PARTICULATE CONTROL HIGHLIGHTS

PARTICULATE TECHNOLOGY BRANCH

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Research Triangle Park, North Carolina 27711

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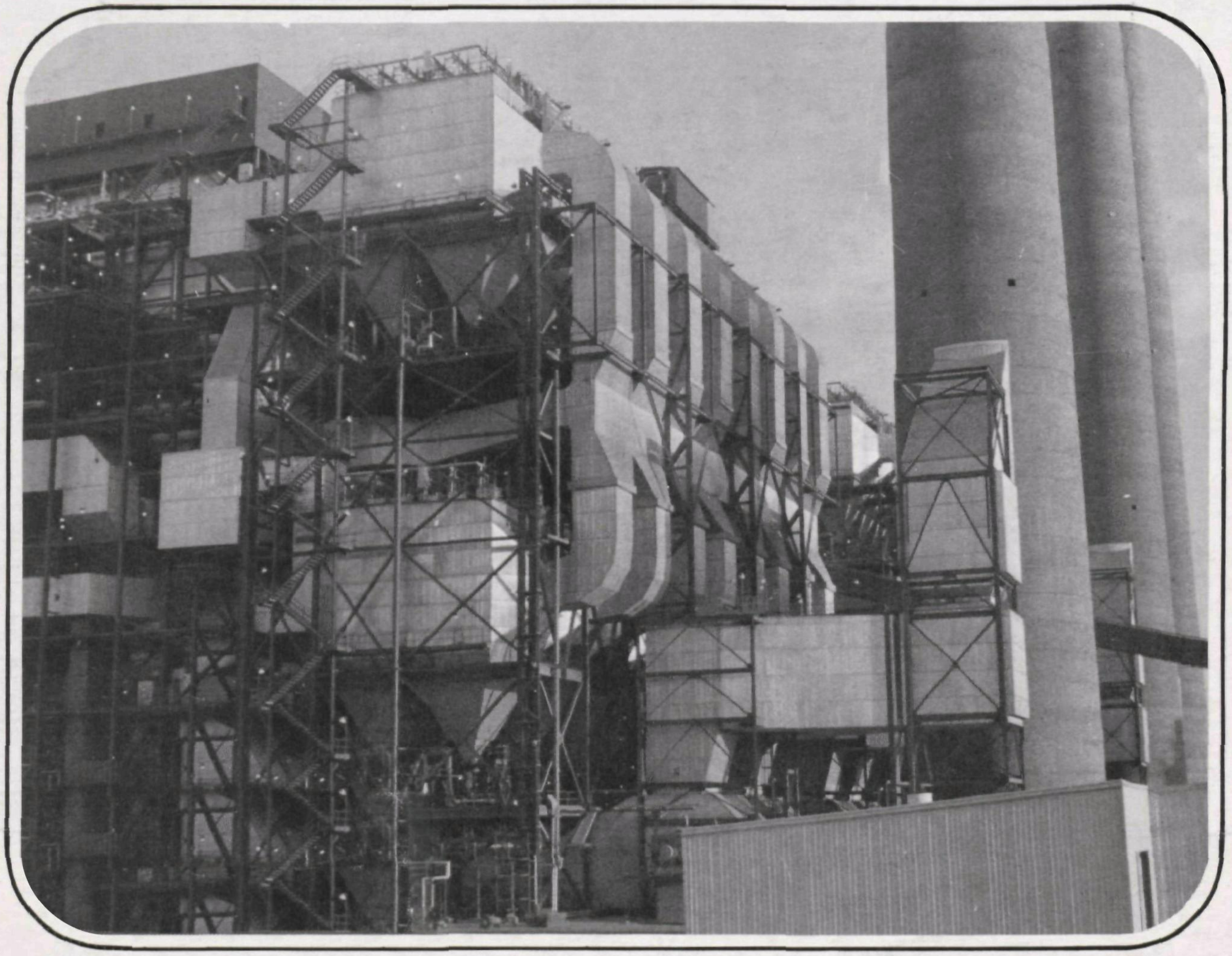
RESEARCH ON ELECTROSTATIC PRECIPITATOR TECHNOLOGY



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THE COVER:
The cover photograph shows a large electrical power plant with electrostatic precipitators installed for gas cleanup. Sixteen precipitators clean the gas from each unit before it goes into the atmosphere.

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PARTICULATE CONTROL HIGHLIGHTS: RESEARCH ON ELECTROSTATIC PRECIPITATOR TECHNOLOGY

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ABSTRACT

A major research program on electrostatic precipitator technology is directed toward improving the performance of precipitators in controlling industrial particulate emissions, notably fly ash from coal combustion in electric power plants. Techniques have been developed for sampling stack gas, measuring particle size distribution of fly ash, and determining collection efficiencies for particles 0.01 - 10 μm in diameter. Techniques for measuring electrical resistivity of fly ash have been assessed. Relationships between electrical effects, such as reverse corona, caused by high resistivity of the deposited fly ash, have been investigated. The influence of particle size and chemical composition of the fly ash on both the resistivity and dielectric strength of the deposited fly ash has also been studied. Relationships have been established between resistivity and chemical composition of fly ash, especially its alkali metal content, for precipitator operating temperatures below about 250 °C. On the basis of these relationships, a mechanism for ionic surface conduction has been proposed that complements the ionic mechanism in bulk conduction in fly ash particles at higher operating temperatures. The efficacy of conditioning fly ash by adding sulfur trioxide to flue gas in order to lower fly ash resistivity was established in trials at electric power plants. Reentrainment of particles from deposited fly ash has been investigated in relation to precipitator rapping procedures and gas flow distribution. A mathematical model of the electrostatic precipitation process has been developed which uses fundamental relationships together with measurements of precipitator geometry, electrical conditions, and particle size distributions to calculate collection efficiency.

