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The Influence of Gas Streams and Magnetic Fields on Electric Discharges

Part 4. Arcs Moving along Straight Parallel Electrodes

by

V. W. Adams

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THE INFLUENCE OF GAS STREAMS AND MAGNETIC FIELDS ON ELECTRIC DISCHARGES

PART 4. ARCS MOVING ALONG STRAIGHT PARALLEL ELECTRODES

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SUMMARY

This report is a continuation of the experimental work in air at one atmosphere on the motion of d.c. arcs along straight open-ended electrodes already reported in Part 3 of this series. The earlier work with the self-field due to the arc current in the electrodes in the same direction as the applied magnetic field has been extended to include results with fields up to 1.0 Wb/m^2. Results are also given for three electrode materials with electrical connections arranged so that the self-field is eliminated, and are shown to differ from those where the self-field is present and approximately calculated.

A method, employing similarity parameters given by Dautov and Zhukov, of collating data on arc motion in transverse magnetic fields is used to compare results for the present series of reports with other published data, and is shown to be effective for a wide range of parameters from eleven different papers, including the present results.

Arc motion with a low-velocity imposed air flow along and relative to the electrodes has been studied, and the simple notion that the algebraic difference between the arc velocities relative to the electrodes in still and moving air is equal to the imposed air velocity is found to be only approximately true when the air stream acts against the arc motion.

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* Replaces R.A.E. Technical Report 67077 - A.R.C. 29302.

CONTENTS

1 INTRODUCTION

Experimental results on the behaviour of direct-current arc discharges in air at a pressure of one atmosphere propelled along various electrode systems by magnetic fields have been published in previous reports[1,2]. The present report is concerned with arcs moving along a pair of straight, parallel, horizontal open-ended electrodes at one atmosphere, and falls into four parts:-

(1) Extension of the previous work on straight brass electrodes with current connections to one end as shown in Fig.1(a) so that the self-magnetic field (i.e. the field at the arc of the arc current in the electrodes) is in the same direction as the externally applied magnetic field. In this work an allowance is made for the self-field using the method of calculation given in Ref.2. The previous results using an arc current of 3700 amp have been extended to include results in a total magnetic field (externally applied field plus self-field) of 1.0 Wb/m^2, resulting in a maximum arc velocity of 580 m/s (Mach No.1.65).

(2) The motion of arcs on straight electrodes where the self-field is, as far as possible, eliminated. In addition to brass electrodes for comparison with the previous work, aluminium and copper electrodes are used. For the earlier work where the self-field is calculated it is thought that the total magnetic field, i.e. applied field plus self-field, cannot be accurately determined at the arc position because of an asymmetric current distribution in the electrodes. Thus, in order to eliminate the self-field and obtain results more nearly representing the effects of the accurately known values of the applied field, balanced current connections are made to both ends of the electrodes, (Fig.1(b)). For practical reasons this limited arc currents, for the present apparatus, to 1000 amp or about one quarter of the previous maximum. The applied field has not yet been taken beyond 0.12 Wb/m^2.

(3) Collation of data on the motion of arcs in transverse magnetic fields using non-dimensional similarity parameters given by Dautov and Zhukov[3]. The results in the present series of reports are compared with other published data for arcs moving in air at one atmosphere.

(4) The motion of arcs on straight electrodes with an imposed air flow relative to the electrodes either aiding or, opposing the effect of the Lorentz force ($I \times B$) on the arc. These experiments necessitated, for practical reasons, the use of electrical connections only to the downstream ends of the electrodes. Hence, it is not possible to eliminate the self-field. With the Lorentz force and air flow opposed, the self-field is in the same direction as

the externally applied field. On the other hand, with the Lorentz force and air flow in the same direction, the electrode polarity, and hence the Lorentz force, is reversed and the self-field opposes the applied field. Corrections for the self-field were made accordingly; the method of calculation given in Ref.2, although approximate, was used. The electrodes were enclosed in a duct which limited arc currents to 600 amp. However, results were obtained for fields up to 1.0 Wb/m^2.

2 APPARATUS AND MEASURING TECHNIQUES

The arc power supplies and electromagnet providing the vertical external driving field have been described in Ref.2.

2.1 Electrodes and ducts

The electrodes used for experiments in still air consisted of a pair of horizontal, flat brass bars, 1.2 m × 0.038 m × 0.0033 m, the arcs being started at one end and confined to the edges (0.0033 m wide). Arc starting was by either fusing a short length of wire, or using a piece of folded metal foil between the electrodes[2]. The electrodes were insulated on the upper and lower surfaces with refractory insulating material.

For the experiments with imposed air flows relative to the electrodes, a pair of flat, horizontal brass bars 0.0033 m thick were used in a long duct as shown in Fig.2. The air flow, provided by a centrifugal blower was fed to the duct by a flexible rubberised fabric hose 0.2 m in diameter. Experiments were made with the imposed flows (including zero flow) either, in the same direction as or, against the Lorentz force on the arc. The top of the duct was made of perspex to permit optical observations. To provide higher flow velocities in the arc gap the duct cross-section was reduced first by wooden spacers and finally, by a resin bonded paper tube fitted with perspex windows, Fig.3. The method of arc starting was dependent on the direction of air flow relative to the arc motion. For flows against the arc motion successful arc starting was only achieved by providing a stagnant region at the downstream end of the electrodes and hence it was convenient to use a piece of metal foil. For flows with the arc motion no stagnant region was necessary and it was more convenient to start the arc by fusing a wire.

2.2 Measuring techniques

Measurements of the mean arc velocity, the total arc voltage and arc current were recorded on a Polaroid camera and Tektronix type 502A oscilloscope using the optical probes and apparatus described in Ref.2. Minimum values of the arc voltage were measured from the records since it was considered that these correspond to arc lengths equal to the electrode spacing. Two optical probes fixed 0.5 ±0.001 m apart and about 5 cm above the centre of the arc gap were used for velocity measurement, and a third probe, placed in front of the first of the two measuring probes and 0.2 m from the starting position of the arc was used to trigger the oscilloscope. In this way any effects due to the initial starting period of the arc were avoided.

Double end current connections necessitated the use of a different arrangement for current and voltage measurements, as shown in Fig.1(b). In this case the arc voltages were measured by using two Tektronix type 6017 ten times attenuation probes connected one to each electrode, the output signals with respect to the earthed connection being algebraically added by making use of the differential operation of the oscilloscope input amplifier. Thus, with this method the measured voltage was proportional to the difference between the two input voltages from the electrodes.

The probe signals, corresponding to the transit time of the arc past the two measuring stations, were reduced by a suitable attenuator and superimposed on the arc current signal by making use of the differential input to the second beam of the oscilloscope. In this way, one two beam oscilloscope was used for recording arc voltage, current and velocity on a common time scale, see Fig.4. Previously it was reported[2] that the arc current records contained high frequency noise signals which were eliminated by means of a low pass filter, e.g. Fig.4. However, the H.F. noise was subsequently traced to its source and the source eliminated. No difference in the results was apparent from this change.

The applied magnetic fields were taken from calibration curves of magnet supply current against magnetic field obtained by using either, a search coil and fluxmeter for fields up to 0.15 Wb/m^2 or, a Hall probe fluxmeter[4] accurate to ±1% for the higher range up to 1.0 Wb/m^2. The two methods were found to be compatible over an overlappping range up to 0.15 Wb/m^2. The self-field due to the arc current in the electrodes was, where appropriate, calculated using the method given in Ref.2 and a correction made to the applied field.

The accuracy of the measuring techniques has been discussed in the previous reports of this series and typical observation errors are shown in the plotted experimental results. A list of errors for all parameters used is given with the list of symbols.

2.3 Photographic observations

High speed photographs of the moving arcs in the previous reports were obtained using a Fastax rotating prism camera (10^4 frames per second), and it was found that changes in the arc shape occurred between successive frames probably due to insufficient framing speed of the camera. It was thus decided that a higher framing rate of at least 10^5 pictures per second would be required. The simplest and most economical camera providing this facility appeared to be the aperture - scanning type used for circuit breaker research[5], and a camera of this type was made at R.A.E. using drawings provided by A. Reyrolle and Co.

3 EXPERIMENTAL RESULTS

The results are collected together in Figs 5 to 17. The extensions to the results for single end connections using brass electrodes are shown in Figs.5 to 7, while Figs.8 to 15 are for electrodes (brass, copper or aluminium) with double end connections and Figs.16 and 17 are for arcs with imposed air flows along the electrodes.

It was found[2] that the arc velocities were consistent only after several arc runs had been made and visible tracks appeared on the electrodes. Thus, the results are for electrodes used between 10 and 100 times.

The photographic observations with the framing speed now available (10^5 pictures per second) showed that the changes in arc shape were gradual with many fewer abrupt changes between successive frames.

We now consider the results for each of the three types of experiment in turn before discussing them in a later section.

3.1 Extension of results with brass electrodes and single end connections

The mean arc velocities, U, and minimum values of arc voltage, V, are plotted against magnetic field, B, in Figs.5 and 6 respectively, for an arc current, I, of 3650 ±50 amp. They are seen to follow the trend of the previous results. Calculated values of the induced voltage due to the arc motion in the magnetic field are shown to be negligible, Fig.6. The earlier work has also been extended by determining the variation of arc velocity with current and field for a larger arc gap, Fig.7.

3.2 Electrodes with double end connections

This configuration eliminated as far as possible the self-field due to the arc current in the electrodes, and the results may be compared with those of the earlier work[2] where the self-field was calculated.

The mean arc velocities are plotted in Figs.8 to 12 against arc current for each electrode material and a range of gap widths, d, and applied magnetic fields. The variation of velocity with arc current and magnetic field is different for each material, and in particular the brass results differ from those for the experiments corrected for single end connections[2], (see section 4 and Table 1).

Minimum values of arc voltage, V, against applied magnetic field and arc current are given in Figs.13 to 15. It may be shown that, with the exception of aluminium, a plot of V against the electrode spacing, d, gives curves with slopes similar to those obtained for experiments with single end connections[2].

3.3 Brass electrodes with single end connections and imposed air flows

The connections to these electrodes had to be made to the downstream ends and corrections for the self-field at the arc gap were made accordingly. With the air flow and arc motion opposed the arcs were started at the downstream ends of the electrodes and the self-field was added to the applied field. Alternatively, with the air flow and arc motion in the same direction the arcs were started at the upstream ends of the electrodes with reversed electrode polarity and the self-field was subtracted from the applied field. The maximum velocity of the air flow was calculated from measurements made after the arc had travelled along the electrodes with a 0.32 cm diameter Pitot tube held at a point midway between the electrodes. No correction was made for the proximity of the electrodes to the Pitot tube. Measurements made with the tube adjacent to the electrode edges gave a value for the velocity about 3/4 of that at the gap centre.

The results are shown in Figs.16 and 17 where the arc velocity relative to the electrodes, U, and the minimum arc voltage, V, are plotted against the magnetic field for each air flow velocity. It can be seen from Fig.16 that with the air flow and arc motion in the same direction the condition was reached where there was no net magnetic field and the arc was driven by the gas stream. The arc velocity was then about $\frac{1}{2}$ the air flow velocity.

Some attempts were also made to approach the condition of zero arc velocity with the gas stream opposing the arc motion by removing the externally applied field, so that the arc was driven only by the self-magnetic field. However, because of the erratic behaviour of the arc and possible damage to the electrodes no velocity measurements were obtained.

High speed photographic observations of the arc showed that the shape of the luminous column when moving under the action either, of the imposed gas stream in the same direction as the arc motion and no applied magnetic field or, of the gas stream plus an externally applied field, differed from the shape for arcs moving through still air in a transverse magnetic field. For arcs moving through still air the luminous column was approximately straight[2], whereas for arcs subjected to an additional gas flow along the direction of motion the luminous column was cusp shaped with the apex of the cusp pointing in the direction of motion, as shown in Fig.18. The relative positions of the frames (approximately 10^5 per second) in this photograph are due to the camera design, described in Ref.4.

4 DISCUSSION

The results described in section 3 will now be considered in more detail and the discussion falls into four parts.

4.1 Effective drag area of arc

Assuming that the arc causes a displacement of the external gas which does not close downstream (i.e. a wake is formed) it is possible to assign a characteristic frontal area to the arc[2]. This is the effective drag area, A, of the arc, so that the drag or retarding force may be equated to the overall Lorentz force:-

$$\frac{1}{2} \rho U^2 A = BId \tag{1}$$

where ρ is the density of the surrounding gas. Using this equation it is possible to calculate values of A for the range of U B and I used.

i.e.,

$$A = 2BId/\rho U^2 \tag{2}$$

A more detailed analysis of A requires estimates of the effective arc width transverse to the direction of motion. High speed photographs taken (i) along the arc axis, (ii) along the direction of motion and (iii) transverse to both the arc axis and direction of motion indicated[2] that the luminous cross-sectional shape of the arc was more elliptical than circular with the major axis transverse to the direction of motion. This suggestion is in accordance with spectroscopic and other recent work[6,7,8]. The present results do not permit estimates of the arc width to be made, and it is only possible to calculate effective drag areas and extend the range already given in Ref.2.

