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A STUDY OF THE FEASIBILITY OF SUPPRESSING INCENDIVE DISCHARGES IN ELECTROSTATIC PRECIPITATORS THROUGH THE USE OF RESISTIVE COLLECTOR PLATES

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A STUDY OF THE FEASIBILITY OF SUPPRESSING INCENDIVE DISCHARGES IN ELECTROSTATIC PRECIPITATORS THROUGH THE USE OF RESISTIVE COLLECTOR PLATES

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Abstract

The possibility of occurrence of energetic spark discharges precludes the use of conventional electrostatic precipitators for the filtration of gases containing flammable dusts or vapours. It has been suggested that the incendivity of such discharges might be suppressed if the collection electrodes were fabricated from a material having a suitably high electrical resistivity. For planar electrodes a simple physical model indicates that the required surface resistivity is dependent on the interplate spacing and electric field strength but is generally of the order $10^8\ \Omega$. Initial experimental observations are in reasonable agreement with the predictions of the model but show an unexpected feature, namely that the suppression effect is nullified when the electrode surfaces are contaminated with particles. Since it is impossible in most precipitator applications to ensure that the collection electrodes will not become contaminated with particles or with films of conducting liquids, it must be concluded that the concept of ignition suppression through the use of resistive plates does not represent a practical approach to the design of intrinsically safe electrostatic precipitators.

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1. INTRODUCTION

Electrostatic precipitators are widely used in industry to reduce the dust content of effluent gases(1). The cleaning of gases by electrostatic precipitation involves two basic steps; firstly, the incoming dust particles are given an electrostatic charge and, secondly, they are deflected by an applied electric field to a collection surface and thus removed from the gas. In a 'single stage' precipitator both processes take place simultaneously in the same region and the dust burden is reduced continuously as the gas flows through the precipitator. One commonly-used electrode arrangement consists of an array of parallel grounded metal plates between which are placed filamentary electrodes, in the form of thin or barbed wires for example, maintained at a high potential. The incoming dust particles acquire charge under bombardment by the ions generated by corona discharges at the high voltage electrodes and are then drawn to the plates under the influence of the electric field. For the cleaning of gases with high dust content several such precipitator units may be employed in series. In the 'two stage' type of precipitator the charging and collection functions are performed in separate sections of the equipment. In this case the collection electrodes usually comprise a set of vertical grounded metal plates interleaved with similar plates held at a high potential.

The two-stage precipitator is generally preferred in applications where the particulate burden is fairly low as, for instance, in ventilation systems. In order to achieve a high capture efficiency the collection electrodes are normally maintained at a potential close to the limit set by electrical breakdown between the plates or over the insulating supports. Whilst certain measures can be taken to reduce the likelihood of discharges, as well as their duration and effect when they do occur, the possibility of energetic spark breakdowns cannot be entirely eliminated. Moreover, since these spark discharges are easily capable of causing ignition, conventional electrostatic precipitators cannot safely be used to filter gases containing flammable vapours or dusts.

To overcome the ignition hazard the energy available in spark discharges must be limited to values below the minimum ignition energy of any flammable gas mixtures liable to be present. This aim might be accomplished through the use of collector plates having a sufficiently high electrical resistivity, an idea suggested by Chubb and independently by Thompson, Fielding and Clark[2,3]. In a discharge between two conducting plates the whole of the electrostatic energy stored in the field between them is available for dissipation in the spark channel. The short timescale of the spark and the high energy density within the channel favour an efficient transfer of energy to the developing flame kernel in the gas. With electrically resistive plates, on the other hand, it should be possible to control the rate of flow of energy into the spark channel so that only a fraction of the total stored energy would be available within the timescale required for efficient thermalisation.

A simple physical model of the electrical breakdown between plane parallel electrodes, presented in section 2, suggests that the surface resistivity of the plate material should be greater than about $10^8 \Omega$ in order to avoid an ignition risk with common hydrocarbon-air mixtures. Since the current associated with the deposition of particles on the plate is relatively low, of the order $1\mu A$, and is distributed over a substantial fraction of the total plate area, the conductivity of such resistive plates will generally be adequate to support the normal particle collection current without an excessive potential drop over the plate area.

Attempts to fabricate carbon-loaded plates with the required resistivities initially encountered considerable difficulty in achieving both a sufficiently homogeneous resistivity within a given sample and a repeatable value from one sample to the next. This problem was eventually overcome through refinements of the casting and curing techniques and a small number of specimen plates having reasonably uniform resistivities in the required range were produced. A limited experimental study was made on the incendivity of discharges between pairs of these resistive plates situated in the most easily ignited mixture of propane and air. The results from these tests cannot be regarded as definitive but they appear to rule out the resistive plate approach as a practical method of suppressing incendive discharges.

2. MODEL OF IGNITION SUPPRESSION BY RESISTIVE PLATES

In the case of conducting collection plates essentially all of the electrostatic energy stored in the capacitor formed by the plates is available for dissipation in any accidental spark discharge between them. Also, unless it is well decoupled, the external circuitry supplying the interplate potential may contribute an additional amount of energy. Considering the simplest case of two plane parallel plates of opposing area A and separation d, electrically decoupled from the high voltage supply, the energy U available at breakdown is given by

$$U = \tfrac{1}{2} CV^2 \qquad (1)$$

$$= \frac{\varepsilon_o A}{2d} V^2 \qquad (2)$$

where C is the interplate capacitance and V the voltage at breakdown. Equation 2 can be written in terms of the electric field strength at breakdown, E_b, as follows

$$U = \left(\frac{\varepsilon_o A}{2}\right) E_b{}^2 d \qquad (3)$$

Table 1 gives corresponding values of E_b and d for clean plates at atmospheric pressure and 20^oC[4]. Also tabulated are calculated values of the energy stored on a capacitor having plates of area 0.0333 m^2, which corresponds to the area of the plates used in the investigations described in section 4.

Table 1 Electrical breakdown field strength for plane parallel plates and corresponding electrostatic energy stored by plates of area 0.0333 m^2

Separation d mm	Breakdown field E_b MVm^{-1}	Stored energy U mJ
1	4.54	3.0
2	3.95	4.5
3	3.67	5.9
4	3.50	7.1
5	3.40	8.4
6	3.30	9.5
8	3.21	12.0
10	3.13	14.3
20	3.00	26.2

These energy values are at least one order of magnitude greater than the minimum ignition energy of common hydrocarbon gas-air mixtures, namely about 0.25 mJ[5].

We now consider the case when the capacitor plates are made from a thin sheet of material having surface resistivity ρ. Since there is little information on the characteristics of electrical discharges between resistive surfaces it has not been possible to derive a rigorous relationship between the discharge energy and the geometrical and electrical parameters. The following physical model of the discharge leads to a relationship that is at best only approximate and needs to be substantiated experimentally.

It seems reasonable to suppose that the energy available for release in a discharge between the plates will be made up of two components. The first part will consist of the energy associated with the direct discharge of a limited region of the plates, centred around the point of inception of the discharge, whilst the second will comprise an additional amount of energy that can be fed into the discharge channel from surrounding areas within some critical time scale related to the time for development and decay of the discharge. An indication of the area of plate susceptible to direct discharge is provided by some early studies of Lichtenberg figures(6). These figures reveal the extent of localised breakdown events over charged dielectric surfaces and may be obtained by means of photographic emulsions or by dusting with charged powders(7). The studies described in Reference 6 relate to the patterns on photographic plates generated by discharges from the point of contact of a small rod electrode with the emulsion, which is supported on a glass sheet over a grounded metal backing plate. The conducting rod in this arrangement may be regarded as analogous to the discharge channel between the resistive plates. Table 2 gives values of the energy calculated for discharges between thin dielectric plates using the radii of Lichtenberg figures quoted by Cobine(6). These energy values are likely to be overestimates since (a) the full supply voltage has been assumed to be available from the foot of the discharge channel and (b) the pattern size corresponds to Lichtenberg figures in the presence of a grounded backing plate, whereas the pattern will be smaller in the absence of such a plate.

