EPA-650/2-74-079

AUGUST 1974

Environmental Protection Technology Series

TECHNIQUES FOR MEASURING FLY ASH RESISTIVITY

Office of Research and Development
U.S. Environmental Protection Agency
Washington, DC 20460

EPA-650/2-74-079

TECHNIQUES FOR MEASURING FLY ASH RESISTIVITY

by

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Contract No. 68-02-1303
ROAP No. 21ADJ-029
Program Element No. 1AB012

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Prepared for

OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460

August 1974

This report has been reviewed by the Environmental Protection Agency and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

ABSTRACT

This report discusses the methods used for the measurement of the electrical resistivity of particulate matter suspended in an effluent gas stream. Factors affecting the resistivity of the particulate matter and its measurement are discussed. A description of the operating characteristics of a variety of currently available devices is given, together with a discussion of the significant differences between the various devices. A discussion is also included of *in-situ* versus laboratory techniques for measuring resistivity and the interpretation of data measured by these methods. Comparative values of resistivity as determined by the various measurement techniques are given for the limited conditions under which simultaneous measurements were made with two or more methods.

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ACKNOWLEDGEMENTS

Information for the preparation of this report was obtained from Dr. R. E. Bickelhaupt, Mr. Sabert Oglesby, Jr., and Dr. Herbert W. Spencer. Dr. C. E. Feazel provided editorial review.

In addition to the above members of the Southern Research Institute staff, assistance was provided by several electric power companies distributed across the United States in allowing measurement programs to be conducted at their plants.

The assistance of Dr. Harry J. White is gratefully acknowledged, especially for discussions and analysis of the work which led to this document.

SECTION I
INTRODUCTION

This report describes the operation, advantages and disadvantages of utilizing a number of different types of resistivity measurement instruments and techniques that are currently available for determining the electrical resistivity of particulate suspended in effluent gas streams. The data presented and the conclusions drawn are the result of work conducted by Southern Research Institute personnel and by others that have been active in this field. As a result of these studies, Southern Research now utilizes the point-to-plane in-situ resistivity probe for field measurement and a modified A.S.M.E. Power test code #28 device for laboratory measurements.

The behavior of an electrostatic precipitator can be related to the value of the resistivity of the suspended particulate in a theoretical manner. The electrical sparking or back corona conditions are related to the electrical breakdown of the dust layer as described later in this report. Therefore, any instrument selected as a measurement tool should provide values that are consistent with those that electrostatic precipitator theory would predict for limiting conditions.

The point-ot-plane probe provides data that are more clearly consistent with observed behavior of operating electrostatic precipitators than the other alternative devices. This factor, together with the similarities between the operation of a precipitator and the instrument are the basis for the selection of the point-to-plane device as the preferred measurement instrument.

SECTION II
SIGNIFICANCE OF PARTICULATE RESISTIVITY TO ELECTROSTATIC PRECIPITATOR OPERATION

The electrical resistivity of particulate matter present in the effluent gas stream is one of the primary factors that determine the operating characteristics of an electrostatic precipitator. In a conventional single-stage, dry-electrode electrostatic precipitator, the total corona current flows through the previously collected dust layer to reach the grounded collection electrode. This flow of current establishes an electric field (E) in the dust layer proportional to the corona current density (j) and the particulate resistivity (ρ) as given by

$$E = j\rho. \qquad (1)$$

The electric field in the dust layer yields a voltage drop (∇V) across the dust layer proportional to the dust layer thickness (t) of

$$\nabla V = Et. \qquad (2)$$

If the resistivity of the dust layer is increased while the current density is held constant, the electric field in the layer increases proportionately (Eq. 1). If the electric field in the dust layer exceeds the field strength for corona initiation (electrical breakdown), an electron avalanche will occur in the dust layer similar to that which occurs adjacent to the corona wire. This electrical breakdown acts as a limit on the allowable electrical conditions in the precipitator as is discussed below.

The manner in which this breakdown limits the precipitator performance is dependent upon the value of the resistivity of the dust and the thickness of the layer. If the resistivity is in the moderately high range ($\sim 10^{11}$ ohm-cm) the breakdown will generally initiate electrical sparkover between the precipitator electrodes; whereas if the resistivity is very high ($\sim 10^{12}$ ohm-cm) breakdown of the dust layer will occur at a voltage too low to propagate a spark across the interelectrode region. This gives rise to a condition of reverse ionization or back corona. Figure 1 illustrates these two conditions. The figure shows the current density as a function of applied voltage for an electrostatic precipitator with a 0.28-cm (0.109-in.) diameter corona wire, a 23-cm (9-in.) plate spacing, and a dust layer thickness of 1 cm. If the dust layer resistivity is in the moderately high range, e.g., 2×10^{11} ohm-cm, electrical breakdown in the dust layer will occur at an applied voltage greater than that required for sparking between clean

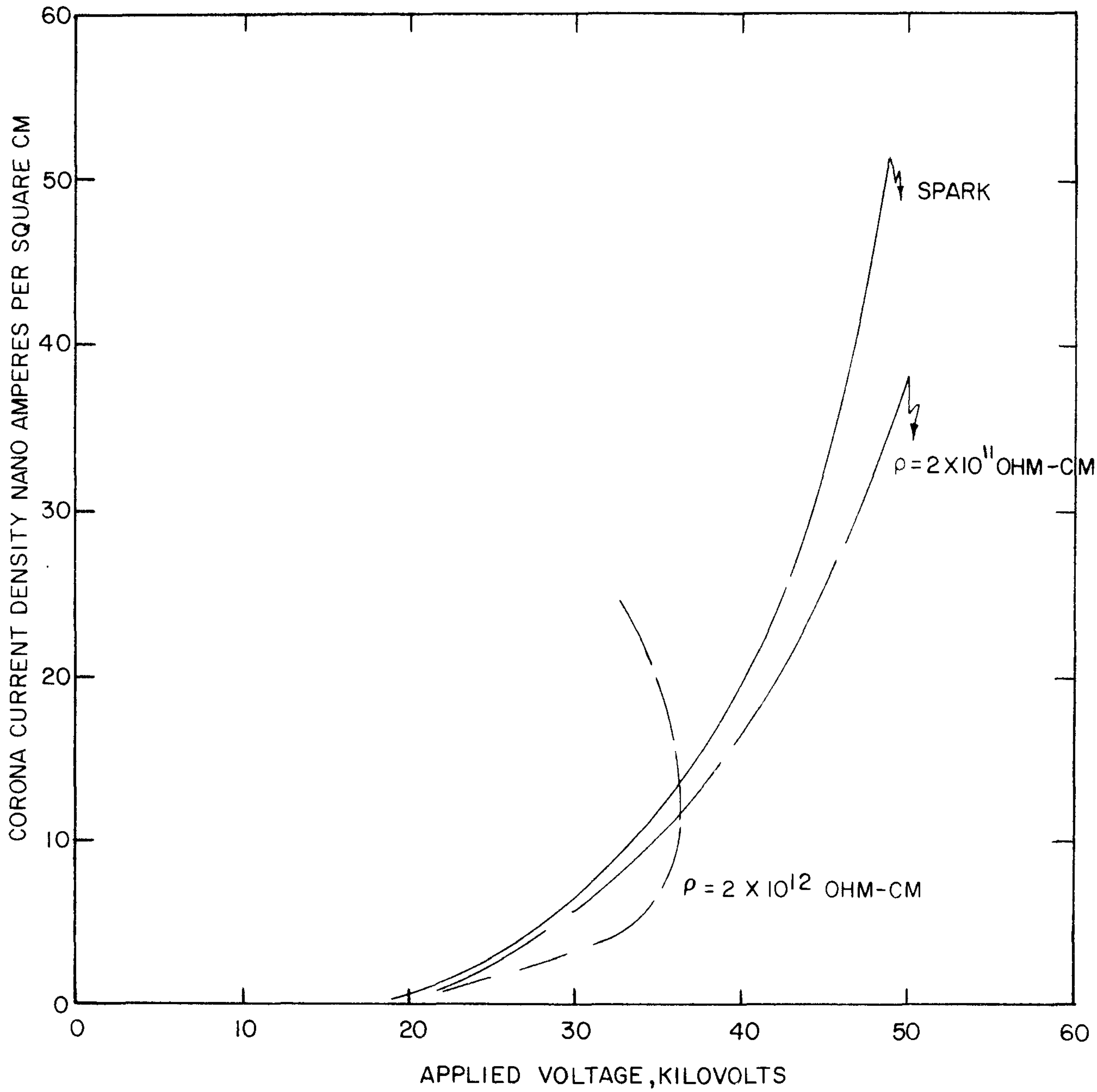

Figure 1. Voltage vs current for a precipitator with 23-cm plate spacing and 0.29-cm corona wire. Solid curve is for a clean electrode. The two dashed curves represent conditions for a 0.5-cm layer of dust with the resistivities indicated.

electrodes, and sparking will occur at a reduced current density. For a very high resistivity dust with the conditions shown, electrical breakdown will occur in the dust layer at a much lower current density and applied voltage. Under these conditions, the dust layer will be continuously broken down electrically and will interject ions of an opposite electrical polarity from those produced by the corona into the interelectrode space. The precipitator electrical operating conditions are thus limited by a high resistivity dust layer and the precipitator is constrained to operate at lower currents and voltages than one collecting a lower-resistivity dust. The magnitude of the reduction in electrical operating conditions is a direct function of the dust resistivity.

In view of the importance of the resistivity of the dust layer as a primary factor in limiting the performance of a precipitator, it becomes necessary to determine the resistivity of the material to be collected in order to estimate the conditions to be expected in a precipitator.[1]

SECTION III
FACTORS INFLUENCING RESISTIVITY

The electrical resistivity of a collected layer of fly ash varies with temperature in a manner illustrated in Figure 2. Above about 225°C, resistivity decreases with increasing temperature and is independent of flue gas composition. Below about 140°C, resistivity decreases with decreasing temperature and is dependent upon moisture and other constituents of the flue gases.

In analyzing the conduction process, it is convenient to consider the resistivity as involving two independent conduction paths, one through the bulk of the material (volume conduction) and the other along the surface of the individual particles, associated with an adsorbed surface layer of some gaseous or condensed material. Either of these paths may become the dominant conduction mode under conditions that exist in operating precipitators, or, as is the general case, both mechanisms may be important. The volume conduction is dependent upon the chemical composition of the particulate material, whereas surface conduction is controlled by the chemical compositions of both the particulate and the effluent gas stream.

FACTORS INFLUENCING VOLUME RESISTIVITY

Volume conduction in fly ash is an ionic process resulting from the migration of alkali metal ions, especially sodium. Whether the conduction takes place through the particles or along the particle surface has not been definitely established. The important distinction is that volume conduction, or volume resistivity, is governed only by the character and composition of the dust and is independent of gas composition.[2]

Volume conduction in all dusts encountered in industrial gas cleaning is temperature dependent. In the case of ionic conduction, increased temperature imparts greater thermal energy to the structure of the material, allowing carrier ions to overcome adjacent energy barriers and to migrate under the influence of an electric field. Thus, for volume conduction, an increase in the temperature produces an increase in the number of carriers available to contribute to the conduction of the particulate layer.

