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# The Electrical Resistivity of Fly-Ash from Bayswater and Newvale Coals

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# The Electrical Resistivity of Fly-Ash from Bayswater and Newvale Coals

WOLLONGONG UNIVERSITY COLLEGE  
THE UNIVERSITY OF NEW SOUTH WALES



***The Electrical Resistivity  
of Fly-Ash  
from Bayswater and Newvale Coals***

O. J. Tassicker

Z. Herceg

K. McLean

DIVISION OF ENGINEERING

DECEMBER, 1966

THE ELECTRICAL RESISTIVITY OF FLY-ASH

FROM BAYSWATER AND NEWVALE COALS

WOLLONGONG UNIVERSITY COLLEGE

TABLE THE UNIVERSITY OF NEW SOUTH WALES

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DECEMBER 1966

## 1. INTRODUCTION

### THE ELECTRICAL RESISTIVITY OF FLY-ASH FROM BAYSWATER AND NEWVALE COALS

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## 1. INTRODUCTION

In collaboration with the Projects Division of the Electricity Commission of New South Wales, staff of the Department of Electrical Engineering participated in tests at Pymont Power Station. The fly-ash fired in the station's boilers was collected in an S.F. Pilot Precipitator.

This report thus represents a detailed on-site and laboratory investigation of the electrical resistivity of the fly-ash obtained from burning coals proposed as fuel for the new Liddell Power Station. Coals from the Newvale seam were fired at Pymont Power Station from the 28th September to the 13th October 1966 and these fly-ashes were tested in-situ and in the laboratory during these periods. Coals from the Bayswater seam were fired from 2nd December, 1966 through to 15th December and these fly-ashes were also tested in-situ and in the laboratory during these periods.

During the period of these tests, samples of the flue-gas were drawn off from the duct inlet to the S.F. Pilot Plant and passed through equipment developed at Wollongong University College. The electrical resistivity of the fly-ash was here measured, as nearly as possible under actual precipitator conditions, as described in the following paragraphs.

The hot flue gases were passed through a small cylindrical electrode precipitator where fly-ash was extracted with an efficiency of almost 100%. Still in contact with the flue-gases at constant temperature and without any contact with the outside atmosphere, the particles were deposited in a second cylindrical

electrode system with precise dimensions and equipped with guard-rings as befitting high-resistivity techniques. The particles were consolidated into position by controlled vibration. The electrode system was held to precise temperatures by eliminating all temperature gradients. Various voltages were applied to the electrode system inducing a range of electric field strengths in the particle layer.

The final results are shown in the form of a series of curves and tables. These show resistivity expressed as a function of temperature for fly-ash conditioned both by the natural flue gas (with and without the addition of  $\text{NH}_3$  and  $\text{H}_2\text{SO}_4$ ).

Alongside these results are shown resistivity/temperature values for the same particle samples which had been later thoroughly dried in a laboratory oven at elevated temperatures and then tested under the same electrical and thermal conditions as the in-situ tests.

The techniques used had been developed and tried over the preceding year by a series of laboratory tests and also in-situ tests at Tallawarra and Pymont Power Stations. The results of these developmental tests were discussed with officers of the Projects Division, when they were compared with results of fly-ash resistivities measured in other parts of the world. to the main system after the main air pre-heater. Since this point in the duct is operating at a negative pressure, a large pump would have been required if the gas had been discharged to the atmosphere. As it was, only a small centrifugal pump was needed to circulate the gas.

#### 4. DIELECTRIC JIG

A general view of the Dielectric Jig, and associated instrumentation, is shown in the foreground of Fig. 2.

## 2. ROLE OF THE E.C.N.S.W. AND THE COLLEGE

Firings of No. 4 Boiler at Pymont Power Station were under the control of the E.C.N.S.W. with various coals.

Temperatures and flow conditions at the exit of the 50kW pre-heater, together with any additives to the flue-gas were all under the control of the Projects Division of the E.C.N.S.W.

Staff from the Wollongong University College thus accepted flue-gases at the temperature already determined and with the dust-burden as already fixed, and removed small quantities of this gas just prior to the S.F. Pilot precipitator.

## 3. LAYOUT OF PLANT

A general schematic view of the layout of the important items of the plant is as shown in Fig. 1.

Gas from the No. 4 boiler passed through the air pre-heater, hence to the main precipitators and out through the stack. As part of the E.C.N.S.W. experimental plant, flue gas was drawn off both before and after the air pre-heater. After being circulated through a mixer/heat exchanger, the gas was drawn through a 50kW heater (not always operative). Between this heater and the S.F. Pilot Plant, the W.U.C. drew off samples of gas via the sampling probe.

After being tested in the W.U.C. equipment, the gas was returned to the main system after the main air pre-heater. Since this point in the duct is operating at a negative pressure, a large pump would have been required if the gas had been discharged to the atmosphere. As it was, only a small centrifugal pump was needed to circulate the gas.

## 4. DIELECTRIC JIG

A general view of the Dielectric Jig, and associated instrumentation, is shown in the foreground of Fig. 2.



