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FLY-ASH RESISTIVITY - ITS MEASUREMENT
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Bruce W. Wilkinson
Major professor

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FLY-ASH RESISTIVITY--ITS MEASUREMENT AND CORRECT INTERPRETATION

By

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ABSTRACT

FLY-ASH RESISTIVITY--ITS MEASUREMENT AND CORRECT INTERPRETATION

By

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Existing literature on the problem of high electrical resistivity of coal fly-ash is surveyed. A 'Point-to-Plane' resistivity probe is fabricated and the two techniques for the measurement of resistivity with this probe are employed. Experiments are conducted over a couple of months' duration at two power plant sites. An attempt is made to resolve some of the prevailing ambiguities concerning the appropriateness of the reported critical ash resistivity. The phenomenon of 'incipient' sparking is postulated to help overcome the non-uniqueness of the experimentally observed 'critical' sparkover point. The 'Point-Plane' technique involving the measurement of 'Clean Plate' and 'Dust-laden Plate' voltage-current characteristics is found to be more accurate and representative than the 'Disc-Plane' technique in which no corona current is used during measurement. Finally a concise manual for the operation of the SRI resistivity probe is included.

ACKNOWLEDGMENTS

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Expressions of gratitude are also extended to Mr. Leo Szafranski and Mr. Don Childs of the Engineering Shop; to the authorities of Power Plant 65 at Michigan State University and the Lansing Board of Water and Light, Lansing, Michigan; and last but not the least, to Dr. M. L. Davis of Civil Engineering.

A.S.

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I. INTRODUCTION

Fly-ash is the generic term given to that portion of coal which is incombustible and which is light enough to be entrained in the hot combustion gases. It may constitute as much as 5 to 12% of most coals and as such the removal of fly-ash from stack gases before the latter are vented off into the atmosphere is a major environmental problem. Ironically enough, as the thirst of this materialistic world continues unabated, coal is burned in ever-increasing amounts, and the significance of 'high-efficiency' gas cleaning equipment has to keep pace with this trend. Today, in terms of the volume of gas cleaned and the mass of particles collected, the 'Electrostatic Precipitator' (ESP) has the widest application and this is expected to continue at least into the near future. To fulfill present day 'air-quality' requirements the ESP is expected to meet efficiency levels of 99 plus %, i.e., over 99% of the particulates in the ash-laden gas stream is to be efficiently collected and rendered harmless from polluting the environment. Quite naturally, to maintain such high quality standards, the factors affecting the precipitator efficiency are of particular interest.

Experience and, to some extent, indirect theoretical evidence have shown that of the many factors influencing this efficiency the fly-ash, particulate electrical 'resistivity' is one of the most common causes of poor electrical precipitation.[1] Many researchers working with coal fly-ash have measured its resistivity and reported it in literature. The techniques and the measuring devices vary. As described later, owing to the poor reproducibility of precipitator fly-ash characteristics under laboratory conditions, 'in-situ' resistivity measurements become imperative. Among the many resistivity devices[2] commonly employed for 'in-situ' resistivity measurement are (a) Point-to-plane probe, (b) Cyclone resistivity probes, (c) Kevatron analyser, and (d) Lurgi resistivity device, etc. Of these, it is claimed by many[2] (at least in the U.S.) that the 'Point-to-Plane' resistivity apparatus is best suited for representative and convenient 'in-situ' resistivity measurements. Two techniques are presently employed with the 'Point-to-Plane' probe. In either technique varying voltages are impressed upon an electrostatically deposited fly-ash layer and the voltage-current readings recorded. It has been observed that the measured resistivity of a compacted layer of high-resistivity particulates decreases as the magnitude of the measuring electric field increases and the reason for this is postulated[8] as arising from the particulate nature of the layer. High electric fields are generated in the vicinity of the contact spots between the particles. This reduces the bulk resistivity of the bed. Also in addition to the flow of charges through the particles themselves charges can now be transferred across the small air-gaps near the contact spots, thus increasing their effective area and reducing the effective resistivity of the layer.[8] The value of the resistivity most commonly quoted is the one calculated just prior to 'total sparkover,' i.e. the point of electrical breakdown of the dust layer whose resistivity is being measured.

The primary objective of this research work was to fabricate a 'point-to-plane' resistivity probe and to apply the two existing techniques* toward measuring the resistivity of power-plant fly-ash. The Michigan State University Power Plant 65 was the first experimental site and later the experiments were extended to the Eckert Power Plant of the Lansing Board of Water and Light, Lansing, Michigan. It was intended to obtain reproducible and dependable results with the Southern Research Institute (SRI) probe and subsequently to prepare an operating manual for future use.

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*Viz., the 'Point-Plane' (P.P.) technique and the 'Disc-Plane' (D.P.) technique.

As the research progressed certain additional objectives came to light. In spite of both the techniques being capable of yielding the resistivity, it was felt that one of them was far superior, both in theory and practice, over the other. Also, it was realized that the common practice of reporting the ash resistivity just prior to sparkover was, in reality, beset with some ambiguities both due to the very nature of the sparking phenomenon and the experimenter's biased judgment. Consequently, the electrical phenomena at and around sparkover was felt in need of investigation and a criterion yielding a more dependable resistivity backed up both by theory and experimental evidence was to be looked for.

Given that fly-ash resistivity is a complex function of such varied properties as coal composition, gas temperature, humidity, applied electric field, etc., the purpose of this research work is less to explore the existence of new theories or methods of its measurement and more to sieve the abundant but scattered existing information on resistivity measurement and to develop a reproducible algorithm of reporting representative ash resistivity in a working precipitator.

II. REVIEW OF THEORY AND PREVIOUS WORK

The field of electrostatic precipitation is at least as old as this century and there exists an extensive amount of literature on the problem of fly-ash resistivity alone. A brief description of the operation of an ESP and the undesirable phenomena arising due to high ash resistivities is given below.

A typical Electrostatic Precipitator consists of parallel plates spaced 8 to 12 inches apart and between which are suspended corona wires at suitable intervals (Figure 1). Very high voltages of the order of 60 - 80 kv are impressed between the wire and plate electrodes. A unipolar, stable, self-maintaining gas discharge (corona) between the emitting wire electrode and the receiving plate electrode is initiated due to such high field intensities. In theory both negative and positive corona are possible but in practice the negative corona is predominantly used as (a) it is stable and (b) it permits about twice the magnitude of the allowable 'collection' voltage (prior to an electrical breakdown) obtainable with a positive corona.[7]

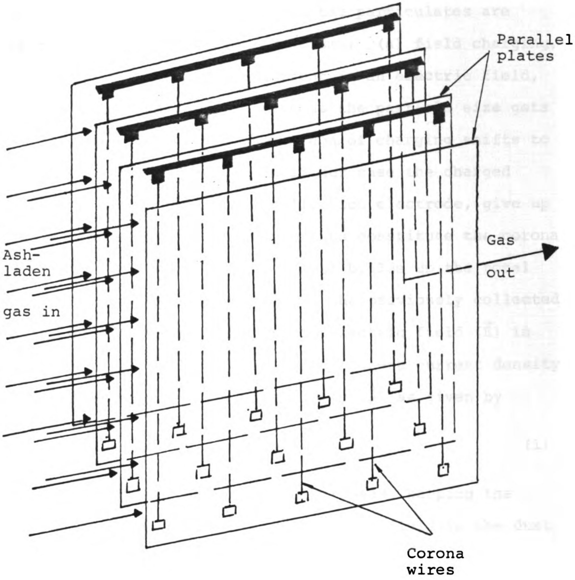

Figure 1.--Simple illustration of conventional single-stage, dry electrode, parallel-plate electrostatic precipitator with suspended corona wires.

Hot combustion gases laden with fly ash pass in between the parallel plates and the particulates are charged by either of two mechanisms: (a) field charging, i.e. charging by an ionic current in an electric field, (b) diffusion charging wherein as the particle size gets smaller and smaller the phenomenon of charging shifts to one of ionic diffusion.* In either case the charged particles drift toward the collection electrode, give up their charge on deposition and thus constitute the corona current. As the particulate layer builds up the total corona current now flows through the previously collected dust layer. This establishes an electric field ($\vec{E}$) in the dust layer proportional to the corona current density ($\vec{j}$) and the particulate resistivity ($\vec{\rho}$) as given by

$$\vec{E} = \vec{j}\vec{\rho} \tag{1}$$

As the resistivity is increased, keeping the current density constant, the electric field in the dust layer increases proportionately (Equation 1). When the electrical field exceeds the field strength for electrical breakdown or corona initiation within the dust layer one of two phenomena, depending on the ash resistivity,

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*i.e., the particles are no more charged by virtue of lying in the path of ions traveling along lines of electric intensity but by ions diffusing haphazardly in the gas stream.

is likely to occur. If the resistivity is moderately high (~ 10^{11} ohm-cm) this breakdown may propagate across the entire air gap and thus cause a spark. This sparking occurs at lower current densities and, unlike some suggestions,[2] it occurs at an applied voltage lower than that required for sparking between clean electrodes. As early as 1918 Walcott,[3] in his studies on the effects of solid and powdered dielectrics on the sparkover voltage, had observed that a layer of porous or fibrous material on the plate electrode lowers the sparking voltage by up to 50% for the negative corona but has little effect on positive corona. Frank[4] in 1933 confirmed Walcott's observations and established for the first time a quantitative relationship between dust resistivity and reduction of sparkover voltage.* On the other hand if the resistivity is very high (~ 10^{12} ohm-cm) breakdown will occur at a voltage too low to propagate a spark across the inter-electrode space.** The dust layer will be

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*In many of the experiments conducted, however, the sparkover point (observed as a sudden surge in the corona current on a current meter) corresponded to an applied voltage greater than that required for sparking between clean electrodes. As pointed out later (under Discussion) among other factors this could be attributed to an inability to record the first few sparks that occur at a lower voltage. The 'incipient' spark point (shown in Figure 2) whose existence and characteristics are to be discussed shortly provides a possible explanation for this 'strange' behavior.

**In other words at lower resistivities (~ 10^{11} ohm-cm) the field breakdown strength of the air gap is continuously broken down electrically and will emit ions of an opposite polarity from that produced by the corona into the interelectrode region, thus initiating the phenomenon of 'back corona'[2] (Figure 2). In either of the above two cases (excessive sparking or back corona formation), the allowable collection voltage and therefore the efficiency of collection in the ESP is appreciably lowered due to the high resistive dust.

From the above discussion it is then abundantly clear that the accurate measurement of the fly-ash resistivity as seen by the ESP is an important factor in estimating the performance of a precipitator. In the following paragraphs a brief outline of the two types of conduction mechanisms and the various factors that affect them in experimental practice is given. For a more detailed and systematic description refer to the Southern Research Institute (SRI) report entitled "Techniques for Measuring Fly Ash Resistivity."[2]

Conduction Mechanisms

When a plot of resistivity on a logarithmic scale vs. the inverse of the absolute temperature is made a

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likely to be reached before that of the dust layer and at higher resistivities of the dust layer ($\sim 10^{12}$ ohm-cm) this trend is reversed and the layer breaks down first. However it is inconceivable of the two phenomena existing independently and a certain amount of overlap of sparkover and back corona is to be expected.

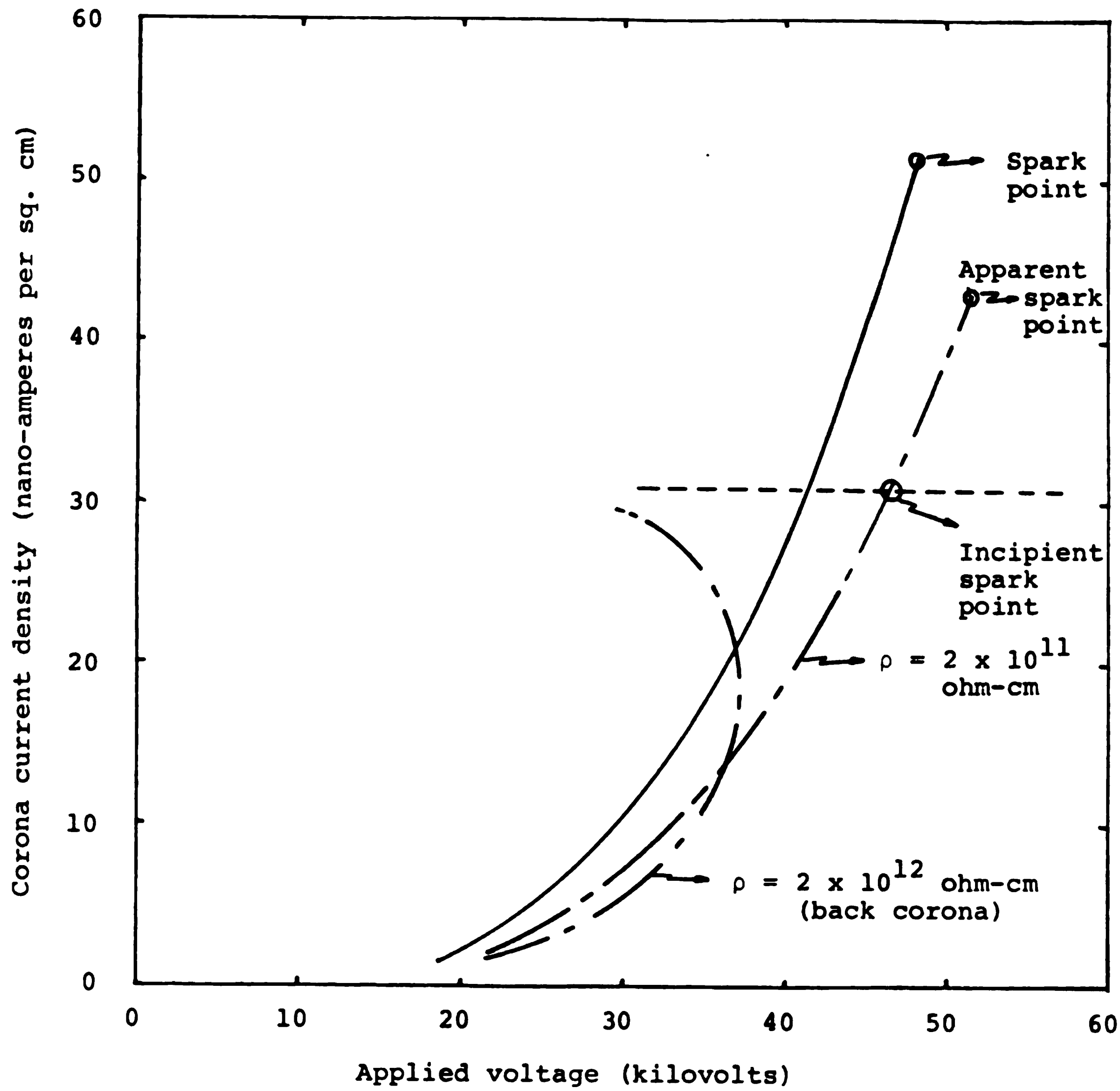

Figure 2.--Voltage vs. current for a precipitator with 23 cm plate spacing and 0.29 cm corona wire. Solid curve is for clean plate electrode. The two dashed curves represent conditions for a 0.5 cm layer of dust with the resistivities indicated (adapted from Figure 1 of reference 2).

curve such as in Figure 3 is obtained.[6] The negative sloped straight line in the high temperature region (above ~ 400°F) corresponds to 'volume' resistivity. The positive sloped gradual curve in the low temperature region (up to ~ 300°F) corresponds to 'surface' resistivity and the region in between is a combination of both. Once the fly-ash particulates are collected on the grounded plates they discharge themselves by one or a combination of both (more generally) of the possible conduction mechanisms.

