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Space-Charge Electrostatic Precipitation

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(M.S. thesis)

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SPACE-CHARGE ELECTROSTATIC PRECIPITATION

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ABSTRACT

This study tests an improved electrostatic precipitator called a space charge precipitator. A space charge precipitator differs from a conventional model in that the fields necessary to move the particles from the gas to the collecting surfaces are provided by a cloud of charged innocuous drops, such as glycerine or water, rather than by a charged electrode system.

The flow conditions, electrical equipment, and physical dimensions of the test precipitator are typical of industrial applications. Experiments using water fog at a velocity of 10 ft/sec and a residence time of 0.6 sec, for a system charged at 25 kV, show a removal of iron oxide particles of approximately 52%. Theoretical calculations, assuming 2 micron particles, predict a removal of 50%. The results with glycerine fog are comparable. Experiments at various flowrates for both water fog and glycerine fog show a trend of decreasing particle removal for increasing flowrate. An identical trend is predicted by the space charge theory. Electron micrographs verify that only particles smaller than two microns are present in the laboratory precipitator.

I. INTRODUCTION

There is, in the United States and many other countries, a growing public pressure to clean up the emissions from chemical and power plants. In many locations, plants are either being shut down or kept from expanding due to the high costs of abatement. Particulates are a major portion of the emissions but they are frequently the hardest and most expensive to separate. With our country's increasing dependence on dust laden coal, oil, and municipal waste fuels, it is time to develop an economic dust scrubber.

Present model dedusters consist of a series of spray towers, wet plate absorbers, cyclones, baghouses, and electrostatic precipitators. After the large particles are separated, the particles smaller than about 10 microns are recovered in a cascade of electrostatic precipitators. The smaller particles are removed last because the collection efficiency of an electrostatic precipitator is an increasing function for particles larger than about 0.1 microns. A flood of large particulates through an electrostatic precipitator would foul the high voltage electrodes and collection plates.

This study tests a modified electrostatic precipitator called a space charge precipitator. A space charge precipitator features a shorter electrode, lower power consumption, smaller size, and simpler design than a conventional precipitator. Since space charge precipitators are self cleaning, they are compatible with a wide range of particle sizes and concentrations.

II. THEORY

In the process called space charge precipitation, a dense cloud of 0.1-0.2 micron fog drops is mixed with the dust flow entering an electrostatic precipitator (See Fig. 1). The dust particles and fog drops are then charged by the electrical breakdown in the gases surrounding a high tension electrode. Because the drops and particles are charged with the same sign, they repel each other and collect on the grounded walls downstream. The collection efficiency of the precipitator is particle size dependent. Space charge precipitators are designed to take advantage of the minimum collection efficiency for 0.1-0.2 micron particles. The fog drops, which are manufactured in this size range, are not efficiently collected in the precipitator. Moreover, the suspended, charged drops maintain the electric fields which are necessary for precipitating the dust particles.

A space charge precipitator differs from a conventional electrostatic precipitator in that the fields necessary to move the particles from the gas to the collecting surfaces are provided by a cloud of charged innocuous drops, such as glycerine or water, rather than by a charged electrode system. A space charge precipitator may use only a 6 in. long electrode for initially charging the particles and fog drops. But a conventional precipitator may have a 100 ft long electrode for continuously forcing dust particles of the same sign to the walls.

When an electrical potential is established between a thin wire electrode and a concentric pipe, a nonuniform electric field inversely proportional to the radius is produced. In the case of a high voltage

wire and tube electrostatic precipitator, the nonuniform electric field leads to electrical breakdown in the gases surrounding the wire. The electrical breakdown creates an ultraviolet glow which is termed corona. Particles and fog drops become charged in the corona region of an electrostatic precipitator.

A negative corona and positive pipe charging section provides a higher particle collection efficiency than a system of reversed polarity. A negative corona is used in this experiment. The mechanism of negative corona formation is as follows.¹ Ionized gas molecules are formed by cosmic rays. The positive ions formed in this way accelerate towards the negative electrode and release electrons from the electrode surface. These electrons accelerate through the strong electric field near the negative electrode and generate new electrons and positive ions by molecular impact. The electrons swarm outside this region and slow to a speed less than that necessary for ionization by collision. These electrons attach themselves to gas molecules forming negative ions. The negative ions transfer their charges upon impact with the passing dust particles and fog drops.

The charged particles and drops enter the collecting region of the precipitator. A mathematical analysis of the space charge fields and their effects on the collection efficiencies of the particles and drops is given below. According to Poisson's² equation, the potential " ϕ " is related to the concentrations " C_k " and charges " Q_k " of the charged species " k ". The charged species in the collecting region are the fog drops and dust particles.

$$\nabla^2 \phi = \frac{1}{\epsilon_0} \left(\sum_{k=1}^{k_{\max}} Q_k C_k \right)$$

where " ϵ_0 " is the permittivity of free space. The continuity equation for each species is:

$$\frac{\partial C_k}{\partial t} = \nabla \cdot \tilde{N}_k$$

where " $\tilde{N}_k$ " is the axial flux of species due mainly to the bulk velocity " $\tilde{V}$ " and the electric field " $\tilde{E}$ ".

$$\tilde{N}_k = C_k \tilde{V} + \lambda_k C_k \tilde{E}$$

$$\tilde{E} = -\nabla \phi$$

Assuming that the mobility " λ_k " of each species is constant and that steady state exists,

$$\nabla \cdot \tilde{N}_k = 0$$

$$= C_k (\nabla \cdot \tilde{V} + \lambda_k \nabla \cdot \tilde{E}) + (\tilde{V} + \lambda_k \tilde{E}) \cdot \nabla C_k$$

Assuming that the fluid density is constant,

$$\nabla \cdot \mathbf{v} = 0$$

$$C_k \left[\frac{\lambda_k}{\epsilon_o} \left(\sum_{k=1}^{k_{\max}} Q_k C_k \right) \right] + (\mathbf{v} + \lambda_k \mathbf{E}) \cdot \nabla C_k = 0$$

Faith³ simplifies this equation for cylindrical plug flow and V_z much larger than $\lambda_k E_z$. "z" is the axial coordinate. These conditions are typical of industrial systems and apply to this experiment.

$$\frac{C_k \lambda_k}{\epsilon_o} \left(\sum_{k=1}^{k_{\max}} Q_k C_k \right) + v_z \left(\frac{dC_k}{dz} \right) = 0$$

Since $t = z/V_z$,

$$\frac{\partial C_k}{\partial t} = \frac{-\lambda_k C_k}{\epsilon_o} \left(\sum_{k=1}^{k_{\max}} Q_k C_k \right)$$

It is valid to relate any two species, say the fog drops "d" and the particles "p", by integrating the Faith³ equation from the entrance concentrations " C_{k0} " to the exit concentrations " C_k ":

$$\frac{C_p}{C_{p0}} = \left[\left(\frac{C_d}{C_{d0}} \right)^{(\lambda_p/\lambda_d)} \right]$$

Under the assumption that the space charge of the particles is small in comparison with that of the dense fog cloud, the fraction of unprecipitated fog drops is obtained from the integrated form of the Faith³ equation:

$$\frac{C_d}{C_{do}} = \frac{1}{1 + \frac{\lambda_d Q_d C_{do} t}{\epsilon_o}}$$

where "t" is the retention time of the fog drops in the collection section of the precipitator.

The previous two equations combine and yield the particle collection efficiency "η_p" of the precipitator:

$$\eta_p = 1 - \left(\frac{1}{1 + \frac{\lambda_d Q_d C_{do} t}{\epsilon_o}} \right)^{(\lambda_p / \lambda_d)}$$

Computer programs and specific values for the mobilities, charges, and concentrations of the particles and fog drops are tabulated by Kostow.⁴ The collection efficiency is independent of the configuration of the collecting surface. The only requirement is that sufficient grounded surface be present to prevent the creation of space charge fields higher than the breakdown field of the gas. It is thus possible to utilize the entire stack of an industrial plant as a massive collecting surface. The fog and particle slurry which forms on the

collecting surface also electrically grounds and washes down the vertical walls. Conventional electrostatic precipitators require expensive rappers for cleaning the network of collecting surfaces and electrodes.

III. PREVIOUS INVESTIGATIONS

Experiments by Webber² and Kostow⁴ substantiate the theory of charge precipitation. Webber² tested a water fog system utilizing a 20 kV corona and 30 cfm air flow in a 3 in. diameter by 5 ft long precipitator. The collection efficiency for a congo-red and water aerosol was about 87%. Space charge theory predicts that an 87% efficiency corresponds to an aerosol size of 11 microns. Even though this size was not experimentally measured, it is a reasonable value and substantiates the space charge theory. Kostow⁴ tested a similar precipitator using glycerine fog. His experiments verified the space charge theory for several particle sizes including 30 micron lycopodium spores, iron oxide dust, tobacco smoke, and oil mist. Using this information, Kostow⁴ compared the economics for industrial scale (100,000 cfm) space charge and conventional precipitators. He concluded that the costs of the two units were roughly the same. The most economic fog drop sizes were about 0.1-0.2 microns. Droplets of these sizes have the lowest collection efficiencies and mobilities. Kostow⁴ estimated that space charge precipitators require only about one-third as much collecting surface as conventional precipitators. He suggested that a pilot scale space charge precipitator should be built for more precise testing.

Carnevali⁵ built a pilot scale space charge precipitator capable operating under various conditions of temperature, humidity, and flow rate. Industrial flue gases are readily simulated in the unit. This study is based on Carnevali's⁵ 6 ft long, 1 ft square, 0-1000 cfm, and 0-16 ft/sec test precipitator.

IV. EXPERIMENTAL APPARATUS

Turning now to the experimental space charge precipitator, the completed unit is illustrated in Figs. 2-6 and Table I. The precipitator and associated equipment are essentially the same as Carnevali⁵ used. Only a summary of the apparatus and modifications is given below. The precipitator is a universal testing unit and is easily adapted to remove dust from various flow regimes.

The five horsepower blower generates the airflow through the precipitator. A butterfly valve in the blower controls the airflow from 0-1000 cfm. The gas stream exiting the precipitator is measured by a venturi and draft gage.

It is possible to heat the airstream to 140-250°F with a natural gas burner. The gas is ignited by a Tesla coil connected to a controller. The controller photocell senses when there is no flame and responds by triggering the Tesla coil. A safety relay shuts off the natural gas when the flame is extinguished for long periods of time and the corona is discharging. The airstream temperature is difficult to set because the burner is designed to operate in a limited heating rate range. Airflows higher than 500 cfm quench the flame. Future experiments should use a set of burners which are individually matched to the heating requirements at different flow rates and temperatures. This would make it possible to simulate industrial stack gases at various flowrates and temperatures. It is important to show the industrial applications of space charge precipitation.

Table I. Schematic legend for the test precipitator.

TEMPERATURES	
T1	dry bulb (use to determine the humidity of the
T2	wet bulb (airflow entering the saturation tower)
T3	gas stream exiting the saturation tower
T4	water fog
T5	cold air inlet to the water fog mixing chamber
T6	gas stream exiting the precipitator
T7	glycerine boiler
GAS FLOWS	
G1	gas stream existing the precipitator
G2	ambient air for supersaturating the gas flow exiting the saturation tower
G3	carrier air in the particle generator
G4	G2 + G3
G5	house air destined for the cold air inlet of the fog mixing chamber
G6	drying air for the high voltage support arms
G7	carrier air in the glycerine boiler
G9	connection between the house vacuum and the filter sampling tanks
G10	connection between the filter sampling tanks and the filters

Table I. Continued.

VOLTAGES AND CURRENTS	
I1	corona current (0-2 milliamps)
V1	corona voltage (0-30,000 volts)
V2	variac controlled voltage (0-120 volts) to one immersion heater in the glycerine and water boilers
V3	120 volts to the second immersion heater in the water boiler
PRESSURES	
P1	water boiler
P2	house air supply
P10,P11	initial and final pressures of the inlet sample vacuum tank
P20,P21	initial and final pressures of the outlet sample vacuum tank
$\Delta P1$	equals $P10-P11$, net pressure change of the inlet sample vacuum tank
$\Delta P2$	equals $P20-P21$, net pressure change of the outlet sample vacuum tank
MISCELLANEOUS	
L1	makeup water flow to the saturation tower
STM	steam
TIM	elapsed sampling time, usually about 5 min
RPM	rotational speed of the one tooth gear in the particle generator.