Figure 3 shows the relationship between volume resistivity and temperature for two fly ash samples produced by combustion of coal. The change of resistivity with temperature can be

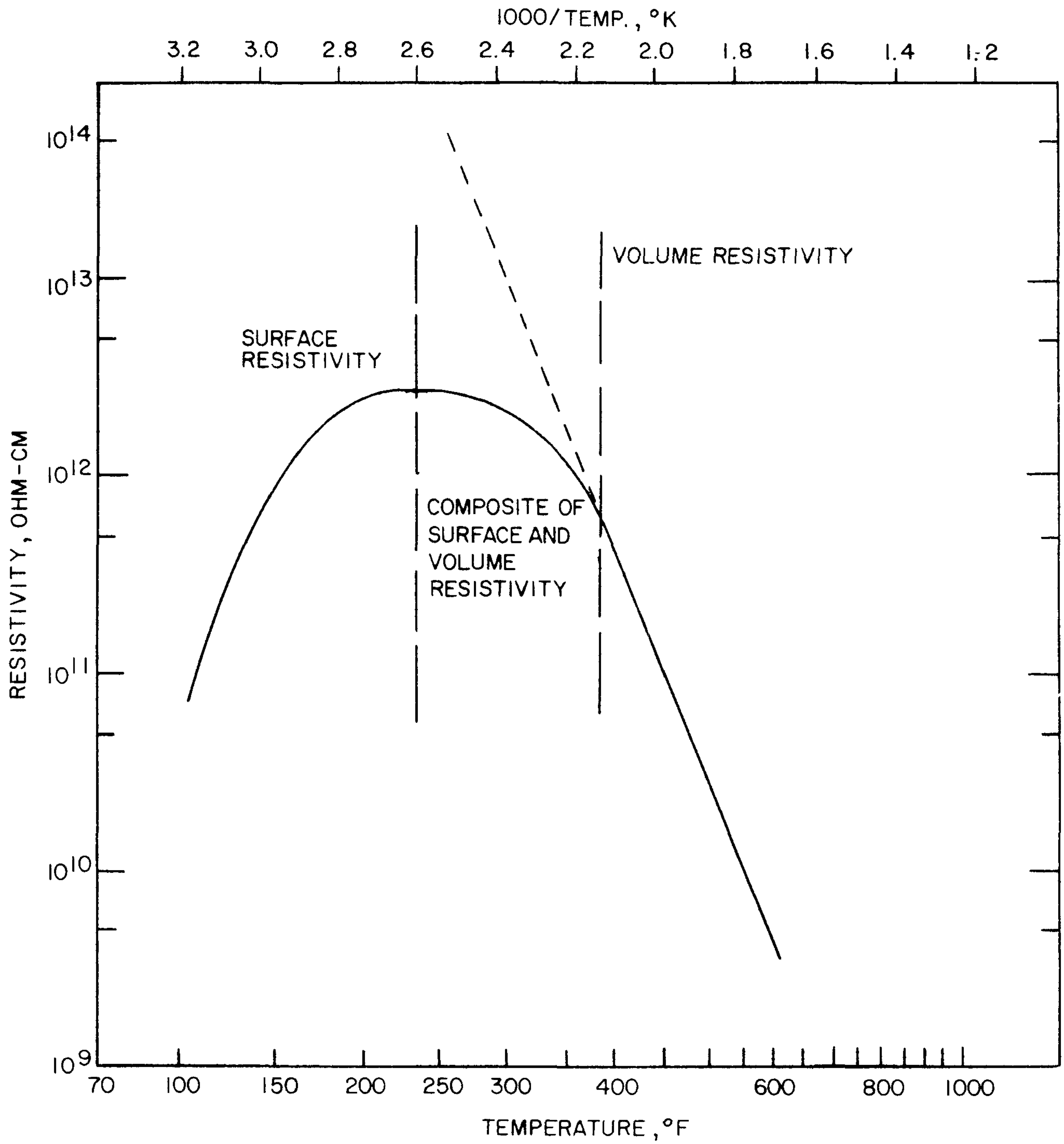

Figure 2. Typical temperature-resistivity relationship for fly ash.

expressed in the form of an Arrhenius equation

$$\rho = \rho_0 \exp (Q/kT) \qquad (3)$$

where ρ is the resistivity, ρ_0 is a material constant, Q is an experimentally determined activation energy, k is Boltzmann's constant, and T is the absolute temperature. For the fly ash example shown in Figure 3, the material constant ρ_0 is different for fly ash with different sodium ion contents. Graphically, a shift in ρ_0 causes a parallel shift in the temperature-resistivity curve. The experimental activation energy Q is a rate phenomenon and represents the slope of the temperature-resistivity curve. The quantities ρ_0 and Q are useful in defining electrical conduction properties of solid or granular materials as a function of temperature.

In some types of dusts, conduction may be electronic instead of ionic. Nevertheless, the Arrhenius equation applies, whether the conduction is electronic or ionic, and the temperature-resistivity relationships are similar, differing only in the values of the constants in the Arrhenius equation.

Volume resistivity of a dust sample is also related to its porosity. Intuitively, one would expect a higher resistivity to be associated with a more porous dust layer due to the smaller quantity of material in a given volume.

For fly ash samples, a 25% change in specimen porosity causes a change of one decade in resistivity. A generalized relationship between specimen porosity and resistivity was found[2] for fly ash to be

$$\log \rho_c = \log \rho_m + S(P_c - P_m) \qquad (4)$$

where

ρ_c = resistivity at porosity P_c

ρ_m = resistivity at porosity P_m

$S = \nabla \log \rho / \nabla \% P = 0.04.$

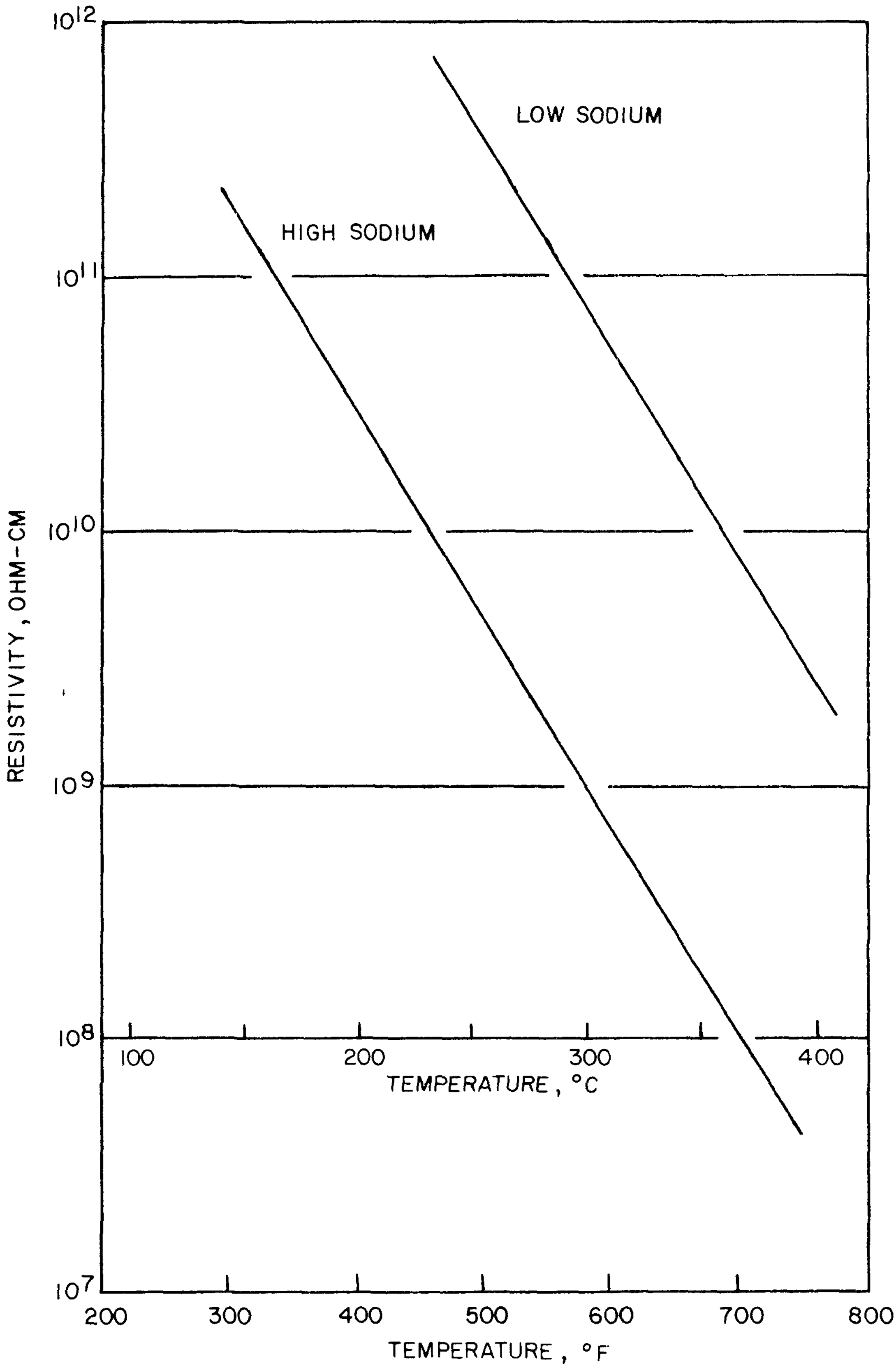

Figure 3. Resistivity vs temperature for two fly ash samples illustrating influence of sodium content.

FACTORS INFLUENCING SURFACE RESISTIVITY

Surface conduction requires the establishment of an adsorbed layer of some material either to provide an independent conduction path or to interact with some component of the particulate material to provide a surface conduction pathway. If the effluent gas stream contains condensable material (e.g., water or sulfuric acid) and if the temperature is low enough that an adsorbed layer can form, then the surface conduction will become significant.

For temperatures below about 150°C (300°F), surface conduction occurs via the lower resistance path created by the absorbed moisture or chemical components which occurs at these lower temperatures. Both moisture and chemically reactive substances such as sulfur oxides and ammonia are commonly present in many industrial gases.

Physical adsorption as well as condensation can be involved in surface conduction. At temperatures below the dew point, the rate of deposition on the surface of a dust would be high. However, for most circumstances the adsorbate is deposited on the dust surface and can provide a surface conduction pathway even at temperatures considerably above the dew point, as is shown in Figure 4.

In surface conduction, the mechanism of charge transport appears to be ionic; however, the migrating species have not been identified. They could be ions extracted from or carried on the dust surface or those deposited from the gas stream.

An example of how surface resistivity of fly ash depends on the composition of the flue gas is the case of fly ash from coal-fired boilers burning sulfur-containing coals. The burning of coal containing sulfur produces sulfur dioxide (SO_2) in quantities dependent on the sulfur content. Under normal conditions, about 0.5 to 1% of the SO_2 present is oxidized to SO_3, which serves to reduce the resistivity of the fly ash, if the temperature is low enough for the SO_3 to be adsorbed on the ash. Thus, high-sulfur coals tend to produce ash with lower resistivities than coals with lower sulfur contents. In general, lowering the flue-gas temperature increases the SO_3 absorption, so that the resistivity of the fly ash can be controlled to some extent by changes in flue gas temperature.

The influence of electric field on conduction in insulating materials has been well documented. In solid materials, increasing electric field permits a greater number of migrating ions to participate in the conduction process. In granular

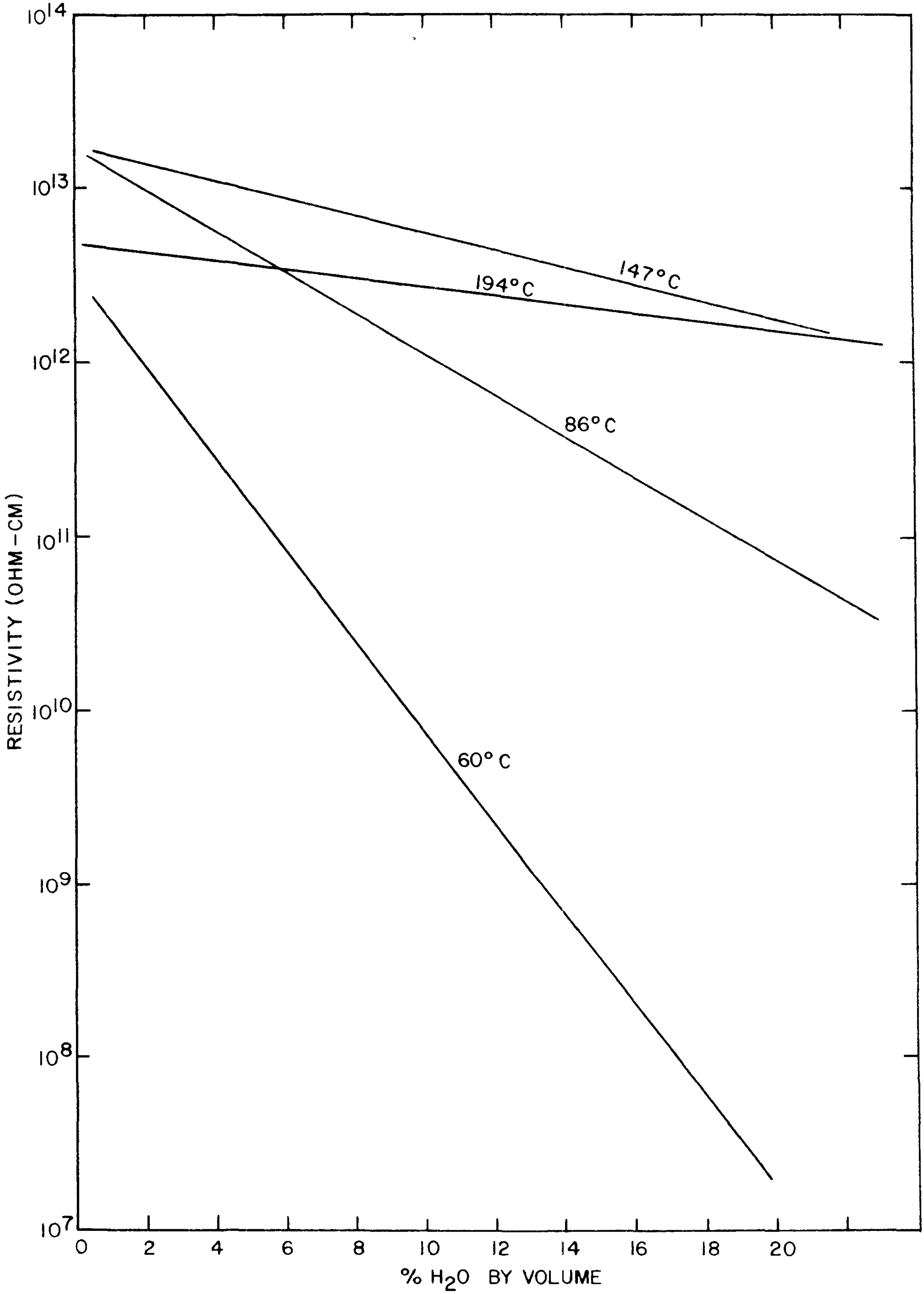

Figure 4. Resistivity as a function of moisture content for a fly ash sample at various temperatures.