CONTENTS

FIGURES

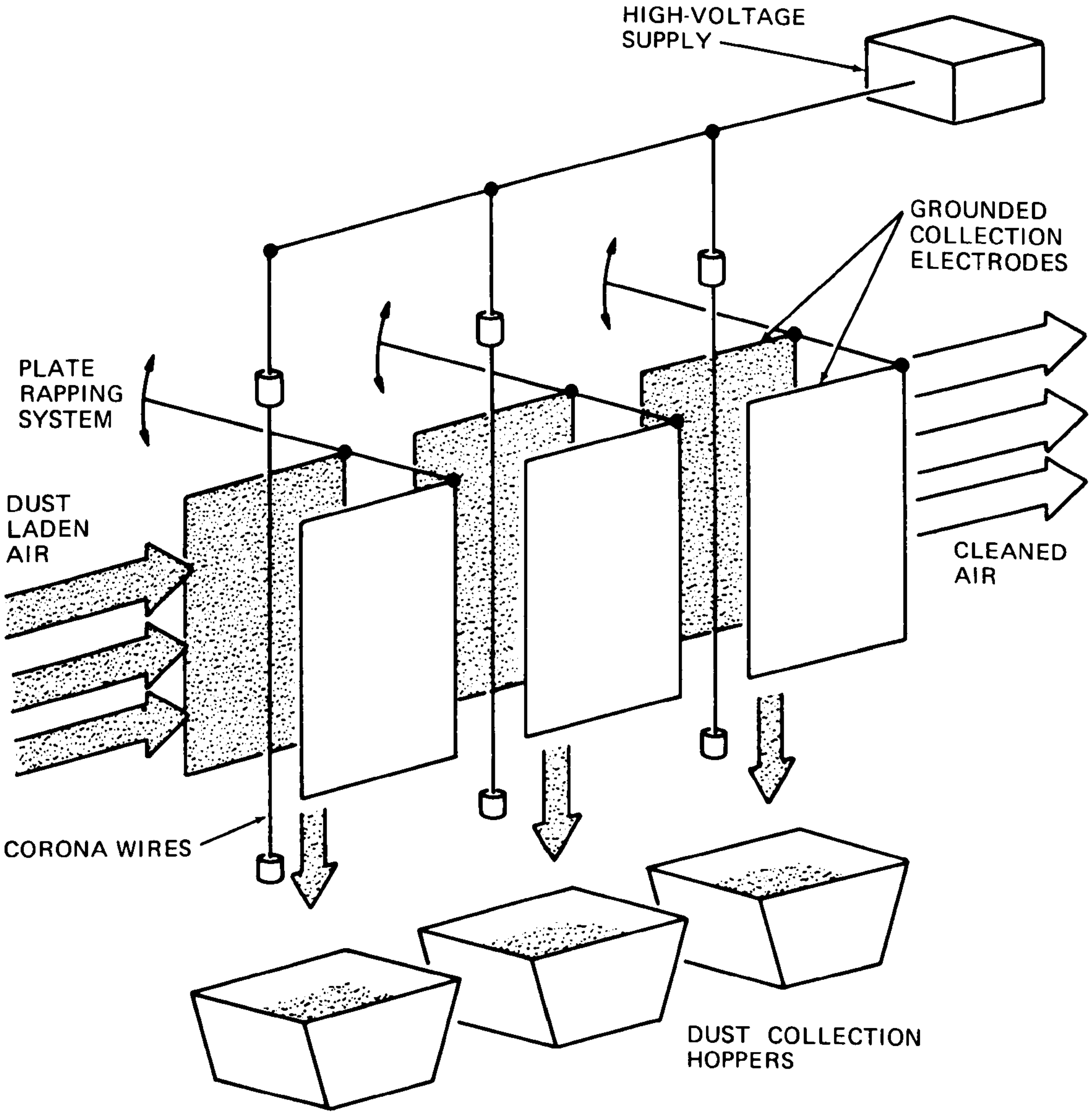

Figure 1. Schematic diagram of an electrostatic precipitator collecting dust.

RESEARCH ON ELECTROSTATIC PRECIPITATOR TECHNOLOGY

A comprehensive research program on electrostatic precipitator technology is being conducted for the U.S. Environmental Protection Agency by Southern Research Institute. It emphasizes the control of airborne particulate emissions from stationary sources.

The program, which was begun in 1969, developed from the Agency's recognition that air pollution by particulate matter from industrial sources is an increasingly serious problem. One of the major pollutants is fly ash from the combustion of coal. A total of more than 3 million tons per year of fly ash is discharged into the atmosphere from coal-burning electric utility power plants, about one-sixth of the industrial particulate emissions in the United States.

Electrostatic precipitators are the most widely used of the high-efficiency devices for the control of fly ash emissions from electric utility power plants. The EPA research was undertaken to explore ways of improving the performance of electrostatic precipitators, specifically by providing data that can be used for precipitator design on a sound engineering basis. This report presents some of the results that have been obtained.

The general structure of the EPA research program was outlined in a systems study carried out early in the program. The program structure takes into account the steps in the precipitation process and the corresponding parameters which thus can influence overall performance in collecting industrial particulate emissions.[1-4]

THE PRECIPITATION PROCESS

In an electrostatic precipitator, the force that is used to separate a particle from the gas stream in which it is suspended results from an electric charge on the particle in the presence of an electric field (see Figure 1). The particle is charged by the attachment of gas ions which are generated by an electrical corona discharge. In most precipitators used for collecting industrial dusts such as fly ash, a negatively charged corona is produced by applying a rectified high voltage to rows of wires or metal strips suspended vertically in a horizontal gas flow. An electric field is established between the wires and grounded metal plates, which are also suspended vertically, parallel to the rows of wires and parallel to the direction of gas flow. In the electric field between the wires and plates, the charged particles move to the plates, where they are deposited. As the layer of deposited particles builds up on the collection electrodes, it is periodically knocked off by a rapper or vibrator on the electrodes, and the particulate material falls into a hopper for removal.

The performance of an electrostatic precipitator is affected by the concentration and size distribution of the particles being collected, the electrical resistivity and cohesivity of the layer of collected particles, and the uniformity of the gas flow.

The mechanism by which the fly ash particles are electrically charged depends on the particle size, in addition to other factors such as the magnitude of the electric field and the ion density. Large particles (those larger than a few micrometers in diameter) are charged by the impact of gas ions travelling along electric field lines, and the charging ceases when the particle reaches a saturation charge that provides a sufficient repelling force. For normal operating currents, the saturation charge is reached rapidly, within a fraction of a second. Small particles are charged more slowly, at a rate dependent on diffusion of the gas ions to the vicinity of the particle.

The electric field in a precipitator is determined by the geometry of the electrode system (the corona field being high near the corona electrode and diminishing with distance toward the collection electrode) and the space charge in the interelectrode region. The magnitude of the space charge is established by the number of elemental charges in this region. Both gas ions and charged particles contribute to the charge.

