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EVALUATION OF CHARGED WATER SPRAYS FOR DUST CONTROL

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Bureau of Mines
United States Department of the Interior

EVALUATION OF CHARGED WATER SPRAYS FOR DUST CONTROL

FOREWORD

This report was prepared by Foster-Miller, Inc. of Waltham, MA, under United States Bureau of Mines (USBM) Contract No. HO212012. It was administered under the technical direction of the Twin Cities Mining Research Center (TCMRC). The Technical Project Officer was Mr. Keith Olson. Mr. R.J. Simonich was the Cntracting Officer for the USBM. The work period covered was from January 1981 to October 1982. This report was submitted by the authors in January 1983.

Technical effort was performed by the mining Division of the Engineering System Group under the supervision of Mr. David A. Monaghan. The Program Manager was Mr. John McCoy. Significant program contributions were made by Mr. Joseph Valentine, Staff Engineer, Mr. Terry Muldoon, Assistant Division Manager, Mr. Jonathan Kelly, Project Engineer, and Mr. Gary Anderson, Engineering Technician. Professor James Melcher, a consultant to Foster-Miller, was responsible for developing the mathematical model presented. Professor Stuart Hoenig consulted on the technology review.

Foster-Miller gratefully acknowledges the cooperation of Amax, Inc. throughout the program.

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EXECUTIVE SUMMARY

ES.1 Introduction

Reports of application of charged water sprays to control dust concentrations in the workplace have existed for less than a decade (1). The purpose of the effort reported here is to evaluate this method as an aid to individuals in the underground mining community who are responsible for specifying and implementing respirable dust control techniques. The work was performed by Foster-Miller, Inc. of Waltham, MA, under United States Bureau of Mines (USBM) Contract No. H0212012. It was administered under the technical direction of the Twin Cities Mining Research Center.

ES.2 Program

The work was divided into two phases:

a. Phase I State-of-the-Art Review
   1. Prior experience
   2. Equipment
   3. Theoretical development

b. Phase II Testing
   1. Laboratory testing
   2. Mine testing.

ES.3 Phase I Findings

Prior efforts by researchers (10, 11) working under contract to the U.S. Environmental Protection Agency have demonstrated significant reductions in fugitive dust values under a range of operating conditions. Data extracted from their results which demonstrates the effect of adding charge to water sprays is presented in Figure ES-1. Others have reported using charged spray for reducing dust in laboratory studies (1, 5, 6, 9), but the evidence presented in Figure ES-1 is the most convincing.

Review of previous theoretical explanations of charged droplet dust scrubbing uncovered little of practical value for the engineering of charged spray systems. In this program, the characteristic time technique of Melcher et al (17) was expanded

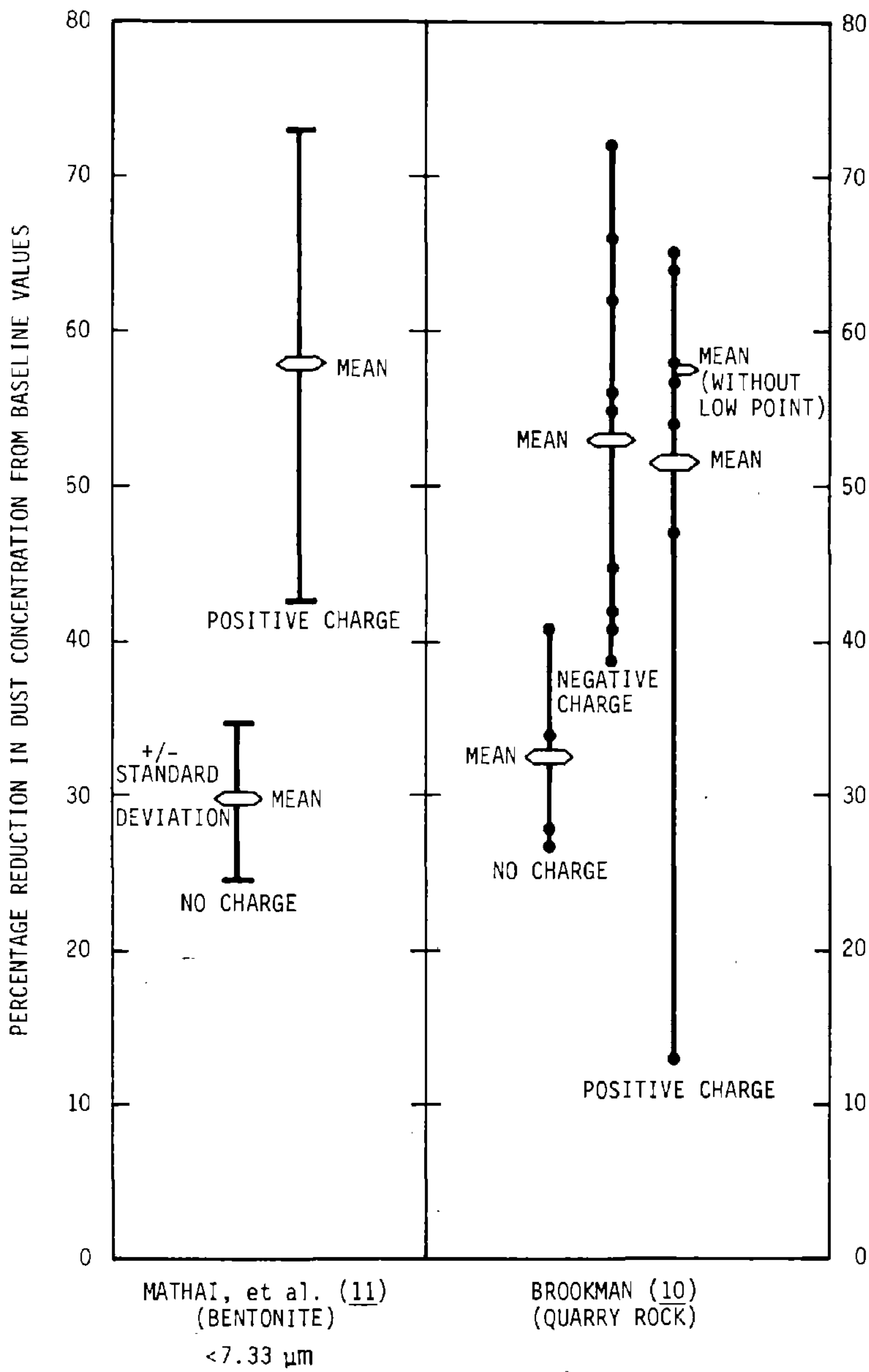


FIGURE ES-1. - Results of field tests performed for EPA.

to mathematically model dust collection efficiencies (see Appendix A). Comparison of the predictions based on this model with the results of experiments indicates the charge on the dust particle to be higher than would be expected naturally. It is felt that the dust particles are charged by ions produced from the charged spray process. The ionically charged dust is then precipitated from the cloud due to repulsive electrostatic forces. This additional dust particle charging leads to reduced characteristic times - the time for a given dust concentration to be reduced by 1/e or to approximately 37 percent of the original level.

Examination of the marketplace identified available charged spray equipment for agricultural, paint spraying and dust control applications. Only one company, Keystone Dynamics, was actively marketing commercially charged sprayers specifically for dust control - under the trade name of Dustron.

ES.4 Phase II Findings

Laboratory Testing

The commercially available charged spray dust control equipment was tested in a laboratory dust chamber. The dust reduction achieved in the presence of charged spray was much greater than for equivalent spray uncharged. On a unit water basis, effectiveness was greater by about a factor of 10 than that expected for hydraulic sprays, even to pressures of 1000 psi. Figure ES-2 shows typical dust decay characteristics for dust in the presence of no sprays, with uncharged water spray and charged water spray. As can be seen, the charged spray reduces dust levels far more rapidly than does the uncharged spray.

The reciprocal of the net slope of the curves for the charged spray (charged spray slope minus the dust only slope) is the characteristic time identified in the mathematical model. In Appendix B, a dust reduction efficiency relationship is developed using the reduction slope and the aerodynamic residence time. With this relationship, laboratory experience may be scaled to full scale applications.

Laboratory tests were performed on three types of dust:

a. Arizona road dust (fine)

b. Milled talc

c. Milled molybdenum ore.

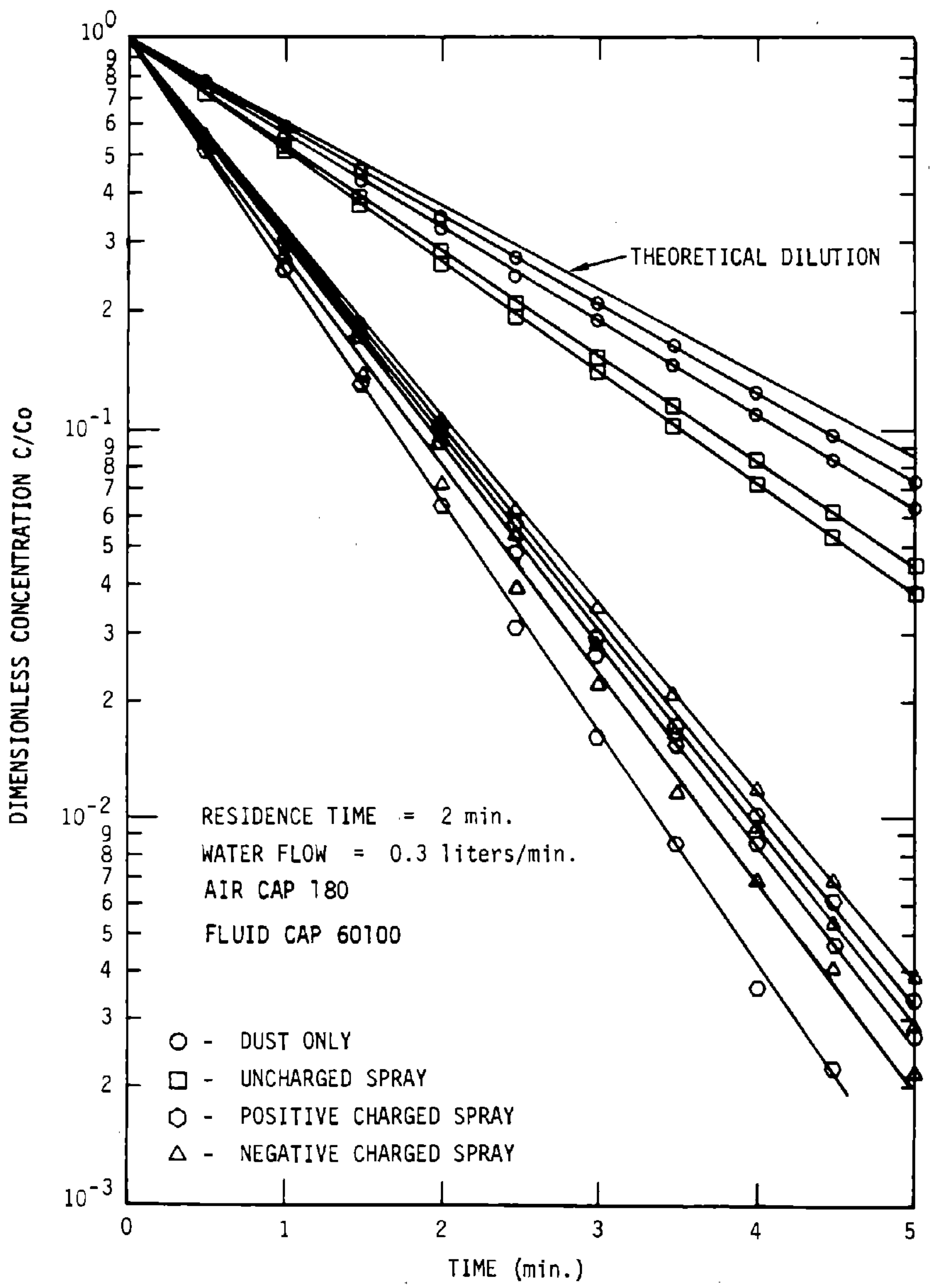


FIGURE ES-2. - Dust concentration decay versus time.

No significant difference in dust reduction effectiveness existed between these dusts or between application of positively or negatively charged spray. These results are contrary to those reported by Hoenig (5), but consistent with Brookman (10). The polarity insensitivity is consistent with ionic charging of the dust particles.

Electric fieldstrength measurements on the charged droplet cloud yielded values as high as 10^5 v/m. This is one-third the electrical breakdown point of air, that is, sparkover. The potential for sparks from the charged droplet cloud is high. For this reason, explosive atmospheres must be avoided.

Mine Testing

A field test of charged water sprays was performed at a mine in Colorado. The test was set up along an underground belt from a primary crushing plant. Six charged spray heads were used. Twice as many units would have been desirable for the air flow encountered, but a purchase cost of about $12,000 for the six units was all the program budget allowed. Predicted dust reduction with the six spray heads ranged from 10 percent to 33 percent depending on the airflow rate at the time. Maximum dust reduction occurs at minimum airflows due to increased residence time.

Predicted dust reductions could not be confirmed. This is due to the presence of solids in the spray water. The spray water was taken from a recirculating mill process water system. This type of water supply typically has suspended and dissolved solid material within it. When the water sprays were activated, measured particulate levels increased several fold over the levels existing prior to activating the sprays. Careful analysis yielded the following explanation. The fine droplets produced by the atomizing sprays evaporated in the ventilation air, leaving behind a dust particle formed from the dissolved solids in the water. This explanation was supported by water analysis indicating high dissolved solids content and by subsequent operation of the spray heads on mine water at our laboratory facility. Lack of Tyndall effect in water samples eliminated suspended solids as a leading candidate.

This occurrence was unexpected. No previous researchers have reported a similar experience. The important lesson -- solids-free water must be used with atomizing sprays, charged or uncharged. Small droplets evaporate rapidly leaving a respirable solid particle that can dramatically increase the respirable dust levels in the air.

ES.5 Conclusions

a. On a unit water use basis, charged sprays are much more effective at dust reduction than traditional hydraulic sprays. Charged sprays offer the most promise for respirable dust control where large amounts of water cannot be used.

b. Unlike hydraulic sprays, charged sprays require a residence time for the charged droplets and the dust particles to interact. Charged sprays are most effective, therefore, where ventilation velocities are low.

c. Charged sprays *must not* be employed in gassy mines because of the spark hazard from the *charged cloud*.

d. Water free of solid material is essential with atomizing sprays to avoid increasing dust loadings in the air.

e. Positively charged and negatively charged droplets are equally effective.

f. Combinations of positively charged and negatively charged droplets are less effective than either alone.

g. Little variation in effectiveness was observed between various types of dust.

h. Models may be employed to predict effectiveness for specific conditions.

ES.5 Recommendations

Charged sprays are most effective where air velocities are low and most desirable where water usage must be minimized. They cannot be applied where methane or other explosive gases are present. Further, equipment costs are high where full scale airflows must be controlled. For these reasons, their application in underground mines is limited. Surface facilities and milling operations are more likely to benefit from the application of charged sprays.

Equipment should be developed to produce large volumes of charged spray at costs below current levels. Such equipment will broaden the applicability of this technology. We believe the basic technology exists but development is required.

Fundamental studies are needed on measuring dust electric mobility (velocity of a charged particle in a unit electric field) in the presence of charged spray. This is an area where little data exists. Speculation was required to correlate this program's experiment with theory.

Present equipment is noisy due to compressed airflow. Further fog produces decreased visibility. Further studies to reduce these problems are warrented.

1. INTRODUCTION

This is the Final Technical Report on USBM Contract No. HO212012, "Evaluation of Charged Water Sprays." Effort on this program spanned the time period from January 15, 1981 to October 15, 1982. The effort expended and results obtained are described herein.

1.1 Background

Respiratory ailments due to fine dust suspended in the workspace air is a major contributor to illness and death for miners. Hence, the development of techniques for reducing respiratory dust levels is of major importance to the mining industry. The U.S. Bureau of Mines initiated and sponsored this effort to evaluate the use of charged water spray or fog for reducing respirable dust concentration levels. Prior research by others has indicated that charged sprays, when applied to airborne dust, produce agglomeration and dust level reductions well beyond that achieved with conventional hydraulic sprays. Objective evaluation and documentation of this technique applied to mining was warranted to provide the basis for a feasibility assessment.

1.2 Objective

The broad objective of this program was to determine and verify the feasibility of using charged water sprays and mists for the control of respirable dust in underground nongassy mines.

1.3 Scope of Effort

The program was divided into two phases:

a. Phase I - Technology Review, Mathematical Model Development and Mine Test Site Selection

b. Phase II - Laboratory and Mine Testing.

Phase I effort included:

a. Evaluation of prior experience in reducing dust concentration levels through charged water sprays

b. Evaluation of commercially available charged water spray equipment

c. Development of a mathematical model for dust reduction by charged water sprays

d. Review of charge levels on dust particles

e. Selection of a mine site for demonstration of charged water sprays

f. Planning for laboratory and mine testing.

The efforts of Phase I were summarized in a Phase I report and presented orally to USBM personnel.

Phase II effort included:

a. Laboratory investigation of dust reduction using commercially available charged spray equipment through:

    1. Direct measurement of dust levels

    2. Measurement of the charge on water clouds

    3. Correlation of dust reduction to mathematical model.

b. Mine site investigation of system performance and limitations.

The presentation of this report parallels the phased effort starting with the technology review through mine tests.

All raw data was submitted to the Technical Project Officer. Interested persons may obtain copies through him.

2. TECHNOLOGY REVIEW

2.1 Historical Review

The equipment for charged droplet removal of airborne dust is divided into two types. The first type is equipment that exists in the middle ground between wet scrubbers and electrostatic precipitators. The origin of this technology is frequently referenced to a 1944 patent by G.W. Penney. In this equipment, the dust is intentionally charged just as it is in an electrostatic precipitator. The charged dust is then brought into contact with charged water droplets where the dust is removed. This equipment is enclosed in a casing with inlet and outlet ducts.

The other charged droplet scrubbing device is operated in open space and is intended for control of fugitive dust emission or dust in large work spaces. This technology is an extension of open water sprays for knockdown of airborne dust. It is this technology that is the subject of interest to this program. The use of intentionally charged water sprays for reducing suspended dust concentrations started with work by Hoenig (1) reported about 1973. Hoenig and others (to be discussed later) have successfully applied charged water sprays to industrial dust pollution sources. Many of these sources are similar to dust sources found in underground mining, such as rock breaking, conveyor loading or chute dumping.

Considering the similarity of the mining situation to the industrial situation and the reported successes in industrial applications, an investigation of the feasibility of applying charged water sprays to underground dust sources was warranted. The remainder of Section 2 develops a picture of the state of the art prior to this program.

2.1.1 Fundamental Concepts

Water sprays, mists and fog are known to remove dust. In mining and industry, water sprays are used to control dust from a wide variety of sources. In nature, cloud droplets and raindrops are the important removers of dust from the earth's atmosphere.

Conventional water sprays (uncharged) rely principally on inertial impaction of smaller dust particles onto larger water drops. The water drop/dust particle(s) then settles out of the air due to gravity or other forces. While inertial impaction is a very important mechanism for uniting the dust particles with water drops, other mechanisms exist, such as:

a. Diffusion (Brownian motion)

b. Electric forces between charged particles.

While these are general categories, finer divisions are made, such as diffusion in the presence of evaporation (condensation) and electric forces between neutral particles in the presence of an external electric field (dipole forces).

The relative effect of these mechanisms depends somewhat on the size of the dust and drops. Particularly size sensitive is the inertial impaction mechanism. It is unfortunate that as the size of the dust particles drops below the 5 µm level (the respirable range), collecting dust by impaction becomes increasingly difficult. More energy must be put into the system to increase the relative velocity between the droplet and the dust and thus increase the probability of impaction.

This limitation may be partially overcome by placing an electrical charge of opposite sign on both the dust and the drop to produce an attractive force (Coulomb force) between them. The mechanism is similar to that of electrostatic precipitators (ESP), where an electric charge is placed on the dust particles and an electric field forces the dust particles to the walls of the system. For charged spray systems, the surfaces of the drops become the "walls" of the system.

Qualitatively, these mechanisms are easily understood. Quantitative understanding of all the details is more difficult. The qualitative understanding of the mechanism probably provided the insight for the design of several electrostatic scrubbers. These devices, while differing in design, use both wet scrubbers (mostly inertial impaction) mechanisms and electrostatic precipitator (electric force) mechanisms for cleaning a confined gas stream. Similar to ESPs, the dust is brought to a high level of charge, then contacted with the charged drops. The intentional dust charging and the enclosed gas stream differentiate this allied branch of technology from that of charged water sprays. Readers interested in electrostatic scrubbers will find further information from the references (2-4).

The subject of this program is the control of suspended dust in open space (not confined by duct work). Intentionally charged water spray (mist or fog) is directed into a dust cloud. No intentional charging of the dust is attempted. This raises the question of the charges on the dust. This question is considered in the following subsection.

2.1.2 Charge on Dust

Key to the concept of charged water sprays for controlling dust is the fact that the dust is naturally electrically charged. Workers in aerosol science (the science of fine liquid or solid particles suspended in air) have long recognized that most dust particles in a dust cloud bear an electric charge. Generally, the clouds possess a nearly neutral net charge (approximately equal numbers of positive and negative charges).

Work by Hoenig (5) and Hässler (6) has shown that finely divided mineral dust in the respirable size range shows a dominance of negatively charged particles. Hoenig measured the net charge by size range on a dust sample fractionated by a cascade impactor. Each stage of the impactor defines a dust particle size range. The apparatus was also able to detect the net charge on each stage. From this data, the net charge by size range in arbitrary units can be constructed. It was recognized that absolute charge units are perferred to arbitrary units; but the experimental procedures would have been considerably more difficult. Results of measurements using this apparatus do, however, provide insight into the charge characteristics of respirable dust. Most materials favor a net negative charge on the respirable size material. In private conversations, Dr. Hoenig indicated that high quartz/silica material always favors a negative charge in the respirable range. Magnetite ore (most Fe_3O_4) however, does show positive charge characteristics in the respirable range.

Hässler's apparatus and experimental procedures were more sophisticated than Hoenig's. The apparatus monitored the trajectory of a single dust particle which was settling due to gravity and subjected to a transverse electric field driven by an applied voltage with a saw-tooth wave form. The size of the particle was deduced by Stoke's settling velocity. The transverse acceleration and velocity due to the electric field was proportional to the charge on the particle. The trajectory of the particles was recorded photographically. From the photographs and the parameters of the experiment, the absolute charge and the particle size were calculated. Like Hoenig's findings, these results for quartz dust also show a dominance of negative charge.

Research indicates that respirable dust generated by underground mining operations is likely to carry an electric charge. High quartz and silica materials show a dominance of negative charge with a minor positively charged fraction. The physics of the mechanisms that charge the dust are not well understood nor have enough experiments been performed to accurately predict the expected magnitudes of charge on dust particles. At this time, common wisdom is that a charge of roughly 50 to 70 elementary units (an elementary charge unit is the magnitude of the charge on electron, 1.6×10^{-19} Coulomb) may be used as typical for respirable dust.

For removal of dust, the complement to charged dust is charged water spray. The following subsection describes the generic mechanisms for producing charged water spray.

2.1.3 Charging Water Sprays

Charged water drops may be produced in a variety of ways. This subsection qualitatively discusses the generic methods. Quantitative discussions are found in the references (7,8). Ramifications of the various approaches applied to dust control in underground, nongassy, noncoal mines are considered.

Basic techniques for charging water drops are:

a. Electrostatic induction

   1. With fluid nozzle grounded

   2. With fluid nozzle at high potential (contact charging)

b. Ion bombardment charging (ionized field charging)

c. Spray electrification.

Discussions of the mechanism are based on Figure 1.

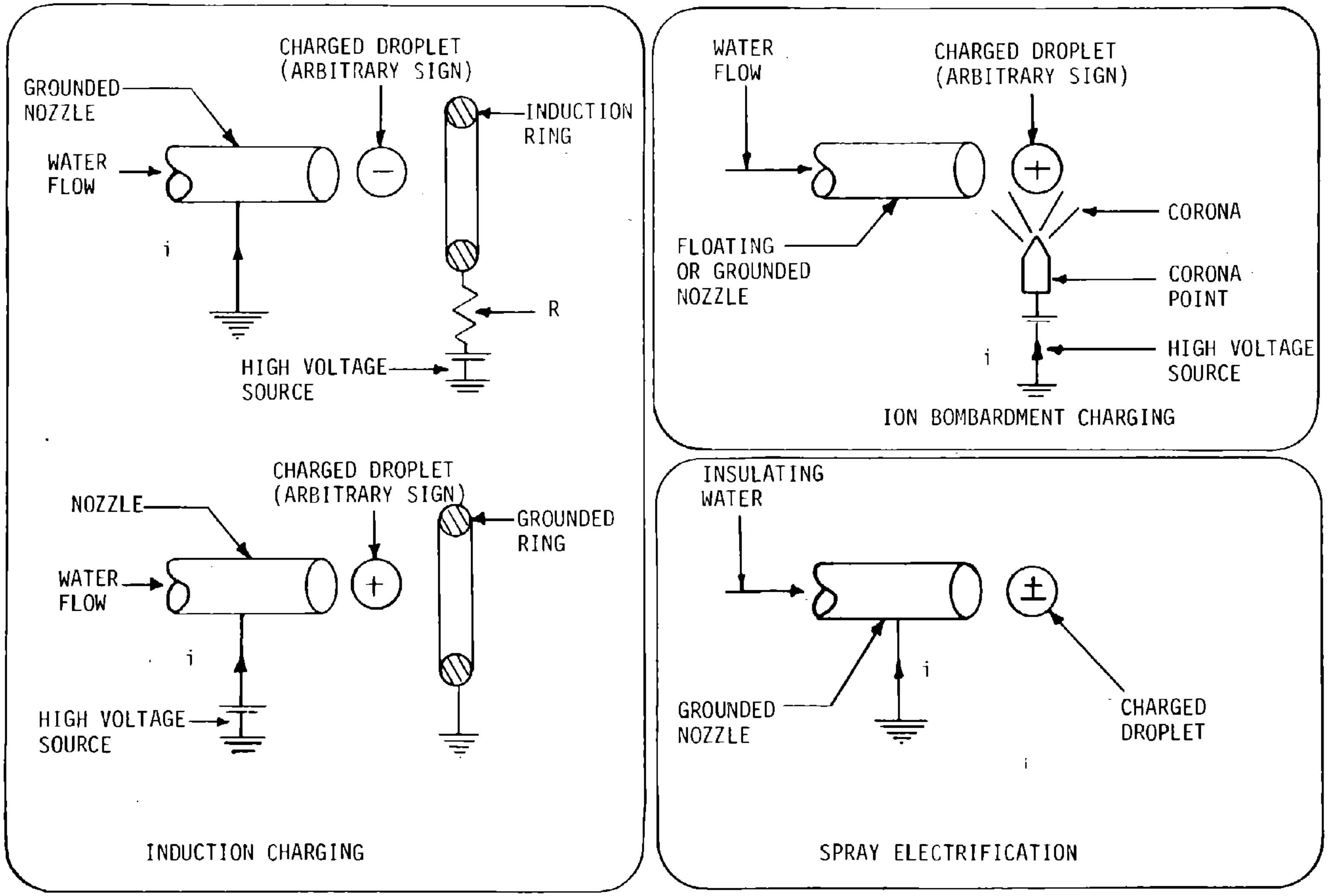


FIGURE 1. - Producing charged sprays.

Inductive Charging

Inductive charging has two forms. In one case, the charged drop is formed from a grounded nozzle, while in the other the charged drop is formed from a nozzle at high potential. Some people prefer to consider the second case a special technique called contact charging. For both cases, the charge is electrostatically induced on the surface of the water or other conducting liquid by an applied electric field before the drop separates from the bulk liquid. Upon separation, the drop carries off the induced charge. The magnitude of the charge on the droplet is determined by:

a. The strength of the electric field

b. The surface area of the drop.

Polarity of the drop is the same polarity as the nozzle. The strength of the electric field depends on the geometry around the forming water droplet and the applied voltage. Operating principles are the same whether the drop leaves from a grounded surface or one at high potential.

In operation, however, there are differences. Referring to Figure 1, for grounded-nozzle induction charging, an induction ring is held at high voltage. The droplet charging current is supplied from ground with no current flowing to the induction ring. That is, while there is potential on the induction ring, no power is supplied to the system by the high voltage (the energy for charging the drop is supplied by the fluid flow through the nozzle). This technique is attractive, since a safety resistor (shown as R in Figure 1) may be used in the high-voltage circuit to limit potentially dangerous inadvertent discharge. Since there is no current, R may be very large. In ordinary operation, the induction ring will be at high voltage. If a person or other conductor should contact the ring, however, current will try to pass through R. When this happens, most of the voltage drop from the power supply will be taken across R, resulting in very little voltage applied to the person.

This safety resistor is adequate for personnel protection, but capacitance in the system is large enough that the potential for a spark capable of igniting an explosive gas atmosphere may exist.

For the high-voltage nozzle (or spinning cup) case, the power supply is attached to the nozzle. In this system, the induction ring may not be present as part of spraying apparatus. The part of the induction ring in these cases is played by the grounded surroundings. Unlike the grounded nozzle case, the charging current to the drops is supplied from the high-voltage power supply. A safety resistor to protect personnel cannot be used. For this reason, a protective enclosure must be designed around the high-voltage surface to protect people from contacting the nozzle.

High-voltage nozzles are the type most commonly used for electrostatic spray painting. When electrically conductive water-based paints are used, however, provisions must be taken to electrically isolate the paint from ground or the nozzle will be shorted out. Charged water spray systems have the same problem. Hoenig (5) has been able to operate a high-voltage nozzle system for charged water spray by using a long plastic feed tube with air bubbles inserted into the water stream. This has worked with a grounded water source of potentials up to 20 kV.

An advantage of the high-voltage nozzle is that a larger charging current can be placed on the spray (5) than for the grounded nozzle case. For the grounded nozzle, there is a tendency at high charging rates for the spray to hit the induction ring. When this occurs, the drops that strike the ring exchange charge and leave the ring with a charge of opposite sign from those leaving the nozzle (the sign of the charge on a grounded nozzle formed droplet is opposite the sign of the induction ring).

Ion Bombardment

Ion bombardment or ionized field charging is the same mechanism as that used for charging dust particles in an electrostatic precipitator. The droplets are brought through a zone of ionized gas (gas molecules with a surplus or deficiency of electrons) from a corona discharge. Ions will attach to the droplets until sufficient charge (saturation charge) is deposited to repel further attachment of ions. The saturation charge will depend on the electric field strength and the corona discharge field strength. At present, no charged water spray systems have been reported to employ this mechanism.

Spray Electrification

Spray electrification works on the principle of charge dissimilarities at interfaces, the same mechanism that charges the dust particles. The physics of this process is the least understood of all charge droplet producing mechanisms. Experience has shown, however, that this is an effective mechanism for producing charged droplets. Hassler (6) has used this mechanism as part of a charged droplet scrubber. The primary disadvantage of this method is the low conductivity (deionized) water required for effective charging. The necessary deionization equipment with attendant servicing requirements make this method unattractive for underground use.

2.1.4 Safety Aspects of Charged Water Sprays in Nongassy Mines

The most obvious potential safety hazard associated with charged water spray for dust control is personnel safety in the presence of high-voltage equipment. The design of any equipment taken underground must be such that personnel cannot contact high-voltage components that are not protected by suitable current limiting resistors. Further, the equipment must be designed such that damage incurred during the mining operation does not leave high-voltage parts exposed.

For nongassy mines, the electrical safety hazards of equipment may be eliminated by suitable design. Further comments on this are found in subsections 2.2.1 and 2.2.2 on commercially available charged spray equipment.

Charged water droplets themselves are as harmless as ordinary water spray. However annoying electrostatic shocks may be experienced by individuals in the vicinity of charged sprays. These shocks are similar to frictional electrostatic shocks felt in dry winter climates. Shocks occur due to accumulation of charged droplets on insulated persons. The individual feels a shock on contacting a grounded conductor.

2.1.5 Experience with Charged Sprays, Fogs, and Mists for Dust Control

Hoenig (1) is the first researcher of record to investigate the use of open charged water sprays for reducing fugitive dust. Some of his earlier work was supported by a grant from the U.S. Environmental Protection Agency (EPA). Ransburg Corporation (principally an electrostatic spray painting equipment manufacturer), with Dr. Hoenig as a consultant, also developed a line of charged water spray equipment (Fogger I and Fogger II). Ransburg Corporation sold the Fogger line to Ritten Corporation, Ltd. in November 1978 (9). Dr. Hoenig continued a relationship with Ritten Corporation until March 1981. During this association, Dr. Hoenig performed and reported laboratory work as well as some field trials, supported by the commercial companies (1,5,9).

EPA has continued to be interested in using charged water droplets for controlling fugitive dust that includes a respirable fraction. The EPA's Environmental Research Laboratory currently has two on-going contracts for evaluating charged droplet effectiveness. This work is being monitored by Dr. Dennis C. Drehmel, EPA, Research Triangle Park, NC. These programs are particularly interesting as the application has much in common with the control of dust in the underground mine environment.

Field tests were performed on a primary crusher in a sand and gravel operation in Connecticut using the Fogger IV, shown in Figure 2, a commercially available charged sprayer from Ritten Corporation. The Foggers consisted of a grounded air-atomized spray nozzle with a 4-in. diameter high-voltage induction ring. The 5-hp fan shown in Figure 2 produces a velocity of 10,000 ft/min through the induction ring, which carries off the charged droplets. Brookman (10) infers that each drop carried 8×10^4 elementary charges at 20 gal/hr assuming an average droplet size of 60 μm diam.

These tests, reported by Brookman (10) were conducted on an outdoor crusher fed by trucks. The plan view of the crushing facility is shown in Figure 3. Two Ritten Fogger IVs were tested at various locations around the crusher pit. High-volume samplers (hi-vols) were placed downward of the pit. The Fogger IVs directed the charged fog into the dust plume. Test equipment positions are shown in Figure 4. It was found that the air blast from the Fogger IVs was strong enough that it competed with the wind in dispersing the dust plume. For this reason, baseline measurements were determined with the Fogger fans operating, but no water sprayed.

Brookman (10) indicates dust concentration reductions of about 65 to 75 percent in the respirable size, with reductions independent of the sign of the charge on the droplets. The 65 to 75 percent reduction reported seems somewhat optimistic; from examination of the results, 50 to 60 percent appears to be somewhat more representative. This will be discussed later in this section. Uncharged drops produced about a 30 to 40 percent reduction in the dust concentration from baseline conditions.