Dust is injected downstream from the burner. The dust is piped from the particle generator to the main airstream. Originally, the dust was injected after the saturation tower. However, moisture caused caking and clogging in the iron oxide feed line.

Steam may be added downstream from the dust nozzle. Steam heats and saturates the airflow. The humidity is measured as a function of the dry bulb temperature (T1) and the wet bulb temperature (T2).

A saturation tower containing three perforated wet plates (0-1 in. of water per plate) insures the complete saturation of the airstream. It is not possible to maintain water on the current plates for flowrates less than about 500 cfm. Water dumps freely through the holes which are too large for the low airflows. More makeup water could be added but the drainage capacity of the tower is limited. It would be advisable to tailor the plate hole size to the flow rate through the precipitator. This would also reduce the water requirement of the saturation tower.

For a water fog system, the airstream must be supersaturated before adding the 0.15 micron fog droplets. The 0.15 micron drops are used because they should produce the maximum collection efficiency. Drops of this size exhibit a 2% vapor pressure enhancement at a typical operating temperature of 150°F. The drops should remain stabilized after they are added to an airstream with the same supersaturation, temperature, and pressure. Higher temperatures, lower pressures, and lower supersaturation levels in the airstream lead to fog evaporation. The opposite limits lead to fog droplet growth. Either deviation should decrease

the collection efficiency. Small quantities of cold, ambient air are injected downstream from the saturation tower into the main air flow. The cold air supersaturates the airstream by cooling it slightly. Water fog is injected between the ambient air nozzle and the electrostatic precipitator. The water fog is manufactured in a Teflon mixing chamber. Steam and -10°F air are mixed at high velocities and at right angles to form a fine, blue fog. The blue color indicates that the drops are small and mono dispersed. The steam is generated in a boiler which is heated by two 1200-watt immersion heaters. A variac controls the power input to one of the heaters. House air is cooled in a dry ice chamber to form the -10°F air. It is necessary to heat the mixing chamber with the input steam line nozzle. The original Teflon steam nozzle has been replaced by a more heat conductive copper nozzle. The hot copper nozzle reduces an icing problem in the mixing chamber. The fog was originally transferred through a 3 ft tube section and injected into the main airflow. The fog turned grey and apparently agglomerated on the tubing walls. Fog agglomeration reduces both the fog concentration and the collection efficiency. This may be why early water fog experiments yielded collection efficiencies below the predicted values. In the final water fog experiments, the fog is injected directly into the main airflow from the mixing chamber. This produces a bluer, smaller fog and enhances the collection efficiency.

For a glycerine fog system, supersaturation is unnecessary. Glycerine fog is thermodynamically and kinetically more stable than water fog. Glycerine is hygroscopic and has a lower vapor pressure than water.

Consequently, glycerine drops remain stabilized and resist evaporation at higher temperatures than do water drops. Glycerine fog is manufactured in the same mixing chamber as the water fog. House air is bubbled through hot (200°C) glycerine and mixed with more air in the mixing chamber. A 1200 watt immersion heater is controlled by a variac. The resulting glycerine fog is injected directly into the main airflow from the mixing chamber. Experiments show that the glycerine fog remains blue throughout the electrostatic precipitator. The blue hue indicates that the droplets are small.

The precipitator is basically an open ended, rectangular box which accomodates various types of charging sections and collection plates. Air containing dust and fog flows longitudinally through the 1 ft wide, by 1 ft high, by 8 ft long stainless steel box. There are three 11 in. high by 6 ft long vertical collection plates. The plates are evenly spaced across the precipitator duct. The dust and water slurry which precipitates on the plates drains through a hole in the bottom of the duct. A Plexiglas lid above the charging section allows the operator to observe the gas flow and corona. Sample filters are inserted into transparent Lucite pipes at the entrance and exit to the precipitator.

The airstream containing dust and either water fog or glycerine fog enters the charging section of the electrostatic precipitator. It is in this region of corona discharge that the dust and fog particles become charged. Four different electrodes were used in this study.

The first system is a square matrix of 16 electrodes spaced evenly across the horizontal 1 ft square duct (see Fig. 7). The electrode

holders are mounted 3 in. apart on a 9 in. square copper grid. The grid is supported on insulated arms. The corona voltage is applied between the grounded duct and the grid. Early experiments use 1.2 in. long by 0.006 in. diameter wire loop electrodes. Similar 1.2 in. long straight electrodes are used in the later experiments. Experiments verify that these electrode types are equally effective. The collection efficiencies are lower than the predicted values. These unfavorable results could be caused by inoperative coronas. Because the corona onset is a step function of the voltage, the misalignment of a particular corona could cause it to remain off while the others remain on. For example, the electrodes near the walls experience different electric fields than the ones near the center of the duct. Say the corona onset voltages are 12 kV and 15 kV for the two cases. If the voltage is set at 14 kV, the center electrodes would not emit coronas. Since all of the electrodes in the experimental system do have a violet glow, the coronas are still operating. Visual experiments are not conclusive evidence that the corona currents are equal in every electrode. It would be instructive to compare this system to one containing electrodes in a uniform array. Then, the electric fields and currents of the electrodes would be equivalent.

The second electrode design is a modification of the first. Each electrode is covered by a 4 in. long by 3 in. diameter pipe. This system is essentially 16 identical charging tubes connected to the same power supply. All of the dust laden air flows through the cylinders. Results for this model and the previous one are equivalent. This means that the discrepancy in location of the electrodes in the

charging section is not the factor which is limiting the collection efficiency.

A third charging system was tested. The electrode grid was replaced by a single rod and electrode extending into one of the cylinder holes. Rubber stopers plug the other 15 holes. The collection efficiencies for this system follow the space charge theory. There is an obvious reason why one but not sixteen electrodes does work. Each electrode is connected to the same unregulated power supply. The power through each electrode is sporadic. Sparkovers, drops of water landing on the electrodes, and eddy air currents contribute to a complex current drain on the power supply. Sometimes the current spikes reduce the voltage and extinguish the corona. When 16 electrodes are interconnected to an unregulated power source, the coronas remain extinguished for a large fraction of the time. Particles are neither charged nor collected while the coronas are off. Future experiments should use separate power supplies for each electrode. An alternative is to isolate the electrodes with current limiting devices.

The entire charging section was also replaced by a single electrode in a concentric 8 in. long by 6 in. diameter pipe. The 6 in. long by 0.031 in. diameter straight electrode extends from a rod attached to one of the insulated arms. Experimental collection efficiencies for this system agree favorably with the space charge theory. The results are discussed in Chapter IX.

V. PARTICLE GENERATOR

An integral part of the space charge electrostatic precipitator is the dust generator. The dust generator must be able to simulate the particulate emissions from industrial plants. The composition, sizes, and concentration of the dust should be comparable in both the test precipitator and a full scale unit. If this is true, then the results in this study should apply to industrial systems. This experiment focuses on the precipitation of iron oxide dust. Iron oxide is a significant byproduct in the waste gas from steel mills. It is readily available in a cheap, pure, and fine particulate form. Iron oxide for this study is obtained from:

1. Fe_2O_3 , 99.9%, approximate 2 micron mesh

Orion Chemical Company
P. O. Box 5578
Huntington Beach, CA 92646
714-963-9117

2. Fe_2O_3 red, 99.5%, #Fe-25
Research Organic and Inorganic Chemical Company
11686 Sheldon Street
Sun Valley, CA 91352
213-877-5631

It is also easy to measure the size and concentration of iron oxide samples in a scanning electron microscope and spectrophotometer. This information permits us to calculate the collection efficiency of the electrostatic precipitator.

A worm gear dust feeder was used in the early experiments (see Fig. 8). The worm was rotated at 0-100 RPM by a gear drive (The Zero-Max Company, drive model E1, Minneapolis, Minnesota 55408). Dust is conveyed via the worm from the hopper to the fluidized bed. The

fluidized bed contains 100 micron glass beads which grind the agglomerated dust. Compressed air facilitates the grinding action of the glass beads and carries the suspended particles to the electrostatic precipitator.

The worm gear feeder is not a reliable particle generator. It has three major drawbacks. First, iron oxide is abrasive and quickly wears the bearings, worm gear, and housing. Second, pressurized dust and glass beads spew through the worn bearing seals. Third, iron oxide becomes compacted in the void spaces of the rotating worm gear. This reduces the transfer of dust and causes the worm to bind to the housing. A fundamental design change is needed to guarantee a continuous generation of particles.

An improved dust feeder is shown on Fig. 9. A vertical dust flow replaces the horizontal dust flow. This system uses the same fluidized bed and geared driver. Gravity forces dust to fall through a 1/4 in. hole in the bottom of the hopper. The rate of falling dust is metered by a rotating valve. The valve operates like a cam. It is a 1 in.-diameter Teflon rod with one large rectangular cut. Teflon resists abrasion and dust packing. Dust captured in the rotating valve falls through a pipe to the fluidized bed below. The rectangular configuration of the cut in the valve reduces the packing area to dust volume ratio. A combination of this small ratio, the free vertical dust path, and a vibrator enhances the continuous transfer of dust to the fluidized bed. The combination reduces clogging and packing in the hopper hole, rotating valve, and feed pipe. The vibrator (Sears Massager #66328270)

is clamped to the feeder housing. Rubber seals and airgaps eliminate abrasion and binding on the shaft and in the bearings. In the former model horizontal feeder, friction between the worm gear, dust, and housing forces the dust to clog the spaces in the worm gear. It is difficult to clean these spaces in an assembled unit. There is no such drawback for the vertical feeder. The fluidized bed breaks up agglomerated iron oxide and produces a smooth stream of particles to the electrostatic precipitator.

About 250 ml of iron oxide is fed to the fluidized bed during each run. The valve rotates at about 20-60 RPM. Experiments indicate that these rates provide adequate filter samples for the collection efficiency calculations. Before each run, the hopper hole and the valve are scraped with a small screwdriver. Large agglomerates of iron oxide are broken up with a spoon. These precautions insure reproducible concentrations of iron oxide in the electrostatic precipitator.

Periodically, the feed pipe below the rotating valve becomes clogged with iron oxide. This seems to occur when the fluidized bed is deficient in glass beads due to a small rate of depletion from entrainment in the exit air. The glass beads help grind and clean the feed pipe. The problem is corrected by reaming the pipe and replacing the glass beads.

VI. METHODS FOR DETERMINING PARTICLE SIZE AND COLLECTION EFFICIENCY

Particles come in all shapes and sizes. Particle collection devices come in many varieties, too. Spray towers, wet plates, and cyclones recover particles larger than about 20 microns from gas streams. Smaller particles are usually separated in an electrostatic precipitator. The space charge electrostatic precipitator in this experiment separates 0.1-2 micron dust.

A formidable problem is the determination of the sizes and concentrations of the dust passing through the precipitator. A survey of the available particle analyzers indicates that the scanning electron microscope (SEM) and the spectrophotometer (colorimeter) are the most versatile instruments. Colorimeters determine the particle concentrations and the SEM analyzes the particle sizes. The collection efficiency is calculated from this information.