The efficiency with which the particles are collected also depends on the particle size. Even though an electrostatic precipitator can achieve a high overall collection efficiency, it will typically have a lower efficiency for some fractions of the smaller particles in the flue gas. As an example, the measured fractional collection efficiency of a precipitator can decrease from 99.9% for particles above 1 μm in diameter to 95% for particles 0.5-1 μm in diameter, and then increase to 99% for particles less than 0.3 μm in diameter.

The minimum in collection efficiency for particles 0.5 - 1 μm in diameter can be explained in terms of the relative contributions of particle charging by different processes.

The collection efficiency is also influenced by the electrical resistivity of the fly ash. The electrical current from the corona discharge passes through the layer of deposited fly ash on the collection electrode, and the voltage drop across the layer depends on the resistivity of the fly ash, the current density, and the thickness of the layer. If the resistance of the dust layer is too high (about 10^{11} ohm-cm), the electric field in the layer can become high enough to exceed the field strength for electrical breakdown or corona discharge. These occurrences limit the voltage and current that can be used, and hence limit performance of the precipitator.

The electrical resistivity of fly ash depends principally on its chemical composition, the flue gas composition, and the temperature at which the precipitator operates. The chemical composition of the fly ash in turn depends on the composition of the coal and accessory minerals from which it is produced in combustion, the type of boiler used, and the combustion temperature. Most of the sulfur in the coal appears as sulfur dioxide in the flue gas, and a small amount of the sulfur dioxide is oxidized further to sulfur trioxide, which reacts with water vapor in the flue gas to produce sulfuric acid vapor. At the temperatures at which most precipitators operate, 150° C or below, some of the sulfuric acid is adsorbed on the surface of the fly ash particles. The adsorbed acid lowers the electrical resistivity of the fly ash, and consequently lowers the resistivity of the layer deposited on the collection electrode. As a rule, coals with sulfur contents of 1.5% or more produce fly ash with a sufficiently low resistivity for good collection; those with less than 1% will present problems in satisfactory collection.

Problems in collecting fly ash with high resistivity can be alleviated in some instances by adding sulfuric acid, sulfur trioxide, or other chemical compounds to the flue gas. Alternately, the electrostatic precipitator may be installed in the flue gas duct upstream of the air heater, where it will operate at 250-400°C. At these temperatures, the resistivity of most fly ashes is sufficiently low that the electric current in the precipitator is not limited by fly ash resistivity.

The collection efficiency of an electrostatic precipitator can also be degraded by losses in rapping the collection electrodes. The transfer of the fly ash deposit to the hopper provides the chance for loss of particles by entrainment in the gas stream. Although the extent of the loss is moderated by the cohesivity of the fly ash, entrainment can be responsible for half of the total emissions from a precipitator.

Other sources of loss and degraded performance are uneven gas flow distribution and passage of particles through the non-electrified space around the electrodes of the precipitator.

MEASUREMENT OF COLLECTION EFFICIENCY

To obtain performance data on operating precipitators and to establish the extent to which selected sampling and analytical techniques can be used for this purpose, tests were made on full-scale industrial electrostatic precipitators used for the control of fly ash emissions from electric power plants.[5] Two of the installations selected were: (1) a precipitator collecting fly ash at an electric utility power plant burning an eastern coal (Gorgas Power Station, Alabama Power Company); (2) a precipitator for fly ash collection installed on the hot gas side of the air heater in an electric utility power plant burning a low-sulfur western coal.

Concentrations of fly ash were measured at the inlet and outlet of each electrostatic precipitator. The average overall mass collection efficiencies were about 99.6% at Plant 1 and about 99.2% at Plant 2. Particle-size distributions were also measured at each inlet and outlet and used for calculating fractional collection efficiencies. The results are shown in Figures 2 and 3.

These figures also show the fractional collection efficiencies of the precipitators calculated with the use of a theory-based computer model of the electrostatic precipitation process. The use of this model, which is discussed in more detail in a later section of this report, involved the preparation of graphs of computed overall mass collection efficiency as a function of specific collecting area (area of the collection electrode per unit volume of gas flow) with the precipitator geometry, electrical conditions, and the measured inlet particle-size distributions used as input data to the computer program for each installation. In addition to these predictions from theory, the effect of variation in gas velocity distribution over the cross-section of the gas stream was taken into account by including values for the standard deviation σ_g in the gas velocity distribution. The computer program also included procedures for estimating losses in collection efficiency due to gas by-passage of the electrified regions of the precipitator and for re-entrainment of particles into the effluent gas stream from the deposited fly ash.

The curves in Figures 2 and 3 represent fractional collection efficiency values that are predicted by the computer model with σ_g assumed to be 25%, a value that is typical for normal operation of an electrostatic precipitator, but with no allowance for loss of collection efficiency from gas by-passage or fly ash re-entrainment.

Figure 2 indicates reasonably good agreement between the predicted and observed values characterizing the performance of the precipitator in Plant 1. In contrast, most of the fractional collection efficiency values measured for the precipitator in Plant 2 were considerably lower than the calculated theoretical values. The difference can be interpreted as the result of a 10-20% loss of collection due to gas by-passage and re-entrainment over each of three stages in the precipitator.

TECHNIQUES FOR MEASURING PARTICLE-SIZE DISTRIBUTION

In evaluating the performance of these and other electrostatic precipitators, particle-size distributions were measured with inertial cascade impactors and optical counters for particle diameters greater than