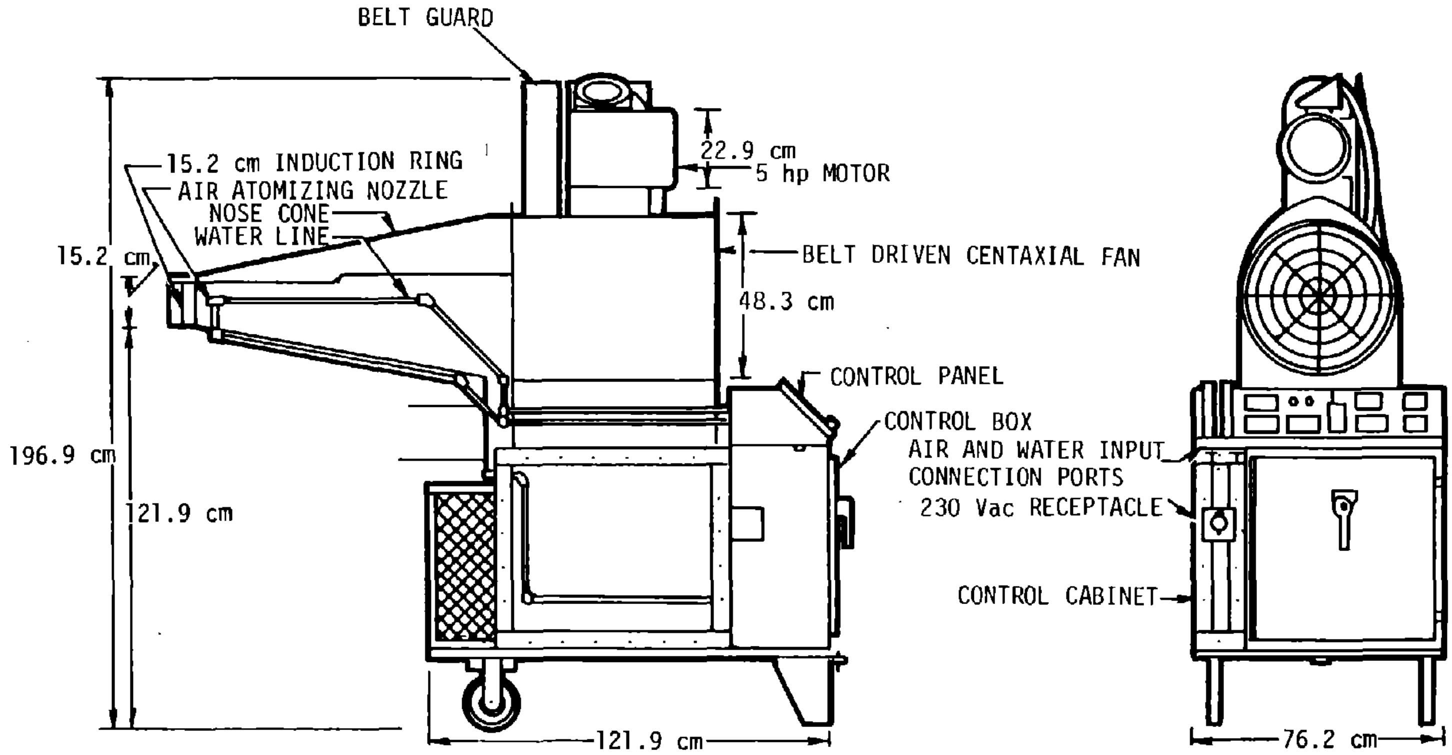


FIGURE 2. - Schematic of the Ritten Corporation's Fogger IV. (10)

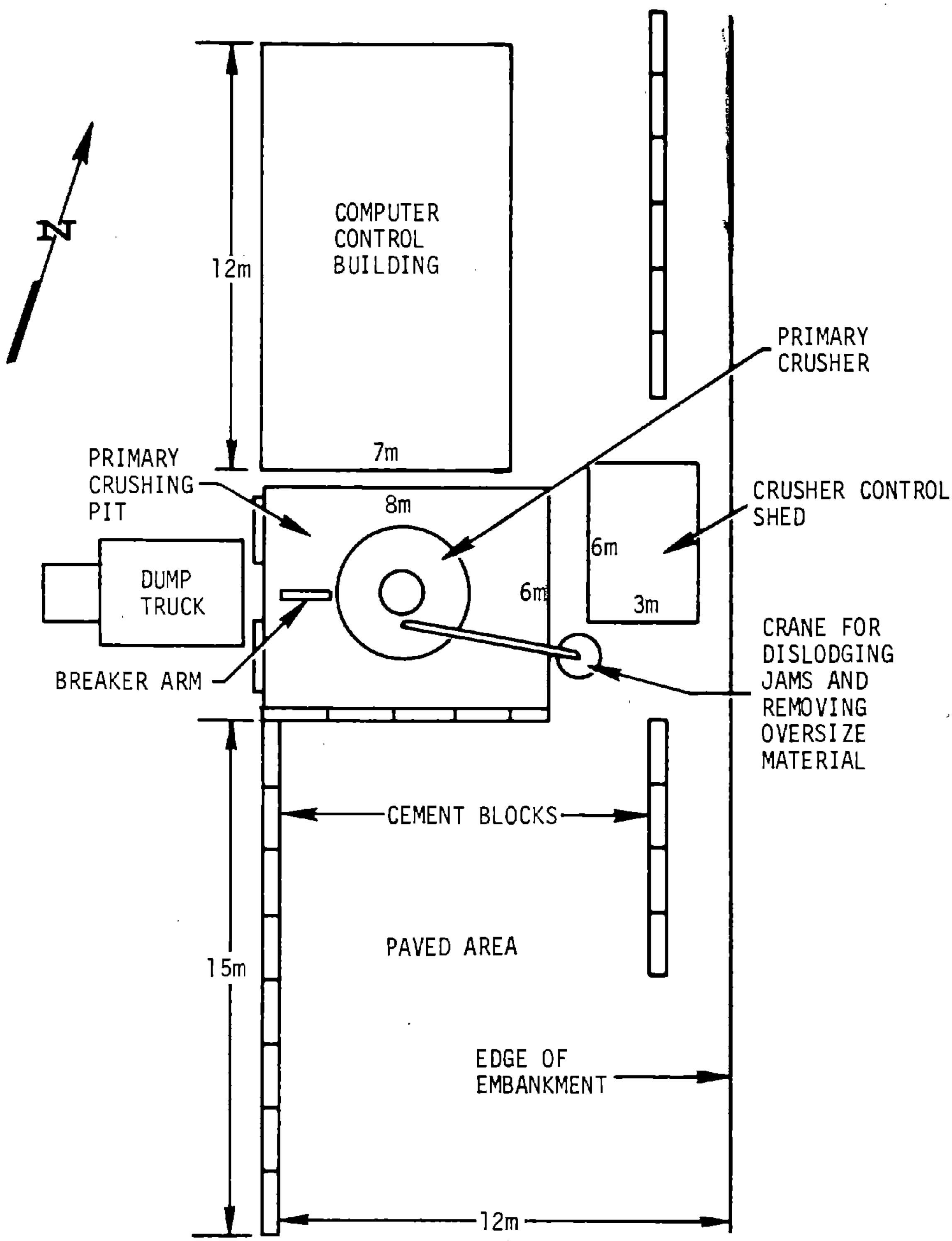


FIGURE 3. - Primary crusher plot plan. (<u>10</u>)

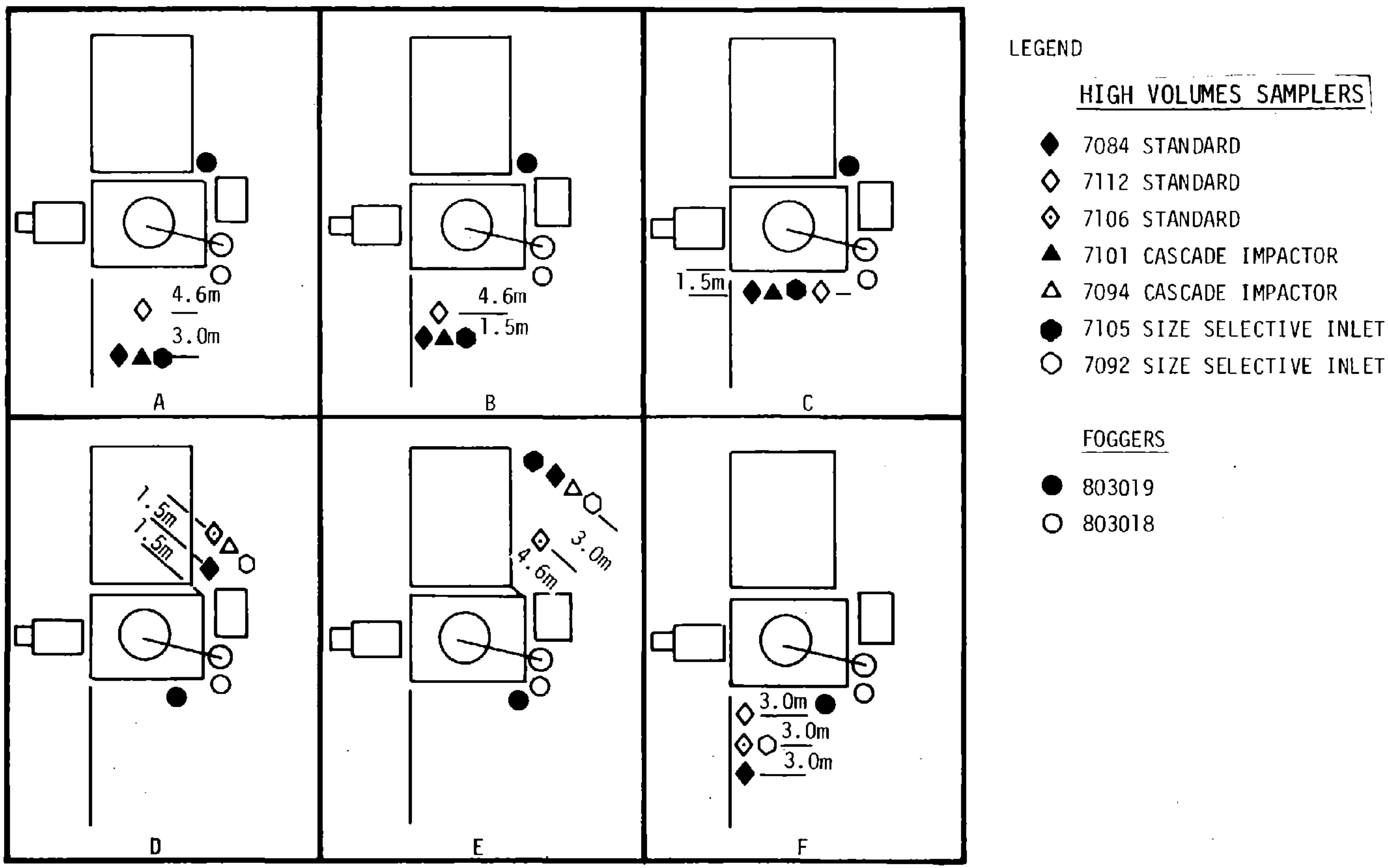


FIGURE 4. - Test equipment positions. (10)

The second EPA fugitive dust control study using charged droplets has been preliminarily reported on by Mathai, et al. (11). In this study, a new type of charged droplet device called a Charged Fog Generator (CFG) has been developed. Figure 5 shows a schematic of the device which is a modified Ray Oil Burner. A cup, spinning at 3600 rpm, is used to atomize water. Water is released into the cup which forms a thin film over interior surfaces due to centrifugal force. At the rim of the cup the water film is broken into droplets by the action of centrifugal force and the air blast from the fan flowing over the outside of the cup. This is a standard atomizing technique used in oil furnaces, paint spraying and other industrial applications. Charging current is placed on the water through a connection between a 15-kVdc power supply and the water line. This makes this system a high potential nozzle induction charging system. Since the water supply line is at high potential, the water supply must be electrically isolated from ground.

For this charged droplet device, Mathai, et al. report a typical charge to mass ratio of 1.2×10^{-6} C/g with a 200-μm mass median diameter drop. This implies a typical 200-μm drop charge of 3×10^{7} elementary charges. The fog emitted covers a volume of 16 to 24 m^3, and the water flow rate is variable from 8 to 70 liters/hr.

The test site was a belt loading hopper at a Wyoming Bentonite Plant (see Figure 6). The CFG and the sampling equipment were located as shown. The cyclone separator of the sampling train passed less than 7.33 μm particles for collection. Baseline conditions were taken with only the fan of the CFG operating (no water flow). Experimental tests were made with charged and uncharged fog. The charged fog was presumably positive, as reference was made to the effect that negative fog tests were planned.

Mathai, et al., results indicate that charged drops reduce dust concentration for the 7.33 μm particles about 63 percent. Uncharged droplets produced about a 30 percent reduction from the baseline.

Examination of data from both Mathai, et al., and Brookman shows a surprising consistency when the differences in processes, charge droplet equipment, and sampling are considered. Figure 7 shows side-by-side plots of both sets of data. From this emerges a pattern of scattered results, with charged droplets reducing

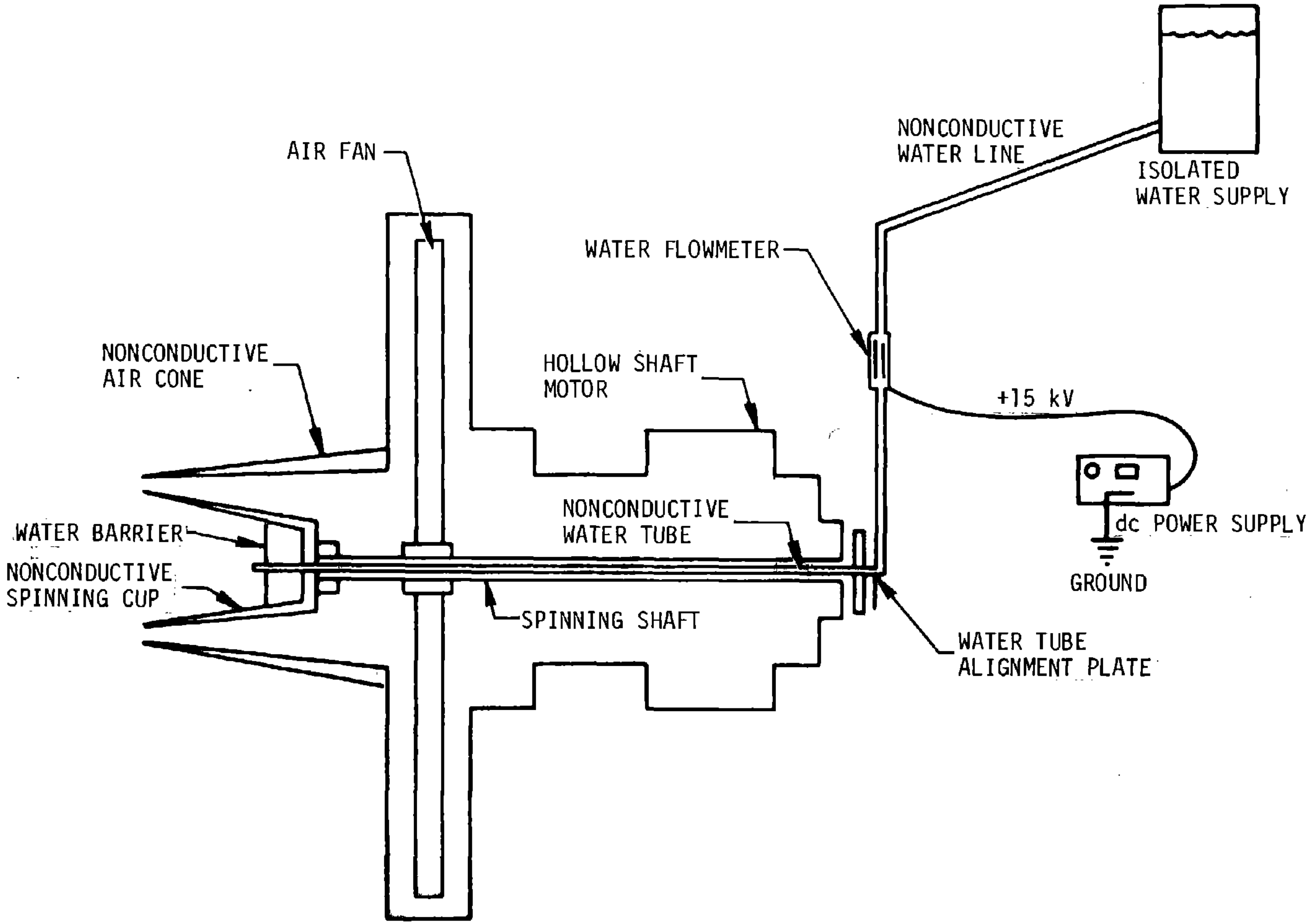


FIGURE 5. - Schematic diagram of the CFG. (11)

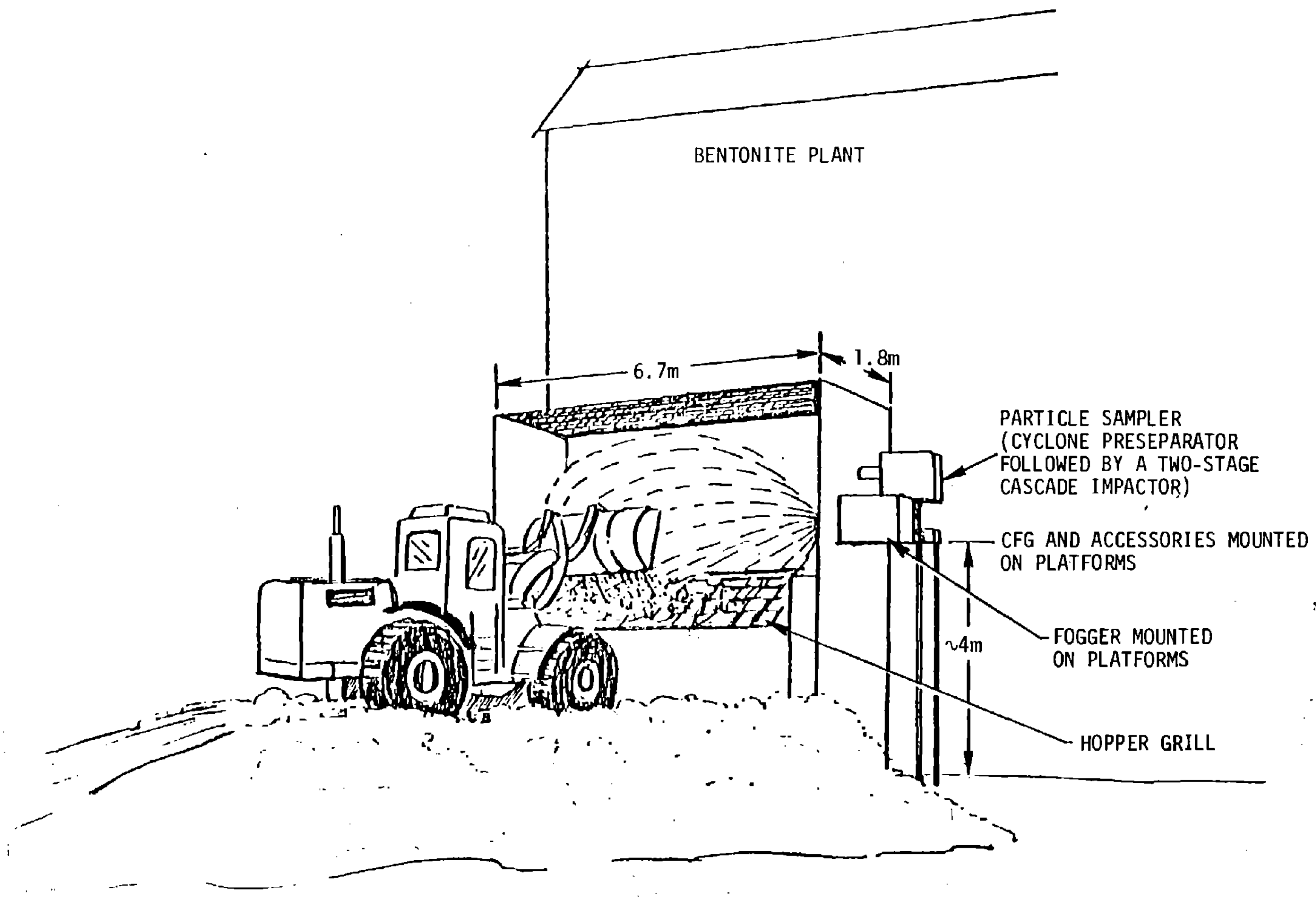


FIGURE 6. - Location of CFG and particle sampler on the side of the hopper. (11)

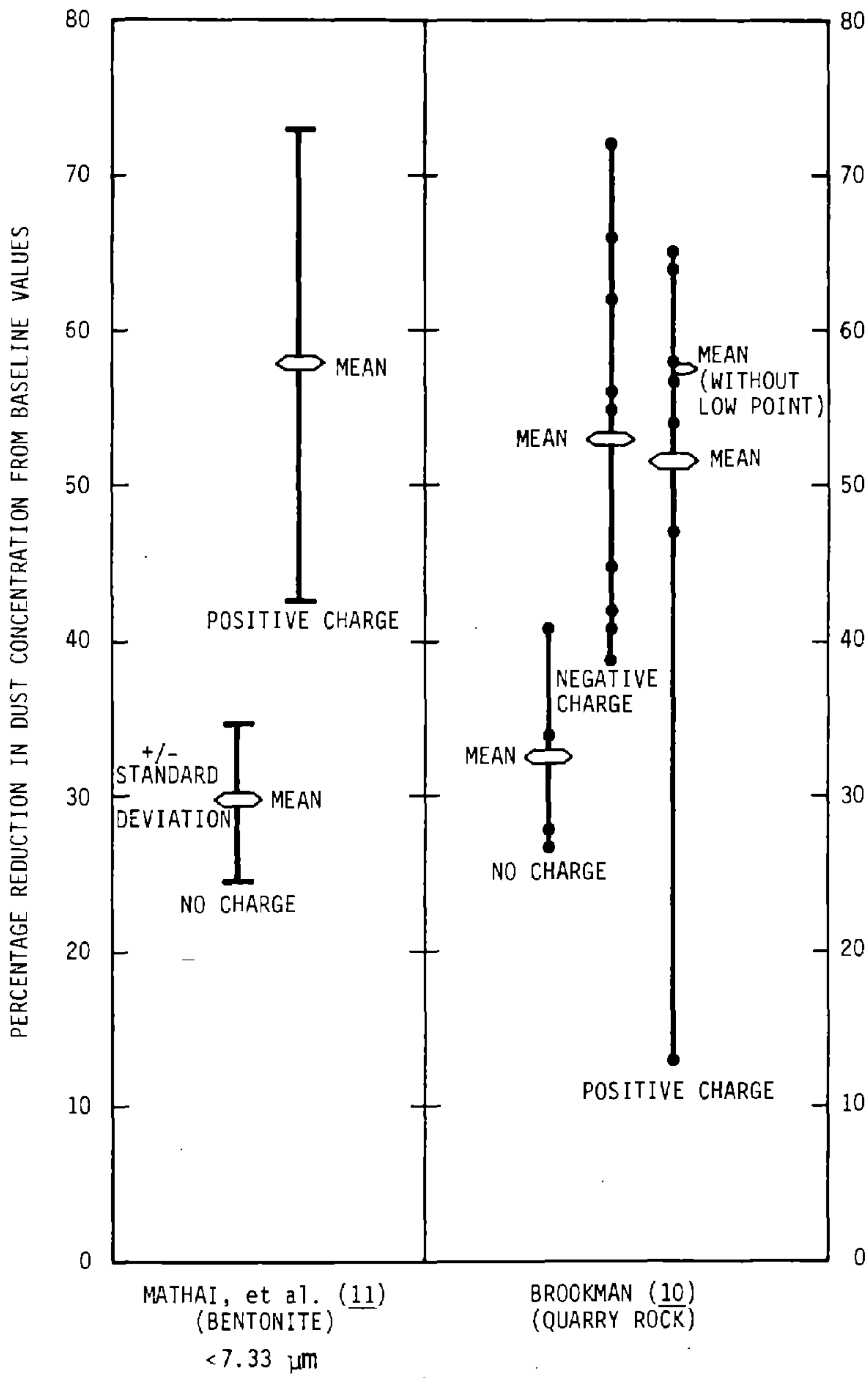


FIGURE 7. - Results of field tests performed for EPA.

dust concentration roughly 55 percent, while uncharged droplets reduced dust concentration only 30 percent. While this data base is limited, it provides a general indication of the magnitude of dust control effectiveness expected from charged water sprays. Further, it is likely that optimum conditions for dust control have not been attained.

2.1.6 Theoretical Considerations

Interest in the collection of small particles by charged droplets originated with workers in cloud physics. Later these workers were joined by investigators who were interested in air cleaning using charged droplets.

Wang, et al. (12), delineates the history of theoretical considerations for the collection of fine dust particles by water drops. They trace the theoretical work directed toward accounting for the various mechanisms that bring single drops and dust particles together. Various investigators (3,12-16) have considered the following mechanisms:

a. *Inertial impaction* - Separation of dust from air streamlines due to inertial forces, such that a collision with the droplet occurs as shown in Figure 8. Investigations have included geometric considerations of interception that accounts for the radius of the dust particle.

b. *Brownian diffusion* - The random movement of dust particles due to molecular collisions. These random motions separate the dust particles from streamlines around the droplet, increasing the probability of the dust particle contacting the droplet surface.

c. *Electrostatic attraction* - The moving together of dust and droplet due to attractive electric forces. As shown in Figure 9, this may be due to charges of opposite sign on the dust and droplet or similar charges on the dust and droplet in the presence of an electric field.

d. *Phoretic forces* - The motion of a dust particle caused by unbalanced momentum flux of air molecules over its surface. This is due to gradients, such as:

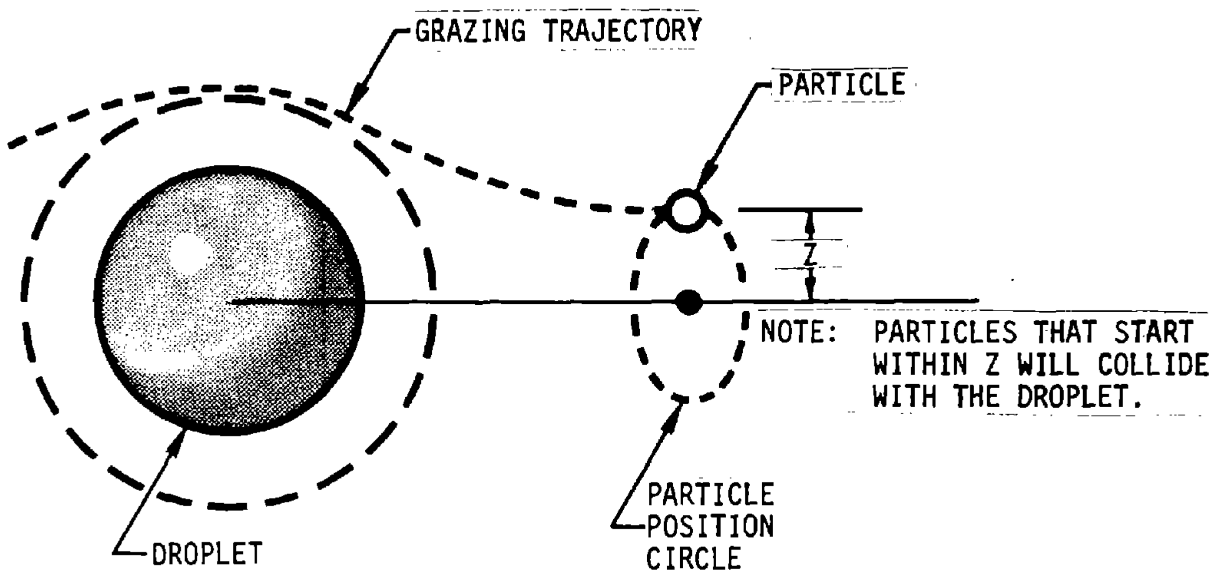


FIGURE 8. - Droplet-particle interaction model. (3)

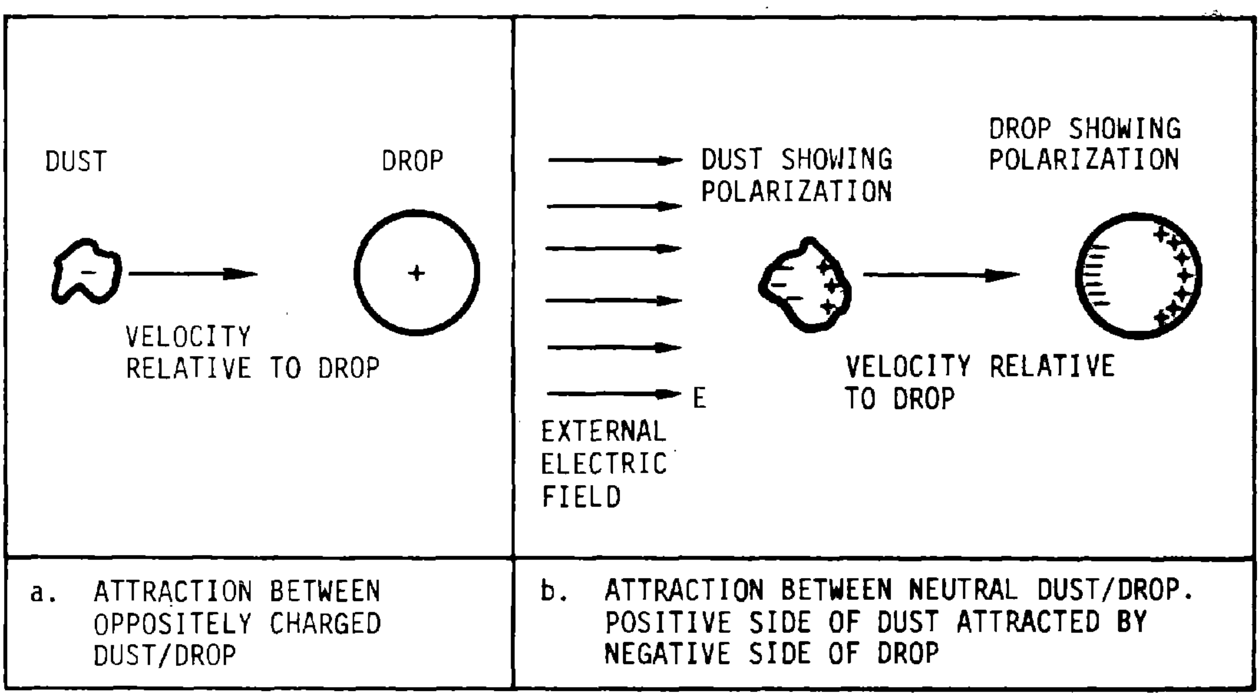


FIGURE 9. - Electrostatic attraction between dust and water droplet.

1. *Diffusiophoresis* - Particle motion in a gas concentration gradient such as the water vapor concentration gradient near an evaporating water droplet

2. *Thermophoresis* - Particle motion in a temperature gradient.

The results of all these investigations indicate that charge on the drops and the presence of an external electric field aid the respirable dust collection efficiency of *single* drops. References (15) and (16) conclude that collection efficiency is larger for small, highly charged drops. This is because the electrical attraction for dust particles dominates the inertial mechanism. Hence a slower-settling, smaller drop sweeps a larger zone of particles (particles assumed charged) than a faster-settling, larger drop. The slower movement allows more time for the electrostatic effects to act.

From these analyses, however, no simple rules-of-thumb emerge for charged spray dust collection. There is a lack of experimentation that correlates with theory. A difference of opinion exists regarding the effects of relative humidity (RH) or evaporation of the droplet. Some calculate that during droplet evaporation (low RH), diffusiophoresis will decrease the collection efficiency of the drop. A more rigorous analysis by Wang, et al. (12), indicates that as the drop evaporates its temperature decreases and the resulting thermophoresis increases the collection efficiency of the drop.

At this time, these analyses have not aided the engineering design of systems for dust removal by charged water spray. The single droplet efficiencies have not been extended to consider effects of interaction of clouds of charged dust and drops.

Melcher, et al. (17), have developed an analytical model for systems of charged particles and droplets based on characteristic times. Based on these characteristic times, collection efficiency of various *systems* (not single drop efficiencies) can be estimated. Systems for electrostatic removal of particles are classified in Figure 10. For charge sprays, the possible electrostatic removal mechanisms are:

a. *Space charge precipitation (SCP)* - Dust of the same sign as the net space charge is self-precipitated due to mutual Coulomb repulsion.

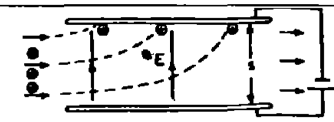
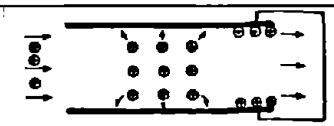
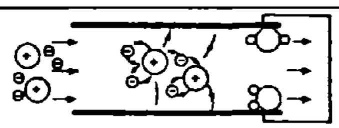
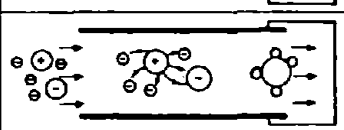
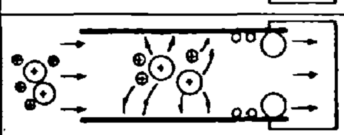
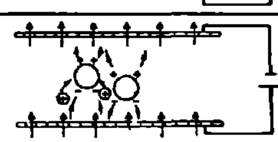
SYSTEM	CONFIGURATION	PARTICLE CHARGE	DROPLET NET CHARGE	AMBIENT FIELD	CHARACTERISTIC TIME
ELECTROSTATIC PRECIPITATOR ESP		UNIPOLAR	NO DROPS	IMPOSED	τ_{pc}
SPACE-CHARGE PRECIPITATOR SCP		UNIPOLAR	NO DROPS	SELF	τ_a
SELF-AGGLOMERATOR SAG		BIPOLAR	NO DROPS	NONE	τ_a
CHARGED DROPLET SCRUBBER CDS - I		UNIPOLAR (+ OR -)	UNIPOLAR (- OR +)	SELF	τ_c, τ_R
CHARGED DROPLET SCRUBBER CDS - II		UNIPOLAR OR BIPOLAR	BIPOLAR	NONE	τ_c, τ_R
CHARGED DROPLET PRECIPITATOR CDP		UNIPOLAR	UNIPOLAR	SELF	τ_c, τ_R
ELECTROFLUIDIZED AND ELECTROPACKED BEDS EFB AND EPB		UNIPOLAR OR BIPOLAR	NONE	IMPOSED	τ_c (BASED ON HALF-CHARGE)

FIGURE 10. - Classification for electrostatic removal of particles.

b. *Charged droplet scrubber (CDS-I)* - The charged droplets collect dust of opposite electrical sign. This is the system usually considered for charged particle removal by charged droplet.

c. *Charged droplet precipitator (CDP)* - This is similar to the SCP, except that droplets with the *same* sign as the dust are injected. Coulomb repulsion precipitates the dust particles out of the system. This may be enhanced by ions that are artifacts of the charged spray equipment attaching to dust particles, as depicted in Figure 11.