1. Volume conduction involves the movement of electrical charges through the interior of the particles. This has been demonstrated[5] as being dependent on an ionic conduction mechanism in which the alkali metal ions, especially sodium, serve as the principal charge carriers. It has been shown that for a given ash chemistry the volume resistivity is a function of the ash layer porosity, field strength and temperature.[6] In short, volume resistivity increases with porosity and decreases with both field strength and temperature.

2. Surface conduction involves the movement of electrical charges through the surface moisture and chemical films adsorbed on the particles. The mechanism of charge transport is generally accepted[7] to be electrolytic or ionic depending principally on the physical and chemical adsorption of certain species

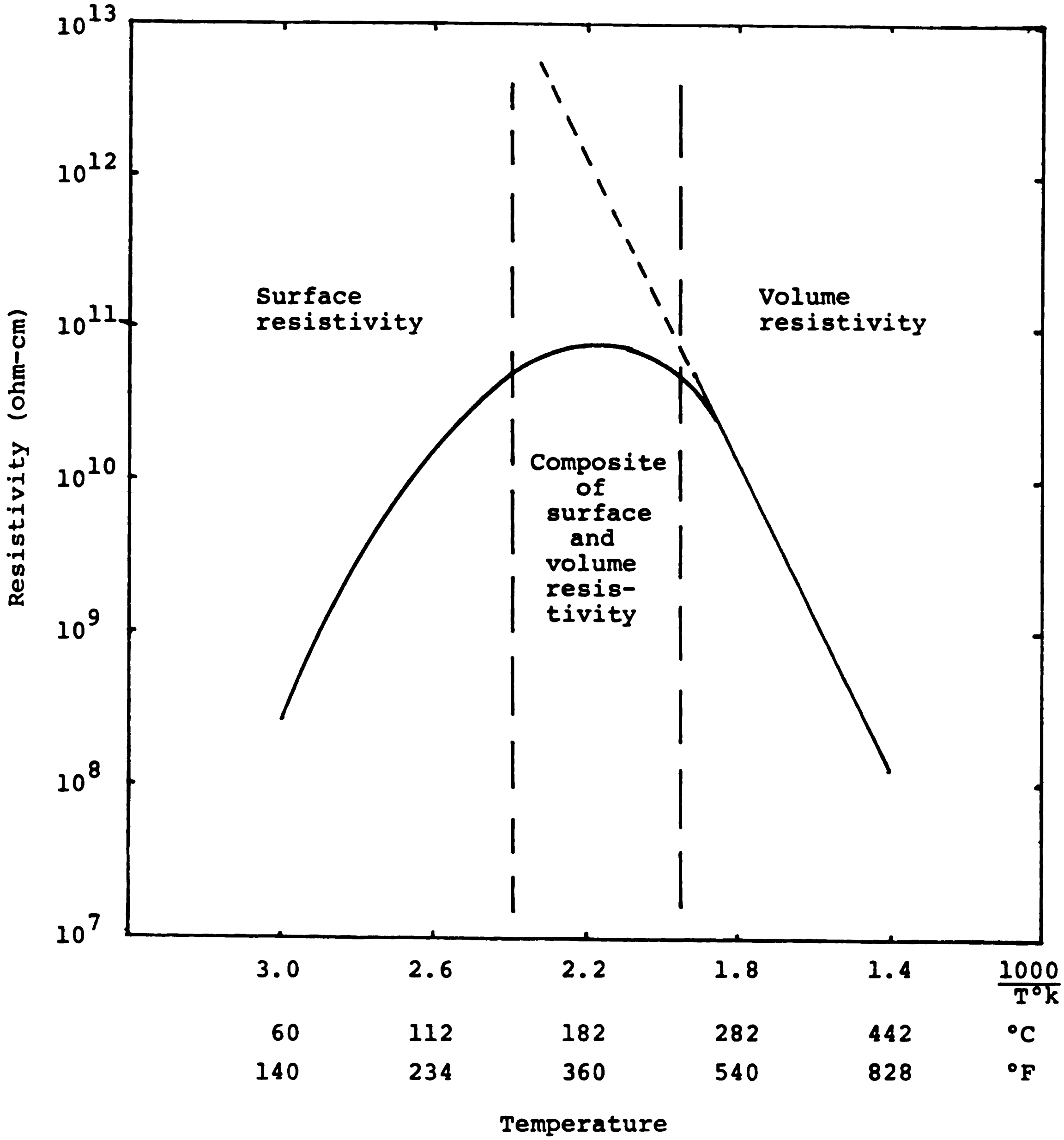

Figure 3.--Typical resistivity data as a function of reciprocal absolute temperature (from Figure 1 of reference 6).

(notably moisture, sulphur oxides, ammonia, etc.) on the ash surface to produce a conducting film. For ashes with similar size distribution, compaction and chemical composition, the surface conduction is mainly a function of the interaction between the ash and its environment (the temperature and the concentrations of gaseous and condensed phases in contact with the ash[6]).

In an attempt to lower the resistivity of many high resistive dusts several approaches have been undertaken. The most important among these are (1) surface conditioning agents and (2) hot precipitators.

When the flue gas temperature is such (< 300-350°F) that surface conduction is predominant, the addition of certain 'conditioning' reagents to the coal fly ash is known to decrease the ash-resistivity. Water is a primary conditioning agent and SO_3 (or H_2SO_4) is the most widely used among the secondary reagents. The primary reagent is bound to the ash particulate by the secondary reagent.* High sulphur coals have (in general) been observed to have lower resistivities than low-sulphur coals[12] although this statement has been challenged by

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*Adsorption of moisture films on chemically inert surfaces is by physical or Van der Waals forces only, and therefore rather weak. Interposition of a chemical binder, which is strongly adsorbed on the surface and in turn strongly adsorbs moisture, results in much greater binding forces and more efective conditioning.[7]

recent Australian experience.[13] Recent discoveries have shown that the presence of sodium in the ash in amounts greater than about 1.5 to 2.0% as Na_2O [12] contributes greatly to reducing ash resistivity. The sodium may be naturally present in the coal or artificially added as Na_2CO_3, Na_2SO_4, NaCl, etc. There is evidence that water vapors and SO_3 in the flue gas attack the glassy surfaces of fly ash particles and thereby release alkali ions for surface migration.[6]

The alternative approach to combat high resistivity problems is to use 'hot' or high temperature precipitators. The latter operate in the range of 600° to 800°F (typically located preceding the air preheaters) where dust resistivity is usually below critical values.[12] Volume conduction prevails and the increased conductivity at higher temperatures does not depend significantly on gas properties. Besides lower resistivities other advantages include elimination of corrosion and hopper plugging problems, better electrical stability and higher corona currents. However, serious disadvantages are encountered. Among these are: over 50% increase of volumetric gas flows; substantially reduced sparkover and hence operating voltages; increased gas viscosity (resulting in lowered precipitation rates); and other structural and mechanical problems.[12]

Factors Affecting the Measurement of Resistivity

Some of the important factors that influence the value of the measured resistivity are listed below.[2]

Particle Size Distribution

It has been shown that smaller size fractions (and therefore lower porosity beds) have lower resistivities.[6] The collection of a sample dust layer that is representative of the precipitator fly ash is difficult to achieve with existing resistivity probe designs.

Source Fluctuations

The inevitable variations in the chemical composition of the coal burned are reflected in the measurements of resistivity and thus can only be remedied by conducting measurements over a long period of time and averaging the results obtained.

Electric Field

As mentioned earlier both surface and volume resistivity decrease with electric field and hence it is important that the resistivity is reported at field strengths comparable with those existing in an electrostatic precipitator.

Mode of Dust Layer Deposition

The degree of dust compaction is believed to influence the resistivity of the ash bed[9] though this has not been quantitatively established. It is desirable that the collection of particulates in a measuring probe be brought about by an electrostatic deposition similar to that in an ESP.

Duration of Collection

It is believed that the resistivity of the bed will usually increase with the time for which the voltage is applied.[8] This effect is more prominent when the charge carriers in the resistive bed are ionic.

Techniques of Measuring Resistivity

In practice resistivity is computed indirectly from voltage-current relationships or in other words from the resistance of a sample of a known geometrical configuration. Irrespective of the geometry the resistivity-resistance relationship is given by

$$\rho = RA/\ell$$

where ρ = resistivity (ohm-cm)

R = resistance (ohm)

A = area of cross section (cm^2)

ℓ = thickness of sample (cm)

The choice of whether a laboratory or an in-situ resistivity measurement is to be made depends on whether volume or surface conduction is the dominant mode. If the temperature is very high (> 200°C) or in the absence of any reactive or condensable material (H_2O, SO_3, etc.) volume conduction prevails and laboratory measurements are justified. However if the temperature is low or if an adsorbed surface layer does exist, as is normally the case, in situ measurements become imperative. In addition, it is believed[2] that in spite of being able to duplicate effluent gas stream compositions in the laboratory, the time expended in collecting, cooling and transporting a sample from the field to the laboratory is more than likely sufficient to promote chemical changes in the surface properties of the ash.

Several resistivity measuring devices exist differing fundamentally in the method of sample collection, mode of sample deposition in the measuring cell, compaction of the collected bed, intensity of field applied and method of maintaining thermal equilibrium. A more detailed description of these different measuring instruments is given by G. B. Nichols.[2] In the author's opinion, as well as in the opinion of many, the 'Point-Plane' resistivity probe, used in the U.S. since the early 1940s,[7] comes the closest in reproducing the resistivity as seen by a precipitator.

Figure 4 corresponds to the 'Point-to-Plane' resistivity probe used by the author.[11] This Southern Research Institute (SRI) probe was fabricated in the Michigan State University (MSU) Engineering Shop from the SRI drawings and its details of construction, maintenance, precautionary measures and step by step operation are listed in Appendix I. The probe is inserted into a dust laden gas stream and allowed to reach thermal equilibrium. A high voltage of the order of 8-20 kv is applied between the corona point and the grounded plate, the point plane spacing being anywhere from ½ to 1½". At such high fields a corona current is initiated and the particulates in the dust-laden stream flowing through the point plane gap are charged either by the ions or free electrons emanating from the corona in a manner similar to that in an ESP.

The charged particulates drift towards the grounded plane due to the applied field and transfer their charge to the electrode by either of the two conduction mechanisms described before. Two major techniques have been employed at present to measure the resistivity of the precipitated dust layer.

In the 'Point-Plane' technique, to start with, the 'Voltage-Current' relationship for the 'clean' plate (the case with no particulate deposition) is obtained.

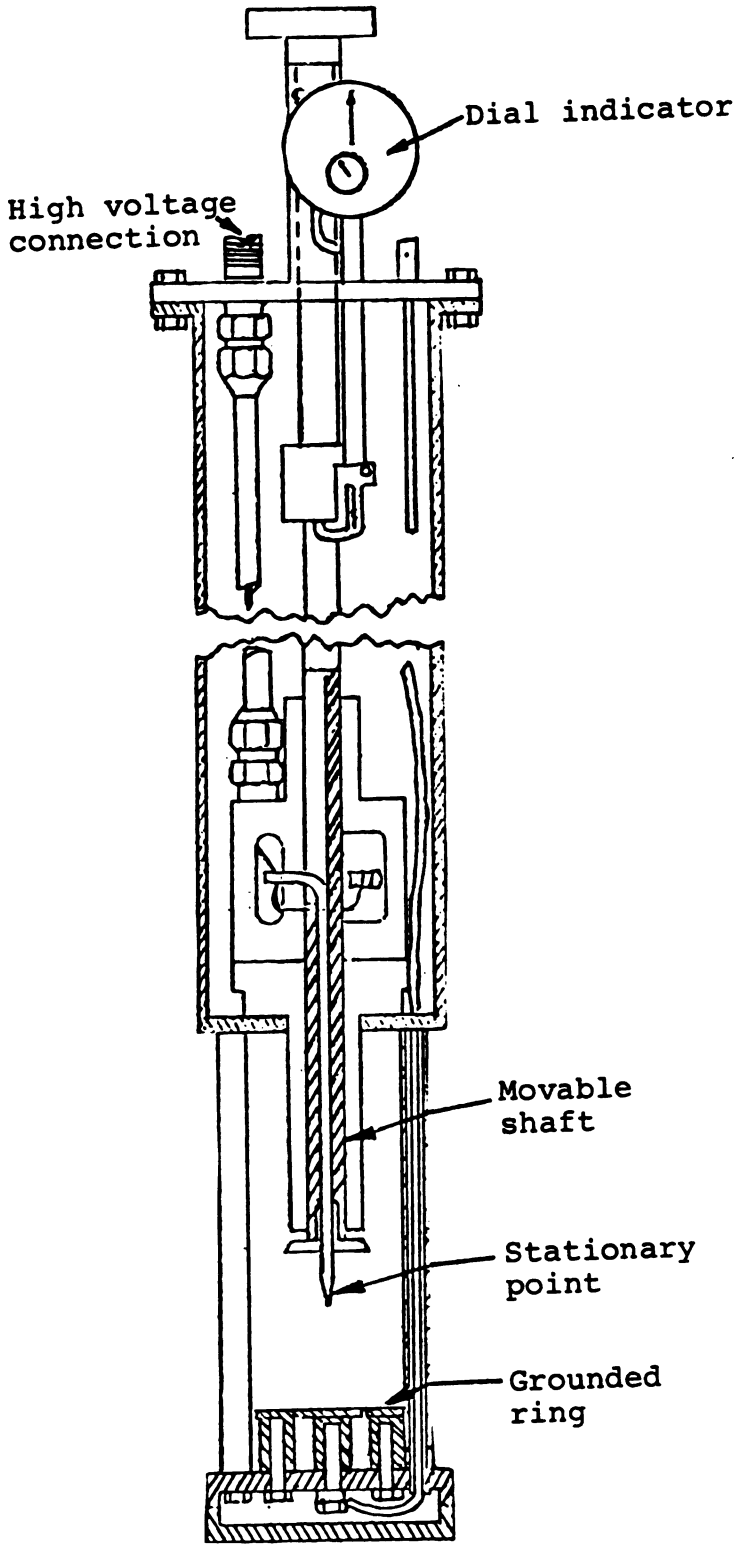

Figure 4.--Point-to-plane resistivity probe.[11]

Next a dust layer is collected over a suitable interval of time and then the 'dirty' (or dust-laden) plate V-I characteristics are obtained. Typical V-I curves for the 'clean' and 'dirty' plate conditions are shown in Figure 5. ΔV corresponds to the voltage drop across the dust layer for a certain corona current I. The clean and dirty plate 'spark' points shown are those observed by experiment.