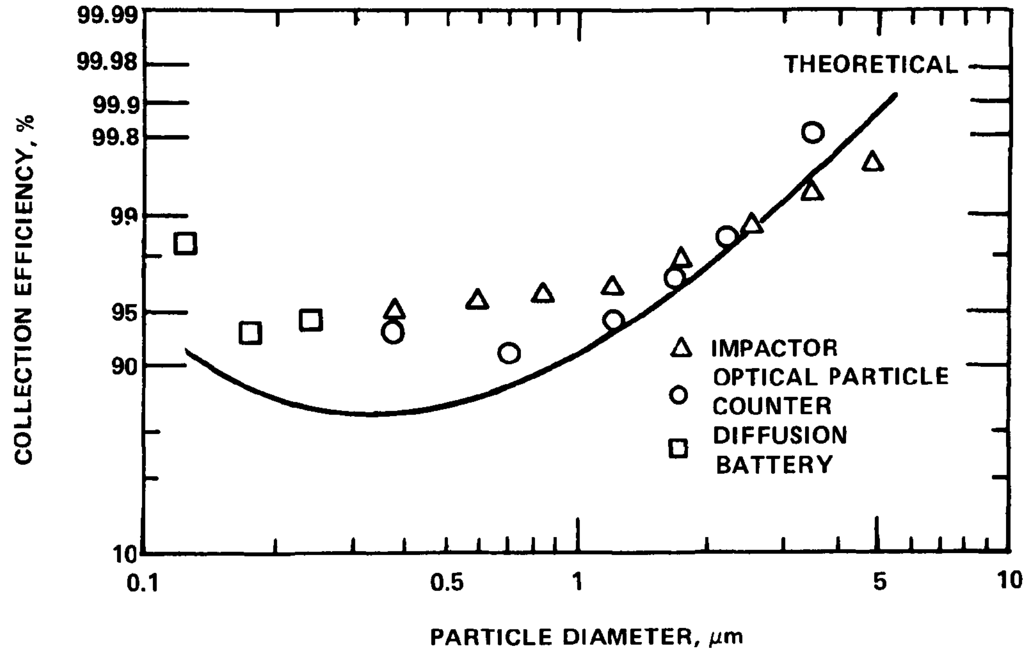

Figure 2. Measured and computed efficiency as a function of particle size for precipitator installation at Plant 1.

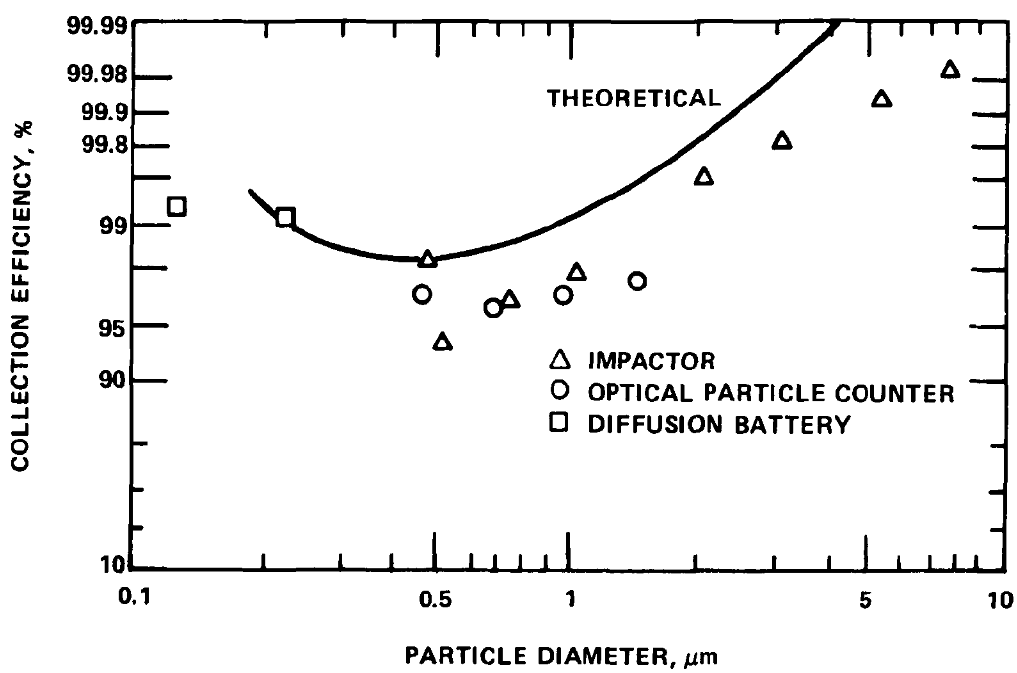

Figure 3. Measured and computed collection efficiency as a function of particle size for hot-side electrostatic precipitation installation, Plant 2.

about 0.3 μm. For particle diameters of 0.005 μm to 0.3 μm, diffusion batteries were used in conjunction with condensation nuclei counters.

The mechanism by which a cascade impactor operates is illustrated in Figure 4. The measurement of particle size is based on the inertial properties of the particle suspended in the gas stream. For each stage in a cascade impactor, the gas stream passes through an orifice and forms a jet which is directed toward an impaction plate. For each stage there is a characteristic particle size, the cut diameter, which has a 50% probability of impaction. Most of the smaller particles will follow the gas stream to the subsequent stages where the jet velocities are progressively higher. After operation for the appropriate length of time, the catch on each stage of the impactor is weighed and the particle-size distribution is calculated.

In evaluating an electrostatic precipitator, a low-volume flow impactor is used at the inlet of the precipitator, where the dust concentration is high, and a high-volume impactor is used at the outlet, where the dust concentration is low. Inlet and outlet measurements are usually made at the same time.

The optical counters used were designed to measure the scattered light from single particles in highly diluted gas samples. The particle size is determined from the amplitude of the scattered light pulses and the concentration of the particles (by number, not mass) from the pulse rate.

The use of diffusion batteries for sizing particles is based on the circumstance that as the gas flows through a narrow channel the suspended particles will diffuse to the channel walls at a predictable rate, the magnitude of which depends on the particle size, for a given battery configuration. The particle concentrations (by number) in the gas at the inlets and outlets of the batteries are measured with condensation nuclei counters. The action of these counters is based on the condensation of supersaturated water vapor on the particles and measurement of the attenuation of a light beam by the resulting fog.

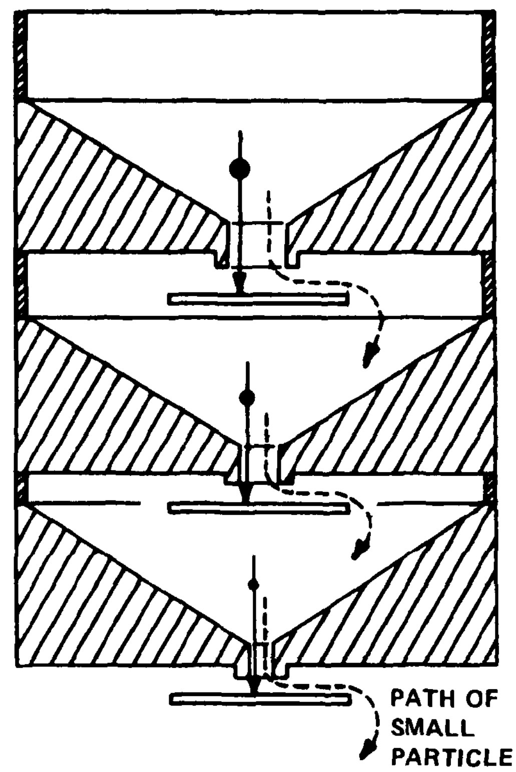

Figure 4. Schematic diagram, operation of cascade impactor.