The electrical time constants in these systems are:

1. Self-precipitation characteristic time of the droplets,

$$\tau_R = \frac{\varepsilon_o}{NQB}$$

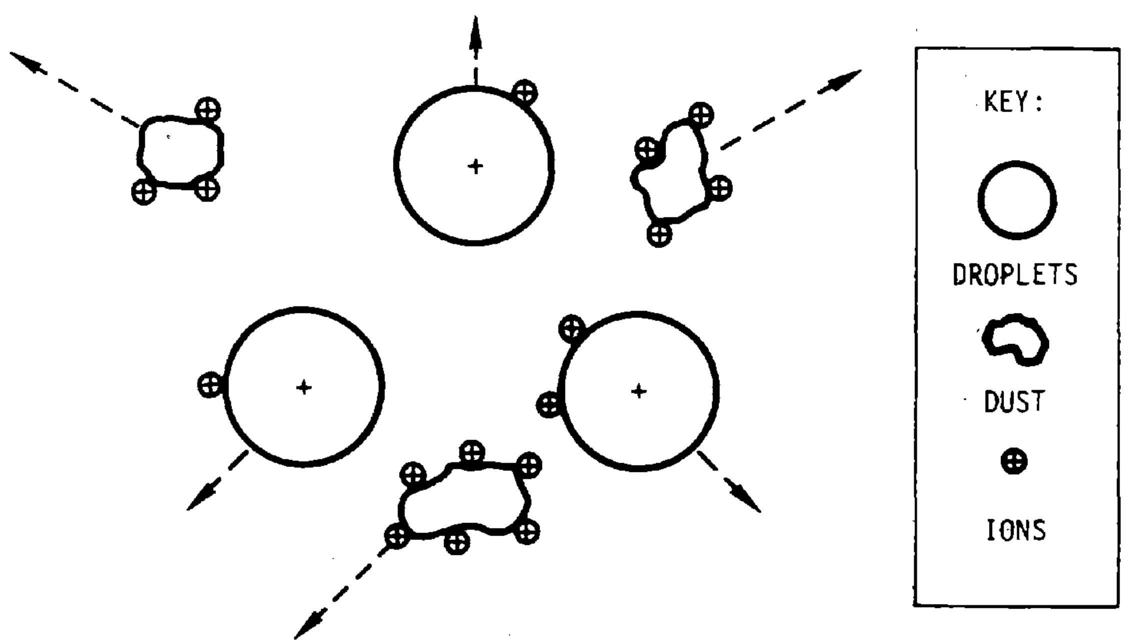


FIGURE 11. - Ion enhanced CDP.

2. The collection characteristic time for the dust to attach to the charged drops,

$$\tau_c = \frac{\varepsilon_o}{NQb}$$

3. The precipitation characteristic time for the dust to be repelled from the system by drops of the same sign,

$$\tau_c = \frac{\varepsilon_o}{NQb}$$

4. The self-precipitation characteristic time for the dust to be repelled from the system,

$$\tau_{pc} = \frac{\varepsilon_o}{nqb}$$

where the nomenclature is:

b = the mobility (velocity in a unit electric field) of the dust (m^2/sV)

B = the mobility of the drops (m^2/sV)

n = the number density of particles ($1/m^3$)

N = the number density of droplets ($1/m^3$)

q = the charge per dust particle (Coulomb)

Q = the charge per droplet (Coulomb)

ε_o = 8.85×10^{-12} **(farad/m).**

To determine scrubbing efficiency, these electrical time constants are compared to the residence times of the dust and droplets in the scrubbing zone. Using this method, Melcher, et al. (17), were able to correlate their theoretical predictions for efficiency experimentally in the laboratory. The application of this method is used in this report to attempt a mathematical estimate of control effectiveness. This is discussed in subsection 2.3.

2.1.7 Concluding Remarks on Historical Review

The use of open charged water sprays to control respirable dust is less than a decade old. There is lack of theory correlated to experiment. For this reason, the technology is considered immature. The capabilities and limitations are only vaguely understood. The work of Hässler (6) seems to be unique in quantitative determination of natural charge on dust particles, hence little is truly known about the character of the dust tested. Theory for the removal of suspended dust by water drops, including electrical effects, has, for the most part, advanced without the support of experiments, the exception being work by Melcher, et al. (17). The independent field tests by Brookman (10) and Mathai, et al. (11), indicated the effectiveness of using charged water spray mist or fog for control of respirable dust (see Figure 7). It is unlikely that this technique is optimized, but it is clear that a demonstrable effect exists that can be used to reduce dust concentrations.

Commercial charged water equipment exists for dust control. This is reviewed in the following section.

2.2 Charged Water Spray Equipment Review

Producing charged water droplets using the techniques described in subsection 2.1.4 is a relatively simple matter. For underground use, however, even for pilot testing, the equipment must be suitably robust and present no personnel hazards.

Two companies have supplied commercial charged spray equipment for dust control. They are:

a. Ritten Corporation, Ltd.

b. Keystone Dynamics, Incorporated.

Recent information indicates that Sonic Development Corporation of Mahwah, NJ has bought the Ritten technology. Inquiries for information should be directed there. Equipment for these companies is discussed in following subsections.

Additionally, Sonic Development Corporation produces a sonic atomizing nozzle that was reported by Hässler (6) to produce autogenous electrically charged fog when deionized water is used. While Sonic Development circulates reprints of Hässler's work, their equipment is not currently available for industrial application. The equipment reported by Mathai, et al. (11) is under evaluation by AeroVironment as a potential commercial product. At present, AeroVironment will build units on a custom developmental contract basis; however, the equipment is not sufficiently developed to ensure safety for unskilled personnel.

Selection of charged spray equipment for testing was limited to the commercially sold units. For Phase II testing, the Keystone Dynamics Dustron unit was selected. Reasons for this selection are discussed in the following subsections.

2.2.1 Ritten Corporation Equipment

The Ritten Corporation is no longer taking orders for their charged spray equipment. Until recently, however, they have promoted a line of four models of charged spray equipment called "Foggers." These units use air atomizing spray nozzles with electrostatic induction rings to charge the droplets. The Fogger IV is shown in Figure 2 and was used by Brookman (10) in tests described in subsection 2.6. Table 1 shows the brochure information for Brookman (10). Foggers III and IV employ fans to blow the charged droplets into the dust cloud. These units are too large to be considered for underground use.

A Foster-Miller project engineer visited Ritten Corporation and discussed application of their Fogger line to the underground dust control problem. Ritten Corporation's recommendation was to use Fogger I units (see Figure 12). Foster-Miller's engineer examined the equipment and identified the following problems:

a. There is an exposed charging ring at a potential of 6 kV. The ring could cause a severe shock, and, because it is believed there is no current limiting resistor in the circuit, may even be capable of causing life threatening shock.

b. There is no visual indication to show whether the charging ring is energized.

TABLE 1a. - Ritten equipment

Fogger	Type of spray	Water consumption (up to) (gal/min)	Air pressure (up to) (lb/in.^{2})	Auxiliary fan discharge velocity (ft/min)	Induction ring charging voltage (kV)	Power consumption
I	Air atomized	1/4	110	None	6	30W
II	High-pressure water	1/2	-	None	6	30W
III	Air atomized	1/3	Not known	7,000	Not known	Not known
IV	Air atomized	2/3	125	10,000	8	8 kW

TABLE 1b. - Dustron equipment

Model	Type of spray	Water consumption (up to) (mil/min)	Air pressure (up to) (lb/in.^{2})	Auxiliary fan discharge velocity (ft/min)	Induction ring charging voltage (kV)	Power consumption
100	Air atomized	300	80	None	8	25W

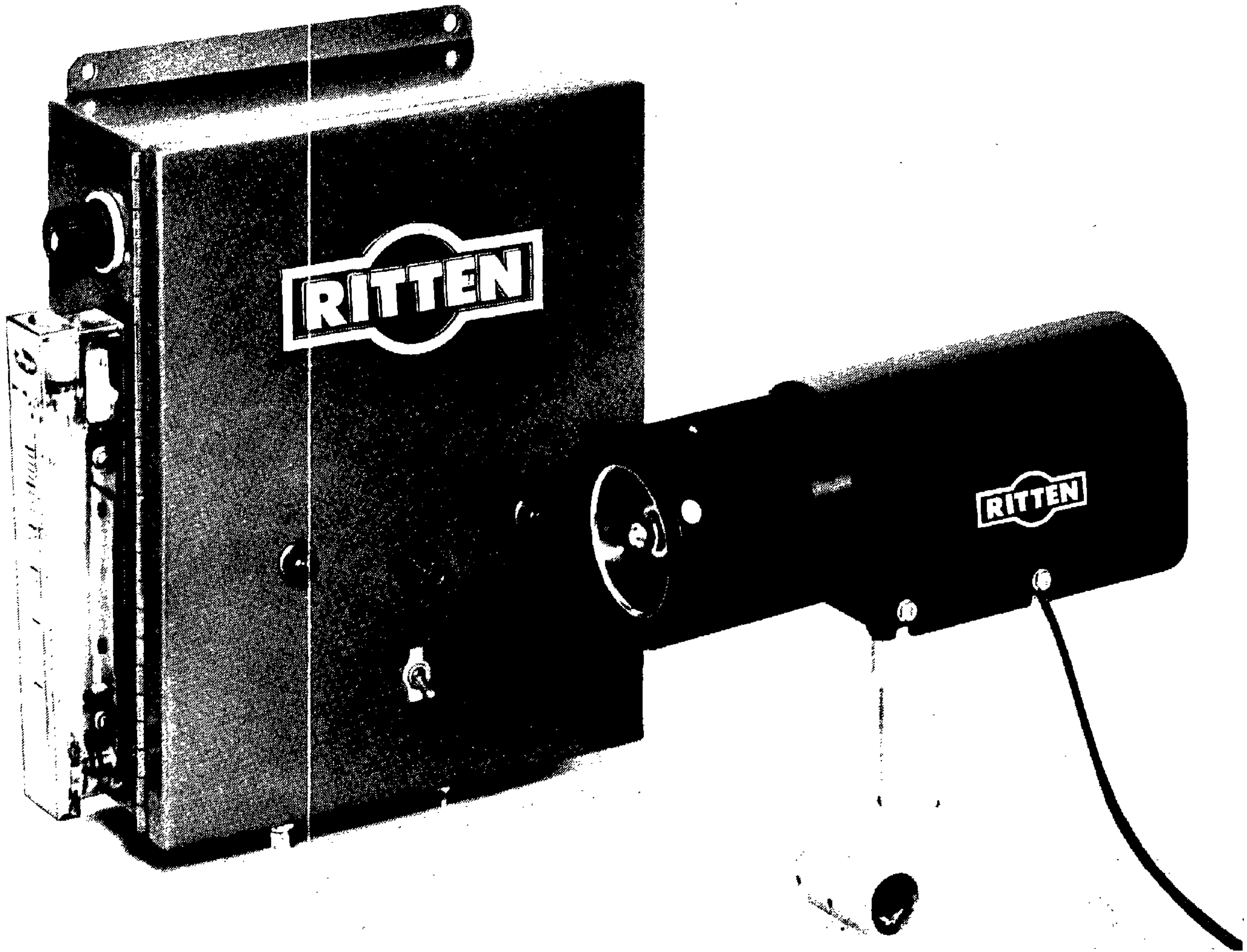


FIGURE 12. - Ritten Fogger I.

c. The power supply to the fogger head is through an unprotected lightweight cable. If this is damaged it can expose personnel and equipment to 6 kV.

d. The fogger head when operated in a damp atmosphere can, under certain conditions, short circuit from the induction ring to ground causing the unit to burn out.

e. The control case contains all three services for the fogger head. It is not considered good practice to mix water and high-voltage electricity in the same case.

f. The control box examined did not have labels on switches or indicator lights to inform an operator of their functions. Neither was there a label on the fogger head to warn of the high voltage.

It was decided, after consideration of these problems, that the Ritten equipment should not be used for an underground demonstration because of excessive risk of personnel injury and potentially unsatisfactory reliability of the equipment.

2.2.2 Keystone Dynamics, Incorporated Equipment

The Dustron Mist Emitter, manufactured by Keystone Dynamics, Inc., Ardmore, PA, was the only charged spray equipment commercially available at the time of equipment selection. The principal of Keystone, Mr. E. Hastings, is a former employee of the Ritten Corporation and the Dustron unit operates in a manner similar to Ritten Corporation's Foggers. The dustron has an air atomizing nozzle with an induction ring for charging the droplets.

Foster-Miller's project engineer visited the Keystone plant and inspected the equipment. The Dustron equipment has several improved design features which make it suitable for industrial applications. More robust packaging would be desirable for general underground use, however.

The Dustron consists of distinct modules, as shown in Figure 13. This approach separates the water and the high-voltage supply. Details of each module are described below.

Power Supply

This is a well-mounted, dustproof and waterproof enclosure (NEMA 4 rated) that contains a low-voltage supply. The electrical input is 115 Vac, 60 Hz, 25W, and it converts the supply

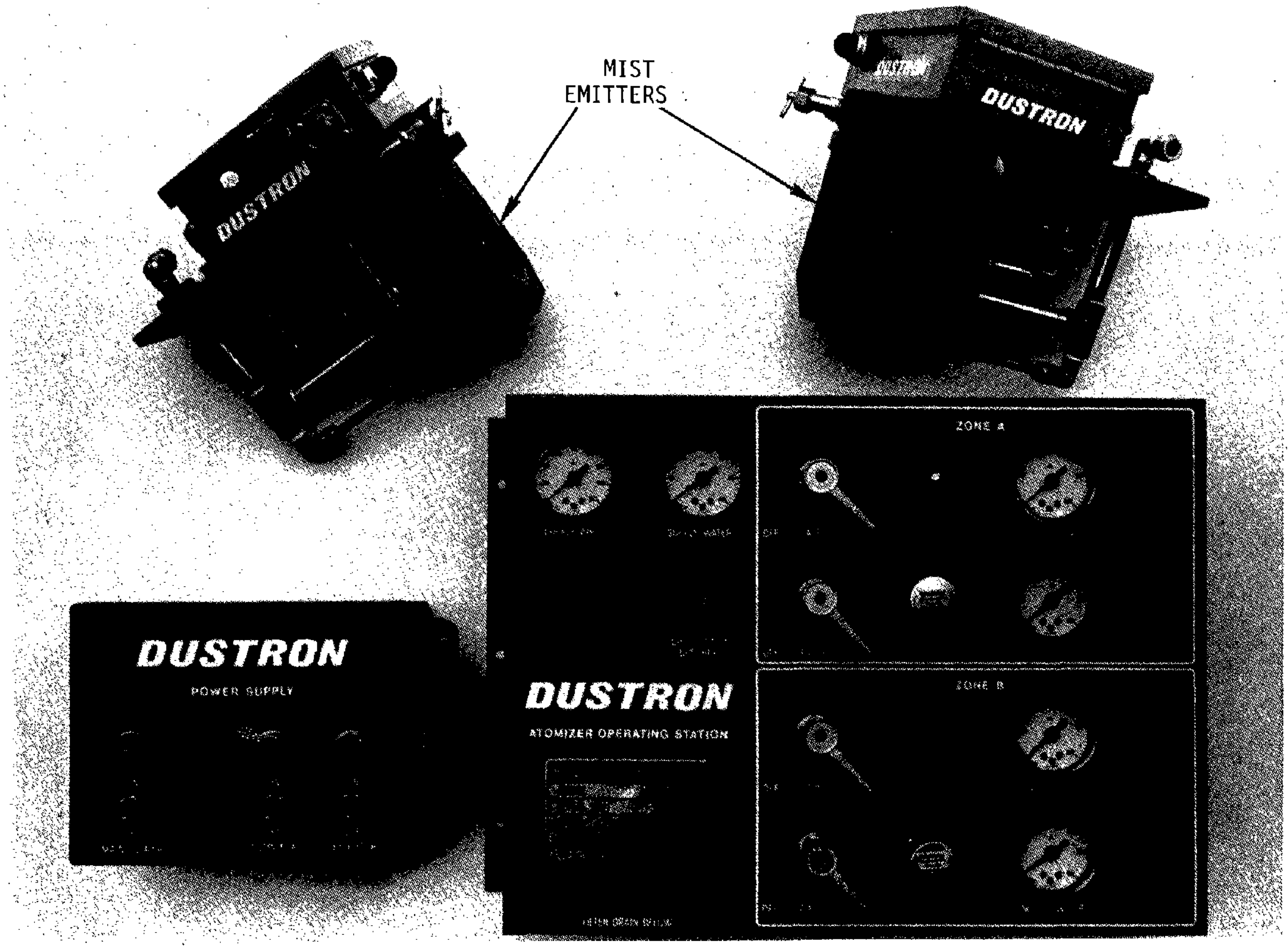


FIGURE 13. - Components of the Dustron.

to 24 Vdc. The unit is usually used to control two mist emitters. It is fitted with display lights to indicate input power and output power. Connectors to the unit are waterproof.

Atomizer Operating Station

The operating station is a wall-mounted enclosure from which the air supply and water supply to the emitter are controlled. It is clearly labelled and is fitted with gauges to permit accurate control of the water and air. The station requires a supply pressure of at least 60 $lb/in.^2$ for water and an air pressure of 80 $lb/in.^2$. The station contains filters for both air and water, but it is likely that these will require some upgrading for mine use.

Mist Emitter

The emitter consists of a phenolic block in which the induction charging ring is encapsulated. An air atomized nozzle is mounted along the centerline of the block. On top of the block is a waterproof enclosure into which there is a 24 Vdc, 5W input. The voltage is converted within the enclosure to about 8 kVdc and supplied through internal connections to the charging ring. Certain design features of the emitter, which are not obvious, do have some specific benefits:

a. The supply to the head is 24 Vdc. Damage to the supply cable will not endanger personnel.

b. The 8 kV induction ring to charge the droplets is encapsulated, preventing personnel from receiving electrical shocks.

c. An annular air gap exists between the head and ground. The air is bled off the supply to the nozzle through this annular gap at a rate of about 2 ft^3/min. This feature is to prevent the unit from shorting to ground when the head becomes saturated with mist.

d. The electrical enclosure is waterproof (NEMA 4) and is fitted with waterproof connectors and a light that indicates when the emitter is powered.

The mist emitter also differs from the Ritten Fogger in that the nozzle is suspended in a hole within the phenolic block. Upon activation, the action of the spray and compressed air from the nozzle induces an airflow through the spray. The Ritten unit has the spray mounted against a bulkhead within a tube. The air atomizing nozzle used for the majority of applications is a Spray Systems Co. 1/4 J-4 using a 601000 fluid cap and a 120 air cap. By using different air caps and varying the compressed airflow and water flow, a wide variety of sprays and droplets sizes can be produced.

The 1981 cost of the Dustron units are as follows:

Dustron Mist Emitter, Model 100	$1,475
Atomizer Operating Station, Model 200	1,025
Power Supply, Model 300	425
Total system with two emitters	$4,480

Keystone provided a Dustron unit free of charge for Foster-Miller's evaluation as part of this program. Several days of testing were performed in Foster-Miller's dust booth. Through these tests, which were primarily environmental in nature, it was found that:

a. The units tolerated a high dust and mist environment without adverse effects such as high-voltage short-circuiting.

b. The phenolic block containing the induction ring could be touched while wet with the ring energized without feeling electric shock.

The Dustron units as presently configured are suitable for operation at some locations underground. At present, the cases and cabinets are not sufficiently robust to be mounted where mining equipment could cause damage, however. This equipment could be "hardened" for more general mine use.

2.2.3 Other Charged Spray Equipment

In searching for charged spray equipment, several electrostatic spray painting equipment manufacturers and several spray nozzle firms were contacted by telephone. Some novel features were discovered which could be incorporated in future developments of dust control charged spray equipment.

Speeflo, of Houston, TX, has a very novel design of an electrostatic paint gun that has no external electrical power requirements. The electrostatic gun has a small 9-ounce cartridge that incorporates an air turbine generator, a miniature high-frequency oscillator and advanced voltage multiplier circuitry. The output from this tiny unit is 55 kVdc with an output current of 100 μA. The air requirement is up to 18 ft^3/min at 70 lb/in.^{2}. This device could be used in a charged water spray device, obviating the requirement for electric power. Under mining conditions where electric power is not available or its application is undesirable, this would be an advantage.

Nordson, Norristown, PA, produces a very wide range of spray guns, several of which spray water-based paints. The most interesting was the electrostatic gun for spraying waterborne coatings. This gun charged the paint particles after they had left the nozzle, eliminating the problem of isolating the fluid line to prevent grounding the charge. The charger operates at a voltage of 76 kVdc. During the search this was the only design of paint spraying system that did not require an isolated fluid line. No distinct advantage has been identified for this approach at this time, but its uniqueness makes it worth noting.

Interrad Corporation, Stamford, CT, sells a French line of spray equipment produced by Sames Division of D'Air Industrie, Grenoble. A specialty of Sames is that they produce a sprayer that uses an ultra-high-speed spinning disc. Air atomized droplets are relatively large. To yield a very high-gloss paint coating, however, the spray gun must produce fine droplets. Electrostatic bells (discs or cups) have been used for some time to generate small droplets, but have not been operated above 3000 rpm. However, because of EPA requirements, the industry has turned towards waterborne paints, which are more difficult to atomize due to a stronger surface tension. Sames has overcome this by electrostatic charging and by using an ultra-high-speed bell. They apply voltage up to 100 kV and spin the disc at 30,000 rpm.

This type of design is probably the only one that can produce uniform small sized droplets. This is ideal for experimental work as it allows investigation optimally sized charged droplets.

The final product of technical interest was the Sonic Nozzle. This atomizing nozzle has an air-driven acoustic oscillator for atomizing liquids by passing them through a pressure field of high-frequency sound waves. Compressed air is accelerated beyond the speed of sound through a convergent/divergent orifice and then reflected back to amplify the primary shock wave. The liquid, upon reaching the shock wave, is shattered into very fine droplets. This novel mechanism results in a very finely atomized spray. Sprays of this type were used by Hässler (6).

The largest manufacturer of spray nozzles in the United States is Spray Systems Co. Foster-Miller contacted them to determine if any of their customers produced charged water spray equipment. They were unaware of any such applications. Their development department, however, had performed particle sizing analysis of sprays for Professor Edward Law, Department of Agricultural Engineering at the University of Georgia. He has published several papers on electrostatic induction spray charging (7) and has developed potential charged spray equipment. His efforts were concentrated on the charged spraying of agricultural fertilizers and pesticides. It is believed the patent rights now belong to FMC and they have yet to market the equipment. If this equipment comes on the market, it may be applicable to mining applications of charged water spray.

2.3 Mathematical Model for Charged Droplet Dust Removal

The development of a predictive mathematical model for dust removal by charged water sprays is a difficult task. The scope may be appreciated by realizing that no such predictive model exists for dust removal by conventional water sprays in a mining type environment. "Cut and try" remains the major water spray system design method for underground applications.

For a developing technology like charged water spray dust control, the objective of the analytical effort is to determine analytical relationships that explain experimental observation - to explore the possible mechanisms and identify those that explain the results. Models yielding results that contradict well-controlled experiments must be rejected in favor of those that appear supportive of the experimental work. To "close the loop," well-controlled experiments must continue to ensure that the model continues to apply under different experimental conditions.

The development of a mathematical model is presented in Appendix A, where several mechanisms for charged spray dust removal are considered and discarded because they do not appear consistent with the results of recent experimentally observed results. Another mechanism - the charging of dust particles by ions emitted with the charged spray - is discussed and offered as a more satisfactory explanation for observed behavior.

In this section we briefly summarize the following:

a. Possible charged spray dust removal mechanisms

b. The simplifying assumptions of the analytical model

c. The comparison of the model output with experimental results

d. An explanation of the "ion charging" mechanism.

2.3.1 Dust Removal Mechanisms

Dust located in the immediate vicinity of the charged droplet generator (sprayer), where drops are decelerating, is subject to the same inertial scrubbing as with conventional sprays plus some enhancement through electrostatic attraction between charged drops and dust particles. Once the droplets have slowed to terminal velocity, charged droplets have many possible mechanisms for promoting dust removal. Some are:

a. Electrostatic forces attract oppositely charged dust (charged droplet scrubbing, CDS). This is the usual qualitative explanation given for charged spray dust control

b. Charged dust particles with the same sign as the charged droplets are repelled or precipitated from the dust cloud due to the electric field from the space charge of the droplets (charged droplet precipitator, CDP)

c. Self-repulsion of the charged drops drives the droplets at velocities greater than gravitational settling, enhancing inertial scrubbing.

It is likely that all three mechanisms presented above contribute in some degree to charged spray dust removal. The purpose of the mathematical model is to identify the dominant mechanism(s).

2.3.2 Assumptions of the Mathematical Model

Since the process is complex, it is necessary to make simplifying assumptions to estimate predictive effects. The assumptions for the model of Appendix A are:

a. Most of the dust removal occurs far from the charged sprayer so that inertial scrubbing during droplet deceleration is ignored.

b. In the volume of interaction between the dust particles and the charged droplets, the dust and droplet concentrations are homogeneously mixed due to turbulence.

c. The dust particles and the water droplets are of uniform size and charge. True distributions are unknown.

d. The space charge density due to the drops is greater than the space charge density due to the dust. This makes the motion of the droplets independent of the dust.

e. The droplets are charged to saturation in the charging field of the droplet generator. This assumption is examined again in light of results.

f. The droplets move due to electrostatic and gravitational forces.

g. Charged dust particles move due to electrostatic forces only; that is, inertial collection is ignored as well as motion of neutral particles in diverging electric fields.

h. The droplets neither evaporate nor coalesce. They are removed only at the boundaries of the interaction volume.

2.3.3 Comparison of Mathematical Model Results with Prior Experiments

By calculating a time for a substantial dust reduction (time constant), assuming the commonly held notion of operation as a CDS, it is found that the predicted time constant is 4.3 min.

This is somewhat long for explaining the dust reductions reported by Brookman. The CDS does not seem to be the dominant dust removal mechanism. In conversation, Brookman reported that self-repulsion of the droplets leaving the generator is not observed. This means that the droplets are not charged to saturation. Therefore, actual time constants for this model should be even longer than calculated. Also, since the droplets are not observed to "explode" out of the generator, they are unlikely to be driven fast enough by the electric field to enhance inertial scrubbing.

Since the CDP has the same numerical time constant as the CDS, it is not likely to be the dominant mechanism either. The basic problem is that the dust particles do not carry enough charge. Without adequate charge, the electric mobility is too low for rapid particle removal. Another mechanism must be identified.

2.3.4 Ion Charging of Dust

It is likely that ions (gas molecules with a surplus or deficiency in electrons) are emitted as artifacts of the charged droplet generators. Emitted ions will attach to dust particles in free air just as they do in the charging section of an electrostatic precipitator. Dust particles so charged will have the same electrical sign as the droplets. Particle mobilities will be higher than those of the naturally-occurring charged dust. The space charge from the drops and ions will produce a precipitating electric field which drives the charged dust out of the cloud. If there are surfaces such as walls, roof, or floor at the edge of the cloud, particles will be deposited there. If not, the dust particles will be forced into clean air. Either way, the amount of dust driven out of the cloud will lead to a decrease in dust concentration. This charging and precipitation mechanism is called a single-stage CDP.

Using estimates for this effect, in Appendix A, a time constant for significant dust removal is found to be 23 sec. This magnitude of time is consistent with the effects observed by Brookman. Further, Brookman's data showed that dust reduction is not dependent on the sign of the charge placed on the droplet. This observation is in accord with the single-stage CDP model as ionic charging of the dust would overwhelm the natural charge on the dust.

It also follows from this model that ion injection without droplets could be an effective dust control technique where use of water spray is undesirable. Exploratory tests of ion injection were conducted during this program. They are described in detail in Section 3 of this report.

3. LABORATORY DUST REDUCTION TESTS

3.1 Introductory Remarks

A series of laboratory tests were performed to assess the effectiveness of charged droplet removal of dust. Dustron equipment was used as it was the only commercially available equipment at the time of testing. Measurements of the time decay of dust concentrations in an enclosed chamber provided the principal test of charged spray effectiveness. This technique is as valid as the more common steady-state dust removal (reduction) measurements but does not require a steady-state dust source which is difficult to achieve. Further, the decay measurements directly relate to the "time constant" of Melcher (8). Appendix B is a development of the experimental phenomenology which shows that linear dust removal mechanisms, such as sedimentation, dilution and charged or uncharged droplet scrubbing may be isolated and quantified. This appendix also shows that the dust removal efficiency due to the droplets is related to the ratio of the residence time and Melcher's time constant. Assumptions on which this approach is based include:

a. The dust behaves as a monodispersed aerosol

b. Removal mechanisms are linear; that is, removal rate of dust is proportional to the concentration of dust.

These assumptions are supported by the log-linear nature of the resulting data. Resulting data shows log-linear time decay for over two orders of magnitude decreases in concentration value.

3.2 Test Chamber

Figure 14 depicts the 420 ft^3 (11.9 m^3) cubical test chamber. The plywood walls are lined with grounded aluminum screening material. This lining ensures that the charged droplet cloud is not affected by external electric fields. A mixing fan mounted near one corner of the chamber maintains homogeneous concentrations of dust and droplets within the chamber.

The chamber is force ventilated. A fan in the inlet duct brings room air in through an orifice meter. The inlet air is directed through a small chamber where two Dustron Mist Emitters are located. Ventilation air is exhausted through an exit in the roof of the chamber. The dust concentration is monitored in the exhaust duct.

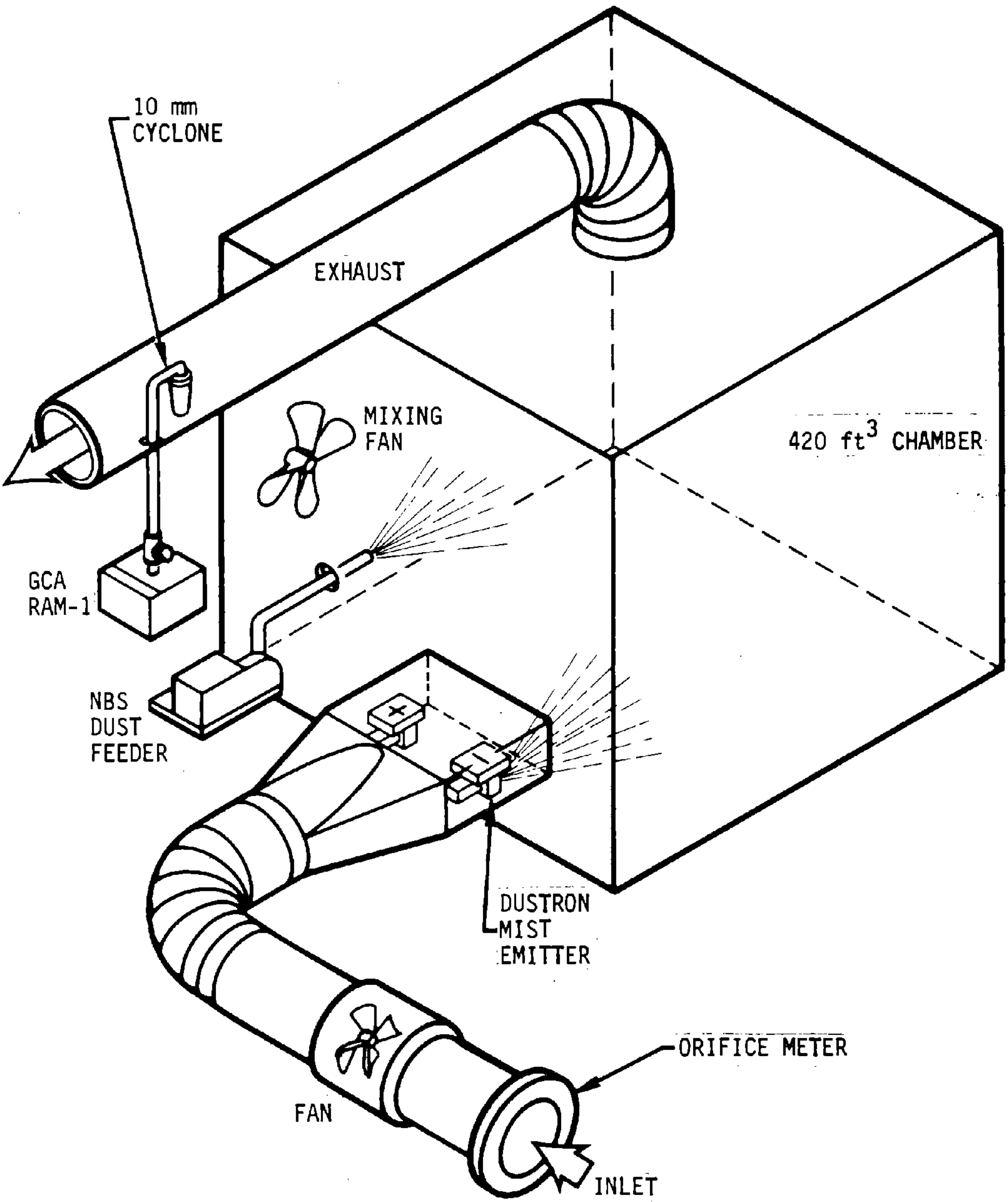


FIGURE 14. - Test chamber.

Dust concentrations were monitored using a GCA Corporation RAM-1, real-time dust monitor. Concentration data was recorded manually and/or with a data logger. Most sampling was through a 10 mm cyclone to determine effects on the respirable dust fraction. Some samples were collected through Model PS-4 particle sizing impactors from GCA Corporation. These impactors are compatible with the RAM-1 instrument. Fifty percent cut points are 8, 4, 2 and 1 μm. The RAM-1 instrument measures the mass concentration which penetrates the impactor selected.

Dust was blown into the chamber with a NBS type dust feeder. Steady-state feed was not achieved nor is it necessary for this testing method.

3.3 Mist Emitters

Dustron Mist Emitters, manufactured by Keystone Dynamics, Inc., are used to produce the charged spray. Both positive and negative emitters are available. Air atomizing nozzles are used to produce a fine spray of droplets. Most of our testing was performed with orifices recommended to us by the manufacturer. These are described as 180 air cap and 60100 water cap. Water flows up to 300 ml/min are monitored through rotometers which are part of the Dustron equipment. A driving air pressure of 60 psi (413 kPa) was used in all dust tests. Air pressures are monitored by pressure gauges that are also part of the Dustron equipment.

3.4 Test Dusts

The three test dusts were:

a. Fine Arizona road dust from the AC Division of General Motors

b. A fine talc powder

c. Molybdenum ore samples milled in a fluid energy mill to approximately 80 percent respirable size.