materials additional influences of electric field may become important.[3] Possible effects are:

- an increase in temperature at the contact points between particles caused by joule heating
- an electric discharge in the dust layer due to the enhanced field near adjacent particles.

FACTORS INFLUENCING MEASUREMENT OF RESISTIVITY

Resistivity of a dust layer is determined experimentally by collecting a sample of the dust from a gas stream and measuring the current and voltage characteristics of a defined geometrical configuration of the dust. The method of collecting the dust from the gas stream, the method of forming the dust layer, and the conditions of measurement all influence the resistivity measurement.

Particle Size

For determination of the true particle size distribution, the sample should be taken from the gas stream in a manner (e.g., isokinetically) that insures that the sample is representative of the particle size distribution of the dust in the gas stream. However, due to problems of probe design, most of the resistivity probes either do not sample isokinetically or do not collect all the particles sampled. In either instance the sample is not representative of the size distribution of the dust in the gas stream.

Even if isokinetic sampling were used, the particle size of the dust layer deposited in each field of a precipitator differs due to the variation in collection efficiency as a function of particle size. Consequently, in determining resistivity to correspond to that of each field of a precipitator, the particle size distribution associated with each field would have to be simulated. In general, such a procedure would be impractical, and some means of obtaining a reasonably representative sample is employed.

It has been shown that the resistivity of fly ash varies with the size fraction, the smaller size fractions having lower resistivities.[4] The extent of variation in resistivity with particle size differs with the conduction mode. In the surface conductivity region, the surface area to mass ratio is higher and a larger percentage of adsorbed gases are present. Also the smaller particle size gives a lower porosity sample.

Source Variability

A second factor influencing resistivity measurement is source variability. In spite of attempts to obtain a uniform boiler fuel by blending the coal supply, the chemical composition of the coal will vary enough to be reflected in observable changes in the SO_2 level of the flue gases and in the chemical composition of the fly ash. Thus, to minimize errors due to source variability, resistivity measurements should be made on samples taken over a sufficiently long period of time, and the results should be averaged to obtain a representative value.

Electric Field

Since the resistivity of a dust varies with electric field, it is important that measurements be made at an electric field corresponding to that in the precipitator and/or that the value of the field at which the measurement is made be specified. In some resistivity probes the voltage is increased until the dust layer breaks down, and the resistivity reported is that corresponding to the condition just prior to breakdown. Other probes impose a fixed voltage across a pair of electrodes to establish a field. Generally the magnitude of the field is very low, of the order of 1 kV/cm for this latter type of instrument.

Figure 5 shows a typical relationship between resistivity and electric field for fly ash (from coals with low and moderate sulfur contents). The reported values would of course be different depending upon whether the measurement was made at a low field or near breakdown.

Method of Depositing Dust Layer

In an electrostatic precipitator, the dust layer is deposited electrostatically and the particles are aligned somewhat as the dust layer is built up. In some sampling probes the dust layer is deposited electrostatically, whereas in other probes the dust is collected by other means and allowed to fall into the measurement cell.

The significance of the method of deposition has not been quantitatively determined. However, to the eye, dust layers deposited electrostatically appear denser than those established by free fall of the dust. In probes in which the dust is allowed to fall into the measurement cell, some attempt is made to vibrate the cell or otherwise establish a reproducible density of the deposited dust. In other probes, measurement

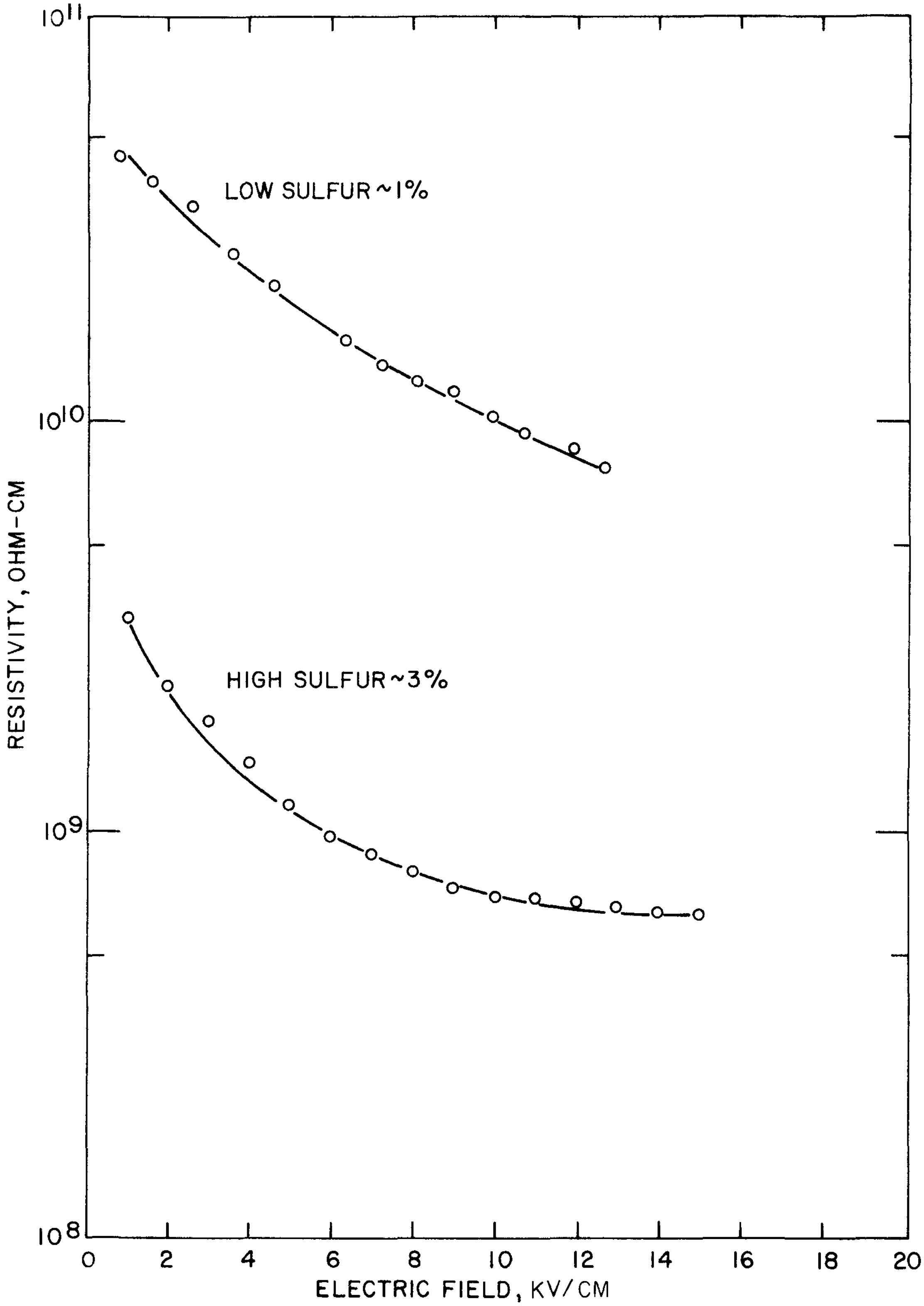

Figure 5. Variation in particulate <u>in-situ</u> resistivity with electric field for the parallel disc measurement method with the point-to-plane probe. Temperature - 265°C (330°F); dust layer thickness - 1.0 mm.

technique involves a disc placed on the dust surface. This disc provides some compaction of the dust layer.

Time of Current Flow

When voltage is applied to a dust layer, the magnitude of the current will initially be high and it will then fall off, rapidly at first and slowly thereafter. The initial current surge is due to absorption current, which charges the capacitance associated with the dust layer. The subsequent decrease in current is due to depletion of the charge carriers or polarization at the dust-electrode interface.

If current is allowed to flow for a considerable time prior to making resistivity measurements, the value will be lower than a measurement made immediately following application of a voltage.

All the above factors aid in complicating what is basically a very simple measurement. Since so many factors affect resistivity, field measurements invariably show a certain amount of scatter - quite often ten-fold. It is thus necessary that several measurements be made to obtain meaningful results.

SECTION IV
METHODS FOR MEASURING RESISTIVITY

The determination of the electrical resistivity of particulate material is made indirectly. None of the available devices is capable of making this measurement directly. The resistivity is computed from the resistance of a sample of the material with a known geometrical configuration. Typically, the geometry of the sample will be either a rectangular or cylindrical solid, or the volume of space between concentric cylindrical electrodes. In each instance, the relationship between the resistivity and resistance of what is considered to be a homogeneous material is given by

$$\rho = RA/l \qquad (5)$$

where

ρ = resistivity (ohm-cm)

R = resistance (ohm)

A = cross sectional area (cm^2)

l = length (cm)

In each measurement device, the amount of material actually utilized for the measurement is on the order of one cubic centimeter or less. Layer thickness from one-half to three millimeters is common. Using this minute sample of material selected from the large quantities of fly ash generated during a measurement period raises serious questions as to just how representative of the total fly ash material this sample can be. This factor may, in part, explain the wide range of scatter actually observed in a resistivity measurement program.

Several techniques can be used for measuring the resistivity, and several types of equipment are available for this purpose, with no general agreement as to their relative merits. However, the choice of method and equipment can be aided by the following considerations.

One consideration is whether an absolute resistivity is to be made for scientific or engineering purposes or whether a relative or rank ordering type of measurement is sufficient. If one is attempting to relate the behavior of an electrostatic precipitator to theoretically derived relationships, then it is important to attempt to evaluate the absolute resistivity of the dust. However, if one has accumulated a considerable quantity of resistivity data over a period of time with one type of device and in addition has similarly accumulated experience as to how a particular type of electrostatic precipitator behaves with the related particulate resistivity, then other methods may be equally applicable for these particular investigators.

As described in Section III, the measured value of resistivity is dependent upon a number of factors. If the measurements are contemplated for rank ordering or relative behavior, then wide latitude is allowed in the selection of a method. For the relative measurement type of investigation, it becomes important to merely assure that the measurement conditions are reasonably well duplicated for each condition, and the selection of method becomes of secondary importance. Either in-situ or laboratory methods may be applicable to a study of this nature if the sample collection conditions, including temperature, are identical. However, if the purpose of the study is to evaluate how an electrostatic precipitator will behave with a new or significantly different type of dust under a given set of conditions, in-situ measurements will probably be necessary.

For comparative evaluations, in-situ measurements must be made with the same instrumentation. As discussed later in this report, extreme care must be exercised in attempting to compare resistivity values obtained with one type of device with those obtained by another type.