The Air Pollution Laboratory at the California Institute of Technology is operated by Dr. Sheldon Friedlander. The laboratory analyzes particle sizes and concentrations with a Climet Company optical counter. A stream of dust flows through a beam of monochromatic light. Dust particles scatter the light according to their size. The scattered light signal is analyzed with a digital counter yielding a size and concentration distribution for the particles. Friedlander has demonstrated that the system differentiates standard size (0.8-2 microns) polystyrene balls. This size range is similar to the dust sizes (0.1-2 microns) in this study. An optical counter also has the advantage of being a continuous analyzer. The required time for each experiment should

be shorter with a continuous analyzer. The gas stream flowing through a space charge electrostatic precipitator consists of dust particles that are diluted in a dense fog. It is unfortunate that the optical counter cannot distinguish fog from dust particles. Another disadvantage is the narrow particle path through the analyzer. Particles undergo a rapid velocity change here. The velocity change is not uniform and depends on the particle size. Fog particles of different sizes would agglomerate. Agglomeration alters the size and concentration distributions of the particles. The optical counter results would not represent the conditions inside the precipitator. A more accurate particle analyzer is needed to calculate the collection efficiency of the precipitator.

The California Department of Public Health has a similar Climet Company particle analyzer. Dr. Walter John is in charge of the laboratory in Lewis Hall at U. C. Berkeley. His optical counter classifies particulates emanating from dry stacks. It is not adaptable to a system containing dense fog. Fog and dust are indistinguishable in an optical counter.

The Lawrence Berkeley Laboratory facility of Dr. Craig Holowell and Dr. Robert Joke contracts pollution work from the Environmental Protection Agency. Their system fractionates dust particles in an impactor. Samples are transferred to Nuclepore filters and analyzed by X-ray spectroscopy. A minicomputer processes the X-ray results and produces an elemental mass analysis. The greatest accuracy (+1%) pertains to heavy element samples. The X-ray system is versatile because

it simultaneously tests for many types of dust. But the sample backlog is about 6 months and X-ray spectroscopy provides no particle size information. The impactor cannot be used in a wet system like the space charge electrostatic precipitator.

Mr. Karels, at the California Air Resources Board in San Francisco, uses a gravimetric particle analysis. In-situ samples are collected for periods of several hours on large vacuum filters. The filters are weighed before and after the sampling period. The weight difference is a crude estimation for the amount of dust in a stack gas. The analysis does not indicate the sizes of the dust. Gravimetric analyses are subject to significant errors. The weight of a filter sample depends on the humidity, temperature, and hygroscopicity of the dust and filter. The Environmental Protection Agency in Alameda, California, performs similar large scale samplings.

Dr. George McSweeney, at the Georgia Institute of Technology, uses a pattern recognition system for determining particle sizes and concentrations. A laser beam is expanded into a 1 in. diameter collimated beam. The beam passes perpendicularly through an air stream containing dust particles. Light is diffracted and scattered by the particles. The transmitted beam is reduced to the original size by a collimating lens. The beam strikes a solid state detector (manufactured by Recognition Systems Inc. of Van Nuys, California). The detector resembles a matrix of photocells but is actually a light sensitive integrated circuit. Signals from the detector are sent to a microprocessor. The microprocessor identifies the pattern of particles

in the wide beam. A digital integrator and counter produces a readout of the particle sizes and concentrations. This system does not disrupt the particle flow, operates continuously, and samples a large segment of the particles. It is unable to distinguish between dust particles and dense fog. But it would probably give an indication of the fog size and concentration distributions. Apparently, there is no other technique available for determining the characteristics of the fog in the experiment. The pattern recognition system is recommended for further studies. Fog particles are not characterized in this experiment.

Experiments indicate that it is impractical to weigh dust samples. About 1-100 micrograms of iron oxide are collected on sample filters (Nuclepore, Millipore, or Gelman) during a run. Filters are dried and weighed before and after each run. The Mettler microbalance has a tolerance of ± 2 micrograms and is located in a constant temperature room. The room humidity is not controlled. Because of instabilities in the humidity of the weighed samples, the gravimetric method is not reproducible for the small samples in this experiment. Samples on the balance vary as much as ± 50 micrograms over a 1 hr period. Weighing is also time consuming so this technique has been abandoned.

Atomic absorption analyses of iron oxide filter samples have been made in the Analytical Laboratory in Lewis Hall at U. C. Berkeley. This technique is time intensive and not reproducible.

Particles larger than about 20 microns can be photographed on a light microscope. A light microscope cannot detect the 0.1-2 micron

dust particles in the space charge electrostatic precipitator. It is necessary to use a scanning electron microscope for these small particles. In situ, dust containing Nuclepore filter samples are analyzed in the electron microscope. The method is described in Chapter VII.

The amount of dust on the filters is determined by spectrophotometry. Iron oxide dust is used because it produces a sensitive colorimetric analysis. The collection efficiency is a function of the amounts or absorbances of iron oxide on the inlet and outlet filters. The colorimetric technique is outlined in Chapter VIII.

The collection efficiency and the particle size are analyzed by different methods. Both methods are mutually exclusive because they destroy the physical appearance of the dust. This introduces a degree of uncertainty in the calculations. Yet, electron scanning and colorimetry are probably the fastest and most accurate methods that are available for determining the collection efficiency as a function of particle size. The specifications of the sample filters are given below:

1. Hydrophilic, 0.8 micron holes, #N-080-CPH-04700 filters
Nuclepore Corporation
7035 Commerce Circle
Pleasanton, CA 94566
415-462-4430
2. Spectroglass fiber filter, 47 mm diameter, #64878 filters
Gelman Instrument Company
Ann Arbor, MI
3. 0.8 micron polycarbonate filter, 47 mm diameter, type AA
Millipore Corporation
1650 Borel Place
San Mateo, CA 94402
415-349-4481

Nuclepore filters were used with water fog and Millipore filters were used with glycerine fog. They were matched in this way to minimize filter clogging. Gelman filters were used only in the preliminary gravimetric experiments. Gelman filters contain impurities which interfere with colorimetry.

VII. PARTICLE SIZE

A scanning electron microscope (SEM) was used for determining the sizes of dust passing through the precipitator. In situ dust samples were collected on filter surfaces. Electron micrographs (5000-10,000x) of these surfaces reveal clear, macroscopic images of the dust particles.

Collection filters are mounted perpendicular to the convective gas flow through the precipitator. This mounting preferentially samples smaller particles on the order of 100 microns or less. Impaction of large, high inertia particles on the filter surface is prevented. Very small particles are not captured but pass through the 0.8 micron holes in the filter. Intermediate size (0.1-100 microns) particles are captured by interception, impaction, and diffusion. It is important to segregate filtered particle sizes in this way. The efficiency of any collection device is based on particle size. Electrostatic precipitators exhibit an increasing efficiency for particles less than or greater than about 0.1-2 microns. This size range is a natural basis for comparing efficiencies in different precipitator systems. Two micron iron oxide dust is the standard particle size in this study.

Particle sizes are determined with a scanning electron microscope. Electron scanning differs from conventional light microscopy in two main ways. First, SEM samples are analyzed in a vacuum and must be dry. Second, SEM samples must be sputtered with a heavy element like gold in order to reflect the electrons from the surface and develop an image on the CRT or photograph.

The preparation of a sample for electron scanning is as follows. The non-ferromagnetic dust on filter sample is dried for several minutes at 110°F in a laboratory oven. A 1 cm² section is cut from the filter and the clean side is glued to a sample holder. The holder is inserted into a gold sputtering chamber which is then evacuated. Gold is sputtered for about 20 sec until a fine, shiny coating covers the filter surface. Gold deposits on the filter and dust surfaces but not in the filter holes. Electron microscope imaging depends on electron scattering from the gold surfaces and penetration through the filter holes.

Electron micrographs of dust samples have been made for various precipitator operating conditions. Iron oxide dust and Nuclepore #N080CPH04700 filters are used in each experimental run. Results from these runs are given below.

A visual scan of each filter indicates that particles are collected uniformly across the filter mat in dry systems only. Whenever a supersaturated (fog or steam) system is tested, water drops temporarily block some holes in the filter. Water blockage is further evidenced by a 50% increase in suction time for supersaturated vs dry systems. It is difficult to observe in-situ clogging and its effect on particle collection. Wet filters cannot be analyzed in a SEM where the filters must be dry. Therefore, dried filters are used as the basis for the filter clogging discussion below.

It does not matter whether particles are spherical, cubical, black, or white. Electrostatic precipitation of particles is almost

independent of their physical properties except size. In this experiment, the space charge electrostatic precipitator cleanses both fog and dust particles from the gas stream. Drier sampling conditions result at the outlet filter. The inlet filter experiences more water blockage and hence, during a typical run has a higher suction pressure operating through the holes which are open than does the outlet filter. It is expected that this higher suction pressure would cause larger, high inertia particles to be collected at the inlet filter. Experimental electron scans for both wet and dry systems disprove this theory. It is observed that particles of equivalent size are collected at the inlet and outlet filters.

Prior to entering the experimental electrostatic precipitator, dust-laden air is treated by a series of unit operations. These operations serve two purposes. First, these operations simulate the condition of flue gases in chemical and power plants. It is important to show that a space charge electrostatic precipitator is compatible with the waste gases from commercial plants. Second, these operations are necessary to produce the fog stream for space charge electrostatic precipitation. Experimental electron scans indicate that these unit operations also alter the dust size distribution in the laboratory electrostatic precipitator. The resulting particle sizes (0.1-2 microns) are accidental but fortunate for the purposes of the tests performed here (see Figs. 10 and 11). Commercial scrubbers do not efficiently remove these small sizes. Small particles are also the most dangerous to health. The main purpose of the space charge electrostatic

precipitator is to eliminate these fine particulates from flue gases. It is indeed favorable for testing purposes that only 0.1-2 micron particles are made available to the laboratory precipitator. In order to understand why the particle sizing is accidental, it is necessary to trace the particle path through the system.

Dust is generated in the fluidized bed. Dust leaving the bed is injected into the air flow 30 ft upstream from the electrostatic precipitator. Any combination of five unit operations including heat, steam saturation, tower saturation, air supersaturation, water fog, and glycerine fog can be used for treating the airstream in this 30 ft section. Four important system combinations are discussed below. In each case, dust is sampled on Nuclepore filters at the precipitator entrance and exit.

First, consider using no unit operations. Light microscope photographs (Fig. 12) show particles less than 100 microns but considerably larger than the desired 2 micron size. Settling of large particles on the dry walls is counteracted by entrainment. Dust agglomerates indicate that the particle generator does not grind dust finely.

Second, saturate the air flow with a wet plate tower. Electron micrographs (Figs. 13 and 14) show many particles approximately 8-10 microns. These results prove that a wet plate tower efficiently cleans large particulates (greater than 10 microns) from gas streams.

Third, supersaturate the air flow with steam and a wet plate tower. Most commercial electrostatic precipitators operate under conditions

approaching these conditions. For example, coal or oil fired power plant stack gases contain steam from combustion. Hot stack gases are frequently treated by a series of cold water sprays and aqueous-phase absorbers for SO_2 removal. In the experiment here, the condensation of 212°F steam by 80°F air produces a 150°F foggy air flow. A light, grey fog even containing rain size drops is observed at the precipitator entrance. A weaker fog without raindrops can be seen at the precipitator exit. Grey fog indicates drops larger than about 0.15 microns. Experiments show that the precipitator completely removes the large raindrops but not the small fog particles. This behavior verifies the fact that collection efficiency is size dependent. The collection efficiency is an increasing function for drops larger than about 0.15 microns. Using these unit operations, the electron micrographs on Figs. 15 and 16 show dust particles less than 5 microns. The steam condensation system here is similar in action to a spray nozzle scrubber; fine water sprays remove large and intermediate size particles. Collection of large particles occurs by settling on the wet walls and plates.

Fourth, consider the unit operations that are associated with space charge electrostatic precipitation and their effect on the particle size in the precipitator. Precise control of the fog drop size is the key to effective precipitation. Metered amounts of flue gas, steam, tower saturation, ambient air, and water fog are mixed in order to maintain the desired drop size. There is one essential difference between this system and the one discussed in the previous paragraph. The addition of water fog removes intermediate size particles.

A comparison of the electron micrographs on Fig. 10, 11, 15 and 16 verifies that the water fog system captures particles larger than 2 microns leaving only particles of approximately that size to be collected on the filters.