The results for arcs moving in still air on brass electrodes, including those for single end connections given in Ref.2, are shown in Fig.19, where A is plotted against U for different arc currents. It can be seen that the electrodes with single end connections show practically no variation with arc current and there is a steady increase of A from 25 m/s to 580 m/s. On the other hand, the results for electrodes with double end connections show that A increases with arc current, and for the highest current of 1000 amp A also increases with arc velocity.

The only difference between the above two sets of results is that those with little or no variation of A with I include calculated corrections to B for the self-magnetic field, while those displaying a variation of A with I are for conditions where the self-field is eliminated. It may be that the corrections for the self-field are insufficiently accurate. The calculations[2] for the self-field are approximate because (i) it is assumed that the current is uniformly distributed in the electrodes, whereas in fact the distribution where the arc joins the electrodes is probably asymmetric, and (ii) only the self-field at the gap centre has been calculated and no account taken of its variation across the gap and along the electrodes. These variations are indicated diagrammatically in Fig.20.

It should be noted, however, that the calculated self-field is in most cases small compared with the applied field (6×10^{-6} I Wb/m^2 for d = 1.27 cm) so that a small error in the value at the gap centre is negligible. Hence, it would seem that the variation across the arc gap and any significant change in the field close to the electrodes due to the asymmetric current distribution must account for the difference in the results. A comparison of arc shapes recorded photographically has shown that on the average they were similar, but for electrodes with single end connections (self-field present) a tendency to produce curved arcs was noticed. This difference was small but could possibly be accounted for by a variation of the magnetic field across the arc gap.

4.2 Relations between U, B, I and d

For comparison with previous results[2] we now obtain relations of the form:-

$$U \simeq K\, I^{n_1}\, B^{n_2} \tag{3}$$

and

$$A \simeq \frac{2}{\rho\, K^2}\, I^{(1-2n_1)}\, B^{(1-2n_2)} \tag{4}$$

where K is an empirical constant and equation (4) is obtained by comparing equations (1) and (3). The values of K, n_1 and n_2 have been obtained for a fixed electrode spacing by plotting $\log_{10} U$ against $\log_{10} B$ at constant values of I, and $\log_{10} U$ against $\log_{10} I$ at constant values of B, and the results are shown in Table 1, together with those given in Ref.2 for brass.

The variations of arc velocity with electrode spacing or arc length has been discussed in the previous reports in this series, and it is seen, (Fig.21) that they are comparable for different electrode configurations and materials, with the exception of aluminium. We may represent the variation of arc velocity with electrode spacing, d, by relations of the form given by equation (3) and Table 1, where K is now not constant but depends on d. Fig.22 shows the variation of K with d, and no simple relation between them could be determined.

The differences between results with single or double end current connections and the same electrode material (brass) could possibly be accounted for by differences in the magnetic field as discussed in the previous section.

4.3 Analysis using similarity relations

It was shown in Ref.2 that an analysis of results on moving arcs using similarity parameters given by Lord[9] for uniform arc columns, and which involved the arc column voltage gradient, depended markedly on the values used for the gradient. The estimated voltage gradients were affected by the part of the curve, through a plot of arc voltage against electrode gap, used to estimate the slope. In addition, it is possible to estimate a voltage gradient by subtracting assumed values for the arc electrode fall voltages and dividing by the arc length or electrode gap. This yields quite different values for the gradient and a different relation between the similarity parameters. Thus, in view of the uncertainty involved and since for short arcs it is doubtful whether a uniform column theory is applicable, the analysis used in Ref.2 is not dealt with here.

An effective method of collating a wide range of data on the motion of arcs (see later) is to use the parameters given by Dautov and Zhukov[3], derived by non-dimensional analysis. These parameters do not include the arc voltage, but include the electrode spacing so that it may be possible to use them for arcs displaying a variation with electrode gap or with non-uniform columns. The derivation used by Dautov and Zhukov makes no suppositions about the form and dimensions of the arc cross-section or of the current density distribution. The conditions of similarity have been described[3] for arcs in the same gases and between the same electrodes, by the following non-dimensional parameters:-

$$U\, d\, \rho^{\frac{1}{2}}/\mu_o\, I^{\frac{1}{2}}, \qquad \mu_o\, I/d\, B, \qquad B^2/\mu_o\, P \quad \text{and} \quad L/d$$

where μ_o is the permeability of free space, P is the ambient pressure, L is the electrode thickness and the other symbols have meanings as already defined. By plotting experimental data from Zalesski and Kukekov[10] for arcs moving along straight electrodes in the form of the dimensionless arc velocity, $U\, d\, \rho^{\frac{1}{2}}/\mu_o\, I^{\frac{1}{2}}$, against $\mu_o\, I/B\, d$, Dautov and Zhukov show[3] that U d/I is a function of I/B d at constant ambient temperature and pressure. The collapse of data also indicated that the variation of U d/I with B^2/μ_o P was small. The present results for brass electrodes are plotted in the same form in Fig.23, together with those from other published data (Refs.2 and 10 to 18), assuming a value for ρ at 300°K. It is seen that results for straight or rail electrodes and for arcs rotating in annular gaps using brass or copper electrodes at atmospheric pressure are approximately collated over a wide range of parameters. This trend, although approximate, is remarkable when one considers the wide range of conditions involved, i.e., 3 amp to 20 K amp, 1.3 m/s to 900 m/s and arc gaps from 0.1 to 10 cm. The plotted results may be approximately represented by:

$$U\, d\, \rho^{\frac{1}{2}}/\mu_o\, I^{\frac{1}{2}} \simeq 1.4(\mu_o\, I/B\, d)^{-0.6} \tag{5}$$

with a scatter about a mean line of approximately ±50%.

In order to obtain a more accurate equation for the dimensionless arc velocity we must take into account its variation with B^2/μ_o P and L/d. Now, since the experimental results are at atmospheric pressure, P is constant but a change in B causes a change in B^2/μ_o P. Also, since the results are for different electrode spacings a change in d causes a change in L/d, and since the results shown in Fig.23 are from different sources using electrodes of different dimensions a change in L also causes a change in L/d. From Table 1, we already know that U depends on a single function of I and B for each electrode spacing, and that this function is different for each electrode configuration. Hence, for each configuration we would expect that, at constant P, and L/d, the dimensionless arc velocity depends only on I, B and d. In terms of the dimensionless parameters we may write:

$$U\ d\ \rho^{\frac{1}{2}}/\mu_o^{\frac{1}{2}}\ I \ = \ \phi[(B^2/\mu_o\ P)\ (\mu_o\ I/B\ d)] \tag{6}$$

for each electrode configuration and constant L/d, where ϕ is some continuous function.

This is demonstrated in Figs.24(a) and (b) where the dimensionless arc velocity is plotted against μ_o I/B d for different values of B using the results in the present series of reports for straight brass electrodes. It should be noticed that the results in Fig.24(b), for double end connections, are for electrode spacings from 1.27 cm to 3.8 cm. Thus, the dependence of U d/I on L/d when d is changed, is small for the range of gaps considered, and now, by plotting the velocity parameter against B^2 at fixed values of μ_o I/B d, (Figs.25(a) and (b)), the form of equation (6) may be determined. By measuring the slopes and extrapolating the lines in Figs.24 and 25 the function ϕ is determined for each set of results at atmospheric pressure, i.e.,

$$U\ d\ \rho^{\frac{1}{2}}/\mu_o^{\frac{1}{2}}\ I \ \approx \ \mu_o^{-1}(B)^{-0.25}\ (\mu_o\ I/B\ d)^{-0.63} \tag{7}$$

for the brass electrodes with single end connections and,

$$U\ d\ \rho^{\frac{1}{2}}/\mu_o\ I \ \approx \ \mu_o^{-1}(B)^{-0.18}\ (\mu_o\ I/B\ d)^{-0.68\ \pm 0.02} \tag{8}$$

for the brass electrodes with double end connections. The difference between the two sets of results can only be accounted for by differences in the magnetic fields resulting from variations in the self-field for the case with single end connections, as discussed in section 4.1.

4.4 Effects of imposed air flows

The effects of an imposed air flow along the electrodes are different depending on the direction of the flow relative to the direction of the Lorentz force.

When the flow acts against the Lorentz force the observed arc velocity relative to the electrodes for constant current and magnetic field is reduced by approximagely the same amount as the measured flow velocity at the gap centre (Fig.16(a)) for -24 m/s and -43 m/s. Thus, for the Lorentz force and air flow in opposition the arc velocity relative to the air is approximately equal to the velocity in still air. This is confirmed by the fact that the total arc voltage, and hence input power at constant current, is unaffected by opposing air flows for constant magnetic field or velocity relative to the air, Fig.17(a), indicating no change in the convection loss.

On the other hand, the additional effect of a flow aiding the Lorentz force varies both with the applied magnetic field and the imposed air velocity, Figs.16(a) and (b) for +46 m/s and +96 m/s. e.g.

(i) at fields between 0.06 Wb/m^2 and 0.09 Wb/m^2 and an imposed air flow of +46 m/s the arc velocity is increased by approximately the same amount as the air flow, but at 0.01 Wb/m^2 the increase is only 28 m/s

(ii) at fields between 0.01 Wb/m^2 and 0.1 Wb/m^2 and an imposed flow of +96 m/s the arc velocity is increased by only about 60 m/s, whereas at 1.0 Wb/m^2 the increase is 80 m/s.

Thus, for the Lorentz force and air flow in the same direction, the arc velocity relative to the air is approximately equal to the velocity in still air only for the low air velocity of 46 m/s and comparatively high arc velocities of 110 m/s to 120 m/s. This is confirmed by the fact that the arc voltages, and hence input power at constant current, are the same for an air flow of +46 m/s and magnetic fields 0.06 Wb/m^2 to 0.09 Wb/m^2 as in still air, Fig.17(a). This indicates no change in the convection loss. However, for the range of field up to (i) about 0.06 Wb/m^2 with +46 m/s flow, Fig.16(a), and (ii) 1.0 Wb/m^2 with +96 m/s flow, Fig.16(b), the arc velocity relative to the air is always less than the velocity in still air for the same range of fields. The arc voltages at constant current over these ranges are greater than for an arc in still air, Fig.17(a) and (b) indicating an increase in the power losses or a change in the arc properties, by the action of the air flow against the arc wake.

5 CONCLUSIONS

This report has shown that there is a difference between results obtained for arcs moving along straight, parallel electrodes in a transverse magnetic field when either,

(i) the self-field due to the arc current in the electrodes is eliminated or,

(ii) an estimate of this self-field is added to the externally applied field.

However, this difference is probably due to the approximate calculation of the self-field; in the absence of time-resolved magnetic field measurements concurrent with the arc motion it has not been possible to resolve the difference.

The effective drag area for the arc has been calculated and it has been shown that this area increases with arc velocity.

Using the results from (i) the present series of reports for brass electrodes and (ii) nine other papers published by different authors for brass or copper electrodes, it has been shown that a method, employing similarity parameters given by Dautov and Zhukov, for collating data on arcs moving in transverse magnetic fields is effective for a wide range of arc velocity, current, field and electrode spacing. In addition, the results for straight brass electrodes in the present series of papers have been analysed in more detail.

The effects of low velocity imposed air flows relative to the electrodes have been described but only limited inferences can be made from this aspect of the work. The simple notion that the increase or decrease in arc velocity, depending on the flow direction, is equal to the flow velocity is only approximately true when the air stream acts against the Lorentz force. The additional effect of a gas stream aiding the Lorentz force varies with the magnetic field or arc velocity in still air, and this variation also depends on the imposed air velocity.

High speed photographic observations at 10^5 frames per second have verified that most of the sudden changes in the arc shape recorded previously[2] were due to insufficient framing speed of the camera.

