggest that precharging the particulate matter could produce substantial space charge precipitation within the baghouse, a possibility worth pursuing. (Again, the structure should be grounded.) Because the cleaning and resistance characteristics of the dust/fabric system are so important and because the electrostatic forces are known to be important in adhesion and cake formation, work in this area, such as that by Penney and Frederick, is quite promising.

Electrostatic precipitation could be furthered by improved particle charging (note the possibility of droplet-particle charge transfer and the questions surrounding ionic mobility and mean thermal speed) and by methods for preventing the flow of gas through areas of low electric field strength. The work on particle charging might well be coordinated with the work on resistivity, because the addition of charge to highly resistive particles may only exacerbate the problems posed by such an aerosol.

Spray scrubbers (including venturi scrubbers) should be able to improve their performance by the application of electrostatic forces between the droplets and the particles as well as the particle-particle repulsion due to space charge. Design of such systems should take into account the time scales emphasized by Melcher and Sachar (see Section V), to assure that the collecting droplets are present for times which are long compared to the characteristic time for particle-droplet collection. At present, mutual repulsion by droplets and particles of the same sign seems promising, as does the collection of particles by droplets of opposite sign (as investigated by Pilat and his colleagues at the University of Washington).

In passing, it can be observed that combustion and flame behavior has been found to be sensitive to electrostatic fields, so that there may even be a role for electrostatics in enhanced incineration.

Finally, as we have noted in Section VIII, the foam scrubber would be a logical candidate for electrostatic augmentation by precharging the particulate matter and using space charge repulsion. The relatively slow flow velocities and long residence times would help and the improvement should be substantial in the fine particle fraction, where much current interest centers (see Section VI for more details).

In general, it would be advantageous for those conducting experimental investigations into electrostatic augmentation to indicate the ranges and values of the parameters listed in Table 33, where applicable. This would allow other researchers to analyze the results more readily and would assure that important parameters are not being unmeasured or unrecorded.

SUMMARY

Possible courses of investigation have been outlined in this section, along with some data reporting suggestions. The section on setting priorities might be useful in judging between the possibilities presented here, even if the estimates which are entered into the methodology are only rough approximations. It is hoped that this work will stimulate the research into applying an inherently energy-efficient means, electrostatic forces, in removing undesirable particulate material from the air.

APPENDIX A

INTRINSIC POWER REQUIREMENTS FOR DUST REMOVAL*

The work done (W) in removing a particle from a gas stream is the integral of the fluid resistance force (F_r) during the particle motion and the path length (ds):

$$W = \int_{S_1}^{S_2} F_r(s)ds \quad .$$

The power (P) is a similar integral, involving the force and the velocity, v(s):

$$P = \int_{S_1}^{S_2} F_r(s)v(s)ds \quad .$$

In both integrals, the total path length is $L = S_2 - S_1$. For times which are long compared to the particle relaxation time (= 3.6×10^{-6}s for 1 μm diameter particle), the particle velocity is the terminal velocity, given by:

$$v(s) = F_e \, C/3\pi\mu d_p$$

in those instances where Stokes law applies (particle Reynolds number much smaller than one),

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* For a very different approach using thermodynamics, see: Soo, S.L., Environ. Sci. and Technol. 7:63 (1973).

where F_e = applied force = F_r

d_p = particle diameter

μ = fluid viscosity

C = Cunningham correction factor (= $1 + 0.16 \times 10^{-4}$ cm/d_p at STP for air.)

The force may be constant or it may change with position. If it is governed by a power law,

$$F_r = F_e = cs^n,$$

the analysis is simplified (n = 0 is the constant force situation).

The work and power integrals become:

$$W = c(S_2^{n+1} - S_1^{n+1})/(n + 1), \; n \neq -1$$

$$P = \int_{S_1}^{S_2} (3\pi\mu d_p/C)v^2(s)ds$$

$$P = \int_{S_1}^{S_2} (C/3\pi\mu d_p)F^2(s)ds$$

$$P = (C/3\pi\mu d_p)\, c^2 \left[S_2^{2n+1} - S_1^{2n+1}\right]/(2n + 1), \; n \neq -\tfrac{1}{2}.$$

In the homogenous force field, n = 0, these integrals reduce to:

$$W = F_r S = (3\pi\mu d_p v/C)S$$

$$P = F_r v = (3\pi\mu d_p v^2/C) \quad .$$

We can average over S and v^2 by using the definition of the average of a quantity x for the particles, which is

$$\bar{x} = \int_{x_{min}}^{x_{max}} x\ f(x)dx$$

where f(x) is the fraction of particles having the value in the range x to x + dx.