Dense, blue water fog is generated in a mixing nozzle 4 ft downstream from the electrostatic precipitator. Fog entering the precipitator is greyish-blue. Fog leaving the precipitator is grey. Optimum size (0.1-0.15 microns) fog is blue. Grey fog is larger and should yield a lower collection efficiency. Apparently, size stabilization has not been achieved in the water fog experiments. Glycerine fog, on the other hand, stays blue throughout the precipitator.

VIII. COLLECTION EFFICIENCY

Colorimetry is a simple and accurate method for determining trace concentrations of iron compounds. Spectrophotometers (colorimeters) directly measure the light absorbances of liquid complexes such as ferric chloride, ferrous phenanthroline, and iron thiocyanate. Different complexes absorb light at characteristic wavelengths. For this reason, it is possible to quantitatively analyze iron in the presence of other reagents. Spectrophotometry is also fast and as many as 12 samples can be tested simultaneously. A comparison between experimental and standard spectrographs yields the amount of iron in the solution. In this experiment, the mass of iron oxide dust on each filter is determined by colorimetry. The collection efficiencies of the electrostatic precipitator are derived from the amounts of dust on the inlet and outlet filters. Collection efficiency is defined as the ratio of dust particles collected to dust particles entering the precipitator. Efficiencies obtained from spectrophotometry are accurate for several reasons. Systematic errors tend to cancel because each sample is analyzed in the same way. The spectrophotometer is very sensitive for iron oxide analysis. A high sensitivity minimizes the absolute errors for individual sample determinations. Collection efficiencies should also be precise because they are based on these samples.

The quantitative analysis of iron oxide dust is simple and well standardized.⁶ The ferrous phenanthroline method has an excellent sensitivity and is used in this study. Very pure reagent chemicals are necessary for an accurate iron oxide analysis. Side reactions

and competing chemical complexes can produce significant errors. The preparation and handling of the reagents is outlined in Appendix C. Iron oxide samples are obtained on Nuclepore and Millipore filters. Both filter types are suitable for iron oxide colorimetry. Gelman filters are not used because they are contaminated with inconsistent amounts of iron.

During each run, sample impregnated filters are placed in 150 ml breakers and sealed with Parafilm. The colormetric analysis of iron oxide begins with the addition of 4 ml of concentrated HCl to each beaker. The beaker is again covered with Parafilm. Parafilm protects the sample from airborne particle contamination and reduces acid evaporation. The acid leaches iron oxide from the filter. Iron dissolves as Fe^{+3} . After 30 min of soaking and periodic slushing, the beaker is placed in an ice bath. The sample is neutralized by 5 ml of base (sodium hydroxide and potassium acetate). The addition of 1 ml of hydroxylamine hydrochloride reduces the Fe^{+3} to Fe^{+2} . One milliliter of phenanthroline is added to the sample solution. The phenanthroline converts Fe^{+2} to ferrous phenanthroline. The final result is that the original iron oxide sample is quantitatively converted to a light absorbing complex. This complex, ferrous phenanthroline, selectively absorbs 508 nanometer light in a spectrophotometer. The potassium acetate that is added in the neutralization step also buffers the solution at a pH of 4. Buffering improves the reproducibility of the colorimetric measurements. Ferrous phenanthroline light absorption is pH dependent.

Calibration and operation of the Beckman #DU-2 Spectrophotometer is detailed in Appendix B. Only a summary is given here. Quartz cuvettes are rinsed and filled with ferrous phenanthroline samples. Standard cells are filled with distilled water or reagent mixtures. The cuvettes are 1 cm deep, by 1 cm wide, by 4.5 cm high. The path length through the cuvettes is 1.0 cm deep with a cross section of 2.0 cm^2 . The cells are inserted four at a time into the sample holders. Absorbance measurements in the spectrophotometer are relative. It is important to compare every sample with the same standard solutions. Therefore, a designated set of standard cuvettes occupy the first two positions in each cell holder. Usually the third and fourth positions contain precipitator input and output samples. This technique eliminates baseline drift in the spectrophotometer. The baseline is easily reset for each group of samples.

The sample holders are placed in the spectrophotometer. The instrument measures relative absorbance on linear (0-100 or 50-150) scales. Each set of four cuvettes requires only 2 min for the absorbance readings. Five sets are conveniently read in 10 min. Figure 17 is a typical absorbance graph. Distilled water is arbitrarily adjusted for zero absorbance. A solution containing the spectrographic reagents has a reading of 3.1. The paired peaks (GH, OJ, and PL) are ferrous phenanthroline solutions derived from iron oxide samples. As an example, consider the "OJ" sample pair. Glycerine fog, 135 cfm main air flow, 30 kV corona, and Millipore filters are used in this run. "O" and "J" have absorbances of 37.5 and 59. In order to calculate the

collection efficiency of the electrostatic precipitator, it is necessary to relate the absorbances to the amounts of iron oxide on the filters.

The amount of iron oxide dust on a sample filter is almost directly proportional to its absorbance. Figure 18 is an experimental graph relating absorbance to formal iron oxide concentration. The graph is a simple dilution curve. 0.042 grams of iron oxide is dissolved in 100 ml of HCl. This stock solution is further diluted in various volumes of HCl. A 4 ml aliquot of each diluted sample is treated by the colorimetric reagents and analyzed in the spectrophotometer. The points of Fig. 18 correspond to the diluted iron oxide samples. The absorbance curve becomes nonlinear for absorbances greater than about 70. It is convenient to define a "true absorbance" curve which is always linear. For each iron oxide concentration, there exists an absorbance and a "true absorbance." Figure 18 allows us to correct for nonlinear deviations in the absorbance vs iron oxide concentration curve. In other words, "true absorbance" is always directly proportional to iron oxide concentration.

An electrostatic precipitator does not remove all of the dust in a flue gas. The collection inefficiency of a precipitator is defined as the mass ratio of exiting particles to entering particles. It is impractical to weigh every particle in a large scale precipitator. Collection inefficiency is more easily defined in terms of filter samples. This experiment samples and analyzes small portions of the flue gas. Each sample filter measures the mass of iron oxide dust contained in a known quantity of air. The ratio of dust mass to air

moles is called the mass concentration. Collection inefficiency is equal to the mass concentration ratio of exiting particles to entering particles. The collection efficiency is equal to one minus the collection inefficiency. The discussion below summarizes how the collection efficiency is calculated in this experiment:

1. "x, r, f, l, and 2" are experimental variables representing arbitrary solution, reagent mixture, filter, inlet filter, and outlet filter, respectively.

2. The mass of iron oxide that is collected on a filter is M_x .

3. The collection times for the inlet and outlet filters in any run are simultaneous and equivalent.

4. The quantity of gas passing through a filter is $V_x \Delta P_x$. V_x is the constant volume of the sampling tanks and equals 20 gallons. ΔP_x is measured on a manometer and varies from about 400-700 torr depending on the suction time and humidity at the filter. Condensed fog clogging of the filter reduces ΔP_x .

5. The mass concentration is $M_x / V_x \Delta P_x$.

6. The absorbance AA_x is measured on a spectrophotometer. AA_x is directly proportional to M_x when AA_x is less than about 70. The linear behavior is shown on Fig. 18.

7. The "true absorbance" A_x is a corrected value for the absorbance AA_x . Whenever the absorbance is larger than about 70, the relation between AA_x and M_x becomes nonlinear. A_x is a linearized replacement curve for AA_x (see Fig. 18).

8. In some experiments, the iron oxide sample is too concentrated for colorimetric analysis. It is necessary to dilute the iron oxide containing filters in excess HCl. Call this excess volume "DIL". Sample filters are normally dissolved in 4 ml of HCl. In either case, only 4 ml of the acidified sample is treated by the reagent chemicals and analyzed in the colorimeter. The dilution changes the absorbance in two ways. The true absorbances of the sample and the impurities in the filter are reduced by the factor:

$$\left(\frac{4}{\text{DIL} + 4} \right)$$

The net "true absorbance" on filter "x" is then:

$$A_x = \left(\frac{\text{DIL} + 4}{4} \right) \left[A_x - \left(\frac{4}{\text{DIL} + 4} \right) (A_f) - A_r \right] + A_f + A_r$$

9. The collection efficiency η is:

$$\begin{aligned} \eta &= 1 - \left(\frac{\frac{M_2}{V_2 \Delta P_2}}{\frac{M_1}{V_1 \Delta P_1}} \right) \\ &= 1 - \left(\frac{M_2 \Delta P_1}{M_1 \Delta P_2} \right) \\ &= \frac{M_1 - M_2 \left(\frac{\Delta P_1}{\Delta P_2} \right)}{M_1} \\ &= \frac{(A_1 - A_r - A_f) - (A_2 - A_r - A_f) (\Delta P_1 / \Delta P_2)}{A_1 - A_r - A_f} \end{aligned}$$

where $V_1 = V_2 = 20$ gallons

M = mass concentration of iron oxide

ΔP = net pressure change in the filter suction lines

A = true absorbance.

The following example illustrates how the collection efficiency is a function of the amounts of dust on the inlet and outlet filters. Consider the "OJ" sample pair described previously. This system utilizes glycerine fog, 135 cfm main air flow, 30 kV corona, and Millipore filters. "O" is the inlet filter and "J" is the outlet filter. Figure 17 shows that the apparent absorbances of "O", "J", and the reagent solutions are 37.5, 59, and 3, respectively. The absorbances are less than 70 so there is no need to correct for nonlinear spectrographs. Previous experiments indicate that impurities on Millipore filters exhibit an absorption of about seven. "O" is dissolved in $(25 + 4 = 29)$ ml of HCl while "J" is dissolved in 4 ml of HCl. The collection efficiency for this case is as follows:

$$A_f = 7$$

$$A_r = 3$$

$$AA_1 = 37.5$$

$$A_1 = \left(\frac{25 + 4}{4} \right) \left(37.5 - \left(\frac{4}{25 + 4} \right) (7) - 3 \right) + 7 + 3$$

$$= 253$$

$$AA_2 = 59$$

$$A_2 = 59$$

$$P_1 = 610$$

$$P_2 = 624$$

$$\eta = \frac{(253 - 7 - 3) - (59 - 7 - 3) (610/624)}{253 - 7 - 3}$$

$$= 0.80$$

= collection efficiency of run 202.

The same method is used for the other collection efficiency calculations. Experiments have shown that Nuclepore filters have an A_f of about zero.

IX. RESULTS

The main purpose of this study is to develop an industrial scale space charge precipitator. The study entails extensive testing and modification of the precipitator built by Carnevali.⁵ The flow conditions, electrical equipment, and physical dimensions of the precipitator are typical of industrial applications. Final results indicate that the test precipitator agrees with the space charge theory introduced by Hanson and Wilke⁷ in 1967.

Like any scientific study, preliminary experiments are designed to identify any problems with the equipment or technique. Discussions in the appendix and previous chapters iron out many of these problems. Most of this study is devoted to perfecting the dust generator, fog generators, charging section, and collection efficiency analysis. The more general problems and final results are listed below.

Examination of the micrographs of Figs. 10-16 reveals iron oxide dust of many shapes and sizes. However, it is assumed in the development of the space charge theory that the particles are perfect spheres of uniform size. It would appear that it is not possible to correlate theoretical and experimental collection efficiencies for the particles. One way around the size and shape dilemma is to define an effective size for the particles. Let the effective size represent the average behavior of a size distribution of particles. In this work it was taken as a sphere, two microns in diameter. Consider a typical water fog run at 600 cfm main airflow and 150°F. Figures 10 and 11 show filter samples containing 0.1-2 micron iron oxide particles. First,

there are more smaller particles than larger particles. Second, the spectrophotometer is more sensitive to the size and not the number of particles. It would take about $(\pi 2^3 / \pi 0.1^3) = 8000$ of the 0.1 micron particles to give the same reading on the spectrophotometer as a single 2 micron particle. Third, the collection efficiency is an increasing function for particles larger than about 0.1 microns. Fourth, the particles are not spheres and so their charges, mobilities, and collection efficiencies are different from the values that the theory predicts. In the final analysis, the collection efficiencies derived from spectrophotometry probably represent the larger (2 micron) particles in the sample. This study assumes that the effective dust size is 2 microns in the water fog experiments. Presumably the same sensitivity for 2 micron particles would occur for glycerine fog. Larger particles are removed before entering the precipitator by the unit operations previously discussed.