The resistance to radial current flow across a narrow annular element of plate surface of width dr at a radial distance r from the axis of the discharge channel is given by

$$R = \frac{\rho}{2\pi r}\,dr$$

The resistance of the annular region between concentric circles of radii 1 and r_2 is thus

$$R = \frac{\rho}{2\pi}\ln\frac{r_2}{r_1}$$

The interplate capacitance element C corresponding to this annular region is given by

$$C = \frac{\varepsilon_o \pi}{d}\left(r_2^2 - r_1^2\right)$$

The time constant τ for charge redistribution in the region of plate around the discharge channel can thus be expressed as

$$\tau = RC = \frac{\varepsilon_o \rho}{d} \left(r_2^2 - r_1^2\right) \ln \left(\frac{r_2}{r_1}\right)$$

The resistance term has been doubled in the above equation, on the assumption that the current flow takes place equally in both plates. In the case of a stacked array of collector plates the capacitance term should also be doubled. Since the purpose of the calculation is to deduce the critical value of ρ for the suppression of incendive discharges, the value of r_2 could be taken as the radius of the circular region that could just store the minimum ignition energy U_o for a given plate spacing and potential. With this criterion

$$U_o = \tfrac{1}{2} CV^2 = \frac{\varepsilon_o \pi}{2d} r_2^2 V^2 = \tfrac{1}{2}\pi \varepsilon_o r_2^2 E^2 d$$

and therefore

$$r_2 = \frac{1}{E} \left(\frac{2U_o}{\pi \varepsilon_o d}\right)^{\frac{1}{2}}$$

The value for r_1 should be taken as the radius of the discharge channel. The results are fairly insensitive to the value of r_1 and the value 10^{-4}m will suffice for present purposes. For efficient transfer of thermal energy from the discharge to the incipient flame kernel the timescale of the discharge must lie in the range 10^{-4} to 10^{-3} s(8-10). In order to allow some margin of safety, the longer time should be chosen as a target value for τ. For many common hydrocarbon gases the minimum ignition energy U_o may be taken as 0.2 mJ, though it should be noted that a few common gases, notably hydrogen, acetylene and carbon disulphide vapour, have considerably lower minimum ignition energies(5). Values of the plate resistivity necessary to limit the discharge energy to below 0.2 mJ have been calculated from the above relationship for various values of the interplate gap and electric field strength and the results are presented in Fig.1.

3. FABRICATION OF THE RESISTIVE PLATES

The resistive plates used in the present investigations were made at AERE Harwell and consisted of a suspension of carbon particles in an amine-cured epoxy resin. A master batch was first prepared by the addition of 5% by weight of acetylene carbon to Araldite HY932 amine hardener. To this batch was added Araldite MY750 epoxy resin and sufficient amine hardener to maintain the ratio (weight of resin/weight of hardener) equal to 100:32 in the resulting mixture. After thorough mixing, the liquid was outgassed in vacuum before being poured into moulds and allowed to cure in an oven at 60°C for several hours. The dimensions of the resulting plates were approximately 260 x 225 x 2 mm. Following removal from the moulds, the plates were cleaned with propan-2-ol and a mild abrasive and the resistance between opposite edges was measured with a multi-megohmeter. The relationship between the carbon loading and the surface resistivity of the material is shown in Table 2.

Table 2 Resistivities of the plates as a function of carbon content

Weight per cent of carbon	Surface resistivity (Ω)
0.90	5×10^{10}
0.96	2×10^{8}
0.98	3.3×10^{7}
1.10	1.3×10^{7}

The very sensitive dependence of resistivity on the carbon content in the resistivity region of interest initially caused much difficulty in achieving the resistivity values required, as well as a sufficient degree of homogeneity over the plate. Details of the manufacturing techniques and the steps taken to overcome the initial difficulties are therefore described more fully in the Appendix.

4. THE INCENDIVITY EXPERIMENTS

4.1 The experimental arrangement

Investigations of the incendivity of discharges between resistive plates utilised the apparatus illustrated in Fig.2. Air and commercial-grade propane metered through 'Rotameter' flow gauges were passed through a mixing chamber and thence via a non-return valve and flame trap into the acrylic ignition cell.

In addition to a non-return vent to the outside atmosphere the cell was provided with an explosion-relief diaphragm in the form of a disc of thick card affixed by a ring of silicone grease over a large circular aperture in the top of the chamber.

The incendivity observations were all performed with the most easily ignited propane-air mixture, containing approximately 5% propane by volume. The gas composition corresponding to the minimum ignition energy was determined empirically using spark discharges of known energy between two 50 mm diameter metal spheres situated in the chamber. The upper sphere was connected to a high voltage supply unit via a decoupling lead having a resistance of the order 10^{10} Ω, whilst the lower one was grounded via a decoupling resistance of 10 MΩ. Thus the energy available for dissipation in the spark channel was determined by the intersphere capacitance and the potential at breakdown and could be varied simply by adjusting the separation of the spheres. The spark energy is given by

$$U = \tfrac{1}{2}CV_b^{\,2}$$

where C is the intersphere capacitance and V_b is the breakdown potential. The capacitance was determined from the expression given by Smythe[11] for the capacitance of a sphere of radius a with respect to an infinite grounded conducting plane at a distance d from the centre of the sphere:

$$C = 4\pi\varepsilon_o a \sinh\alpha \sum_{n=1}^{\infty} \operatorname{csch} n\alpha$$

where α is defined by cosh α = d/a. The second sphere can be considered as being formed by the image of the first sphere in the ground plane hence, taking a factor 2 into account, the capacitance of the two spheres can be written

$$C = 2\pi\varepsilon_o a \sinh \alpha \sum_{n=1}^{\infty} \operatorname{csch} n\alpha \qquad (4)$$

where $S = 2a \cosh\alpha$ is the distance between the centres of the spheres. The relationship between capacitance and sphere separation was obtained from a computer solution of the above equation for 50 mm diameter spheres and is shown in Fig.3.

The breakdown potential for the 50 mm diameter spheres was measured as a function of separation and the results are shown in Fig.4. Figure 5 gives the electrostatic energy of the two spheres as calculated from equation (4) with the values of V_b taken from Fig.4. If the HT supply voltage V_s is applied to the upper sphere its potential will increase with time according to the relation

$$V = V_s \left(1 - e^{-\frac{t}{RC}}\right)$$

where C is the intersphere capacitance and R is the resistance of the charging lead. Since C is a few picofarads and R is of order 10^{10} Ω, the charging time constant RC is about 0.1 s. If $V_s > V_b$, breakdown of the gap will occur when $V = V_b$; the sphere will then recharge with time constant RC and repetitive sparks of well defined energy $\frac{1}{2}CV_b^2$ will result. It will be noted that variation in the supply voltage will cause only a change in the spark repetition rate and will not affect the spark energy. Thus, for a given sphere separation the spark energy can be determined from the curve in Fig.5.

4.2 Optimisation of the gas composition

In the ignition tests the propane-air mixture was passed through the ignition chamber at a steady rate for several minutes, after which the flow was stopped. The potential was then applied to the upper sphere and adjusted to give a convenient rate of sparking with a known gap, such that the sparks could be individually counted. To allow for the statistical nature of spark ignition at least 100 discharges without any resulting ignition were allowed to occur before concluding that the sparks under those particular conditions were not incendive.

With a given gas mixture the discharge energy was reduced until ignitions no longer occurred, thus establishing the minimum ignition energy for that composition. The results obtained are shown in Fig.6, together with those of Lewis and von Elbe[5] for comparison. The difference between the two curves is not surprising in view of the relative simplicity of the present arrangement and is not significant for the purpose of these tests. It is possible that much of the discrepancy arises from the use of commercial-grade propane in the present work. This grade contains significant proportions of other hydrocarbons, which are known to influence the ignition characteristics of the mixture[12]. The present observations indicate that the most easily ignitable mixture contains approximately 5.6% commercial propane and has a minimum ignition energy of 0.16 mJ; this mixture was used in all subsequent tests.

4.3 Incendivity of discharges between conducting plates

As a preliminary to tests with the resistive plates, the incendivity of discharges between two plane parallel metal plates was investigated. These plates had lateral dimensions of 190 x 175 mm and a thickness of about 3 mm, with rounded edges to prevent corona discharge. The upper plate was gradually raised to a high potential via a decoupling lead having a suitably high resistance. For plate separations greater than the quenching distance, about 2 mm for this gas composition, explosions occurred immediately spark breakdown was initiated. As Table 1 shows, the stored energy is at least an order of magnitude greater than the minimum ignition energy. At a separation of 5 mm, for example, a plate area of only 8×10^{-4} m^2 (e.g. square plates with 28 mm sides) would suffice to provide the minimum ignition energy.

4.4 Incendivity of discharges between resistive plates

The plates prepared at AERE Harwell and having the resistivities shown in Table 2 were tested in a 5.6% propane-air mixture in a similar way to the metal plates. Voltages up to 20 kV were applied to the plates via a 10 MΩ decoupling resistor and the plate separation was varied between 3 and 6 mm.

No explosions were obtained using the pairs of plates having surface resistivities of 5×10^{10} Ω, 2×10^{8} Ω and 3.3×10^{7} Ω, although several weak localised spark-like discharges were detected, followed by a purple glow in the space between the plates. It was thus concluded that, although the capacitor formed by the plates stored a total quantity of electrostatic energy comparable to that stored on the similar metal plates (about 5 mJ), only a small fraction of this appeared to be available for dissipation in a concentrated discharge channel. The plates having a surface resistivity of 1.3×10^{7} Ω permitted incendive discharges. The critical value of surface resistivity required to prevent incendive discharges thus appears to lie within the range 1.3×10^{7} Ω to 3.3×10^{7} Ω. This observation is in good agreement with the predicted value of 4×10^{7} Ω, bearing in mind the uncertainties and approximations inherent in the model.