3.5 General Test Procedures

Tests were run to determine the time decay of the suspended dust under the following conditions:

a. Dust without any spray applied

b. Dust with uncharged (not intentionally charged) spray applied

c. Dust with charged spray applied.

Three ventilation flow rates were used: 210, 420 and 840 ft^3.min (5.9, 11.9 and 23.8 m^3/sec). These rates corresponded to residence times (V/Q or chamber volume to ventilation flow ratios) of 2, 1 and 0.5 min, respectively.

In performing a test, ventilation flow and spray was first established. A background concentrations reading from the RAM-1 instrument was determined. Background readings consisted of room dust and sensitivity of the RAM-1 to the water mist. Typical values were below 0.12 mg/m^3 for no spray and charged spray while uncharged sprays produced values below 0.24 mg/m^3.

Having established the background levels, the test dust was injected until a concentration of over 15 mg/m^3 was achieved. At this point, dust injection was stopped. As the dust concentration decayed to about 15 mg/m^3, the initial concentration, C_o, was taken at time $t = 0$ and then the dust concentration, C, was recorded as a function of time, t, for several residence times. After five or more residence times, the ventilation flow flushed out the chamber to the initial background level. (Also see Table of Symbols B-1 in Appendix B.)

Background concentration readings were subtracted from all the recorded values to obtain net C_o and C of t. The logarithm of the ratio C/C_o was plotted against time and/or a linear regression fit of $\ln C/C_o$ versus t was determined.

3.6 Dust Decay Results

Linear regressions of $\ln C/C_o$ versus t have correlation coefficients exceeding 0.999 for concentration decays over two orders of magnitude to about 0.15 mg/m^3. This verifies the assumptions that the important removal mechanisms are linear and that, for the purpose here, the respirable dust fraction and impactor penetration fractions behave as though monodispersed. Linearity of the mechanisms is important because it permits the magnitude of the various dust removal mechanisms, especially the charged droplets, to be isolated and quantified. For example, subtracting the absolute value of the dust only decay slope (from the linear regressions equation or from the graph) from the slope determined when charged spray is applied gives the net decay slope due to the charged droplets. The reciprocal of this slope is the characteristic time or time constant for droplets to reduce the dust concentration. In one time constant the measured dust concentration decreases to about 37 percent of initial value.

Figure 15 shows typical results for dust concentration decay with time for the various test cases. Actual experimental data points are shown. Figures 16 to 19 show the dust decay curves for all tests. The lines shown in these curves are from the slopes determined by linear regression fit of the test points. These cases cover:

a. Dusts
   1. Arizona road dust (fine)
   2. Talc
   3. Milled molybdenum ore

b. Residence times of:
   1. 0.5 min
   2. 1.0 min
   3. 2.0 min

c. Spray water flow rates of:
   1. 100 ml/min
   2. 200 ml/min
   3. 300 ml/min

d. Droplet charge
   1. Positively charged
   2. Negatively charged
   3. Combined positively and negatively charged
   4. Uncharged

e. Dust sampled through:
   1. A cyclone
   2. Impactor separators.

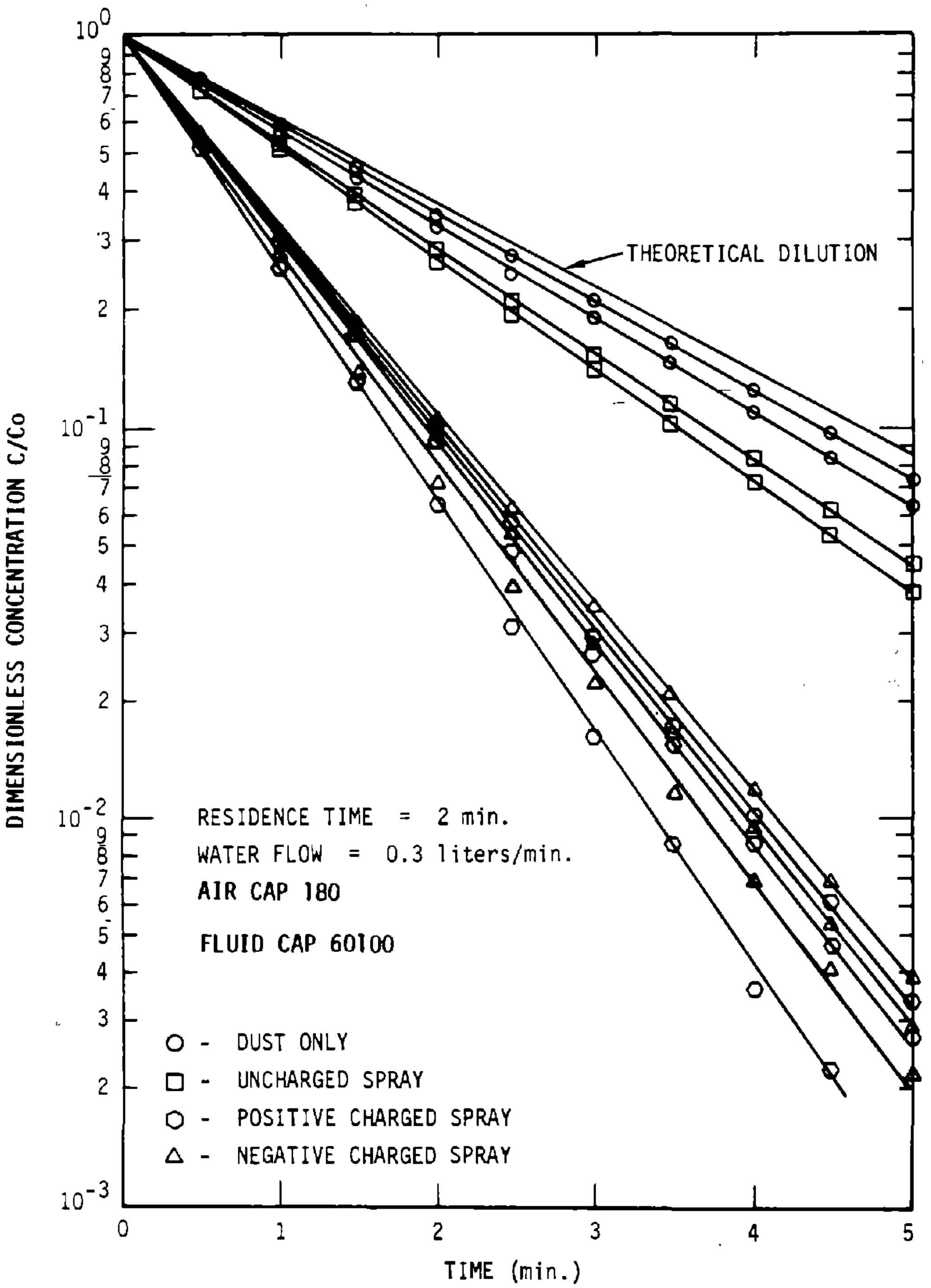


FIGURE 15. - Dust concentration decay versus time.

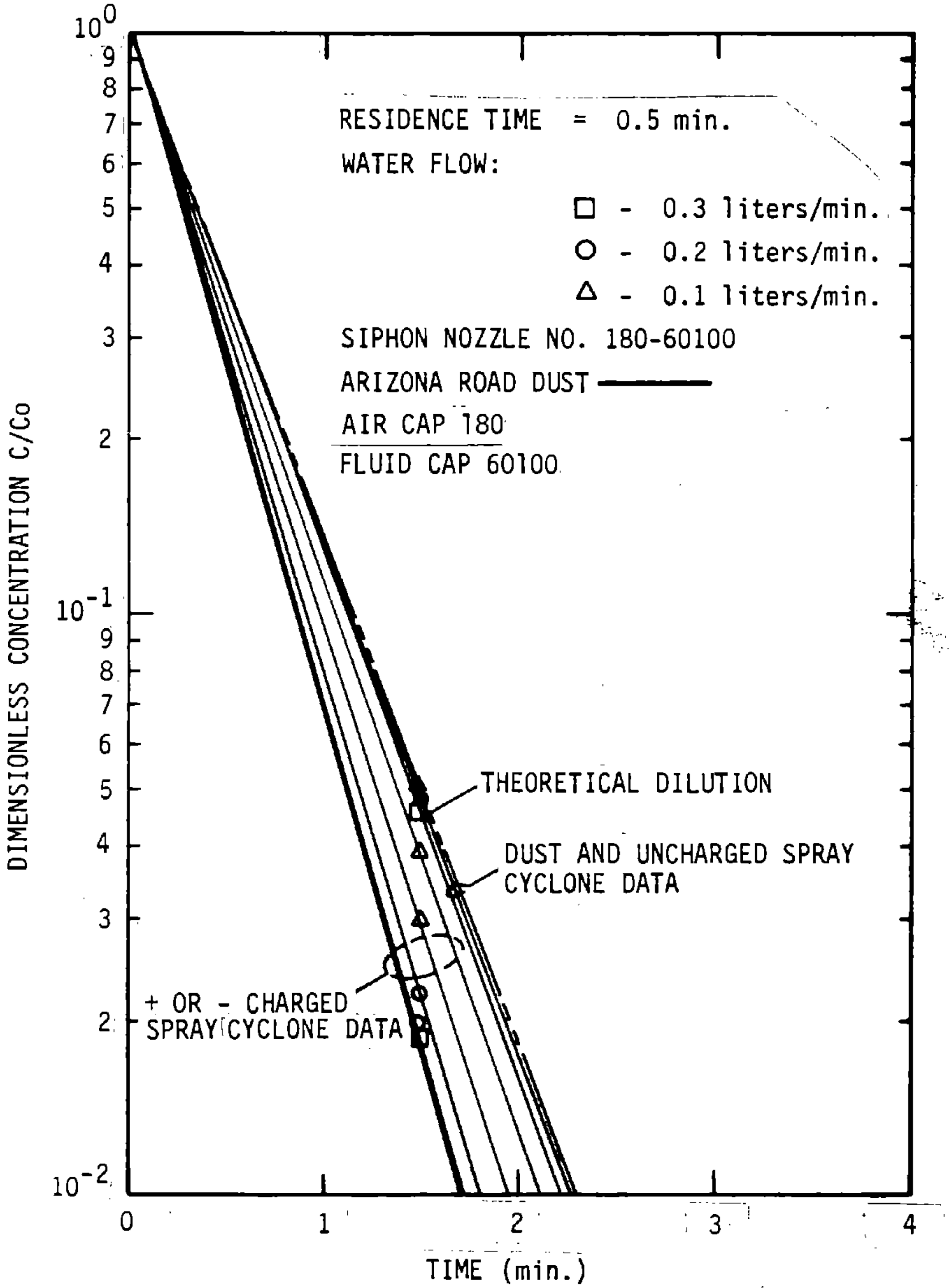


FIGURE 16. - Concentration decay.

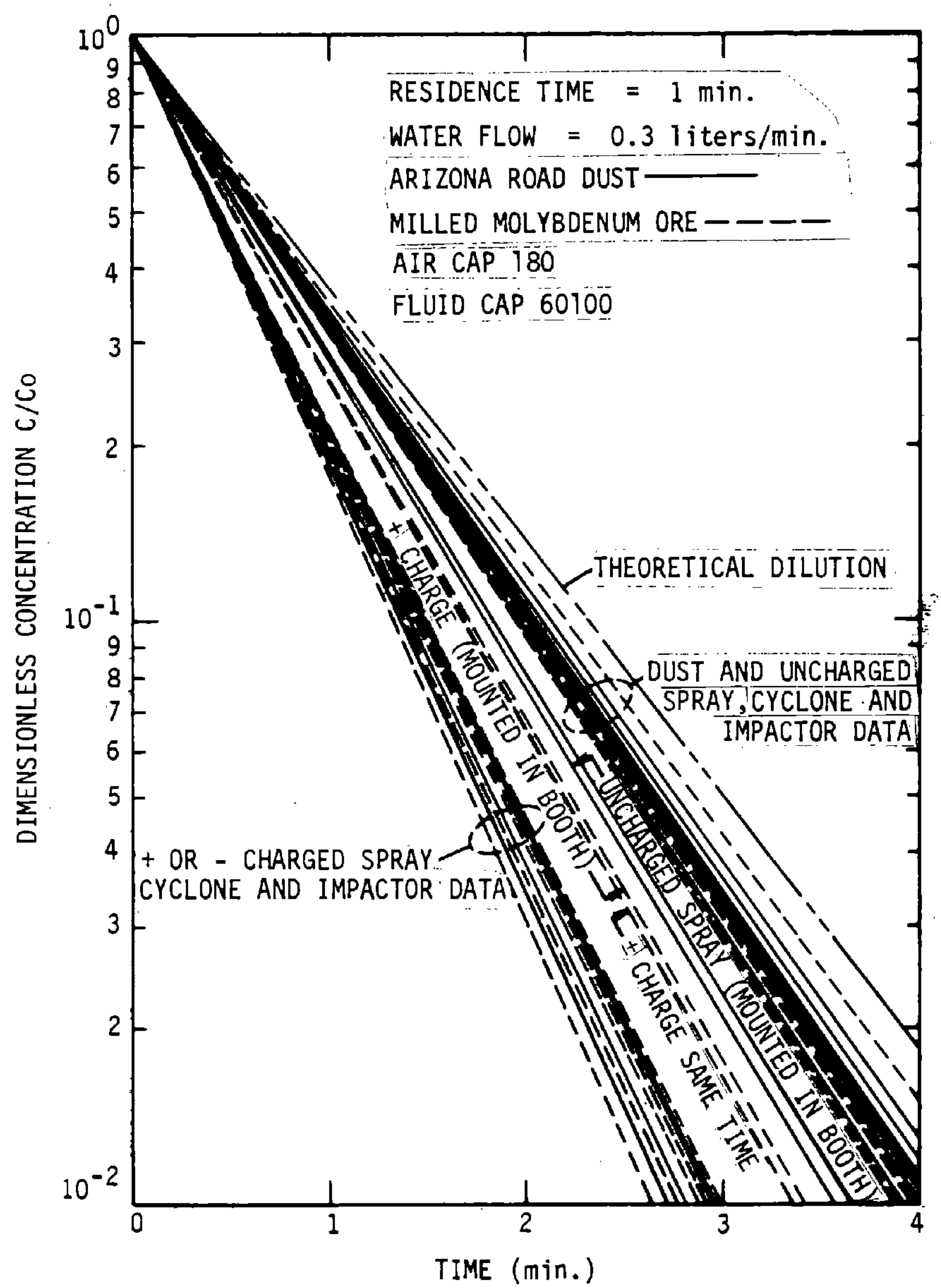


FIGURE 17. - Concentration decay.

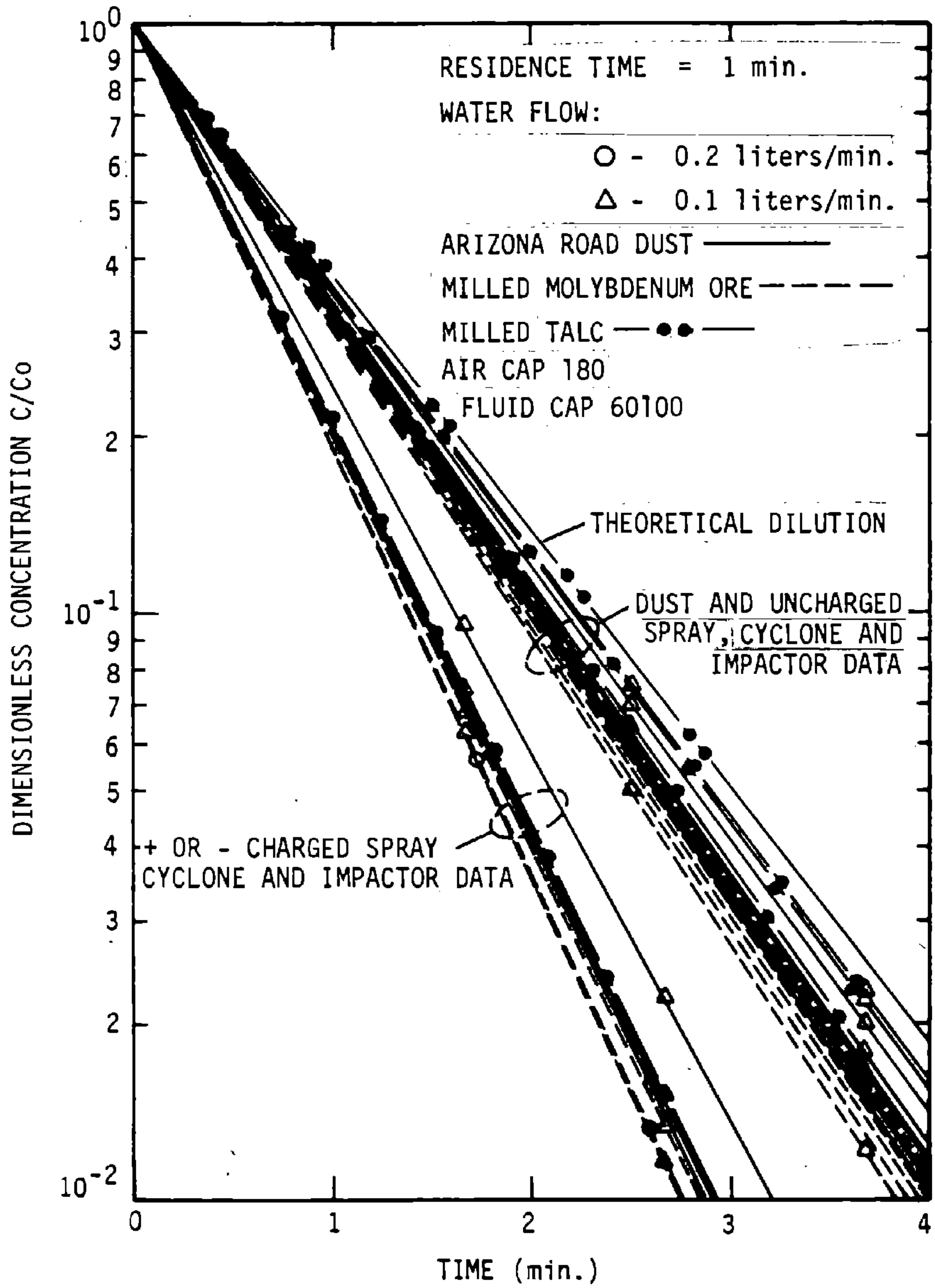


FIGURE 18. - Concentration decay.

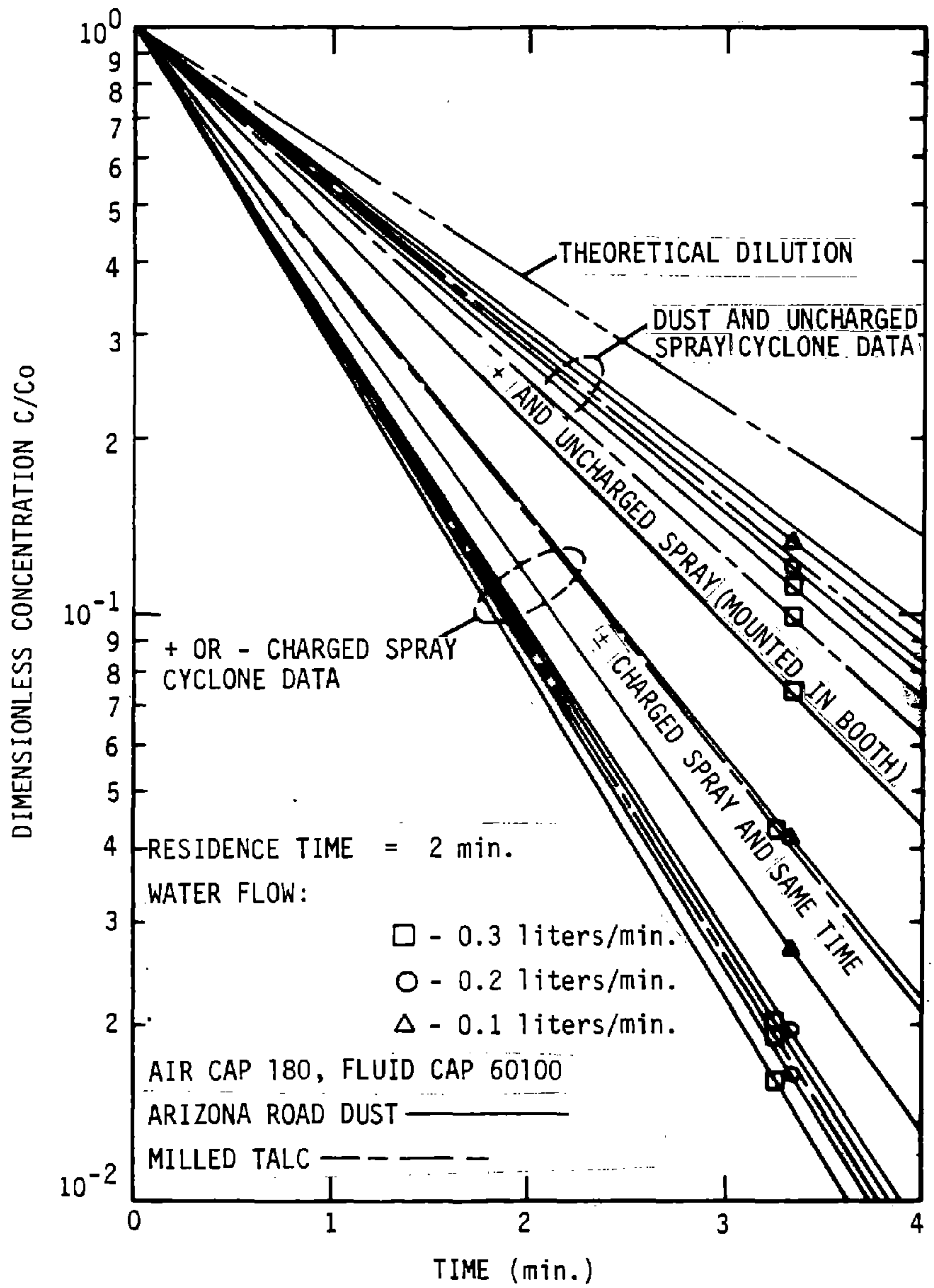


FIGURE 19. - Concentration decay.

Figure 20 shows set results of sampling through the impactor separators compared with sampling through a cyclone separator. Note the small spread among impactor fractions and between impactor fractions and cyclone fraction. The reason for the slow decay rate for the less than 8 μm impactor fraction is not understood.

Table 2 summarizes the decay rate data for respirable dusts. The values ΔR_D are the net slopes when charged spray is applied. The time constant for dust removal by charged spray is $1/\Delta R_D$.

3.7 Other Tests

Tests run in addition to the dust reduction testing included:

a. Electric field measurements due to the charged droplet cloud in the chamber

b. Electric currents to the spray nozzle and from the charged spray

c. Droplet sizes

d. Net charge on respirable dust.

3.7.1 Electric Field Measurements

The electric field was monitored at a point near the center of the chamber wall behind the mixing fan (Figure 14) during dust decay tests using a Monroe Model 245 Electrostatic Field Meter. For a given geometry such as the dust testing chamber, the electric field is proportional to net space charge (the charge suspended in the air principally due to the charged droplets cloud). The time constant is inversely proportional to the space charge density due to droplets. Hence, the decay rate of dust concentration should be higher for higher space charge densities which also yield higher electric field strengths.

The electric field strength from the dust clouds without charged droplets averaged about 0.3 kV/m. This value was near the threshold of instrument detection capability. Sprays that were not intentionally charged produced electric field strengths averaging about 2 kV/m.

Charged sprays, either positive or negative, produced electric field strengths that ranged from over 1×10^5 V/m (for two minute residence times and 300 ml/min water flow rates) down to

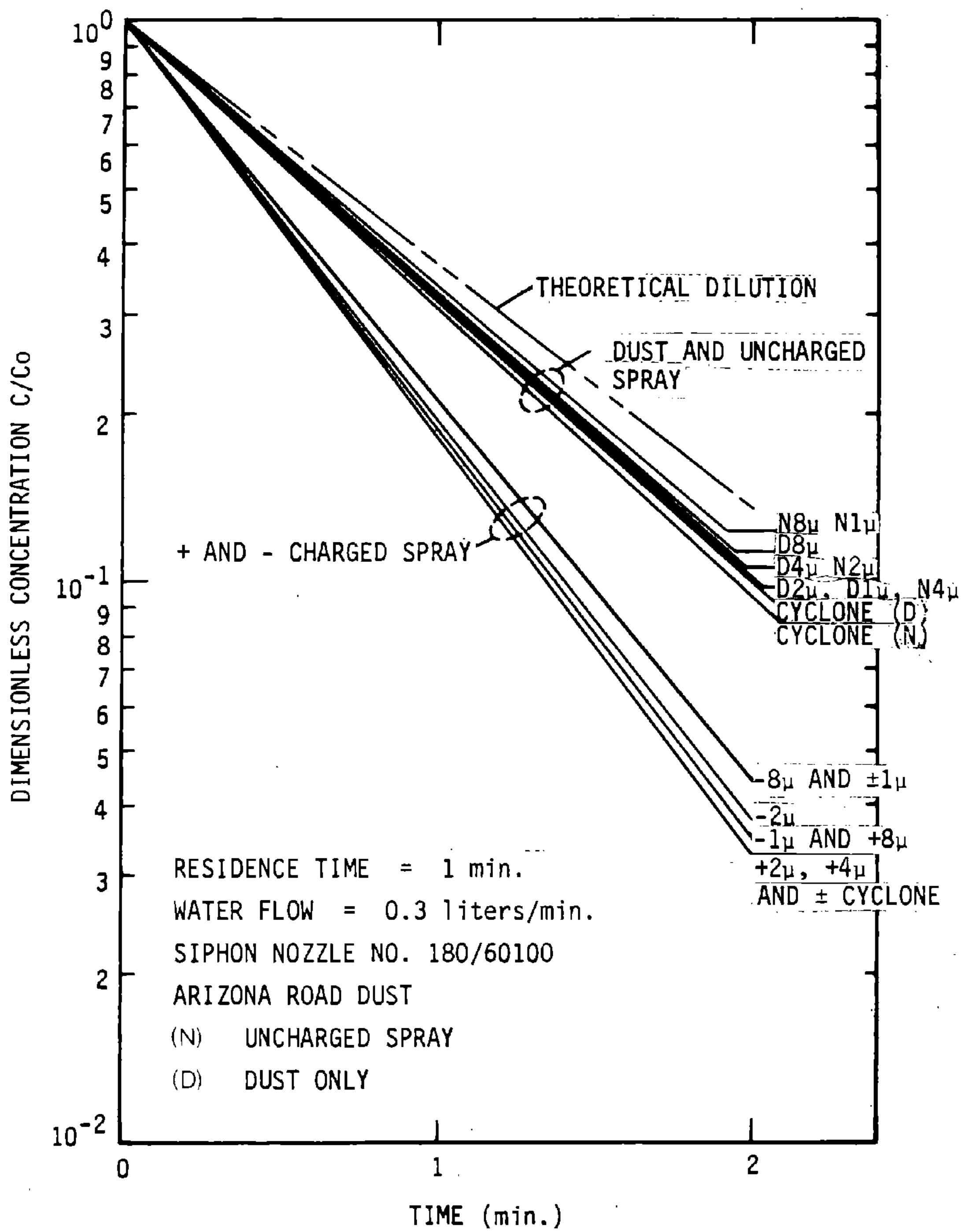


FIGURE 20. - Concentration decay, impactor and cyclone comparison.

rates

TABLE 2. - Respirable dust decay rates
$R\ (min^{-1}) = 1/\tau$

Milled molybedenum ore						
Spray flow q	V/Q (min)	Dust	+ Spray	- Spray	ΔR_D, +	ΔR_D, -
100 ml/min	1.0	1.166	1.619	1.675	0.453	0.509
200 ml/min	1.0	1.166	1.680	1.667	0.514	0.501
300 ml/min	1.0	1.166	1.682	1.665	0.516	0.499
Milled talc						
Spray flow q	V/Q (min)	Dust	+ Spray	- Spray	ΔR_D, +	ΔR_D, -
300 ml/min	2.0	0.623	1.206	1.252	0.583	0.629
Arizona road dust						
Spray flow q	V/Q (min)	Dust	+ Spray	- Spray	ΔR_D, +	ΔR_D, -
100 ml/min	0.5	2.0382	2.3603	2.1836	0.322	0.145
	1.0	1.1481	1.432	1.5018	0.284	0.354
	2.0	0.5859	1.0709	0.9480	0.485	0.362
200 ml/min	0.5	2.0382	2.6738	2.5637	0.636	0.526
	1.0	1.1481	1.5025	1.6027	0.454	0.455
	2.0	0.5859	1.2175	1.1700	0.632	0.584
300 ml/min	0.5	2.0382	2.6869	2.6623	0.649	0.624
	1.0	1.1481	1.6905	1.6952	0.542	0.547
	2.0	0.5859	1.253	1.183	0.667	0.597

about 3×10^4 V/m (for half minute residence time at 100 ml/min water flow rates). For a given residence time, electric field strength increased with water flow. For a given water flow, electric field strength decreased with residence times.

Electric field strength values varied spatially within the chamber. If the charge was uniformly distributed throughout the chamber, Gauss' Law predicts maximum field strength at the center of chamber walls. Experimentally, however, traversing into the chamber with the field meter probe indicated larger field strengths away from the walls. Field strengths of 5×10^5 to 10×10^5 V/m were found at the chamber interior, versus strengths of 1×10^5 at the wall. This indicates the space charge density was not uniform inside the chamber but was probably concentrated in the spray plume.

3.7.2 Spray Currents

Electric current flowing from ground to the spray nozzle and electric current flowing from the resulting droplet cloud to ground were measured. Measurements of charging current, spray water flow rate and droplet size permit an estimate of typical droplet charge. Theory indicates that, when all else is equal, higher charge on the droplets produces faster dust removal (see P.40).

The Dustron Mist Emitters use electrostatic induction to charge droplets. This requires current flow from ground to the spray nozzle. The spray nozzle was electrically isolated such that all droplet charging current flowed through a Keithley 600B electrometer. This provided a measurement of current flowing to the droplets or current to the spray.

The spray plume of charged droplets was directed into a cylinder of aluminum screening material closed on one end. Most of the water droplets coalesced and discharged on the screening. The electrometer connected between the screen and ground measured the current *from* the spray.

Figure 21 shows the currents *to* and *from* the spray as a function of water flow. The flattening out of the curves has been observed by Law (7). An unproven explanation of this flattening at higher flow rates is that the water on the outside of the forming spray shields the water on the inside. The current to the spray nozzle is consistently higher than the current collected from the spray plume in the screening material. Reasons for this difference may include:

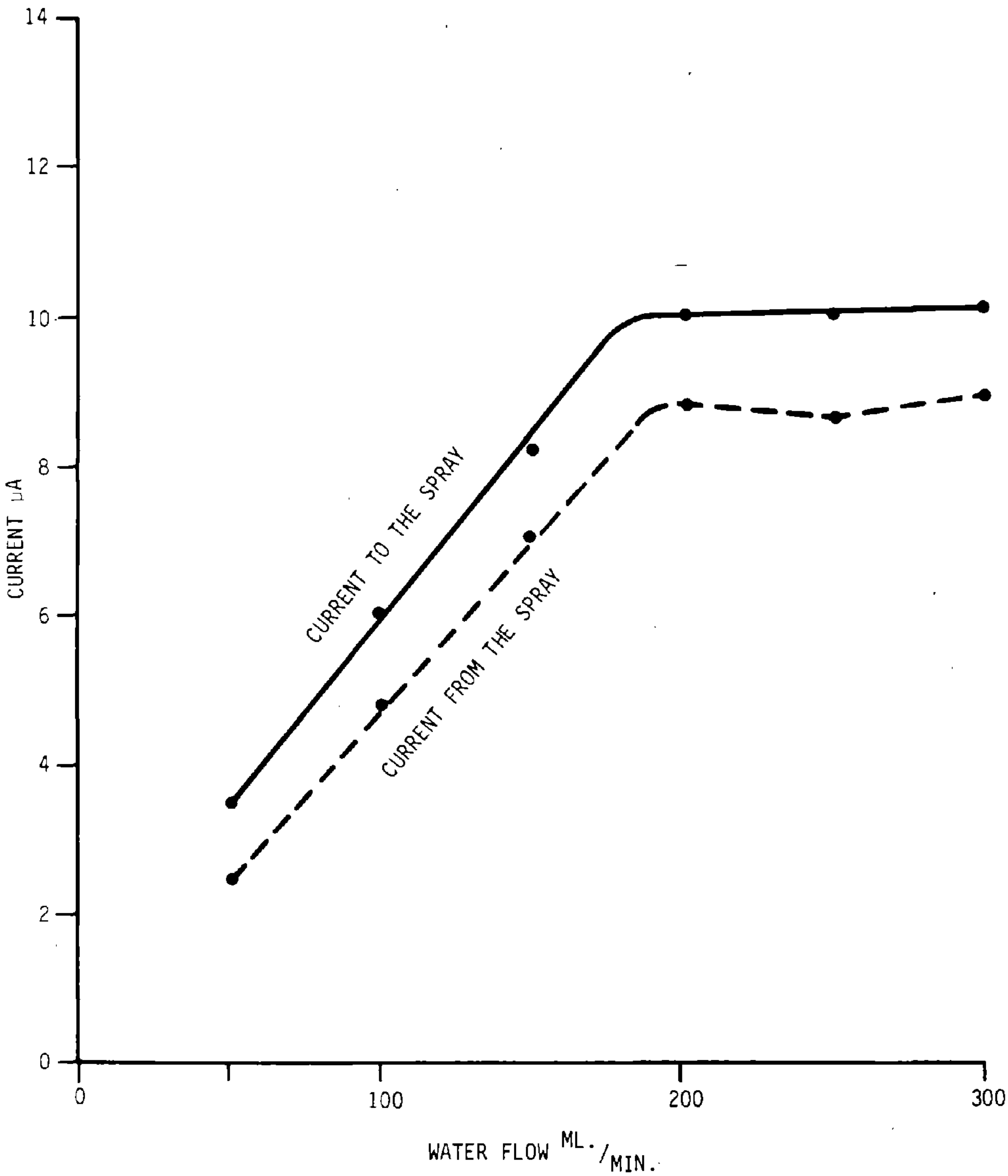


FIGURE 21. - Spray currents (air pressure 60 psi).

a. Corona or other currents from the spray nozzle which reach the induction ring bypassing the electrometer connected to the screening

b. Charged droplets which pass through the screening material without being collected.

The second reason is the most likely since we observed some droplets passing through the screening. The small difference in the two measurements indicates that the current flowing to the spray is a good estimate of the charge placed on the droplets.