Although water and glycerine fog are certainly spherical, they are present in many sizes. Observation of the water fog at the precipitator entrance shows that most of the drops are small. There are a lesser number of rain size drops which are created by water entrainment in the saturation tower and condensation in the precipitator duct. With the corona on, the larger drops are precipitated, and only small, rather uniform drops are observed at the precipitator exit. It is convenient to assign an effective size to these small drops. They maintain essentially all of the space charge field necessary for

precipitating the dust particles. The same definition of effective size applies to glycerine fog drops as well.

In order to establish that the laboratory precipitator operates through the principle of space charge provided by the fog, various runs were made without fog but with other features of the equipment operating. Consider runs 114-126, which are all at 600 cfm with the corona on. Table II lists the collection efficiencies for these runs. Runs 114-119 were accomplished with dry air, and show a collection efficiency of 21-41%. The addition of steam and the wet plate scrubber improves the efficiency to 52-57% in runs 120-123. The addition of water fog in runs 124-126 improves the efficiency to 64-66%.

The experimental efficiencies for a particular system vary from day to day. The simplest explanation is that the size distribution of dust particles is not constant. The degree of dust agglomeration in the particle generator depends on the humidity and flowrate of the carrier air, the concentration of glass beads, and the batch of iron oxide. This problem is minimized by carrying out a whole series of experiments during each day. We also try to reproduce the same experimental conditions for every run.

It is expected that no precipitation would occur with the corona off. Experimental runs 101-105 with collection efficiencies of -1% to +5% verify this for dry air, steam, and water fog systems. See Table III for the efficiencies. These results imply that the overall accuracy of the experimental collection efficiencies is about +5%.

Table II. Experimental runs 114-126.

Run	Condition	Main Air Stream	Corona			Collection Efficiency (η)
		Flowrate (cfm)	Voltage (kV)	Current (ma)		
114	dry	600	19.5	1.0	0.31	
115	dry	600	19.5	1.0	0.41	
116	dry	600	20.5	1.0	0.30	
117	dry	600	20.0	1.0	0.27	
118	dry	600	19.5	1.0	0.29	
119	dry	600	19.6	1.0	0.21	
120	Saturation Tower and Steam	600	24.0	1.0	0.52	
121	Saturation Tower and Steam	600	24.0	1.0	0.56	
122	Saturation Tower and Steam	600	24.0	1.0	0.52	
123	Saturation Tower and Steam	600	24.0	1.0	0.57	
124	Saturation Tower, Steam, and Water Fog	600	24.0	1.0	0.66	
125	Saturation Tower, Steam, and Water Fog	600	24.0	1.0	0.64	
126	Saturation Tower, Steam, and Water Fog	600	24.0	1.0	0.64	

Table III. Experimental runs 101-105.

Run	Main Air Stream Condition	Corona	Collection Efficiency (%)
101	dry	no	0.051
102	Saturation Tower, Steam, and Water Fog	no	0.033
103	Saturation Tower, Steam, and Water Fog	no	0.001
104	Saturation Tower and Steam	no	-0.024
105	Saturation Tower and Steam	no	-0.010

Early experiments, including those cited in Table II, used a multiple corona grid connected to a single power source (see Chapter IV). Sparkovers, drops of water landing on the electrodes, and eddy air current lead to a complex power drain. When 16 electrodes are interconnected to the power supply, the coronas remain extinguished for a large fraction of the time. The net result is that the experimental collection efficiencies are lower than the predicted values. In the final precipitator, the problem was corrected by wiring only one electrode to the power supply.

The final experiments indicate that the test precipitator agrees favorably with the space charge theory. Graphs and tables summarizing the results are given below.

Figure 19 relates the experimental and theoretical collection efficiencies for space charge precipitation using glycerine fog. the experimental data are tabulated on Table IV. The theoretical curve is plotted from the equations listed in Chapter II. As an example, the theoretical collection efficiency corresponding to run 197 is calculated below:

1. The experimental parameters are a 0.031 in. diameter by 6 in. long corona wire, a 30,000 volt corona, a 6 in. diameter by 8 in. long cylindrical charging section, a 1 ft square by 6 ft long collection section, and a 540 cfm main airflow.

2. According to Smoluchowski's^{8,9} equation as refined by Kostow,⁴ the initial concentration " C_{d0} " of glycerine fog drops in the charging section is about 10^8 drops per cm^3 . The drop size should be about 0.15 microns.

Table IV. Final glycerine fog experiments.

Run	Main Air Stream		Corona		Collection Efficiency (η)
	Condition	Flowrate (cfm)	Voltage (kV)	Current (ma)	
197	Saturation Tower and Glycerine Fog	540	30	0.11	0.36
198	Saturation Tower and Glycerine Fog	540	30	0.11	0.47
199	Saturation Tower and Glycerine Fog	270	30	0.07	0.76
200	Saturation Tower and Glycerine Fog	270	30	0.07	0.57
202	Saturation Tower and Glycerine Fog	135	30	0.04	0.80
203	Saturation Tower and Glycerine Fog	135	30	0.05	0.73
204	Saturation Tower and Glycerine Fog	15	29	0.02	0.94
205	Saturation Tower and Glycerine Fog	15	29	0.02	0.95

3. The residence time "t" of the drops and particles in the collection section is:

$$t = \frac{(6 \text{ ft})(1 \text{ ft}^2)}{540 \text{ ft}^3/\text{minute}}$$

$$= 0.67 \text{ sec}$$

4. The velocity "U" of air through the charging section is:

$$U = \frac{540 \text{ ft}^3/\text{min}}{(\pi/4)(6 \text{ ft}/12)^2(60 \text{ sec}/\text{min})}$$

$$= 46 \text{ ft}/\text{sec}$$

5. Kostow's⁴ Fortran program "Charge" predicts the average charge "Q_d" of the fog drops. The program is listed in Appendix D. Program output for run 197 is given on Table V. Using a similar airflow (50 ft/sec) as in run 197 (46 ft/sec), Table V indicates that the drop charge level is almost saturated at 3.59 electronic charges after 0.01 sec. For this reason, a (50 ft/sec) (0.01 sec) = 6 in. electrode is used in the experiment. The drops retain their charges in the collection section of the precipitator.

6. The mobility "λ" is obtained from a balance of the drag and electronic forces on the particle or drop:

$$QE = \frac{3\pi\mu UD}{(K_c)}$$

$$\lambda = U/E$$

$$= \frac{QK_c}{3\pi\mu D}$$

For the 0.15 micron fog drops,

$$\begin{aligned}
 (K_c)_d &= \text{Cunningham correction factor for fog drops defined in} \\
 &\quad \text{Kostow}^4 \\
 &= 1 + (L/D_d) (1.644 + 0.552 \exp(-0.656 D_d/L)) \\
 &= 1 + (0.1/0.15) (1.644 + 0.552 \exp(-0.656 \times 0.15/0.1)) \\
 &= 2.23
 \end{aligned}$$

where

L = mean free path of the air molecules and is about 0.1 microns
in this experiment

μ = viscosity of the air at 80°F
= 0.019 centipoise

Q_d = 3.59 electronic charges

$$\lambda_d = \frac{(3.59) (1.59 \times 10^{-19}) (2.23)}{3\pi (1.9 \times 10^{-5}) (1.5 \times 10^{-7})}$$

$$= 4.7 \times 10^{-8} \text{ meters}^2/\text{volt-sec}$$

DROP CHARGING
 DROP DIAM = .15 MICRONS
 DROP CONC = .1000E+09 PER CC
 WIRE DIAM = .0310 IN
 TUBE DIAM = 6.00 IN
 GAS VELOCITY = 50.0 FT/SEC
 VOLTAGE APPLIED = 30000.
 CORONA STARTING FIELD = 70566. VOLTS/CM
 CORONA STARTING VOLTAGE = 14629.

TIME MSEC	CURRENT MA/METER	AVE DROP CHG ELEC
.2	1.039	.78
.4	.825	1.15
.6	.740	1.41
.8	.684	1.60
1.0	.642	1.76
1.5	.609	2.08
2.0	.575	2.31
4.0	.501	2.93
6.0	.368	3.23
8.0	.332	3.44
10.0	.295	3.56

FINAL PARTICLE CHARGE

SIZE MICRONS	CHARGE ELEC
.01	.05
.05	.68
.10	1.95
.15	3.59
.20	5.61
.50	26.53
1.00	93.85
2.00	387.05
5.00	2394.25

DROP CHARGING
 DROP DIAM = .15 MICRONS
 DROP CONC = .1000E+09 PER CC
 WIRE DIAM = .0310 IN
 TUBE DIAM = 6.00 IN
 GAS VELOCITY = 50.0 FT/SEC
 VOLTAGE APPLIED = 30000.
 CORONA STARTING FIELD = 70566. VOLTS/CM
 CORONA STARTING VOLTAGE = 14629.

FINAL CONDITIONS AT 10 MSEC AND 6.0 INCHES
 TOTAL CURRENT = .0670 MA

Table V. Charges of particles and fog drops for a 30 kV corona and 600 CFM main airflow.

RADIUS IN	VOLTAGE V	FIELD V/CM	ION CONC N/CCM	DROP CHG ELEC
.0155	30000.0	70566.0	.1700E+10	78.52
.0191	29414.7	57191.0	.1609E+10	63.64
.0236	28829.1	46351.0	.1698E+10	51.53
.0292	28243.0	37595.2	.1696E+10	41.83
.0360	27656.2	30503.2	.1604E+10	33.94
.0444	27068.2	24760.3	.1689E+10	27.56
.0548	26475.5	20139.1	.1683E+10	22.40
.0677	25886.1	16403.0	.1674E+10	18.25
.0836	25280.8	13397.6	.1660E+10	14.90
.1032	24687.4	10957.3	.1640E+10	12.24
.1274	24075.9	9053.7	.1611E+10	10.16
.1572	23450.0	7539.2	.1569E+10	8.62
.1941	22805.7	6342.6	.1510E+10	7.59
.2396	22131.0	5415.5	.1433E+10	7.01
.2958	21413.7	4705.8	.1335E+10	6.67
.3651	20625.6	4180.5	.1218E+10	6.42
.4507	19774.0	3793.9	.1087E+10	6.20
.5564	18797.9	3517.1	.9502E+09	5.99
.6868	17669.9	3322.0	.8148E+09	5.76
.8478	16343.3	3135.0	.6877E+09	5.52
1.0466	14761.5	3097.0	.5735E+09	5.27
1.2919	12855.4	3036.7	.4739E+09	5.02
1.5948	10540.8	2955.8	.3892E+09	4.76
1.9687	7715.2	2968.7	.3181E+09	4.50
2.4302	4252.9	2950.7	.2593E+09	4.25
3.0000	0.	2923.4	.2120E+09	4.00

AVERAGE DROP CHARGE = 4.61 ELECTRONIC CHGS

Table V (continued).

For the 2 micron dust particles,

Q_p = average charge of the 2 micron particles is found on Table V

$$= 387$$

$$(K_c)_p = 1.08$$

$$\lambda_p = \frac{(387)(1.59 \times 10^{-19})(1.08)}{3\pi(1.9 \times 10^{-5})(2 \times 10^{-6})}$$

$$= 1.9 \times 10^{-7} \text{ meters}^2/\text{volt-sec.}$$

7. The theoretical collection efficiency " η_p " of the particles in run 197 is obtained from the equations outlined in Chapter II:

$$\eta_p = 1 - \left(\frac{1}{1 + \frac{\lambda_{p,d} Q_d C_{do} t}{\epsilon_0}} \right)^{(\lambda_p / \lambda_d)}$$

$$= 1 - \left(\frac{1}{1 + \frac{(4.7 \times 10^{-8})(3.59)(1.59 \times 10^{-19})(10^{14})(0.67)}{8.85 \times 10^{-12}}} \right)^{\left(\frac{1.9 \times 10^{-7}}{4.7 \times 10^{-8}} \right)}$$

$$= 0.52$$

Even through the data on Fig. 19 show considerable uncertainty, the theoretical and experimental curves follow identical trends of decreasing efficiency with increasing flowrate.