4.5 Effect of particulate contamination

The effect of the presence of particulates on the incendivity behaviour was examined using particles of iron powder and of filings from one of the highly resistive plates. With either kind of particulate present a relatively energetic discharge was observed when the voltage was first applied to the plates. In all cases this single discharge proved to be incendive, even with the plates having the highest surface resistivity of 5×10^{10} Ω. A typical sample of the iron particles is shown magnified in Fig.7. The particles are seen to have rough surfaces and sharp edges. The latter in particular are likely to act as stress concentrators, thus favouring the development of a localised high density discharge channel.

4.6 Visual appearance of the discharges

Discharges between metal plates appeared as distinct, intense purple-white streamers. In the case of resistive plates on the other hand, several faint pink-white discharges occurred over a localised region of the plate at a critical potential as the applied voltage was increased. Following these initial discharges a diffuse purple glow spread out over the whole surface of the negative plate. The current drawn from the HV supply increased rapidly to a limiting value and thereafter the applied potential could be reduced while maintaining the diffuse purple glow.

When particles of iron powder or material filed from the resistive plates were scattered on the lower electrode the initial breakdown took the form of a single energetic pink-white discharge followed by the onset of the glow discharge. Again, the voltage could be subsequently reduced while maintaining the glow. An I-V characteristic showing this hysteresis is shown in Fig.8. After prolonged exposure to discharges particular areas of the plates became pitted and Fig.9 shows a scanning electron microscope photograph which includes several of these erosion pits.

4.7 Observation of the discharge current characteristics

Two types of current probe used to record the characteristics of discharges from resistive surfaces are shown schematically in Fig.10. In the first version, depicted in Fig.10a. the probe comprised a 4 mm diameter metal cylinder having a domed end which protruded slightly through a circular hole in a conducting plate. This cylinder was supported by a 40 mm diameter copper disc which was grounded via ten 10 Ω low inductance resistors spaced uniformly around the circumference. The signal developed in this 1 Ω resistance by discharges to the probe was monitored on an oscilloscope having an input impedance matching the interconnecting 50 Ω coaxial cable.

The second probe, shown in Fig.10b, consisted of a metal rod of diameter 2 mm with a rounded end slightly protruding through a circular hole in the grounded plate. The other end of the rod was joined to a coaxial hollow metal cylinder, the top of which was fixed to the metal plate. A single loop magnetic flux coil was placed close to the outer cylinder to detect the flux change associated with the discharge current pulse to the probe. Since the signal from the coil is proportional to $\frac{dB}{dt}$ and hence to $\frac{di}{dt}$, the flux coil was connected to the oscilloscope through a simple integrating circuit so that the discharge current profile was displayed directly. Owing to time limitations the probe was not calibrated but used only for comparison of pulse heights.

Discharges from a positively charged metal plate at a separation of 5 mm from the grounded plate gave current traces having a rise time of a few nanoseconds, a peak value of several amperes and a decay time constant of approximately 30 ns. Discharges between the resistive plates and the conducting ground plate showed similar current profiles but with much reduced amplitudes. Table 3 summarises some preliminary observations on these discharges. Plates made from a sheet of carbon paper pasted onto an insulating board were also tested but these were found to decompose rapidly under discharges.

The value of these measurements is limited by the fact that only one of the plates in the parallel plate arrangement was resistive. The observations nevertheless demonstrate qualitatively the reduced discharge currents that characterise discharges from poorly conducting surfaces.

5. DISCUSSION AND CONCLUSIONS

The proposition that the incendivity of electrical discharges between oppositely charged plates can be suppressed by the use of plates made from a suitably resistive material has been demonstrated experimentally. A simple physical model of the breakdown process between resistive electrodes shows that the required resistivity value depends on the interplate gap and electric field strength at breakdown. For a plate gap of 6 mm and breakdown field strength of 3 MVm^{-1} the value of surface resistivity needed to prevent ignition of the most easily ignited propane-air mixture was found experimentally to lie somewhere in the range $3.3 \times 10^7\ \Omega$ to $1.3 \times 10^7\ \Omega$. For these conditions the critical resistivity predicted by the model lies between $5 \times 10^7\ \Omega$ and $5 \times 10^8\ \Omega$, depending on the optimum thermalisation time assumed for the gas mixture. The agreement between the predicted and observed values is considered satisfactory in view of the uncertainties and approximations involved.

It was found that discharges between resistive electrodes on the surface of which particles had been loosely deposited could be incendive even with high plate resistivities. The reason for this behaviour is uncertain but it is possible that the particles act as electrical stress concentrators which favour a more continuous arc-like discharge with a localised high density current channel.

Though this proposition was not tested in the present experiments it is reasonable to expect that the effect of the resistive electrode material would also be nullified if the plates became coated with a conducting film. Such a film might result from a combination of condensed moisture and an accumulation of ionic compounds on the electrode surface, for example.

The sensitivity of the incendivity suppression to the state of cleanliness of the electrode surface appears to preclude the resistive collector plate approach to the design of intrinsically safe electrostatic precipitators. The principle of ignition suppression described here may, however, find application in situations where the above limitation would not apply.

Acknowledgement

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Table 3 Summary of observations on discharges between plates of various materials and a grounded metal plane. Interplate gap = 5 mm

Positive plate	Surface resistivity Ω	Rise time ns	Decay time constant ns	Current amplitude A
Metal	$\sim 10^{-7}$	10	30	30
Polymer A[1]	3.3×10^{11}	10	45	0.15
Polymer B[2]	1.2×10^{9}	10	15	0.8
Polymer C[3]	4.6×10^{7}	4	9	0.15
Polyurethane film	8×10^{11}	10	30	0.6
Polypropylene	8×10^{11}	10	12	1.5
Nylon	$\sim 10^{10}$	10	12	1.5
Harwell plates	$\sim 10^{9}$	10	45	0.5

1 54% suspension PVC paste polymer, 43% phthalate stabiliser, 2.8% tribasic lead sulphate stabiliser

2 54% emulsion PVC paste polymer, 43% synthetic triaryl phosphate, 2.8% stabiliser

3 polymer containing quaternary ammonium antistatic agent

APPENDIX

Notes on preparation of resistive electrodes

In the first plates to be manufactured the resistivity was found to vary by several orders of magnitude over different regions of the plate. To test the uniformity, resistivity measurements were made in mutually perpendicular directions and, in addition, some plates were cut into quarters and the observations repeated on the resulting pieces. Some typical measurements are shown in Fig.A1.

During the casting and curing process the plates were held in a vertical plane and it was suspected that sedimentation of the carbon particles might be responsible for the lack of uniformity since the resistivity is a sensitive function of the carbon loading[13,14]. To test this proposition some of the plates were cut into strips about 10 mm wide and the resistances of these strips measured. The resistivity of the material could then be plotted as a function of the distance from the bottom or side of the plate, with respect to the orientation in which the plates were cured. Typical measurements are shown in Figs.A2 and A3 for the case of a plate cut into horizontal strips. Those of Fig.A2 showed a factor of 10^5 increase in resistivity from the bottom to the top, strongly supporting the suggestion that the carbon particles gravitate to the bottom during casting and curing. Further confirmation is provided by the observation, illustrated by Fig.A4, that the resistances of vertical strips are relatively constant across the plate.

The first plates to be prepared were cured for 6 hours at $100^{o}C$. In an attempt to avoid sedimentation, the curing of subsequent plates was performed for a longer time of 20 hours at the lower temperature of $60^{o}C$. Sample strips trimmed from the edges of the first few plates prepared in this way showed little regional variation of resistivity and these plates were employed for the incendivity investigations.

Whilst the relations developed in section 2 refer to the surface resistivity, for experimental convenience the resistivity of the sample plates was measured and expressed in terms of the normal volume resistivity $\rho_\nu(\Omega.m)$. The term surface resistivity is often used to describe current flow over a surface, as with antistatic coatings for example, and is defined as the resistance between opposite edges of a unit square. The resistance across a square is independent of its size and the units of surface resistivity is the ohm, though the description 'ohms per square' is sometimes used. In reality, however, a conducting surface must consist of a conducting layer of finite thickness t, thus the effective surface resistivity ρ is related to the volume resistivity of the layer by

$$\rho = \frac{\rho_\nu}{t}$$

Since the thickness of the plates used in these studies, namely 2 mm, was small compared to their lateral dimensions and to the plate separation it is reasonable to assume a uniform current distribution throughout the thickness of the plate. The effective surface resistivity of the 2 mm thick plates is thus given by $\rho = 500\ \rho_\nu(\Omega)$.