Air pressure affected spray current. Increases or decreases in air pressure to the nozzle produced corresponding increases and decreases in spray current. This is probably due to droplet size. For a given water flow, higher air pressures are expected to produce smaller droplets which will have a larger surface to volume ratio than larger droplets. The charge induced on the droplets is expected to be proportional to the droplet surface area. Hence, higher air pressures will produce higher spray currents.

The Dustron equipment has a fixed induction ring voltage. No attempt was made to alter this voltage to change droplet charge levels.

3.7.3 Droplet Size

Droplet size information is necessary for correlating experimental results with theory. From droplet size information, droplet number density and droplet charge information may be inferred. Droplet size information was obtained on a droplet analyzer at Bete Fog Nozzle, Inc. in Greenfield, MA. They have developed a video computer system for analyzing spray droplets. A small volume of the spray to be analyzed is imaged inside a video camera using a strobe light to stop the motion. The image is frozen and automatically processed using the known optics of the system to provide information on droplet size. Images may also be examined on a video monitor to ensure proper focus.

Tabulated in Appendix C is the computer printout of the sized droplets for the conditions of:

a. 100, 200 and 300 ml/min flows at 60 psi air pressure

b. Negative and no charge applied to droplets.

Summarized in Table 3 are the volume mean sizes for the various test conditions.

TABLE 3. - Volume mean diameter μm

Charge/Flow	100 ml/min	200 ml/min	300 ml/min
-	25	30	33
0	23	30	35

A large number of drops would improve the statistical estimate of droplet mean sizes. However, the sparse population of droplets in the spray made gathering such a large number impractical. The values here are, therefore, only suitable for estimating theoretical performance.

3.7.4 Net Charge on Respirable Dust

Early workers in charged fogging for dust control implied that fog opposite in charge polarity to the net charge on the dust should be used for maximum effectiveness. In an attempt to measure the net charge on the dust, a personal sampler with cyclone and modified filter was used. The filter holder was enclosed in an isolated metal guard so that any charge deposited on the filter would electrostatically induce an opposite but equal charge on the metal guard. A Keithley 600B electrometer set on the coulomb scale was connected between the guard and ground.

No net charge was detected when dust was sampled from the test chamber. This could be due to:

a. No charge on the individual dust particles

b. Approximately equal amounts of positive and negative charges distributed over the dust (charged but no net charge).

Since individual dust particles usually carry some charge, it is probable that the dust is charged with virtually no net charge.

3.8 Correlation with Theory

A comparison of theoretical prediction using the model of Appendix A with experimental results indicates a plausible correlation. Definitive correlation requires a measurement of dust mobility (velocity of charged dust particle in a unit electric field) which we did not attempt to measure in this testing program.

We expect that the effort to make this measurement alone could be greater than the entire experimental program reported here. Hence, we directed resources toward measurements which could be made within the scope of the program.

Consider the conditions shown in Table 4. These conditions are representative for all dusts tested. The model indicates that dust concentration will decrease with a time constant of:

$$\tau = \frac{\varepsilon_o}{N\, Q_e\, b}$$

where

ε_o = 8.85×10^{-12} F/m

N = droplet number density (m^{-3})

Q_e = charge per drop (C/drop)

b = dust mobility (m/s/V/m).

TABLE 4. - Test conditions

Chamber volume	=	11.9 m^3
Chamber floor area	=	5.2 m^3
Chamber edge length	=	2.3 m
Spray water flow	=	0.2 ℓ/min = 3.3×10^{-6} m^3/s
Spray water current	=	μa
Volume average drop diam	=	30 μm
(Implied droplet rate	=	2.6×10^8 drops/sec)
(Implied droplet charge	=	3.8×10^{-4} C/drop = Q_e)
Electric field (E) just inside chamber	=	3×10^{-5} V/m
Measured time constant, τ	=	120s (= $1/R_D$, R_D = 0.5 min^{-1})
Ventilation residence time	=	1 min

Further, the analysis predicts an equilibrium number density, N, for droplets in a homogeneous system given a droplet rate, that accounts for droplet losses due to:

a. Electrostatic self precipitation of droplets from the cloud

b. Gravitational settling out of droplets

c. Ventilation dilution.

Using the conditions from Table 4, the major droplet removal mechanism is self precipitation and a value of $N = 2.6 \times 10^7$ drops/m^3 is calculated.

To the best of our knowledge, a likely estimate of b is 1×10^{-8} m/s/V/m. This is based on a 5 μm diameter particle charged to the equivalent of 50 electronic units ($50 \times 1.6 \times 10^{-19}$ C). With this assumed mobility and $Q_e = 3.8 \times 10^{-14}$ C/drop,

$$\tau = \frac{\varepsilon_o}{N\, Q_e\, b} = 890 \text{ sec}$$

This value is 7.4 times longer than the 120 sec measured. That is, the estimate predicts a slower dust removal than was measured. Several possible explanations are available for this difference.

We speculate that ions, which could be artifacts of the charged spraying process, are liberated and charge the dust particles to levels greater than estimated leading to more rapid dust capture. Some qualitative observations made with a probe grounded through the electrometer indicated that fast, probably dry, charged particles fly out radially from the charged spray plume emitted from the Mist Emitters. These could be ions left after very small (less than 5 μm) droplets evaporate. Further evidence supporting evaporation as a mechanism surfaced during the droplet sizing tests. There was a problem focusing on droplets near the Mist Emitter. Further away from the emitter droplets were easily focused. One possibility for the focusing problem could be the presence of many droplets smaller than 5 μm. If these fine droplets evaporated and were gone at longer distance from the emitters, focus would be possible.

An alternative ion source might be corona currents from forming droplets; however, we observed nothing to support or refute this possibility. Corona from the Mist Emitters was not observed in the absence of water flow.

An entirely different possibility for the difference between prediction and experiment may lie in nonhomogeneous distributions within the chamber. The good log-linear time decay of measured dust concentrations argues that the dust is well mixed. However, visual observations of the plume from the Mist Emitter indicate that a core of densely populated droplets exists within a cloud of less densely populated droplets. Also, electric field readings in a uniform space charge, should monotonically decrease as the field meter probe is traversed from the wall to the center of the chamber. However, we found on traversing, the electric field increased as the probe was traversed from the wall to the chamber center. For example, values increased from about 1×10^5 V/m near the wall to 5×10^5 V/m about one-third meter from the wall. Values increased slowly from that point to almost 10×10^5 V/m. Nonhomogeneous space charge could lead to erroneous estimates of droplet number density.

From electric field measurements, an estimate of NQ_e may be independently made. Gauss' law indicates that the net space charge density, which is NQ_e, is related to a spherical cloud of charge by

$$NQ_e = 3 \varepsilon_o r E$$

Where r is the radius of the spherical cloud and E is the electric field strength at r. The cubical test chamber can be roughly approximated by a sphere of one meter radius. Take a value of $E = 3 \times 10^5$ V/m at roughly one meter from the center of the chamber, then,

$$NQ_e = (2.6 \times 10^7)(3.8 \times 10^{-14}) = 9.9 \times 10^{-7} \text{ C/m}^3$$

This estimated value is eight times larger than predicted by the model. The effect this has is to reduce the time constant, that is,

$$\tau = \frac{890 \text{ sec}}{8} = 110 \text{ sec}$$

This is hauntingly close to the value determined by experiment. However, the charge density estimated here is based on the crude sphere-cube correspondence. Also, the Gauss' law equation used is rigorous only for uniform space charge density. The resulting number is, therefore, more impressive than the underlying logic.

We feel, in summary, that the correspondence between theory and experiment is good considering the realities of nonhomogeneities intrinsic to any practical scale dust removal system and the uncertainty in dust mobility. Future experiments along these lines should include the effort necessary to measure dust mobility and perhaps a better test chamber such as a long cylindrical chamber where axial symetry might be approximated. This geometry would aid analytical modeling. We expect that with additional effort, better theoretical-experimental closure can be achieved. At this time, the experimental values from this program define the expected dust removal of the commercially available Dustron equipment. We think we can estimate the field performance of the Dustron system and estimate the field performance of conventional hydraulic sprays for dust control.

3.9 Concluding Discussion of Laboratory Results

3.9.1 General

Charged droplets remove dust much more effectively than uncharged droplets. As discussed quantitatively in Appendix A, the dust scrubbing of a unit water basis is:

$$\text{scrubbing value} = \frac{\text{Volume of air cleaned}}{\text{Volume of water used}}$$

Typical test data from this experimental program indicate that this ratio is approximately 30,000 when the droplets are intentionally charged. We have measured the scrubbing value for 15 hydraulic atomized nozzles in another program. The largest value we measured was just over 3,000 or one order of magnitude less than that for typical charged sprays.

We believe at this time, on the basis of our laboratory testing, that charged spray dust control offers considerable potential for health protection. Our reservations are concerned with the appropriate engineering of dust control systems rather than the fundamentals. Gassy mines are off limits. We measured electric field strengths due to the charged droplet cloud as high as one-third the breakdown (spark over) point of air. Spark hazard is certain with this technique. The engineering challenges are learning how and where to locate charge spray equipment and, in our opinion, reducing equipment cost.

3.9.2 Polarity

Earlier work by Hoenig (1) implied that the polarity of the fog applied can affect the dust removal. We have not observed this. Neither have Brookman* and Mathai** on rock crusher dust and bentonite dust, respectively. We believe polarity insensitivity is due to the nature of the two removal mechanisms:

a. Charged dust particles are attracted to oppositely charged droplets.

b. The space charge simultaneously precipitates out of the cloud dust charged similarly to the droplets.

We see no advantage of one polarity over another for dust removal based on these mechanisms.

Combined positive and negative sprays are poorer dust removers. Combined spray is roughly half as effective as spray of either polarity alone. We believe the reason for this may be neutralization of droplets and or any ions within the cloud

*Brookman, E.T., Private communication, 1981.

**Mathai, C.V., Private communication, 1981.

as well as a cancelling out of the global electric field strength from the cloud of oppositely charged droplets. Details have not been investigated.

3.9.3 Effects on Various Dusts

We observed no significant difference in effectiveness on the three dust materials tested.

Arizona road dust showed a slight general improvement in removal rate with water flow as expected. This is not evident with the milled molybdenum ore; however, ore testing was not sufficiently extensive due to program timing, to exclude data scatter as cause for a flatter response to water flow. At this time, we believe charged water spray to be equally effective on these three materials and probably similar for most other materials.

3.9.4 Dustron Equipment

The Dustron equipment is capable of producing good charge to mass on the water spray. Best flow rates are near 200 ml/min with a charge of about 3 microcoulomb/gram. This compares well with other charged spray equipment reported. The equipment is robust and safe enough for testing in some mine environments. We detected a major problem when the equipment was operated within a cloud of its own charged mist. Under these conditions the charged fog is electrostatically precipitated onto the induction ring, shorting out the ring. This causes no physical harm to the instrument but reduces the charge on the spray by roughly an order of magnitude. The effect of this is dramatically poorer dust reduction. If the equipment is operated in air relatively free of charged droplets and the charged fog is propelled into the dust cloud region, no problem exists.

We think that the shorting out problem can be designed out of the system and that the cost of the equipment can be reduced if sufficient demand exists. Nozzles like those described by Law (7) are a likely route to achieve both these objectives.

4. MINE TESTING

Laboratory test results indicated demonstrable increases in dust reduction due to the addition of electrical charge to water spray droplets. The quantitative information obtained permitted scaling of the laboratory results to predict performance in specific full-scale applications.

Field testing was performed to:

a. Evaluate the applicability of charged spray dust control to mining

b. Confirm the validity of the dust reduction predictions

c. Identify limitations to underground application of the equipment.

Predicted dust reduction for the conditions at the test site ranged from 10 to 33 percent; the range is due to variations in airflow. During testing, particulate matter generated from contaminants in the water supplied to the atomizing spray nozzles completely masked any reduction in ambient dust levels. The test program allowed no time or resources for correcting the problem once identified. No quantitative verification of charged spray performance was achieved.

The testing program did identify several important and interesting facts that may be significant in future applications of charged sprays or other dust control technologies. These are presented and discussed throughout the remainder of this section.

Specifically presented are:

a. A description of the test equipment

b. A description of the test site

c. A description of the testing procedures

d. Operational observation

e. A discussion of results

f. Operational recommendations and considerations.

4.1 Description of Equipment

The equipment used for testing at the mine was similar to that used during laboratory testing. Major equipment elements included:

a. Six dual polarity Keystone Dynamics Model 109 Mist Emitters (Figure 22). These are controlled by a Model 206 Atomizer Station and a Model 304 Power Supply. Air and water spray caps, Models 180 and 60100 respectively, were used on the spray nozzle. Purchase cost for all charged spray equipment was $12,000.

b. Three GCA RAM-1 respirable aerosol monitors with 10-mm cyclone preseparators installed.

c. Three Rustrak stripchart recorders for RAM-1 outputs.

d. Four-channel, HP3467A logging multimeter (data logger) for RAM-1 outputs.

e. Vane anemometer and smoke tubs for air velocity measurements.

f. Electrostatic fieldmeter, Monroe Model 245.

Application of this equipment is described in a following section.

4.2 Description of Test Site

Field tests of the charged spray system were conducted in a conveyor tunnel leading from a primary crusher to surface stockpiles. The general layout of the test site is shown in Figure 23). The underground conveyor tunnel from the base of the crusher to the transition house on the surface (approximately 525 ft) is 15-ft diam steel conduit and is sloped at approximately 14 deg. The tunnel is partially separated from the crusher building by a bulkhead. The belt conveyor is 60 in. wide and travels at approximately 500 ft/min. A cross-section of the conveyor tunnel is illustrated in Figure 24. The tunnel is supplied with power, compressed air, water, and acetylene along the side of the walkway.

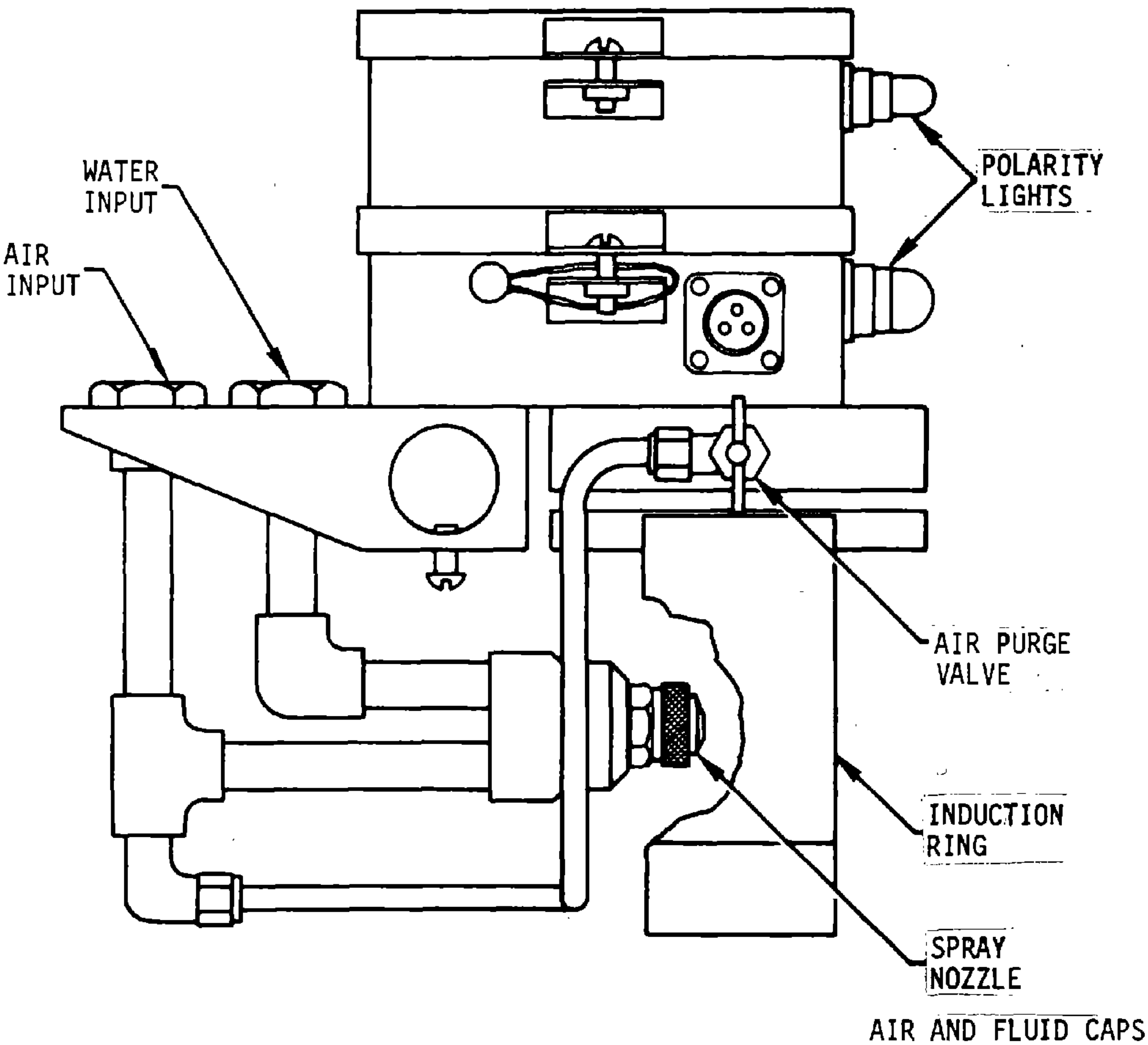


FIGURE 22. - Dual polarity Mist Emitter.

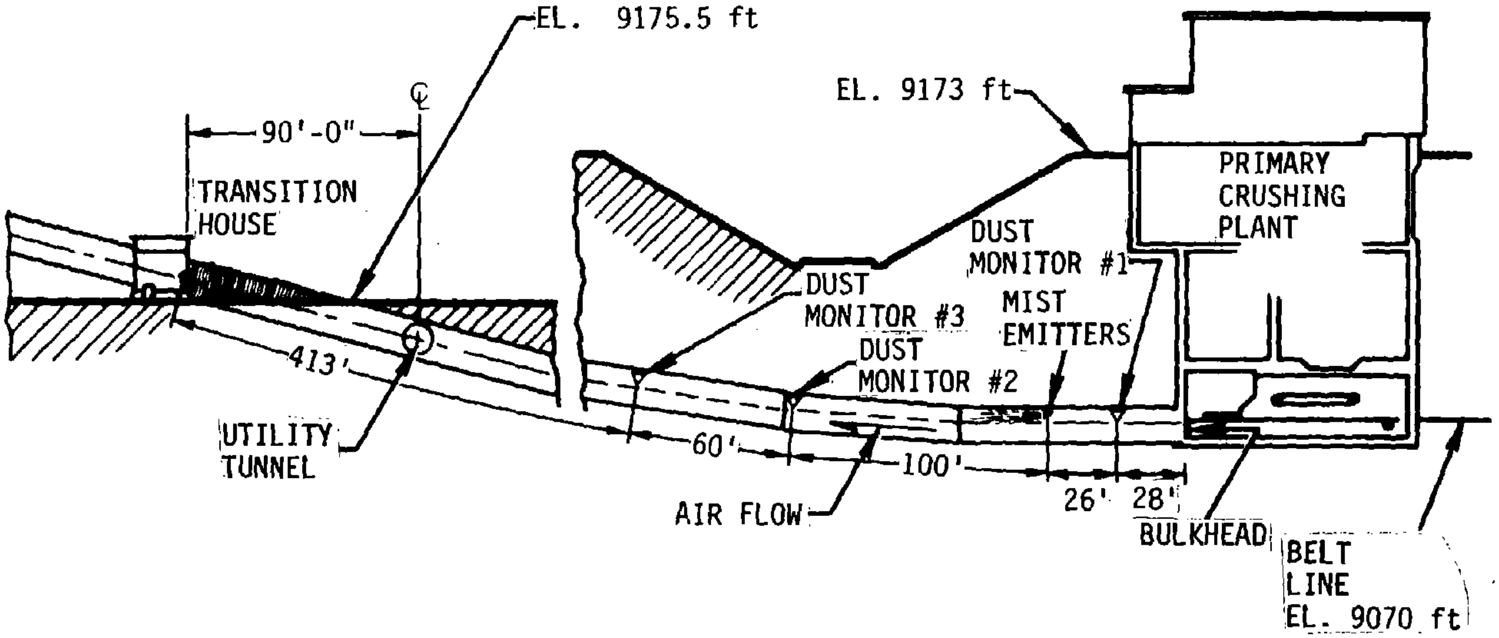


FIGURE 23. - General mill site arrangement belt conveyor no. 1 elevation.

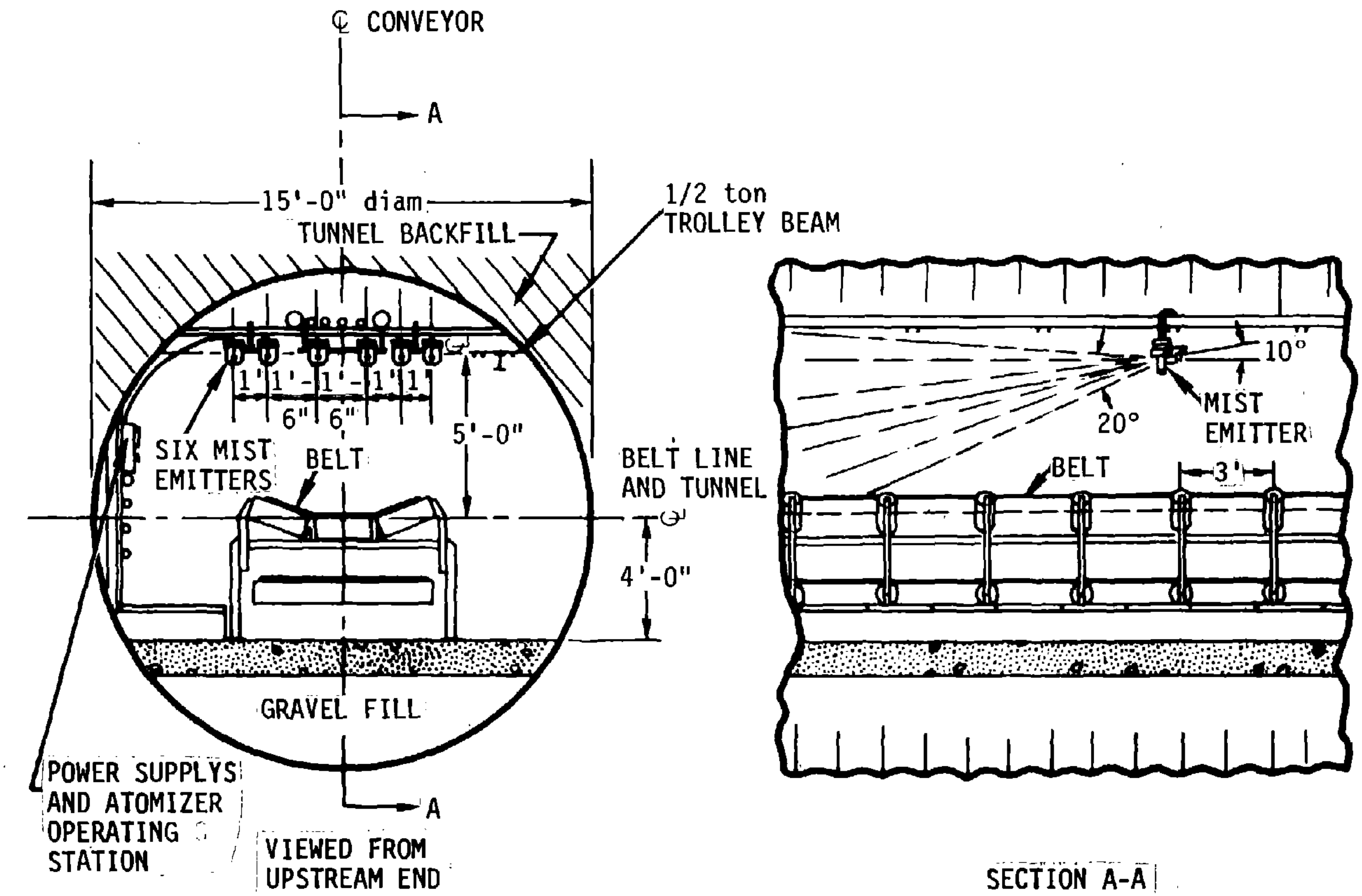


FIGURE 24. - A cross-section of conveyor tunnel.

Respirable dust in the conveyor tunnel is generated by the freshly crushed ore on the moving belt and also from the return side of the belt and belt idlers. Dust appeared to be generated along the entire conveyor length (dust levels increased along the length of the tunnel going from the crusher building to the transition house).

The discharge of the crusher was enclosed and equipped with effective dust collection hoods. Little of the dust in the conveyor tunnel can be attributed to the crusher discharge. Dust collection hoods were also operating in the conveyor drive house and the head house where the ore is discharged to the stockpiles.

Ventilation in the conveyor tunnel flows from the crusher towards the head house. This flow is induced by the dust collectors in the drive and head houses, by natural draft, and by fans mounted along the length of the gallery. The ventilation through the tunnel, however, is extremely variable ranging from less than 50 to almost 200 ft/min. This variability seems to be caused by such things as local weather conditions, whether doors are opened or closed in the tunnel and crusher building, and whether the crusher pocket is full or empty. The conveyor belt also appeared to influence the ventilation signficantly, with the highest velocities measured with the belt operating.

For the charged spray field evaluation, six Mist Emitters were mounted over the conveyor as shown in Figure 24, 54 ft from the crusher building bulkhead. The heads were suspended 5 ft above the conveyor using clamps on an overhead power cable support strut. The sprays were oriented with the ventilation flow and angled downward 10 deg. The two middle heads were aimed along the centerline of the belt. The two pairs of outside heads were angled toward the belt centerline so that the spray cones overlapped. The power, compressed air, and water supply lines to each head were bundled and strapped to the strut. The charging station and water/compressed air controls were mounted on supply pipes along the tunnel wall upstream of the heads.

Cyclones for the instantaneous dust monitors were suspended from the overhead struts at three locations:

a. Location 1 - 26 ft upstream of the heads

b. Location 2 - 100 ft downstream of the heads

c. Location 3 - 160 ft downstream of the heads.

The locations were based on considerations of cable lengths and support structure. The instantaneous monitors were mounted on the tunnel floor with Tygon tubing connecting the monitor and cyclones. A data logger and the stripchart recorders were mounted beside the spray control station.

4.3 Testing Procedures

Initial test plans called for monitoring dust levels in the tunnel with and without the spray system operating. Plans called for varying the number of heads and for alternating between sprays with no charge, positive charge, and negative charge. When actual testing started, however, levels measured by the instantaneous dust monitors were significantly higher when the sprays were operating. It was suspected that the higher readings were caused by the solid particulates released following evaporation of the extremely fine water droplets emitted by the charged spray system. This unexpected turn of events resulted in a modification of the sampling plan in an attempt to cancel out the effect of these particles introduced by the water sprays.

Normal operations at the mill result in the conveyor belt being down for the first and last hour of each production shift. During this time dust levels in the tunnel drop to practically zero. This time was used to measure background levels due to only the spray mist. It was intended that three background levels be subtracted from data measured during system tests with the belt operating to account for the particulate introduced by the spray mist.

The standard test sequence was basically the same for all tests and consisted of the following:

a. Set up instrumentation and calibrate

b. Record background dust levels without water sprays

c. Turn sprays "on" for 10 min

d. Turn sprays "off" and monitor levels as concentrations decay back to a uniform background level.

This testing sequence was repeated with the following spray variations:

a. Six heads - no charge
b. Six heads - positive charge
c. Six heads - negative charge
d. Two heads - no charge
e. Two heads - positive charge
f. Two heads - negative charge.

Each Mist Emitter was operated a 50 psi air with a 300 ml/min water flow.

During each test dust concentration data was recorded continuously on the stripchart recorders and every 30 sec on the data logger. In addition, ventilation velocities were measured at the beginning and end of each spray test. Operational conditions such as belt loading were also observed and recorded as were temperature and relative humidity.

4.4 General Field Observations

The detailed results of the charged spray field tests are presented in subsection 4.5. Prior to that discussion, we present some general observations which may impact the use of such systems.

4.4.1 Visibility

Because the charged spray heads emit very small droplets a fog is created downstream of the heads. When only two heads were operating the fog was not very dense and visibility was not impaired. With six heads operating, however, a dense cloud of fog was created in the first 50 ft of the tunnel downstream from the heads and visibility was limited. Beyond 50 ft the density of the cloud diminished but the fog did not completely dissipate. Fog could still be seen in the airstream at the transition house over 500 ft downstream. Visibility restrictions is a problem for both charged and uncharged fog techniques.

4.4.2 Surface Wetness

The charged sprays wet the surfaces of the tunnel and conveyor belt only for 10 to 20 ft downstream of the heads. This wetness is a dew like coating on the surfaces and is not excessive.

4.4.3 Noise

Noise levels measured beside the heads in the walkway ranged from 90 dBA with two heads operating to 97 to 99 dBA with six heads operating. These high noise levels result from the compressed air used by the air atomizing type nozzles. Personnel exposure would be limited to two to four hr for the six-head case.

4.4.4 Electrical Charge

The electrical charge in the fog was quite noticeable within the first 10 to 15 ft downstream of the heads. In this region, with six heads operating, the charge would cause the hair on one's arm to react and would also cause a shock whenever a grounded surface touched.

It was also observed that by standing in the fog holding a metal object a 1/4-in. arc could be established and maintained between the metal object and ground. Although the charge levels are not dangerous in themselves, the discharge could cause one to jump or lose balance resulting in a dangerous situation in the presence of machinery. In an explosive atmosphere this discharge can to cause an ignition.

4.5 Results and Conclusions

4.5.1 Results of Field Test Program

Typical dust concentration data collected by the data logger from the RAM-1 monitors are plotted in Figure 25. Dust levels are variable depending on operating conditions. Note however that the presence of sprays produces an overwhelming increase in measured signal with uncharged sprays producing a much larger signal than charged sprays.

As stated earlier this spray effect has been determined to be caused by solids within the water supplied to the spray heads. An alternate water supply was unavailable and all attempts to cancel out the effects of this effect failed.

Table 5 presents data for all completed tests including test conditions, airflow and the mass flow of particulate matter. The total particulate mass flow was determined from the airflow rate and the RAM measured dust concentration. This mass flow eliminates the dilution effect of increased airflows, providing a clearer picture of the actual changes in particulate level. When no water sprays are operating this mass flow represents the total ambient dust make. The dust level increases due to water spray activation are seen to overwhelm the ambient dust levels.

Figures 26 through 28 graphically present the data from Table 5. Comparison of the three figures dramatically shows the increase in total dust level when the water sprays are turned on. Figures 27 and 28, both presenting data with sprays on, indicate that dust levels tend to increase with airflow whether or not the belt is operating. Figure 26, no sprays operating, curiously demonstrates more complex behavior. When the belt is off dust levels are independent of airflow. Dust levels appear to increase with airflow when the belt is on, however. We offer no particular explanation for this phenomenon which introduced additional uncertainty into the experimental results.

A survey was made using the electrostatic fieldmeter to determine the characteristics of the field established. Field strength data versus distance from the Mist Emitter is tabulated in Table 6. This survey was performed with six emitters operating in the negative spray mode. Positive sprays produced field strengths of similar magnitude.

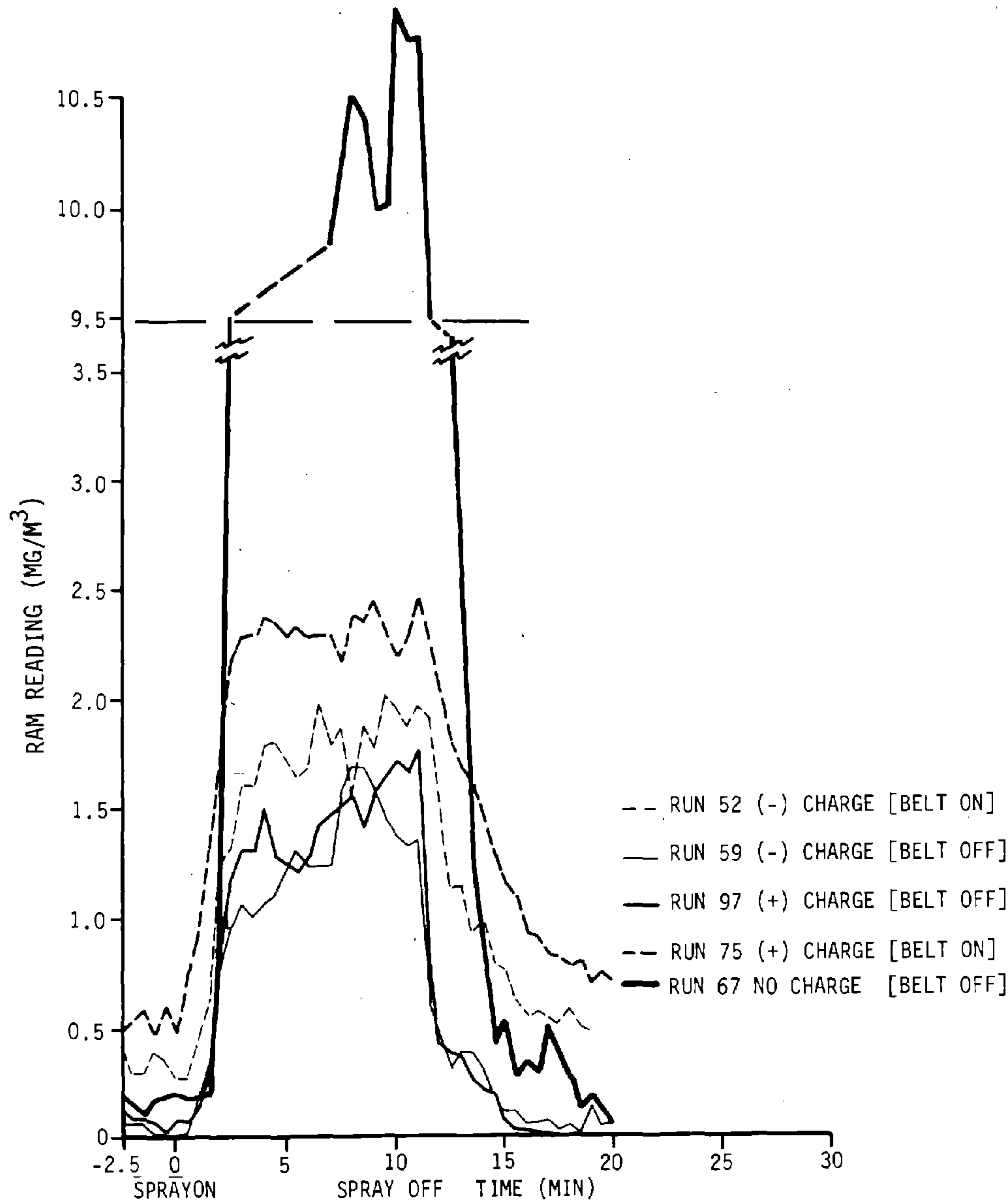


FIGURE 25. - Typical concentration values from RAM-1 monitors.