To obtain the dust thickness ℓ a sliding disc of the same cross-sectional area as the grounded plate is lowered onto the dust layer and the thickness carefully measured by a sensitive screw micrometer. In the 'Disc-Plane' technique no 'clean' or 'dirty' plate characteristics are necessary. After collection of a suitable dust thickness the disc is lowered to measure the dust thickness and increasing voltages are then applied to the layer. The current-voltage characteristics obtained are recorded until the dust layer breaks down electrically and sparking occurs.

Given a dust layer of thickness ℓ, across which is applied a voltage drop ΔV and through which passes a corona current of magnitude I, the bulk dust resistivity ρ_b is given by

$$\rho_b = \frac{\Delta V \times A}{I \times \ell}$$

where A is the area of the collection surface.

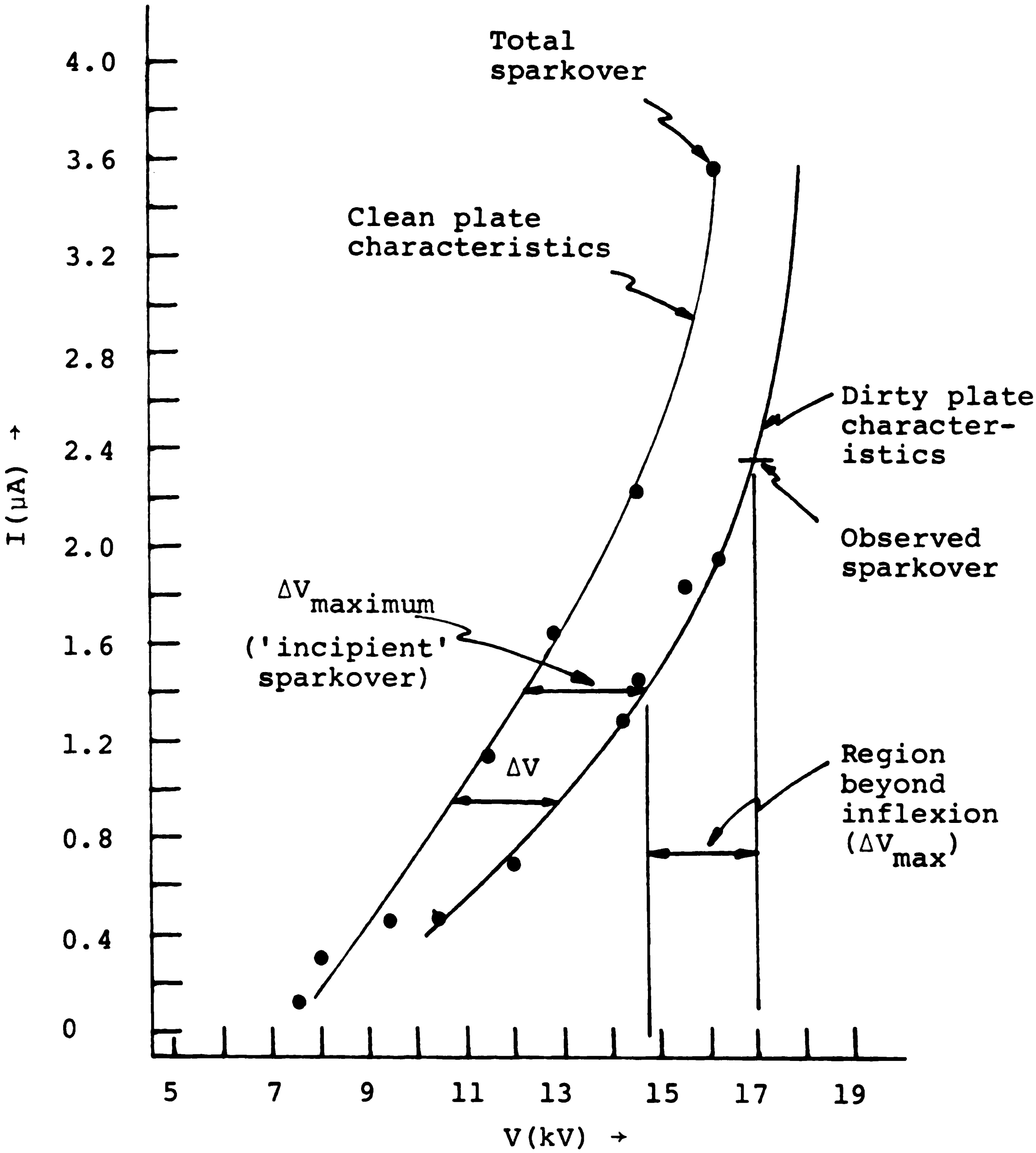

Figure 5.--Plot showing the voltage-current characteristics of clean and dirty plates (data corresponding to 4/10/78).

As pointed out in the Introduction, ρ_b is a function of the voltage drop across the dust layer, ΔV, and due to the particulate nature of this dust layer,[8] decreases continuously with increasing ΔV.

In both the techniques it is common practice to report the resistivity just prior to sparking. From experience it is known that it is exactly at such a condition when resistivity causes the most problems in a working precipitator. Listed below are some of the advantages and disadvantages[2] of using a Point-Plane resistivity measurement device for in-situ measurements.

Advantages

1. The mechanism of particulate collection is very similar to the one observed in an Electrostatic Precipitator.
2. The dust-gas and dust-electrode interfaces are the same as those found in an ESP.
3. The electric field and corona current densities during measurement are comparable to those in a precipitator.
4. Flue gas properties are maintained.
5. Two techniques can be simultaneously employed providing for double checking.

6. The dust layer is virtually undisturbed during measurement.

Disadvantages

1. Dust layer thickness measurement is difficult and liable to be inaccurate.* Also there is no means of checking the integrity of the dust layer during measurement.
2. Very high voltages are required for collection.
3. Time for each experimental run is too long (> 1 hr)
4. Particle size distribution of ash layer deposited is not representative of that in the flue gas.
5. Sample size is too small and due to other irregular experimental conditions considerable scatter in results is to be expected. Measurements in a series of runs have therefore to be made to yield some average value.
6. Experienced personnel are required to conduct the tests.
7. Carbon in ash can obstruct proper measurements especially in those by the 'Disc-Plane' method.

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*Check 'Sources of Error.'

Measures to minimize some of the above disadvantages are discussed under 'Sources of Error and Recommendations' and also in the 'Step-by-Step' operating guideline laid out in Appendix I-D. A computer program designed to search for a unique point at which resistivity may be reported (thus eliminating the dependance of the results on the experimenter's keen observation) is included in Appendix II-A.

III. EXPERIMENTATION

The entire experimental program was carried out in three distinct phases.

Phase I:

Location: Power Plant 65, Michigan State University; inlet port to ESP, Boiler No. 3.

Duration: January and February of 1978.

Special Comments: Only the 'Disc-Plane' method was used as the author and his colleague were unaware of the 'Point-Plane' technique during this time.

Phase II:

Location: Eckert Plant of the Board of Water and Light, Lansing, Michigan; inlet port of ESP, Boiler Nos. 4 and 6.

Duration: April and May of 1978.

Special Comments: Both the techniques were used during the first half but later the 'Disc-Plane' technique was dropped owing to a number of reasons listed under the topic of 'Discussion of Experimental Technique.'

Phase III:

Location: Power Plant 65, Michigan State University; inlet port to ESP, Boiler No. 3 and 'model ESP inlet.'

Duration: August and September 1978.

Special Comments: Only the 'Point-Plane' technique was employed.

Discussion of Experimental Technique

Appendix I-C contains a schematic diagram of the experimental set up (Figure 9) and Appendix I-D includes a step-by-step guideline for the experimental procedure. In brief, a high voltage (8-16 kv) is applied across the point-plane gap in the resistivity probe. As in an ESP, the particulates in the gas stream are charged and precipitated onto the ground plane. Once a substantial layer of dust (.5 ~ 1 mm) accumulates, the collection is stopped. Next the Voltage-Current characteristics (with the dust layer behaving as a dielectric) for both the 'Point-Plane' (P.P.) and 'Disc-Plane' (D.P.) techniques are recorded till a spark is observed on the current meter. The collection voltage, time of collection, temperature of dust layer (initial and final), and other essential information (date, point-plane distance, etc.) are also recorded. The dust layer thickness is measured from the initial and final micrometer dial readings.

Having obtained the required data for the measurement of resistivity by both the techniques we now arrive at the crux of this research endeavor viz., the correct interpretation of this data towards reporting a relevant, reproducible and unique fly-ash resistivity.

As mentioned earlier the resistivity reported by the 'D.P.' technique is given simply as

$$\rho_B = \frac{V}{i} \times \frac{A}{\ell}$$

where V and i are the last values of the applied voltage and measured current, respectively, that could be registered before 'sparking.' The current here is not from a corona point but due to a flow of electrons through a bed of resistive particulates under the influence of an applied field.

In the 'P.P.' technique the voltage-current (V-I) relationships are obtained and plotted as in Figure 5, both for the 'clean' plate and the 'dirty' or dust-coated plate conditions. The ΔV for a finite current value i (Figure 5) corresponds to that part of the total applied voltage which is applied across the dust layer. As in the 'D.P.' technique the resistivity of the bed is given by

$$\rho_b = \frac{\Delta V}{i} \times \frac{A}{\ell}$$

Again in common practice, the resistivity reported is calculated from those values of ΔV and i that correspond to the 'spark' point for the 'dirty' plate experiment.

In the author's viewpoint, the 'P.P.' technique is superior to the 'D.P.' technique for the following reasons:

1. In the 'D.P.' technique the resistivity measurements are taken after the disc has been lowered onto the uncompacted dust layer. This could disturb the integrity of the bed and in cases of high thickness well dislodge a portion of it.[1] McLean has reported that resistivity could change due to rearrangement of particles in a layer when pressure is first applied.[9]

2. There is a possibility that all of the disc may not touch the ash layer resulting in air gaps[1] and hence premature sparking.

3. In the 'P.P.' method a spark travels across an air gap and then through the accumulated dust layer just as in a working precipitator. The air gap is absent in the 'D.P.' method.

4. A very sensitive current measuring device is required in the 'D.P.' method (~ nano-ampere scale). This was not available and instead a microammeter was used. Thus large layer thicknesses are required for appreciable leakage currents which in turn would necessitate much longer collection times.

5. In many cases when back corona might have set in before the sparkover phenomenon is visually

observed on the microammeter some knowledge of the V-I characteristics prior to 'total' sparkover leads to the definition of an 'incipient' sparkover point (explained later in this section). The latter is useful in providing a 'break-down threshold' and therefore a positive safety margin when reporting the resistivity.

6. Carbon in the ash, especially for thin dust layers, can seriously hamper the measurements by the 'D.P.' technique.

As a substantial number of sets of V-I characteristics were obtained by the 'P.P.' method and the 'clean' and 'dirty' plate curves drawn on graph papers an unusual trend was noticed. Whereas it was always known that the bulk resistivity ρ_b varied inversely with ΔV (the voltage applied across the dust layer), in many instances a reversal of this trend was observed at a point close to the visually determined sparkover point (refer to Appendix I-D for experimental procedure). This point shall be called the point of 'incipient' sparkover as shall be made clear from the explanation to follow. The V-I data was then fitted with second order polynomials by the least squares normal equations method (on the computer). The choice of the parabolic equation was made due to two reasons: (1) its relative insensitivity to the data points close to sparkover which is desirable* and more important (2) the form for the voltage current relationship** for a point-to-plane corona is suggested by many to be parabolic.[10] As observed with the preliminary plots over half the V-I data exhibited the inflexion point though some not so strongly as others.

Possible Explanation

When the voltage across a dust layer is gradually increased a point is reached when all conditions are favorable for a spark to jump right across the corona air gap and through the dust layer. This spark followed by a few other 'early' or 'incipient' sparks is not sufficient to cause an appreciable surge in the corona current so as to be identified on the current meter as a 'sparking condition.' In the process a few holes are burned through the dust layer. These holes now act as back corona points and emit ions opposite

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*A third or higher-order polynomial is extremely sensitive in this region and predicts a rapidly decreasing applied voltage with increasing corona currents. This is obviously impossible!

**The suggested relationship is of the form $I = V^2 + BV + C$ where I is the corona current and V is the applied voltage. However, the form used in this work (an inadvertent slip) was of the form $V = I^2 + BI + C$. It was later confirmed using the above suggested form that this interchange of variables does not affect the results appreciably.

in nature to those arriving from the negative corona point (see Figure 6). Thus the voltage drop, ΔV, existing across the dust layer prior to sparkover, is reduced by an opposing field set up by the back corona points. The resistivity however continues to decrease as the corona current is all the while increasing with increasing applied voltage.