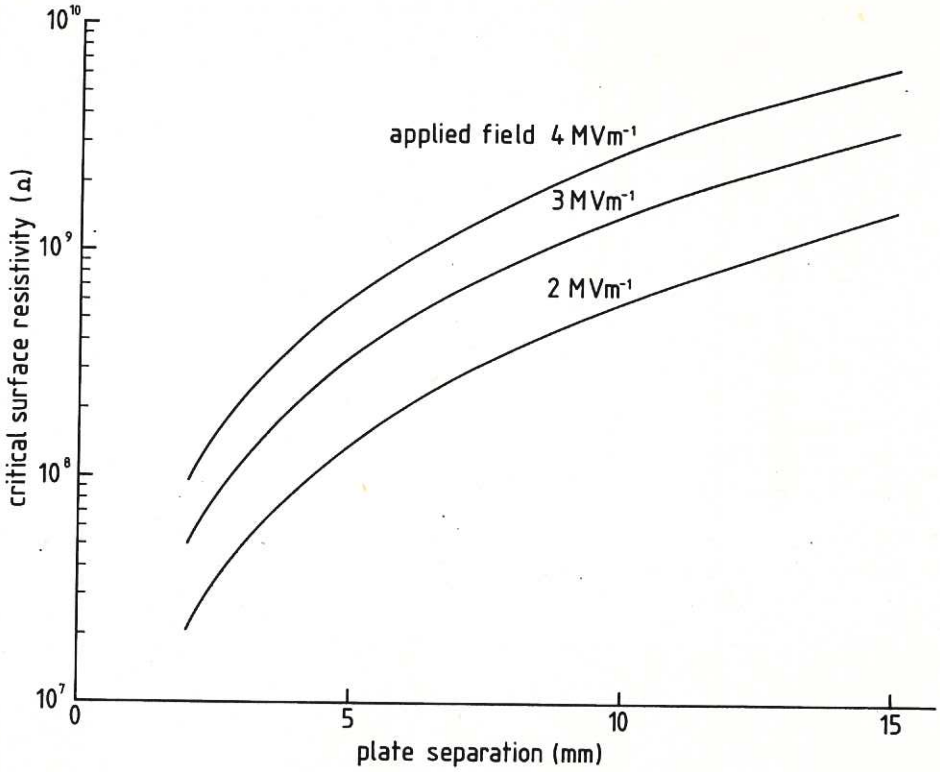

Fig.1 Calculated values of the critical electrode resistivity for ignition suppression, assuming a thermalisation time of 10^{-3} s.

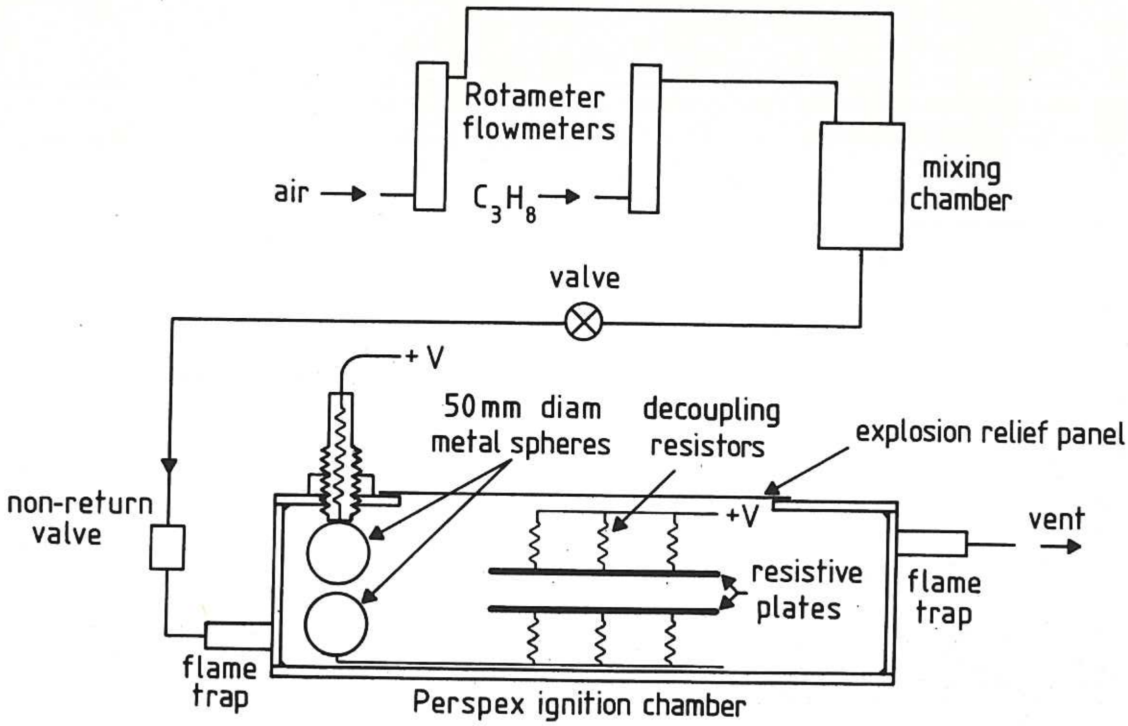

Fig.2 Schematic diagram of the experimental arrangement for the incendivity tests.

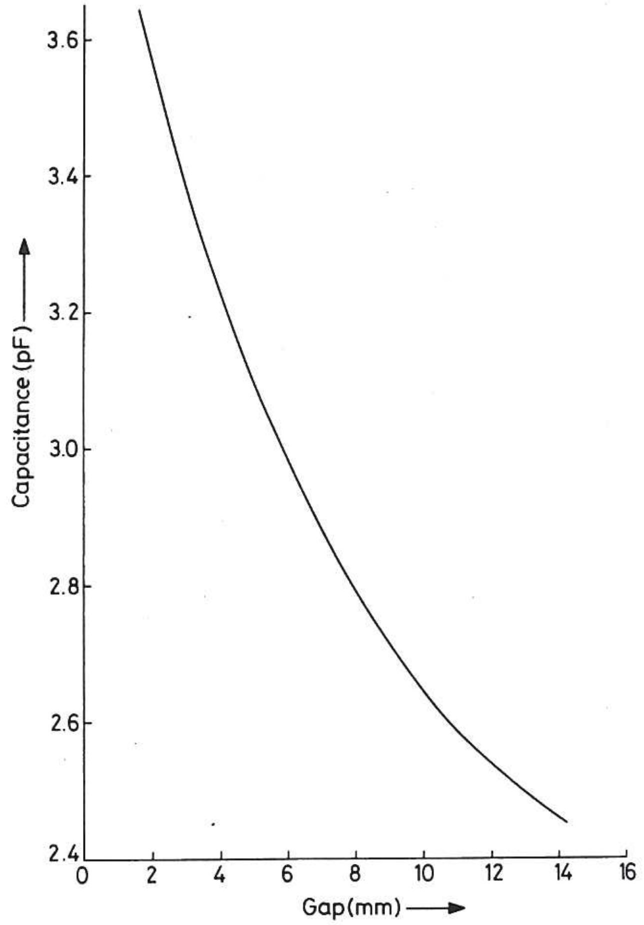

Fig.3 Computed relationship between capacitance and intersphere gap for 50 mm diameter spheres.

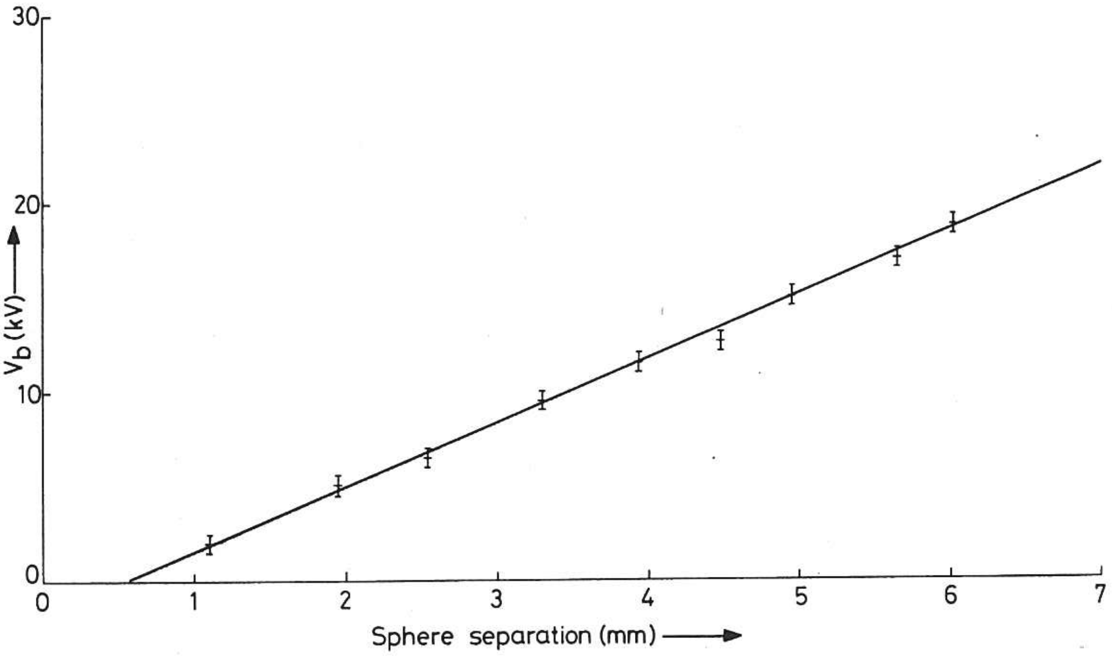

Fig.4 Measured breakdown potential for the 50 mm diameter spheres as a function of the intersphere gap.