The object of the Jig, is to measure the resistivity of any powder, but particularly of dispersoids carried in a gas. It aims to measure such resistivities under conditions which are as nearly as possible identical with those obtaining on the collecting electrode of an electrostatic precipitator. There are a number of other methods of measuring such resistivities, but all of them suffer from technical disadvantages making it difficult or impossible to repeat measurements, or to interpret the results obtained. The present Dielectric Jig is a significant advance on other devices as will become clear from the following description.

#### 4.1 ISOKINETIC SAMPLING OF GAS

The Sampling Probe (Fig. 1) is inserted into the gas stream to be tested in such a way as to extract representative samples of flue gas. The Probe nozzle was of  $\frac{1}{2}$ " diameter and extraction was isokinetic. A typical gas flow was about 2 CFM.

#### 4.2 ELECTROSTATIC COLLECTION OF PARTICLES

On being passed through the Electrostatic Precipitating Chamber of the Dielectric Jig, dust was extracted from the flue gas with an efficiency in excess of 99%. The cylindrical electrode system is most effective for this purpose since it removes all sized particles with reasonable efficiency, in contrast to other devices using point to plane collection when larger particles - far from being collected - may be actually repelled.

An adequate sample of dust being collected in about 45 minutes, the Precipitator Chamber is then rapped, upon which the dust falls into the annular space between the Electrodes in the Dielectric Jig as illustrated in Fig. 4.

\* "Mechanism of Current Conduction through Precipitated Fly-Ash".  
Bulletin No. 10, W.U.C. O.J. Tassicker, E. Harong, K. McLean.

#### 4.3 MEASURING ELECTRODES

The specimen to be measured thus is annular in shape, with a radial depth of a few millimetres so that the electric field within it is uniform. D.C. potentials of either polarity are placed across the Central and Outer Electrodes. The Outer Electrode has guard-rings at earth potential, ensuring a uniform field and eliminating edge effects, as befits high-resistivity techniques.

Ceramics of optimum thermal and dielectric properties support the base of the Central Electrode and are also used in several other critical places in the assembly.

#### 4.4 COMPACTION OF THE SPECIMEN

It is important to secure uniform and repeatable compaction in the specimen. At high temperatures, the dust tends to flow freely, and compaction can be achieved in a shorter time. The influence of compaction is illustrated by Fig. 6 which shows that after a period of vibration at a fixed frequency (100 cps) and acceleration of the Dielectric Jig, the resistivity does not change further. Compaction was thus always carried out in a repeatable manner.

#### 4.5 TEMPERATURE CONTROL

If meaningful results are to be obtained from any measurements on an intrinsic semi-conductor, close temperature control of the specimen must be obtained.

In an earlier work, the writers shown that a temperature error of 1°C made measurable changes in the resistivity of a specimen.\*

\* "Mechanism of Current Conduction through Precipitated Fly-Ash". Bulletin No. 10, W.U.C. O.J.Tassicker, Z.Herceg, K.McLean.

Referring again to Fig. 1 and Fig. 4, the gas is kept at a constant temperature from the time it enters the Sampling Probe through electrically heated piping to the Precipitator. The Precipitator Chamber and both Outer and Central Electrodes are individually heated and controlled so as to allow for greater precision. Different thermal time-constants in all parts of the system and heat-transfer between them must be considered if temperature gradients within the Chamber and across the Dust Specimen are to be kept below  $1^{\circ}\text{C}$ . Matched thermocouples in direct thermal contact with the Central Electrode and the Outer Electrode were joined in series opposition, so that small temperature differences could be detected and corrected during measurements.

Equipment used to control temperatures is illustrated in Fig. 3.

#### 4.6 GAS AND PARTICLE ENVIRONMENT

It will be observed that the equipment maintains the particles in a constant environment from the moment they are drawn into the Sampling Probe. Since the equipment is at an isothermal throughout and gas is passing through the Chamber at all times, the particles maintain their surface condition which plays such an important part in their bulk conduction properties.

In this equipment, the particles are not exposed to the atmosphere or to any other contaminating influence even for a short period. The vapour state of the flue-gas is also left unaltered.

However, the flexible thermal control enables the temperature of the Sampling Probe Post-Heater to be raised or lowered around the temperature of the gas in the main duct stream. Since the relationship between resistivity and temperature is of considerable

importance, the ability to change the temperature of the gas, dust specimen and Dielectric Jig at will is valuable.

#### 4.7 ASSOCIATED INSTRUMENTATION

A general view of the complete instrumentation is shown in Fig. 2. From left to right, is shown the:

Centrifugal Pump

Gas meter

Thermal Control Unit

30kV D.C. power supply

Dielectric Jig and Vibrator

Temperature Controller

Thermocouple monitor and galvanometer

500V D.C. power supply

Electrometer

Microammeter

2.5kV D.C. power supply

Since the resistivity of the dust is shown to vary from  $10^7$  to  $10^{15}$  ohm-cm, for a constant d.c. current through the dust layer, widely differing H.T. power supplies were needed.

Precipitation was carried out at between 10 and 15kV.

Low currents flowed in high-resistivity dust requiring the use of a sensitive Electrometer to measure them.