LABORATORY VS IN-SITU MEASUREMENTS

The determination of whether the particulate resistivity should be measured in the laboratory or in-situ is based on an evaluation of the significance of the surface conduction component. If the surface conduction is negligible because of high temperature (>200°C) or because of the absence of any reactive or condensable material (H_2O, SO_3, etc.) in the effluent gas stream, then laboratory measurements are appropriate.

However, if reactive constituents are present and if the temperature is in the vicinity of the dew point of the condensables, such that there is a reasonable probability that an adsorbed surface layer will exist, then it is imperative that the resistivity be measured in-situ.

It is important to make measurements in the effluent gas stream rather than in the laboratory even though the chemical composition of the gas stream can be duplicated in the laboratory. The reason for this distinction is that as the particulate sample is collected, cooled and transported to the laboratory, there is a reasonable probability for chemical reactions to occur that would modify the particulate matter prior to measurement.

LABORATORY MEASUREMENTS

The standard technique for conducting laboratory resistivity measurements is described in the American Society of Mechanical Engineers Power Test Code 28, Determining the Properties of Fine Particulate Matter. This code was adopted by the Society in 1965 as a standard practice for the determination of all the properties of fine particulate matter which are involved in the design and evaluation of dust-separating apparatus. The tests include such properties as terminal settling velocity distribution, particle size, bulk electrical resistivity, water-soluble sulfate content, bulk density, and specific surface.

The document defines bulk electrical resistivity as the resistance to current flow, expressed in ohm-centimeters, through a dust sample contained in a cubic volume one centimeter on a side when exposed to an electrical voltage equivalent to 90% of the breakdown voltage of the sample, applied uniformly across two opposite faces of the cube. The code specifies that the property is to be determined at 150°C (300°F) and at a humidity of 5% by volume, unless otherwise specified.

Apparatus

The basic conductivity cell is shown in Figure 6. It consists of a cup which contains the ash sample and which also serves as an electrode, and an upper electrode with a guard ring. To conform with the code, the high-voltage conductivity cell must have the same dimensions as shown, and must use electrodes constructed from 25-micron porosity sintered stainless steel.

The controlled environmental conditions required for the measurement of resistivity in the laboratory can be achieved by an electric oven with thermostatic temperature control and with good thermal insulation to maintain uniform internal temperature, and a means to control humidity. Humidity may be controlled by any one of several conventional means, including circulation of pre-conditioned gas through the oven, injection of a controlled amount of steam, use of a temperature-controlled circulating water bath, or the use of chemical solutions which control water vapor pressure. It is desirable to circulate the humidified gas directly through the dust layer; hence the reason for the porous electrodes. Figure 7 illustrates a suitable set-up for resistivity measurements.

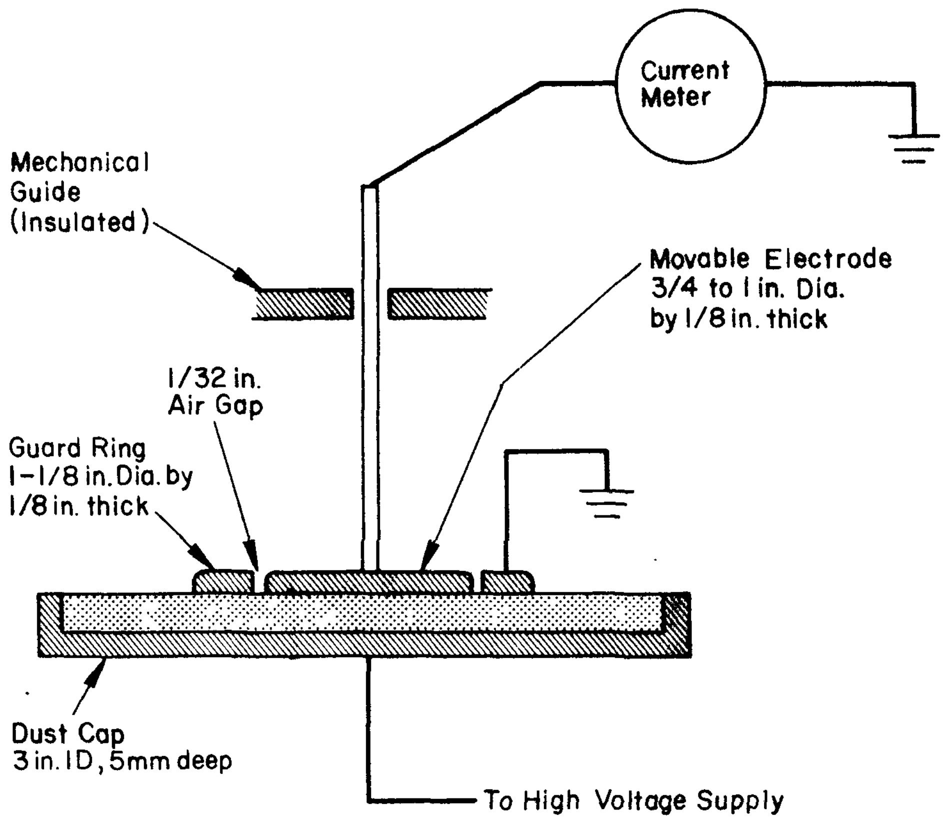

Figure 6. Bulk Electrical Resistivity Apparatus, General Arrangement.

The movable disk electrode is weighted so that the pressure on the dust layer due to gravitational force is 10 grams per square centimeter. The nominal thickness of the dust layer is 5 millimeters. The actual thickness is to be determined with the movable electrode resting on the surface of the dust. All electrode surfaces in the region of the dust layer are to be well rounded to eliminate high electric field stresses.

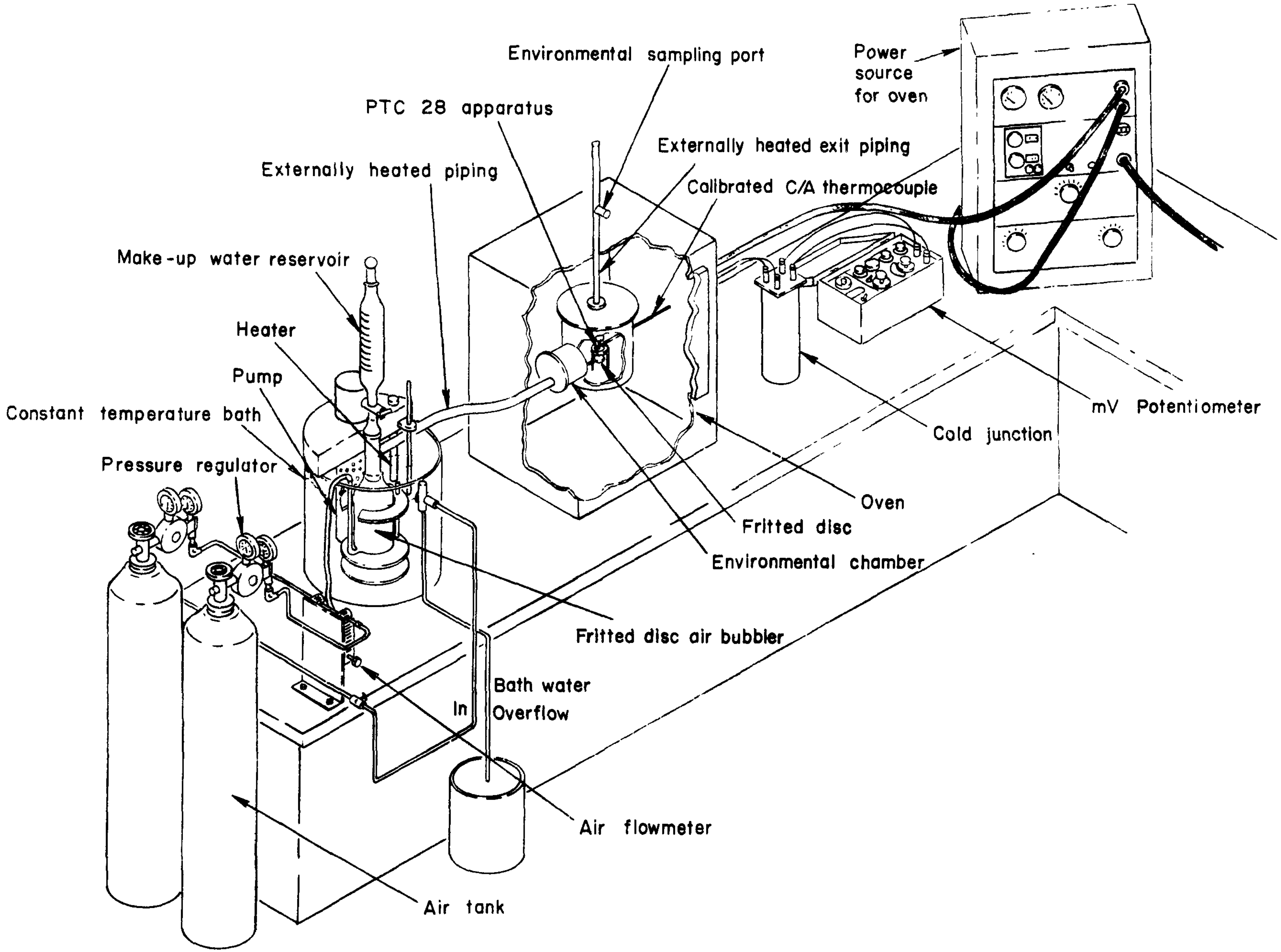

Figure 7. Schematic of Apparatus Set-up for Resistivity Measurements

Procedure for Laboratory Resistivity Measurements

The first problem encountered in making any resistivity measurement is obtaining an appropriate dust sample. The prescribed procedure for PTC 28 Code assumes that samples of gas-borne dust are taken from a duct in accordance with the Test Code for Determining Dust Concentration in a Gas Stream (PTC 27-1957). The PTC 27 Code involves isokinetic dust sampling at various points in the duct. It is recommended that samples should not be obtained from a large bulk of material in a hopper, silo, or similar location. If it is necessary that samples be obtained from such a location, procedures which will insure that the sample is representative of the whole must be used. For any resistivity test to be performed on a bulk sample, it is necessary that a random sample be obtained. This can be done by quartering the bulk sample to obtain the test sample.

To break up agglomerates and to remove foreign matter, e.g., collection plate scale, the specimen can be passed through an 80-mesh screen.

The procedure for making the resistivity measurement according to Power Test Code 28 follows:

1) The sample is placed in the cup of the conductivity cell by means of a spatula. Then it is leveled by drawing a straight edge blade vertically, across the top of the cup.

2) The disc electrode is gently lowered onto the surface. It should rest freely on the sample surface without binding on any supports.

3) The conductivity cell is mounted in the environmental chamber and equilibrium temperature and humidity are established. The Code specifies that a temperature of 150°C (300°F) and a humidity of 5% by volume are to be used for the test, unless otherwise specified.

4) A low voltage is applied to the cell and then gradually raised in a series of steps up to the point of electrical breakdown of the sample layer. Current transients will occur when the voltage is first applied or increased across the cell. It is necessary that these die away before recording current and voltage readings (approximately one minute). A record of the current-

voltage characteristic of the dust is obtained. Preferably using another sample, the above is repeated; when another sample is not available, the sample layer should be remixed and releveled after each run in order to break up any spark channels that may have been formed in the dust layer. A total of three runs should be made. The average breakdown voltage is then calculated. Before taking the samples to breakdown, it is necessary to determine whether the temperature and moisture content of the sample are in equilibrium with temperature and humidity of the controlled environment. A test for equilibrium is that the voltage-current measurements are reproducible to within 10% when determined by two successive measurements made 15 minutes apart.

5) The resistivity of the samples is then calculated in the range of 85 to 95% of the average breakdown voltage, using the corresponding currents from the previously recorded voltage-current characteristics.

Laboratory use of the PTC 28 apparatus to study characteristics of dust resistivity involves a slightly different procedure than that described above. Usually it is not necessary to determine the breakdown voltage of the dust layer; hence, a fixed potential is applied across the cell, and then the factors under investigation such as ash chemistry and bulk density are varied.

Calculations

Resistivity can be calculated in the following way. First, calculate the resistance of the dust layer R.

$$R(\text{ohms}) = \frac{V(\text{volts})}{I(\text{amps})} \tag{6}$$

Then calculate the resistivity ρ.

$$\rho(\text{ohm-cm}) = R(\text{ohms})\,\frac{A(\text{cm}^2)}{l(\text{cm})} \tag{7}$$

The moisture content of the air in the environmental chamber can be determined by weighing a tube filled with calcium sulfate (Drierite) before and after passage of a measured volume of air through it. The volume of dry air passed through the tube is determined from the flow rate and the sampling time.