TABLE 5. - Measured particulate mass flow with and without spray

Test no.	Test conditions	Airflow (m^3/min)	100 ft test location mass flow (mg/min)		160 ft test location mass flow (mg/min)	
			Before spray	Spray on*	Before spray	Spray on*
39	Without charge, belt off	194	1.9	339	3.9	460
59	Without charge, belt off	453	25.0	616	36.2	672
101	Without charge, belt off	272	-	-	24.5	519
42	Without charge, belt on	375	120.0	624	214.0	691
44	Without charge, belt on	343	-	-	134.0	629
48	Without charge, belt on	481	164.0	732	164.0	785
50	Without charge, belt on	312	59.0	563	94.0	788
52	Without charge, belt on	467	187.0	709	205.0	866
54	Without charge, belt on	481	218.0	716	202.0	921
99	Without charge, belt on	456	-	-	187.0	816
63	With charge, belt off	283	14.0	627	28.3	614
93	With charge, belt off	255	16.3	437	30.6	554
97	With charge, belt off	326	9.8	496	19.6	506
105	With charge, belt off	249	-	-	19.9	500
71	With charge, belt on	370	274.0	672	259.0	878
75	With charge, belt on	410	258.0	801	250.0	947
77	With charge, belt on	346	214.0	662	209.0	734
81	With charge, belt on	510	265.0	843	250.0	982
83	With charge, belt on	571	-	-	231.0	1036
87	With charge, belt on	493	-	-	192.0	853

*Values shown are averages for last 3 min before turning off sprays.

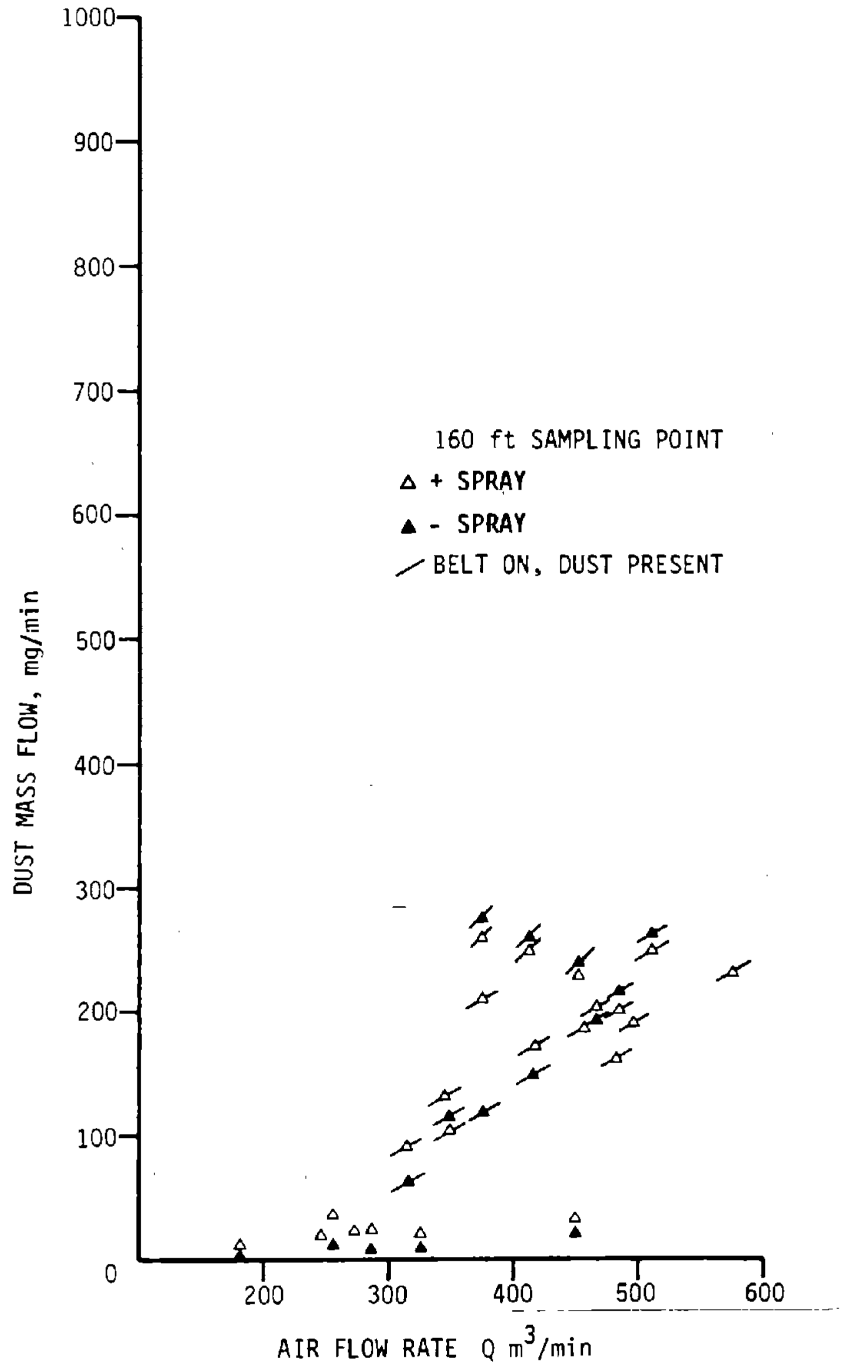


FIGURE 26. - Dust mass flow with water sprays applied.

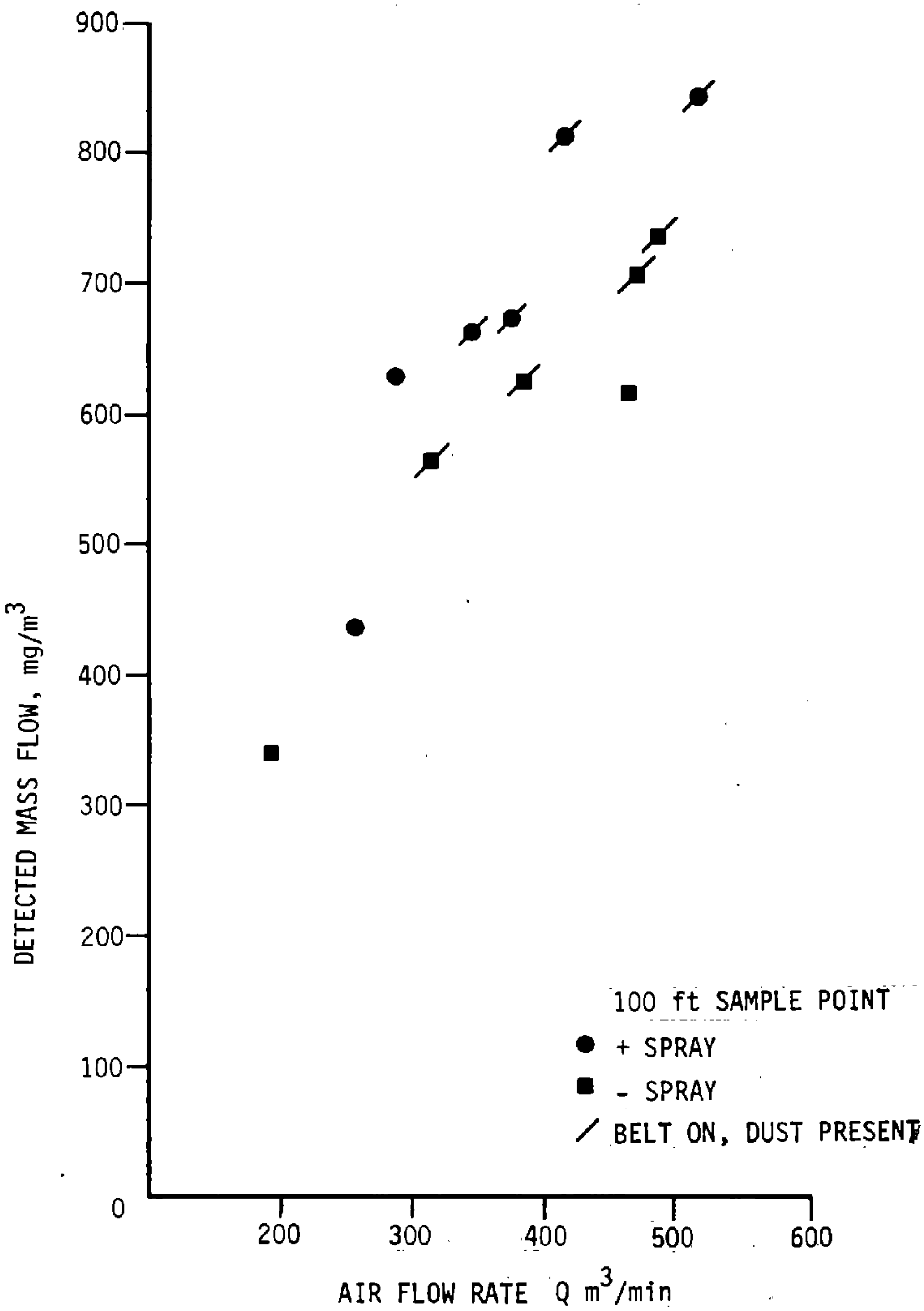


FIGURE 27. - Detected mass flow at the 100 ft downstream sampling point with water sprays applied.

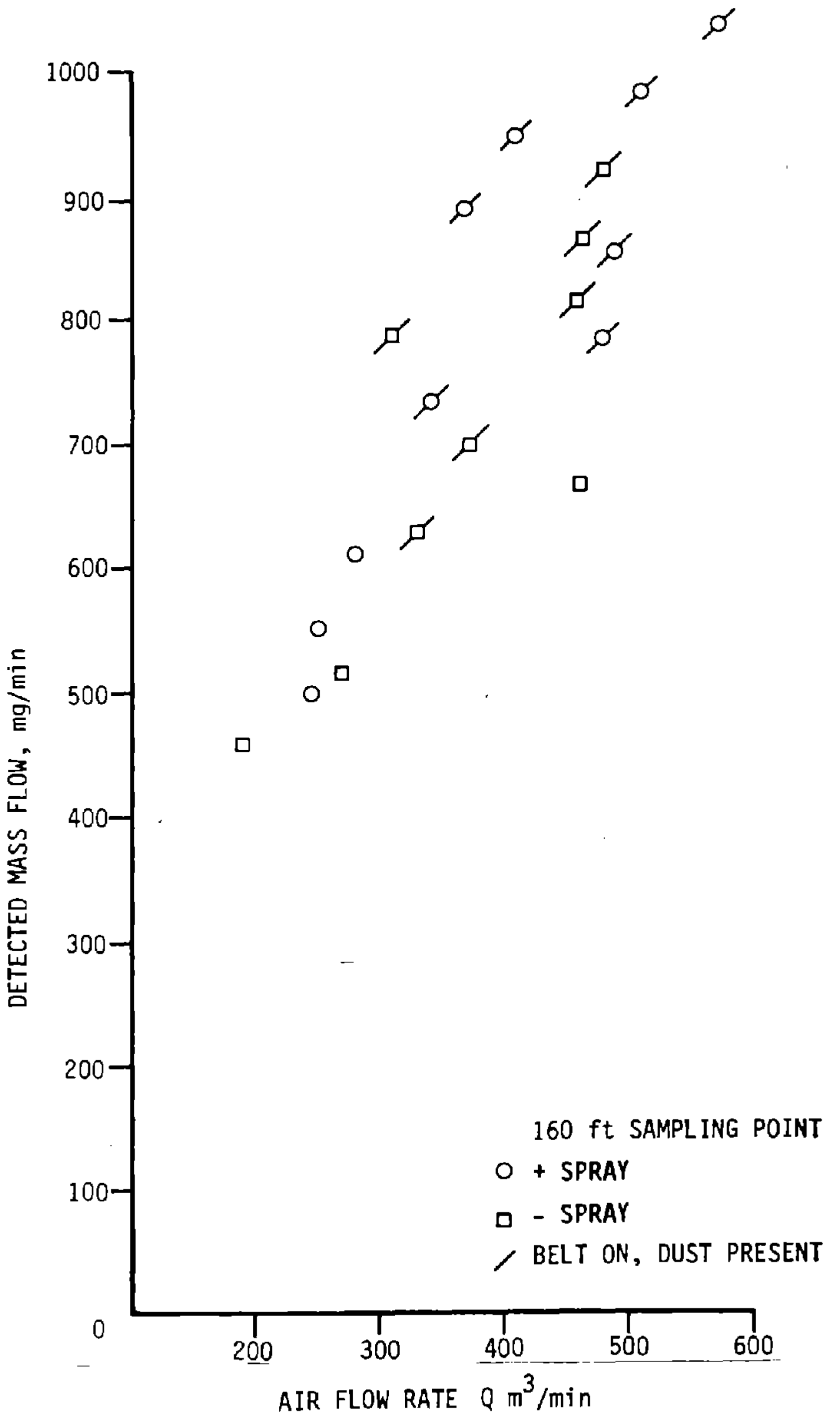


FIGURE 28. - Detected mass flow at the 160 ft downstream sampling point with water sprays applied.

TABLE 6. - Electric field strengths

Distance from Mist Emitters (ft)	Electric field strength (V/M) × 10^{-4}	
	Along centerline	Along wall
10	60.0	5.0
20	35.0	7.0
30	20.0	5.0
40	16.0	4.0
50	14.0	4.5
60	12.0	3.5
70	10.0	3.5
80	8.5	3.0
90	6.0	3.0
100	4.0	1.6
110	4.5	1.8
120	4.5	2.0
130	4.5	2.0
140	4.0	1.6
150	3.5	1.3
160	3.0	1.3
170	3.0	1.4
180	3.0	1.2
190	3.0	1.3
200	2.5	1.1
210	2.5	1.1
230	2.5	1.1
250	2.2	1.0
280	2.5	1.0

According to Gauss' Law, a uniform charge density would produce higher field strengths at the wall than at the centerline. The higher field strengths at the centerline indicate that uniform charge density, an assumption of the mathematical model, has not been achieved. However, laboratory tests showed a similar nonuniform charge density effect which produced a higher field strength near the center of the test chamber. The peak centerline field strengths are similar to some of those measured in the laboratory. This implies that dust reduction effects should be similar to those measured in the laboratory tests.

4.5.2 Discussion of Test Results

The discussion of the field test results includes a prediction of the reduction in dust concentration for the field conditions based on the analytical model. This is followed by an explanation of the phenomenon that interfered with verification of this prediction.

Predicted Dust Reduction

Appendix B developed an equation for predicting fractional dust reduction, η, in terms of net decay rate, ΔR_D, and residence time, t.

$$\eta = 1 - e^{-\Delta R_D t}$$

For the field tests, the residence time is taken as the transit time between the Mist Emitters and the measurement stations located at 100 and 160 ft from the Mist Emitters. This time is just the air velocity divided into the distance. The decay rate (ΔR_D) is assumed to be similar to the values determined in laboratory testing for equivalent water spray to air loadings. Figure 29 shows a plot of the data from laboratory testing. The operating region for the mine test was in the neighborhood of the lowest of the laboratory tests. This is consistent with the measured values of electric field strength. The mine tests field strengths were comparable to those measured in the laboratory when the water loading was low. This provides some support for scaling the decay rate with water loading.

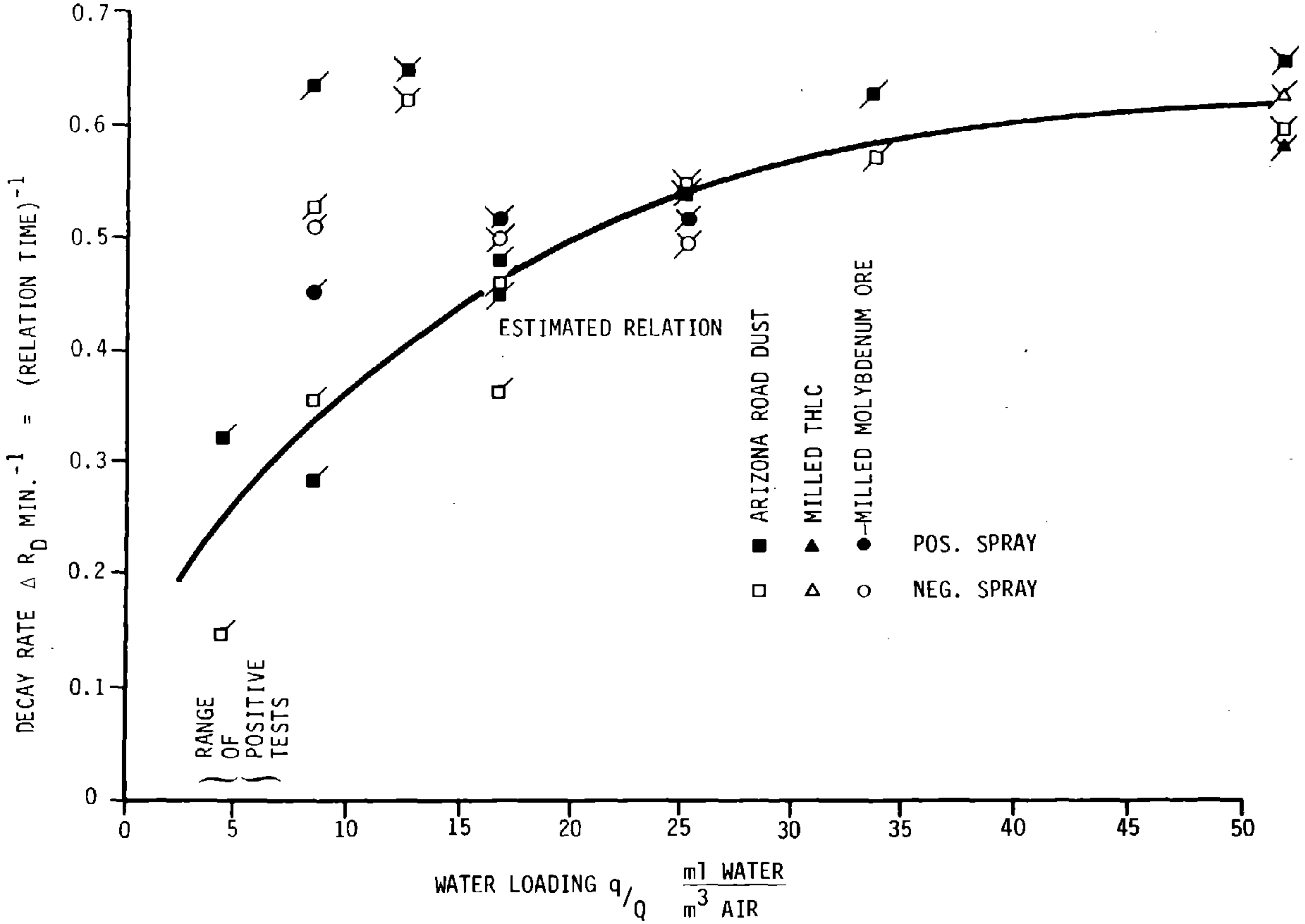


FIGURE 29. - Laboratory data of ΔR_D versus water loading on airflow.

Table 7 shows predictions for dust reduction under the conditions of several mine tests using positive sprays. For these test conditions, predicted dust reductions range from 0.10 (10 percent) to 0.33 (33 percent). The range is due primarily to variations in air velocity which directly affect residence time. Air velocity (flow) affects decay rate (ΔR_D) slightly due to changes in water loading (Figure 7a). Dust reductions of 30 percent should be detectable by direct measurement, with 10 percent reductions likely to be identifiable through statistical techniques.

The high dust concentrations indicated by the RAMs when the sprays were activated totally masked any actual reduction in the ambient dust levels. For example, according to Table 7, the conditions for Test No. 77 predict dust reductions of 33 percent at a point 160 ft from the emitters. The data from Table 6 indicates that activation of the water sprays increased the measured total dust levels at this location by a factor of 3.5 from 209 to 734 mg/min. A 33 percent reduction in the original dust concentration would be totally overwhelmed by the particulates introduced by the water sprays.

TABLE 7. - Predicted dust reduction

Test no.	q/Q (ml, water/ m^3, air)	Estimated ΔR_D $(min)^{-1}$	Fractional dust reduction	
			At 100 ft	At 160 ft
71	4.87	0.26	0.18	0.27
75	4.39	0.24	0.15	0.23
77	5.21	0.31	0.22	0.33
81	3.53	0.23	0.12	0.18
83	3.15	0.22	0.10	0.16
87	3.65	0.26	0.14	0.21

Spray Effects on RAM-1 Monitors

The response of the RAM aerosol monitors to the water sprays produced considerable consternation initially. No such response had been observed by us during the laboratory evaluation of the Mist Emitters or during other underground investigations. Other researchers such as Thakur (20) have also indicated that the RAM-1 monitors have a very low response to water mist. Reasons for this insensitivity are not completely understood, but it is accepted through empirical experience by RAM-1 users in underground dust control work.

Analysis of the situation indicates that disolved solids in the water supply are responsible for the unanticipated behavior of the RAM monitors. While the RAM-1 is noted for insensitivity to fine water droplets, it is documented as very sensitive to solid particulate matter. Spraying very fine droplets into unsaturated air produces a spray drying effect that leaves a solid aerosol particle or perhaps a droplet of precipitated solute slurry which is detected by the RAM-1. Quantitatively the potential exists for the dissolved solids to produce the particulate concentration measured. The mine measured the dissolved content of the service water at 1900 ppm. For Test No. 77, wet bulb and dry bulb temperatures were measured upstream and downstream of the spray injection. Conditions were:

a. Temperature upstream - 60°/67°F wet bulb/dry bulb

b. Temperature downstream - 64°/67°F wet bulb/dry bulb

c. Pressure - ∿21 in. Hg (9000 ft elevation)

d. Water flow - 1800 ml/min

e. Airflow - 346 m^3/min.

Using psychrometric charts to calculate evaporation rate and assuming all dissolved solid is released from evaporated water as an aerosol, a particulate mass flow of 2000 mg/m^3 is calculated. This corresponds to a particulate concentration of 5.8 mg/m^3. The measured value at the 160 ft sampling point was 2.1 mg/m^3. Thus, the high RAM readings could be explained by the detection of only one-third of the total solids present in the sprayed water.

Many reasons can be offered for detecting only a fraction of the total solids present. These include:

a. Particles of solute are highly charged and therefore driven out of the airstream by the charged droplet cloud. (This theory is supported by experimental data indicating that uncharged spray produces much higher measured concentrations than charged spray clouds.)

b. Droplets not evaporated to annihilation may just concentrate solute without forming a solid particle detectable by the RAM.

c. Water on the floor and walls may evaporate without releasing solute into the air.

An alternative to dissolved solids in the water is a colloidal suspensions in the water which would produce the same effect. No evidence exists that a colloid is present, however.

An important result of this observation is that atomizing sprays (charged or uncharged) must be used carefully. If sprayed into unsaturated air, dissolved or suspended solids in the water are likely to increase the respirable dust concentrations in the air and become a health hazard. This material becomes a real part of the dust burden. Both low humidity air and ventilation flow increase evaporation and lead to higher release of solute particles into the atmosphere. The only way to avoid the problem is to use water free of dissolved solids or suspended material.

A test with a gravimetric sampler showed that the aerosol particles are not an artifact of sampling with the RAM-1 instrument. With sprays operating and the presence of dust expected to be nil, a dried filter indicated 1.3 mg/m^3 of dust. No correspondence reading was made with the RAM-1.

This dramatic effect of dissolved solids on measured dust levels was totally unforeseen. It is hoped that others will take warning and be prepared for it during testing and operation of atomizing sprays for dust control.

4.6 Operational Recommendations and Considerations

Operational recommendations can be made regarding the application of charged water sprays even in light of the inconclusive test results. Solids content of the water is to be eliminated or minimized. Additional recommendations apply only to equipment with characteristics similar to the Dustron Mist Emitters, which is able to produce charge on the spray on the order of 3 $\mu C/g$ with a characteristic droplet size of 30 μm.

The expected fractional dust reduction may be estimated by:

$$\eta = 1 - e^{-\Delta R_D t}$$

where

η = fractional dust reduction

ΔR_D = estimated dust decay rate based on the water loading (see Figure 29)

t = residence time in minutes

For practical purposes, water loading should be in the range of about 25 to 35 ml, water/m^3, air. The lower value is for effectiveness. The higher value is for cost considerations (note the flattening of the curve in Figure 29).

Residence times for the dust and spray to be in contact should be 1 min or more. The longer the residence time, the greater the dust reduction.

Gassy mines or other explosive atmospheres must not use charged sprays. Even if the equipment is made permissible, the charge cloud is a spark hazard. During field tests, personnel within the cloud produced electric sparks on many occasions when touching grounded objects. Their footwear insulated them sufficiently for the charged droplets to accumulate a charge on their bodies which arced to ground when a finger came close to a grounded conductor. Further, electric field strengths of 6 KV/cm (6×10^5 V/m) were measured inside the cloud. This is one-fifth the spark-over point of air, hence the droplet cloud was operating close to the point of initiating sparks (at some sharp, grounded points this may have been occurring without being observed). The spark hazard should prevent the use of charged spray systems where explosion is possible.

Personnel safety requires consideration. The electrical effects are low energy, static effects which are not electric shock hazards as such. However, electrostatic shock could cause someone to jump resulting in a fall or a hazardous entanglement with moving machinery. Fog sufficient for rapid dust reduction reduces visibility considerably. In the darkened, underground environment, this may expose individuals to increased dangers. These factors must be examined on a case by case basis for any underground application.

Compressed air atomizers present a potential health hazard. Noise levels for six units would limit a worker to about a 3 hr exposure. The noise factor must be considered in practical installations.

A characteristic of the Dustron Mist Emitters, and perhaps of other equipment that might be used, is that the charged droplet are attracted to the induction rings which shorts out the induction ring circuit. This markedly reduces charge on the spray produced. For this reason, the Mist Emitter must be placed so that ventilation air carries virtually all the droplets away from the Mist Emitters. The Emitter should not be immersed in the fog it generates.

5. CONCLUSIONS AND RECOMMENDATIONS

Conclusions and recommendations for future research are presented and discussed in some detail in the following subsections.

5.1 Conclusions

On a unit water basis charged sprays offer considerably higher dust removal potential than do sprays not intentionally charged.

On a unit water basis, dust removal exceeds any level expected for hydraulically atomized water sprays. To gain some feeling for this, the highest water spray flow rate used in this program was the less than 1/2 gpm (1.8 liters/min) used in the field tests. Even at this extremely low flow rate, a 33 percent dust reduction was expected for one case. The recommended flow rate for highly charged sprays in 1 gpm water flow to 10,000 cfm airflow. This is considerably lower water usage than expected for conventional sprays.

Significant contact time between the charged spray and the dust cloud is required for effective dust removal.

While hydraulic sprays work virtually instantaneously on exposed dust, charged sprays require times on the order of a minute to produce good dust reduction. To obtain this time, ventilation velocities must be low so as to provide a long residence time for the spray dust interaction. This restriction limits potential underground sites. Desirable sites are therefore places with low ventilation velocities and a need to restrict or conserve water.

Some general conclusions on the nature of charged spray dust reduction are:

a. Either polarity alone is more effective than combined polarities.

b. Positive and negative polarities are equally effective.

c. Little difference in effectiveness exists among various dust types.

Engineering predictions for dust reduction may be made. These were not confirmed by field trial so the accuracy of the predictions is presently unknown. However, the predictive model provides the dust control designer with an estimating tool for scoping equipment requirements and expected performance.

Charged spray must not be used in gassy mines. Sparks observed during the mine tests demonstrated conclusively that the charged cloud (not equipment) produced electric arcs. While not an electrical danger to personnel, the charged cloud will lead to an ignition source in an explosive atmosphere.

Good quality water must be used with any water atomizing sprayers - not just for charged sprays. This was an unexpected finding of this program. Dissolved or suspended solids in the spray water can be released as dust into the atmosphere as small droplets are evaporated to annihilation. This leads to the respirable dust burden counter to the general dust reduction objective.

5.2 Recommendations for Future Research

Surface sites for appropriate application of charged spray dust control should be identified. Since low ventilation velocity and restricted water requirements are not common, underground surface mining and mill applications may prove more suitable. Surface sites will also have lower probabilities of explosive atmospheres.

Equipment should be developed to produce larger volumes of charged spray at costs significantly below these currently achieved. Larger quantities of highly charged water spray at a lower cost than simply combining existing systems are necessary for the technique to be attractive for mine-scale dust problems. For the mine test in this program, about four times the charged water spray for the cost would seem appropriate. The noise level from the compressed air atomizers must be reduced for multiple units. Also for practicality the equipment should be able to operate effectively while immersed in the charged cloud. Design approaches using charging and atomizing techniques other than those employed in the currently available commercial systems should be explored.

Fundamental experimental measurements of dust electrical mobility should be undertaken. Little information exists regarding the charge on dust particles. This has required some speculation when estimating mobility during theoretical considerations.

Electric mobility analyzers are difficult to build and calibrate. This is one reason data is scarce. A data void for respirable particles exists and should be filled. Aerosols exposed to charged spray as well as naturally occurring dust should be investigated. Mobility valves are essential to better quantification of the mechanism of charged spray dust removal.

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APPENDIX A

THEORETICAL ANALYSIS AND MATHEMATICAL MODELING

A.1 Introduction

In this appendix a theoretical analysis is developed for the process of removing respirable dust using charged water droplets. An exact analysis is very complex because of many factors which include:

a. Three dimensional space variations of water droplet and dust particle sizes

b. A spectrum of droplet sizes and dust particle sizes

c. Unsteady flow effects

d. Turbulent mixing

e. Unknown levels of charge on the droplets and dust particles

f. Unknown size distribution of particles and droplets.

To gain some understanding of the process, a simple model of charged dust and charged droplets is formulated using conservation of mass of each species and simplified force equations. The resulting equations for this well-mixed model can be used to estimate the effectiveness of dust removal by charged droplets.

Analysis using the simple model indicates that the removal of dust by electrostatic attraction between charged droplets and oppositely charged dust, the charged droplet scrubber (CDS), would take so long that this is an unlikely explanation of reported successful tests. Likewise precipitation of the naturally charged dust due to the space charge from the droplets, charge droplet precipitator (CDP), would take as long. However, ions produced from the process of generating charged droplets could attach to the dust particles and increase particle mobility, thereby, making dust precipitate faster due to the field from the droplet space charge. This system operating as a single stage space charged precipitator can remove dust quickly enough to be practical and explains reported successes. Previous work of record has not recognized the importance of the ionic contribution, this is likely due to holding the hypothesis that the significant mechanism for dust removal is collection of dust on droplets. Recent field tests (10) have shown little difference between the sign of the charge on the droplets and dust control effectiveness. This observation is consistant with the single stage space charge precipitator model identified here as the significant mechanism.

A.2 The (Simple) Well-Mixed Model

The simplified theoretical model used for this analysis is to consider a volume V containing particle-laden air into which liquid droplets are introduced at a rate of R_d droplets per second as illustrated in Figure A-1. All droplets are the same size (radius R) and carry the same charge Q. The droplets do not evaporate or coalesce. The droplets move because of the electric and gravitational forces exerted on them. The droplets are assumed to be uniformly distributed in space because of the turbulent mixing caused by the liquid injection and by the drafts and circulations which exist because of vehicle and personnel motion, in the surrounding region. The dust particles are similarly assumed to be of uniform size, equally charged, and distributed evenly in the same volume V.

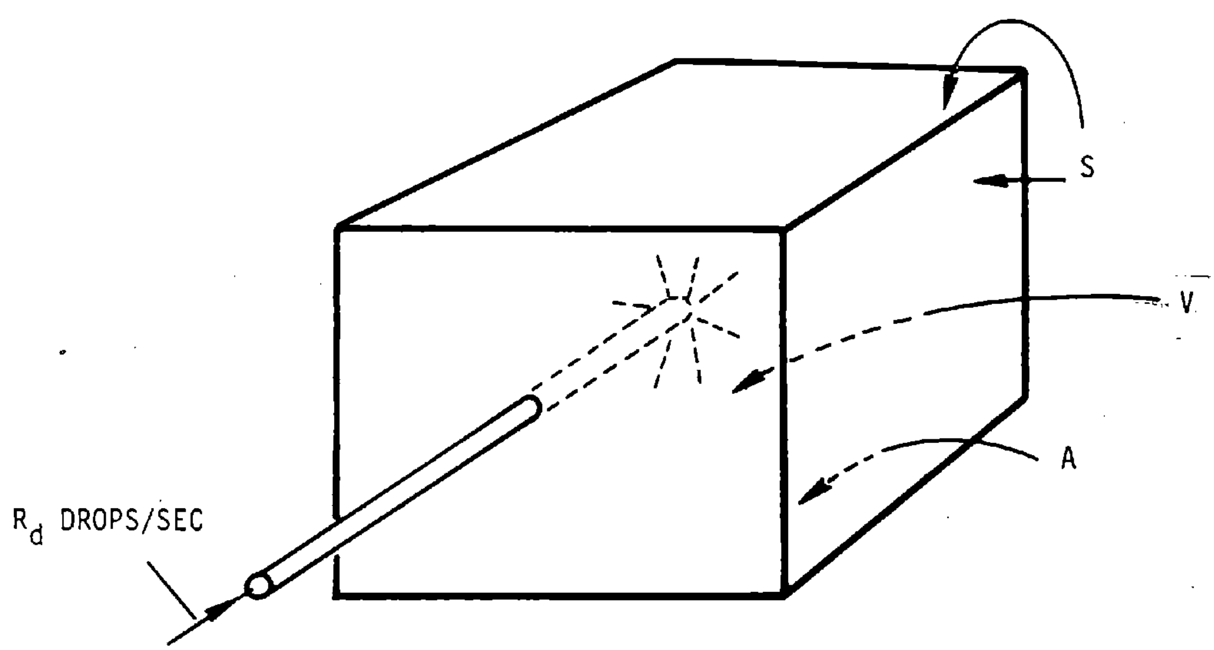

FIGURE A-1. - Definition of mixed interaction volume.

The space charge density due to the dust is assumed to be small compared with the charge density due to the droplets. This assumption permits the motion of the droplets to be uncoupled from the motion of the dust cloud. Consequently, the dynamics of the droplets can be investigated first, followed by the study of dust particle captured by the droplets or by the precipitation out of the volume of interest due to the space charge from the droplets.

A.3 Droplet and Dust Motion

A.3.1 Droplet Motion

After the droplets are injected into the air at high velocity, they are rapidly decelerated toward the velocity of the surrounding air. The period of interest, for this discussion, follows this deceleration. Inertial forces, therefore, can be ignored and the important forces on the droplet are electrical, gravitational and viscous. Using Stoke's law for fluid drag at low Reynold's number yields

$$6\pi\eta R(\bar{v}_R - \bar{v}) = Q\bar{E} + \frac{4}{3}\pi R\rho_M\bar{g} \qquad \text{(A-1)}$$

where the variables are as defined in Table A-1.