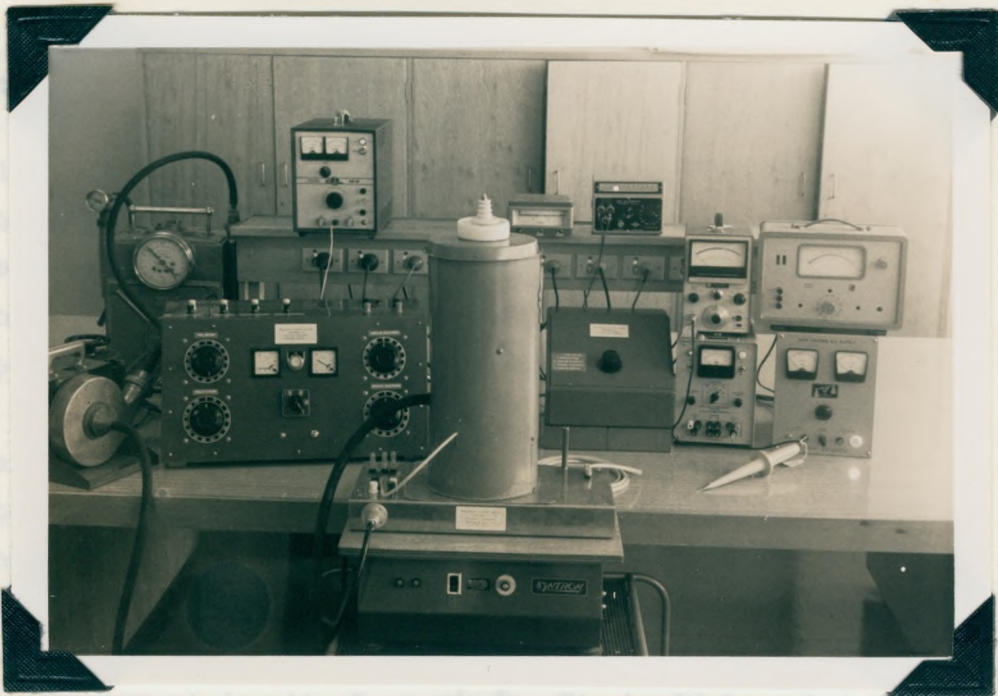


FIG. 2. General view of the Dielectric Dispersoid Jig and associated thermal and electrical instrumentation.

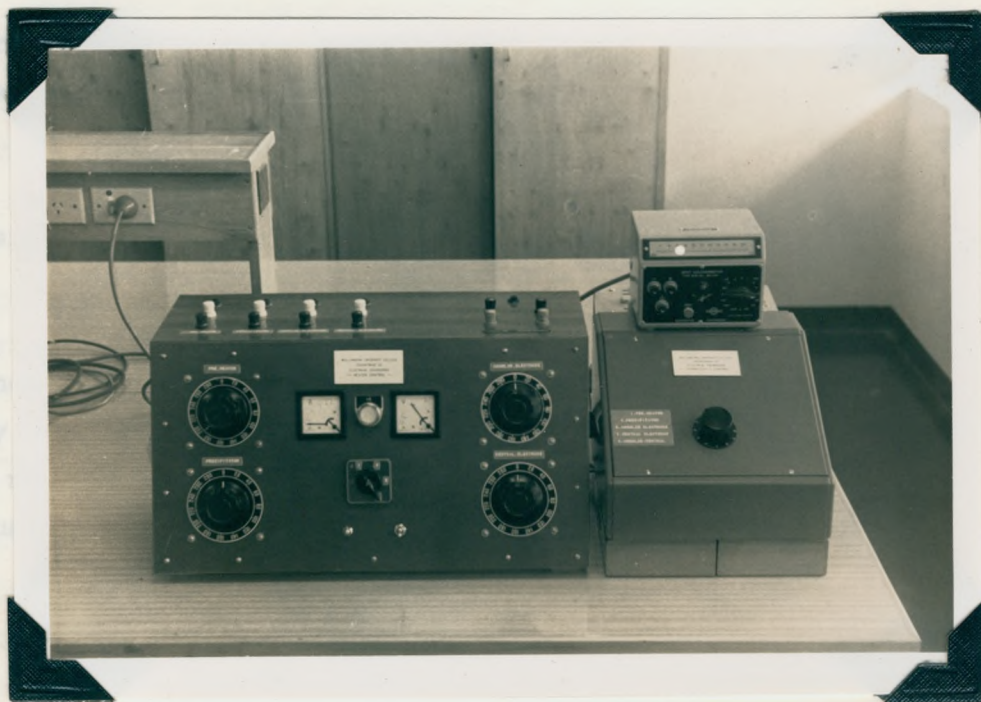


FIG. 3. Temperature control and measuring equipment.

#### 4.8 MEASUREMENT TECHNIQUES

The applied voltage between the Central and Outer Electrodes was raised successively with currents measured at each step, care being taken to distinguish between transient charging and steady-state effects. Results for rising and falling voltage were obtained since in some specimens hysteresis was exhibited.