From the above discussion two important conclusions may be drawn. Firstly, the 'Point-Plane' technique is a more accurate method of measuring resistivity and, secondly, in the light of the possible coexistence of back corona and sparkover prior to the visual identification of the sparkover point, it is more appropriate to report the resistivity at the condition of 'incipient' sparkover which then provides a convenient '<u>threshold breakdown</u>' region and a point of uniqueness for a given set of data. Also, reporting the resistivity at such a point avoids the inevitable complicacies that arise once sparking has been well established. Figure 7 is a computer plot of ρ_b vs. ΔV for the set of data represented in Figure 5. The fortran program is written so as to identify the approximate region of the inflexion point and then concentrate in that region to pin down the exact point of inflexion. The program is listed in Appendix II-A. Listed in Appendix II-B are the 'clean'

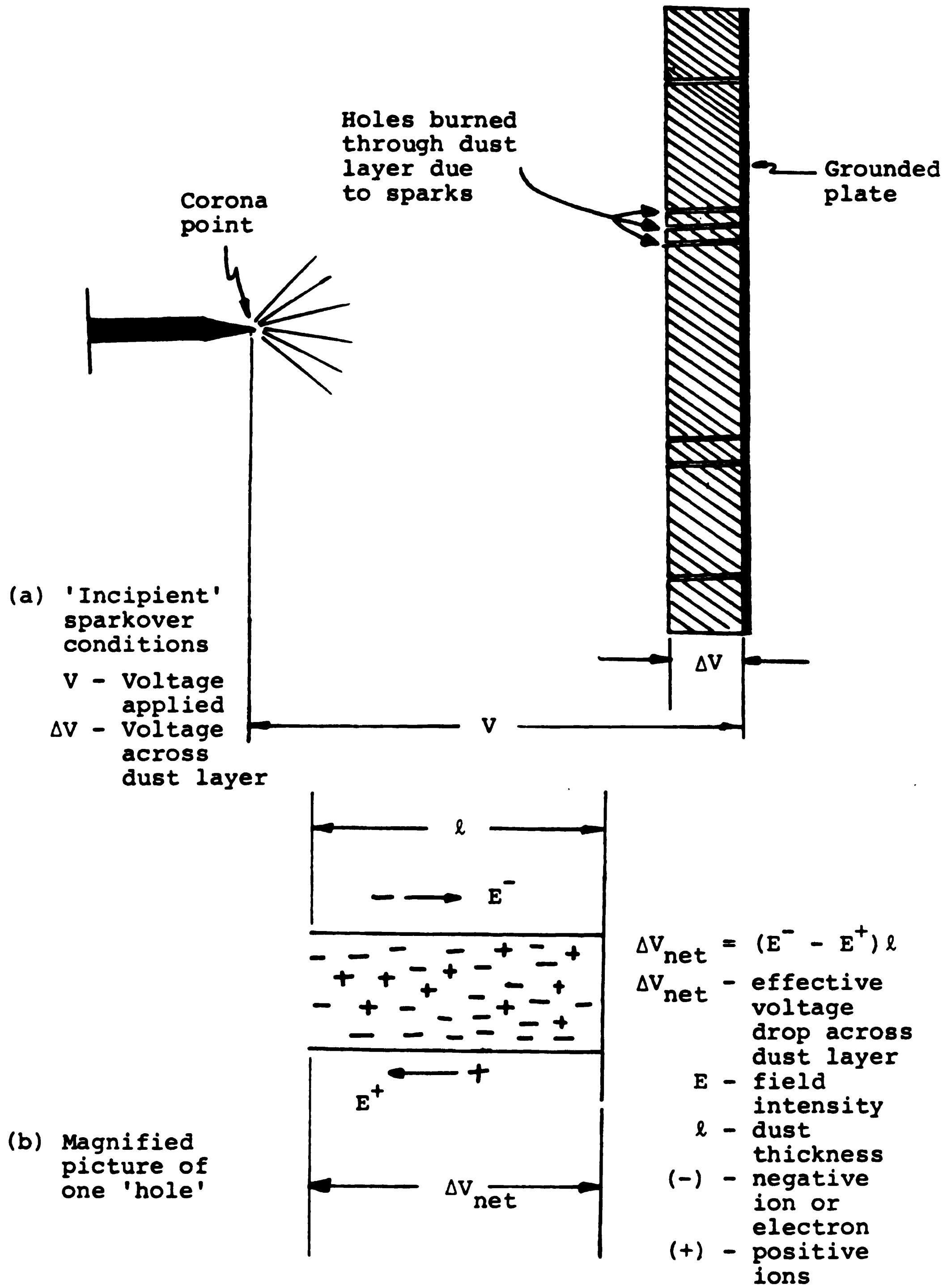

Figure 6.--Explanation of reversal in ΔV vs. ρ_b relationship.

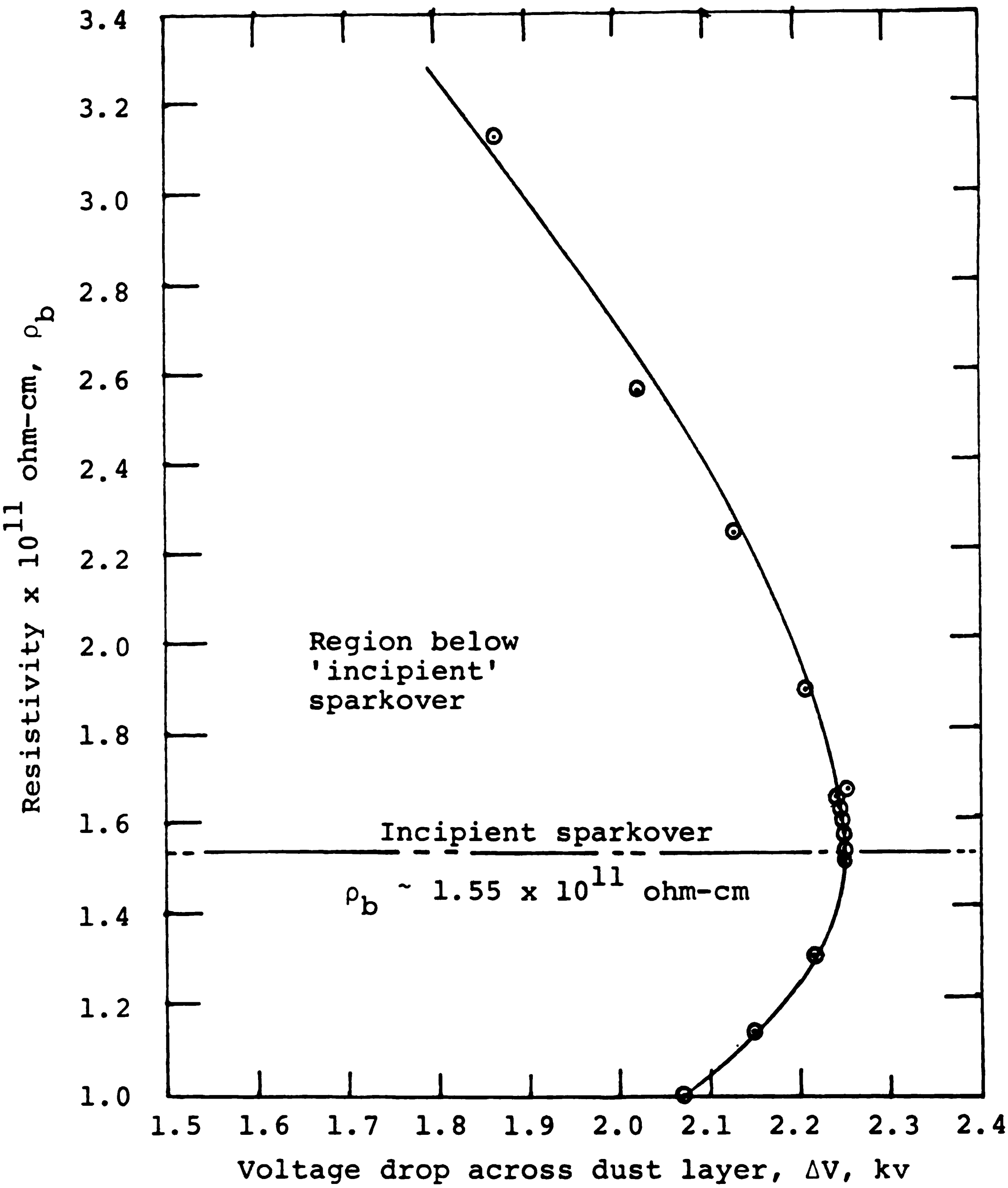

Figure 7.--Variation of resistivity with ΔV (from data corresponding to Figure 5).

and 'dirty' plate recorded data for both Eckert and M.S.U. plants. Tables 1-A and 1-B comprise the data recorded and the resistivities calculated by the 'Disc-Plane' technique in Phase I and II respectively. Tables 2 and 3 contain a summary of the calculated resistivities and other pertinent information using the 'Point-Plane' technique for Phase II and III, respectively.

Recording of Data and Calculation of Resistivity

Shown below is an example data sheet (with data obtained on 4/10/78) resembling the one used in Phase II and III experiments.[1]

SAMPLE DATA SHEET

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1. Date: 4/10/78
2. Test No.: 7
3. Personnel: Mr. X
4. Plant: Eckert Station
5. Boiler No.: 4
6. Port Location: Inlet to ESP
7. Point-plane distance: 1½"
8. Probe orientation: Vertical
9. Boiler Condition: Full load

'POINT-PLANE' TECHNIQUE

10. Initial Temperature (T_i): 285°F
11. Initial Dial Reading: 8.39
12. Final Dial Reading: 8.34
13. Difference: .05 mm

14.	Voltage (kv):	7.5	8.0	9.3	11.4	12.8	14.5	16.1	>17.0
	Current (μA):	0.15	0.3	0.45	1.15	1.65	2.25	3.6	Spark

<u>Collection Data</u>

15. Collection Voltage: 16.1 - 16.5 kv

16. Initial Corona Current: 2.8 μA

17. Start: 11:59 a.m. 18. Stop: 12:14 p.m.

19. Collection time: 15 minutes

<u>Dirty Plate Characteristics</u>

20.	Voltage (kv):	10.4	12.0	14.2	14.6	15.5	16.5	>17.0
	Current (μA):	0.45	0.7	1.3	1.45	1.85	2.2	Spark

21. Final Dial Reading: 7.89

22. Dust Thickness: 0.45 to 0.50 mm

23. Final Temperature (T_F): 286°F

'DISC-PLANE' TECHNIQUE

24.	Voltage (V) -	740	1000	1100	>
	Current (μA) -	0.1	0.13	0.15	Spark

<u>Auxiliary Data</u>

25. Type of Coal: MAPCO

26. Percentage Sulphur: .85

27. Special Observations and Comments: Technique II inaccurate - Current meter resolution poor - Dust thickness insufficient - Premature sparking.

Tabulation of Results

Disc-Plane Technique

$$\rho_b = \frac{\Delta V}{i} \times \frac{A}{\ell} \times 10^{10}$$

ΔV = voltage drop across dust layer during measurement (in kv)

i = corona current during measurement (in μA)

ρ_b = bulk ash resistivity (in 10^{11} ohm-cm)

A = area of cross-section of collection plate ($\simeq$ 5.0 cm^2)

ℓ = thickness of dust layer (in mm)

Additional notations:

T_i = initial temperature of grounded plate (in °F)

T_F = final temperature of grounded plate (in °F)

V_c = collection voltage (in kv)

t = time of collection (in minutes)

(see Tables 1-A and 1-B)

Point-Plane Technique

$$\rho_b = \frac{\Delta V}{i} \times \frac{A}{\ell} \times 10^{10}$$

Notations:

P.P. Gap = Point-to-plane gap in inches

T_i = initial temperature of grounded plate in °F

T_F = final temperature of grounded plate in °F

TABLE 1-A.--Phase I results by the 'D.P.' technique.

Date	Collection					Measurement		ρ_b
	t	V_c	T_i	T_f	ℓ	ΔV	i	
1/ 5/78	-	11.7	208	-	.37	*1.5	0.6	3.38
1/10/78	48	7.0	223	231	.33	*0.5	0.8	0.95
1/10/78	-	6.4	222	-	.39	*0.75	0.17	5.66
1/11/78	60	7.1	225	227	.55	0.5	0.3	1.52
						0.7	0.4	1.59
						*0.75	0.6	1.14
1/13	-		220	220	.51	0.5	0.19	2.58
						1.0	0.55	1.65
						*1.3	2.2	0.58
1/14/78	-	6.8	165	-	.50	.25	0.6	0.42
						.50	1.8	0.28
						* .75	4.6	0.16
1/15/78	-	6.6	180	-	.36	.25	0.2	1.74
						.50	1.0	.70
						* .75	1.8	.58
1/16/78	-	6.6	225	-	.19	.25	1	.64
						* .50	4.8	.27
1/16/78	-	6.7	237	-	.67	.50	0.2	1.87
						.75	0.39	1.44
						1.0	0.85	.88
						*1.3	2.40	.40
1/27/78	83	7.6	217	-	.60	1.0	0.3	2.78
						1.2	0.6	1.67
						1.29	0.8	1.25
						*1.32	1.0	1.1
1/30/78	-	8.0	208	-	.38	.62	.25	3.26
						.80	.50	2.11
						*1.0	1.5	.88
2/ 5/78	92	8.7	200	203	.59	.55	.85	.55
						.77	1.6	.41
						* .82	2.5	.28
2/ 5/78	-	8.3	200	200	.48	.42	.65	.67
						.50	1.3	.40
						* .61	2.2	.29
2/12/78	-	7.5	225	-	.44	.92	0.25	4.14
						*1.3	0.5	2.92
2/19/78	98	8.4	221	226	.46	* .4	0.4	1.09
2/19/78	-	8.1	223	-	.70	1.0	0.5	1.41
						*1.4	1.0	.99

*Values corresponding to last measurement before sparkover.

TABLE 1.B.--Phase II results by the 'D.P.' technique.

Date	t	V_c	T_c	T_f	ℓ	V-I Measurements							ρ_b*
4/ 2/78	35	16.0	314	295	2.37	ΔV	1.62	3.0	4.0				1.88
						I	.15	.20	.45				
4/ 4/78	15	14.8	303	305	.46	ΔV	.48	.65	.85	1.08	1.15		.53
						I	.25	.65	.90	1.65	2.0		
4/ 5/78	15	14.2	290	289	.81	ΔV	.28	.41	.53	.62	.67	.71	.23
						I	.20	.50	.90	1.35	1.55	1.9	
4/ 5/78	15	16.1	289	280	.50	ΔV	.69	.85	1.0	1.12			.67
						I	.15	.45	.85	1.65			
4/10/78	15	16.2	280	285	.28	ΔV	.48	.60					7.14
						I	0.1	0.15					
4/10/78	15	16.3	285	286	.46	ΔV	.74	1.0	1.1				7.97
						I	.10	.13	.15				
4/12/78	15	12.0	308	330	1.39	ΔV	.96						3.45
						I	0.1						
4/24/78	15	7.7	348	360	.71	ΔV	1.08	1.22					2.86
						I	0.2	0.3					
4/24/78	16	7.4	350	360	.28	ΔV	.64						3.80
						I	.30						
4/25/78	-	7.0	324	320	1.29	ΔV	.44						.34
						I	.50						
4/25/78	17	10.0	317	350	.54	ΔV	1.30	1.65					2.03
						I	0.5	0.75					

*Resistivity calculated at last recorded set of V-I measurements.