Concurrently with the demonstration that cascade impactors can be used in evaluating the performance of electrostatic precipitators, improved techniques for their use were being developed.[6,7]

An experimental study was made of the precision, or reproducibility, of measuring particle-size distribution by impactors. Since the amount of dust that can be collected within a reasonable test time usually weighs less than 10 milligrams per stage, it is impractical to determine the weight of the catch by weighing the relatively heavy metal collection plate before and after sampling. Therefore, a glass fiber mat was placed on the collection plate to serve as the collection substrate.

Before this substrate was recommended for use in field tests, it was tested in the laboratory under conditions simulating those encountered in sampling stack gases. When clean air (temperature 120° C) was drawn through an impactor containing glass fiber mats for 6 hours, the mats lost 0.1 - 0.2 mg each, a value that was considered tolerable for most tests in which the impactor would be used. A more serious change in weight was a gain of up to 5 mg per mat that was observed on exposure of the glass fiber substrates to flue gas from coal combustion.

Chemical analysis showed that most of the weight gain was soluble sulfate salts, evidently formed by reaction of sulfur oxides in the flue gas with alkaline components of the glass fiber. Exposure of the glass fiber mat for several hours to flue gas from which the particulate matter had been removed by filtration reduced the weight gain during subsequent use by a factor of about ten.

Another error in sampling flue gas can be produced by electrostatic forces due to charges on the suspended particles. Preliminary experiments on neutralizing the particle charges indicated that this is more of a problem for collection on bare metal plates in an impactor than for collection on glass fiber substrates.

When an impactor is operated at a flow rate higher than some critical value, errors can result from particle bounce or jet scouring, with subsequent collection of particles on the wrong stages. Laboratory tests were conducted with monodisperse aerosols to determine the values of jet velocity that allowed satisfactory deposition on impactor stages.

Cyclones have been used less than impactors for making particle size distribution measurements; they are bulky and give less complete separation than impactors. However, they are useful when larger samples are needed, e.g., for chemical analysis. An example is a system of three cyclones that were designed for collection of samples of fly ash having average particle sizes in the respirable range (below 3 μm). The cyclones, with cut points of 0.5 μm, 0.95 μm, and 2.6 μm, were mounted in series with a back-up filter. The system was designed for a sample flow rate of 28 liters/min and will fit through a 15-cm diameter port.

ELECTRICAL EFFECTS, PARTICLE SIZE, AND RESISTIVITY

Electrical effects in an electrostatic precipitator were studied in a laboratory wire-plate apparatus that simulated some of the behavior of a precipitator when its performance is governed by the electrical characteristics of the layer of collected dust.[8]

The dust layer affects the electrical behavior of the precipitator by introducing a resistance element with non-linear characteristics into the electrical circuit. When electrical breakdown of the dust layer occurs, the resulting back corona discharge limits precipitator performance: it reduces the voltage and current at which the precipitator can operate without sparkover.

The laboratory experiments included the measurement of the corona characteristics of layers formed from different particle-size fractions of fly ash, such as those produced in the fractionation of fly ash that occurs as the flue gas passes through the precipitator.

Particle size of the fly ash and the porosity of the collected layer of fly ash affected precipitator operation indirectly through changes they caused in electrical resistivity of the collected layer. No relation was found between dielectric strength and resistivity.

Voltage-current curves measured in the wire-plate apparatus showed that the fine particle size had the highest sparkover voltage and the lowest resistivity.

The variation in resistivity with particle size was large enough that the resistivity of the fly ash would be decreased by a factor of two, with a corresponding increase in operating current density, as the fly ash is fractionated on its passage through a precipitator.

In the laboratory apparatus, peak current densities for the formation of back corona were within about 20% of the value at which the electric field in the collected dust would have exceeded the dielectric strength of the dust layer. A survey of full-scale electrostatic precipitator installations collecting fly ash showed operating current densities varying over a wide range. The corresponding values of electric field in the collected fly ash layer in some installations would have exceeded the dielectric strength of the layer.

RESISTIVITY AND CHEMICAL COMPOSITION OF FLY ASH

Since the electrical resistivity of fly ash is one of the most critical parameters affecting its collection in an electrostatic precipitator, considerable effort has been devoted to exploring the basic mechanisms involved in electrical conduction in fly ash and specifically the relationships between conductivity and chemical composition of the ash.

It had previously been shown that in precipitators operating at flue gas temperatures above about 250 °C, electrical conduction in fly ash takes place through the bulk of the particles and depends on an ionic mechanism.[9] Sodium ions are the principal charge carriers, with lithium ions carrying a small amount of the current. At flue gas temperatures below about 150° C, the pathway of electrical conduction appears to be along the ash surface and the conduction is influenced by the alkali metal concentration in the ash and the flue gas species adsorbed on the surface. At intermediate temperatures of 150° to 250° C, both surface and volume mechanisms contribute to conduction. With increasing temperature, the surface resistivity increases and the volume resistivity decreases. These effects are shown in Figure 5.

In order to elucidate the mechanism of surface conduction, the effect of the chemical composition of fly ash on its electrical resistivity at temperatures below 250°C was studied.[10]

Samples of fly ash collected from flue gas from the combustion of representative eastern and western coals were examined. Resistivities were measured at voltage gradients of about 400 V/cm at 60 to 250°C in a controlled atmosphere of air containing about 9 vol-% water. A correlation was established between the resistivity and the combined contents of sodium and lithium in the ash. Transference experiments on fly ash samples subjected to a 2000 V/cm voltage gradient for several hundred hours at 60° C in air containing about 9 vol-% of water showed appreciable migration of lithium, sodium, and in some instances, potassium ions to the negative electrode. The major portion of the charge transported could be accounted for by the change in composition. Cross correlations of the resistivity data indicated that iron in the ash accelerated the release of potassium ions, perhaps by promoting the dissolution of the ash surface.

The results suggest a mechanism for surface conduction in which certain chemical species react on the surface of the fly ash particle with an agent such as water in the surrounding atmosphere to release alkali metal ions from the surface to serve as charge carriers. The number of ions released can be expected to depend on the concentration of ions available, the chemical durability of the ash in the hostile environment, the temperature, and the types and concentrations of environmental species brought into contact with the ash particle surface.