Results for the final water fog runs further support the space charge theory. These runs are summarized on Fig. 20 and Table VI. A lower corona voltage (25 kV) is used because the water fog has a greater tendency to arc over in the electrode support arms. The theoretical curve on Fig. 20 is based on the particle and drop charges in Table VII and on the glycerine fog discussion above.

It is encouraging that both the water fog and glycerine fog experiments agree closely with the space charge theory at high airflows. Flowrates of 540 cfm and 300 cfm correspond to air velocities of 9 ft/sec and 5 ft/sec. Such velocities are typical of many industrial applications. These results should enable engineers to design other space charge precipitators at comparable gas velocities. The engineers must merely match the space charge theory to the particular efficiency and gas flow requirements. Large gas flow would probably be treated by a modular array of space charge precipitators. Each module would resemble the one in this experiment. The dimensions are limited by the configuration of the high voltage equipment. In other words, corona voltages higher than about 60,000 volts are not used because the power supplies and insulators would be prohibitively expensive. The diameter of the charging section cannot be too large because minor imperfections in the tube wall would then produce a competitive positive corona on the tube wall. The net result would be a reduced collection efficiency. Consider the glycerine fog run 197 discussed previously. Table V verifies that the space charge field (3421 volts/cm) at the wall is well under the approximate 20,000 volts/cm breakdown field of the gas, and that

Table VI. Final water fog experiments.

Run	Main Air Stream		Corona		Collection Efficiency (η)
	Condition	Flowrate (cfm)	Voltage (kV)	Current (ma)	
206	Saturation Tower, Steam, and Water Fog	17	25	0.13	0.79
207	Saturation Tower, Steam, and Water Fog	17	25	0.08	0.95
212	Saturation Tower, Steam, and Water Fog	300	25	0.05	0.45
213	Saturation Tower, Steam, and Water Fog	300	25	0.05	0.54
214	Saturation Tower, Steam, and Water Fog	150	25	0.03	0.81
215	Saturation Tower, Steam, and Water Fog	150	25	0.03	0.84

DROP CHARGING
 DROP DIAM = .15 MICRONS
 DROP CONC = .1000E+09 PER CC
 WIRE DIAM = .0310 IN
 TUBE DIAM = 6.00 IN
 GAS VELOCITY = 50.0 FT/SEC
 VOLTAGE APPLIED = 25000.
 CORONA STARTING FIELD = 70566. VOLTS/CM
 CORONA STARTING VOLTAGE = 14629.

TIME MSEC	CURRENT MA/METER	AVE DROP CHG ELEC
.2	.568	.54
.4	.451	.83
.6	.395	1.03
.8	.357	1.19
1.0	.329	1.32
1.5	.306	1.52
2.0	.262	1.77
4.0	.232	2.27
6.0	.152	2.50
8.0	.116	2.66
10.0	.093	2.77

FINAL PARTICLE CHARGE

SIZE MICRONS	CHARGE ELEC
.01	.03
.05	.49
.10	1.48
.15	2.77
.20	4.31
.50	13.85
1.00	63.94
2.00	237.83
5.00	1438.91

DROP CHARGING
 DROP DIAM = .15 MICRONS
 DROP CONC = .1000E+09 PER CC
 WIRE DIAM = .0310 IN
 TUBE DIAM = 6.00 IN
 GAS VELOCITY = 50.0 FT/SEC
 VOLTAGE APPLIED = 25000.
 CORONA STARTING FIELD = 70566. VOLTS/CM
 CORONA STARTING VOLTAGE = 14629.

FINAL CONDITIONS AT 10 MSEC AND 6.0 INCHES
 TOTAL CURRENT = .0288 MA

Table VII. Charges of particles and fog drops for a 25 kv corona and 600 CFM main airflow.

RADIUS IN	VOLTAGE	FIELD V/CM	ION CONC N/CUCM	DROP CHG ELEC
.0155	25000.0	70566.0	.1517E+09	62.78
.0191	24414.4	57251.0	.1515E+09	50.92
.0236	23827.9	46463.3	.1512E+09	41.32
.0292	23240.1	37725.2	.1509E+09	33.54
.0360	22650.9	30647.6	.1504E+09	27.24
.0444	22059.8	24915.4	.1499E+09	22.14
.0548	21466.3	20273.4	.1492E+09	18.02
.0677	20859.8	16515.0	.1484E+09	14.68
.0836	20260.7	13472.8	.1474E+09	12.00
.1032	19664.7	11011.6	.1461E+09	9.86
.1274	19053.7	9022.2	.1444E+09	8.18
.1572	18434.7	7416.7	.1423E+09	6.89
.1941	17805.3	6124.7	.1396E+09	5.92
.2396	17161.8	5089.9	.1361E+09	5.23
.2958	16498.0	4267.3	.1315E+09	4.74
.3651	15809.0	3621.7	.1255E+09	4.41
.4507	15080.7	3125.0	.1178E+09	4.18
.5564	14297.1	2754.1	.1083E+09	3.99
.6868	13434.1	2489.6	.9705E+08	3.80
.8478	12457.7	2314.7	.8456E+08	3.59
1.0466	11320.8	2215.0	.7158E+08	3.37
1.2910	9958.2	2178.1	.5897E+08	3.14
1.5948	8284.8	2194.0	.4742E+08	2.90
1.9687	6181.3	2254.5	.3739E+08	2.66
2.4302	3490.4	2353.7	.2901E+08	2.43
3.0000	0	2463.2	.2245E+08	2.20

AVERAGE DROP CHARGE = 2.77 ELECTRONIC CHGS

Table VII (continued).

a very small radius of curvature at the tube wall would be necessary to achieve breakdown. This applies to the other glycerine fog and water fog experiments, too.

In order to better correlate space charge theory with experiment, Kostow's⁴ program "Charge" has been run for both fog and no fog systems. Considering the final glycerine fog experiments, Table VIII predicts that the corona current without fog should be 0.1584 milliamps. Experiments without fog show a current of 0.20 milliamps. Table V predicts a current of 0.0670 milliamps for glycerine fog runs 197 and 198. These fog runs indicate a current of 0.11 milliamps. With or without glycerine fog, the theoretical currents are about 0.04 milliamps higher than the experimental values. Neglecting this apparent systematic difference, the addition of glycerine fog does quench part of the current as the space charge theory predicts. Larger charge carriers like fog drops have lower mobilities than smaller air molecules. Mobility is a measure of the current carrying ability of a drop or molecule.

DROD CHARGING

DROP DIAM = .15 MICRONS
 DROP CONC = -. PER CC
 WIRE DIAM = .0310 IN
 TUBE DIAM = 6.00 IN
 GAS VELOCITY = 50.0 FT/SEC
 VOLTAGE APPLIED = 30000.
 CORONA STARTING FIELD = 70566. VOLTS/CM
 CORONA STARTING VOLTAGE = 14629.

TIME MSEC	CURRENT MA/METER	AVE DROP CHG ELEC
.2	1.030	.78
.4	1.030	1.23
.6	1.030	1.57
.8	1.030	1.83
1.0	1.030	2.04
1.5	1.030	2.47
2.0	1.030	2.77
4.0	1.030	3.57
6.0	1.030	4.01
8.0	1.030	4.34
10.0	1.030	4.61

FINAL PARTICLE CHARGE

SIZE MICRONS	CHARGE ELEC
.01	.09
.05	1.00
.10	2.64
.15	4.61
.20	6.92
.50	32.27
1.00	124.28
2.00	404.02
5.00	3079.31

DROD CHARGING

DROP DIAM = .15 MICRONS
 DROP CONC = -. PER CC
 WIRE DIAM = .0310 IN
 TUBE DIAM = 6.00 IN
 GAS VELOCITY = 50.0 FT/SEC
 VOLTAGE APPLIED = 30000.
 CORONA STARTING FIELD = 70566. VOLTS/CM
 CORONA STARTING VOLTAGE = 14629.

FINAL CONDITIONS AT 10 MSEC AND 6.0 INCHES
 TOTAL CURRENT = .1564 MA

Table VIII. Charges of particles for a 30 kV corona, 600 CFM main airflow, and no fog.

RADIUS IN	VOLTAGE	FIELD V/CM	ION CONC N/CCM	DROP CHG ELEC
.0155	30000.0	70556.0	.4810E+09	72.97
.0151	29414.3	57270.7	.4810E+09	59.21
.0236	28827.5	46400.5	.4799E+09	48.06
.0292	28230.1	37776.3	.4786E+09	39.04
.0360	27648.8	30712.6	.4768E+09	31.73
.0444	27056.2	24993.0	.4747E+09	25.81
.0548	26470.5	20385.6	.4719E+09	21.03
.0677	25860.2	16621.6	.4684E+09	17.16
.0836	25256.0	13535.0	.4639E+09	14.03
.1032	24644.6	11151.3	.4582E+09	11.53
.1274	24024.4	9181.8	.4508E+09	9.56
.1572	23392.5	7500.2	.4412E+09	8.04
.1941	22744.8	6333.0	.4288E+09	6.93
.2396	22075.4	5321.0	.4127E+09	6.17
.2958	21375.6	4475.7	.3920E+09	5.70
.3651	20632.8	3746.7	.3655E+09	5.40
.4507	19828.4	3102.1	.3340E+09	5.16
.5564	18936.3	3187.8	.2972E+09	4.94
.6866	17920.2	2582.3	.2574E+09	4.72
.8475	16730.5	2067.2	.2169E+09	4.48
1.0466	15300.1	2627.1	.1782E+09	4.23
1.2919	13538.5	2950.1	.1432E+09	3.97
1.5945	11325.3	2827.6	.1129E+09	3.71
1.9657	8404.0	3056.0	.8761E+08	3.47
2.4302	4822.5	3232.6	.6710E+08	3.24
3.0000	0.	3421.0	.5136E+08	3.01

AVERAGE DROP CHARGE = 3.59 ELECTRONIC CHGS

Table VIII (continued).

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APPENDICES

The appendices include operating instructions for the spectrophotometer and precipitator. They also outline the technique for preparing and handling the spectrophotometric chemicals. A copy of Kostow's⁴ Fortran program "Charge" for calculating the particle and drop charges is included.

APPENDIX A: PRECIPITATOR OPERATION

Nearly 100 experimental runs have been made with the test precipitator. With this experience at hand, a guide for the experimental technique has been prepared. The guide clarifies the functions of the experimental apparatus. A schematic diagram for the test precipitator is outlined on Fig. 6 and Table I. The instruction guide is divided into four sections. Section II applies to a water fog system while Section III is for a glycerine fog system. Sections I and IV apply to both fog types. For brevity, the guide lists only the control settings for systems containing 600 cfm and 150°F main airflows. Carnevali⁵ summarizes the gauge settings for various other fog conditions in the precipitator. For systems without fog, steam, saturation, etc., the appropriate steps should be omitted from the instructions below:

I. Startup

1. Inspect and repair any faulty equipment or leaks.
2. Clean the Lucite viewing ports.
3. Turn on the main circuitbreakers mounted on the wall.
4. Fill the water or glycerine boiler to the mark.
5. Preheat the glycerine or water by turning V2 to 110 volts. For water also turn on V3.
6. Siphon the waste slurry water from the settling drum.
7. Prepare two sample filters on a clean and covered table: Clean the filter holder with Kimwipes. Use soap and water as necessary. Place the filter holder vertically in your left hand. Using tweezers in your right hand, place a clean filter on the holder.

Center a Teflon gasket on the filter. Place the cover over the filter. Secure the cover with the three thumbscrews. Set the holder on the clean table. Do not let anything touch the filter surface.