V_c = Collection voltage in kv

t = duration of collection in minutes

ℓ = dust layer thickness in mm

V_s' = observed sparkover voltage in kv

V_s = incipient sparkover voltage in kv

ρ_b' = resistivity at V_s' in 1×10^{11} ohm-cm

ρ_b = resistivity at incipient sparkover voltage V_s in 1×10^{11} ohm-cm

i' = corona current at V_s' in μA

i = corona current at V_s in μA

(see Tables 2 and 3)

TABLE 2.--Phase II results by the 'P.P.' technique.

Date	P.P. Gap	T_i	T_f	t	ℓ	V_c	V_s'	V_s	i'	i	ρ_b'	ρ_b
4/ 2/78	1½	314	295	35	2.37	16.0	17.37	*17.37	.75	.75	1.858	1.858
4/ 4/78	1½	303	305	15	.46	14.8	16.39	15.52	1.85	1.33	1.827	2.707
4/ 5/78	1½	290	289	15	.81	14.2	a	17.37	3.65	1.89	a	.81
4/ 5/78	1½	289	280	15	.50	16.1	a	18.91	2.45	2.32	a	1.27
4/ 6/78	1½	287	282	33	1.15	16.5	15.94	14.24	2.5	1.28	.256	.969
4/10/78	1½	280	285	15	.28	16.]	16.0	14.59	2.4	1.64	1.238	2.459
4/10/78	1½	285	286	15	.45	16.3	16.38	15.04	2.2	1.59	1.036	1.537
4/12/78	1½	308	330	15	1.39	12.0	12.7	12.3	1.0	.77	1.016	1.438
4/14/78	1	345	354	16	1.29	7.0	9.21	9.10	1.5	1.14	.847	1.177
4/24/78	1	348	360	15	.71	7.7	8.30	8.23	1.2	1.04	1.28	1.522
4/24/78	1	350	360	16	.28	7.4	8.18	7.97	2.3	1.92	.961	1.20
4/25/78	1	324	320	-	1.29	7.0	10.24	*10.24	4.5	4.5	1.673	1.673
4/25/78	1	317	350	17	.54	10.0	9.29	8.72	2.5	1.47	.767	1.481
4/26/78	1	330	315	18	.68	7.5	10.58	10.34	2.1	2.01	1.315	1.376

[a] No sparking observed!

TABLE 2.--Continued.

Date	P.P. Gap	T_i	T_f	t	ℓ	V_c	V_s'	V_s	i'	i	ρ_b'	ρ
4/27/78	1	320	315	19	.76	8.0	9.93	9.75	2.75	2.24	.742	.939
4/27/78	1	314	310	18	.44	7.4	9.50	*9.50	1.65	1.65	2.267	2.267
5/15/78	1	276	286	20	.25	8.4	10.18	*10.18	4.0	4.0	1.178	1.178
5/15/78	1	309	305	-	1.34	9.5	10.85	10.77	3.0	2.09	.438	.713
5/16/78	1	287	289	25	1.13	8.0	10.93	10.88	2.1	1.99	.807	.856
5/16/78	1	280	280	25	.72	7.9	9.39	*9.39	1.35	1.35	1.583	1.583
5/17/78	1	305	312	23	.53	8.5	9.9	*9.9	1.40	1.40	2.452	2.452
5/17/78	1	297	310	20	.41	8.0	9.8	9.61	2.5	1.71	1.338	2.179
5/19/78	1	301	300	15	1.32	9.5	11.3	11.23	3.5	2.31	.380	.676
5/19/78	1	301	307	14	1.15	8.6	11.5	11.24	4.5	2.63	.307	.649
5/24/78	1	288	293	20	.81	9.9	10.84	10.65	2.6	2.22	.777	.938
5/24/78	1	280	295	18	1.45	9.5	10.89	*10.89	3.0	3.0	.369	.369
5/26/78	1	285	280	8	.57	9.0	8.86	*8.86	1.25	1.25	1.72	1.72
5/26/78	1½	280	283	15	1.11	13.4	15.16	14.6	1.0	.73	2.216	3.234

*Implies that no inflexion in the ΔV vs ρ_b relationship was observed.

TABLE 3.--Phase III results by the 'P.P.' technique.

Date	Gap	T_i	T_f	t	ℓ	V_c	V_s'	V_s	i	i'	ρ_b	ρ_b'
8/16/78	1	325	340	0	.44	8.5	10.5	*10.5	1.0	1.0	4.969	4.969
8/17/78	1	354	356.5	-	.24	7.55	9.6	9.64	.90	.60	7.852	12.70
8/17/78	1	357	356	-	.25	8.0	9.5	*9.5	.61	.61	10.86	10.86
8/17/78	1	342	342	21	.20	8.0	8.65	8.64	2.4	1.29	2.356	5.52
8/18/78	1	347	347	13	.28	8.0	8.77	[b]8.74	.60	.49	10.36	12.78
8/18/78	1	348	348.5	13	.21	8.5	10.0	9.99	1.34	1.07	6.03	7.513
8/20/78	1	343	343	-	.33	8.0	9.0	[b]8.97	1.0	1.0	4.220	4.464
8/20/78	$1\frac{1}{2}$	355	354	49	.44	16.6	18.5	17.25	7.0	2.85	.164	1.894
8/30/78	1	224	224.5	-	.20	7.5	9.23	*9.23	3.9	3.9	1.425	1.425
9/ 2/78	1	238	239	0	.44	8.5	11.5	10.36	4.3	3.19	.889	1.316
9/ 2/78	1	250	250	-	.55	9.0	9.93	9.89	3.3	2.58	.917	1.264
9/ 2/78	1	226	226	-	.48	9.0	12.0	12.59	8.5	5.3	.989	.39
9/ 3/78	1	253	253	-	.36	10.0	11.46	11.26			.820	1.019

*No inflection in ρ_b vs ΔV has occurred.

[b]No 'definite' inflexions (see 'Summary of Results')

IV. SUMMARY OF RESULTS

Owing to the strong dependance of resistivity on temperature and sulphur content (both of which varied over the duration of the experiments), it is not possible to obtain a representative value of the ash resistivity without stating the relevant conditions. Four different categories of coal sulphur content were observed centered around the average values of 0.5%, 1.1%, 1.98% and 2.2%. The coal used at the MSU site was always low in sulphur (< .75%). In Phase I the temperatures ranged from 200 to 240°F. In Phase II three distinct temperature zones were observed, 280-300°F, 300-320°F and 340-360°F. Finally in Phase III the resistivity measurements were taken at two locations; one at the ESP inlet (340-360°F) and the other at the 'model* ESP' inlet (220-255°F).

From the very outset the purpose of this work was not so much to verify the dependance of ash-resistivity on temperature or sulphur content (or any other factor) as to establish (if possible) the reproducibility of the measuring probe and to interpret the data obtained

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*A model ESP was fabricated for conducting certain 'conditioning' and related experiments by the author's colleague.

towards gaining further insight into the resistivity problem. The reproducibility, here, refers to how close the calculated values (of resistivity) for two or more consecutive experiments (on the same day) compare with each other. Listed in Table 4 are the percentage deviations from the arithmetic average of resistivities estimated in a single day. As the table suggests the deviations are within normal allowances for experimental uncertainties.

However when the resistivity results were plotted against temperature considerable scatter was observed (not shown here) and in the absence of proper sulphur content information (day to day) no definite regions (of conductivity) were observed. A more systematic effort (varying one parameter at a time like temperature, or coal sulphur content, etc.) than the one undertaken in this work is essential to obtain any dependable variation of resistivity with some parameter.

Regarding the insight gained from the interpretation of the results by the 'Point-Plane' technique the possible existence of an 'incipient sparkover' point was suggested from an observed inflexion in the ρ_b vs. ΔV (voltage across dust layer) relationship. Of the Phase II experiments 71% showed the inflexion with 51% depicting a 'definite'* inflexion in the ρ_b - ΔV plot.

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*By definite is meant that an appreciable (> 20% or so) difference between the corona currents

TABLE 4.--Percentage deviation from mean.

Phase	Technique	Date	Mean ρ_b (ohm-cm)	% Deviation
I	D.P.	1/10/78	3.30×10^{11}	-71.0, +71.0
I	D.P.	1/16/78	$.34 \times 10^{11}$	-19.4, +19.4
I	D.P.	2/ 5/78	$.28 \times 10^{11}$	- 3.5, + 3.5
I	D.P.	2/19/78	1.04×10^{11}	- 4.8, + 4.8
II	D.P.	4/ 5/78	$.45 \times 10^{11}$	-48.9, +48.9
II	D.P.	4/10/78	7.56×10^{11}	- 5.5, + 5.5
II	D.P.	4/24/78	3.33×10^{11}	-14.1, +14.1
II	D.P.	4/25/78	1.19×10^{11}	-71.0, +71.0
II	P.P.	4/ 5/78	1.04×10^{11}	-22.1, +22.1
II	P.P.	4/10/78	2.00×10^{11}	-23.0, +23.0
II	P.P.	4/24/78	1.36×10^{11}	-11.8, +11.8
II	P.P.	4/25/78	1.58×10^{11}	- 6.1, + 6.1
II	P.P.	4/27/78	1.60×10^{11}	-41.4, +41.4
II	P.P.	5/15/78	$.95 \times 10^{11}$	-24.5, +24.5
II	P.P.	5/16/78	1.22×10^{11}	-29.8, +29.8
II	P.P.	5/17/78	2.32×10^{11}	- 5.9, + 5.9
II	P.P.	5/19/78	$.66 \times 10^{11}$	- 2.0, + 2.0
II	P.P.	5/24/78	$.65 \times 10^{11}$	-43.7, +43.7
II	P.P.	5/26/78	2.48×10^{11}	-30.5, +30.5
III	P.P.	8/17/78	9.69×10^{11}	-31.0, -12.1, +43.0
III	P.P.	8/18/78	10.14×10^{11}	-25.9, +25.9
III	P.P.	8/20/78	3.18×10^{11}	-40.0, +40.0
III	P.P.	9/ 2/78	$.99 \times 10^{11}$	-32.9, -27.7, +60.6

Sixty-nine percent of the Phase III experiments exhibited this reversal phenomenon with 54% showing noticeable evidence.

The reason why <u>all</u> of the experiments did not possess a characteristic 'incipient' sparkover point is not very clear at this point. Among other explanations it could be suggested that the nature of collection of the dust layer and the care with which the V-I data are recorded (i.e. care in avoiding any sparking) may decide as to whether the observed sparking point would precede or succeed any possible coexistence of sparking and back corona.

Given below are some crude estimates of the ash resistivities obtained from an arithmetic-averaging of the values calculated.

Phase	Temperature range °F	Average resistivity ohm-cm
I (D-P)	200-240	1.292×10^{11}
II (D-P)	280-360	2.81×10^{11}
II (P-P)	280-300	1.41×10^{11}
	300-320	1.40×10^{11}
	340-360	1.30×10^{11}
III (P-P)	220-255	1.05×10^{11}
	340-360	7.82×10^{11}

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at 'observed' sparkover and 'incipient' sparkover was observed.

V. SOURCES OF ERROR AND RECOMMENDATIONS

Among the many factors that could not be held constant over the entire period of 'in-situ' resistivity measurements (such as sulphur content, temperature, quality of coal burned, particle size distribution, humidity, gas flow rate, etc.) only the first two varied enough to be of significance in the calculation of resistivity. The coal sulphur content varied from as much as 0.5 to 2.5% but generally remained around 1%. Temperatures varied considerably in both the sites. At the Eckert Plant the range was from 280 to 360°F. At the M.S.U. plant two temperature ranges existed; one at the precipitator inlet (340-360°F) and the other at the 'race-track unit' inlet (225-250°F).

Another source of error could be involved in the measurement of the dust-layer thickness. During the recording of the 'Clean-Plate Characteristics' it is unavoidable for some ash to be collected in spite of the probe orientation being unfavorable for such a deposition. With certain precautionary measures (like partly covering up the slots in the coverplate, or pulling the probe closer to the precipitator wall, etc.) the dust collected could be limited to about .05 mm which then results in a maximum error of about 10% (for a .5 mm dust layer thickness) in the calculated resistivity. The clean-plate deposition tends to decrease the slope of the clean-plate curve which in turn reduces the ΔV and therefore the resistivity.

In the measurement of the corona current (especially at low current values), the resolution and sensitivity of the microammeter was found to be highly inadequate and it is suggested that one use a pico- or nanoammeter in all future work.

The resolution of the H.V. supply was found to be insufficient. An H.V. supply with a better resolution (.25 kv) and a greater range of available voltage (0-30 kv) is recommended.

Among other recommendations may be included: (1) A pump attachment on the probe supplying compressed air to clean up the accumulated dust layer (between experiments). In this way a large amount of experimental time can be reduced in that the coverplate need not be dismantled and the probe allowed to reattain thermal equilibrium prior to the next experiment. (2) The point-to-plane distance could be made continuously adjustable so that 'optimum'* collection fields may be set up for

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*'Optimum' in terms of substantial build up of dust layer (> 1.0 mm) in the shortest possible time

each experiment. (3) It would be helpful if the micrometer dial needle were calibrated as a function of temperature so that the exact error due to a change in temperature during an experiment may be gauged.

(< 30 min) and with little or no disturbance of the dust layer due to sparking during collection. This is judged from a few trial runs.

VI. CONCLUSIONS

With the aid of the Southern Research Institute drawings a 'Point-to-Plane' resistivity probe was fabricated at the M.S.U. Engineering Shop. Its functions were tested with a series of resistivity measurements conducted over a couple of months at two different power plants burning coal. A manual for convenient operation was put together. The probe was found to yield quite reproducible results (see Summary of Results) and was also found suitable for 'in-situ' resistivity measurements. From the resistivity data recorded a rough estimate of the fly-ash resistivity at each site was obtained.

For a number of reasons the 'Point-Plane' technique was found to be more accurate and representative than the 'Disc-Plane' technique. Also the value of this technique was strengthened by the discovery that a 'threshold breakdown' voltage range may exist for the sparkover voltage. A computer program was written to facilitate accurate data fitting and to focus on the point of 'incipient' sparkover.

REFERENCES

REFERENCES

1. P. N. Shukla, A. V. Someshwar, and B. W. Wilkinson. "Reliable Fly Ash Resistivity Measurement and the Criteria for Determination and Documentation," presented at the National Conference on '<u>Quality Assurance of Environmental Measurement</u>,' Nov. (1978).

2. G. B. Nichols, "Techniques for Measuring Fly Ash Resistivity," Rep. no. EPA-650/2-74-079, prepared by U. S. Environmental Protection Agency, August (1974).

3. E. R. Walcott, "Effects of Dielectrics on the Sparking Voltage," <u>Phys. Rev</u>., XII (Oct. 1918).

4. S. Frank, "Spark Discharges in Air-Dust Mixtures," <u>Z. Physik</u>. <u>87</u>:323 (1933).

5. R. E. Bickelhaupt, "Electrical Volume Conduction in Fly Ash," <u>J. Air Poll. Control Assoc</u>. <u>24</u>: 251 (1974).