The conducting pathway can be established even at temperatures considerably above the dew point of the flue gas, i.e., above the temperature at which water or other components of the gas would begin condensing to liquids.

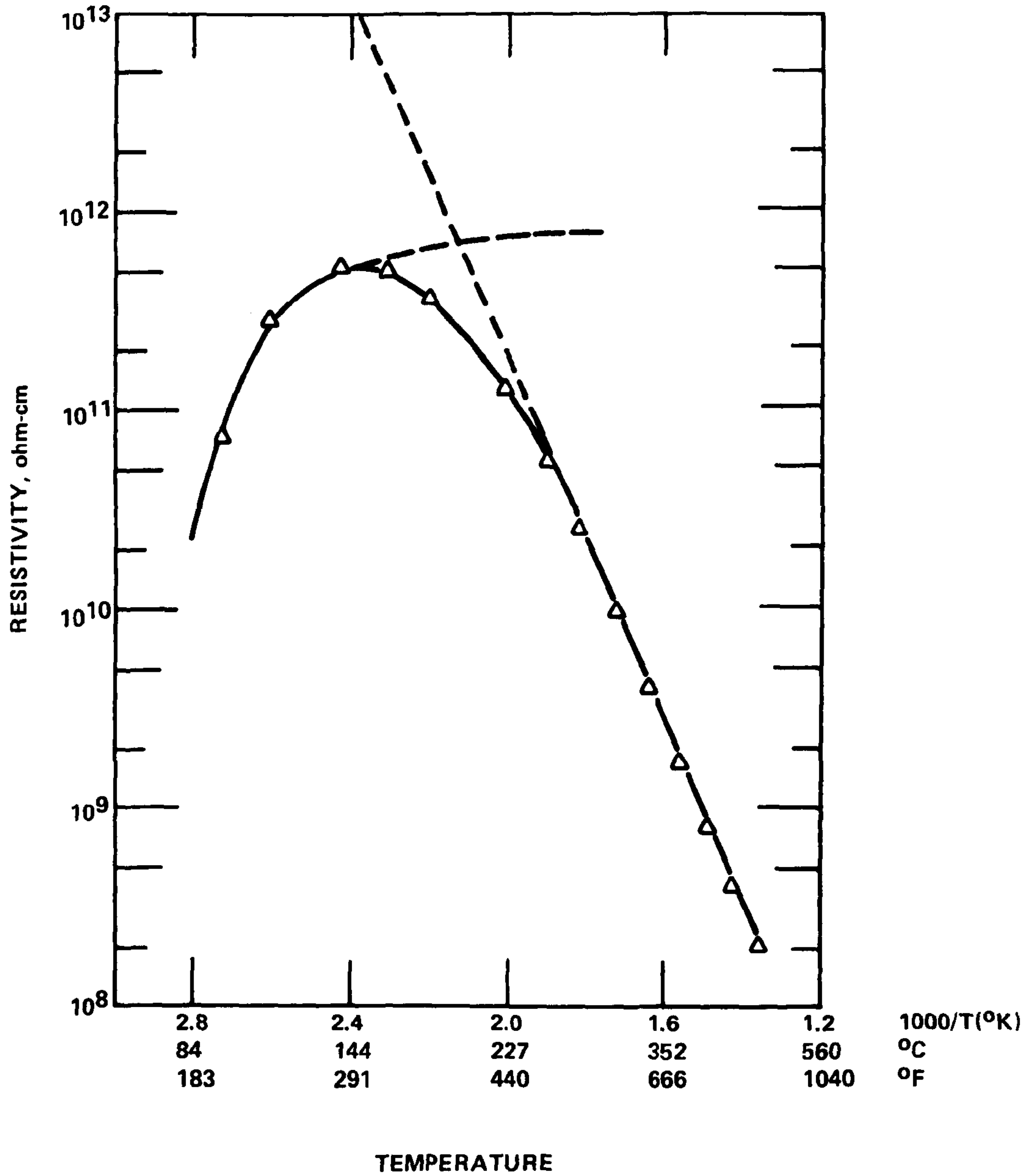

Figure 5. Electrical resistivity of fly ash as a function of temperature.

TECHNIQUES FOR MEASURING ELECTRICAL RESISTIVITY

As part of the supporting work that had to be done for the tests of precipitator performance, it was necessary to make sure that suitable equipment and techniques were available for measuring the electrical resistivity of collected dust (primarily fly ash). An assessment of equipment and techniques for this use was made.[11]

The disk-electrode apparatus specified in the American Society of Mechanical Engineers Power Test Code 28 was judged to be satisfactory for laboratory measurement of electrical resistivity.

Several probe designs are available for measuring the electrical resistivity of fly ash in installed electrostatic precipitators, the measurements being made either on fly ash collected in the flue duct or on fly ash collected immediately outside the flue duct from a sampled gas stream.

A point-to-plane probe designed at Southern Research Institute is illustrated in Figure 6. This probe can be inserted in the flue for collection of fly ash and measurement of its electrical resistivity in the duct. The fly ash is deposited in the cell electrostatically.

Other instruments that are available are:

-The Simon-Carves instrument. The dust is collected in a small cyclone and compacted into a measurement cell by a vibrator. Designs are available for use in or out of the stack.

-The Kevatron apparatus. The dust is collected in a small wire-pipe electrostatic precipitator, operated out of stack, and dumped into a measurement cell.

-The Lurgi probe. The dust is collected electrostatically and its resistivity measured in place. It can be operated in or out of the stack.