Other laboratory techniques may be desirable to determine certain electrical characteristics of the ash, for example, the method being used in research on the resistivity of fly ash at elevated temperature. The technique utilizes a self-supporting sintered disc of fly ash, rather than a loose powder. This technique is commonly used in the electrical evaluation of ceramic insulators. It was selected for the study of volume resistivity because it allows certain post-test analytical work to be done. The details of specimen preparation and measurement technique are given by Bickelhaupt.[5]

Simulated Flue Gas

Another refinement to the usual laboratory method is based on more nearly duplicating the gaseous environment to which the dust is exposed. Either the PTC 28 device or one of the *in-situ* devices described below could be utilized in a controlled environment that is used to simulate, e.g., the flue gas conditions of the effluent gas stream from a boiler.

In the case of the *in-situ* devices the particulate material may be redispersed in this controlled environment to simulate the *in-situ* conditions. The principal drawback to this technique is the strong possibility that chemically active compounds present on the particles may modify their properties in the time between collection and measurement.

IN-SITU MEASUREMENTS

Several decisions must be made in setting up and conducting *in-situ* resistivity measurements. These decisions involve device selection and operation, site selection, determination of the number of samples required to characterize the dusts, and the auxiliary data required, as well as safety precautions. The selection of the device is dependent upon a number of factors, including the availability of each device and one's past experience. The operating characteristics of each device, which are discussed below, will supply the rationale for device selection and operation.

In-situ Probes

A number of different instruments are available for making resistivity measurements. These instruments differ fundamentally in the method of sample collection, degree of compaction of the dust sample, and the values of the electric field and current density utilized for the measurement, as well as the method of maintaining thermal equilibrium and the method of deposition in the measurement cell. These differences in operation lead to differences in the characteristics of the sample and in the values obtained for the resistivity. Each device is discussed individually with some discussion of the advantages and disadvantages for actual use.

Instruments utilizing electrostatic collection and measurements on the undisturbed dust layer measure the resistance of a dust layer that was formed by collecting individual particles aligned by the electric field identical to the conditions in a standard precipitator. This procedure leads to a compact dust layer with good interparticle contact. Those devices that utilize dust layers collected and redeposited will be operating on a disturbed and recompacted layer. This difference in operation may lead to differences in contact potential between the adjacent particles and to different porosity in the sample that may influence the value obtained for the resistivity.

Point-to-Plane Probe

The point-to-plane probe for measuring resistivity has been in use since the early 1940's in this country.[1] Two models of this device are shown in Figure 8. The probe is inserted directly into the dust-laden gas stream and allowed to come to thermal equilibrium. The particulate sample is deposited electrically onto the measurement cell through the electrostatic action of the corona point and plate electrode. A high voltage is impressed across the point and plate electrode system such that a corona is formed in the vicinity of the point. The dust particles are charged by the ions and perhaps by free electrons from this corona in a manner analogous to that occurring in a precipitator.

The dust layer is formed through the interaction of the charged particulate with the electrostatic field adjacent to the collection plate. Thus, this device is intended to simulate the behavior of a full-scale electrostatic precipitator and to provide a realistic value for the resistivity of the dust that would be comparable to that in the actual device.

In the point-to-plane technique, two methods of making measurements on the same sample may be used. The first is the "V-I" method. In this method, a voltage-current curve is obtained before the electrostatic deposition of the dust, while the collecting disc is clean. A second voltage-current curve is obtained after the dust layer has been collected. After the layer has been collected and the clean and dirty voltage-current curves obtained, the second method of making a measurement may be used. In the second method, a disc the same size

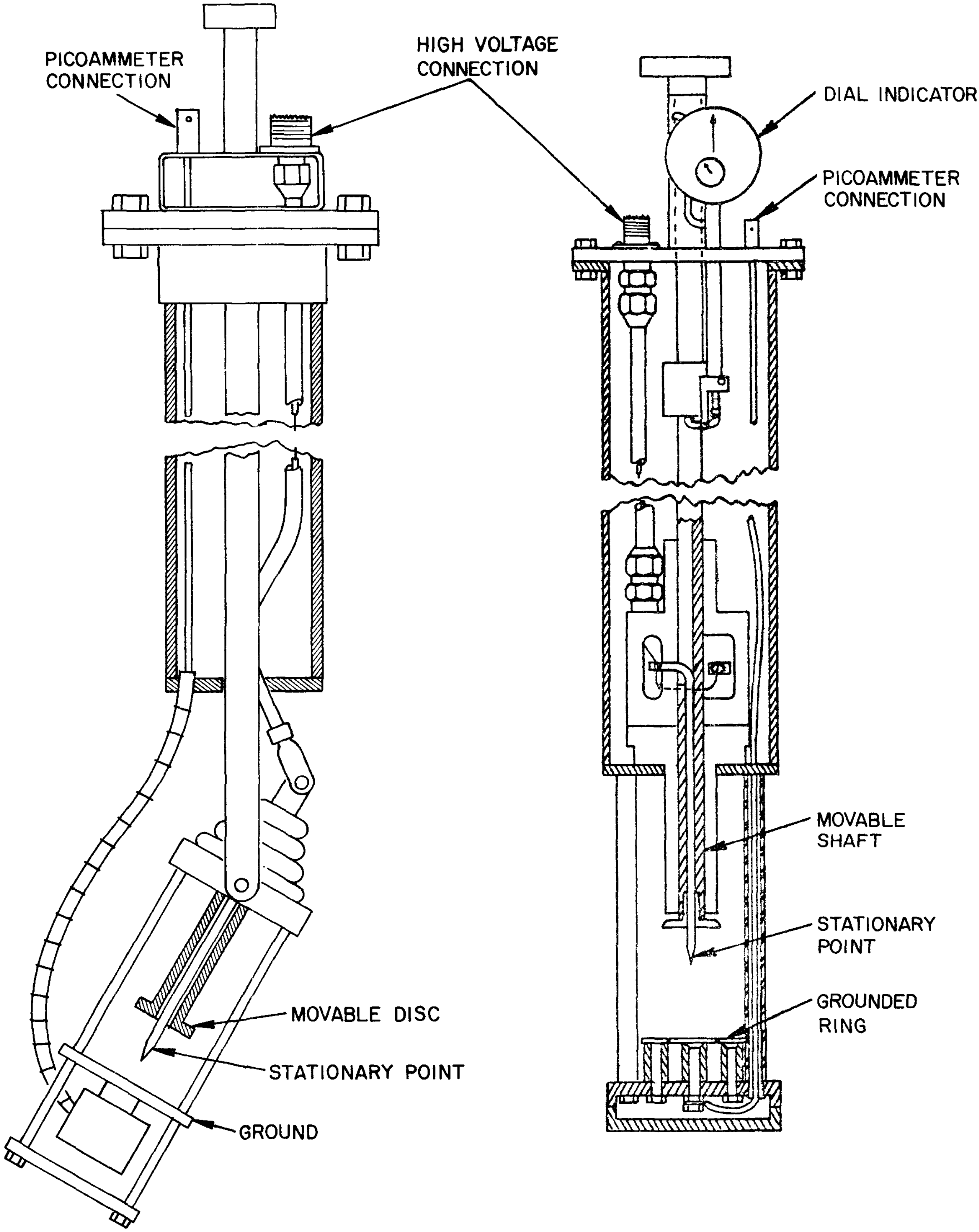

Figure 8. Point-to-plane resistivity probes equipped for thickness measurement.

as the collecting disc is lowered on the collected sample. Increasing voltages are then applied to the dust layer and the current obtained is recorded until the dust layer breaks down electrically and sparkover occurs. The geometry of the dust sample, together with the applied voltage and current, provide sufficient information for determination of the dust resistivity.

In the point-to-plane method, the voltage drop across the dust layer is determined by the shift in the voltage-vs-current characteristics along the voltage axis as shown in Figure 9. The situation shown is for resistivity values ranging from 10^9 to 10^{11} ohm-cm.

If the parallel disc method is used, dust resistance is determined from the voltage measured just prior to sparkover. In both methods the resistivity is calculated as the ratio of the electric field to the current density.

The practice of measuring the resistivity with increasing voltage has evolved because the dust layer behaves as a nonlinear resistor. As the applied voltage is increased, the current increases greater than that attributable to the increase in voltage. Therefore, as described in the A.S.M.E. Power Test Code Number 28 procedure, the value just prior to sparkover is reported as the resistivity.

There is considerable justification for using the value of resistivity prior to electrical breakdown as the resistivity, since it is precisely at electrical breakdown that the resistivity causes problems within the precipitator. The electrical breakdown in the dust layer in the operating precipitator either initiates electrical sparkover or reverse ionization (back corona) when the resistivity is the factor limiting precipitator behavior. If neither of these events occur, the dust layer merely represents an additional voltage drop to the precipitator power supply.

Even though there are many similarities between the operation of the point-to-plane device and a full-scale precipitator, several problems also exist. The first problem encountered is the determination of the thickness of the dust layer. Some devices make use of a thickness measurement system built into the probe. In other devices, the instrument is withdrawn from the duct and the thickness of the layer is estimated visually by inspecting the dust layer. However, the dust layer is almost always disturbed by the air flow through the sampling port and extreme care is required to preserve the layer intact.

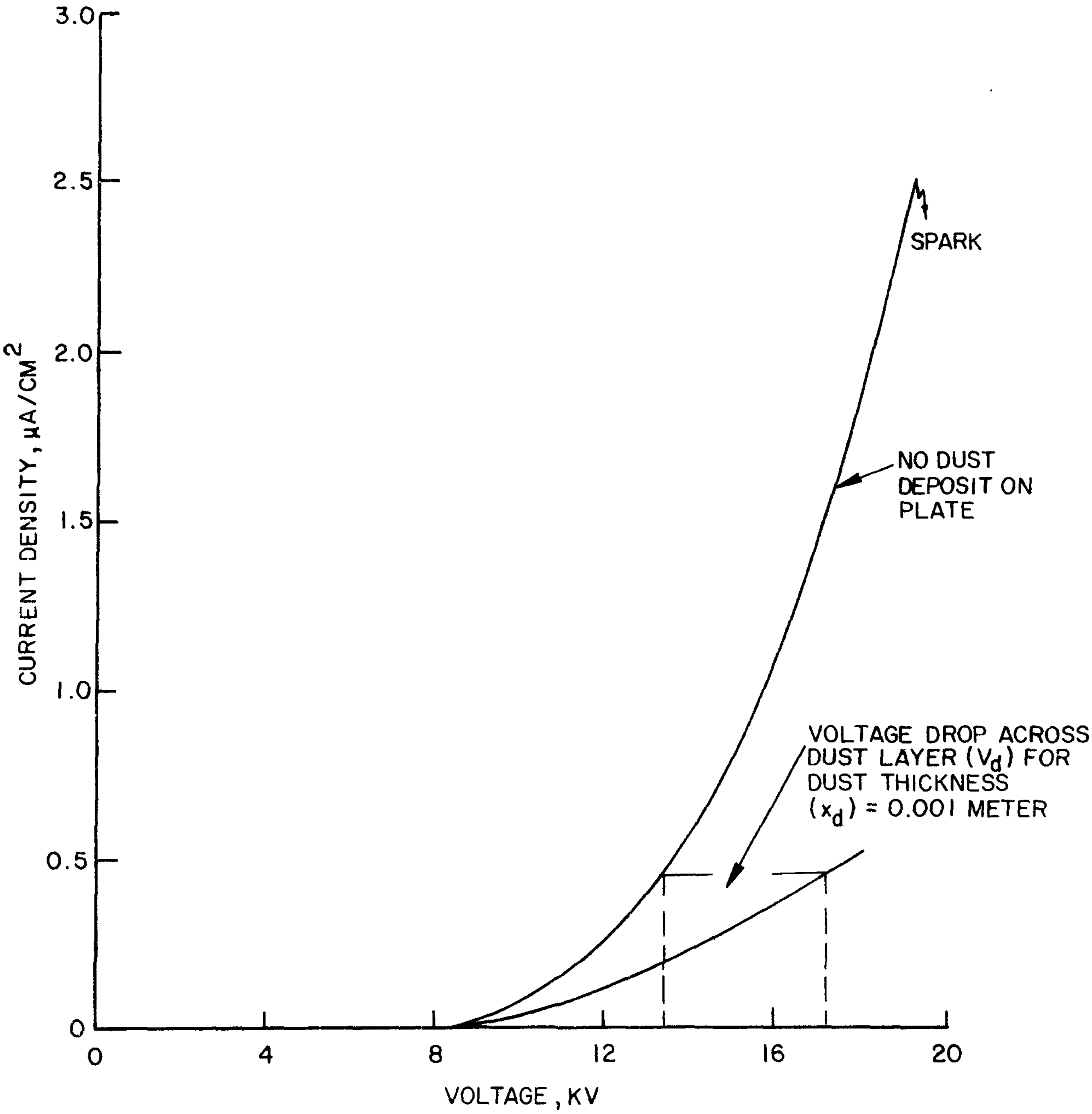

Figure 9. Typical voltage-current relationships for point-to-plane resistivity probe.