A typical V/I curve is shown in Fig. 5 where it will be observed that the relationship is not linear. This phenomenon has been examined in an earlier study\* when a theory for dry dust conditions was proposed. It must be accepted that the resistivity of the dust is not constant but is a function of the electrical field strength  $F$  volts/cm or the current density  $J$  amps/cm<sup>2</sup>. It should be noted that the simple Ohms Law relationship is:

$$V = IR \quad \dots (1)$$

#### 5. RESISTIVITY MEASUREMENTS

For the annular dust specimen fixed by the simple geometrical shape of the cell described in Fig. 4,

$$R = \frac{RA}{L} \quad \text{ohm - cm} \quad \dots (2)$$

where  $A$  = cross sectional area of the dust specimens:

$$= (\pi DW) \text{ cm}^2$$

$L$  = depth of annulus cm.

Since  $L \ll D$ , logarithmic corrections are unnecessary, and in any case would be mistaken in principle since the dust resistivity is non-linear.

Equation (1) may be generalised in the usual way by writing:

$$\frac{V}{L} = \frac{I \cdot RA}{L}$$

$$\text{hence } F = J \rho \quad \dots (3)$$

\* loc. cit.

Since the resistivity is not linear, to be exact, it should be specified at either a particular field strength  $F$  or else at a particular current density  $J$ . This point is taken up more fully in Section 6 Commentary on Results, but at this stage it should be pointed out, that in a commercial precipitator, the corona current per unit receiving electrode is known within limits. Hence  $J$  is a more valuable parameter than  $F$ .

#### 4.9 LABORATORY TESTS

Laboratory tests were conducted on dust specimens collected in the Dielectric Dispersoid Cell in the field. They were removed to the Laboratory, and thoroughly dried in an oven for 48 hours. The moisture-free dust was then compacted in the Cell and electrically tested as previously described.

#### 5. RESISTIVITY - TEMPERATURE MEASUREMENTS

Two basic series of resistivity measurements were conducted. The first was on the fly-ash resulting from the firing of Newvale coal in No. 4 boiler at Pymont Power Station and the second was on Bayswater Coal fired in the same boiler. For each of these two coals, laboratory as well as in-situ tests were conducted. The laboratory tests were on dried dust samples, and at high temperatures where they may be properly compared, these tests confirm the field tests to a high level of correlation.

#### 5.1 NEWVALE SPECIMENS - IN-SITU

The in-situ tests on the Newvale fly ash were limited to a total of four separate specimens, each tested at a separate temperature. The sparse nature of the in-situ results from this coal is regretted, but was due to the fact that the Dielectric

Dispersoid Cell was then still under development.

The in-situ tests were carried out as described in Sections 2 to 4. A summary of the results for Newvale specimens, together with figures for moisture content in the flue gas and combustibile content in the fly-ash is shown in Table 1. Results for moisture-free ash as determined in the laboratory are shown in Table 2. These results are also depicted in Fig. 7 where they may be compared with Bayswater Coals. The resistivities for the Newvale fly-ash are displayed for a constant field strength of 1667 volts/cm. There is no special significance in this numerical value, except that it is compatible with the geometry of the Dielectric Dispersoid Cell and is of the same order of magnitude of values that might be expected in a commercial precipitator.

Predictably, the resistivity for the in-situ tests reached a maximum and then began to fall away rapidly at low temperatures. This familiar effect is due to the attachment of  $H_2O$  molecules to the surface of the particles.

Samples from other firings of Newvale coal during the same series of tests strongly indicated a parallel shift of the resistivity curve shown to values about five times higher. However, not enough data was available to conclude whether this was due to a change in combustion conditions or to random variations in the coal. Because of scant data they are not depicted in Fig. 7.

## 5.2 NEWVALE SPECIMENS - MOISTURE FREE

Upon drying the Newvale specimens in the laboratory oven and repeating the electrical tests, satisfactory agreement was obtained at high temperatures where coincidence was expected. More data here is obviously desirable, but that which was obtained is listed in Table 2.



### 5.3 BAYSWATER SPECIMENS - IN-SITU TESTS

The in-situ results for the Bayswater specimens are summarised in Table 3. Some eleven specimens collected at different times and adjusted to different temperature levels and all without the presence of conditioning agents, are shown. For the sake of completeness, data provided by the E.C.N.S.W. is shown alongside resistivity figures. These other factors, viz, mean particle size, combustible content in the fly-ash, water and carbon dioxide content in the flue gas are all presumed to have a possible effect on resistivity.

For each temperature, the resistivity was calculated at a field strength of 1.667Kvolts/cm and also at a current density of  $1.58 \times 10^{-8}$  amps/cm<sup>2</sup> ( $\frac{1}{4}$  14 micro-amp/sq.ft.)

The solid line curves in Fig. 7 depict the resistivity/temperature relationship for the Bayswater specimens. The in-situ results show the expected maximum in resistivity at the low temperature end.

### 5.4 BAYSWATER SPECIMENS - MOISTURE FREE

Upon drying the Bayswater specimens in the laboratory oven, the electrical tests were repeated, the results of which are shown in Table 4. Sufficient data is available to claim a good degree of correlation between the in-situ and moisture free tests at the high temperature end. The shape of the moisture free relationship, though not considered further in this report, agrees with intrinsic semi-conductor theory discussed in an earlier study.\* The specimen tested in the laboratory was a mixture of several samples from tests 66 to 76.

\* loc. cit.