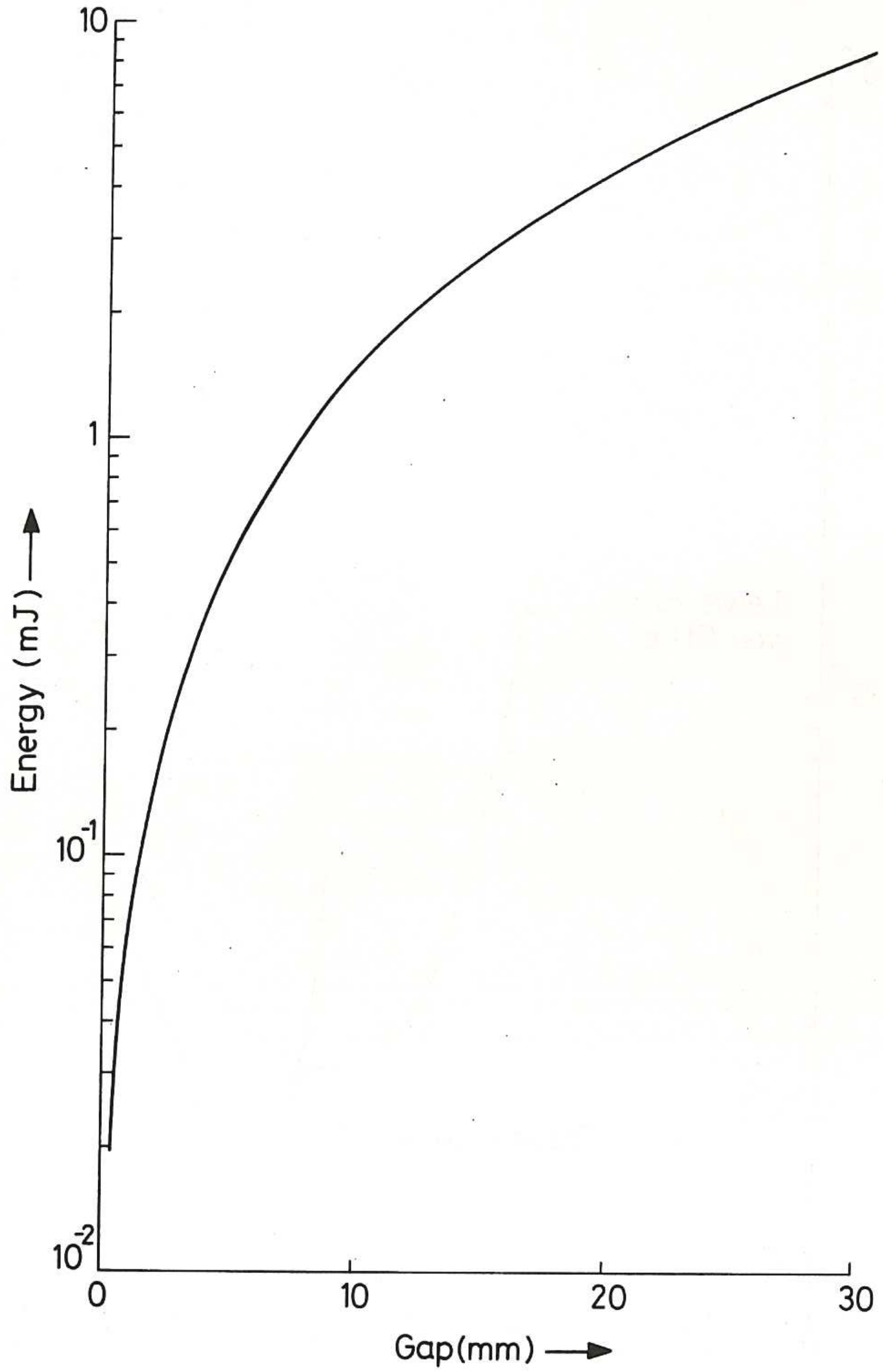

Fig.5 Graph showing the calculated energy of electrostatic sparks between 50mm diameter spheres as a function of the intersphere gap and with the values of breakdown potential given in Fig.4.

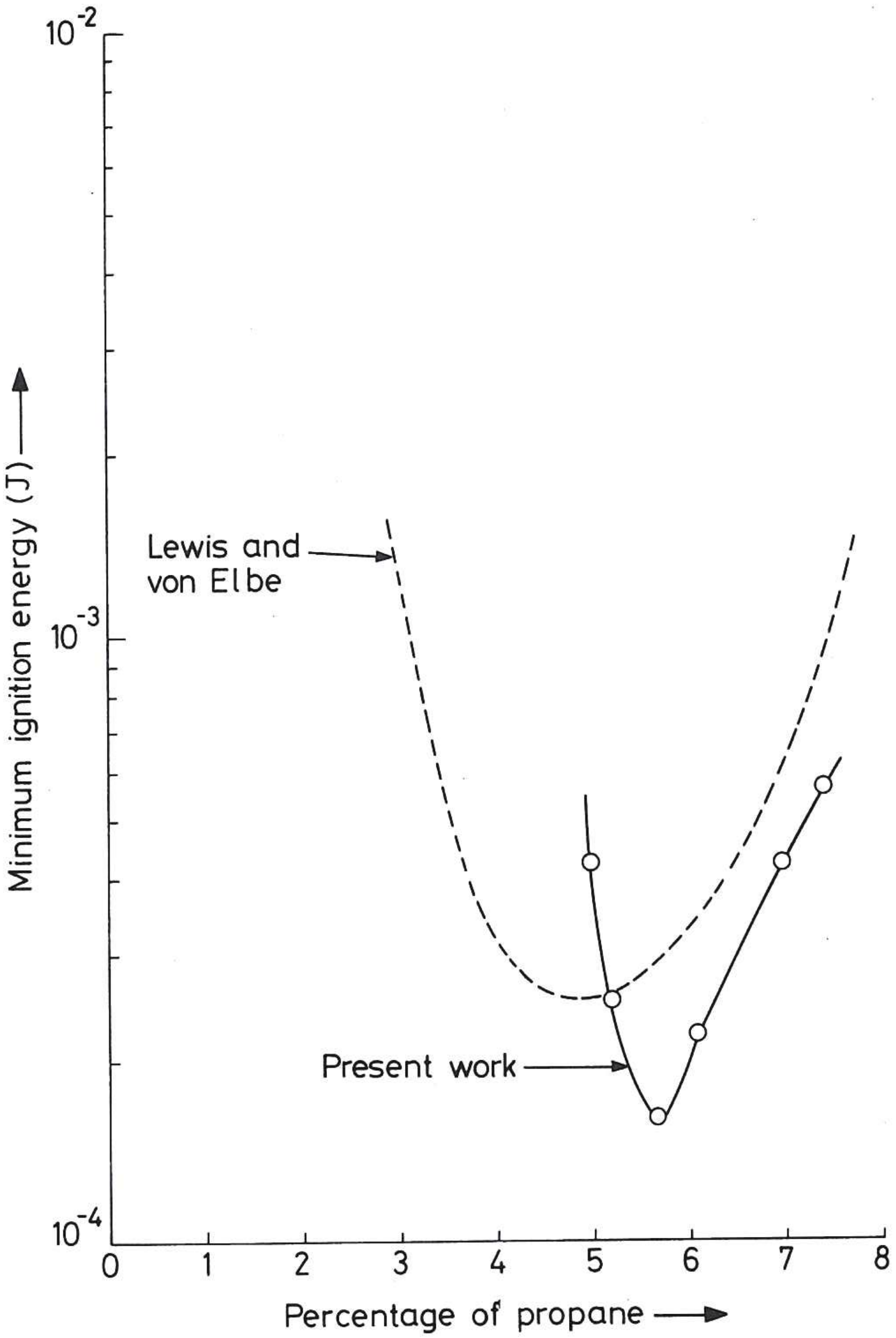

Fig.6 Minimum ignition energy versus volume percentage of propane.