The work in removing particles always increases as the mean particle-to-collector distance, $\bar{S}$ increases. The integrals for power show a very marked increase in power consumption as the particle mean squared velocity, $\overline{v^2}$, increases.

A simple formula for penetration, Pn, the ratio of outlet to inlet particle concentrations for a control device, is

$$Pn = e^{-vA/Q}$$

where A = collection area perpendicular to particle migration velocity, v,

Q = volume rate of flow.

In a homogeneous force field (or for a field adequately represented by using an average force):

$$v = P^{\frac{1}{2}}(C/3\pi\mu d_p)^{\frac{1}{2}} \quad .$$

This can be substituted into the exponential expression to give the power required to achieve a given penetration:

$$Pn = e^{-P^{\frac{1}{2}}(C/3\pi\mu d_p)^{\frac{1}{2}}} .$$

For 95 percent efficiency (Pn = 0.05), one needs

$$P^{\frac{1}{2}} (C/3\pi\mu d_p)^{\frac{1}{2}} (A/Q) = 3$$

or

$$P = 9(Q/A)^2/(C/3\pi\mu d_p) .$$

The ratio of flow rate to collecting area, Q/A, can be converted to the ratio of control device volume to collecting area times the average linear gas velocity divided by the flow path length:

$$Q/A = (V/A)(U/L) .$$

This is also just $(V/A)/t_{res}$; for the residence time, t_{res}. For an electrostatic precipitator with V/A = 25 cm = 0.25 m, and t_{res} = 1 sec, the power needed for Pn = 0.05 for <u>one</u> 1 μm particle would be

$$P = 9(0.25 \text{ m/s})^2/(6.8 \times 10^9 \text{ s/kg})$$

$$P = 8.3 \times 10^{-11}(\text{kg} - \text{m/s}^2)(\text{m/s})$$

$$P = 8.3 \times 10^{-11} \text{ W} .$$

A particle concentration of 1 g/m^3 would be $1.9 \times 10^{12}/m^3$ number concentration if the mass mean diameter of the aerosol were 1 μm and the particle density that of water. At a 4.7 m^3/s (10,000 cfm) flow rate, the precipitator volume would be 4.7 m^3 (1 second residence time) and the total power consumption:

$$P = (8.3 \times 10^{-11}\ W)(1.9 \times 10^{12}/m^3)(4.7\ m^3)$$

$$= 741\ W.$$

Soo (1973) indicates typical actual power consumptions about five times this value for precipitators and 50 times this value for high-energy scrubbers. Our theoretical value, though low, is more than an order of magnitude higher than Soo's theoretical values and seems an improvement on his approach.

When the device volume, V, the mass concentration, m, and the mass mean diameter, $\overline{d_p^{\,3}}$, are used in the expression for power, one obtains

$$P = \left(\frac{6\ m}{\pi \overline{d_p^{\,3}} \rho_p}\right) V\ (9\ Q^2/A^2)(3\pi\mu \overline{d_p}/C)\,.$$

From this equation, it is clear that the following factors will increase intrinsic power requirements:

1. Increased mass concentration for the same size distribution;

2. Decreased mean size for the same mass concentration;

3. Increased volume for the same ratio of flow rate to collection area; and

4. Increased flow rate for the same geometry.

Because penetration is related to the square root of power through an exponential relationship (given above), to change the penetration from

e^{-1} (0.37) to e^{-3} (0.05), for example, can be done by increasing the ratio of the collecting area to the flow by a factor of 3, or the power per particle by a factor of 9.

This appendix is just a preliminary analysis of the intrinsic power consumption question. The power so estimated is expected to be less than that usually expended by control devices because the analysis assumes that all power goes to the collection of the particulate material, although in fact much of it may go to gas/collector flow resistance as well. This kind of analysis should indicate minimum power requirements and should suggest ways in which control devices in the future can approach these minimum values. Electrostatic augmentation of control device efficiency is attractive because the electrostatic forces are applied directly to the particles, rather than indirectly as is done with methods which rely on particle inertia, such as scrubbers or cyclones.

APPENDIX B

INSULATOR PARTICLES CAN BEHAVE AS CONDUCTORS

Fuchs[1] notes that experimental work with oil and mercury droplets showed that the oil droplets behaved as though they were conductors ($\chi \rightarrow 1$). The following calculation indicates why this is so. An uncharged cubical particle (L x L x L) aligned with an electric field (E) perpendicular to one set of faces would, if a conductor, have charges +q and -q migrate to the faces to offset the electric field's potential difference, EL = V The current would be

$$I = V/R \doteq 2q/\Delta t$$

where R = resistance

V = voltage difference

Δt = time to reach equilibrium.