6. R. E. Bickelhaupt, "Surface Resistivity and the Chemical Composition of Fly Ash," <u>J. Air Poll. Control Assoc</u>. <u>25</u>:148 (1975).

7. Harry J. White, "Resistivity Problems in Electrostatic Precipitation," <u>J. Air Poll. Control Assoc</u>. <u>24</u>:313 (1974).

8. K. J. McLean and Prof. R. M. Huey, "Influence of Electric Field on the Resistivity of a Particulate Layer," <u>Proc. IEE</u>, Vol. <u>121</u>, No. 1, January (1974).

9. K. J. McLean, "Factors Affecting the Resistivity of a Particulate Layer in Electrostatic Precipitators," <u>J. of Air Poll. Control Assoc</u>., <u>26</u>, No. 9, Sept. (1976).

10. J. D. Cobine, "Gaseous Conductors - Theory and Engineering Applications," McGraw-Hill, New York, pp. 261 (1941).

11. G. B. Nichols, "Methods and Apparatus for Conducting Resistivity Measurement," Rep. no. EPA-68-02-1083, prepared by U. S. Environmental Protection Agency, March (1975).

12. H. J. White, "Electro-static Precipitation of Fly-ash," J. Air Poll. Control Assoc. 27:115, Feb. (1977).

13. E. C. Potter, "Electro-static Precipitation Technology," J. Air. Poll. Control Assoc. 28: 40. Jan. (1978).

APPENDICES

APPENDIX I-A

DRAWING OF THE SRI POINT-PLANE RESISTIVITY PROBE AND PHOTOGRAPHS OF PROBE AND OTHER EQUIPMENT

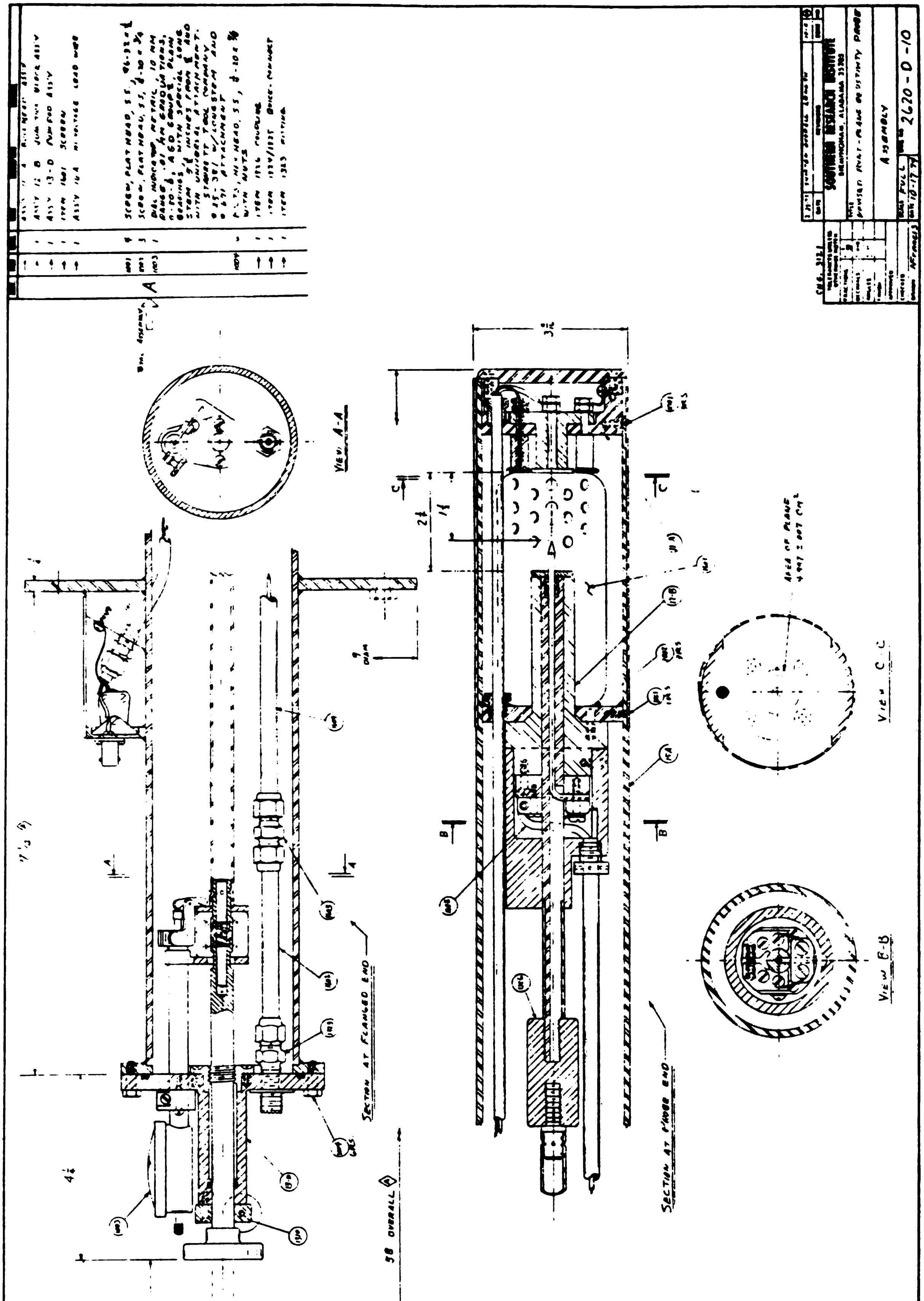
VIEW A-A
SECTION AT FLANGED END
58 OVERALL
SECTION AT PROBE END
VIEW C-C
VIEW B-B
SOUTHERN RESEARCH INSTITUTE
BIRMINGHAM, ALABAMA 35205
ASSEMBLY
2620-D-10

Figure 8(a).--Point-to-plane (SRI) resistivity probe.

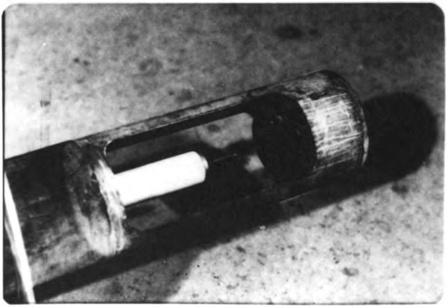

Figure 8(b).--Close-up of point and plane.

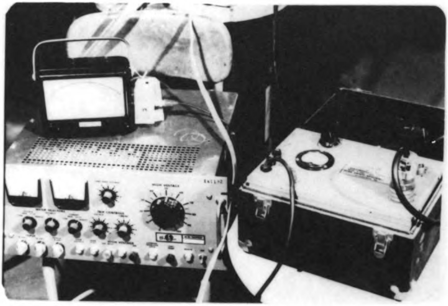

Figure 8(c).--High and low voltage supplies, ammeter.

APPENDIX I-B

EQUIPMENT UTILIZED

APPENDIX I-B

EQUIPMENT UTILIZED

High Voltage Supply: 'M-S-A Electrostatic Sampler'
115 volts, 60 cycle
0-20 kv, FS - 150 μA

Microammeter: 'Hickok'
[D.C.] range -15 μA to +15 μA

Temperature Measuring Device:
(a) 'Honeywell' Strip Chart Recorder (calibrated for iron-constantan thermocouple
(b) 'Mini-mite' (iron-constantan thermocouple)

Low Voltage Supply: 'Sorensen' H. V. Supply (1003-200)
Ranges: 0-0.3 kv, 0-3.0 kv, 0-1.0 kv

Resistivity Probe, cover plate, spare corona points, wooden supports, iron clamp with heavy base plate, cylindrical flanges, etc.

Brush, piece of cloth, leather and cloth gloves, tool box, spare fuses, ear plugs, etc.

APPENDIX I-C

SCHEMATIC DIAGRAM FOR PROBE SYSTEM[11]

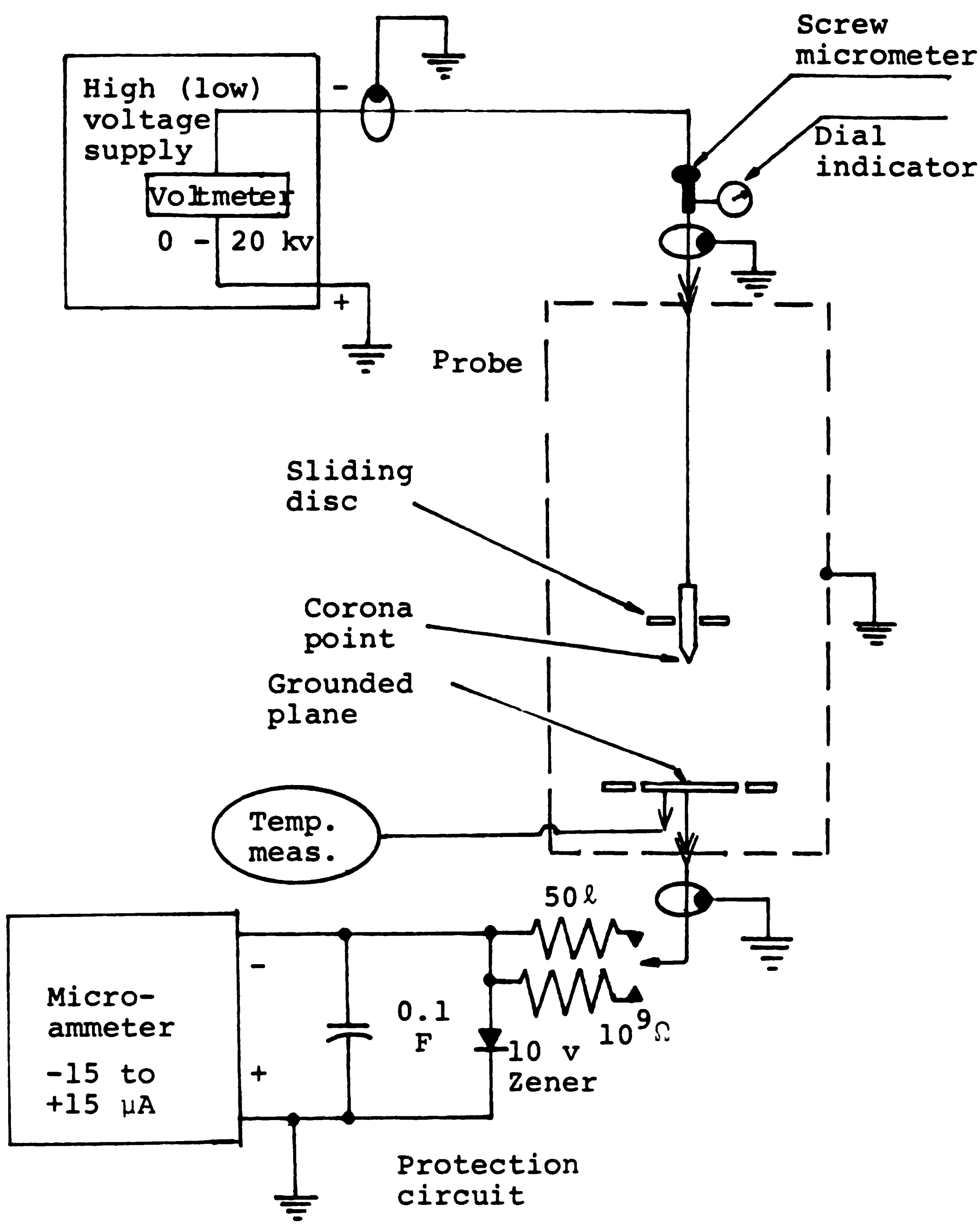

Figure 9.--Schematic diagram for probe system.[11]

APPENDIX I-D

OPERATING INSTRUCTIONS

APPFNDIX I-D

OPERATING INSTRUCTIONS

Preparation

1. At the start of the day's experiment check to ensure that the stem, point and plane of the resistivity probe are clean. Unscrew the sliding disc gradually until the micrometer dial guage reads zero. After a few more turns pull the stem gently all the way back. With a light anti-clockwise tug lock the stem in this position.

2. Put on the desired coverplate with the slots or holes away from the gas flow.*

3. Screw on the high voltage cable to the rear end of the probe and insert the microammeter lead into the BNC (Figure 8) on the probe surface. Plug in the

---

*Sometimes due to poor gas flow conditions it might be desirable to position the holes facing the gas flow to hasten collection. Also the choice of the point-plane (P.P.) gap rests with the experimenter. If a few pilot runs indicate that the collection rate is too small a smaller P-P gap may be tried. On the other hand if excessive sparking is observed during collection and measurement a larger P-P gap should be used. It was observed from these experiments that the selection of the P-P gap does not affect the ash resistivity. It only affects the collection characteristics of the dust layer.

thermocouple male joint into the female one adjacent to the current junction.

4. Connect the HV supply to the nearest available 220 V single phase supply line.

5. Check to make sure the outer surface of probe has been correctly grounded by a long, several stranded, copper wire.

6. If flanging mechanism or support for probe is needed prepare the same for proper probe positioning.

7. Carefully open cap of test port. Note that substantial ash could have accumulated on the inside of cap. Also check for pressure at port. If pressure is positive exercise extreme care to avoid contact with SO_2 and other obnoxious gases and dust in effluent stream.

8. Insert probe to a depth of about 1½ to 2' inside the ESP inlet duct or such that the boundary regions are avoided. Rotate the probe to yield the best possible gas flow pattern in terms of the fastest collection and least entrainment.* Mark this orientation.

9. Make sure that the gap between the port and the probe is well sealed to avoid dilution or alteration of gas composition or temperature at the point-plane region.

---

*This is determined from one or two trial runs.

10. Rotate the probe by 90° to the position in (8) and allow the temperature of the plane to rise. Check this temperature every five minutes until two consecutive temperatures are the same. This 'thermal stabilization' period runs from 20 to 30 minutes.

11. Once temperature has stabilized record it as T_i. Now unlock the stem, push it in gently until it moves no further; then screw on in clockwise direction until sliding disc contacts the plane and the dial needle stops rotating.* Record the micrometer dial reading.

12. Unscrew the sliding disc and lock it in the raised position as before. The clean plate V-I characteristics can now be measured.

Measurements by the 'Point-Plane' Technique

13. Switch on the high-voltage power supply. Adjust for any zero-error in volt-meter reading.

14. With coverplate openings perpendicular to gas flow direction as in (10) raise the voltage very gradually until the ammeter registers a current. Next increase the applied voltage in steps of 0.5-1.0 kv and record the voltage-current relationship.