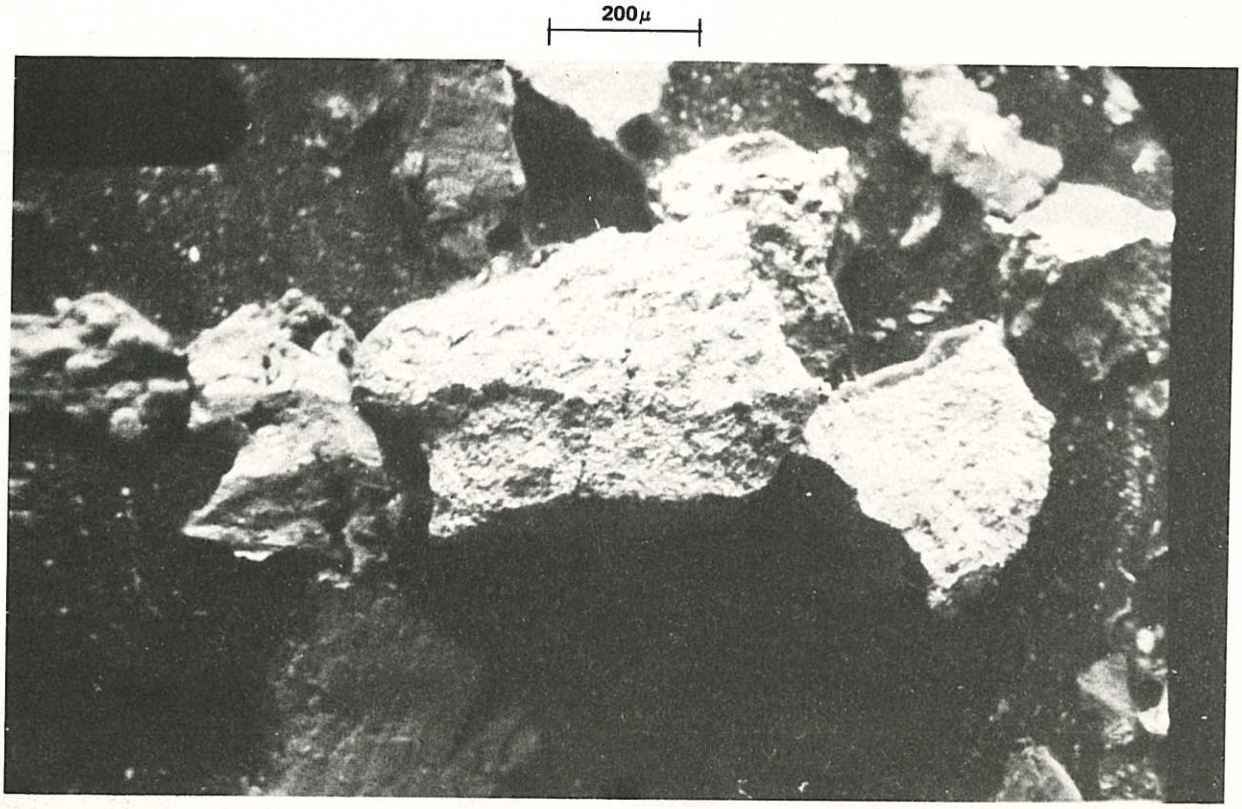

Fig.7 Scanning electron microscope picture of typical iron particles that produced incendive discharges when introduced between the resistive electrodes.

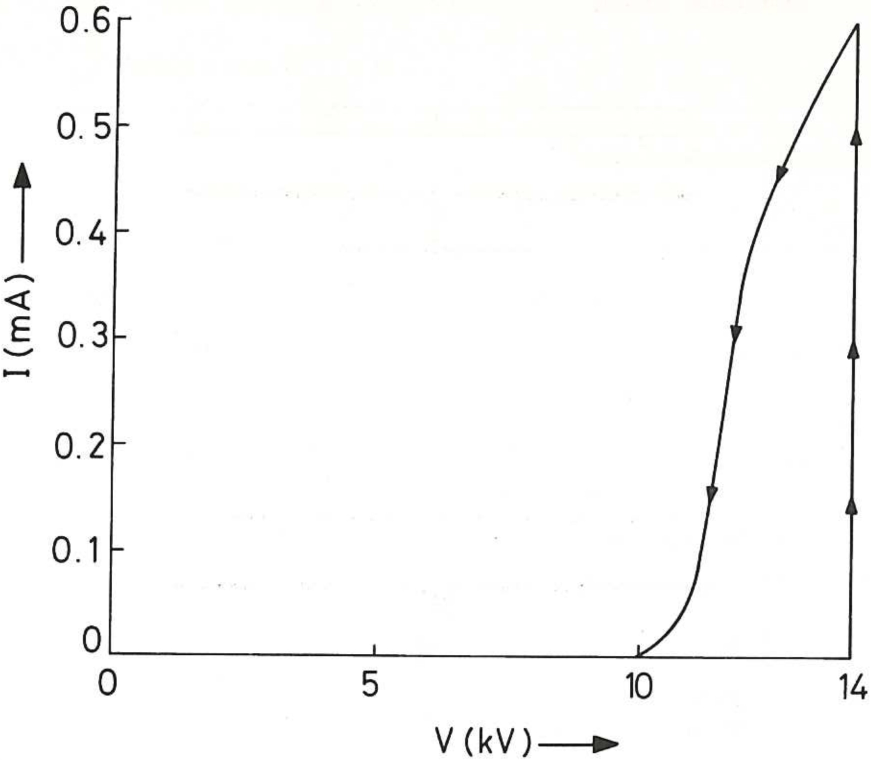

Fig.8 I–V characteristics of the continuous discharges between resistive electrodes with particles present, showing hysteresis.

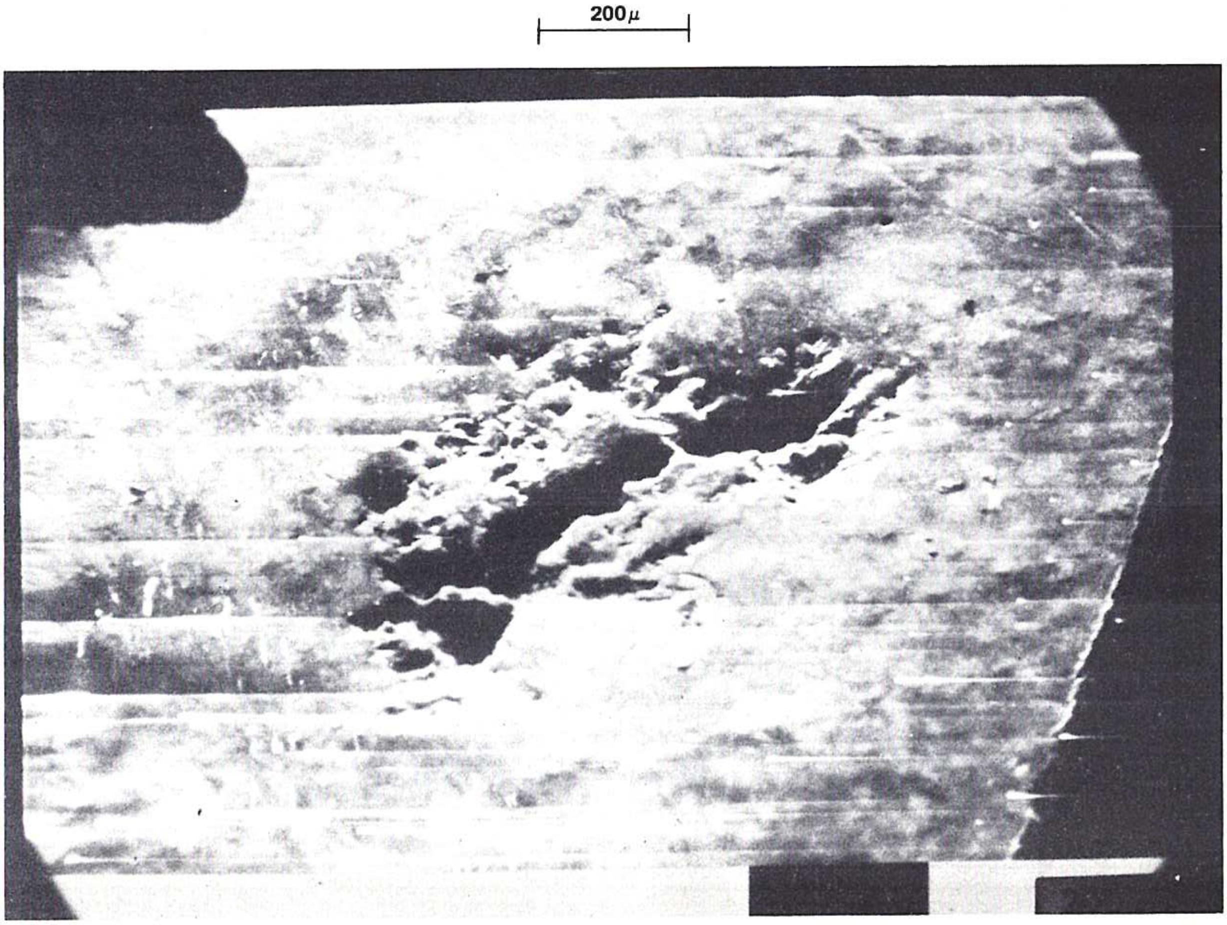

Fig.9 Scanning electron microscope photograph showing erosion pits formed after prolonged discharges between the resistive plates.