### 5.5 BAYSWATER SPECIMENS - CHEMICAL CONDITIONING

The first conditioned flue-gas tests in which ammonia was added are summarised in the second section of Table 3. They showed such a surprising fall in resistivity, that all tests were conducted at about the same temperature in order to provide confirmation.

Whilst examining tests 94 and 95, it must be borne in mind that the quantity of conditioning agents injected was not very steady, difficulties in control being experienced.

Conditioning by sulphur trioxide, effected by injecting sulphuric acid into the flue-gas stream also brought a dramatic fall in resistivity. The first such test, No. 103, indicated such a low value of resistivity that, in order to verify that the order of magnitude was correct, other tests were conducted at about the same temperature.

### 6. COMMENTARY ON RESULTS

(a) The electrical resistivity of the specimens of New Vale and Bayswater fly-ash in the unconditioned states are of the same general shape and of the same order of magnitude.

(b) The resistivity/temperature dependence is of the expected form, with maxima occurring at the low temperature end.

(c) The general shape and order of magnitude of the results depicted in Fig. 7 are much the same whether the constant-current or constant-voltage modes are considered.

(d) It must be remarked that if current densities of  $1.6 \times 10^{-8}$  amp/cm<sup>2</sup> (14 micro-amps/ft) had actually been forced through some of the high resistivity specimens, breakdown would

TABLE 1

have occurred. Therefore such points on the curve were extrapolated from data measured at lower current densities.

Since current densities of 14 micro-amp, ft.<sup>2</sup> are quite normal in precipitator practice, it must be concluded that back-ionization would be present in unconditioned dust deposited on the collecting electrode.

(e) Either SO<sub>3</sub> or NH<sub>3</sub> conditioning effects a very large reduction in electrical resistivity. In this respect, SO<sub>3</sub> appears to be the more effective.

TABLE 2

RESISTIVITY OF MOISTURE-FREE NEWVALE FLY-ASH

(Results are shown in Fig. 7)

Sample From Test No.*	Temp. °F	Resistivity ohm-cm at F-1667 V/cm	Fly Ash †	
			mean size †	combustible %
10	265	2.4 × 10 <sup>13</sup>	11.2	8.1
12	280	1.5 × 10 <sup>13</sup>	11.3	8.5
12	280	8.9 × 10 <sup>12</sup>	11.3	8.5
12	450	4.8 × 10 <sup>11</sup>	11.3	8.5

\* E.C.R.S.W. Test No.

† Data supplied by E.C.R.S.W.

TABLE 1

IN-SITU RESISTIVITY OF NEWVALE FLY ASH  
(Results are shown in Fig. 7)

Test No.*	Temp °F	Resistivity ohm-cm at F=1667 V/CM	Fly Ash +		Gas Composition	
			mean size	combustible %	moisture %	CO <sub>2</sub> % <sup>2</sup>
10	265	1.1 x 10 <sup>13</sup>	11.2	8.1	6.2	12.0
12	281	9.7 x 10 <sup>12</sup>	11.3	8.5	4.7	12.0
12	343	2.7 x 10 <sup>12</sup>	11.3	8.5	4.7	12.0

TABLE 2

RESISTIVITY OF MOISTURE-FREE NEWVALE FLY-ASH  
(Results are shown in Fig. 7)

Sample from Test No.*	Temp. °F	Resistivity ohm-cm at F=1667 V/CM	Fly Ash +	
			mean size	combustible %
10	265	2.4 x 10 <sup>13</sup>	11.2	8.1
12	289	1.5 x 10 <sup>13</sup>	11.3	8.5
12	320	8.9 x 10 <sup>12</sup>	11.3	8.5
12	455	4.8 x 10 <sup>11</sup>	11.3	8.5

\* E.C.N.S.W. Test No.

+ Data supplied by E.C.N.S.W.

TABLE 3

"IN-SITU" RESISTIVITY OF BAYSWATER FLY ASH  
(Results are shown in Fig. 7)