Advantages and Disadvantages -

The advantages of utilizing the point-to-plane probe for in-situ measurements are:

1. The particulate collection mechanism is the same as that in an electrostatic precipitator.

2. The dust-gas and dust-electrode interfaces are the same as those in an electrostatic precipitator.

3. The measurement electric field and current densities are comparable to those in the precipitator.

4. Flue gas conditions are preserved.

5. The values obtained for the resistivity are in general consistent with the electrical behavior observed in the precipitator.

6. Measurements can often be made by two different methods.

The disadvantages are:

1. The measurement of the dust layer thickness can be difficult.

2. High voltages are required for collection.

3. Considerable time is required for each test.

4. Experienced personnel are required for testing.

5. A number of measurements are required for gaining confidence in the measured value (there is considerable scatter in the data).

6. Particle size of the collected dust is not representative.

7. Sample size is small.

8. Carbon in the ash can hamper resistivity measurements.

Cyclone Resistivity Probes

The cyclone resistivity probe measures the resistivity of a particulate sample that is extracted from the effluent gas stream by an inertial cyclone collector. The dust sample is deposited between two concentric cylindrical measurement electrodes. The dust-laden gas sample is extracted through a sampling nozzle by a pump into the cyclone separator where the collected dust falls into the measurement cell. The gas flow rate is adjusted to provide an isokinetic sample if desired. As mentioned previously, the collection characteristics of the cyclone are such that even though the sampling system is operating isokinetically, the dust sample collected is not identical with that in the gas stream. Notwithstanding this, it is often desirable to use isokinetic conditions.

By applying a voltage across the cell and monitoring the current flowing through the cell, the filling of the cell can be observed by the increase in current through the cell. When the current levels off, the cell is full and the sampling is stopped. The current is then monitored until it stabilizes.

The resistivity of the sample is calculated from

$$\rho = KR \tag{8}$$

where R is the resistance of the dust layer (ohm) and K is a constant for any particular cell (cm). The constant K is defined by

$$K = \frac{2\pi L}{\ln\,(r_2/r_1)} \tag{9}$$

where

L = length of cell (cm)
r_1 = radius of inner electrode (cm)
r_2 = radius of outer electrode (cm)

The Simon-Carves cyclone resistivity instrument, as described by Cohen and Dickinson[6], is one of the more widely used cyclonic devices. The sample collection and measurement cell is located in a temperature-controlled chamber as shown in Figure 10, external to the duct, with the sample extracted through a sample probe. The sampling line must be thermally controlled to preserve the flue gas condition. The dust sample is compacted into the measurement cell by the action of a vibrator.

A somewhat different design of this device is made to be inserted directly in the flue. The dust is collected and measured while the device is retained in the flue gas environment.

The probe is operated in the following manner: It is inserted into the flue and permitted to come to thermal equilibrium with the flue gas. A sample is then drawn through the apparatus by a pump, and the gas flow measured. Isokinetic sampling can be achieved by adjusting the flow so that the inlet velocity of the gas to the probe and the flue gas velccity are the same. A

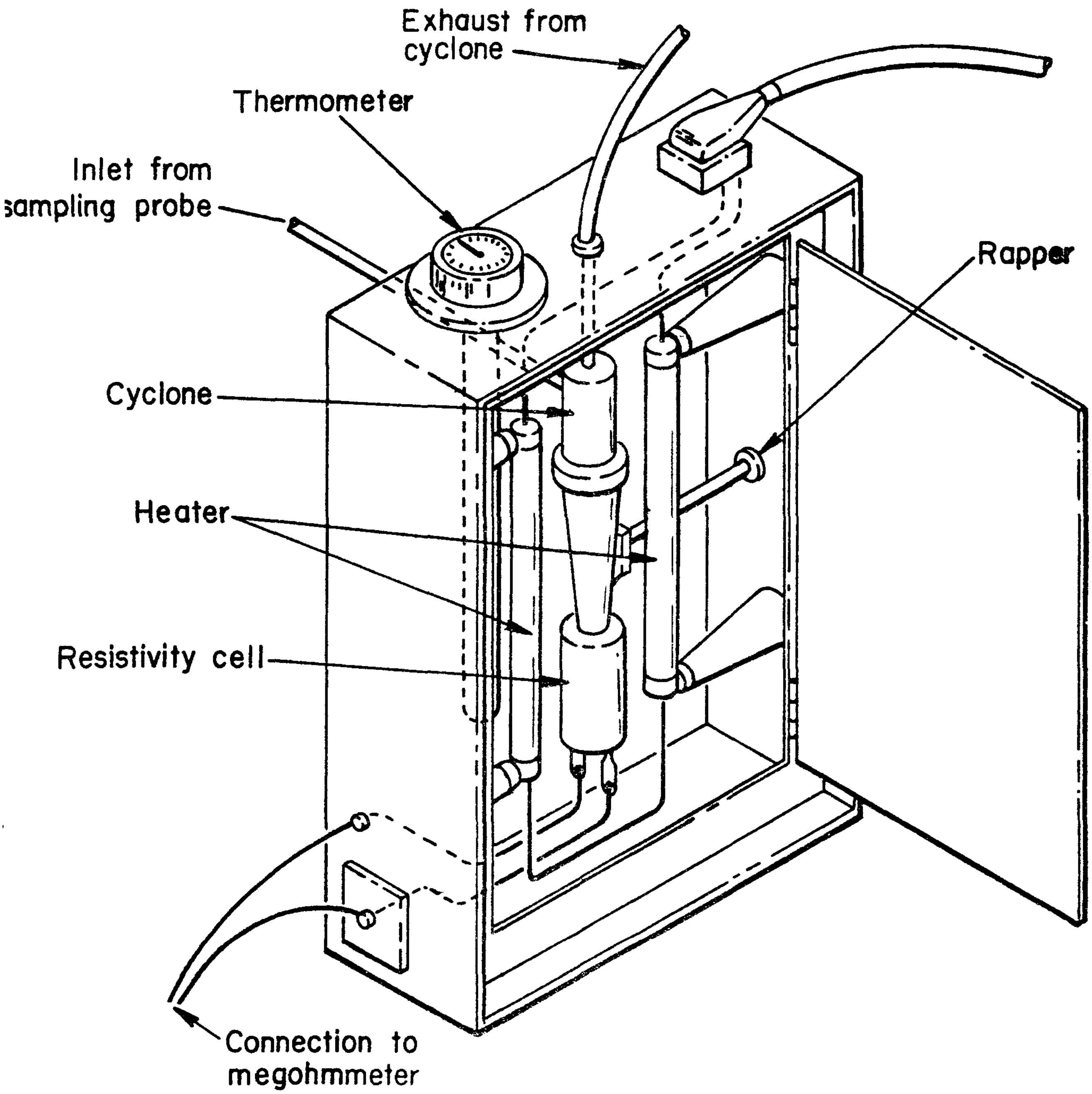

Figure 10. Resistivity apparatus using mechanical cyclone dust collector [from Cohen and Dickinson[6]]

vibrator attached to the probe is used to keep dust from collecting on the walls of the probe and to give uniform compaction. Figure 11 shows a schematic of this instrument.

Advantages:

1. Low voltage instrumentation may be used.
2. Dust layer thickness is fixed by cell geometry.
3. The electric field is easily duplicated from test to test.

Disadvantages:

1. The cylindrical cell yields a non-uniform electric field.
2. The electrical noise is unusually high.
3. It is difficult to determine when the sample cell is full.
4. Compaction of the dust layer is not reproducible.
5. The thermal control of the external model is difficult.
6. The values of resistivity obtained are unrealistically high for electrostatic precipitator applications.
7. Particle size of dust is not representative.
8. The dust layer in the cell is not electrostatically deposited.

Kevatron Electrostatic Precipitator Analyzer

The Kevatron resistivity device[7] is designed to simulate in-situ measurements in an external thermally-controlled cell. The sampling probe is inserted directly into the flue gas for extracting an isokinetic sample. The sampling line leads to a miniature wire-pipe type of electrostatic precipitator, where the particulate material is collected on the surface of the pipe. The collected dust layer is removed from the pipe and deposited in a concentric cylindrical measurement cell by removing the electrical energization and applying an acceleration to the pipe. A schematic drawing of the system is shown in Figure 12.

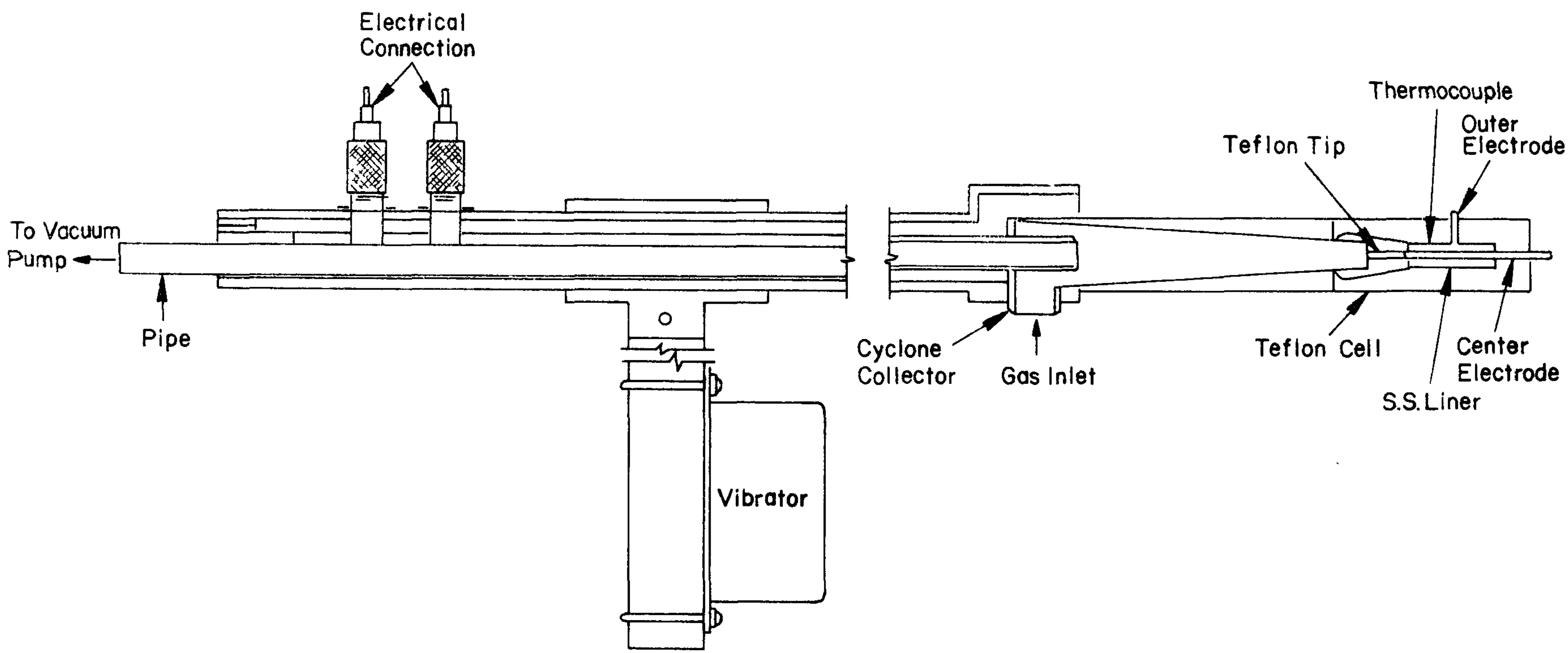

Figure 11. Cyclone probe inserted in duct.