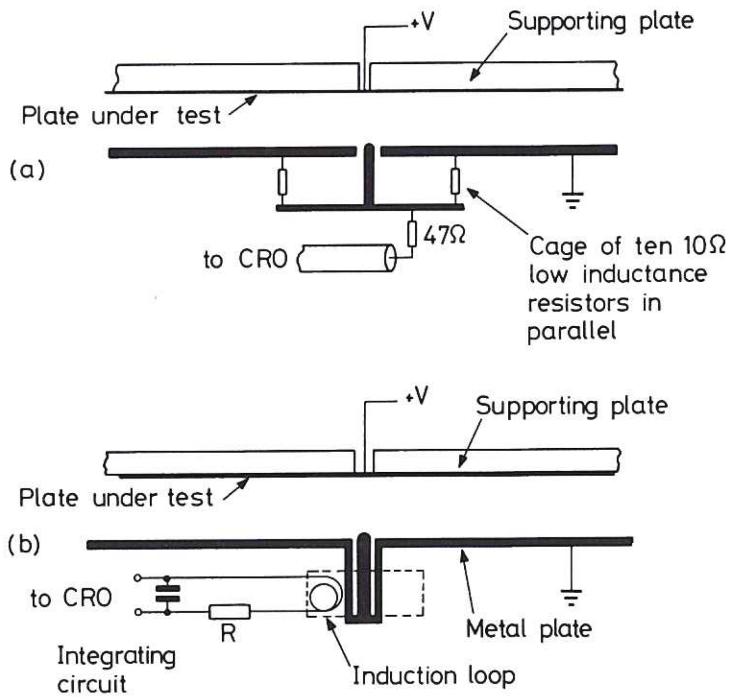

Fig.10 Current probes used to investigate the characteristics of discharges between plates.

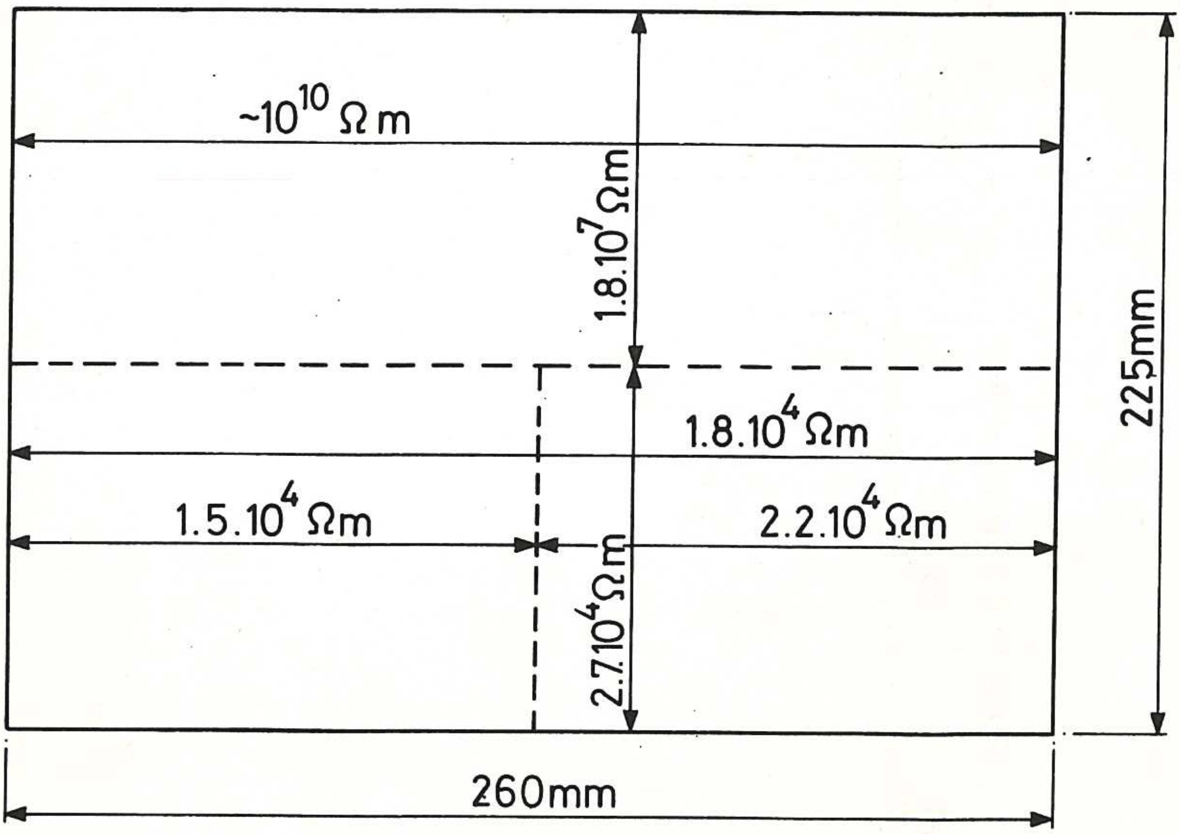

Fig. A1 Results of resistivity measurements on various zones of plate 37A.

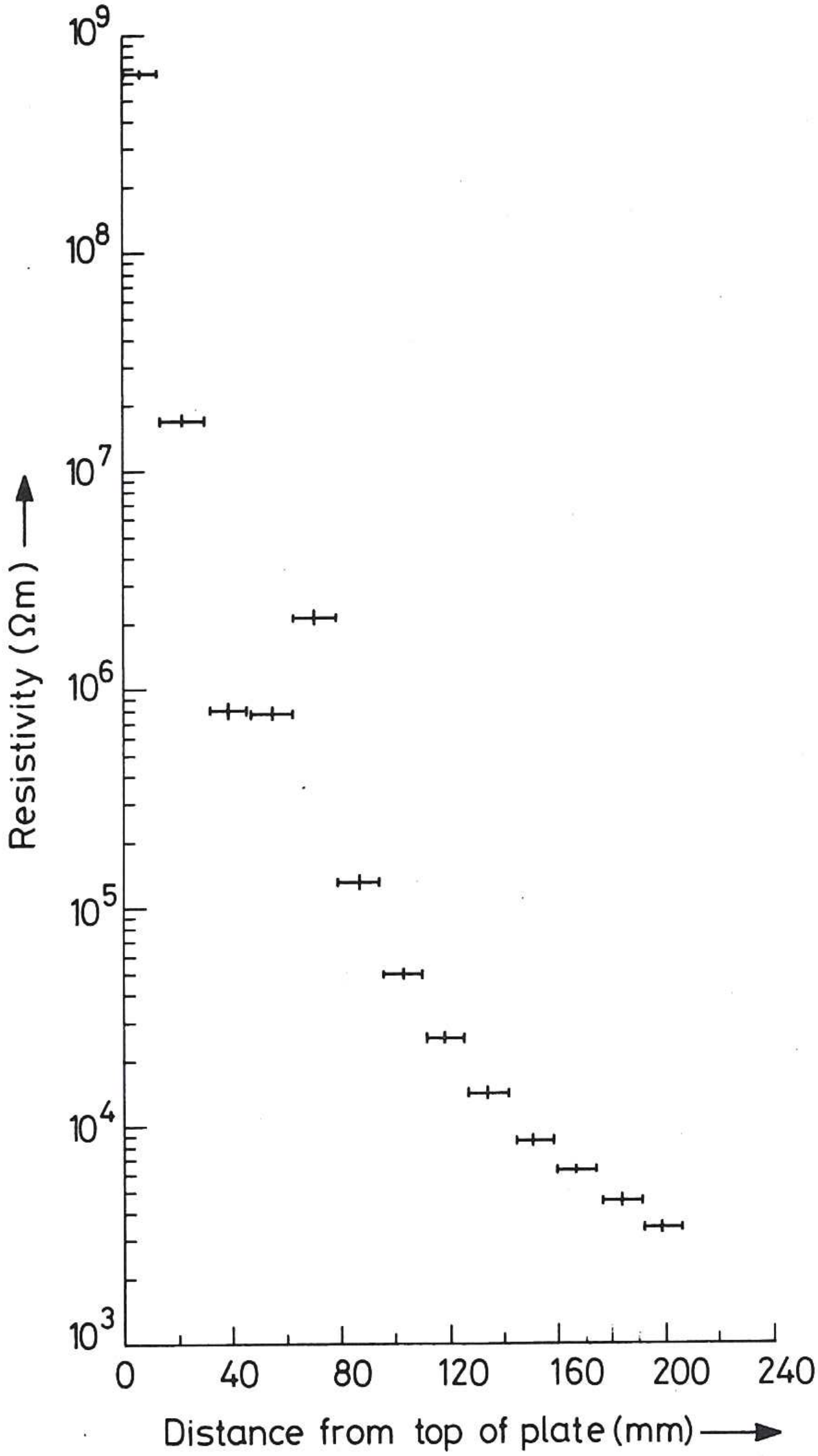

Fig.A2 Graph showing resistivity against distance from the top edge of plate 38A.