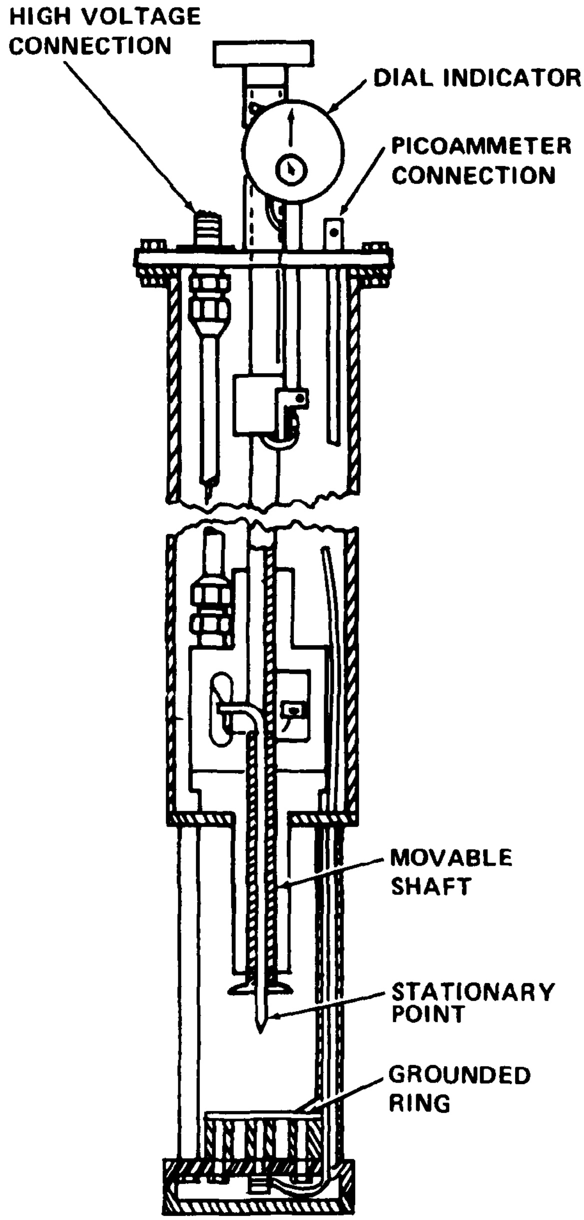

Figure 6. Point-to-plane resistivity probes equipped for thickness measurement.

None of the collection devices gives a sample with a particle-size distribution representative of the distribution of the dust particles in the flue duct. Neither the cyclone nor the electrostatic precipitator is an efficient collector of fine particles, so the particle size distribution in the sample is biased toward the larger particles.

Electrostatic collection of the dust in the Southern Research Institute probe and the Lurgi probe can be expected to produce some alignment of the dust particles and a denser deposit than those in the other instruments.

The measurements in the Kevatron and Simon-Carves instruments are made at relatively low electric fields, whereas the measurements in the Southern Research Institute probe are made at fields near electrical breakdown.

These differences are sufficient to explain the 10-fold variation in resistivity values reported by different investigators.

CONDITIONING OF FLY ASH

Treating, or conditioning, fly ash with chemicals in the flue duct to increase the extent of its collection in an electrostatic precipitator was investigated on full-scale power-plant installations.[12] The chemical agents used were sulfur trioxide (or sulfuric acid) and ammonia. An attempt was made to find circumstances under which the chemicals were most effective.

The results of the tests indicated that various methods for injecting concentrated sulfuric acid, anhydrous sulfur trioxide, or sulfur trioxide from the catalytic oxidation of sulfur dioxide, were equally effective when the equipment was properly engineered and maintained. The injection site in the flue gas duct could be upstream from the electrostatic precipitator, upstream from the combination of a precipitator and a mechanical fly ash collector, or between the precipitator and the mechanical collector.

The minimum concentration of sulfur trioxide required was 5-20 ppm of the flue gas, depending on the flue gas temperature and the chemical composition of the fly ash. The resistivity of the fly ash was decreased from 10^{12} ohm-cm to an acceptable value of 10^{10} ohm-cm. Fly ash of widely varying chemical compositions could be successfully conditioned, larger quantities of sulfur trioxide being required for highly alkaline fly ash. The conditioning was effective at flue gas temperatures from 110°C to at least 160°C and perhaps near 200°C.

Chemical analysis of the treated fly ash indicated that the lowering of the fly ash resistivity by sulfur trioxide resulted from deposition of sulfuric acid on the surfaces of the fly ash particles, either by adsorption or condensation. The electrical conduction of the fly ash particles may involve hydrogen ion transport in a surface film of sulfuric acid or transport by alkali metal ions from the fly ash dissolved in a surface film.

The sulfur trioxide also increased the cohesiveness of the collected fly ash particles and thus reduced the extent of their re-entrainment in the flue gas when the precipitator electrodes were rapped to dislodge the collected ash. Such an effect might be of practical value in the use of sulfur trioxide as a conditioning agent for low-resistivity fly ash. If the resistivity is too far below the normal range of values (10^{10}-10^{11} ohm-cm), the electrical force in the deposited fly ash layer will not provide sufficient restraint against reentrainment.

The effectiveness of sulfur trioxide was also reflected in improved operation of the electrostatic precipitators. Injection of sulfur trioxide generally permitted both higher current densities and higher voltages to be reached without the occurrence of excessive sparking.

The results of a few plant tests with ammonia as a conditioning agent indicated that it is not as widely applicable as sulfur trioxide. However, it improved the collection efficiency of fly ash from some coals with a range of sulfur contents. These coals produced fly ashes with resistivities that were not excessively high, and the injection of ammonia had little if any effect on the resistivity. The effect of ammonia appeared to be an increase in the space charge in the precipitator, with a resulting enhancement of the electric field and increased collection efficiency. This mechanism could involve the formation of fine particles of ammonium sulfate or bisulfate, which become electrically charged in the precipitator and which lower the average mobility of the charge carriers. With fly ash of abnormally low resistivity, ammonia also appeared to increase the cohesiveness of the ash.

RAPPING RE-ENTRAINMENT OF FLY ASH

In a continuously operating electrostatic precipitator, the collected fly ash is removed periodically from the collecting plate electrode by rapping it. The dislodged dust falls in agglomerates into a hopper below the electrodes. A mechanical conveyer removes the fly ash from the bottom of the hopper for disposal. The rap is made automatically by a hammer or vibrator according to a time schedule that can be set to give rapping cycles of a few minutes to a few hours, depending on the fly ash properties. In this way, the rapping process can be adjusted for maximum effectiveness on a specific fly ash. Also, complicated rapping sequences can be established that involve applying schedules with different rapping intervals to different plates in the precipitator.

Two general approaches to rapping are used. One is to rap often and to provide a high intensity of rapping, in an attempt to minimize the thickness of the residual dust layer. The other is to vary the intensity and frequency of rapping in an attempt to minimize the quantity of material reentrained in the gas stream.

An appreciable amount (up to 5%) of the collected fly ash can be re-entrained in the gas and lost in the gas emitted from the precipitator and from the power plant stack. This re-entrained fly ash can amount to half of the total particulate emissions.