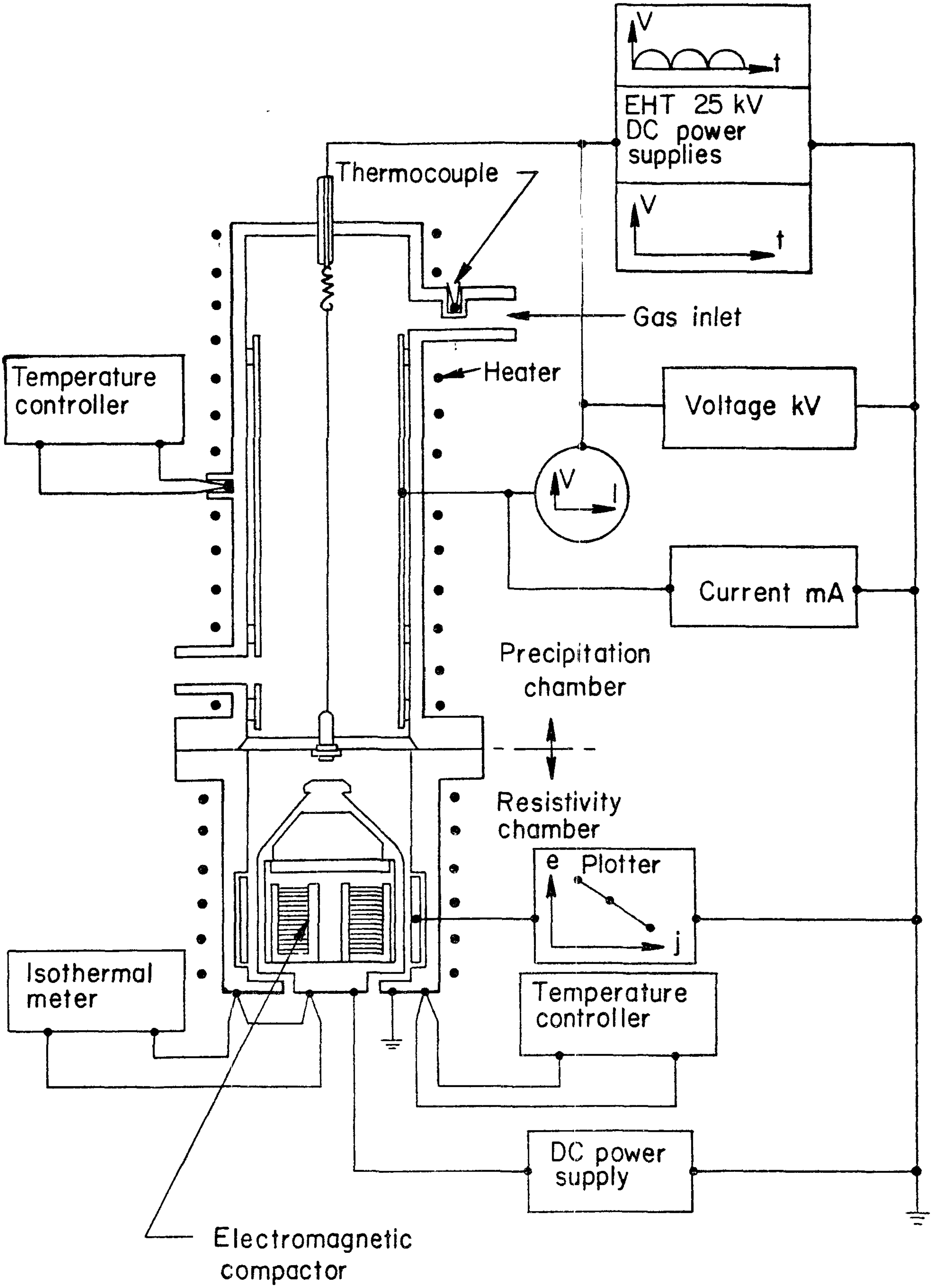

Figure 12. Kevatron resistivity probe [from Tassicker, *et al*[7]]

The particulate is in the flue gas environment throughout the entire measurement period. The flue gas flows through the sampling lines and wire-pipe precipitator and exhausts to the atmosphere. Provisions must be made to preserve the thermal conditions in the flue duct through the sampling line to avoid upsetting the chemical equilibrium conditions in the flue. Without this precaution, a temperature drop in the sampling line may lead to an increased absorption for any naturally occurring conditioning agents such as sulfur trioxide and moisture in the effluent gas stream.

The instrument is designed to internally compute the resistivity of the dust in the measurement cell, when used with the graph paper supplied. The system projects a spot of light on the graph grid, thus eliminating the computation of resistivity that is required for other instruments. The measurement is conducted with applied voltage of 3, 30 or 300 volts across an electrode spacing of 0.2 cm for electric fields of 15, 150 or 1500 volts per centimeter, respectively.

Advantages:

1. The resistivity is internally computed, obviating field calculation.

2. Clean electrode and dust-covered electrode voltage-current curves can be obtained.

3. Some variation in electric field is allowable in the measurement.

Disadvantages:

1. The equipment is very heavy and bulky, difficult for field work.

2. Sampling lines require temperature control.

3. Mirror alignment in resistivity computation is critical.

4. Particle size of the dust is not representative.

5. Density of dust in the cell is not reproducible.

6. Dust is not deposited in the cell electrostatically.

7. Resistivity values can be unreasonably high.

Lurgi Electrostatic Collection Resistivity Device

The Lurgi Apparatebau-Gesellschaft mbh in Frankfurt, West Germany, developed an in-situ resistivity probe described by Eishold,[8] consisting of two corona wire electrodes equally spaced from an interlocking comb arrangement as shown in Figure 13. This device is inserted either directly into the flue duct for in-situ measurements or into a thermally and environmentally controlled chamber for simulated in-situ laboratory measurements.

The dust is collected on the interlocking comb structure by electrostatic forces. The dust layer forms on the surface of the comb structure and fills the region between the two comb segments. After the sample is collected, a potential is applied across the dust layer. The configuration of the cell (the cross-sectional area and spacing between the electrodes) is such that the resistivity of the sample is ten times the measured resistance. This factor of ten is based on neglect of any electrical fringing through the adjacent fly ash. The measurements are made using an ohm-meter without specifying the electric field at which the measurements are made.

COMPARISON OF RESISTIVITY PROBES

The resistivity probes described in Section IV differ primarily in the manner of collection of the dust particles from the gas stream, the manner of dust deposition in the measuring cell, the cell geometry, and the electrical conditions during measurement.

Reiterating from earlier in this report, because of the nature of the collection devices, the size distributions of the particles in the samples are not representative of the size distribution of the dust particles in the duct. Neither the cyclone nor the electrostatic devices are efficient collectors of fine particles, so the particle size distribution in the resistivity sample is biased toward the larger particles. This condition can cause some variation in the results obtained with different devices.

A second difference in the resistivity probes is the manner of depositing the dust in the measuring cell. The point-plane probes and the Lurgi probe deposit the dust electrostatically onto the surface of the measuring cell. Consequently, some alignment of the dust particles occurs and in general the deposited dust layer is more dense than that in the other types of measurement apparatus.

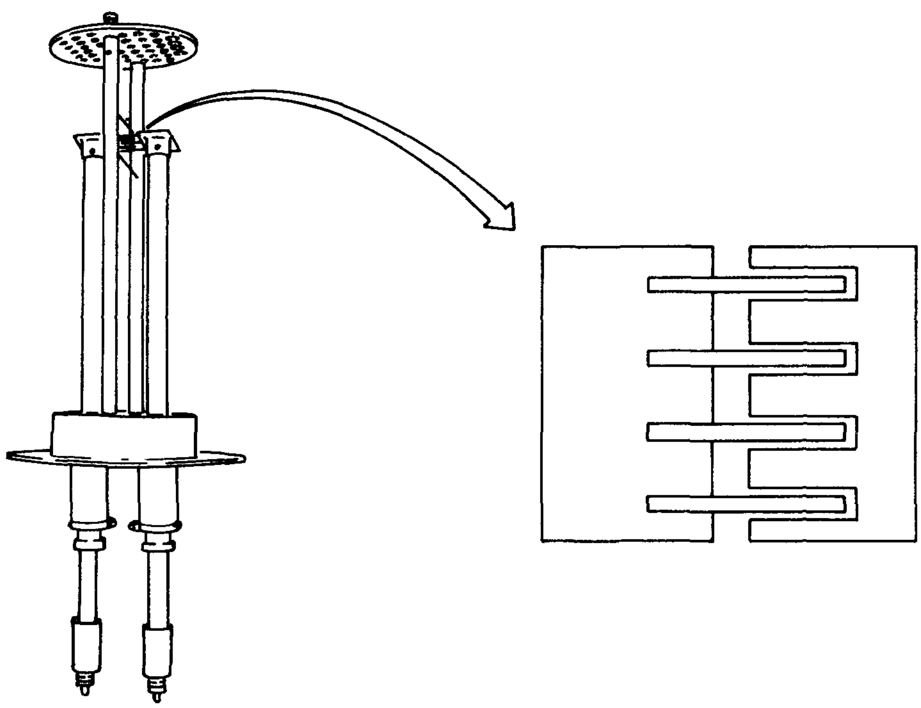

Figure 13. Lurgi in-situ resistivity probe.

The effect of alignment on dust resistivity has not been quantitatively determined. However, variations in density can influence resistivity values by as much as 10-fold, as reported by Cohen and Dickinson.[6]

A third difference in the resistivity probes is the value of the electric field at which resistivity is measured. Standard procedures for the Kevatron and Simon-Carves probes are to measure resistivity at relatively low electric fields. By contrast, the procedure for the point-plane probe is to measure the resistivity at a field near breakdown. As a consequence, the values of resistivity as measured by the different methods vary by as much as a decade due to electric field differences.

The combined effect of these variables is that the resistivity values reported by investigators using different techniques vary widely. Upper values of resistivity measured by a point-plane probe in the vicinity of 10^{12} to 10^{13} ohm-cm have been reported, whereas upper values of 10^{14} to 10^{15} ohm-cm have been reported by other techniques.

There have been no definitive studies to compare results of resistivity measurements by the various devices. However, limited studies have been conducted at electric power generating plants using the in-stack cyclone, Kevatron, and point-plane probes.[9] Resistivity values measured by these probes are compared in Figures 14 and 15. Figure 14 shows the settled-out cyclone data plotted against the point-plane data, using the point-plane data at 2.5 kV/cm, which corresponds to the field in the cyclone apparatus.

Figure 15 shows the peak values of resistivity from the Kevatron and cyclone probes plotted against point-plane data from the same (2.5 kV/cm) field. In this case, much better agreement is obtained between the cyclone and point-plane data. The Kevatron data are still higher than the average of the cyclone or point-plane data, although there are statistically insufficient data to draw firm conclusions regarding the Kevatron values.

The logic of comparing the peak values of resistivity from the cyclone with the point-plane data can be rationalized to some extent by the fact that fresh dust is being deposited on the surface during the precipitation process.

In view of the scatter of the data obtained with any one probe, as noted earlier in Section III, the discrepancies shown in Figures 14 and 15 are not unexpected.