Test No.*	Temp °F	Resistivity ohm-cm		Fly Ash <sup>+</sup>		Gas Composition		Conditioning	
		For E = 1,667 V/cm	For J = $1.58 \times 10^{-8}$ A/cm <sup>2</sup>	mean size	combustible %	moisture %	CO <sub>2</sub> %	agent	ppm approx.
66	200	$1.0 \times 10^{14}$	$2.5 \times 10^{13}$	11.6	12.7	6.4	11.4	none	
65	202	$5.9 \times 10^{13}$	$1.8 \times 10^{13}$	10.9	11.2	5.7	11.4	"	
60	220	$1.3 \times 10^{14}$	$4.3 \times 10^{13}$	11.8	8.9	6.9	11.8	"	
58	228	$1.7 \times 10^{14}$	$5.7 \times 10^{13}$	11.1	10.1	6.3	11.8	"	
90	250	$2.9 \times 10^{14}$	$1.1 \times 10^{14}$	10.1	8.9	7.3	12.2	"	
91	250	$2.5 \times 10^{14}$	$9.8 \times 10^{13}$	9.9	9.1	7.0	12.2	"	
61	275	$2.4 \times 10^{14}$	$8.0 \times 10^{13}$	10.0	9.4	5.9	11.8	"	
73	345	$4.6 \times 10^{13}$	$1.4 \times 10^{13}$	11.1	10.8	6.1	12.0	"	
74	420	$6.3 \times 10^{12}$	$2.1 \times 10^{12}$	10.2	9.9	5.9	12.0	"	
75	430	$5.4 \times 10^{12}$	$1.9 \times 10^{12}$	10.2	9.2	6.9	12.0	"	
76	430	$7.0 \times 10^{12}$	$2.1 \times 10^{12}$	10.3	10.5	6.5	12.0	"	
93	250	$5.3 \times 10^{10}$	$6.6 \times 10^{10}$	9.8	13.8	6.4	12.0	NH <sub>3</sub>	20
94	257	$4.5 \times 10^8$	$2.4 \times 10^9$	9.7	9.1	5.6	12.0	"	40
95	256	$6.6 \times 10^7$	$2.5 \times 10^7$	9.9	10.3	6.2	12.2	"	40
103	284	$5.0 \times 10^6$	$6.0 \times 10^7$	9.7	9.4	4.9	12.0	H <sub>2</sub> SO <sub>4</sub>	12
104	281	$1.6 \times 10^7$	$8.3 \times 10^7$	9.9	10.6	6.4	12.0	"	12
105	271	$1.5 \times 10^7$	$9.3 \times 10^7$	10.1	10.7	5.7	12.0	"	12
106	292	$1.0 \times 10^7$	$4.1 \times 10^7$	9.9	10.7	5.1	11.9	"	12
107	279	$1.5 \times 10^7$	$9.7 \times 10^7$	10.1	7.9	6.4	11.4	"	12

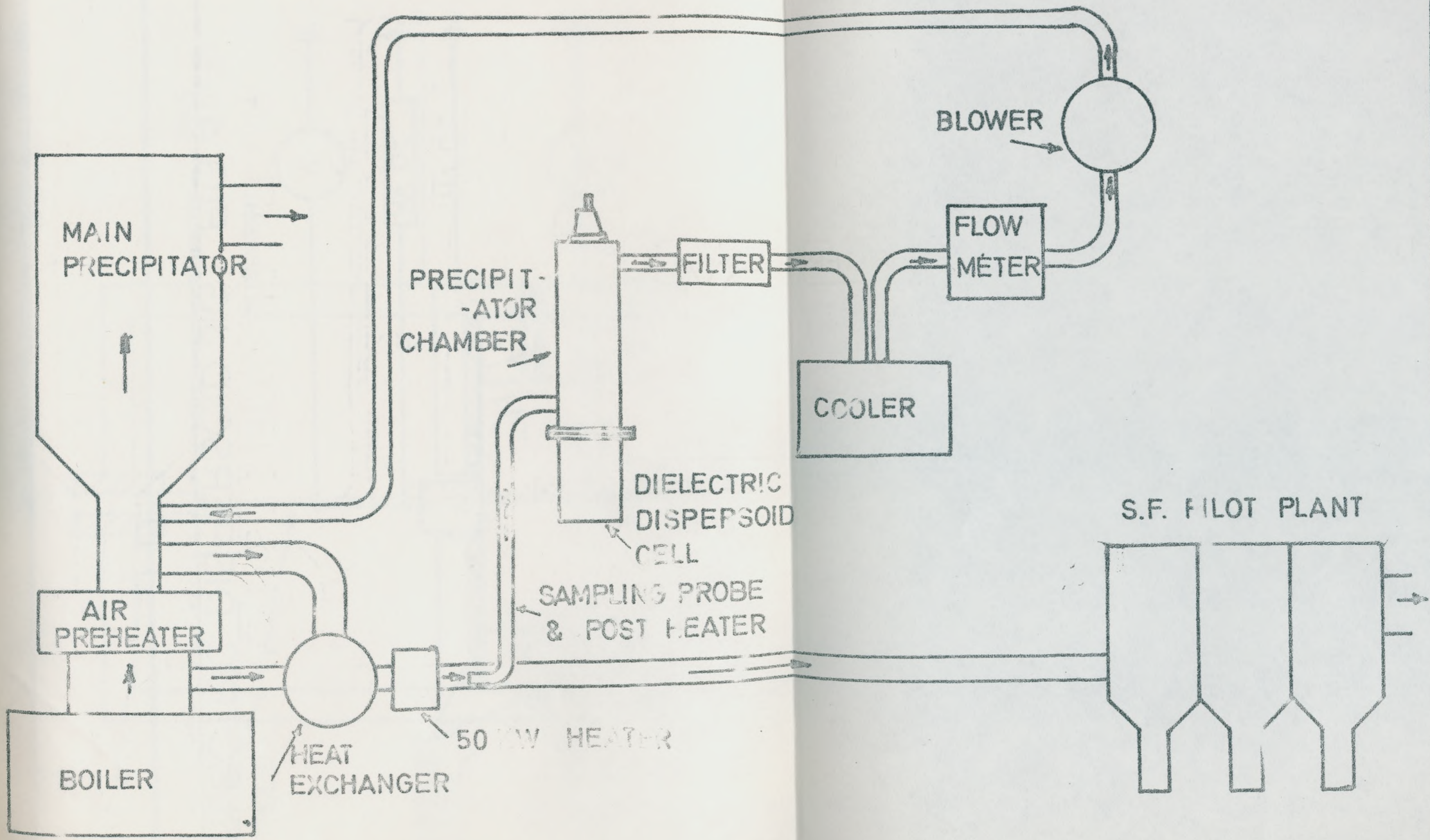
\* E.C.N.S.W. Test No.