Table 1

Values of K, n_1, n_2, $2/\rho K^2$, $(1-2n_1)$ and $(1-2n_2)$ in equations (3) and (4), (M.K.S. units)

$$U \approx K I^{n_1} B^{n_2} \qquad (3)$$

$$A \approx \frac{2}{\rho K^2} I^{(1-2n_1)} B^{(1-2n_2)} \qquad (4)$$

Electrodes: Connections	Material	d(cm)	K	n_1	n_2	$2/\rho K^2$	$(1-2n_1)$	$(1-2n_2)$	U(m/s)	B(Wb/m^2)	I(amp)
Single-ended (self-field calculated) (present results and Ref.2)	Brass	1.27	22 ±1	0.40 ±0.01	0.40 ±0.01	0.0032 to 0.0038	0.20 ±0.02	0.20 ±0.02	30-275 70-580	0.04 -0.49 0.12 -1.0	100-1250 200-3700
			- -	0.50 ±0.01 -	- 0.20 ±0.01	- -	0 ±0.02 -	- 0.60 ±0.02	30-100 210-270	0.026-0.037 0.05 -0.15	100-1200 3700
Double-ended (no self-field)	Brass	1.27	36.5 ±1.5	0.34 ±0.01	0.45 ±0.01	0.0012 to 0.00135	0.32 ±0.02	0.1 ±0.02	30-124	0.031-0.1075	100-1000
			-	0.43 ±0.01	-	-	0.14 ±0.02	-	20-46	0.0155	100-1000
	Copper	1.27	32.2 ±2	0.40 ±0.01	0.40 ±0.01	0.0014 to 0.0018	0.20 ±0.02	0.20 ±0.02	27-125	0.012-0.108	400-1000
			-	-	0.50 ±0.01	-	-	0 ±0.02	27-80	0.012-0.108	200
	Aluminium	2.54	53 ±3	0.26 ±0.01	0.54 ±0.01	0.00055 to 0.0007	0.48 ±0.02	-0.08 ±0.02	24-88 18-88	0.025-0.109 0.014-0.109	200-900 400-900
			- -	0.33 ±0.01 -	- 0.61 ±0.01	- -	0.34 ±0.02 -	- -0.22 ±0.02	18-30 18-64	0.014 0.04 -0.109	200-900 200

Note: The variation of K with d is shown in Fig.22

SYMBOLS

A	effective drag area	(m^2)
B	magnetic field	(Wb/m^2)
C_D	drag coefficient	
d	electrode gap width	(m)
I	mean arc current	(amp)
K	constant of proportionality	
L	electrode thickness	(m)
n_1, n_2	indicies in simple power relations	
P	pressure	(Nt/m^2)
U	mean arc velocity relative to electrodes	(m/s)
V	minimum arc voltage	(volt)
ρ	density of air	(Kg/m^3)
μ_o	magnetic permeability of free space ($= 4\pi \times 10^{-7}$)	(Henry/m)

Estimated experimental errors

A	±13%
B	±5%
d	±0.05 cm
I	±10%
U	±5%
U_a	±5%
V	±10%
Ud/I	±12%
I/Bd	±12%
B^2/P	±7% (const. P)

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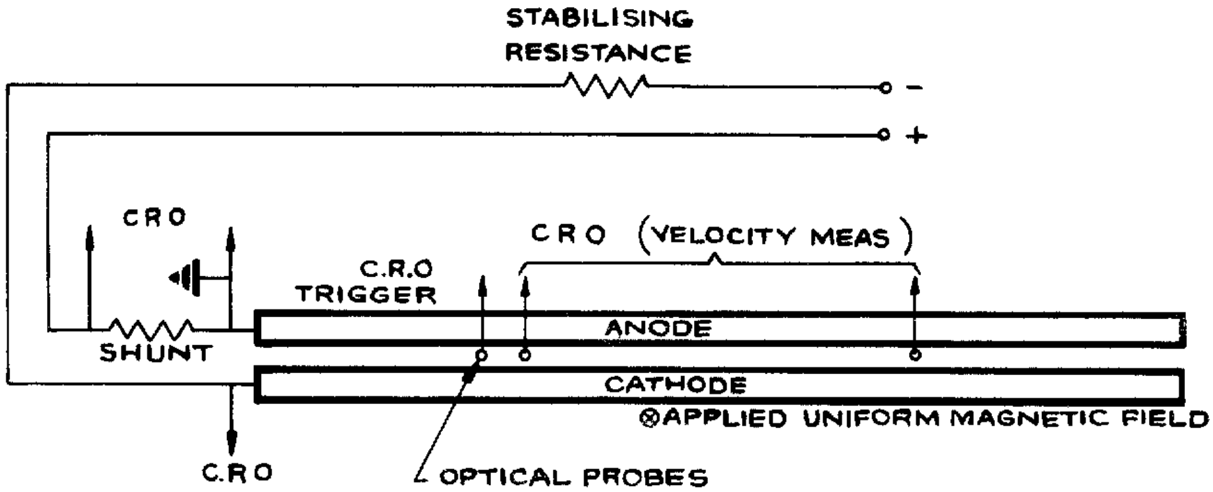
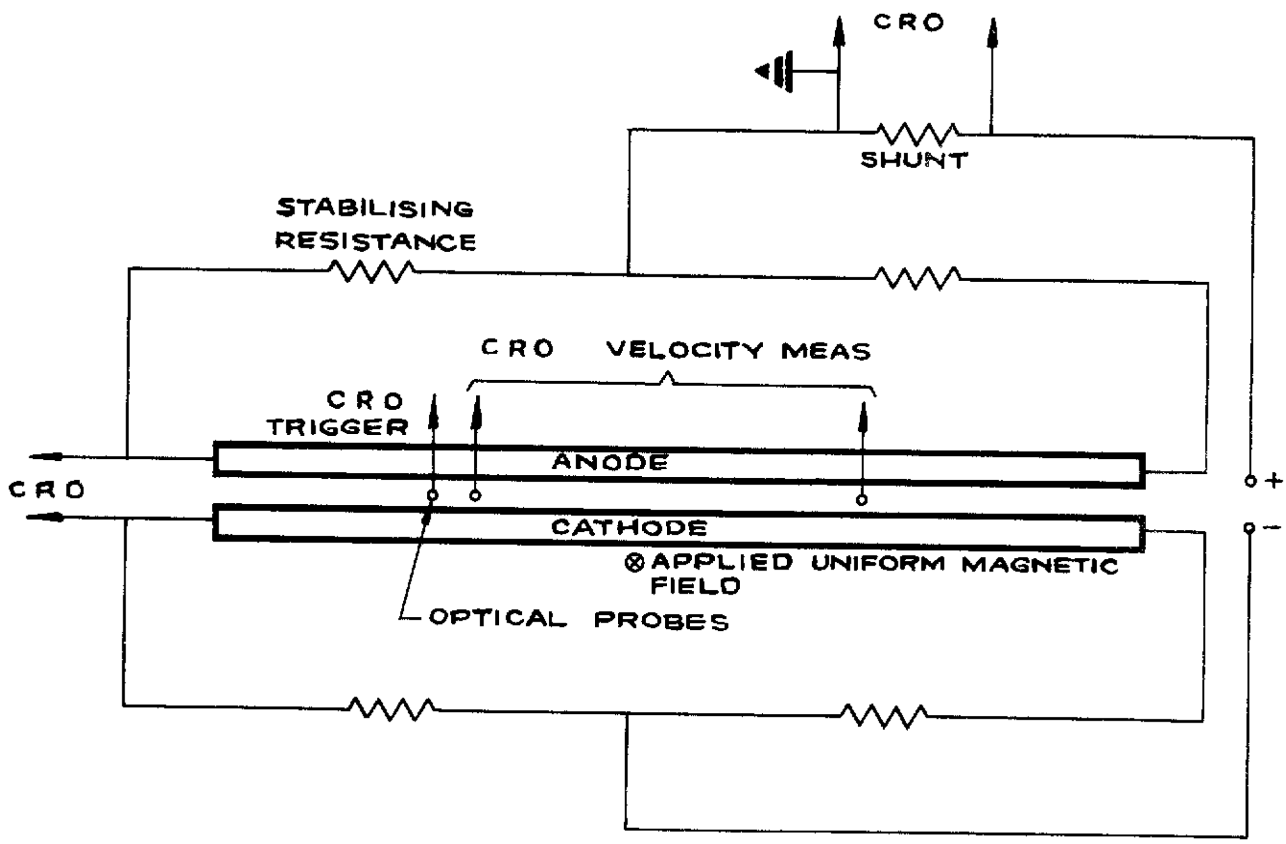
17	H.C. Spink A.E. Guile	The movement of high-current arcs in transverse external and self-magnetic fields in air at atmospheric pressure. A.R.C. C.P. 777, May 1964
18	E.D. Blix A.E. Guile	The magnetic deflection of short arcs rotating between annular electrodes above and below atmospheric pressure. A.R.C. C.P. 843, October 1964



a SINGLE END CURRENT CONNECTIONS



b DOUBLE END CURRENT CONNECTIONS

FIG. 1a & b CONNECTIONS TO ELECTRODES

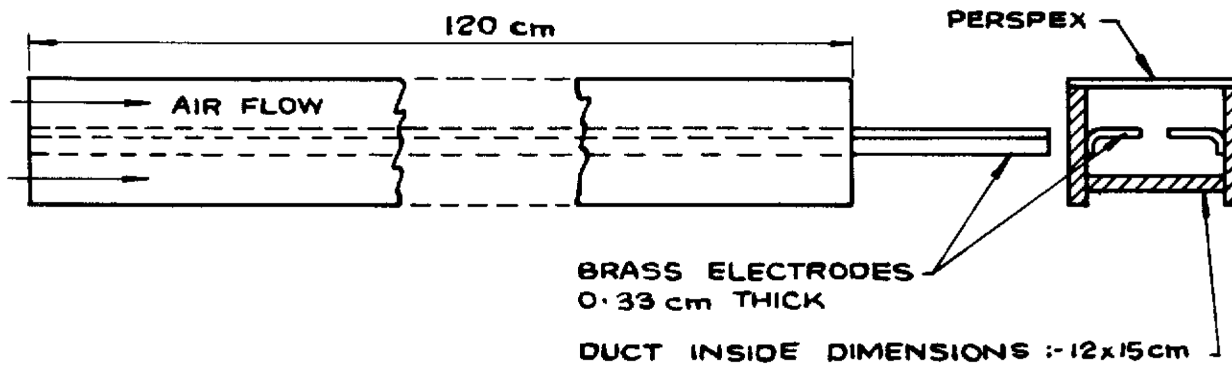


FIG. 2 PAIR OF BRASS ELECTRODES IN DUCT.
(ELECTRODES INSULATED ON UPPER AND LOWER SURFACES WITH THIN ALUMINIUM OXIDE COATING)

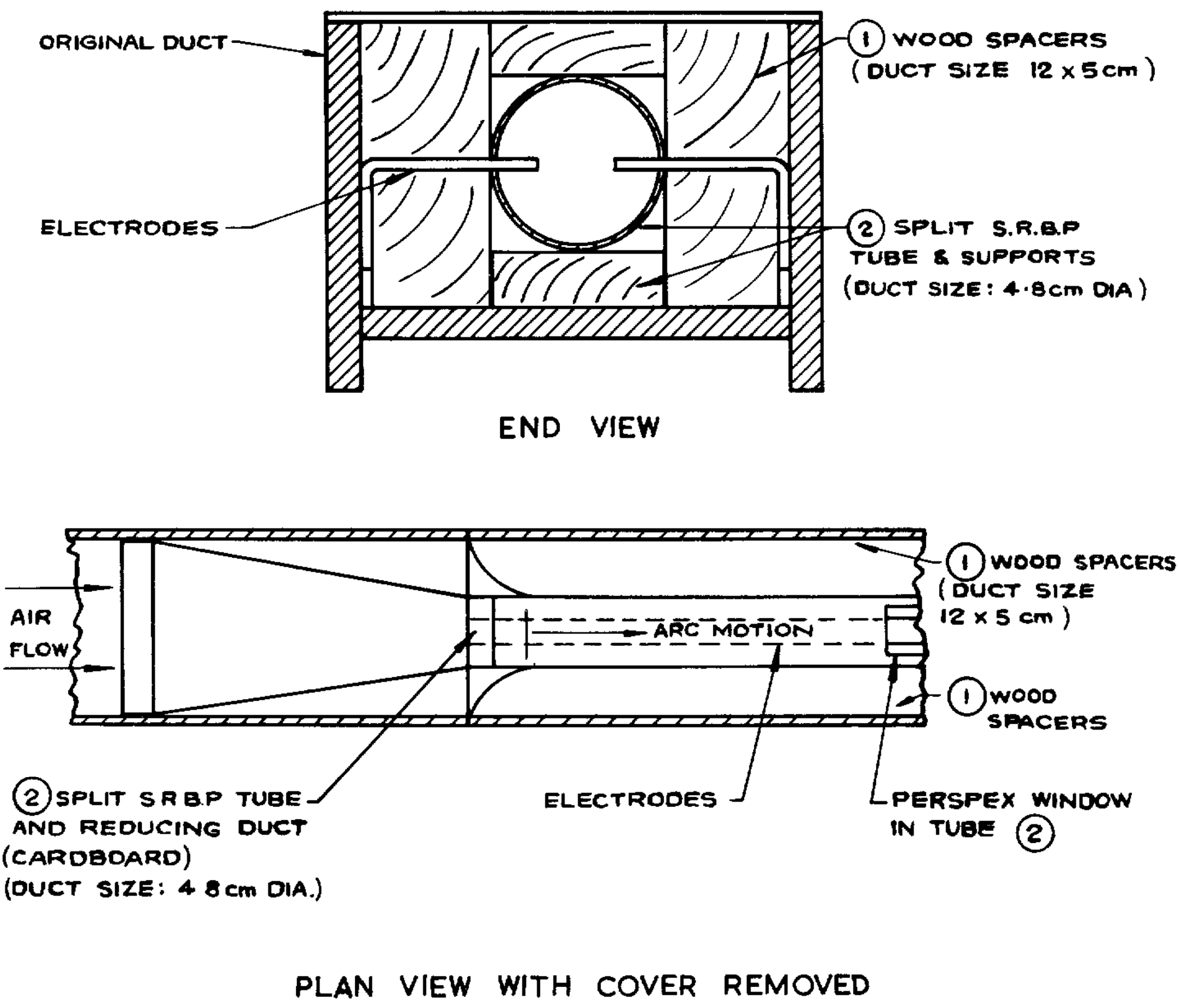
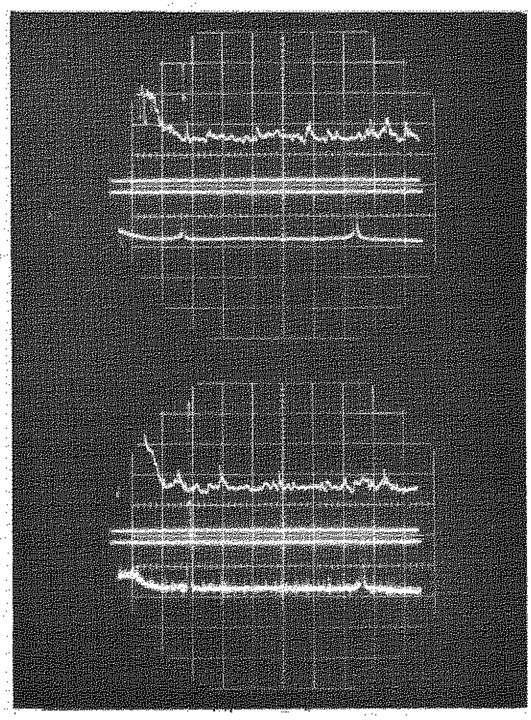


FIG. 3 ARRANGEMENTS FOR REDUCING DUCT SIZE
(① AND ②)



With low-pass filter

Without low-pass filter

Records for arcs on pair of brass electrodes.