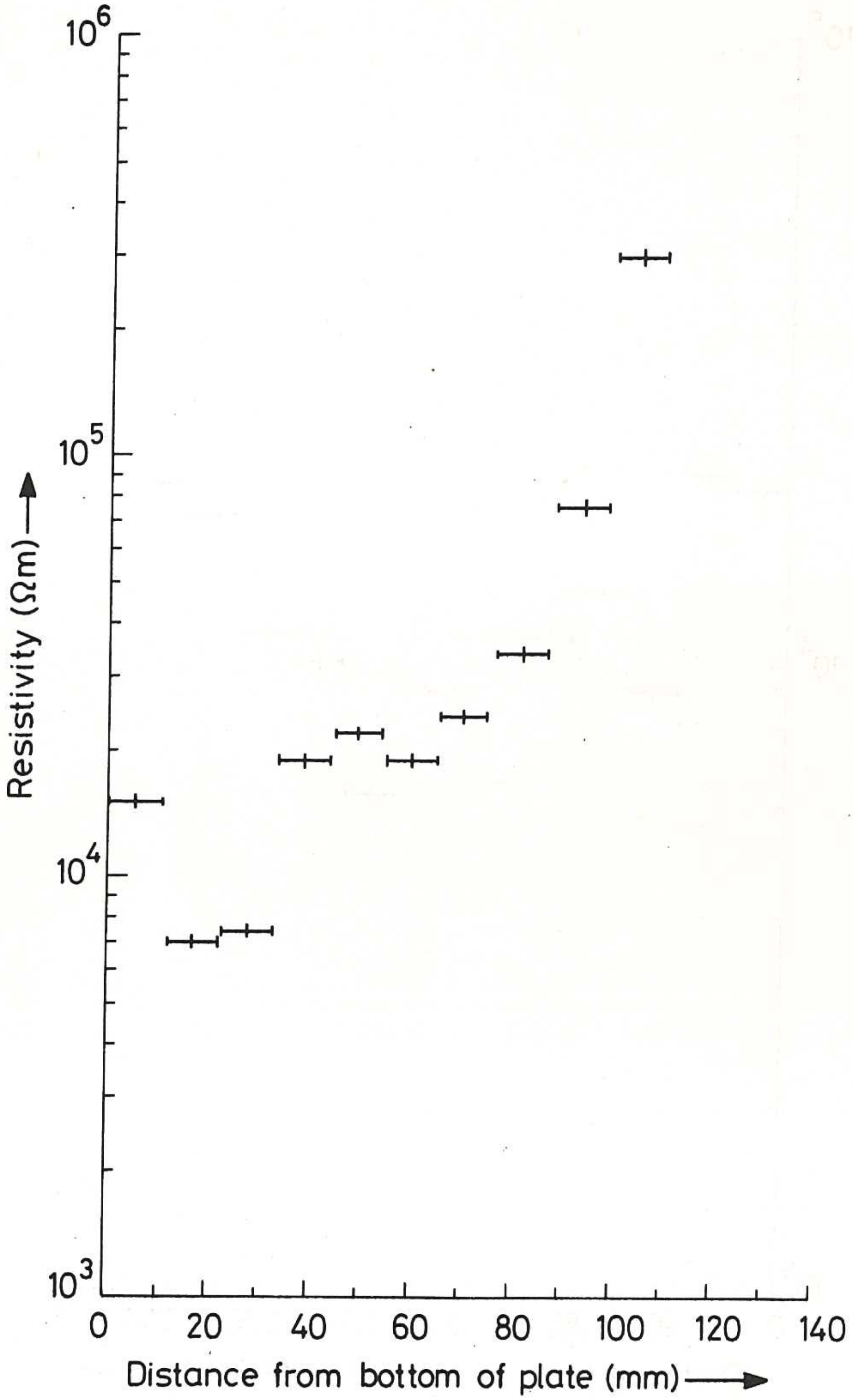

Fig.A3 Graph showing resistivity against distance from the bottom edge of plate ESP38.

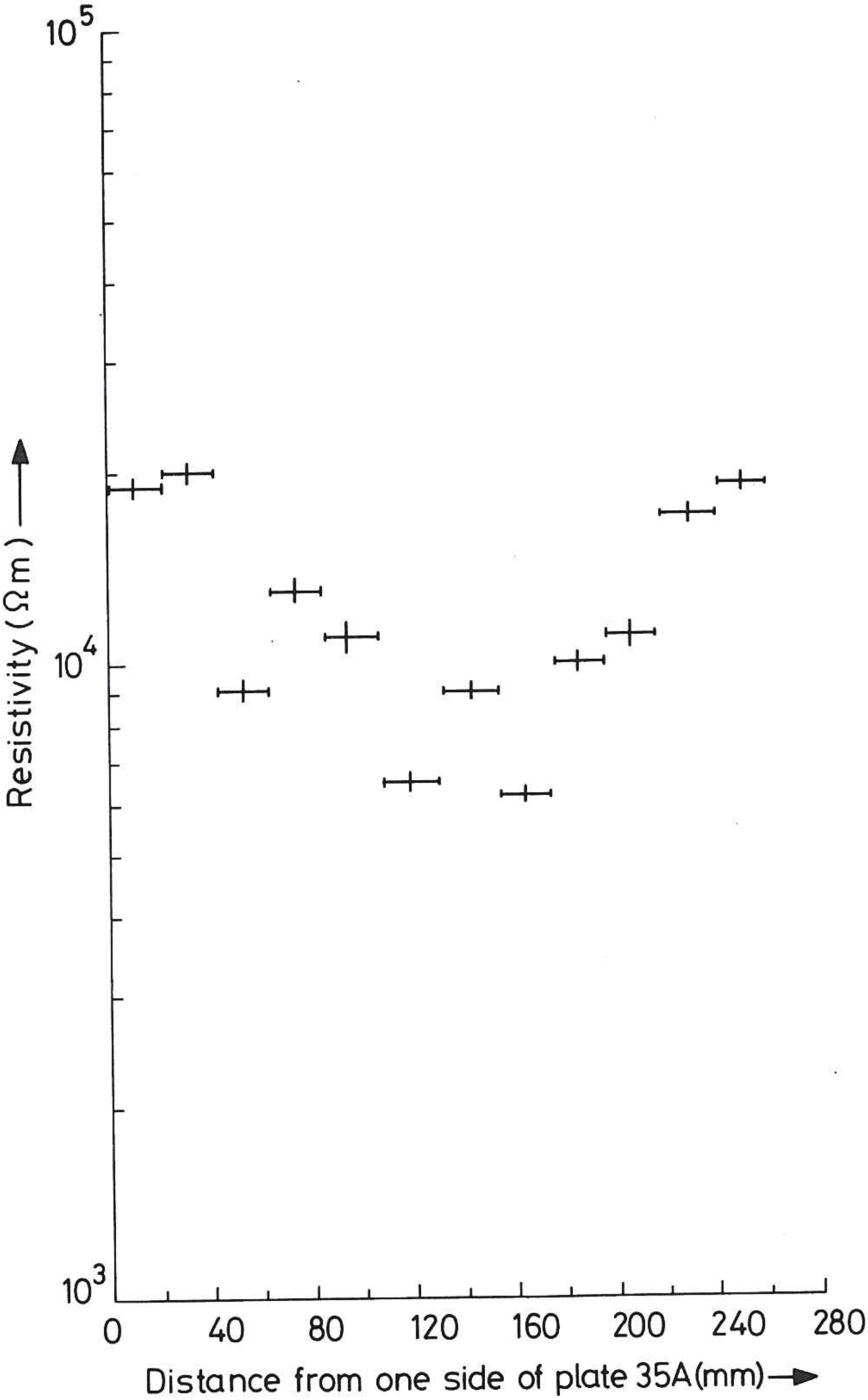

Fig.A4 Resistivity against distance across plate 35A.

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