+ Data Supplied by E.C.N.S.W.

TABLE 4

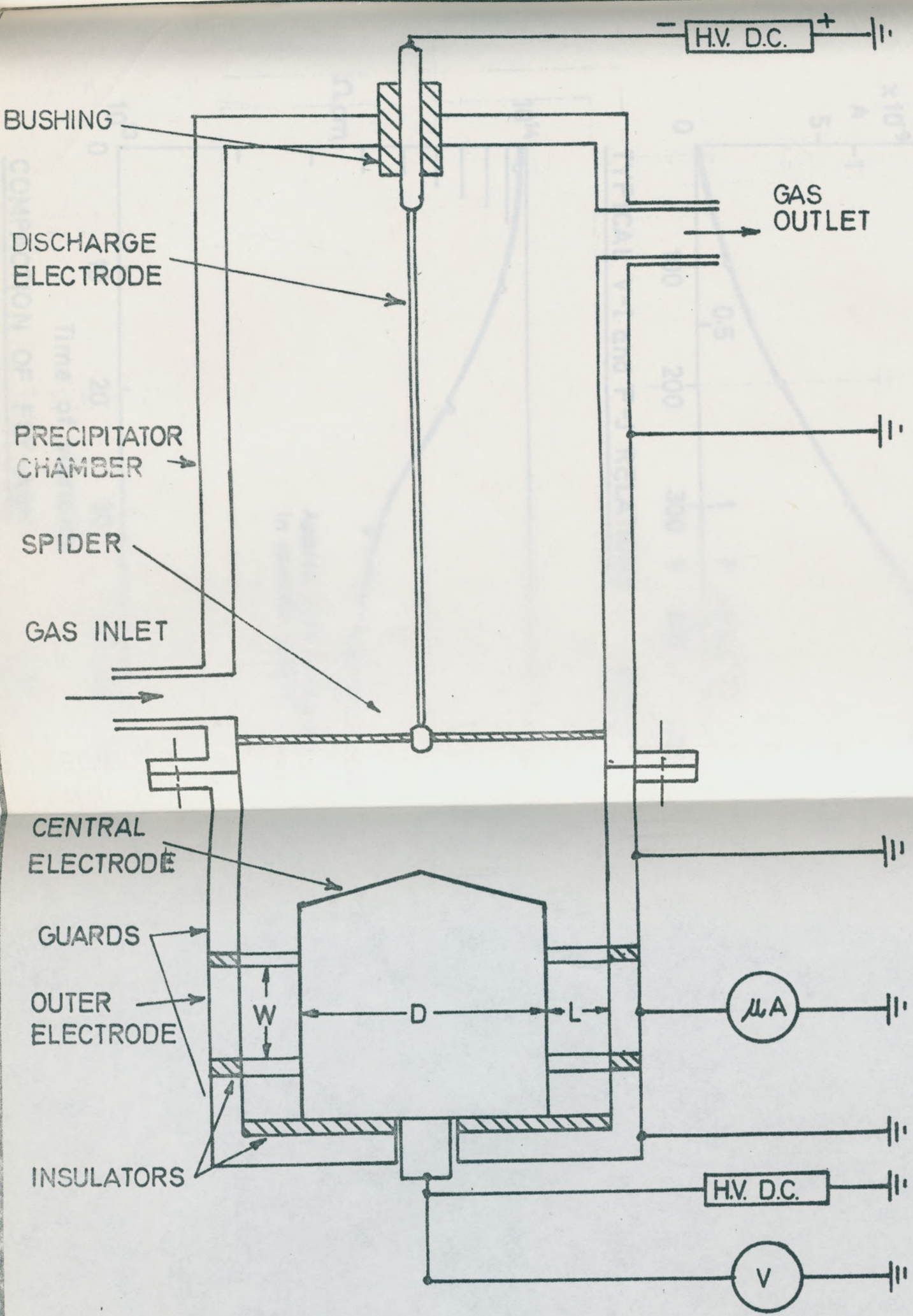
RESISTIVITY OF A COMPOSITE MIXTURE OF  
MOISTURE-FREE BAYSWATER FLY ASH

Temp. °F	E V/cm	Resistivity ohm-cm.
462	1,667	$2.3 \times 10^{12}$
394	1,667	$1.3 \times 10^{13}$
322	1,667	$9.7 \times 10^{13}$
270	1,667	$4.0 \times 10^{14}$
241	1,667	$8.9 \times 10^{14}$