Upper traces: arc voltage (50 V/cm)

Lower traces: arc current (100 A/cm) and optical probe signals superimposed (probe signals reduced by 4 dB attenuator)

$B = 0.023\ Wb/m^2$ GAP = 1.27 cm Time base = 2 msec/cm (zero time at R.H.S.)

Fig.4. Comparison of oscilloscope records with and without use of low-pass filter

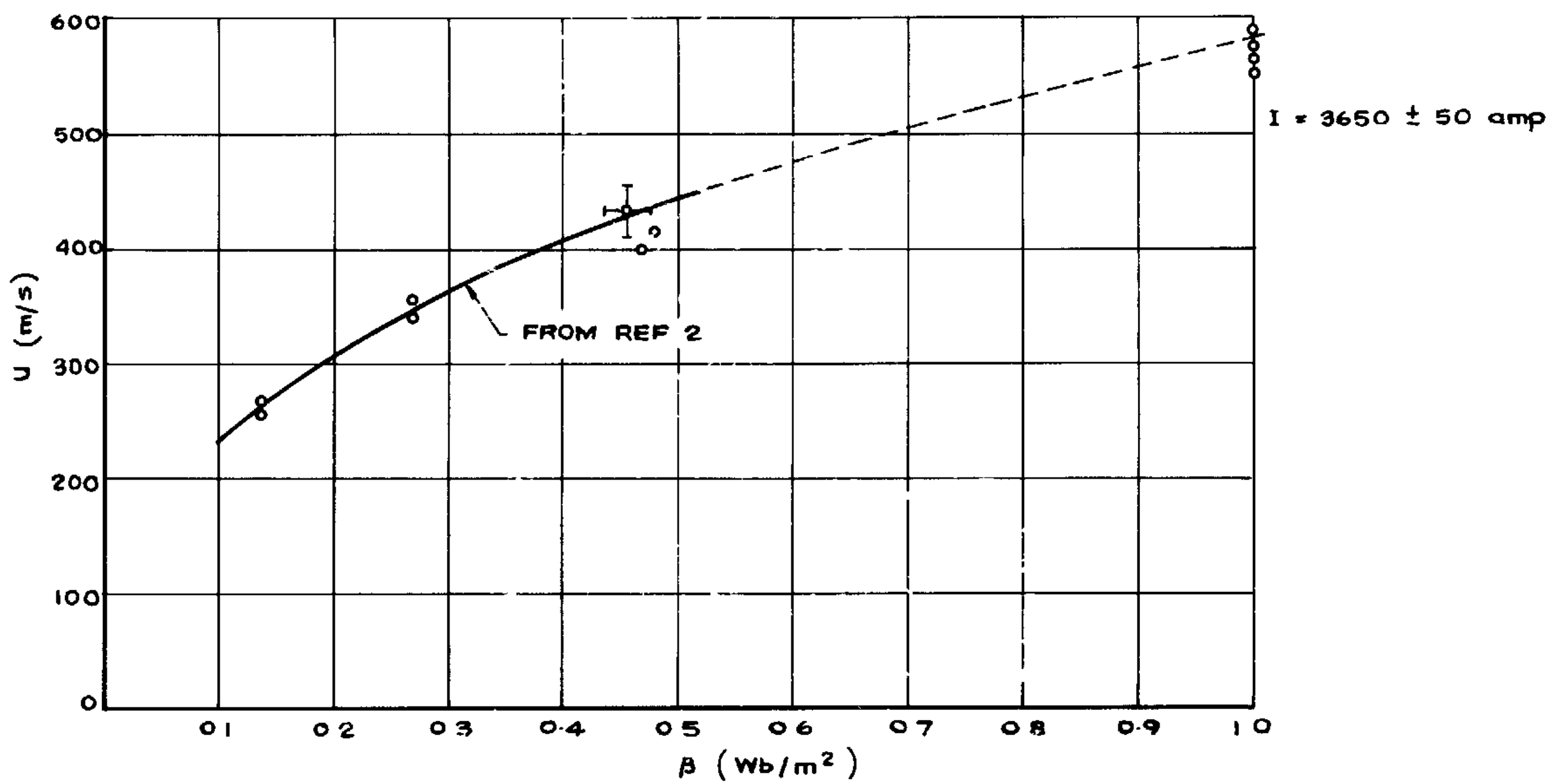


FIG 5. ARC VELOCITY AGAINST MAGNETIC FIELD FOR BRASS ELECTRODES WITH SINGLE END CONNECTIONS (d=1·27 cm)

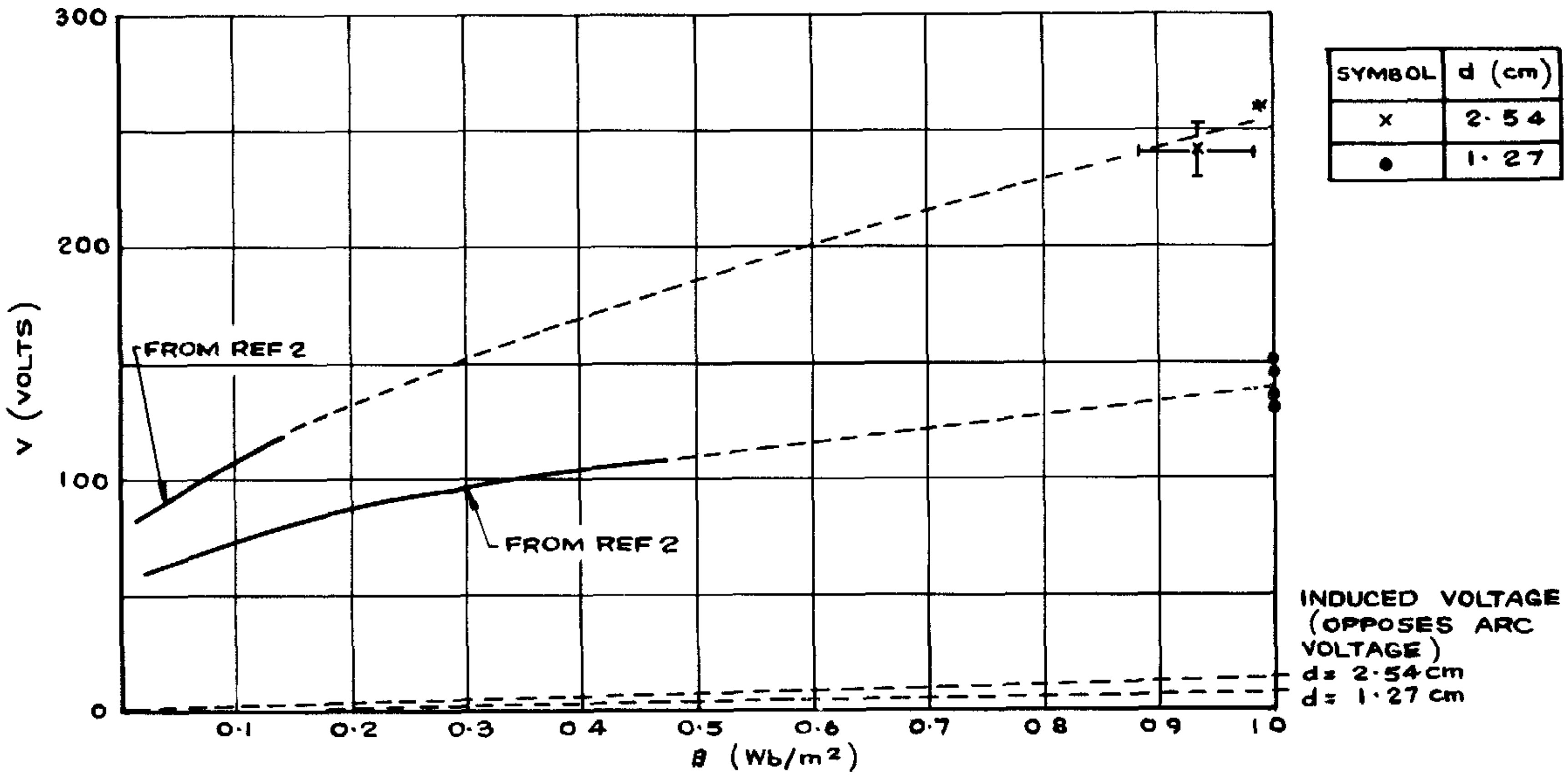
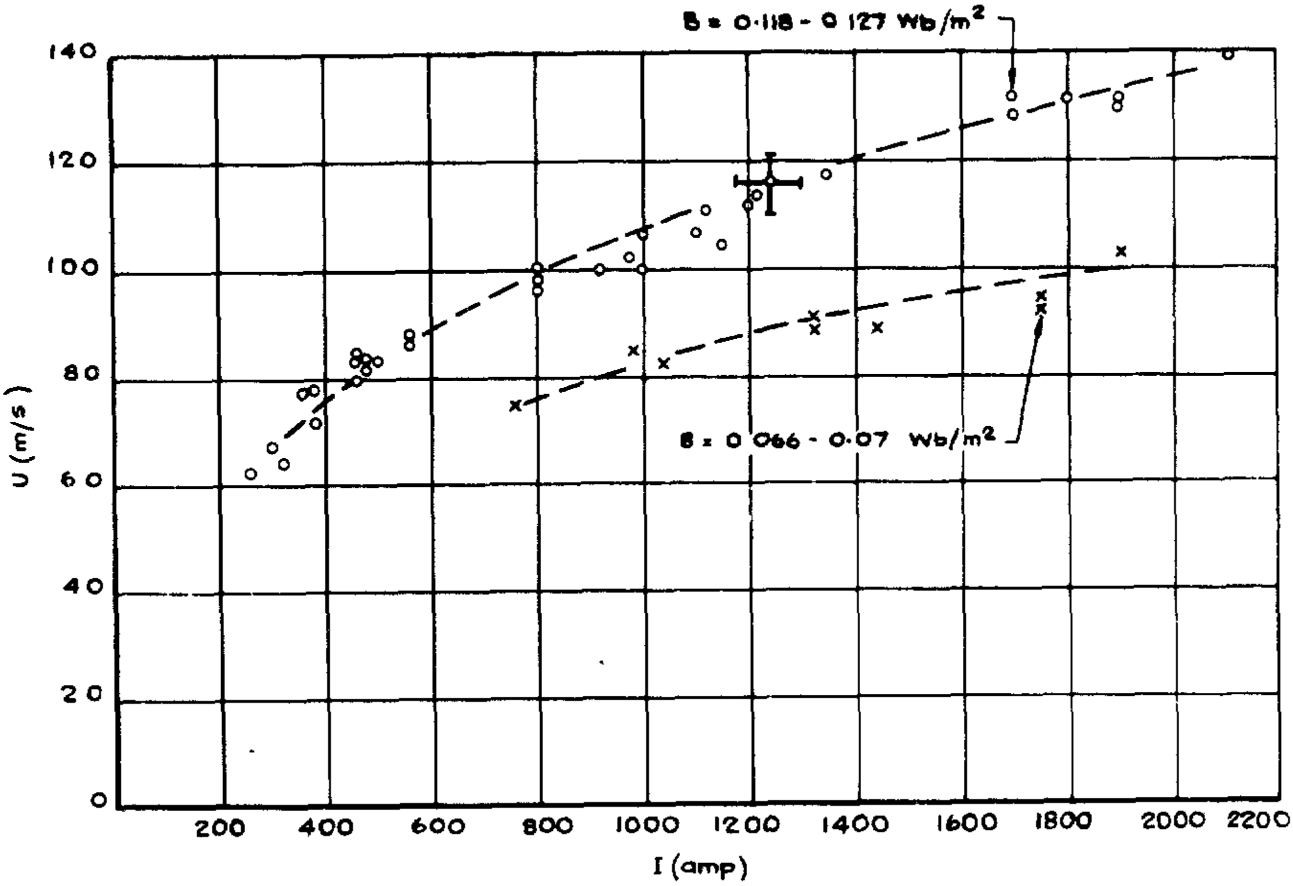