The droplet flux density $\bar{\Gamma}$ is then given by

$$\bar{\Gamma} = N\bar{v}_R = NB\bar{E} + NB_g\bar{g} + N\bar{v} \qquad \text{(A-2)}$$

where B and B_g are defined in the table of nomenclature.

Conservation of droplet mass for volume V states that

$$0 = \begin{array}{c}\text{rate of charge}\\ \text{of droplet mass}\\ \text{within volume V}\end{array} + \begin{array}{c}\text{flux of droplets}\\ \text{out through board-}\\ \text{ing area of V}\end{array} - \begin{array}{c}\text{droplets}\\ \text{injected}\\ \text{into V}\end{array}$$

or

$$0 = \frac{d}{dt}\int_V N dV + \oint_S \bar{\Gamma}\cdot\bar{n} ds - R_d$$

TABLE A-1. - Nomenclature (units are MKS)

A	=	"floor" area of V
a	=	radius of dust particles
B	=	electric mobility of droplets
B_g	=	gravitional mobility of droplets
b	=	electric mobility of dust particles
b_g	=	gravitational mobility of dust particles
ds	=	elemental area of surface
$\overline{E}$	=	electric field
E_c	=	contact charging electric field
E_{in}	=	induction charging electric field
G	=	rate of dust particle collection on a drop
G_i	=	rate of ion collection on a dust particle
g	=	acceleration of gravity
M	=	droplet mass
N	=	droplet number density
$\underline{N}$	=	$N(B_g gA/R_d)$, normalized droplet number denisty
$\underline{N}_{eq}$	=	N in steady state
N_{eq}	=	$N_{eq}(B_g gA/R_d)$, normalized, steady-state, droplet number density
n	=	dust number density
$\overline{n}$	=	outward unit vector normal to ds
n_{eq}	=	dust particle number density
n_i	=	ion number density
n_o	=	dust particle number density at t=0
$n(t)$	=	removal rate of dust particles
Q	=	charge on a droplet

TABLE A-1. - Nomenclature (units are MKS) (Continued)

Q_V	=	water flow rate to droplet generator
$\underline{Q}^2$	≡	$VR_d BQ/B_g{}^2 g^2 A^2 \varepsilon_c$ = ratio of electric repulsion to gravity forces
q	=	charge on dust particle
q_i	=	ion charge
q_s	=	saturation charge on dust particle
R	=	radius or droplet
R_d	=	droplet injection rate
r_d	=	dust particle injection rate
r_i	=	ion injection rate
S	=	surface of V
t	=	time
$\underline{t}$	≡	$t(B_g gA/V)$ = normalized time
V	=	droplet/dust interation volume
$\bar{v}$	=	air velocity
$\bar{v}_R$	=	droplet velocity
$\bar{\Gamma}$	=	droplet flux density
$\bar{\gamma}$	=	dust particle flux density
ε_o	=	permittivity constant of free space, 8.85×10^{-12} (farad/meter)
η	=	air viscosity
ρ_M	=	mass density of droplet
ρ_m	=	mass density of dust particle
τ_c	=	decay rate time constant for dust particles
τ_n	=	time constant for droplet build-up

Solving for R_d yields

$$R_d = \frac{d}{dt}\int_V N dV + \oint_S \overline{\Gamma} \cdot \overline{n} ds \qquad \text{(A-3)}$$

Combining Equations (A-2) and (A-3) yields

$$R_d = \frac{d}{dt}\int_V N dV + \oint_S N B \overline{E} \cdot \overline{n} ds$$
$$+ \oint_S N B_g \overline{g} \cdot \overline{n} ds + \oint_S N \overline{v} \cdot \overline{n} ds \qquad \text{(A-4)}$$

The contribution of the last term is taken to be negligible at the boundaries of the volume V because the gas velocity $\overline{v}$ is expected to be small at the boundaries. (If the boundaries of the volume V are taken to be those of a rigid box, the normal component $\overline{v} \cdot \overline{n}$ vanishes completely). The gravitational force is assumed to be vertically downward so the third term on the right-hand side is integrated over the vertically projected area A ("floor" area). The complete mixing assumption states that N is a constant. Therefore, Equation (A-4) becomes

$$R_d = V\frac{dN}{dt} + NB \oint_S \overline{E} \cdot \overline{n} ds + N B_g g A \qquad \text{(A-5)}$$

Integration of the electric field intensity in the second term on the right is accomplished using Gauss' law in integral form which yields

$$\oint_S E \cdot n ds = \frac{1}{\varepsilon_o}\int_V NQ dV = \frac{NQV}{\varepsilon_o} \qquad \text{(A-6)}$$

Thus, Equation A-5 becomes the desired drop conservation statement.

$$\frac{R_d}{V} = \frac{dN}{dt} + \frac{BQ}{\varepsilon_o} N^2 + \frac{B_g g A}{V} N \qquad \text{(A-7)}$$

The maximum number density of drops is obtained when the time rate of change has reached zero. In a steady-state condition, Equation A-7 takes the form of a quadratic expression in N. With the steady-state number density defined as N_{eq}, the resulting expression is

$$\underline{Q}^2 N_{eq}^{\;2} + \underline{N}_{eq} - 1 = 0 \qquad \text{(A-8)}$$

where the equilibrium number density has been normalized such that

$$\underline{N}_{eq} \equiv N_{eq} \left(\frac{B_g g A}{R_d} \right) \qquad \text{(A-9)}$$

and the parameter expressing the ratio of electrical repulsion forces to those of gravity is

$$\underline{Q}^2 \equiv \frac{V R_d B Q}{B_g^{\,2} g^2 A^2 \varepsilon_o} \qquad \text{(A-10)}$$

The normalized equilibrium drop number density is shown in Figure A-2 as a function of this parameter.

If the process by which this equilibrium is reached is of interest, then Equation A-7 must be solved. In particular, consider the transient that results from suddenly turning on the drop injection when $t=0$. Then, for $t > 0$, Equation A-7 is written in the normalized form

$$1 = \frac{d\underline{N}}{d\underline{t}} + \underline{Q}^2 \underline{N}^2 + \underline{N} \qquad \text{(A-11)}$$

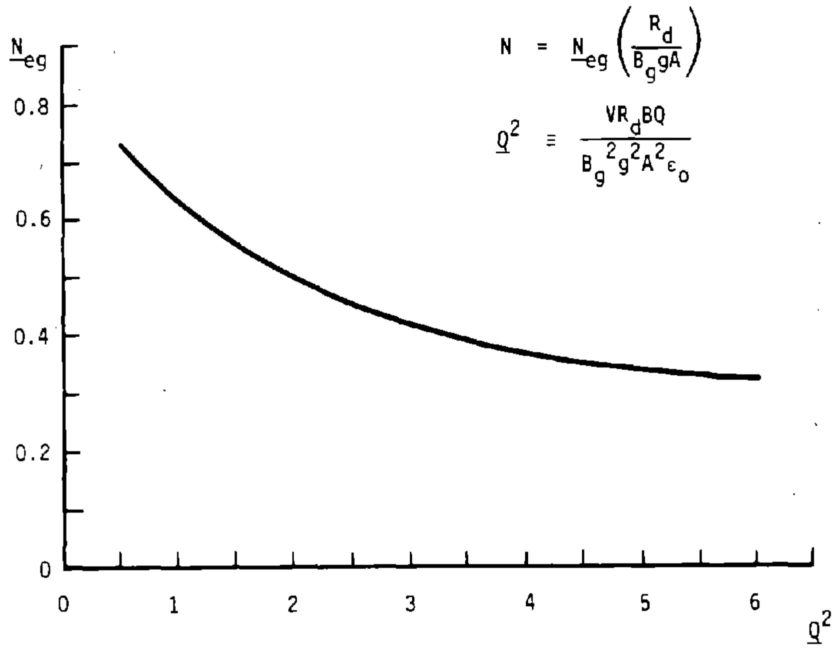

FIGURE A-2. - Equilibrium drop density versus charge.

where in a manner similar to Equation A-9, the drop number density is normalized such that

$$\underline{N} = N\left(\frac{B_g gA}{R_d}\right) \qquad \text{(A-12)}$$

and time is normalized to a time scale reflecting the rate of drop sedimentation.

$$\underline{t} = t\left(\frac{B_g gA}{V}\right) \qquad \text{(A-13)}$$

In terms of these normalized variables, the temporal buildup of the drop number density is shown in Figure A-3 with the dimensionless parameter representing the effect of the drop charge as a parameter. The asymptotic values of N are, of course, the equilibrium values given by Figure A-2. These curves have been obtained by numerically integrating Equation A-11 using the initial condition that N=0. Analytical expressions for the time

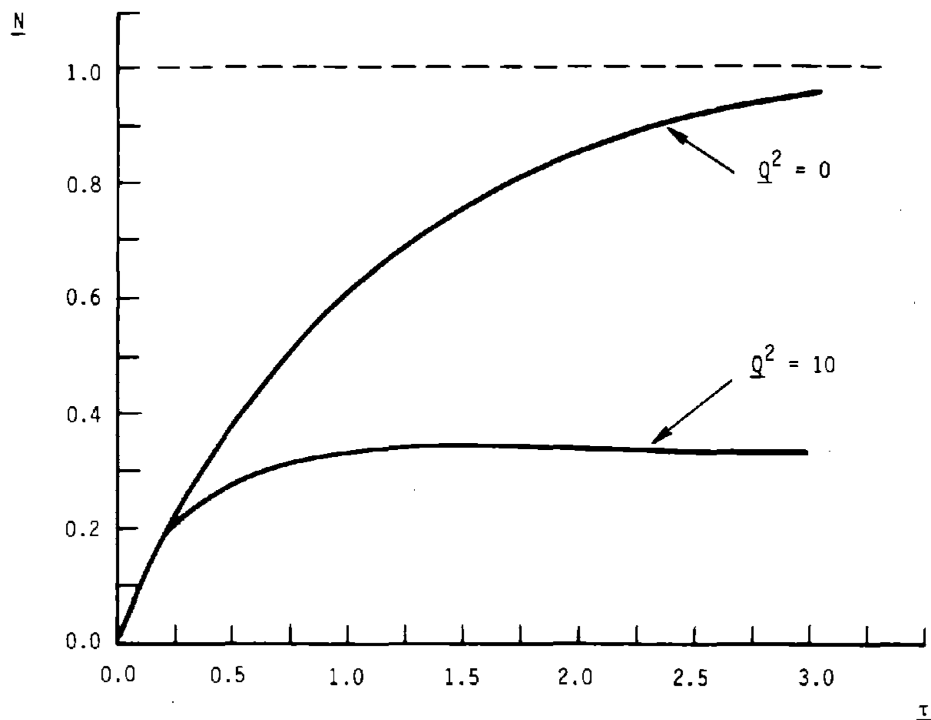

FIGURE A-3. - Drop density versus time.

dependence are easily obtained for the limiting cases of large and small $\underline{Q}^2$. First, if $\underline{Q}^2$ is small, Equation A-11 becomes

$$1 = \frac{d\underline{N}}{d\underline{t}} + \underline{N} \qquad \text{(A-14)}$$

and the solution is simply

$$\underline{N} = 1 - e^{-\underline{t}} \qquad \text{(A-15)}$$

For the opposite extreme where $\underline{Q}^2$ is large compared to unity Equation A-11 reduces to

$$\int_0^{\underline{t}} d\underline{t} = \int_0^{\underline{N}} \frac{d\underline{N}}{1 - \underline{Q}^2\underline{N}^2} \qquad \text{(A-16)}$$

and integration of this expression gives

$$\underline{N} = \frac{1}{\underline{Q}}\left(\frac{1 - e^{-2\underline{Q}t}}{1 + e^{-2\underline{Q}t}}\right) \qquad \text{(A-17)}$$

A.3.2 Dust Particle Motion

The motion of the particles, under the initial assumptions, depends on the droplet charge. In an induction or contacting drop charger, the drops carry a charge away from the atomizer, determined by the electric field at the point of breakaway. This charge is of the order of

$$Q \sim 12\pi\varepsilon_o R^2 E_{in} \qquad \text{(A-18)}$$

where E_{in} is the induction electric field existing in the neighborhood of the point of drop breakaway. Using drops having the reported average radius $R = 10 \times 10^{-6}$m and assuming that E_{in} is about 10^6 v/m (within a factor of 3 of the breakdown strength of air), Equation A-18 gives 2×10^5 electronic charges. Hoenig (5) reports 8×10^5 electronic charges.

Once in the drop jet or the well mixed volume, the drop is subject to an electric field that is the sum of the field from the high voltage on the atomizer and the space charge from the drops. The electric field strength far from the atomizer is much less than at the atomizer, where the field tends to concentrate. It also is expected that the field due to the drops is much less than a value approaching electrical breakdown. Thus, it is reasonable to presume that, within the zone of interest, the drops have a charge that exceeds the saturation charge of the drop based on its local macroscopic electric field intensity. This gives an optimistic view of the effectiveness of positive drops in collecting negative particulates. If the collection is not sufficiently predicted here, other mechanisms are important and must be explored.

The rates of collection of charged particles by an oppositely charged drop is derived elsewhere by Melcher (8). It is shown there that if a charge on the drop exceeds the local saturation value (so that all of the drop surface is active in collecting oppositely charged particles) then the rate at which particles are collected on a drop is

$$G = \frac{nbQ}{\varepsilon_o}, \text{ dust particles/sec} \qquad \text{(A-19)}$$

where b is the mobility of the dust particle. (This is the collection law for a drop in either regime i or k of Figure 5.5.3 in Melcher.) (8)

Situations of interest include the following:

a. When $t = 0$ there are n_o dust particles/m^3 in the interaction volume and the drops are suddenly turned on. How rapidly is the dust removed, that is, what is $n(t)$?

b. Dust is injected into the volume at a rate of r_d dust particles/second. To what equilibrium level can the drops reduce the ambient number density of particles in the interaction volume?

A collection law that describes both of these situations, and hence the flux density of dust particles, is given by

$$\bar{\gamma} = \pm nb\bar{E} + n\bar{v} + nb_g\bar{g} \qquad \text{(A-20)}$$

where the upper and lower signs refer to positive and negative dust particles and $b_g \equiv 2a^2\rho_m/9\eta$.

Then, the statement that the rate of dust injection is equal to the sum of the rate of increase of dust in the volume, the rate of loss through the surface S enclosing the volume and the rate of collection on the drops within the volume is

$$r_d = \frac{d}{dt}\int_V n dV + \oint_S \bar{\gamma}\cdot\bar{n}ds + \int_V GNdV \qquad \text{(A-21)}$$

Again, it is assumed that either because the volume is bounded by rigid walls or the gas velocity is inconsequential by the time the wall is reached, the convective contribution to $\bar{\gamma}$ on S is ignorable. This assumption is consistent with taking the view that dust leaving the volume because of drafts should not be regarded as controlled.

It is now necessary to distinguish the fate of positive and negative dust particles. For purposes of discussion, consider the drops as having a positive charge. (It is a simple matter to reverse the roles of the positive and negative dust particles if the drops are in fact negative.)

Positive dust particles are repelled by the drops. For these particles, the system behaves as a CDP (see Section 2), and the contribution of the last term in Equation A-21 is zero. The flux term represents the repulsion of the particles to the walls by the drop space charge field. Thus, for the dust particles having the same sign as the drops, Equation A-21 (with the complete mixing approximation incorporated) becomes

$$r_d = V\frac{dn}{dt} + nb\oint_S \bar{E} \cdot \bar{n}ds + nb_g \oint \bar{g}\cdot\bar{n}ds \qquad \text{(A-22)}$$

Since $\bar{g}$ is downward, the last integration is nil except for A, the floor areas. As was done for the drops, the integration of the outward directed electric flux can be made (independent of geometry) by using the integral form of Gauss' law, expressed by Equation A-6. Thus, the expression for the CDP precipitation is

$$r_d = V\frac{dn}{dt} + V\left(\frac{bNQ}{\varepsilon_o}\right)n + nb_g Ag \qquad \text{(A-23)}$$

Now consider the collection of the negative particles. In this case, the flux of particles called by the electrical term in Equation A-21 is inward. With the assumption that the surface S is either composed of solid walls or of regions in which the dust particle density is zero, it is clear that this term makes no contribution. This time it is the drop collection term that makes the electrical contribution to Equation A-21. With the complete mixing approximation and the use of Equation A-19, it follows that the equation for predicting the performance of the CDS action which prevails for oppositely charged drops and dust particles is

$$r_d = V\frac{dn}{dt} + V\left(\frac{nbQ}{\varepsilon_o}\right)N + nb_g Ag \qquad \text{(A-24)}$$

Note that the expressions predicting the density of dust having like and having opposite charge to that of the drops are the same. That is, the CDP and CDS collections predicted by Equations A-23 and A-24, respectively, are the same. In practice, it would be expected that the CDP operation would be more dependent on the physical nature of the interaction volume boundaries. That is, the repulsion of particles from the interaction volume would serve little useful purpose unless the particles eventually encountered the tunnel floor, and walls or parts in the train or material being loaded.

In general, the drop number density is itself time varying, so that Equations A-22 and A-24 can be solved only after the solution of the expression representing the temporal evolution of the drop density $N(t)$. In general, $N(t)$ is represented by the numerical results of Figure A-3. Limiting forms are given by the analytical expressions of Equations A-15 and A-17.

It is likely that the drop transient is short-lived compared to the collection precipitation transient. In that case, N can be taken as the equilibrium value (Figure A-2) and Equations A-22 and A-24 solved taking N as the constant N_{eq}. Both the steady-state and batch processes of dust reduction are represented by considering the case where the rate of dust input, r_d, is constant and where $n = n_o$ when $t = 0$. In that case the dust particle density has the time dependence

$$n = n_o e^{-t/\tau_c} + n_{eq}\left(1 - e^{-t/\tau_c}\right) \qquad \text{(A-25)}$$

where the dust equilibrium number density is

$$n_{eg} \equiv \frac{r_d}{V\left(\frac{NbQ}{\varepsilon_o}\right) + b_g Ag} \qquad \text{(A-26)}$$

and the transient for the collection or precipitation processes is governed by the time-constant,

$$\tau_c = \frac{V}{V\left(\frac{NbQ}{\varepsilon_o}\right) + b_g Ag} \qquad \text{(A-27)}$$

Thus, when $t = 0$ the number density is n_o while as $t \to \infty$ it approaches n_{eq}. The latter can be greater than or less than the starting value, as illustrated in Figure A-4. In the case where the drop transient is completed on a time scale which is short compared to the scrubbing or precipitation processes, the dust number density has the time dependence shown. In the batch

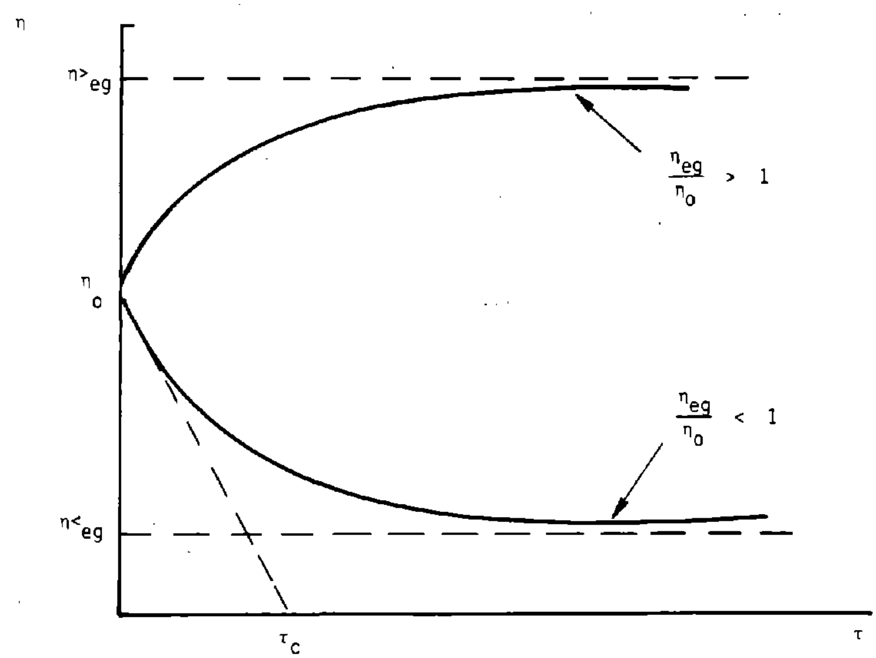

FIGURE A-4. - Dust number density versus time.

experiment, there is no input of particles and therefore the asymptotic value of n is zero. The decay rate of the exponential particle density governed by τ_c is as given by Equation A-27.

A.3.3 Discussion of the Effect of Q on τ_c

Considering the time dependence of the dust particle density given by Equation A-25, the transient for the electrical cleaning process is governed from Equation A-27 by the time-constant:

$$\tau_c = \frac{\varepsilon_o}{N_{eg} Q b} \qquad \text{(A-28)}$$

The mobility of the dust particles derived from Stokes law, is given by the following equation

$$b = \frac{q}{6\pi\eta a} \qquad \text{(A-29)}$$

The mobility b is therefore a constant because the variables given in Equation A-29 are fixed.

To see how the remaining terms affect the time constant, we need to rewrite Equation A-25 in terms of the variable parameter $\underline{Q}$.

Given the following equations from our previous discussion:

$$N_{eg} = \underline{N}_{eg}\left(\frac{R_d}{B_g\ A_g}\right) \tag{A-30}$$

$$R_d = \frac{Q_v}{4/3\pi R^3} \tag{A-31}$$

$$\underline{N}_{eg} = \frac{-1 + \sqrt{1 + 4\underline{Q}^2}}{2\underline{Q}^2} \tag{A-32}$$

and that

$$\underline{Q}^2 = \alpha Q_v Q^2 \tag{A-33}$$

where

$$\alpha = \frac{V/2\eta\ \varepsilon_o}{(2\pi R^2\ AgB_g)^2}$$

the time constant τ_c can be rewritten as follows:

$$\tau_c = \frac{K}{\left[\dfrac{-1 + \sqrt{1 + 4\underline{Q}^2}}{\underline{Q}}\right]} \tag{A-34}$$

where

$$K = \frac{2\ \varepsilon_o}{\left(\frac{R_d}{B_g A g}\right) \frac{b}{\sqrt{\alpha Q_v}}}$$

If we wish to minimize the time constant we must maximize the denominator of Equation A-34.

$$G(\underline{Q}) = \frac{-1\ \sqrt{1 + 4\underline{Q}^2}}{\underline{Q}} \qquad \text{(A-35)}$$

Using the first derivative test to determine maxima points:

$$\frac{dG}{d\underline{Q}} = \frac{1}{\underline{Q}^2} + \frac{4}{\sqrt{1 + 4\underline{Q}^2}} - \frac{\sqrt{1 + 4\underline{Q}^2}}{\underline{Q}^2} = 0 \qquad \text{(A-36)}$$

By careful examination of Equation A-36, we see that in the limit as $\underline{Q}^2$ approaches infinity the first derivative goes to zero.

This result tells us that the highest value of the parameter $\underline{Q}^2$, which is directly proportional to the charge on the drop, will maximize the function $G(\underline{Q})$ and therefore minimize the time constant τ_c.

Realizing that there is a cost factor involved with the generation of the charge on the drop, it is useful to consider a graph of the characteristic time-constant, τ_c, as a function of the parameter $\underline{Q}$. Using Equation A-33 one can therefore predict the collection time constant from the graph pictured in Figure A-5 or from Equation A-34. As can be seen, an optimum operating point is the range of 1 to 3 for $\underline{Q}$.

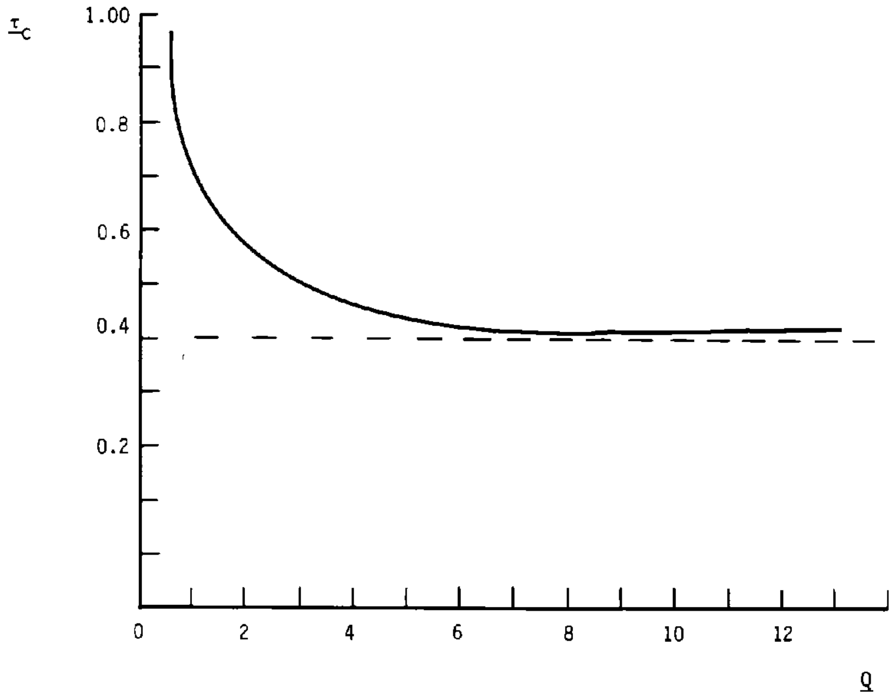

FIGURE A-5. - Normalized collection time τ_c versus drop charge.

A.4 Evaluation of Dust Removal

There are two uses to which the model can be put. First is the evaluation of air cleaning performance for a given system. Second is the design and optimization of a new system. In this second regard, the theory serves as a framework within which parameters such as the drop size, density and charge are selected with some optimal usage of resources in view. In this section, an outline is given illustrating how the model can be applied to evaluate the performance of a particular system - a CDS. The question to be answered is whether the observed or expected air-cleaning can be reasonably explained by the charged-drop mechanism inherent to the model.

Let Q_v be the volume rate of flow of the water feeding the charged-drop generator. Then, with R, the drop radius, and R_d, the number of drops injected into the cleaning volume per second,

$$R_d = Q_v/\left(\frac{4}{3}\pi R^3\right) \text{ drops/sec} \tag{A-37}$$

For example, for a volume rate of flow of 10 liters/min (Q_V = 1.67×10^{-4} m^3/sec) and drops of 60 μm diam

$$R_d = 14.5 \times 10^8 \text{ drops/sec} \qquad \text{(A-38)}$$

Perhaps the charge per drop is known from measurements of the volume rate of flow, the drop size and the drop stream current. (Such measurements may be tainted by some of the measured current actually being carried by ions.) Whether generated by induction (contact charging) or by ion impact, the charge per drop is roughly the order of:

$$Q \gtrsim 12\pi\varepsilon_o R^2 E_c \qquad \text{(A-39)}$$

where E_c is typically of the order of the breakdown strength of air. Taking E_c as 5×10^5 v/m and drops of 60 μm diam gives

$$Q = (12)\ (\pi)\ \varepsilon_o\ (3 \times 10^{-5})^2\ (5 \times 10^5)$$

$$= 1.5 \times 10^{-13} C \qquad \text{(A-40)}$$

or $\sim 9 \times 10^5$ electronic charges. This is comparable to the estimate of 8×10^5 electronic charges given for drops of this size by Hoenig (5).

It is now possible to determine the gravitational and electrical drop mobilities using definitions following Equation C-2

$$B \equiv Q/6\pi\eta R = (1.5 \times 10^{-13})/(6\pi)(2 \times 10^{-5})$$

$$(3 \times 10^{-5}) = 1.3 \times 10^{-5} \qquad \text{(A-41)}$$

$$B_g \equiv 2R^2\rho_m/9\eta = (2)(3 \times 10^{-5})^2$$

$$(10^3)/9(2 \times 10^{-5}) = 1 \times 10^{-2} \qquad \text{(A-42)}$$

To proceed further, it is necessary to have an estimate of the active cleaning volume, V, and the vertically projected area of this volume, A. For examples, take dimensions that approximate the size of a typical mine site:

$$A = 20\ m^2$$
$$V = 60\ m^3 \qquad (A-43)$$

Then, it is possible to evaluate the parameters

$$R_d/B_g gA = 1.45 \times 10^9/(10^{-2})(9.8)(20)$$
$$= 7.4 \times 10^8 \qquad (A-44)$$

$$\underline{Q}^2 \equiv \frac{VR_dBQ}{B_g{}^2g^2A^2\varepsilon_o}$$

$$= \frac{(60)(2.9 \times 10^8)(1.3 \times 10^{-5})(1.5 \times 10^{-13})}{(10^{-2})^2(9.8)^2(20)^2(8.85 \times 10^{-12})}$$

$$= 4.99 \times 10^3 \qquad (A-45)$$

From this latter parameter, Equation A-8 (or Figure A-1) can be used to evaluate the normalized drop number density.

$$\underline{N}_{eq} = \frac{-1 + \sqrt{1 + 4\underline{Q}^2}}{2\underline{Q}^2} = 0.0143 \qquad (A-46)$$

Note that because $\underline{Q}^2 >> 1$, self-precipitation dominates gravitational sedimentation. To a good approximation, $\underline{N}_{eq} = 1/\underline{Q}$. With the use of the parameter evlauated in Equation A-44, it follows from Equation A-9 that the actual drop number density is

$$N_{eq} = \underline{N}_{eq} \left(\frac{R_d}{B_g gA}\right) = (0.0311)(1.48 \times 10^8)$$

$$= 10.6 \times 10^6 \text{ drops/m}^3 \qquad \text{(A-47)}$$

Because self-precipitation of the drops is the dominant mechanism in determining the equilibrium drop number density, Equation A-17 represents the buildup of drops. In this expression, the characteristic time for drop buildup is

$$\tau_N = \left(\frac{V}{B_g gA}\right) \frac{1}{2} \frac{1}{\underline{Q}} = \sqrt{\frac{\varepsilon_o V}{4R_d BQ}} \qquad \text{(A-48)}$$

and for the specific example

$$\tau_N = \sqrt{\frac{(8.85 \times 10^{-12})(60)}{(4)(14.5 \times 10^8)(1.3 \times 10^{-5})(1.5 \times 10^{-13})}}$$

$$= 0.21 \text{ sec}$$

Thus, the drops establish an equilibrium density in a relatively short period of time.

The rate of dust cleaning is represented by Equation A-25. In this expression the time dependence is exponential and normalized to the collection time constant, τ_c, given by Equation A-27. For example, if the scrubber were turned on when $t = 0$ with there being some initial dust concentration but no further generation of dust, the decay of the dust concentration would be exponential with the time constant

$$\tau_c = \frac{\varepsilon_o}{NQb} = \frac{8.85 \times 10^{-12}}{(10.5 \times 10^6)(1.5 \times 10^{-13})b}$$

$$= \frac{2.56 \times 10^{-6}}{b} \qquad \text{(A-49)}$$

This time is certain to be long compared to that required for the drops to establish their equilibrium density, so the approximation that the drop number density is essentially constant ($N = N_{eq}$) over the cleaning period is likely to be good.

Equation A-49 is left with the mobility of the particles to be collected in algebraic form because there is considerable uncertainty about the magnitude of charge on the dust. Estimates have been given that particles might have as much as 60 electronic charges. The size is also an important parameter, almost certainly entering directly through the mobility expression and indirectly through the dependence of the charge of the radius, a, of the dust particles. With η the viscosity of air and q the dust charge,

$$b = \frac{q}{6\pi\eta a} \qquad \text{(A-50)}$$

Thus, for particles having a 5-μm diam and 60 electronic charges, the mobility is

$$b = \frac{(60)(1.6 \times 10^{-19})}{6\pi(2 \times 10^{-5})(2.5 \times 10^{-6})} = 10^{-8}\ m^2/sv \qquad \text{(A-51)}$$

and it follows from Equation A-49 that the time constant for cleaning of the dust is

$$\tau_c = 260\ \text{sec} = 4.3\ \text{min} \qquad \text{(A-52)}$$

CDS and CDP both have the same time constant value. Therefore, with a 4.3 min cleaning time, neither mechanism indicates practical performance. Moreover, since the drops are not appreciably affected in their observed distribution and general appearance by the charging process, the NQ product used in these calculations is considerably higher than obtained in devices under consideration. If charged to the values used here, droplet plumes would be observed to move rapidly in electrostatic repulsion.

In summary, it is extremely unlikely that electrical interaction with naturally charged fine particles would be of practical interest. This is true whether the actual mode of particle collection is the collection of charged particles by oppositely charged drops (CDS) or the precipitation of charged particles by the field due to drops charged to the same sign (CDP). This conclusion is contrary to the mechanism hypothesized by others as explaining dust control by charged water spray (10, 11).

In the next section, the crucial role of ions generated by the same device used to generate the charged drops is explored as a mechanism to explain observed dust control by charged water sprays. In this case, the devices are seen to operate as single-stage charged droplet precipitators. In this mode of operation, which seems to have been inadvertantly used in demonstrations, the collections times can be short enough to make the approach plausible and explain successful reports of dust control.

A.5 Single-State Charged Droplet Precipitator Model

The electrical enhancement of charged fog collection, observed in experiments such as those of Mathai (11) and Brookman (10), suggests that phenomena not accounted for in the charged droplet scrubber model are actually at work. It is very likely that under practical conditions any of the various charged droplet generators are to one degree or another also generators of ions. Certainly this is the case if the drops are generated by electrodynamic spray [see Hoburg and Melcher (18) for example]. The simultaneous generation of ions and drops was undoubtedly a major contributor to the performance of the TRW "charged droplet scrubber," which actually functions in the single-stage charged droplet precipitator mode described in this section.

In devices where mechanical effects are used to atomize (such as the spinning disk or air atomizers) the generation of ions along with the charged drops is not so obvious. But, it is very likely that in these devices (where the combination of electric and mechanical effects participate in the drop formation), corona breakdown intermingles with the atomization process to give rise to ions as well.

Ions generated by the drop generating devices have the same polarity as the drops. In the case of the Ritten Corp. Fogger IV (10), a fraction could easily be carried into the cleaning volume by the air flow. This is a reasonable conjecture because of the high gas velocity in the region between the nozzle and the inducer electrode. It would require a field of approximately 5×10^5 V/m to make an ion complete in its migration with the air flow (50 m/sec). Thus, if ions are generated in the neighborhood of the nozzle, a significant fraction could be expected to be carried into the cleaning volume by the gas being injected into that region by the fogger. In the AeroVironment CFG (11), it would be expected that ions are generated where the spray is formed and that these would be carried into the cleaning volume along lines of force where the gas and field act in consort to carry the ions.