---

*Rotate very gradually when approaching the plane or the dust layer. Get a feel for when the dust layer is 'approached.'

15. When ammeter needle takes an abrupt jump note the voltage and current just prior to jump and then lower the voltage back to zero. Shut off the H-V source supply.

16. Check the temperature once again. Next lower the sliding disc onto the plane and record dial reading. If necessary* some of the coverplate holes should be covered to avoid dust collection during 'clean' plate V-I measurements.

17. Rotate the probe to position the holes in the path of the gas stream as in (8).

18. Switch on the H.V. supply. Gradually increase the voltage until the microammeter needle registers a sudden jump. Lower the voltage by about 1-2 kv and record the applied voltage and initial current.

19. Collection has begun. The current falls rapidly** and then remains almost steady at some low

---

*If the reading is significantly different (by > .05 mm) from the one recorded earlier then appreciable dust has collected during V-I measurements or, alternatively, the temperature has changed considerably. In either case this is undesirable.

**If the current does not register a rapid or steady fall then one of the following could be the cause: (1) Re-entrainment of deposited fly ash is too significant. In such a situation re-orient the slots, or change the slot pattern (to one with lesser flow area) or invert the cover plate with holes away from the gas flow (to reduce gas flow rate). (2) Point-plane gap may be too large. (3) The applied voltage may not be high enough.

value (0.5-1.5 μA). From previous trial runs obtain the approximate collection time required to deposit a dust layer of 0.5-1.0 mm thickness (about 20-40 minutes, in our case). Once the current stays constant at some low value for 10 to 15 minutes rotate the probe carefully to position as in (10) without switching off the power supply. This helps to prevent any re-entrainment of dust particles were the power supply to be turned off.

20. Now lower the voltage knob to zero and check the temperature reading.

21. Next increase the voltage gradually and record the V-I characteristics for the 'Dirty' plate condition. Record at steps of about 0.5 μA until the first spark is noticed on the microammeter. Avoid excessive sparking so as to preserve the dust layer integrity for measurements by the 'D.P.' technique. Lower the voltage to zero and shut off supply.

Dust Layer Measurement

22. Unlock the stem and lower the disc. As the disc approaches the dust layer rotate the micrometer knob very gradually. The sensitive needle of the micrometer gauge quits from moving as soon as the disc touches the ash layer. Sometimes a slight compaction of the layer is unavoidable. Record the dial reading and also the temperature. Now the 'D.P.' technique may be applied.

Measurement by the 'Disc-Plane' Technique

23. Replace the H.V. supply connection by the low voltage (0-3 kv) supply cable. Turn on the L.V. supply.

24. Raise the voltage very gradually in steps of 100 V. Note that due to (a) poor sensitivity of ammeter used (μA range), (b) thin dust layer collected and (c) inherent nature of this technique, sparking occurs at low voltages (.75 ~ 1.5 kv) and rather rapidly. At least two to three points of V-I data must be taken for some reliability. Sparking may be intermittent in which case proper judgment is to be made.* Once sparking occurs record the V-I values prior to sparking, lower the voltage knob and shut off power supply.

Clean-up Procedure

25. Remove the probe from the port very carefully with a pair of leather gloves and place it horizontally on the two wooden supports. Replace the port cap. Do not pull back the stem yet. Unscrew the cover-plate immediately. Unscrew the stem very slightly and check to see if the visual approximation of the dust

---

*If the microammeter needle is unsteady but nevertheless does not surge ahead appreciably this could be due to (a) voltage supply fluctuations, (b) incipient sparks too few to cause appreciable current rise or (c) rearrangement of the field in the dust layer, etc.

layer is compatible with the measured value. Clean the stem, point and plane thoroughly with a brush. Also clean the coverplate and the probe interior. Unscrew and then pull back the stem all the way and lock it. Reassemble the cover plate. Replace the L.V. supply cable with the H.V. supply cable. Reinsert the probe into the port for another run as before.

At the end of the day's experiments clean up the probe assembly, screw on the port cap securely, and unplug the main power supply. Cover all equipment with a piece of cloth or plastic sheet and return all accessories to their proper place. Also obtain the type of coal burned, sulphur content, boiler load, etc. from the proper sources.

APPENDIX II-A

FORTRAN LISTING

(Computer program using example data
of Phase III experiments)

```
C       MSU RESISTIVITITY TESTS AUGUST 1978.
C    X,Y, ARE THE CURRENT,VOLTAGE VALUES. A(3,4) ARE THE COEFFICIENTS OF
C    THE NORMAL EQUTIONS MATRIX. Z(3) ARE THE PARAMETERS OF THE POLYNOMIAL
C    Y=Z(1)+Z(2)*X+Z(3)*X**2.V,C ARE THE FITTED POLYNOMIAL VOLTAGE AND
C    AND CURRENT VALUES.
C       NC AND ND ARE THE TOTAL NUMBER OF CLEAN AND DIRTY PLATE POINT
C                   DELX IS THE DUST LAYER THICKNESS. CL AND CU ARE THE
C    SMALLEST AND LARGEST CURRENT VALUES FOR THE DIRTY PLATE READINGS.
C    TC,TD ARE THE INITIAL AND FINAL TEMERATURES OF THE DUST LAYER.
C    VS IS THE ESTIMATED SPARKOVER VOLTAGE.
C       RO AND RE ARE THE RESISTIVITY AND RESISTANCE (RO * DELX)
C       RESPECTIVELY. E IS THE DATE OF THE EXPERIMENT.
        PROGRAM CURFIT(INPUT,OUTPUT)
        DIMENSION X(2,15),Y(2,15),A(3,4),Z(3),V(2),P(2,4),NC(13),ND(13),DE
     3LX(13),CL(13),CU(13),E(13),TC(13),TD(13),RO(13),VS(13),RE(13)
           DATA DELX/.44,.24,.257,.197,.281,.212,.33,.439,.20,.442,.553,
     6.479,.361/
          DATA ND/6,3,6,7,5,5,4,11,9,6,9,12,13/
          DATA NC/9,7,7,8,9,11,11,12,8,12,11,14,14/
        DATA CL/8.6,8.5,7.65,7.2,7.6,8.0,8.0,9.65,6.0,8.0,5.77,6.0,4.95/
        DATA CU/10.5,9.6,9.5,8.65,8.77,10.0,9.8,10.5,9.5,10.5,10.0,12.0,11
     3.7/
           DATA E/8.16,8.17,8.17,8.17,8.18,8.18,8.20,8.20,8.30,9.2,9.2,9
     6.2,9.3/
           DATA TC/325.,354.,357.,342.,347.,348.,343.,355.,224.5,238.,25
     60.,226.,253./
            DATA TD/340.,356.5,356.,342.,347.,348.5,343.,354.,224.5,239.
     6,250.,226.,253./
        DO 10000 M=1,13
        KC=NC(M) $ KD=ND(M)
        READ 10,(Y(1,J),J=1,KC)
        READ 10,(X(1,J),J=1,KC)
        READ 10,(Y(2,J),J=1,KD)
        READ 10,(X(2,J),J=1,KD)
   10   FORMAT(16F5.2)
        C=CL(M) $ D=CU(M)
C    DELV EVALUATED AT STEP INCREASES OF CURRENT DC. SETTING DC.
        IF((D-C).LE.0.75) DC=0.15
        IF((D-C).GT.0.75.AND.(D-C).LE.1.75) DC=0.20
        IF((D-C).GT.1.75) DC=0.25
        DO 1000 I=1,2
C    IF I.EQ.1 CLEAN PLATE DATA FITTING
C    IF I.EQ.2 DIRTY PLATE DATA FITTING
        IF (I.EQ.1) N=NC(M)
        IF (I.EQ.2) N=ND(M)
        PRINT 25,(Y(I,J),J=1,N)
   25   FORMAT((2X,15(F5.2,1X)),/)
        PRINT 25,(X(I,J),J=1,N)
        DO 30 J=1,3
        DO 40 K=1,4
   40   A(J,K)=0.0
        DO 50 L=1,N
C    EVALUATING NORMAL EQUATIONS MATRIX COEFFICIENTS
        A(J,1)=A(J,1)+Y(I,L)**(J-1)
        A(J,2)=A(J,2)+Y(I,L)**J
        A(J,3)=A(J,3)+Y(I,L)**(J+1)
        A(J,4)=A(J,4)+Y(I,L)**(J-1)*X(I,L)
   50   CONTINUE
   30   CONTINUE
        NROW=3 $ NCOL=4
        CALL GOSELM(A,NROW,NCOL)
        CALL BACKSO(A,NROW,NCOL,Z)
        PRINT 90
   90    FORMAT(5X,*PARAMETERS OF POLYNOMIAL*,/)
        PRINT 100,(J,Z(J),J=1,3)
  100   FORMAT(10X,* *3(*Z(*I2*)= *,F8.5,3X)/)
        DO 105 L=1,3
  105   P(I,L)=Z(L)
 1000   CONTINUE
        PRINT 110
  110   FORMAT(7X,*MICS*,6X,*DELV*,10X,*RES*,7X,*V(1)*,8X,*V(2)*,/)
        IREC=0 $ DELV=0.0
  111   DO 125 I=1,2
C     NOTE. C HAS BEEN INITIALISED TO CL(M)
  125   V(I)=P(I,1)+P(I,2)*C+P(I,3)*C**2.
        F=DELV
        DELV=V(2)-V(1)
C     IF IREC.EQ.1  INFLEXION HAS OCCURRED
        IF(IREC.EQ.1) GO TO 115
        IF(F.GE.DELV) GO TO 150
  115   RES=DELV*5.0*10.**10/(C*DELX(M))
```

```
      PRINT 120,(C,DELV,RES,V(1),V(2))
  120 FORMAT(6X,F5.2,5X,F5.3,4X,E12.5,3X,F5.2,7X,F5.2,/)
      VSPK=V(2)
      C=C+DC
      IF(C.GT.(D+.1)) GO TO 130
      GO TO 111
C  IF IREC REMAINS AS ZERO NO INFLEXION HAS OCURRED
  130 IF(IREC.EQ.0) GO TO 160
C  DEFINING CURRENT RANGE FOR ZEROING IN ON THE INFLEXION POINT
      D=CINF+0.15
      C=CINF-.21
      PRINT 140
  140 FORMAT(10X,*INFLECTION OF VOLTAGE ACROSS DUST AT SPARKOVER*,/)
      PRINT 110
      DELV=0.0
C  RECALCULATE DELV AND RESISTIVITY AROUND POINT OF INFLEXION
  141 DO 142 I=1,2
  142 V(I)=P(I,1)+P(I,2)*C+P(I,3)*C**2.
      F=DELV
      DELV=V(2)-V(1)
      IF(F.GE.DELV) GO TO 160
      VSPK=V(2)
      RES=DELV*5.0*10.**10/(C*DELX(M))
      PRINT 120,(C,DELV,RES,V(1),V(2))
      C=C+0.03
      IF(C.GT.D) GO TO 160
      GO TO 141
  150 IREC=1
C  RECORD APPROXIMATE CURRENT AT INFLEXION OF DELV VS RO
      CINF=C-DC
      GO TO 115
  160 R=RES*DELX(M)
      RE(M)=R $ RO(M)=RES $ VS(M)=VSPK
      PRINT 180
  180 FORMAT(40X,*SPARKING CHARACTERISTICS*,/)
      PRINT 190
  190 FORMAT(10X,*DATE      RESISTIVITY      SPARK VOLTAGE      RESISTANCE
     6     DUST THICKNESS      TSTART      TEND      COMMENTS*//)
      PRINT 200,(E(M),RES,VSPK,R,DELX(M),TC(M),TD(M))
  200 FORMAT(10X,F4.2,5X,E11.5,9X,F5.2,8X,E11.5,10X,F4.2,10X,F5.1,5X,F5.
     61,///)
10000 CONTINUE
      PRINT 205
  205 FORMAT(1H1,20X,*SUMMARY OF RESULTS*,//)
      PRINT 190
      K=13
      DO 210 M=1,K
      PRINT 200,(E(M),RO(M),VS(M),RE(M),DELX(M),TC(M),TD(M))
  210 CONTINUE
      END
      SUBROUTINE GOSELM(A,NROW,NCOL)
C  REDUCE THE NORMAL EQUATIONS MATRIX TO THE UPPER TRIANGULAR FORM BY
C  THE "GAUSS ELIMINATION" TECHNIQUE.
      DIMENSION A(3,4)
C     INITIALISING PIVOTS
      K=0 $N=NROW-1
   10 CONTINUE
      K=K+1 $ INDIC =K
      PIV=ABS(A(K,K))
C     SCAN FOR PIVOT ELEMENTS
      DO 20 I=K,NROW
      IF(PIV.LT.ABS(A(I,K))) 30,20
   30 PIV = ABS (A(I,K))
      INDIC =I
   20 CONTINUE
      IF(INDIC.EQ.K) 55,40
C     SWITCHING ROWS
   40 DO 50 J=1,NCOL
      D=A(INDIC,J)
      A(INDIC,J)=A(K,J)
      A(K,J)=D
   50 CONTINUE
C     ROW OPERATIONS
   55 PIV = A(K,K)
      DO 60 I = K,NCOL
   60 A(K,I) = A(K,I)/PIV
      KM = K+1
      DO 80 J = KM,NROW
      FM = A(J,K)
      DO 70 L = K, NCOL
   70 A(J,L) = A(J,L)-FM*A(K,L)
```

```
   80 CONTINUE
      IF (K.EQ.N) 90,10
   90 IF(A(NROW,NROW).NE.0.0) 100,110
  100 A(NROW,NCOL)=A(NROW,NCOL)/A(NROW,NROW)
      A(NROW,NROW)=1.0
  110 RETURN
      END
      SUBROUTINE BACKSO (A,NROW,NCOL,Z)
C     BACKSOLUTION METHOD TO SOLVE THE UPPER TRIANGULAR MATRIX FOR Z
      DIMENSION A(3,4),Z(3)
      Z(NROW)=A(NROW,NCOL)
      N=NROW-1
      DO 80 I=1,N
      J=NROW-I
      SUM=0.0
      DO 90 K=J,N
   90 SUM=SUM+A(J,K+1)*Z(K+1)
      Z(J)=A(J,NCOL)-SUM
   80 CONTINUE
      RETURN
      END
```