FIG. 6 MINIMUM ARC VOLTAGE AGAINST MAGNETIC FIELD FOR BRASS ELECTRODES WITH SINGLE END CONNECTIONS



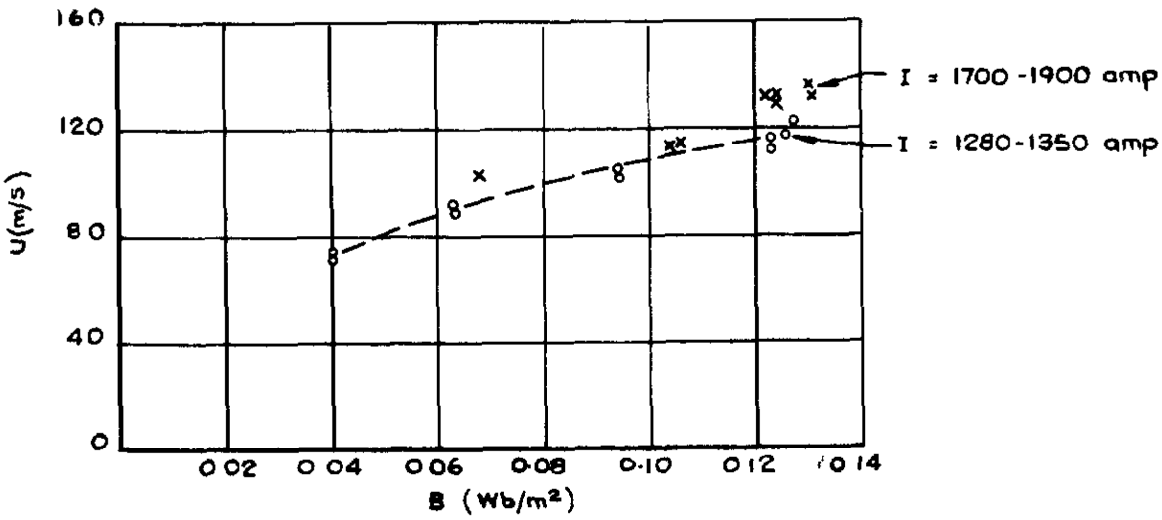
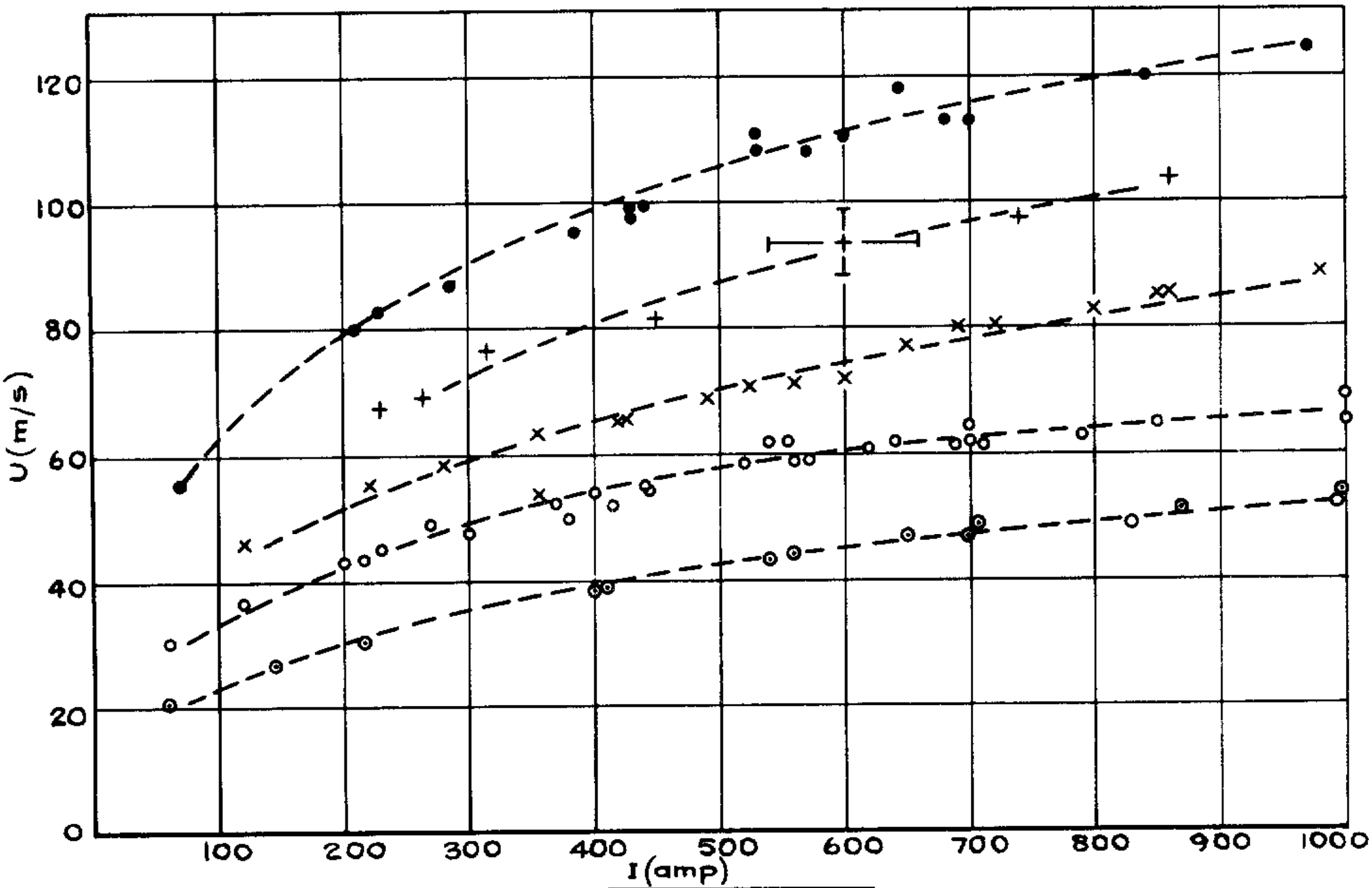
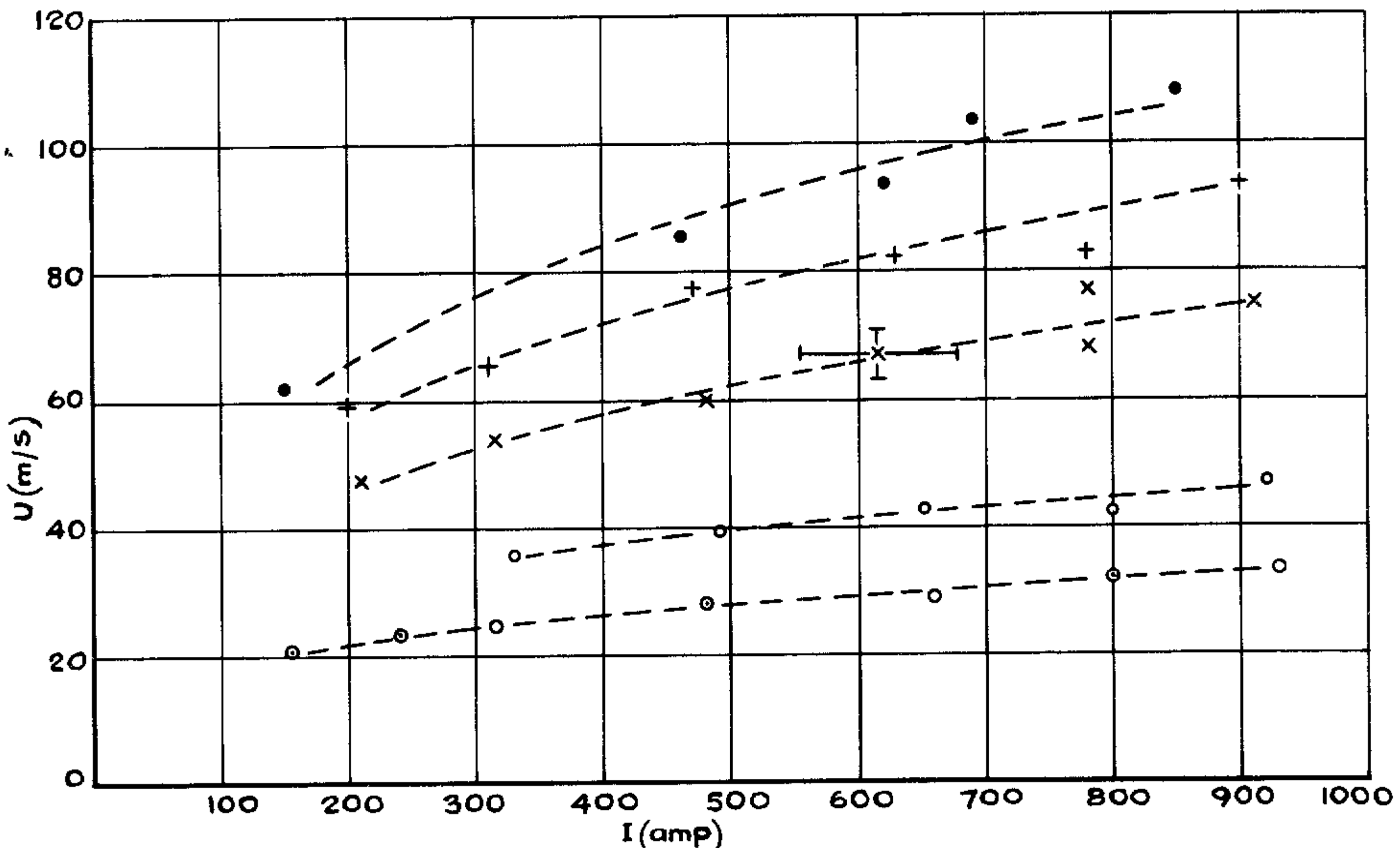


FIG. 7 ARC VELOCITY AGAINST ARC CURRENT AND MAGNETIC FIELD FOR BRASS ELECTRODES WITH SINGLE END CONNECTIONS (d = 3·5 cm)