8. Set G6 to 35-100.
9. Set G2 to 51.8.

II. Water Fog

1. Turn on the main blower and adjust G1 to 0.80. This corresponds to 600 cfm main airflow through the precipitator.
2. Adjust L1 for 1 in. of water on the saturation tower plates. Usually this occurs when the top two water valves on the tower are each opened one turn.
3. Adjust the steam so that T3 is 150°F.
4. Set G5 to 35.4.
5. Scrape the dust generator hopper and one tooth gear valve with a small screwdriver. Fill the hopper with iron oxide dust.
6. Fill the cold air chamber with dry ice.
7. Set P2 in accordance with the chart on the gauge. The chart corrects the house air pressure for variable room temperatures.
8. Adjust V2 until P1 is about 3.
9. Adjust G7 until T5 is -10°F.
10. Close G9. Record P10 and P20.
11. Turn on the corona power supply. Set V1 and I1 to the desired voltage and current. Usually this corresponds to a voltage slightly less than the sparkover voltage.

12. Set G3 to 12; i.e., set G4 to 63.8.
13. Shine a microscope light through the Lucite viewing ports at the inlet and outlet to the precipitator. Observe whether there is fog in the airstream.
14. Visually verify that all of the coronas are glowing.
15. The following steps should be performed as quickly as possible. This will reduce contamination on the filters.
16. Insert the inlet and outlet filter holders. Refer to step I.7. Attach the suction lines to the holders.
17. Turn on the vibrator. Turn on the dust feeder and adjust the RPM to about 60.
18. Repeat Steps II.1, 2, 3, 4, 8, 9, 11, and 13 as necessary.
19. Simultaneously open G10 and turn on the timer.
20. Repeat step II.18 constantly during the run.
21. After about 5 min, record the time, P11, and P20; remove the suction lines from the filters; remove the filters from the precipitator; and turn off the timer.
22. Turn off the vibrator and dust feeder.
23. Open G9 and close G10.
24. Close G2 and G3.
25. Turn off the corona power supply.
26. Mark two cleaned and Parafilm covered 150 ml beakers with the number of the experiment. Mark one of the beakers "inlet" and the other "outlet." Remove the Parafilm from the "inlet" beaker. Place the inlet sample holder vertically in your left hand.

- Carefully lift off the filter cover and Teflon gasket. Use tweezers for the gasket. Place the beaker upside down over the filter holder. The dirty side of the filter sticks to the bottom of the beaker. Remove and cover the beaker with Parafilm. Repeat this procedure for the outlet sample. The samples are now ready for analysis in the scanning electron microscope or spectrophotometer.
27. Return to step II.1 until all of the desired runs have been made.

III. Glycerine Fog

1. Perform Setps II. 1, 2, 4, 5, and 7.
2. Adjust V2 until T7 is 200°C.
3. Adjust G7 to 20.
4. Perform steps II.10 and 11.
5. Set G3 to 12.
6. Perform steps II.13-17.
7. Repeat steps III.1-6 as necessary.
8. Simultaneously open G10 and turn on the timer.
9. Repeat step III.7 constantly during the run.
10. Perform steps II.21, 22, 23, 25, and 26.
11. Return to step III.1 until all of the desired runs have been made.

IV. Shutdown

1. Turn off G5, G6, L1, V2, V3, steam, and corona power supply.
2. Turn off the blower and close G1.
3. Turn off the main circuitbreakers.
4. Inspect and repair any leads or faulty equipment.
5. QEF.

APPENDIX B. SPECTROPHOTOMETER OPERATION

Iron oxide dust samples are quantitatively reacted with colorimetric reagents to form the ferrous phenanthroline complex. A Beckman #DU-2 Spectrophotometer with 10 in. chart recorder is used to measure the absorbances of the ferrous phenanthroline solutions. Figure 18 relates these absorbances to the amounts of iron oxide on the filters. The collection efficiency of the electrostatic precipitator is derived from this information. Cuvettes containing ferrous phenanthroline solutions are tested directly in the light beam of the colorimeter. The spectrophotometer operates as follows:

1. Set the following controls:

Recorder

RANGE	100 millivolts
SPEED	2 in. per minute
FUNCTION	linear
POWER	standby
PEN	down

Spectrophotometer

RESISTOR	medium
FREQUENCY	508 nanometers
LAMP	visible
SLIT WIDTH	0.02 mm
SLIT	closed
READOUT	PM voltage
POWER	on

2. Adjust the PM VOLTAGE to 44 on the meter.
3. Insert the cuvette holder into the spectrophotometer. Position the holder so that the cuvette containing distilled water is in the light beam path.
4. Turn the SLIT to "open."
5. Turn the FUNCTION to "linear," the READOUT to "PM voltage," and the recorder POWER to "record."
6. Adjust the ZERO for a zero reading on the recorder.
7. Turn the FUNCTION to "log" and the READOUT to "recorder."
8. Adjust the 100% ADJUST for a zero reading on the recorder.
9. Repeat steps 5-8 until there is no change.
10. Advance the cuvette holder to the next position.
11. Record the absorbance on the chart recorder.
12. Go to step 10 unless all of the cuvettes in the holder have been tested.
13. Turn the recorder POWER to "standby" and the SLIT to "closed."
14. Remove the cuvette holder from the spectrophotometer.

15. Go to step 3 if any cuvettes remain to be tested.
16. Turn the recorder and spectrophotometer POWER switches to "off."
17. Push the PEN to the "up" position.
18. Clean the cuvettes in distilled water.
19. Tear off the spectrophotometer graph and determine the collection efficiency of the precipitator.

APPENDIX C. REAGENT CHEMICALS FOR THE SPECTROPHOTOMETER

The spectrophotometric analysis requires very pure reagent chemicals.

The ones listed below are used in this experiment and purification is unnecessary:

1. o-Phenanthroline crystals
MCB Company #PX460, CB905
Reagent grade ACS
2. Hydroxylamine hydrochloride crystals
Mallinkrodt Chemical Works #5258
ACS specifications, 96% pure, 0.0005% Fe
3. Hydrochloric acid
J. T. Baker Chemical Company #3-9535
ACS specifications, 37.6% HCl, 0.1% Fe
4. Sodium hydroxide pellets
Mallinkrodt Chemical Works #7708
ACS analytical reagent, 98% NaOH
5. Potassium acetate crystals
Mallinkrodt Chemical Works #6700
ACS specifications

The reagents and equipment used in colorimetry must be carefully prepared and handled. This rule applies especially to this experiment. Trace quantities (1-100 micrograms) of iron oxide are tested. Even slight contamination destroys the experimental reproducibility. For example, preliminary filter samples are studied in uncovered beakers. Iron containing room dust settles in these open beakers after cleaning and during the experiments. The colorimetric results for the samples in these beakers are absurd. The problem has been corrected. Beakers are now covered with Parafilm after washing and during the experiments. The beakers, flasks, pipets, and associated analytical equipment are washed in soap and rinsed in distilled water before use. Distilled

water is utilized exclusively in the reagents. Volumetric pipets are used for transferring into the sample beakers.

The reagent solutions are prepared in sufficient quantities to last several months. Hydrochloric acid is handled in the original bottle. The other reagents are stored in screw top Nalgene bottles. Phenanthroline, which is photoreactive, is kept in the dark. The chemicals are toxic and noxious and must be handled in a fume hood.

One and five tenths liters of water is poured into a 2.00 liter volumetric flask. Six hundred and sixty-eight grams of NaOH is slowly transferred to the flask. The flask is swirled in an ice bath to effect dissolution of the NaOH and remove heat. Four hundred grams of potassium acetate is added to this solution in the same manner. The flask is cooled to 20°C and water is added to the mark. The 2.00 liter basic reagent solution is used for neutralizing and buffering acidified iron oxide samples. Figure 21 is a titration curve for the neutralization of 4 ml of HCl by 4.6-5.2 ml of base reagent. Potassium acetate buffers the system at about pH 3-5. In an actual sample analysis, 5 ml of base, 1 ml of hydroxylamine hydrochloride, and 1 ml of phenanthroline are added to a 4 ml solution of iron oxide in HCl. Experiments indicate that this combination of reagents is buffered and has a pH near 4. Buffering improves the reproducibility of the colorimetric measurements. Ferrous phenanthroline light absorption is pH dependent.

3.496 grams of o-phenanthroline and 0.8 liters of water is transferred to a 2 liter beaker. The beaker is heated and stirred on a hot plate and magnetic stirrer. After the phenanthroline dissolves

in the water, the solution is poured into a 1.00 liter volumetric flask. The solution cools to room temperature (20°C) and water is added to the mark. The final reagent solution is 0.0176 M phenanthroline.

Similarly, 100 grams of hydroxylamine hydrochloride is dissolved in water. This 1.00 liter reagent solution is 1.44 M hydroxylamine hydrochloride.

Figure 18 indicates a clear advantage for analyzing iron oxide samples that are less than 100 micrograms. Absorbance is almost directly proportional to iron oxide concentration. Variations in absorbance and true absorbance are easily corrected in this range. This is not true for samples larger than 100 micrograms. Samples in this study are generally less than 100 micrograms. Larger samples are diluted in excess HCl. In either case, only a 4 ml acidified aliquot of iron oxide is treated by the colorimetric reagents and analyzed in the spectrophotometer.

Iron oxide samples are treated with excess concentrations of the colorimetric reagents. This insures the complete conversion of iron oxide to the light absorbing (ferrous phenanthroline) complex. With the aid of Figures 18 and 21, iron oxide can be quantitatively analyzed in a colorimeter. Sandell's⁶ recommendations for reagent concentrations are followed in this study. One milliliter each of 1.44 M hydroxylamine hydrochloride and 0.0176 M o-phenanthroline are mixed with the neutralized iron oxide solutions. Assume that the maximum iron oxide sample is 100 micrograms. The resulting ferrous phenanthroline solution contains iron oxide, o-phenanthroline, and hydroxylamine hydrochloride

in the formal concentration ratio of 1:10:804. This ratio should be adequate for promoting a quantitative reaction between ferrous ion and phenanthroline ion.

APPENDIX D. COMPUTER PROGRAM "CHARGE"

Kostow's⁴ program "Charge" calculates the charges of the particles and fog drops in the test precipitator. It determines the space charge electric field, ion density, and current density as a function of radius and residence time in the charging section. Various charging sections and main airstream conditions may be analyzed with this program.

16.36.09 11/24/76 OUTPUT

```

CHARGE      FORTRAN COMPILATION      RUN 2.3C0-75274      24 NOV 76 16:35:03 P

000003      PROGRAM CHARGE (INPUT,OUTPUT)
              DIMENSION V(52),VO(51),R(51),RHOD(51),CI(51),
              1 CF(52,53),Z(51),E2Z(51),E(51),QD(51,9),DP(9),QDPAVE(9),
              2 SUMQ(9)
000003      COMMON CF,V
000003      REAL LAMI,I,IC,IP
000003      READ 4,KD
000011      4 FORMAT (I1)
000011      READ 10,VAPP,DWIRE,DTUBE,CDP,VEL,(DP(K),K=1,9)
000035      10 FORMAT (F10.0)
000035      ND=50
000036      A=DWIRE/2.0*2.54E-2
000040      B=DTUBE/2.0*2.54E-2
000042      LAMI=2.02E-4
000044      E0=8.85E-12
000045      RGC=8.3144
000047      F=96500.
000050      CHAR=4FB.
000052      PI=3.1416
000053      CD=CDP*1.0E6
000055      DEL=293.7/322.
000057      EONSET=(30.0*DEL+9.0*SQRT(DEL/(A*100.0)))*1.0E5
000070      VONSET=A*FONSET*ALOG(B/A)
000076      PRINT 20
000101      20 FORMAT (/1X,*DROP CHARGING*)
000101      PRINT 21,DP(KD)
000107      21 FORMAT (5X,*DROP DIAM =*,F4.2,* MICRONS*)
000107      PRINT 22,CDP
000115      22 FORMAT (5X,*DROP CONC =*,E10.4,* PER CC*)
000115      PRINT 23,DWIRE
000123      23 FORMAT (5X,*WIRE DIAM =*,F6.4,* IN*)
000123      PRINT 24,DTUBE
000131      24 FORMAT (5X,*TUBE DIAM =*,F5.2,* IN*)
000131      PRINT 25,VEL
000137      25 FORMAT (5X,*GAS VELOCITY =*,F5.1,* FT/SEC*)
000137      PRINT 26,VAPP
000145      26 FORMAT (5X,*VOLTAGE APPLIED =*,F7.0)
000145      EONSEP=EONSET*1.0E-2
000147      PRINT 30,EONSEP
000155      30 FORMAT (5X,*CORONA STARTING FIELD =*,F7.0,* VOLTS/CM*)
000155      PRINT 31,VONSET
000163      31 FORMAT (5X,*CORONA STARTING VOLTAGE =*,F7.0)
000163      PRINT 32
000167      32 FORMAT (/3X,*TIME*,6X,*CURRENT*,3X,*AVE DROP CHG*/
              1 3X,*MSEC*,6X,*MA/METER*,6X,*ELEC*)
              I=8.0*PI*E0*LAMI/B**2*((VAPP-VONSET)**2+VONSET*
              1 (VAPP-VONSET)/ALOG(B/A))
              DZ=ALOG(B/A)/FLOAT(ND)
000206      NDPI=ND+1
000215      DO 34 J=1,NDPI
000217      DO 33 K=1,9
000220      33 DD(J,K)=0.0
000221      RHOD(J)=0.0
000227      Z(J)=FLOAT(J-1)*DZ+ALOG(A)
000230