APPENDIX II-B

EXPERIMENTAL DATA

Eckert (Phase II) V-I Data

```
 DIMENSION X(2,14),Y(2,14),A(4,5),Z(4),V(2),P(2,4),NC(28),ND(28),DE
3LX(28),CL(28),CU(28),E(28),TC(28),TD(28),RO(28),VS(28),RE(28)
      DATA DELX/2.37,0.46,0.81,0.50,1.15,0.28,0.46,1.39,1.29,0.71,0
6.28,1.29,0.54,0.68,0.76,0.44,0.25,1.34,1.13,0.72,0.53,0.41,1.32,1.
115,0.81,1.45,0.57,1.11/
 DATA ND/4,7,8,7,7,4,6,3,5,4,4,10,5,4,6,3,7,6,5,4,3,7,7,7,6,6,5,4/
 DATA NC/9,5,6,6,10,10,7,8,8,6,6,8,7,7,9,7,14,14,10,6,10,8,14,13,8,
812,14,13/
      DATA CL/0.20,0.05,0.30,0.45,0.50,0.90,0.45,0.20,0.20,0.10,0.55
5,0.50,0.50,0.35,0.30,0.40,0.50,0.5,0.15,0.15,0.25,0.30,0.5,0.5,0.5
6,.40,0.45,0.25/
      DATA CU/0.75,1.85,2.35,2.45,2.50,2.4,2.2,1.0,1.5,1.2,2.3,5.0,2
5.5,2.1,3.0,1.65,4.0,3.0,2.15,1.4,1.4,2.5,3.5,4.5,2.75,3.0,1.25,1.7
      DATA E/4.2,4.4,4.5,4.5,4.6,4.10,4.10,4.12,4.14,4.24,4.24,4.25,
64.25,4.26,4.27,4.27,5.15,5.15,5.16,5.16,5.17,5.17,5.19,5.19,5.24,5
6.24,5.26,5.26/
      DATA TC/314.0,303.0,290.0,289.0,287.0,280.0,285.0,308.0,345.
90,348.0,350.0,324.0,317.0,330.0,320.0,314.0,276.0,309.0,287.0,280.
80,305.0,297.0,305.0,301.0,288.0,280.0,285.0,280.0/
      DATA TD/295.0,305.0,289.0,280.0,282.0,285.0,286.0,330.0,354.
50,360.0,360.0,320.0,315.0,315.0,315.0,310.0,286.0,305.0,289.0,290.
60,312.0,310.0,300.0,307.0,293.0,295.0,280.0,283.0/
        8.0  10.0 11.0 12.0 13.0 14.0 15.0 16.0 17.0
4/2     0.10 0.35 0.85 1.20 1.35 1.80 2.60 3.20 3.75
        10.8 15.4 16.0 17.5
        0.2  0.5  0.6  0.75
        8.0  9.3  11.7 12.5 13.5
4/4     0.25 0.55 1.10 1.5  2.0
        9.6  10.8 12.0 13.5 15.0 16.0 16.5
        0.15 0.3  0.5  0.75 1.2  1.6  1.85
        10.8512.7 14.6 15.7 18.1 19.1
4/5     0.65 1.15 1.75 2.20 3.6  4.2
        11.0 12.6 15.1 15.9 16.6 17.5 18.4 19.8
        0.3  0.6  1.1  1.35 1.7  2.0  2.35 3.65
        10.8512.7 14.6 15.7 18.1 19.1
4/5     0.65 1.15 1.75 2.20 3.6  4.2
        10.5 12.0 13.9 16.3 17.1 18.6 19.2
        0.15 0.45 0.85 1.45 1.65 2.20 2.45
        8.6  9.5  10.4 11.3 12.0 13.3 14.8 15.1 15.7 16.0
4/6     0.5  0.75 1.0  1.25 1.5  2.0  2.5  3.0  3.5  4.0
        9.0  11.1 12.3 13.4 14.6 15.6 16.1
        0.25 0.5  0.75 1.0  1.5  2.0  2.5
        6.0  8.0  10.0 11.4 12.4 13.3 14.2 16.0 17.2 18.4
4/10    0.1  0.35 0.8  1.15 1.5  2.0  2.45 3.6  4.65 5.3
```

	11.7	13.0	14.5	16.0										
4/10	0.9	1.2	1.6	2.4										
	7.5	8.0	9.3	11.4	12.8	14.5	16.1							
	0.15	0.3	0.45	1.15	1.65	2.25	3.6							
4/10	10.4	12.0	14.2	14.6	15.5	16.5								
	0.45	0.7	1.3	1.45	1.85	2.2								
	6.8	8.0	10.0	12.0	13.4	15.0	16.4	18.1						
4/12	0.1	0.4	0.9	1.8	2.2	3.5	4.6	6.2						
	10.3	11.2	12.7											
	0.35	0.5	1.0											
	5.0	5.55	6.0	6.4	6.6	6.8	7.1	7.5						
4/14	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0						
	7.3	8.0	8.55	9.0	9.2									
	0.25	0.5	0.75	1.0	1.5									
	5.4	6.0	6.6	7.6	7.9	8.2								
4/24	0.5	1.0	1.7	3.6	4.35	5.1								
	6.6	7.1	7.7	8.3										
	0.35	0.5	0.7	1.2										
	5.4	6.0	6.6	7.6	7.9	8.2								
4/24	0.5	1.0	1.7	3.6	4.35	5.1								
	6.15	6.9	7.45	8.2										
	0.6	0.9	1.45	2.3										
	5.85	6.4	6.9	7.3	7.4	7.75	8.0	8.4						
4/25	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5						
	6.55	7.0	7.5	8.3	8.6	9.05	9.15	9.65	9.9	10.4				
	0.25	0.50	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5				
	5.85	6.4	6.9	7.3	7.4	7.75	8.0	8.4						
4/25	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5						
	7.4	8.5	8.75	9.1	9.3									
	0.5	1.25	1.5	2.0	2.5									
	5.5	5.8	6.35	7.0	7.5	8.2	8.6							
4/26	0.4	0.85	1.75	2.5	3.8	5.4	6.4							
	7.5	8.5	9.4	10.4										
	0.4	0.7	1.25	2.1										
	5.6	6.2	6.95	7.4	8.0	9.0	9.6	10.1	10.8					
	0.9	1.75	2.65	3.6	4.9	7.4	9.6	11.5	13.1					
4/27	6.9	7.8	8.5	9.0	9.8	10.0								
	0.3	0.5	0.95	1.55	2.45	2.75								
	5.6	6.0	6.7	7.15	7.6	8.4	9.1							
4/27	0.6	1.4	2.5	3.4	4.3	5.9	8.6							
	8.0	8.8	9.5											
	0.4	0.95	1.65											
	5.6	6.0	6.9	7.1	7.45	7.8	8.35	8.6	9.0	9.4	9.55	9.90	10.0	10.1
5/15	0.5	1.0	2.0	2.5	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	10.5	11.0
	6.95	7.5	8.6	9.0	9.45	9.9	10.15							
	0.5	1.0	2.0	2.5	3.0	3.5	4.0							

	5.65	6.0	6.75	7.05	7.4	8.0	8.35	8.75	9.0	9.4	9.55	9.9	10.02	10.20
5/15	0.5	1.0	2.0	2.5	3.0	4.0	5.0	6.0	6.5	7.5	8.5	9.0	10.0	11.0
	8.0	9.55	10.35	10.5	10.75	11.01								
	0.5	1.0	1.5	2.0	2.5	3.0								
	5.8	6.3	6.65	7.1	7.45	7.8	8.3	8.8	9.4	9.8				
5/16	0.3	0.8	1.4	2.0	2.6	3.4	4.4	5.4	6.8	8.4				
	7.0	8.5	9.4	10.2	11.0									
	0.25	0.60	1.0	1.5	2.1									
	6.0	6.7	7.0	7.35	8.0	8.5								
5/16	1.0	1.8	2.2	2.9	3.9	4.85								
	7.3	8.0	8.6	9.4										
	0.2	0.45	0.8	1.35										
	5.35	5.9	6.5	7.0	7.6	8.05	8.5	8.95	9.4	9.7				
5/17	0.45	0.9	1.6	2.3	3.2	4.1	4.95	6.3	7.5	8.7				
	8.0	9.0	9.9											
	0.35	0.85	1.4											
	5.8	6.15	6.4	7.0	7.5	8.0	8.5	8.8						
5/17	0.5	1.1	1.55	2.45	3.25	4.2	5.1	6.0						
	7.9	8.2	8.7	9.0	9.3	9.55	9.8							
	0.4	0.6	0.85	1.05	1.30	1.70	2.5							
	5.85	6.2	7.0	7.35	7.5	7.9	8.0	8.5	9.0	9.45	9.70	10.0	10.4	10.6
5/19	0.5	1.0	2.0	2.5	3.0	3.5	4.0	5.0	6.0	7.0	8.25	9.0	10.0	11.0
	8.51	9.85	10.5	11.0	11.2	11.35	11.4							
	0.5	1.0	1.5	2.0	2.5	3.0	3.5							
	6.0	6.25	7.08	7.55	8.05	8.5	9.0	9.4	9.5	9.77	10.0	10.2	10.55	
5/19	0.75	1.0	2.0	3.0	4.0	5.0	6.0	6.5	7.5	8.55	9.5	10.5	11.0	
	8.6	9.85	10.5	10.85	11.15	11.45	11.65							
	0.5	1.0	1.5	2.0	3.0	3.5	4.5							
	5.2	6.0	6.55	7.15	7.5	8.35	8.9	9.4						
5/24	0.3	0.6	1.3	2.1	2.7	3.5	4.7	5.6						
	6.5	7.9	8.5	10.0	10.35	11.0								
	0.4	0.8	0.9	1.7	2.15	2.6								
	4.5	5.3	5.4	6.35	6.5	7.0	7.6	8.1	8.6	8.8	9.1	9.3		
5/24	0.35	0.5	0.9	1.3	1.65	2.25	2.8	3.8	4.6	5.0	5.6	6.2		
	7.4	8.15	8.9	9.1	9.8	10.9								
	0.4	0.8	1.45	1.55	2.1	3.0								
	6.05	6.5	6.87	7.2	7.5	8.0	8.25	8.5	9.0	9.5	10.0	10.3	11.2	11.4
5/26	1.0	1.5	2.0	2.5	3.0	4.0	4.75	5.25	6.5	8.0	9.5	10.5	14.0	15.0
	6.5	7.5	8.2	8.5	8.9									
	0.25	0.5	0.8	1.0	1.25									
	7.0	8.5	9.55	10.5	11.7	12.0	13.1	14.4	15.1	16.4	16.7	17.5	18.8	
5/26	0.25	0.5	0.75	1.0	1.25	1.5	2.0	2.5	3.0	3.5	4.0	4.3	5.05	
	11.75	13.65	14.55	15.2										
	0.25	0.5	0.75	1.0										

M.S.U. (Phase III) V-I Data

C DATA . V,I (CLEAN PLATE),,FOLLOWED BYV,I(DIRTY PLATE)

8/1	5.5	5.85	6.2	6.5	7.0	7.55	8.0	8.5	8.8					
	0.25	0.40	1.2	1.8	2.75	4.2	5.75	7.25	7.8					
	8.6	9.2	9.5	9.85	10.2	10.5								
	0.18	0.2	0.38	0.6	0.85	1.0								
8/1	5.25	5.75	6.5	7.0	7.55	8.0	8.2							
	0.1	0.3	0.7	2.2	3.55	4.6	6.37							
	8.5	9.0	9.6											
	0.1	0.25	0.9											
8/1	5.25	5.75	6.5	7.0	7.55	8.0	8.2							
	0.1	0.3	0.7	2.2	3.55	4.6	6.37							
	7.65	8.48	8.59	8.85	9.25	9.5								
	0.09	0.2	0.35	0.4	0.55	0.61								
8/1	5.3	5.5	6.0	6.5	7.1	7.5	8.0	8.35						
	0.08	0.75	1.83	2.8	3.8	4.95	6.45	7.45						
	7.2	7.49	7.8	8.0	8.15	8.55	8.65							
	0.1	0.2	0.3	0.4	0.7	1.3	2.4							
8/1	5.0	5.4	5.77	6.0	6.5	7.0	7.5	8.0	8.35					
	0.19	0.65	1.25	1.8	2.45	3.3	4.2	5.3	6.4					
	7.6	8.0	8.3	8.5	8.77									
	0.1	0.2	0.25	0.35	0.6									
8/1	6.1	6.5	6.75	7.0	7.5	8.0	8.2	8.5	8.75	9.0	9.2			
	0.1	0.5	1.4	2.4	3.6	5.0	5.6	6.5	7.3	8.4	9.2			
	8.9	8.3	8.7	9.6	10.0									
	0.06	0.1	0.19	0.7	1.34									
8/2	5.9	6.25	6.55	6.75	7.0	7.3	7.5	7.8	8.0	8.25	8.5			
	0.6	0.85	1.9	2.3	3.2	3.6	4.35	5.55	6.2	6.7	7.8			
	8.0	8.5	8.75	9.0										
	0.2	0.5	0.7	1.0										
8/2	7.8	8.4	9.4	10.0	11.0	11.5	12.0	12.55	13.55	14.55	17.14	18.0		
	0.2	0.6	1.0	1.2	1.75	2.02	2.4	2.9	3.6	4.6	8.8	9.2		
	9.65	10.6	11.45	12.5	13.7	14.8	15.45	16.77	17.15	18.1	18.5			
	0.1	0.2	0.4	0.58	0.79	1.12	1.41	2.3	3.2	5.8	7.0			
8/3	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.65						
	0.5	1.85	3.1	4.82	6.45	8.22	10.2	12.3						
	6.0	6.3	6.64	7.0	7.5	8.0	8.5	9.0	9.5					
	0.7	0.8	1.05	1.29	1.7	2.18	2.77	3.62	3.9					
9/2	5.3	6.0	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	12.0		
	0.7	1.83	3.6	4.67	6.32	8.08	9.83	12.2	14.05	16.5	19.2	24.6		
	8.0	8.5	9.0	9.5	10.0	10.5								
	0.95	1.2	1.5	1.85	2.8	4.3								
9/2	4.75	5.5	6.5	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.5			
	0.18	0.72	2.39	5.1	6.5	8.38	10.03	11.9	14.2	16.3	22.0			
	5.77	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0					
	0.2	0.4	0.58	0.73	1.0	1.29	1.68	2.2	3.3					
9/2	5.25	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.5	12.0
	0.25	0.82	2.0	2.8	3.98	4.92	6.06	7.54	9.2	10.8	12.5	14.75	17.0	21.5
	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.5	11.5	12.0			
	0.55	0.77	0.98	1.19	1.5	1.82	2.25	2.8	3.55	6.03	8.5			
9/3	5.45	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5
	0.3	0.5	1.14	2.18	3.28	4.25	5.8	7.42	9.2	12.07	14.4	16.0	19.7	22.1
	4.95	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.7	
	0.2	0.34	0.41	0.63	0.83	1.02	1.2	1.9	2.15	2.9	3.65	4.03	6.0	