SYMBOL	⊙	○	×	+	●
B (Wb/m²)	0 0155	0 031	0·05	0 0706	0·1075

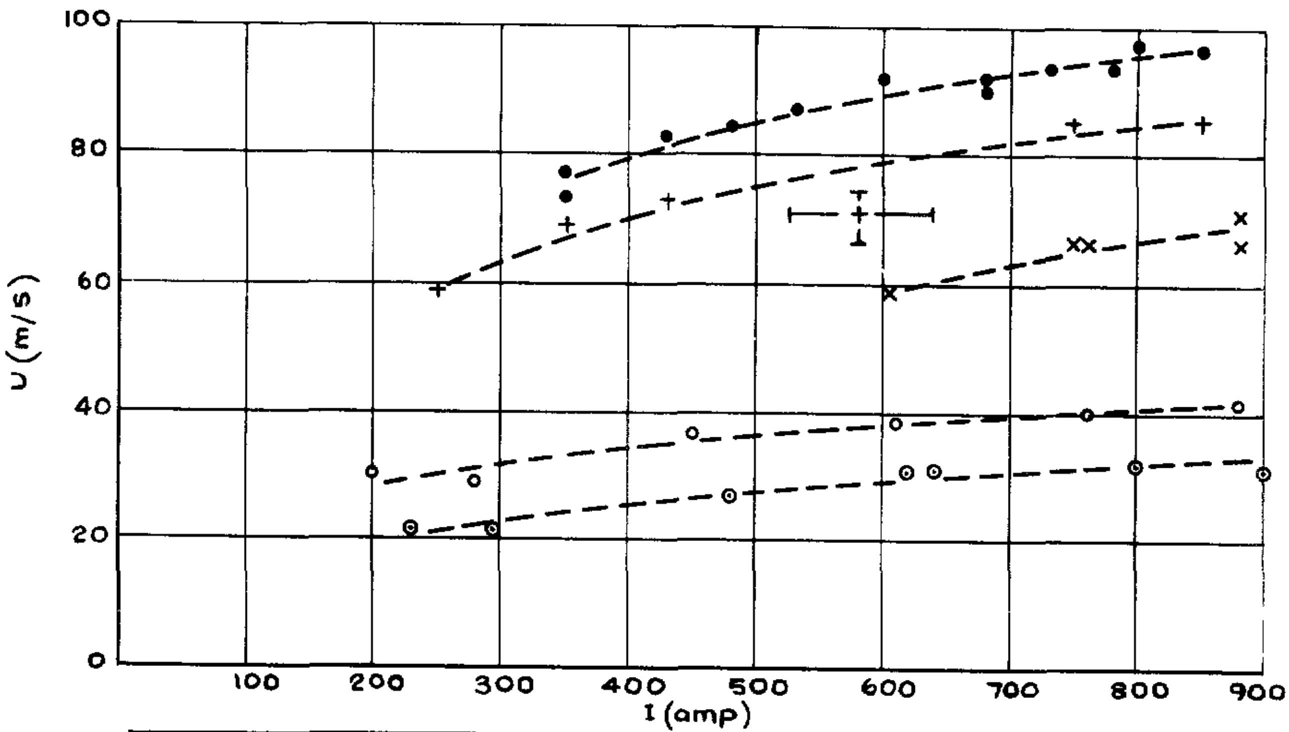
d = 1·27 cm



SYMBOL	⊙	○	×	+	●
B (Wb/m²)	0·015	0·025	0·0435	0 081	0·109

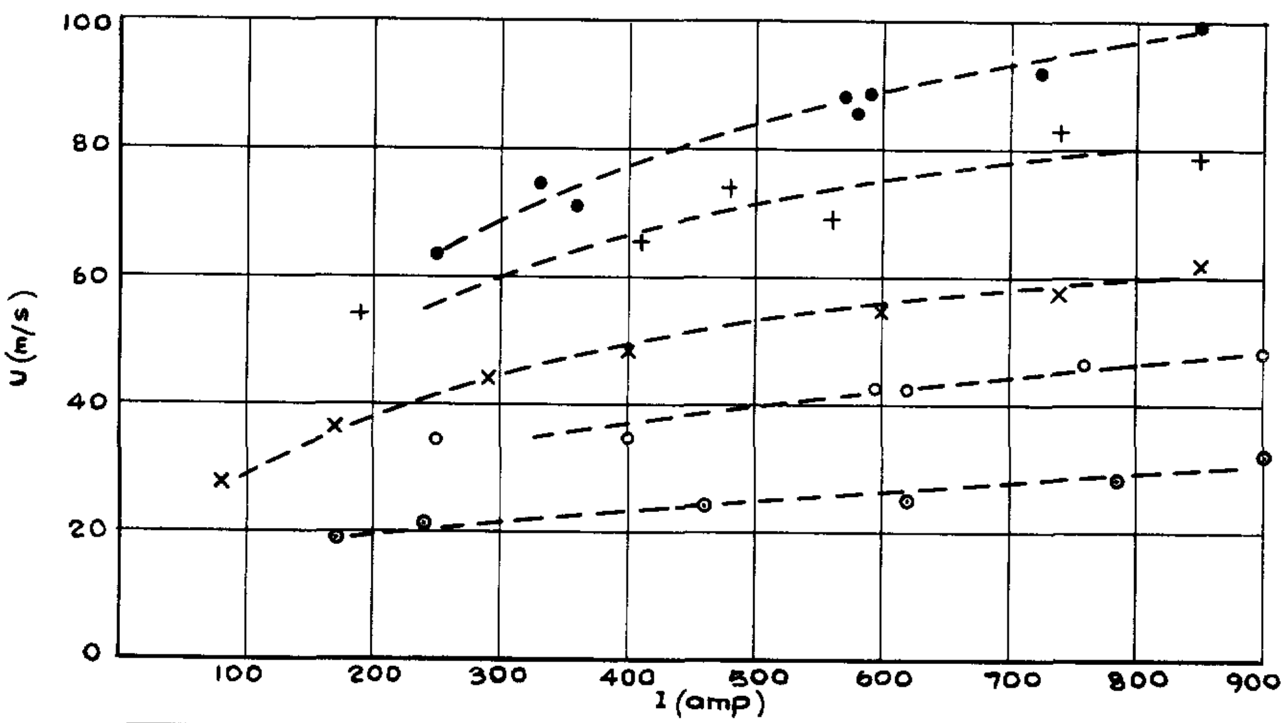
d = 2·54 cm

FIG. 8. ARC VELOCITY AGAINST ARC CURRENT FOR DOUBLE END CONNECTIONS TO BRASS ELECTRODES



SYMBOL	⊙	o	X	+	•
B (Wb/m²)	0 015	0·026	0 0505	0 0805	0·1075

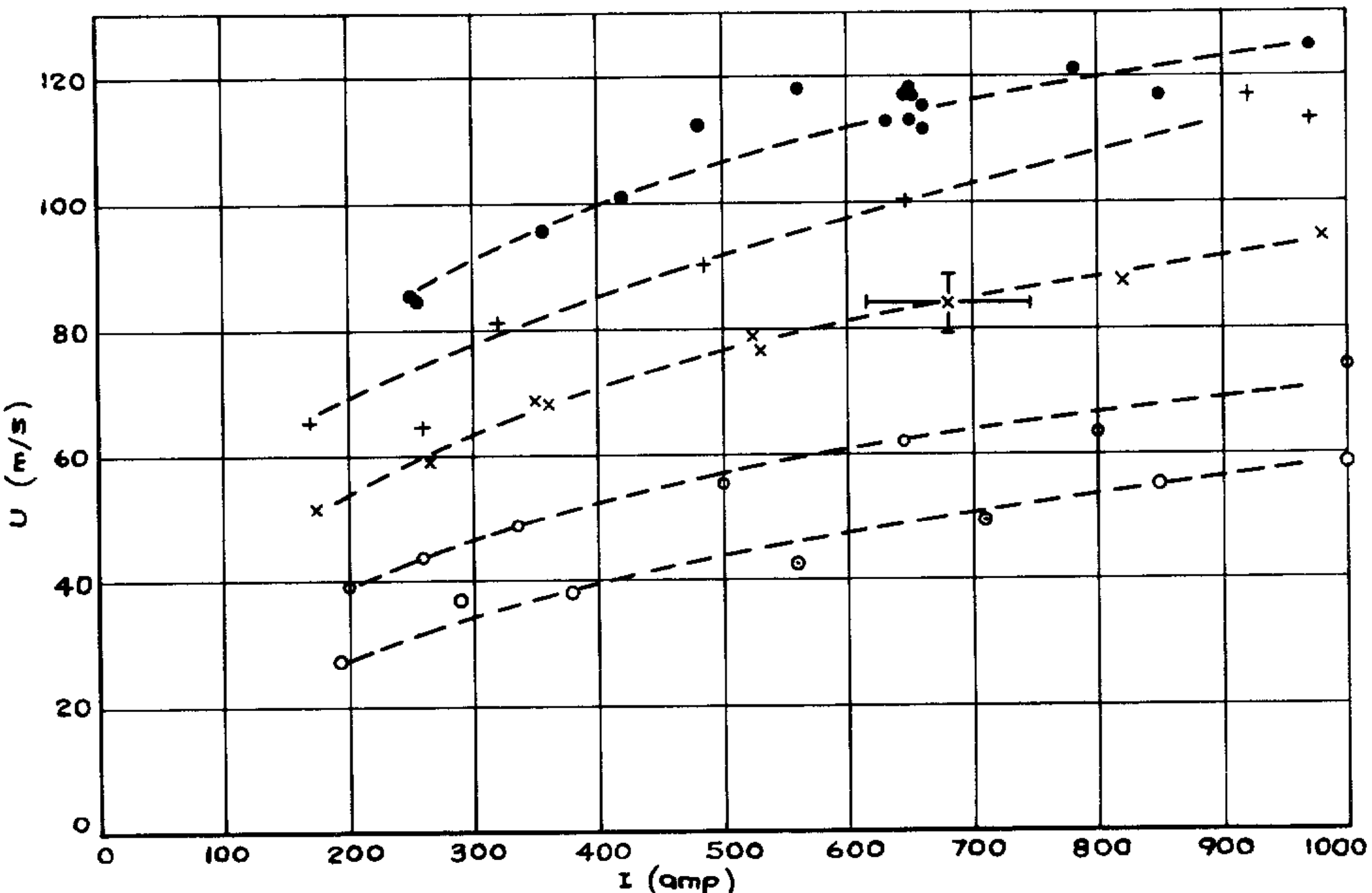
d = 3·2 cm



SYMBOL	⊙	o	X	+	•
B (Wb/m²)	0·0155	0 031	0 050	0 081	0 109

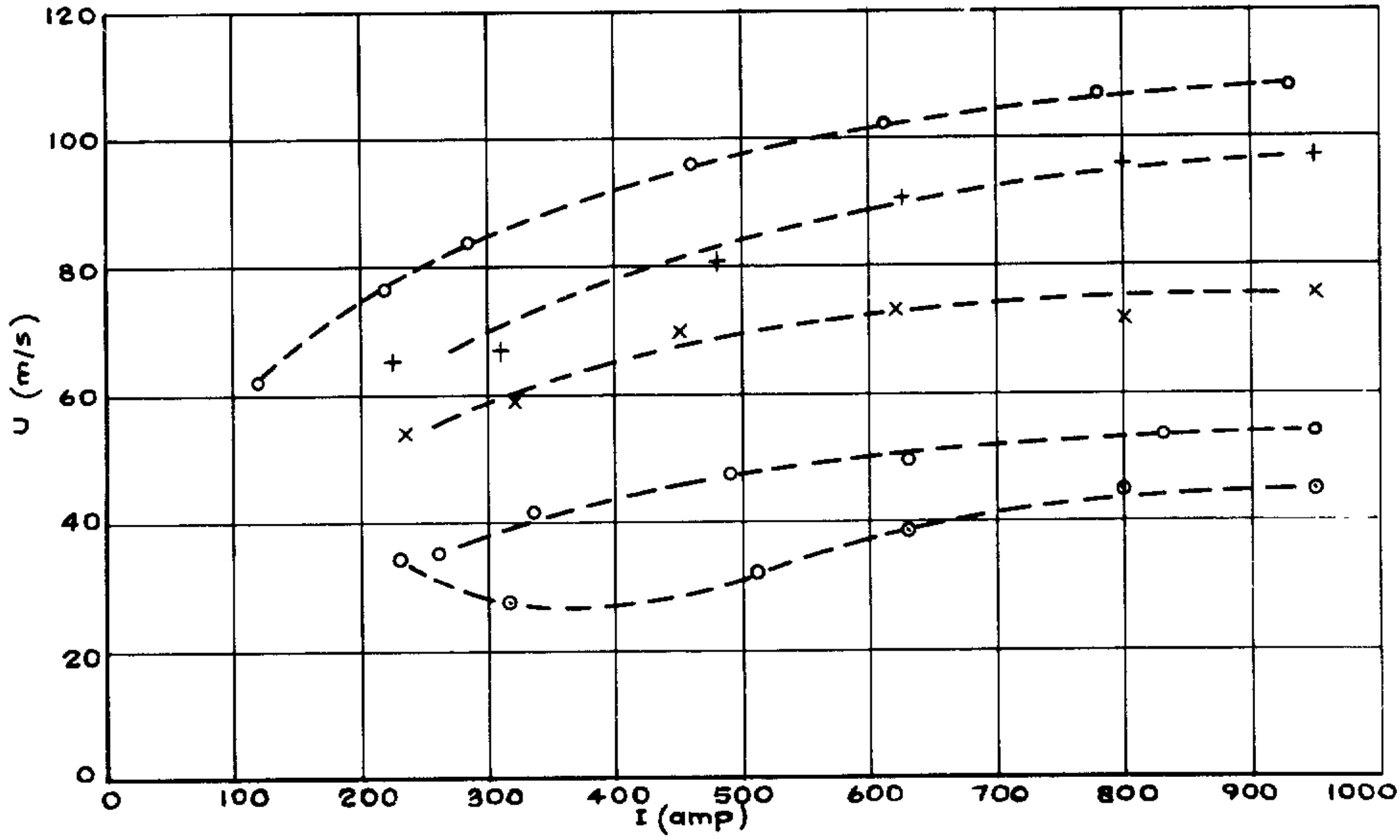
d = 3· 8 cm