An insulator is just a poor conductor, requiring a much larger Δt than the conductor. The resistance, R, is given in general by

$$R = \rho L/A = \rho L/L^2 = \rho/L$$

where ρ = material resistivity

A = cross-sectional area .

Then,

$$\Delta t \doteq 2q\, R/V$$

$$\doteq 2q\, \rho/LV \quad .$$

The final charge will be such that

$$V = 2q/L$$

so,

$$\Delta t \doteq \rho .$$

The time is equal to the resistivity, ρ, which is given in ohm-cm or sec, because[2]

$$1 \text{ sec} = 9 \times 10^{11} \text{ ohm-cm.}$$

A list of some substances and their resistivities (thus, charge equilibration times) is given in Table 40.

Table 40. SOME SUBSTANCES AND THEIR RESISTIVITIES

Substance	Resistivity, ρ (ohm-cm)	Charge equilibrium time (s)
Glass	$\sim 10^{13}$	10^{1}
NaCl	$\sim 10^{9}$	10^{-3}
Si	$\sim 10^{4}$	10^{-8}
C	$\sim 10^{-2}$	10^{-14}
Cu	$\sim 10^{-6}$	10^{-18}

Particles travelling ~ 1 cm/s would spend ~ 10^{-3} s in the vicinity of a collector of L ~ 10 μm, and 10^{-3} s would be sufficient time for polarization for particles less resistive than pure NaCl, so that such particles would act as conductors.

Particles with adsorbed water will act as conductors, too, even if they are made of highly insulating material. Thus, most particles will be charged collected as though they were conductive.

REFERENCES

1. Fuchs, N. A. Mechanics of Aerosols. Pergamon, New York. 1964.
2. Jackson, J. D. Classical Electrodynamics. John Wiley & Sons, Inc. New York. 1962.

APPENDIX C

NOTES ON EXPONENTIAL PENETRATION FORMULAE

A generalized collection configuration is shown in Figure 58. Collecting surfaces each having a total area, A_s, and an area normal to flow, A_c, are present in a collector which itself has cross-sectional area, A_o, and mean face velocity, v_o (also called the free stream velocity), which velocity is assumed to have the same mean throughout the collection device, for simplicity.

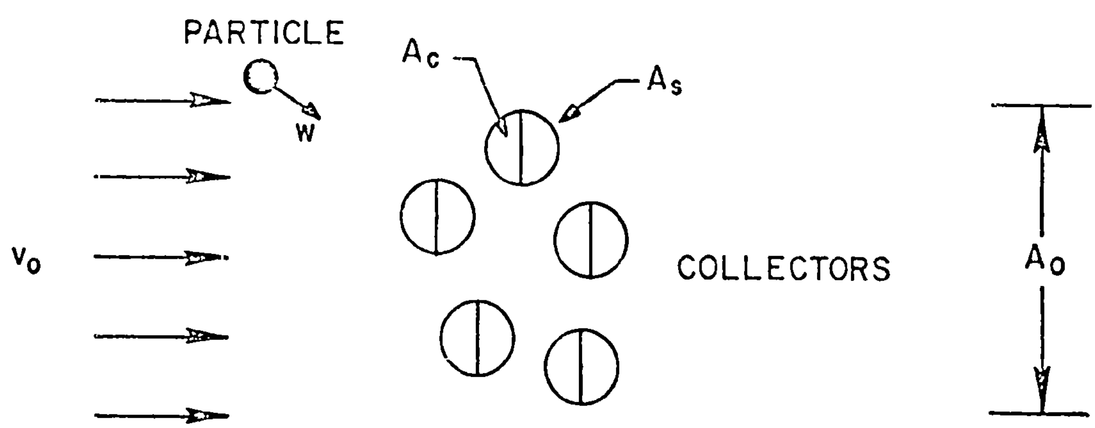

Figure 58. Model for particle collection by obstacles

Two frequently-used forms of penetration equations are

$$Pn = e^{-w(\Sigma A_s)/Q} = e^{-w(\Sigma A_s)/v_o A_o}$$

where Q is the volume flow rate, A_s the total collector surface, and

$$Pn = e^{-\eta\, n_c A_c L}$$

where $n_c A_c$ is the cross-sectional area of collectors per unit volume and L is the length (parallel to the mean flow) of the collection section, η is the single collector efficiency.