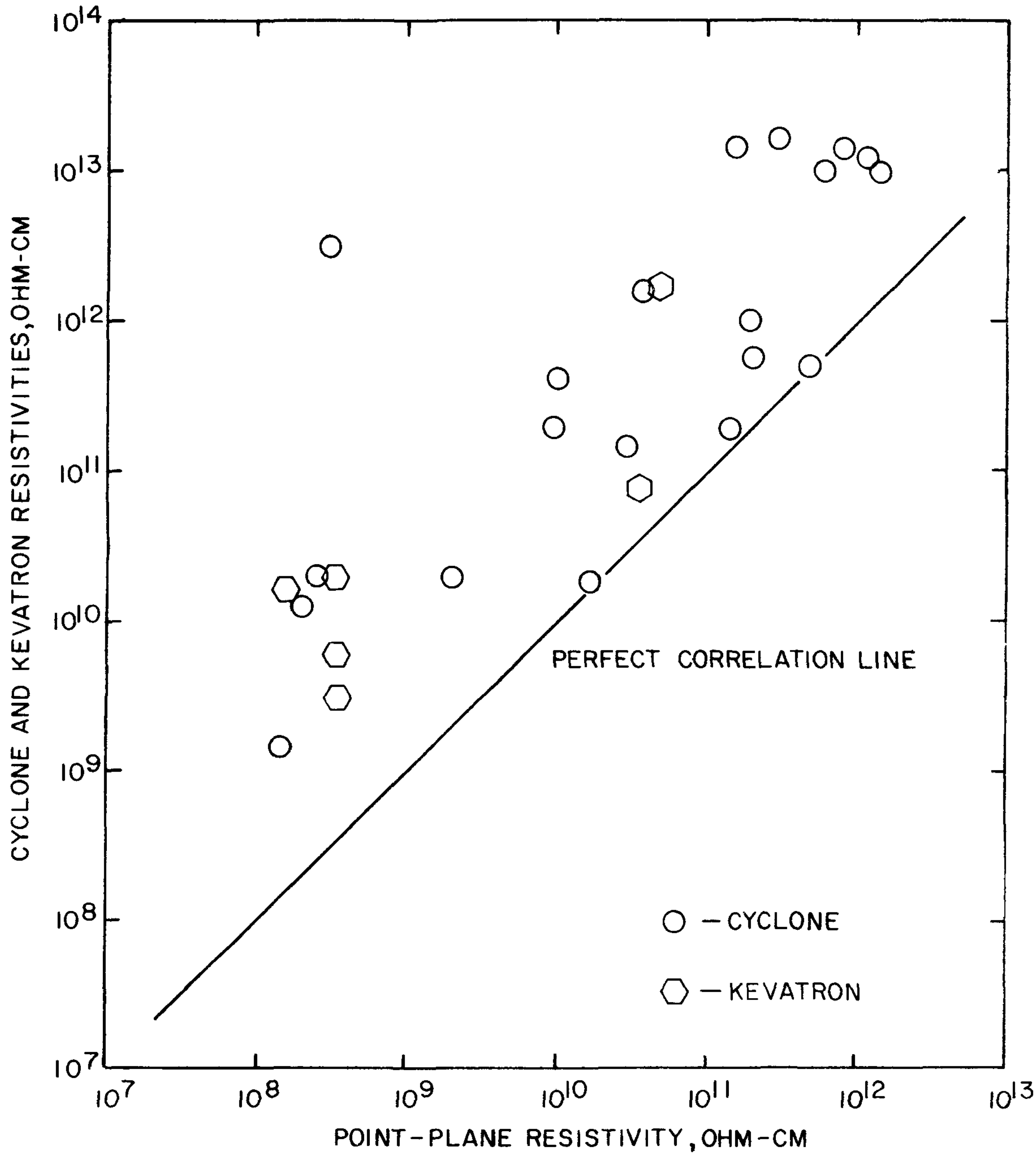

Figure 14. Comparison of Kevatron and cyclone resistivities with point-plane resistivities at an electric field of 2.5 kV/cm. Settled values for cyclone peak values for Kevatron.

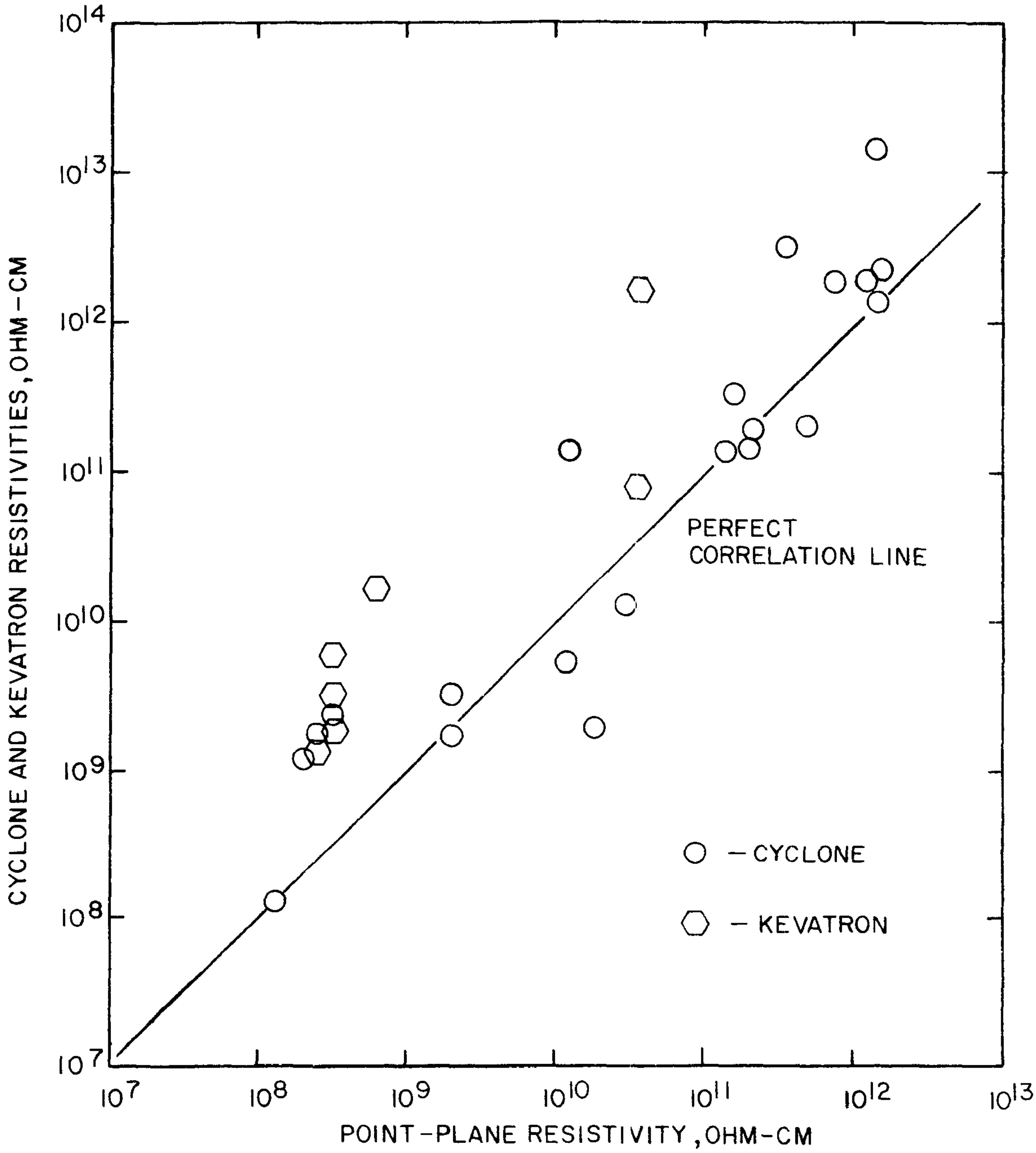

Figure 15. Comparison of Kevatron and cyclone resistivities with point-plane resistivities at an electric field of 2.5 kV/cm. Peak current values used for Cyclone and Kevatron.

PRACTICAL FACTORS IN RESISTIVITY MEASUREMENTS

Selection of Sampling Sites

The first priority in selection of a sampling site is the location of a point in the operating system where the conditions of the gas and the gas-borne dust particles are representative of the environment for which resistivity is being determined. That is, the gas temperature, gas composition, and particle history must be the same as that found, for example, in the precipitator. Usually the inlet of the precipitator is selected as the point for making resistivity measurements. However, sampling at several points across the duct may be required to obtain a representative measurement where there are variations in temperature across the duct. Variations in gas flow velocity and dust loading in the duct must also be taken into account, since these conditions can result in non-representative dust samples with some types of resistivity apparatus.

When selecting a site for the measurements, practical considerations must also be remembered. At the site location, sampling ports must exist or be installed. The normal practice is to use 4-inch pipe for the ports. Electrical power (117-120 VAC, 60 cycle), must be available at the site location for the operation of the measuring equipment. In many locations, adapters will be required for mating of plant electrical outlets with the standard three-prong plugs found on most laboratory equipment.

Determination of Number of Measurements

The determination of the number of individual measurements required to characterize the resistivity of the dust is related to the range of operating conditions anticipated and the variability in the coal. It is desirable when designing a new precipitator installation that the worst operating conditions be covered in the test schedule.

The variability in plant operating conditions that is of the greatest concern is the variation in flue gas temperature throughout the year. The change in the ambient air temperature from winter to summer can cause the flue gas temperature to vary as much as 15°C (30°F) while the temperature variation across the duct downstream from a rotating (Ljundstrom) air heater may be 25°C (50°F). This combined temperature spread may cause a significant variation in the dust resistivity and care must be exercised to assure that the widest variation is covered.

As mentioned in Section III, the day-to-day variations in characteristics of the coal supply may also cause significant variations in the particulate resistivity. This variability will show up as a considerable scatter in the measured value of resistivity over the measurement period. When this variation occurs, it becomes imperative to make a sufficient number of measurements at each temperature to obtain a statistically significant value for the resistivity at each of the ranges of conditions encountered.

The precipitator acts to smooth out short-term variations in particulate resistivity. Dust layers ranging from perhaps one centimeter on the inlet plates to some lower value, perhaps only a millimeter, on the outlet plates build up during several hours of collection time. The average buildup rate on the precipitator plates is on the order of one millimeter per hour, exponentially distributed through the precipitator, such that the dust layer on the plates may represent an averaging of the instantaneous dust conditions of many hours of operation. Therefore, there is a rationale for averaging the measured values of resistivity for each temperature condition to arrive at the resistivity representative of the particular installation.

The determination of how many measurement points are required is therefore based on the variability of the source and the experience of the technician making the measurements. Typically, six to ten measurements at intervals of 10°C (20°F) are sufficient if plant conditions are reasonably constant.

The auxiliary data required when conducting tests on an operating precipitator include:

- coal samples for proximate and ultimate analysis
- flue gas temperature and composition (including concentration of SO_3)
- precipitator voltage-current relationships
- fly ash samples for laboratory analysis.

Safety Precautions

Extreme caution must be exercised when conducting measurements in ducts containing flue gas. Typically, the flue gas at temperatures exceeding 150°C (300°F) will contain a significant quantity of sulfur oxides and fly ash particles. If the access port has been covered for a period of time, significant amounts of fly ash will accumulate in the port. Some ducts will be under a positive pressure of a few inches of water; in others, there exists the probability of "puffing". Therefore, extreme care must be exercised when opening ports and when inserting or extracting probes because of this presence of particulate and sulfur oxides in the gas.

Additional care must be exercised when utilizing resistivity probes with high voltages. Sufficient electrical grounds must be attached prior to handling any probe connected to an electrical supply.

A shock hazard also exists when inserting or extracting any ungrounded probe. An ungrounded probe inserted into a particulate-laden gas stream may become electrically charged by a triboelectric mechanism. Therefore, probes should be grounded prior to insertion into a flue duct.

A hazard also exists because of the location of the sampling ports. Often, the ports were installed after the construction of the plant at locations remote from standard walkways. All scaffolds and walkways should be tested prior to use and all hazards that can be reasonably detected should be corrected.

SECTION V
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TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-650/2-74-079	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE Techniques for Measuring Fly Ash Resistivity		5. REPORT DATE August 1974
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Grady B. Nichols		8. PERFORMING ORGANIZATION REPORT NO. SORI-EAS-75-366 3134-XIV
9. PERFORMING ORGANIZATION NAME AND ADDRESS Southern Research Institute 2000 Ninth Avenue South Birmingham, Alabama 35205		10. PROGRAM ELEMENT NO. 1AB012; ROAP 21ADJ-029
		11. CONTRACT/GRANT NO. 68-02-1303
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development NERC-RTP, Control Systems Laboratory Research Triangle Park, NC 27711		13. TYPE OF REPORT AND PERIOD COVERED Final
		14. SPONSORING AGENCY CODE
15. SUPPLEMENTARY NOTES		

16. ABSTRACT

The report summarizes significant factors related to the measurement of electrical resistivity of the particulate matter suspended in a gas stream. It describes some of the mechanisms of electrical conduction in fly ash from coal combustion as it influences resistivity and its measurement. The report also reviews techniques for measuring resistivity and the problems associated with each. It presents some data comparing the values of resistivity obtained by different techniques.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution	Air Pollution Control	13B
Measurement	Stationary Sources	14B
Electrical Resistivity	Particulates	
	Gas Stream	20C
Fly Ash		21B
Coal		21D
Combustion		

18. DISTRIBUTION STATEMENT Unlimited	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 49
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (9-73)