FIG.9. ARC VELOCITY AGAINST ARC CURRENT FOR DOUBLE END CONNECTIONS TO BRASS ELECTRODES



SYMBOL	⊙	○	×	+	●
B (Wb/m^2)	0·012	0·025	0·0535	0·081	0·108

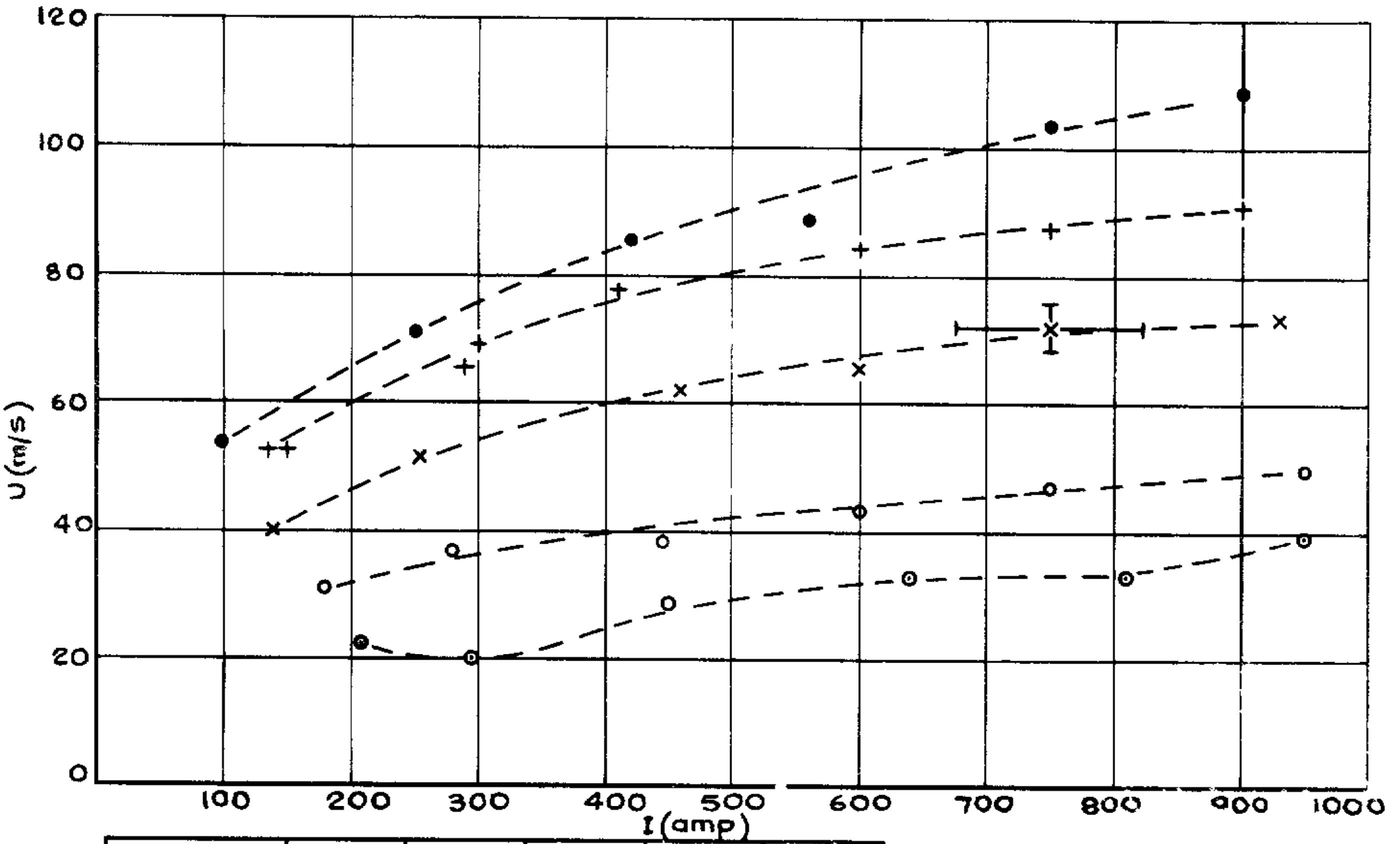
d = 1·27 cm



SYMBOL	⊙	○	×	+	●
B (Wb/m^2)	0·0125	0·026	0·0535	0·082	0·108

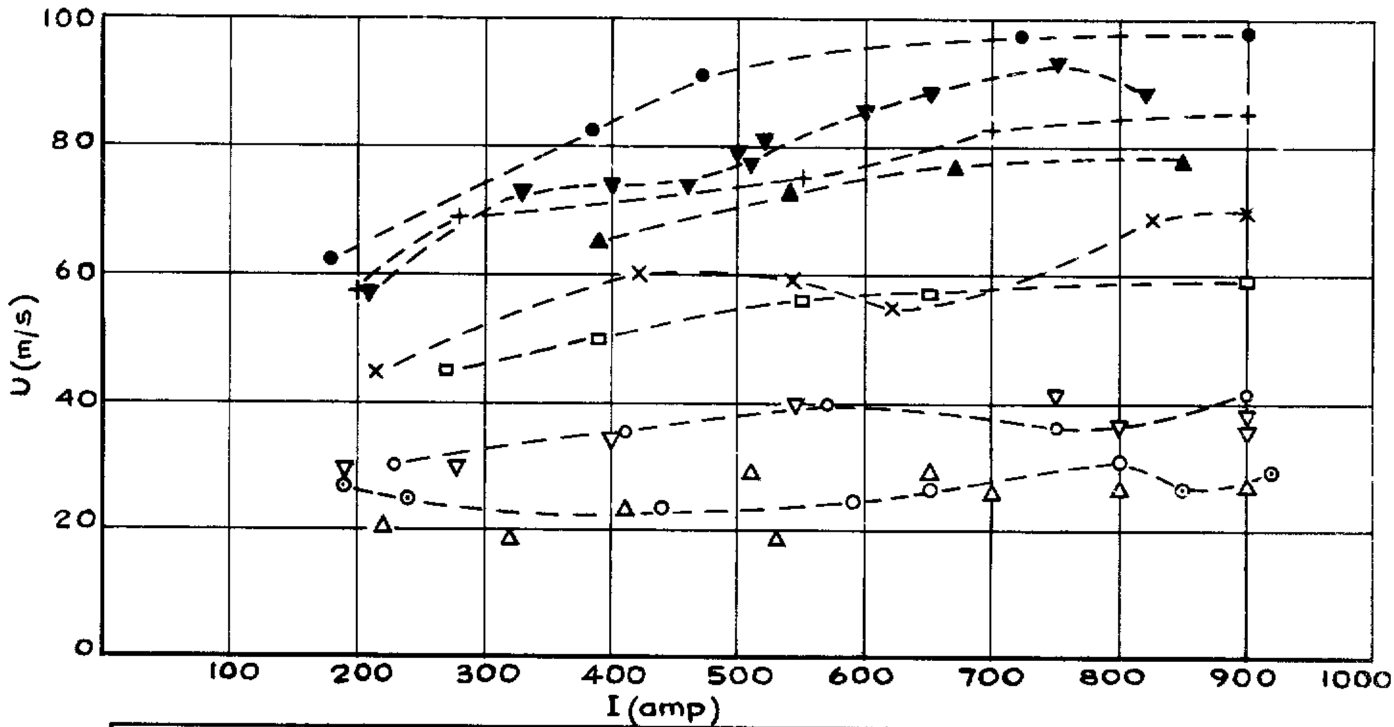
d = 1·91 cm

FIG.10 ARC VELOCITY AGAINST ARC CURRENT FOR DOUBLE END CONNECTIONS TO COPPER ELECTRODES



SYMBOL	⊙	○	×	+	●
B (Wb/m²)	0·0125	0·027	0 054	0 081	0·108

d = 2·54 cm



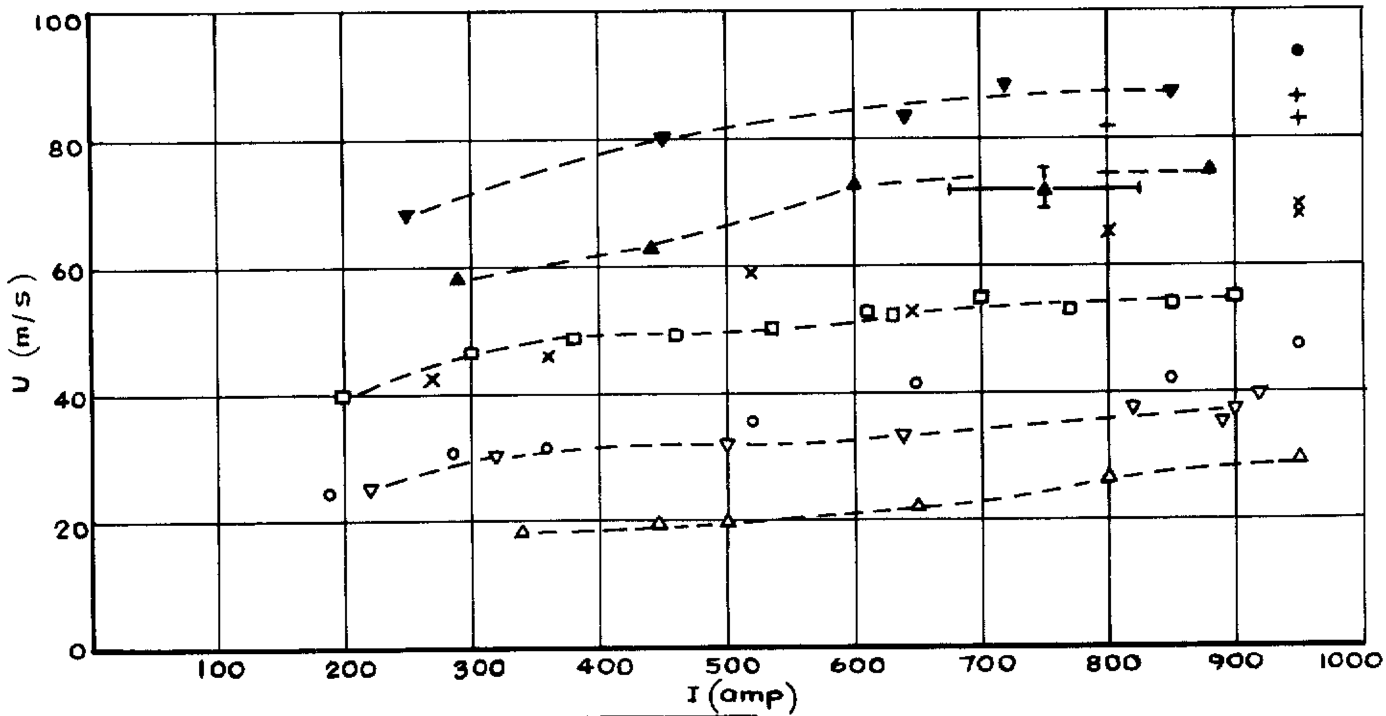
SYMBOL	⊙	○	×	+	●
B (Wb/m²)	0·0125	0 024	0·052	0·081	0·108