An experimental study of rapping techniques was carried out to explore the effects of operating pararneters on the extent of reentrainment.[13] The measurements were made on a large experimental wire-plate electrostatic precipitator that represented one electrical section of a full-scale unit with horizontal gas flow. The experiments involved the collection of a redispersed fly ash, the particles of which had (before redispersion) a mass median diameter of 16 μm, with a geometric standard deviation of 5 μm. (This particle-size distribution is typical of fly ash from pulverized coal-fired boilers.) The gas flowing through the precipitator and in which the fly ash was suspended was a simulated flue gas, obtained from an oil burner. The gas temperature was 125-140°C, typical of flue gas from coal-fired boilers in power plants (on the downstream side of the air preheater).

The concentrations of fly ash in the flue gas at the inlet and outlet of the electrostatic precipitator were measured. The particle size distribution of the fly ash was determined by the use of impactors inserted in the flue at the inlet and outlet of the precipitator. For both types of measurement, traverses across the cross section of the duct were made to ensure representative sampling.

When the time interval between the raps was increased from 12 to 52 minutes, the following effects were observed:

(1) The total rate of fly ash emissions from the precipitator decreased from 12 kg/hr to 8 kg/hr.

(2) At the 12-minute interval, the emissions due to rapping were 6 kg/hr (50% of the total). At the 52-minute interval, the emissions due to rapping were 1 kg/hr (12% of the total).

(3) The average size of the fly ash particles emitted from the precipitator increased as the result of the rapping reentrainment, and the percentage contribution of the fine particles, i.e., those < 3 μm in diameter, to the total mass of fly ash emitted from the precipitator decreased from 25% to 10%.

(4) The overall collection efficiency of the precipitator increased from 88.6% to 93.9%.

These effects of lengthening the time between raps may be explained as being due to an increase in the size and number of aggregates of fly ash particles which, as they are dislodged from the collecting plate, are coherent enough to reach the hopper without being broken up and re-entrained in the gas stream. The layer of fly ash on the collecting plate is apparently compacted by electrical or mechanical forces after it is deposited.

Not all the deposit was removed by the rapping. On some of the plates, a residual dust layer was built up that was not removed from the plate at values of rapping intensity sufficient for removing freshly deposited fly ash, calculated to be 1-3 kg/m^2 for 100% removal. These results suggest that auxiliary, heavier rappers might profitably be used on a regular, perhaps daily, basis.

The fly ash emitted from the lower third of the precipitator was 60-80% of the total mass, due to a vertical gradient in dust concentration in the flue gas. This in turn could be ascribed to uneven distribution of the suspended fly ash resulting from gravitational settling and re-entrainnment of fly ash from the hoppers. It was evident from photographs that a large part of the re-entrainment was due to a boil-up or rebound of particles from the hoppers.

A MATHEMATICAL MODEL OF ELECTROSTATIC PRECIPITATION

The first successful electrostatic precipitators for controlling industrial dust emissions were installed in 1910. Within a few years, it was recognized that the efficiency of dust collection was exponentially related to parameters such as gas velocity and collecting plate area.

In 1922 W. Deutsch put this relationship into a more comprehensive form that incorporated concepts from electrical theory. The Deutsch equation gives the efficiency of collecting dust from a gas stream as a function of the collecting plate area, the flow rate of the gas, and the size of the dust particle and its migration velocity. The migration velocity is the net velocity to the collecting plate resulting from the opposition of two forces, the force of electrostatic attraction and the viscous drag of the gas that retards the movement of the particle.

A mathematical model for electrostatic precipitation has been developed that is based on the Deutsch equation.[14] Mathematical expressions for the components of the equation can be formulated from theoretical relationships which have been confirmed by experimental data. These expressions are used to calculate the electric field, particle charging rates, and the space charge resulting from the presence of charged particles, and the results are used in the computer program from which particle collection efficiency is computed.

The Deutsch equation is idealized in that it assumes thorough mixing of the gas due to turbulent flow, a uniform concentration of dust particles, and a constant migration velocity for all particles. These assumptions or conditions hold true only for particles of nearly the same size and only for short lengths through the precipitator.

Therefore, in constructing the mathematical model, the precipitator is divided into one-foot segments down its length, and each successive segment is considered as an incremental length in calculating the amount of fly ash collected from the gas stream as it moves through the precipitator. In this way, the Deutsch equation can be used more accurately than for the precipitator as a whole.

In an analogous manner, the variation in collection efficiency for different particle sizes can be taken into account by considering the suspended fly ash to be composed of a mixture of particles in a set of size ranges that fits the curve of particle size distribution. A value for migration velocity is calculated for each particle-size range in each increment of length.

After these calculations have been performed for all the increments of length, the overall collection efficiency (by mass) is calculated.

Corrections are made, on the basis of operating experience, for non-ideal performance: the gas flow is not uniform over the cross-section of the precipitator, some of the collected fly ash is entrained in the gas flow leaving the precipitator, and some of the dust-laden gas by-passes the electrified regions of the precipitator.

The mathematical model that was obtained by these methods has proven to be useful in predicting the performance of full-scale industrial electrostatic precipitators operating on flue gas from coal-fired electric power boilers.

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16. ABSTRACT The report gives highlights of a major EPA research program on electrostatic precipitator (ESP) technology, directed toward improving the performance of ESPs in controlling industrial particulate emissions, notably fly ash from coal combustion in electric power plants. Relationships between electrical effects, such as reverse corona, caused by high resistivity of the deposited fly ash, have been investigated. The influence of fly ash particle size and chemical composition on the resistivity and dielectric strength of the deposited fly ash has also been studied. Relationships have been established between fly ash resistivity and chemical composition, especially its alkali metal content, for ESP operating temperatures below about 250 C. Based on these relationships, a mechanism for ionic surface conduction has been proposed that complements the ionic mechanism in bulk conduction in fly ash particles at higher operating temperatures. The efficacy of conditioning fly ash by adding SO3 to flue gas (to lower fly ash resistivity) was established in trials at electric power plants. Reentrainment of particles from deposited fly ash has also been investigated in relation to ESP rapping procedures and gas flow distribution. A mathematical model of the ESP process has been developed, using fundamental relationships together with measurements of ESP geometry, electrical conditions, and particle size distribution.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Air Pollution	Fly Ash	Air Pollution Control	13B	21B
Electrostatic Precipitators	Coal	Stationary Sources		21D
	Combustion	Particulates		
Dust	Electric Power	Reverse Corona	11G	
Emission	Plants	Collection Efficiency		10B
Industrial Processes	Electric Corona		13H	20C

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