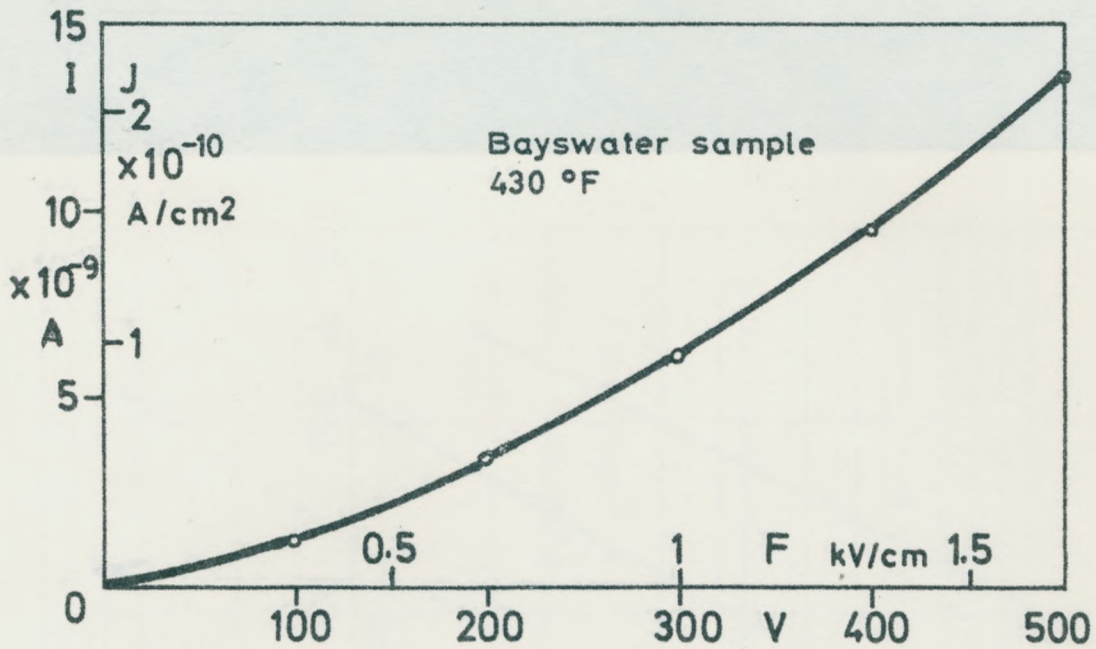


SCHEMATIC PLANT LAYOUT

FIG.1

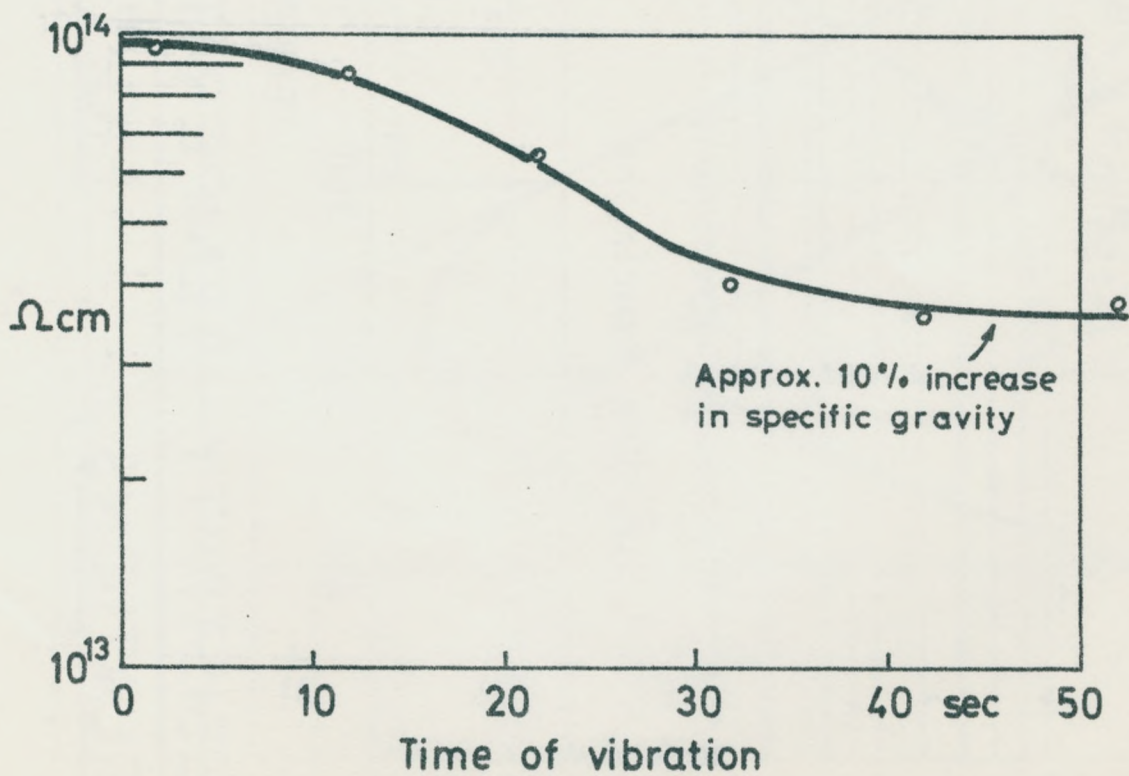


DIELECTRIC DISPERSOID JIG FIG. 4.



TYPICAL V-I and F-J RELATIONS

FIG. 5



COMPACTION OF FLY-ASH

FIG. 6