The first expression can be obtained by equating the change in number concentration in a volume to the number per volume reaching surface, A_s, at perpendicular velocity, w:

$$-\frac{dn}{dt} = \frac{1}{V} \oint n\vec{v}_p \cdot d\vec{A}_s$$

$$\vec{v}_p = \vec{w} + \vec{v}_g$$

$\vec{w}$ = velocity with respect to gas

$\vec{v}_g$ = gas velocity.

Because

$$\oint \vec{v} \cdot d\vec{A}_s = \oint (\vec{\nabla} \cdot \vec{v}) dV$$

by Gauss's Theorem (dV is the volume element), and because

$$\vec{\nabla} \cdot \vec{v}_g = 0$$

for incompressible gas flow (Mach <<1), then

$$\frac{dn}{dt} = -\frac{1}{V}\oint n\vec{w} \cdot d\vec{A}_s$$

or

$$\frac{dn}{dt} = -\frac{1}{V} nw(\Sigma A_s),$$

where the migration velocity is perpendicular to the collecting surface. Thus,

$$n = e^{-w(\Sigma A_s)t/V}$$

$$n = e^{-w(\Sigma A_s)/Q}.$$

The other formula is derived similarly, assuming that each collector removes $\eta A_c/A_o$ of the particles approaching it from a great distance.

The connection between these formulae would be

$$w(\Sigma A_s)/v_o A_o = \eta n_c A_c L$$

$$= \eta(\Sigma A_c)L/A_o L$$

or

$$(w/v_o)(\Sigma A_s)/A_o = \eta(\Sigma A_c)/A_o.$$

Thus

$$\eta = (w/v_o)(\Sigma A_s/\Sigma A_c),$$

APPENDIX D

APPROXIMATE CALCULATION OF COLLECTION EFFICIENCY FOR CENTRAL-FORCE COLLECTOR

In Figure 59 is given the geometry for the following discussion of collection of an aerosol particle by a collector which produces a central force given by the equation:

$$F_r = k/r^n$$

in which r is the radial distance from the center of the collector, k is a constant of proportionality, and n is the exponent associated with the force (Coulomb force would have n=1 for a collecting cylinder and n=2 for a collecting sphere). The collector has radius R. The net flux into an imaginary surface at R* is just the integrated product of the net migration velocity of the particle under the force F_r with the concentration at that surface and the surface area. We can define R* such that it is the distance at which this integrated product equals the product of the free-stream velocity, v_o, and the free stream concentration, N_o, and the geometrical cross-section of this imaginary ("Gaussian") surface for a spherical collector:

$$v_o N_o \pi R^{*2} = w^* N 4\pi R^{*2} \quad .$$

We also know that, for negligible inertia, the migration velocity is the product of F_r (r = R*) and particle mobility, B:

$$w^* = Bk/(R^*)^n$$

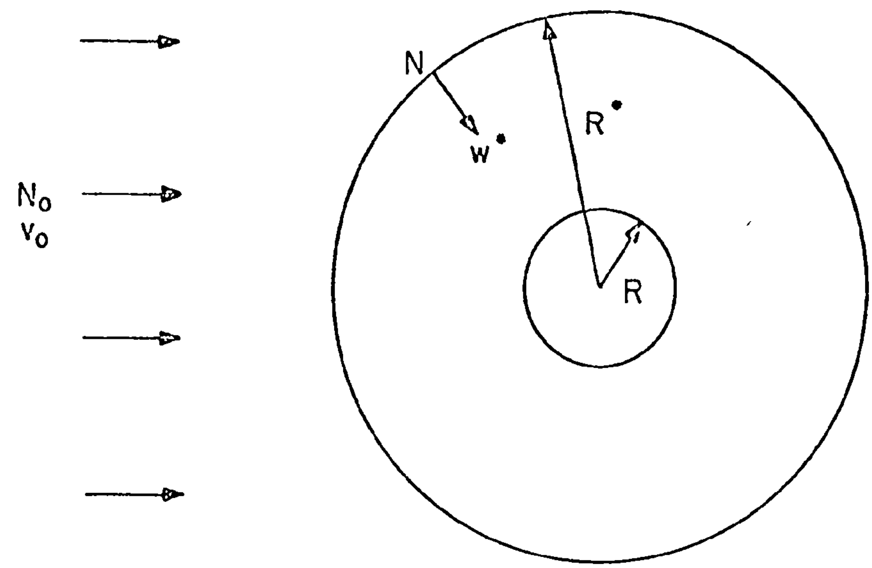

Figure 59. Geometry for approximate calculation of collector efficiency for central forces