```


-75-

```

CHARGE      FORTRAN COMPILATION      RUN 2.3C0-75274      24 NOV 76 16:35:03 F

C00237      L2Z(J)=EXP(2.0*Z(J))
C00244      34 F(J)=EXP(Z(J))
C00253      FAC=VAPP/ALOG(B/A)
C00260      V(1)=VAPP
C00261      V(NDP1)=0.0
C00262      DO 35 J=2,ND
C00264      35 V(J)=FAC*(ALOG(B)-Z(J))
C00273      C=1/(LAMI*E0*2.0*PI)
C00300      NDP2=NDP1+1
C00302      NDP3=NDP2+1
C00303      TOTCUR=0.0
C00304      NT=0
C00305      TIME=0.0
C00306      DT=.0002
C00307      36 DO 37 J=1,NDP1
C00311      37 VD(J)=V(J)
C00315      IO=1
C00316      DO 40 K=1,NDP2
C00320      DO 40 J=1,NDP3
C00321      40 CF(K,J)=0.0
C00332      CF(1,1)=1.0
C00333      CF(1,NDP3)=VAPP
C00337      DO 45 K=2,ND
C00340      DVDZ=(V(K+1)-V(K-1))/(2.0*DZ)
C00344      AC=1.0/E2Z(K)-DZ/2.0*(C/DVDZ**2)
C00354      PC=-2.0/L2Z(K)
C00356      DC=1.0/E2Z(K)+DZ/2.0*(C/DVDZ**2)
C00360      HC=-(DZ**2/DVDZ)
C00370      GC=DZ**2*(-RHOD(K)/E0+C/DVDZ)
C00375      CF(K,K-1)=AC
C00401      CF(K,K)=BC
C00404      CF(K,K+1)=DC
C00410      CF(K,NDP2)=HC
C00413      45 CF(K,NDP3)=GC
C00421      CF(NDP1,NDP1)=1.0
C00424      CF(NDP2,1)=1.0/(2.0*DZ)
C00430      CF(NDP2,2)=-4.0/(2.0*DZ)
C00432      CF(NDP2,3)=1.0/(2.0*DZ)
C00434      CF(NDP2,NDP3)=E0NSEY*A
C00440      CALL TRIAN (NDP2)
C00442      C=V(NDP2)
C00444      I=C*LAMI*E0*2.0*PI
C00450      DO 49 J=1,NDP1
C00452      IF (ABS(V(J)-VD(J))-0.01) 48,48,36
C00457      48 CONTINUE
C00462      IF (ABS(I-I7)-1.0E-6) 50,50,36
C00466      50 CONTINUE
C00466      TIME=TIME+DT
C00470      DTP=1.0E3*DT
C00472      TIMEP=1.0E3*TIME
C00473      IP=I*1.0E3
C00475      SEG=DT*VEL*12.
C00477      CURR=I*SEG*2.54E-2*1.0E3
C00501      TOTCUR=TOTCUR+CURR

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CHARGE      FORTRAN COMPILATION      RUN 2.3C0-75274      24 NOV 76 16:35:03 P

000502      IF (I) 52,52,54
000503      52 PRINT 53
000507      53 FORMAT (//10X,*CURRENT ZERO AT ALL FURTHER SEGMENTS*)
000507      GO TO 199
000510      54 DO 65 J=2,ND
000512      65 E(J)=(V(J-1)-V(J+1))/(2.0*DZ)/R(J)
000522      E(1)=(3.0*V(1)-4.0*V(2)+V(3))/(2.0*DZ)/A
000533      E(NDP1)=(-3.0*V(NDP1)+4.0*V(ND)-V(ND-1))/(2.0*DZ)/B
000545      DO 66 J=1,NDP1
000546      55 CI(J)=1/(E(J)*LAMI*2.0*PI*E(J)*1.5921E-19)
000557      DO 75 J=1,NDP1
000561      DO 74 K=1,9
000562      QDS=3.0*PI*E(J)*DP(K)**2*1.0E-12
000570      IF (QDS-QD(J,K)) 70,70,68
000575      68 FAC=DT*(CI(J)*1.5921E-19*LAMI)/(4.0*EO)
000604      QDQ=QDS*(FAC*(1.0-QD(J,K)/QDS)**2)/
      1 (FAC*(1.0-QD(J,K)/QDS)+1.0)
      GO TO 71
000617      70 QDQ=0.0
000620      71 FAC1=F/(2.0*PI*EO*DP(K)*1.0E-6*RG*322.)
000630      IF (QD(J,K)*FAC1-20.) 72,73,73
000636      72 FAC2=1.5921E-19*PI*DP(K)**2*1.0E-12*CBAR*CI(J)/4.0
000646      QDQ=1.0/FAC1*ALOG(FAC1*FAC2*DT+EXP(QD(J,K)*FAC1))-QD(J,K)
000666      GO TO 74
000667      73 QDQ=0.0
000670      74 QD(J,K)=QD(J,K)+QDQ+QDQ
000700      75 RHOD(J)=QD(J,KD)*CD
000706      DO 87 K=1,9
000710      SUMQ(K)=0.0
000711      DO 86 J=2,ND,2
000713      86 SUMQ(K)=SUMQ(K)+(QD(J-1,K)*R(J-1)**2+4.0*QD(J,K)*R(J)**2
      1 +QD(J+1,K)*R(J+1)**2)
      SUMQ(K)=SUMQ(K)*2.0/3.0*PI*DZ
000743      87 QDPAVE(K)=SUMQ(K)/(1.5921E-19*PI*(B**2-A**2))
000750      PRINT 88,TIMEP,IF,QDPAVE(KC)
000757      88 FORMAT (3X,F4.1,5X,E7.3,7X,F5.2)
000770      NT=NT+1
000772      IF (NT-5) 36,89,89
000773      39 DT=.0005
000776      IF (NT-7) 36,90,90
001000      40 DT=.002
001002      IF (NT-11) 36,92,92
001004      92 PRINT 93
001010      93 FORMAT (//1X,*FINAL PARTICLE CHARGE*/)
001010      PRINT 94
001014      94 FORMAT (5X,*SIZE*,8X,*CHARGE*/4X,*MICRONS*,7X,*ELEC*)
001014      PRINT 97,(DP(K),QDPAVE(K),K=1,9)
001030      97 FORMAT (5X,F5.2,5X,E10.2)
001030      PRINT 20
001034      PRINT 21,OP(KD)
001042      PRINT 22,CDP
001050      PRINT 23,DWIRE
001056      PRINT 24,DTUBF
001064      PRINT 25,VEL

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CHARGE      FORTRAN COMPILATION      RUN 2.3C0-75274      24 NOV 76 16:35:03 P

001072      PRINT 26,VAPP
001100      PRINT 30,ECNSFP
001106      PRINT 31,VONSET
001114      CORLEN=VEL*12,*.010
001116      PRINT 100,CORLEN
001124      100 FORMAT (//IX,*FINAL CONDITIONS AT 10 MSEC AND *,F3.1,* INCHES*)
001124      PRINT 101,TOTCUR
001132      101 FORMAT (5X,*TOTAL CURRENT =*,F6.4,* MA*)
001132      PRINT 110
001136      110 FORMAT (//4X,*RADIUS*,3X,*VOLTAGE*,4X,*FIELD*,6X,*ION CONC*,
1 3X,*DROK CHG*/6X,*IN*,17X,*V/CM*,7X,*N/CUCM*,6X,*ELEC*)
001136      DO 115 J=1,NDP1,2
001140      EP=R(J)/2.54E-2
001142      EP=E(J)*1.0E-2
001144      CIP=CI(J)*1.0E-6
001146      QDP=QD(J,KD)/1.5921E-19
001152      PRINT 111,RP,V(J),EP,CIP,QDP
001170      111 FORMAT (4X,F6.4,3X,F7.1,2X,F9.1,3X,E9.4,4X,F6.2)
001170      115 CONTINUE
001173      PRINT 118,QDPAVE(KC)
001200      118 FORMAT (//5X,*AVERAGE DROK CHARGE =*,F6.2,* ELECTRONIC CHGS*)
001200      199 STOP
001202      END

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      TRIAN      FORTRAN COMPILATION      RUN 2.3C0-75274      24 NOV 76 16:35:03  H
      SUBROUTINE TRIAN (N)
000003      DIMENSION X(52),C(52,53),CT(53)
000003      COMMON C,X
000003      NP=N+1
000005      DO 50 L=1,N
000006      LP=L+1
000010      IF (L-N) 5,25,99
000012      5 K=1
000014      DO 7 J=LP,N
000016      IF (ABS(C(J,L))-ABS(C(K,L))) 7,7,6
000027      6 K=J
000031      7 CONTINUE
000034      IF (K-L) 99,25,8
000036      8 DO 10 I=1,NP
000040      CT(I)=C(L,I)
000044      C(L,I)=C(K,I)
000051      10 C(K,I)=CT(I)
000056      25 CO=C(L,L)
000062      DO 26 I=L,NP
000063      26 C(L,I)=C(L,I)/CO
000072      IF (L-N) 28,50,50
000074      28 DO 40 J=LP,N
000076      CO=C(J,L)
000102      IF (CO) 30,40,30
000103      30 DO 35 I=L,NP
000105      C(J,I)=C(J,I)/CO
000111      35 C(J,I)=C(J,I)-C(L,I)
000121      40 CONTINUE
000124      50 CONTINUE
000127      DO 60 I=1,N
000130      60 X(I)=0.0
000133      L=N
000134      DO 75 K=1,N
000135      S=C(L,NP)
000141      DO 70 I=1,N
000143      70 S=S-C(L,I)*X(I)
000154      X(L)=S
000156      75 L=L-1
000161      99 RETURN
000162      END

```

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Fig. 1

XBL 772-5078

Fig. 2

CBB 772-738

CBB 772-736

Fig. 3

Fig. 4

CBB 772-742

Fig. 5

CBB 772-740

XBL772-5076

Fig. 6

XBL 772-5079

Fig. 7

XBL 772-5080

Fig. 8

XBL 772-5077

Fig. 9

2 μ

XBB 772-730

Fig. 10

2 μ

XBB 772-729

Fig. 11

100 μ 30 μ

XBB 772-735

Fig. 12

2 μ

Fig. 13

XBB 772-732

2 μ

XBB 772-733

Fig. 14

2 μ

XBB 772-731

Fig. 15

2μ

XBB 772-734

Fig. 16

XBL 772-5075

Fig. 17

Fig. 18

XBL 772-5074

Fig. 19

XBL 772-5106

Fig. 20

XBL 772-5107

XBL 772-5073

Fig. 21