In the cleaning volume there is, then, a mixture of ions and drops having the same polarity and dust particles with essentially no initial charge. Because of the space charge in this region (to be shown to be largely due to the charged drops) it is filled with an ambient electric field. In the working volume, drops serve as the distributed electrode of an electrostatic precipitator. The combination of this field and the ions is all that is required to give rise to impact charging of the dust throughout the working volume, but especially at its extremities where the electric field is the greatest.

Thus, the electric field serves both to provide for ion impact charging of the dust to the same polarity as the drops and to precipitate the dust on the boundaries in the vicinity of the working volume. In the sense of conventional electrostatic precipitators, the configuration is a single-stage one. It will be seen in the following developments that this type of interaction is governed by essentially the same parameters as the "two-stage" charged droplet precipitator except that the mobility of the particulate to be collected, b, is far larger than what can be expected from "natural" processes. Whether inadvertant or by design, this approach has the advantage of not depending on nature for the requisite dust charge.

In general, the simultaneous charging of dust by the ion flux and the ambient electric field adds considerable complexity to the dynamics of the collection process. To see what approximations underlie an extension of the previously derived results to this case, consider the conservation laws that now describe the cleaning volume.

Once again, this region is taken as one where the distributions of species are essentially uniform. In the case of the dust, and to some extent the drops, this is a matter of turbulence inducing mixing. For the ions, which move with much greater velocity in the ambient electric field, turbulence has little effect and the collection volume model represents an average of a distribution of ion densities over the working volume.

The drops are likely to be generated in a region of sufficiently high electric stress that their induced charge exceeds their saturation charge, $12\pi\varepsilon_0 R^2|E|$, experienced by the drop in the working volume. (Remember that the saturation charge is proportional to the local electric field intensity.) In this case, there is no ion impaction on the drops. Even though the dust particles become charged to the same polarity as the drops, because they are in an ambient electric field, there is the possibility of some dust particles collecting on the drops. However, again because the drop charge exceeds the local saturation charge, the dust does not collect on the drops. This means that there is no drop discharge (collection of oppositely charged dust) in the working volume. Thus, the drop conservation equation is the same as for the two-stage interaction described by Equation A-5.

$$R_d = V\frac{dN}{dt} + NB \oint_S \bar{E} \cdot \bar{n}ds + NB_g gA \qquad \text{(A-53)}$$

Again, because the dust is not collected on the drops, the dust conservation equation for the completely mixed working volume is

$$r_d = V\frac{dn}{dt} + nb \oint_S \bar{E} \cdot \bar{n}ds + nb_g \oint_S \bar{g} \cdot \bar{n}ds \qquad \text{(A-54)}$$

What is new is the ion conservation equation, which expresses the fate of ions injected into the volume at the rate of r_i ions per second.

$$r_i = V\frac{dn_i}{dt} + n_i b_i \oint_S \bar{E} \cdot \bar{n}ds + \int_V G_i n dV \qquad \text{(A-55)}$$

As for the other species, the first term on the right is the rate of ion accumulation (ion density n_i) in the volume, while the second is the rate of migration to the walls. The last term represents the loss of ions from the volume because of impact charging of the dust. The number of ions collected by a single dust particle per second, G_i, is taken as being that due to impact (8).

$$G_i = \begin{cases} 3\pi a^2 b_i n_i |E| \; 1 - \left(\frac{q}{q_s}\right); & -q_s < q < q_s \\ 0 & ; \; q_s < q \end{cases} \qquad \text{(A-56)}$$

where $q_s \equiv 12\pi\varepsilon_o a^2 |E|$, the saturation charge of the dust particle This law prevails for dust particles larger than about 0.5 μm diam.

Because the ambient electric field plays a crucial role both in precipitating the drops and dust and in charging the dust, Gauss' Law is at the heart of the interaction

$$\oint_S \bar{E} \times \bar{n} ds = \int_V \left[\frac{NQ}{\varepsilon_o} + \frac{nq}{\varepsilon_o} + \frac{n_i q_i}{\varepsilon_o}\right] dV$$

$$\cong \left[\frac{NQ}{\varepsilon_o} + \frac{nq}{\varepsilon_o} + \frac{n_i q_i}{\varepsilon_o}\right] V \qquad \text{(A-57)}$$

To complete the description, each dust particle is assumed to have radius a and charge q, so that

$$\frac{dq}{dt} = 3\pi a^2 b_i n_i q_i |E| \left(1 - \frac{q}{|g_s|}\right)^2 \quad ; \; b \equiv \frac{q}{6\pi q a} \qquad \text{(A-58)}$$

Here, $|E|$ is taken as an average over the volume of the ambient electric field intensity;

$$|E| \simeq cE_w$$

where E_w is the field intensity at the surface bounding the working volume and c is a constant somewhat less than unity.

Note that in general these laws represent five differential equations determining the evaluation of the five dependent variables:

a. N

b. $\oint_S \bar{E} \times \bar{n} ds$

c. n

d. q (or b)

e. n_i.

In view of the uncertainty in parameters for the systems under consideration, a solution of the full set of equations is not called for at this time. The following discussion bears on the essentials of the physical process and serves to further emphasize what the existence of the ion flux adds to the feasibility of the charged fog approach to dust control.

1. Because the drops enter the volume (Figure A-1) with a charge greater than the saturation value in the interaction volume, it has not been necessary to write an expression analogous to Equation A-58 governing the rate of drop charging. Thus, the drop charge can be taken as constant.

2. In Equation A-57, the contribution of the drops and the ions to the space charge greatly exceeds that of the dust.

$$\frac{NQ}{\varepsilon_o} + \frac{n_i q_i}{\varepsilon_o} >> \frac{nq}{\varepsilon_o} \qquad \text{(A-59)}$$

This assumption depends on the mass loading of the dust. It is certainly justified if the loadings are small enough. In fact, if it is not true, then the device can be operated as a space charge precipitator and the fogger source should be replaced with one that supplies ions only and not ions and drops.

Typical numbers for the example from subsection A-4 are:

$$\frac{NQ}{\varepsilon_o} = \frac{(10.5 \times 10^6)(1.5 \times 10^{-13})}{8.85 \times 15^{12}} = 1.8 \times 10^5$$

While to achieve an ion charging time of 0.1 sec, it is necessary that $\varepsilon_o/n_i q_i b_i = 0.1$ from which it follows that $n_i q_i/\varepsilon_o = 1/0.1\ b_i \simeq 10^5$. Thus, if the ion charging is to proceed on a sufficiently short time scale to make the ion impact charging appreciable, it appears that the space charge generated by the ions would be on the order of that due to the drops. It is possible to operate at higher drop space charge densities, so the relative importance of the ion and drop space charges needs to be examined in every case.

Two limits are helpful in delineating the collection efficiency without the need for solving the coupled equations. First, the drop space charge density can be taken as dominating that due to the ions.

$$NQ \gg n_i q_i \tag{A-60}$$

In this case, the drop dynamics are as described in subsection A-3. In the second extreme, where the ion space charge dominates that due to the drops

$$NQ \ll n_i q_i \tag{A-61}$$

it is necessary to reconsider the effect of space charge on the precipitation of the drops.

For the present purposes, the first of these extremes is considered. It appears that in experiments so far conducted, ion space charge and drop space charge effects are on the same order but for purposes of estimating, this limiting case is sufficient. The expression for the drop conservation, Equation A-7, is then still valid.

3. The dust charging process occurs on the time scale $\varepsilon_o/n_i q_i b_i$ (whether the process is one of ion impact or ion diffusion). Subject to verification later, it is assumed that at the outset that the charging process represented by Equation A-58 is essentially complete on a time scale that is short compared to the dust collection time. This means that at a location where the ambient electric field intensity is $|E|$, the dust charge and hence mobility is

$$q = 12\pi\varepsilon_o a^2 \, |E| \Rightarrow b = \frac{2\varepsilon_o a}{7} |E| \qquad \text{(A-62)}$$

For estimation purposes, let $|E|$ be an average over the working volume. If that volume is taken as having a typical radius r_o, then because the field is due to the drop space charge it follows that the average field is $\langle E \rangle \cong NQr_o/4\varepsilon_o$ or that the mobility given by Equation A-62 is on the average

$$b = \frac{aNQr_o}{27} \qquad \text{(A-63)}$$

With this as the particle mobility, it is possible to evaluate the characteristic dust precipitation time, as given previously by Equation A-27. In this single stage charged-drop precipitation configuration, this time becomes

$$\tau_c = \frac{\varepsilon_o}{NQb} = \frac{27\varepsilon_o}{(NQ)^2 a} \left(\frac{4\pi}{3V}\right)^{1/3} \qquad \text{(A-64)}$$

Using numbers from subsection A.3,

$$\tau_c = \frac{2(2 \times 10^{-5})\varepsilon_o}{\left[(10.5 \times 10^6)(1.5 \times 10^{-13})\right]^2 (2.5 \times 10^{-6})} \left[\frac{4\pi}{(3)(60)}\right]^{1/3}$$

$$= 23 \text{ sec}$$

The 23-sec value is an order of magnitude estimate. Data for precise calculation is nonexistent. This value confirms that dust level improvements observed by applying charged droplets are plausible assuming ions play a role in charging the dust particles. No previous work of record for charged water spray dust control has recognized the importance of the ionic contribution. This is most likely due to holding the hypothesis that the droplets collected the dust (CDS).

What ion current from the drop source would be required to account for this mode of operation? From Equation A-55 (in the steady state) it follows that the ion current, $r_i q_i$, is

$$i_i \equiv r_i q_i = \frac{n_i q_i b_i}{\varepsilon_o} NQV \qquad \text{(A-65)}$$

Rewritten, this expression becomes one for the rate at which ions charge the dust

$$\frac{\varepsilon_o}{n_i q_i b_i} = \frac{NQV}{i_i} \qquad \text{(A-66)}$$

A reasonable *guess* at the level of ion current is 100 μA. In this case, Equation A-66, evaluated using numbers from subsection A.3, gives a charging time of

$$\frac{NQV}{i_i} = \frac{(4.6 \times 10^{6})(1.5 \times 10^{-13})(60)}{10^{-4}}$$

$$= 0.4 \text{ sec}$$

This time is indeed short compared to the collection time, thus justifying the assumption that the charging process is virtually instantaneous on the time scale of the dust collection.

If the space charge due to the ions is indeed of the same order as that due to the charged drops, what purpose does the fog serve? Certainly it provides a "wet-wall" environment. Thus, dust that once encounters a surface is almost certain not to be reentrained. Also, the ionic current would tend to charge objects (including people) if the environment were dry. The fog ensures that surfaces are wet enough to provide a rapid leakage of charge to ground. One consequence is a reduced likelihood of having undesired electrical discharges in the working volume.

A.6 Concluding Remarks

In attempting to sort out the various mechanisms for charged drop control of dust, it should first be recognized that there is a well established theoretical framework for the basic interactions between the charged dust and the drops. If experimental conditions are carefully controlled, the observed performance of various charged droplet "scrubber" configurations can be predicted with good accuracy (8). These studies include correlations between predictions and observed results for two-stage Space-Charge Precipitators (SCPs)(where the dust is charged and precipitates under its own self-field), Charged Droplet Scrubbers (CDSs)(where charged dust is collected on oppositely charged drops) and Charged Droplet Precipitators (CDPs)(where charged dust is precipitated by the electric field associated with the space charge of drops having the same sign).

Unfortunately, experiments have been reported in which controls over dust charging and the associated effects of stray fields and ions are lacking (1, 5, 9, 19). Because these experimental results have not been subjected to meaningful scrutiny, the data should be regarded as suspect. Even though qualitative explanations given in these works dispose the reader to the idea that charged drops are collecting dust that is oppositely charged, the experimental controls and quantitative evaluation of experimental results by means of models that have been substantiated under controlled conditions are lacking.

Experiments carried out under practical but uncontrolled conditions *do* suggest an augmentation of the dust control through the use of an electric field (10, 11). Either the charged drop scrubber or the charged drop precipitator can give rise to effects of the order observed provided that the dust particles are charged to levels that are typical of electrostatic precipitators. In the equipment described (10, 11), the most plausible way in which this would happen is if ions generated along with the drops are charged to the same polarity as the drops. Hence, the devices must function in the single-stage charged droplet precipitator (CDP) mode.

If, in fact, it is true that the devices really function in the CDP mode, then it seems clear that their performance can be improved. Because the wrong physical picture has been given to what is happening in the electrically augmented scrubber, attention has not been given to the generation of ions and to the effect of their dispersal in the working volume on the space charge generated ambient electric field. It appears that there may be considerable room for improvement of the existing devices. Any future work should include measurements of the fogger current that makes it possible to discriminate the current component being carried by ions and by drops. Further, consideration should be given to a mode of operation in which drops are not used, but rather only ions are carried into the working volume by means of a gas stream.

APPENDIX B

PHENOMENOLOGY OF DUST DECAY

B.1 Introduction

This appendix describes the phenomenology of dust removal from transient concentration measurements in a well mixed chamber. The analysis is restricted to linear dust removal mechanisms, that is, mechanisms where the time rate of dust concentration change is proportional to the instantaneous concentration. Examples of linear loss mechanisms are gravity sedimentation, electrostatic precipitation and dilution. Autocoagulation of dust is an example of a nonlinear dust removal mechanism. In practice, autocoagulation is usually important only for aerosols of very high number density where collision frequency between particles is high.

This analysis treats the dust as monodispersed. That is, no account is made for variations in dust particle size. The respirable dust fraction (approximately less than 5 μm) may be close enough to monodispersed behavior for practical work. In any case, the effects of these restrictions can be checked experimentally. This analysis predicts, in the absence of dust production within the chamber, any dust concentration will have a log-linear or exponential time decay curve. Experimentally this is checked by plotting the logarithm of concentration corrected for any background concentration against time. If the curve is linear, then effects due to nonlinear dust reduction and polydispersed aerosols may be neglected.

The following develops the analysis for experiment. Also presented is an extention of how time constants or rates of dust removal relate to dust reductions for steady-state inputs of dust concentrations. The symbols are described in Table B-1.

B.2 Dust Removal Rate

Consider the process in Figure B-1. A well mixed chamber is ventilated in a steady-state manner. Dust removal spray is operating at steady-state. Dust concentration has been built-up and the dust source removed with time allowed for dust concentration to become uniform throughout the chamber. Time begins with the initial dust concentration defined at this time. The dust concentration then decays as a function of time.

TABLE B-1. - Symbols

C	-	dust concentration
C_o	-	initial dust concentration
C_{in}	-	inlet dust concentration
C_{out}	-	outlet dust concentration
f_i	-	dust removal mechanism (volume flow units)
F	=	$\sum_{i=1}^{r} f_i$
M	-	total dust mass = CV
Q	-	ventilation flow
t	-	time
R	=	$\frac{-\ln C/C_o}{t}$, test decay rate of dust
R_D	-	decay rate for dust only
ΔR_D	=	$R-R_D$
V	-	volume
η	=	dust reduction efficiency
τ	=	$1/\Delta R_D$, time constant
τ_r	=	V/Q

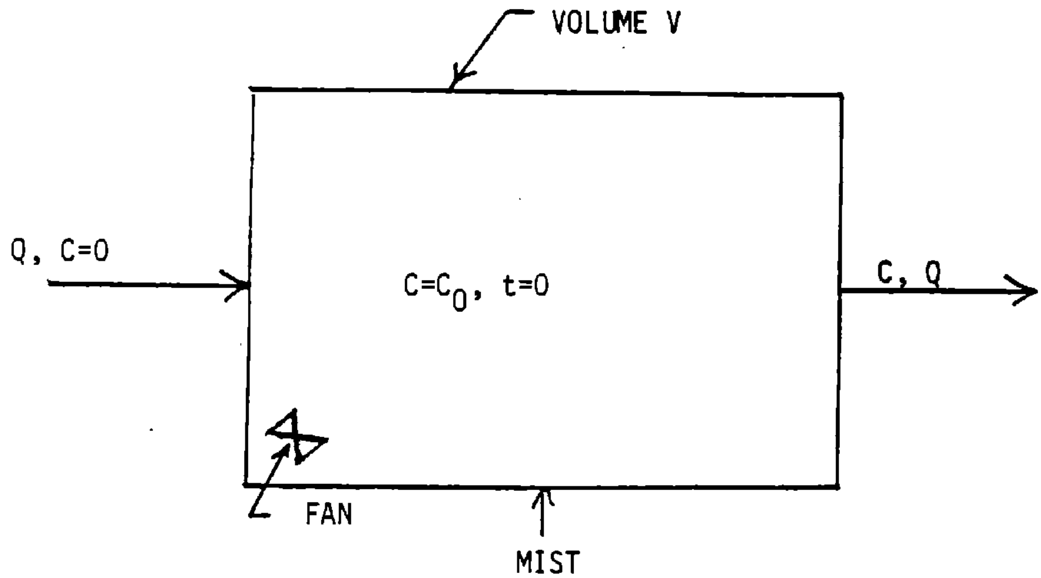

FIGURE B-1. - Dust chamber.

Conservation of mass requires that,

$$\frac{dM}{dt} = V\frac{dc}{dt} = -C\left(Q + f_1 + f_2 + f_3 + \ldots f_n\right)$$

or

$$V\frac{dC}{dt} = -C\ (Q + F)$$

with variables defined in Table B-1.

This differential equation is integrated within the limits, $C = C_o$ when $t = o$ and $C = C$ when $t = t$. With rearranging,

$$\frac{\ln C/C_o}{t} = -(Q/V + F/V)$$

This expression is the log-slope of the dust concentration decay curve. The term Q/V is the decay rate due to flushing or ventilating the chamber. The clean ventilation air may be thought of as diluting the dust. The F/V term is the lumped sum of linear removal mechanisms.

By experiment, the various removal mechanisms may be separated. Consider the set of experiments at constant ventilation where:

a. The decay of dust concentration with the application of charged spray is measured

b. The decay of dust concentration without spray is measured.

In the first case:

$$R = \left(\frac{Q+F}{V}\right)$$

While in the second case:

$$R_D = \left(\frac{Q+F_D}{V}\right)$$

Take the difference:

$$R - R_D = \Delta R_D$$

$$\Delta R_D = \frac{F-F_D}{V} = \frac{\Delta F_D}{V}$$

The term ΔR_D is just the net decay due to the application of the charged spray. Dilution effects and gravitational settling of the dust have been subtracted out.

The reciprocal $1/\Delta R_D$ defines the time constant of the decay due to application of charged spray. This is the time for the concentrations to decrease to $1/e$ or ~37 percent of initial value.

B.3 Reduction Efficiency

Steady-state dust reduction efficiency is linked to the ventilation residence time and the dust decay time constant. In Figure B-2, dust is brought into a dust reduction volume where acted upon by charge spray.

The reduction efficiency is defined by:

$$\eta = \frac{C_{in} - C_{out}}{C_{in}} = 1 - \frac{C_{out}}{C_{in}}$$

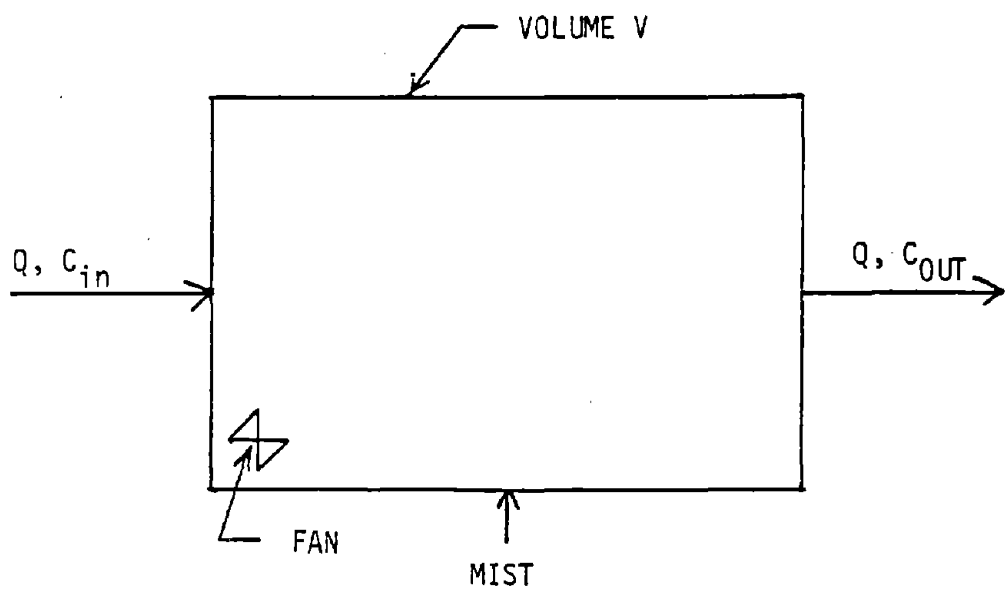

FIGURE B-2. - Generalized dust scrubber.

The ventilation residence time is

$$\tau_r = V/Q$$

Now in this time, the dust concentration reduction due to the charge spray is by definition of ΔR_D

$$\frac{C_{out}}{C_{in}} = e^{-\Delta R_D \tau_r}$$

Therefore, the dust reduction efficiency due to charged spray is

$$\eta = 1 - e^{-\Delta R_D \tau_r}$$

or

$$\eta = 1 - e^{-\Delta R\ V/Q}$$

Note that if V, Q and ΔR_D are known, the efficiency may be predicted. This also allows scaling. By applying the same laboratory charged spray condition scaled for volume, that is, $\Delta F_D = V\Delta R_D$ and knowing the flow rate Q, the dust reduction efficiency for a full-scale application may be estimated.

APPENDIX C

DROPLET SIZE DATA

Presented herein are copies of the computer printout of the droplet sizing performed by the Bete Fog Nozzle droplet analyzer. Shown are the droplets counted by size range as well as computed statistics on the population sampled.

Bete Fog Nozzle, Inc. in Greenfield, MA have developed a video computer system for analyzing spray droplets. A small volume of the spray to be analyzed is imaged inside a video camera using a strobe light to stop the motion. The image is frozen and automatically processed using the known optics of the system to provide information on droplet size.

DATE: 1/21/82 DUSTRON CHARGED SPRAY NOZZLE

TEST NUMBER 245 NOZZLE: 180/60100 -VE 60PA .3L/M SPATIAL DATA

AT 0.00 - 0.00 PSI / 0 - 0 AZ. ANGLE

0 - 0 CONICAL ANGLES / 36.00 - 36.00 IN. DISTANCE/

DIAMETER (MICRONS)	DROPS	% OCCURRENCE	% SURFACE AREA	% VOLUME	CUM % VOLUME	CLASS CHECK
5.2 - 6.6	17	10.37	0.33	0.04	0.04	0.000
6.6 - 8.2	6	3.66	0.24	0.04	0.09	0.000
8.2 - 10.2	1	0.61	0.06	0.01	0.10	0.000
10.2 - 12.8	6	3.66	0.57	0.16	0.26	0.000
12.8 - 16.0	14	8.54	1.92	0.66	0.92	0.001
16.0 - 20.0	19	11.59	4.00	1.71	2.63	0.002
20.0 - 25.0	22	13.41	7.83	4.34	6.97	0.005
25.0 - 31.3	23	14.02	12.06	8.12	15.09	0.009
31.3 - 39.1	26	15.85	20.91	17.46	32.55	0.019
39.1 - 48.8	16	9.76	20.05	20.87	53.42	0.023
48.8 - 61.0	10	6.10	18.44	23.19	76.61	0.026
61.0 - 76.3	4	2.44	13.59	23.39	100.00	0.026
	164.	100.00	100.00	100.00	100.00	

AVERAGE DIAMETERS:

ARITHMETIC MEAN = 26.09
SURFACE MEAN = 30.01
VOLUME MEAN = 33.45
SAUTER MEAN = 41.56
WEIGHT MEAN = 47.82
VOLUME MEDIAN = 47.40

MAXIMUM DIAMETER = 76.31
MINIMUM DIAMETER = 5.38
TOTAL # DROPS IN SAMPLE = 164
TOTAL # FRAMES IN SAMPLE = 100
DROPS PER FRAME = 1.64
SAMPLE SIZE CHECK = 0.07
DEVIATION = 0.44

RELATIVE SPAN = (69.86 - 27.75)/ 47.40 = 0.89

DATE: 1/21/82

DUSTRON CHARGED SPRAY NOZZLE

TEST NUMBER 244 NOZZLE: 180/60100 NC 60PA .3L/M SPATIAL DATA

AT 0.00 - 0.00 PSI / 0 - 0 AZ. ANGLE

0 - 0 CONICAL ANGLES / 36.00 - 36.00 IN. DISTANCE/

DIAMETER (MICRONS)	DROPS	% OCCURRENCE	% SURFACE AREA	% VOLUME	CUM % VOLUME	CLASS CHECK
5.2 - 6.5	30	14.63	0.46	0.05	0.05	0.000
6.5 - 8.1	12	5.85	0.37	0.06	0.11	0.000
8.1 - 10.1	2	0.98	0.09	0.02	0.13	0.000
10.1 - 12.6	9	4.39	0.64	0.15	0.28	0.000
12.6 - 15.8	15	7.32	1.53	0.44	0.72	0.000
15.8 - 19.7	25	12.20	4.22	1.56	2.28	0.002
19.7 - 24.6	17	8.29	4.34	1.97	4.24	0.002
24.6 - 30.8	27	13.17	10.83	6.17	10.41	0.007
30.8 - 38.5	33	16.10	20.14	14.13	24.54	0.016
38.5 - 48.1	18	8.78	18.04	16.22	40.76	0.018
48.1 - 60.1	9	4.39	14.10	15.87	56.63	0.018
60.1 - 75.2	6	2.93	14.88	21.04	77.67	0.023
75.2 - 93.9	1	0.49	3.04	4.72	82.39	0.005
93.9 - 117.4	1	0.49	7.30	17.61	100.00	0.020
	205.	100.00	100.00	100.00	100.00	

AVERAGE DIAMETERS:

ARITHMETIC MEAN = 25.04
SURFACE MEAN = 30.35
VOLUME MEAN = 35.53
SAUTER MEAN = 48.71
WEIGHT MEAN = 62.05
VOLUME MEDIAN = 55.25

MAXIMUM DIAMETER = 117.43
MINIMUM DIAMETER = 5.38
TOTAL # DROPS IN SAMPLE = 205
TOTAL # FRAMES IN SAMPLE = 100
DROPS PER FRAME = 2.05
SAMPLE SIZE CHECK = 0.18
DEVIATION = 0.54

RELATIVE SPAN = (104.00 - 30.48)/ 55.25 = 1.33

DATE: 1/21/82

DUSTRON CHARGED SPRAY NOZZLE

TEST NUMBER 247 NOZZLE: 180/60100 -VE 60PA .2L/M SPATIAL DATA

AT 0.00 - 0.00 PSI / 0 - 0 AZ. ANGLE

0 - 0 CONICAL ANGLES / 36.00 - 36.00 IN. DISTANCE/

DIAMETER (MICRONS)	DROPS	% OCCURRENCE	% SURFACE AREA	% VOLUME	CUM % VOLUME	CLASS CHECK
5.0 - 6.3	7	5.98	0.23	0.04	0.04	0.000
6.3 - 7.8	7	5.98	0.47	0.10	0.14	0.000
9.8 - 12.3	8	6.84	1.17	0.37	0.51	0.000
12.3 - 15.3	7	5.98	1.63	0.66	1.17	0.001
15.3 - 19.2	9	7.69	3.06	1.50	2.66	0.002
19.2 - 23.9	28	23.93	14.85	9.06	11.72	0.010
23.9 - 29.9	18	15.38	15.21	11.72	23.44	0.013
29.9 - 37.4	16	13.68	21.54	20.92	44.36	0.023
37.4 - 46.8	9	7.69	18.74	22.66	67.03	0.025
46.8 - 58.5	8	6.84	23.10	32.97	100.00	0.037
	117.	100.00	100.00	100.00	100.00	

AVERAGE DIAMETERS:

ARITHMETIC MEAN = 24.37
SURFACE MEAN = 27.27
VOLUME MEAN = 29.75
SAUTER MEAN = 35.41
WEIGHT MEAN = 39.30
VOLUME MEDIAN = 39.92

MAXIMUM DIAMETER = 58.47
MINIMUM DIAMETER = 5.38
TOTAL # DROPS IN SAMPLE = 117
TOTAL # FRAMES IN SAMPLE = 100
DROPS PER FRAME = 1.17
SAMPLE SIZE CHECK = 0.06
DEVIATION = 0.39

RELATIVE SPAN = (55.13 - 23.38)/ 39.92 = 0.80

DATE: 1/21/82 DUSTRON CHARGED SPRAY NOZZLE

TEST NUMBER 246 NOZZLE: 180/60100 NC 60PA .2L/M SPATIAL DATA

AT 0.00 - 0.00 PSI / 0 - 0 AZ. ANGLE

0 - 0 CONICAL ANGLES / 36.00 - 36.00 IN. DISTANCE/

DIAMETER (MICRONS)	DROPS	% OCCURRENCE	% SURFACE AREA	% VOLUME	CUM % VOLUME	CLASS CHECK
4.5 - 5.6	10	8.62	0.36	0.05	0.05	0.000
7.0 - 8.8	10	8.62	0.72	0.15	0.20	0.000
8.8 - 10.9	2	1.72	0.25	0.07	0.27	0.000
10.9 - 13.7	7	6.03	1.44	0.50	0.78	0.001
13.7 - 17.1	16	13.79	5.03	2.19	2.97	0.002
17.1 - 21.4	17	14.66	7.72	4.04	7.01	0.004
21.4 - 26.7	11	9.48	7.65	4.97	11.98	0.006
26.7 - 33.4	22	18.97	23.78	19.23	31.21	0.021
33.4 - 41.8	10	8.62	17.53	17.99	49.20	0.020
41.8 - 52.2	9	7.76	25.29	32.87	82.07	0.037
52.2 - 65.3	2	1.72	10.24	17.93	100.00	0.020
	116.	100.00	100.00	100.00	100.00	

AVERAGE DIAMETERS:

ARITHMETIC MEAN = 22.93
SURFACE MEAN = 26.37
VOLUME MEAN = 29.44
SAUTER MEAN = 36.70
WEIGHT MEAN = 42.15
VOLUME MEDIAN = 42.06

MAXIMUM DIAMETER = 65.26
MINIMUM DIAMETER = 5.38
TOTAL # DROPS IN SAMPLE = 116
TOTAL # FRAMES IN SAMPLE = 100
DROPS PER FRAME = 1.16
SAMPLE SIZE CHECK = 0.09
DEVIATION = 0.46

RELATIVE SPAN = (57.94 - 24.79)/ 42.06 = 0.79

DATE: 1/21/82

DUSTRON CHARGED SPRAY NOZZLE

TEST NUMBER 243 NOZZLE: 180/60100 -VE 60PA .1L/M SPATIAL DATA

AT 0.00 - 0.00 PSI / 0 - 0 AZ. ANGLE

0 - 0 CONICAL ANGLES / 36.00 - 36.00 IN. DISTANCE/

DIAMETER (MICRONS)	DROPS	% OCCURRENCE	% SURFACE AREA	% VOLUME	CUM % VOLUME	CLASS CHECK
4.5 - 5.6	13	12.62	0.77	0.13	0.13	0.000
7.0 - 8.8	10	9.71	1.19	0.28	0.41	0.000
8.8 - 10.9	8	7.77	1.72	0.55	0.96	0.001
10.9 - 13.7	7	6.80	2.38	0.95	1.92	0.001
13.7 - 17.1	13	12.62	6.29	3.02	4.94	0.003
17.1 - 21.4	13	12.62	9.98	6.03	10.97	0.007
21.4 - 26.7	19	18.45	22.03	16.40	27.37	0.018
26.7 - 33.4	12	11.65	21.38	19.72	47.09	0.022
33.4 - 41.8	4	3.88	10.93	12.52	59.61	0.014
41.8 - 52.2	2	1.94	8.02	11.04	70.66	0.012
52.2 - 65.3	2	1.94	15.32	29.34	100.00	0.033
	103.	100.00	100.00	100.00	100.00	

AVERAGE DIAMETERS:

ARITHMETIC MEAN = 18.72
SURFACE MEAN = 21.76
VOLUME MEAN = 24.79
SAUTER MEAN = 32.15
WEIGHT MEAN = 39.36
VOLUME MEDIAN = 35.36

MAXIMUM DIAMETER = 65.26
MINIMUM DIAMETER = 5.38
TOTAL # DROPS IN SAMPLE = 103
TOTAL # FRAMES IN SAMPLE = 100
DROPS PER FRAME = 1.03
SAMPLE SIZE CHECK = 0.18
DEVIATION = 0.47

RELATIVE SPAN = (60.99 - 20.84)/ 35.36 = 1.14

DATE: 1/21/82 DUSTRON CHARGED SPRAY NOZZLE

TEST NUMBER 242 NOZZLE: 180/60100NC60PA.1L/M SPATIAL DATA

AT 0.00 - 0.00 PSI / 0 - 0 AZ. ANGLE

0 - 0 CONICAL ANGLES / 36.00 - 36.00 IN. DISTANCE/

DIAMETER (MICRONS)	DROPS	% OCCURRENCE	% SURFACE AREA	% VOLUME	CUM % VOLUME	CLASS CHECK
4.4 - 5.5	12	11.76	0.81	0.16	0.16	0.000
6.8 - 8.5	10	9.80	1.35	0.38	0.54	0.000
8.5 - 10.6	3	2.94	0.61	0.21	0.74	0.000
10.6 - 13.3	15	14.71	4.93	2.16	2.90	0.002
13.3 - 16.6	8	7.84	4.12	2.25	5.15	0.002
16.6 - 20.8	12	11.76	10.05	7.01	12.16	0.008
20.8 - 26.0	23	22.55	29.42	25.41	37.56	0.028
26.0 - 32.5	- 12	11.76	24.02	25.94	63.50	0.029
32.5 - 40.6	5	4.90	14.44	18.68	82.19	0.021
40.6 - 50.8	2	1.96	10.26	17.81	100.00	0.020
	102.	100.00	100.00	100.00	100.00	

AVERAGE DIAMETERS:

ARITHMETIC MEAN = 18.14
SURFACE MEAN = 20.52
VOLUME MEAN = 22.57
SAUTER MEAN = 27.31
WEIGHT MEAN = 30.82
VOLUME MEDIAN = 29.36

MAXIMUM DIAMETER = 50.78
MINIMUM DIAMETER = 5.38
TOTAL # DROPS IN SAMPLE = 102
TOTAL # FRAMES IN SAMPLE = 100
DROPS PER FRAME = 1.02
SAMPLE SIZE CHECK = 0.11
DEVIATION = 0.38

RELATIVE SPAN = (45.04 - 19.77)/ 29.36 = 0.86