The single target efficiency is defined as the ratio of the cross-sectional area swept clean by a collector to the geometrical cross-sectional area:

$$E_s = (R^*/R)^2$$

for spheres and

$$E_s = (R^*/R)^1$$

for collecting cylinders. Analysts of such problems, such as Kraemer and Johnstone,[1] usually try to get collection efficiency in terms of the ratio of the value of the central force at the surface of the collector, F_R, to the drag force on the particle, F_D, at the free stream velocity of the gas. For a collecting sphere, and assuming that $N \doteq N_o$ (an important assumption), the migration velocity at R^* can be put in terms of the free stream velocity, allowing the formulation of an expression for R*:

$$w^* = v_o\ (N_o/N)/4 \doteq v_o/4$$

$$R^* = \left(Bk/w^*\right)^{1/n} \doteq \left(4Bk/v_o\right)^{1/n} \quad .$$

Noting that

$$k/R^n = F_r,$$

and

$$v_o/B = F_D$$

we have, for a spherical collector

$$E_s = (R^*/R)^2$$

$$E_s \doteq \left[(4\ Bk/v_o\ R^n)^{1/n}\right]^2$$

$$E_s \doteq \left(4\ F_R/F_D\right)^{2/n} \quad .$$

For cylindrical collectors, the ratio of surface area to cross-sectional area is π rather than 4 and the exponent becomes 1/n rather than 2/n.

The efficiencies thus calculated match those of Kraemer and Johnstone[1] for the Coulomb force (for which $N = N_o$ exactly) with spherical and cylindrical collectors and have the same exponent and nearly the same coefficient as the efficiency expressions given by Kraemer and Johnstone for image force collection on spheres and cylinders. The Kraemer and Johnstone calculations required assuming specific flow velocity profiles, whereas this approach clearly does not.

Actually, the collection efficiency approach masks the physics: the size of the collector is not really determining the collection due to electrostatic interaction...instead it is the size of R* which indicates how far from the center of the collector is the central force effective in cleaning:

$$R^* \propto (F_R/F_D)^{1/n}$$

$$R^* \propto (kB/v_o)^{1/n} \quad .$$

Other things being equal, this means smaller particles, at slower gas velocities, at smaller n (coulomb rather than image, etc.) are favored. (The factor k can alter this, however, as it includes particle-size-dependent factors such as charge.)

This appendix has presented a convenient and novel method for estimating the collection achieved by a central force from the known expression for that force, the velocity of the gas stream to be cleaned, and the particle mobility.

REFERENCES

1. Kraemer, H. F. and H. F. Johnstone. Collection of Aerosol Particles in the Presence of Electrostatic Fields. Indus. Eng. Chem. 47:2426. (Correction in Indus. Eng. Chem. 48:812(A56). 1955.)

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16. ABSTRACT The report reviews electrostatic augmentation of control devices for fine particulate: the addition of electrical forces to scrubbing and filtration and the enhancement of electrostatic precipitation. It gives the major electrostatic force equations and their evaluation for some reasonable values of particle and collector charge and geometry. It includes a bibliography on electrostatic augmentation. It analyzes the following programs on electrostatic augmentation of filters, scrubbers, and electrostatic precipitators: fiber beds used to capture particles electrostatically, dust/fabric electrostatic effects, electric fields applied across filters or generated within filters, a collector using oppositely charged particles and droplets, a charged droplet scrubber (accelerates droplets electrostatically and uses them to transfer charge to particles for electrostatic precipitation), various polarities and configurations for charged droplet scrubbing of charged particles, nuclear radiation used to charge particles for electrostatic precipitation, various configurations and uses for an 'electric curtain,' and improvement of particle-charging in connection with pre-charging chambers. Other research in electrostatic augmentation, especially on filters, is discussed briefly. Analysis of two other possible systems is presented: an electrostatically augmented cyclone and a foam scrubber that uses particle pre-charging.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Air Pollution	Dust Filters	Air Pollution Control	13B	13K
Electrostatics	Scrubbers	Stationary Sources	20C	
Dust	Fibers	Fine Particulate	11G	11E
Electrostatic Precipitation	Fabrics	Electrostatic Augmentation		
	Nuclear Radiation		13H	18H, 20H
Electrostatic Precipitators	Cyclone Separators	Charged Droplets		07A
	Foam		09C	

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