d = 3·2 cm

SYMBOL	△	▽	□	▲	▼
B (Wb/m²)	0·012	0·0245	0 0525	0·0805	0 108

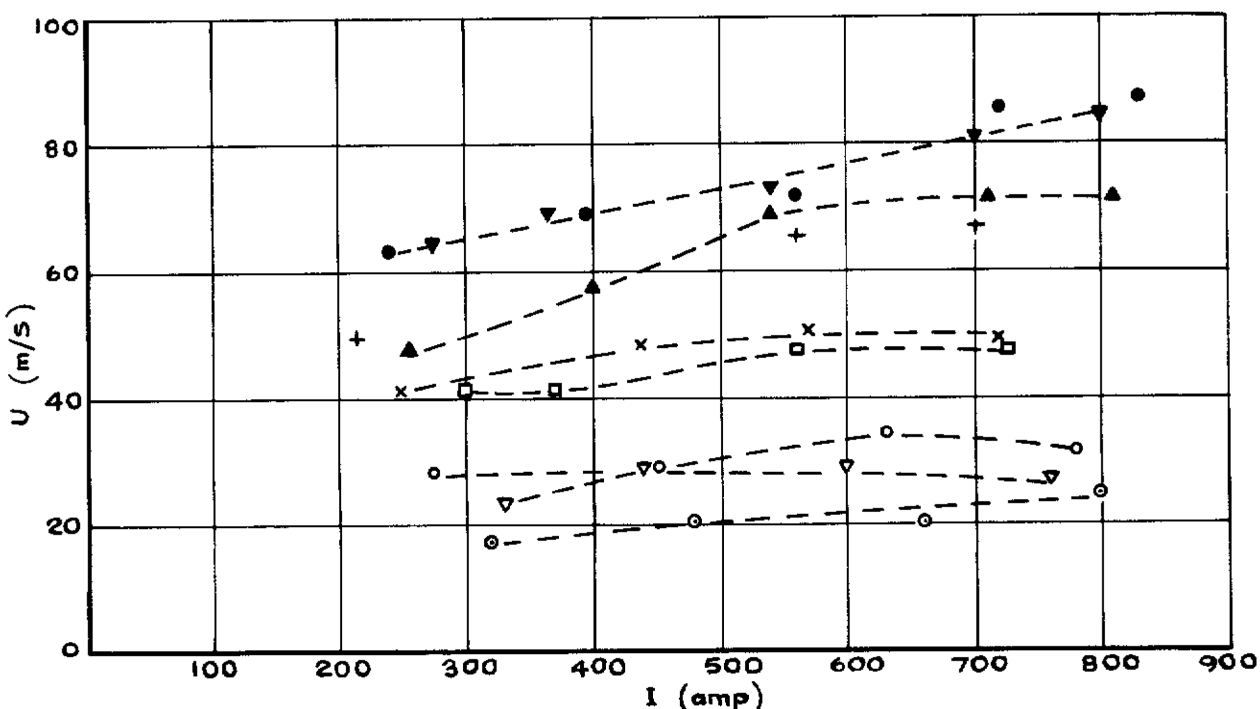
d = 3·8 cm

FIG.11. ARC VELOCITY AGAINST ARC CURRENT FOR DOUBLE END CONNECTIONS TO COPPER ELECTRODES



SYMBOL	●	+	×	○	
B (Wb/m²)	0·1055	0 081	0 053	0 0255	d = 1·27 cm

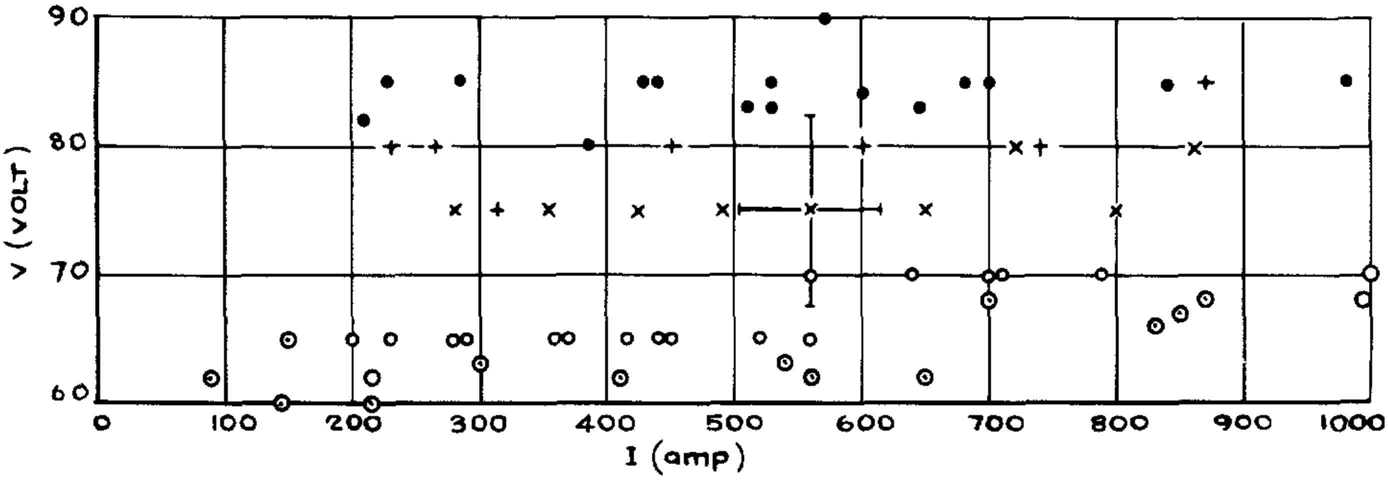
SYMBOL	▼	▲	□	▽	△	
B (Wb/m²)	0·109	0 082	0 0525	0 025	0·014	d = 2 54 cm



SYMBOL	⊙	○	×	+	●	
B (Wb/m²)	0·014	0·026	0 053	0 080	0 108	d = 3 2 cm

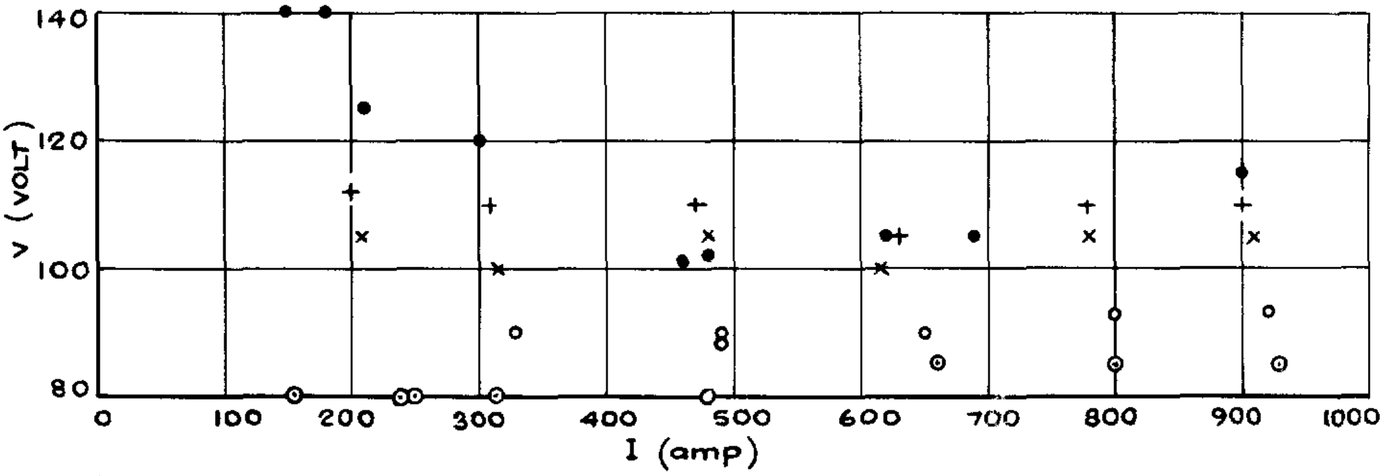
SYMBOL	▽	□	▲	▼	
B (Wb/m²)	0·0235	0·053	0 0815	0 1075	d = 3 7 cm

FIG. 12 ARC VELOCITY AGAINST ARC CURRENT FOR DOUBLE END CONNECTIONS TO ALUMINIUM ELECTRODES



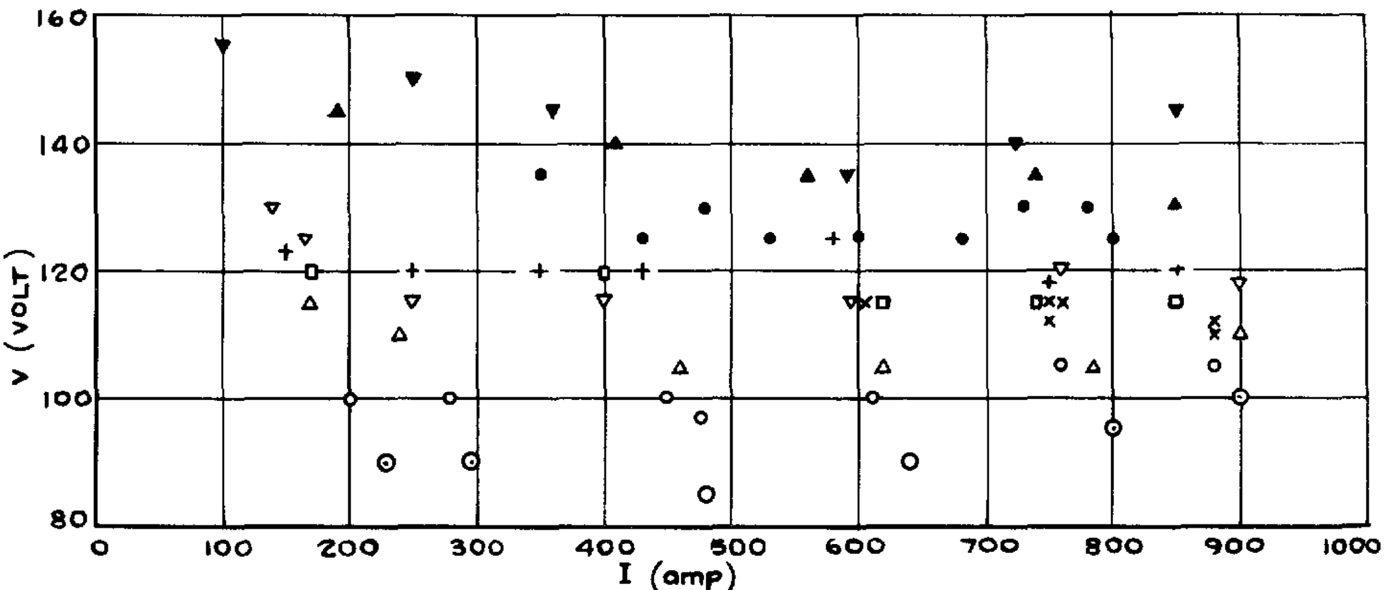
SYMBOL	⊙	∘	×	+	●
B (Wb/m^2)	0·0155	0 031	0·05	0·0705	0·1075

d = 1·27 cm



SYMBOL	⊙	∘	×	+	●
B (Wb/m^2)	0·015	0·025	0·0435	0·081	0·109

d = 2·54 cm



SYMBOL	⊙	∘	×	+	●
B (Wb/m^2)	0·015	0·026	0 0505	0 0805	0 1075

d = 3 2 cm

SYMBOL	△	▽	□	▲	▼
B (Wb/m^2)	0 0155	0 031	0 050	0·081	0·109

d = 3·8 cm

FIG.13 MINIMUM ARC VOLTAGES FOR DOUBLE END CONNECTIONS TO BRASS ELECTRODES

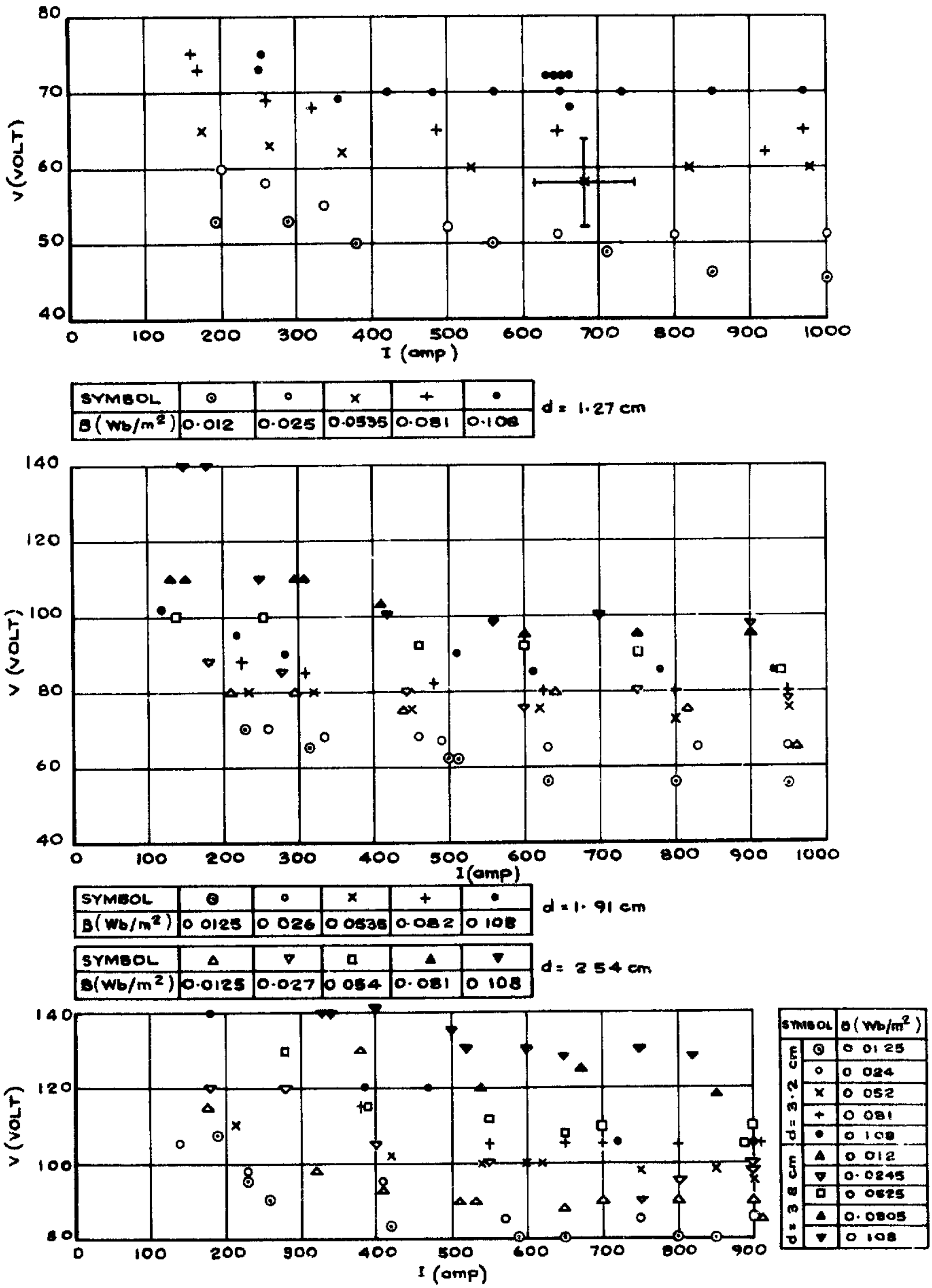
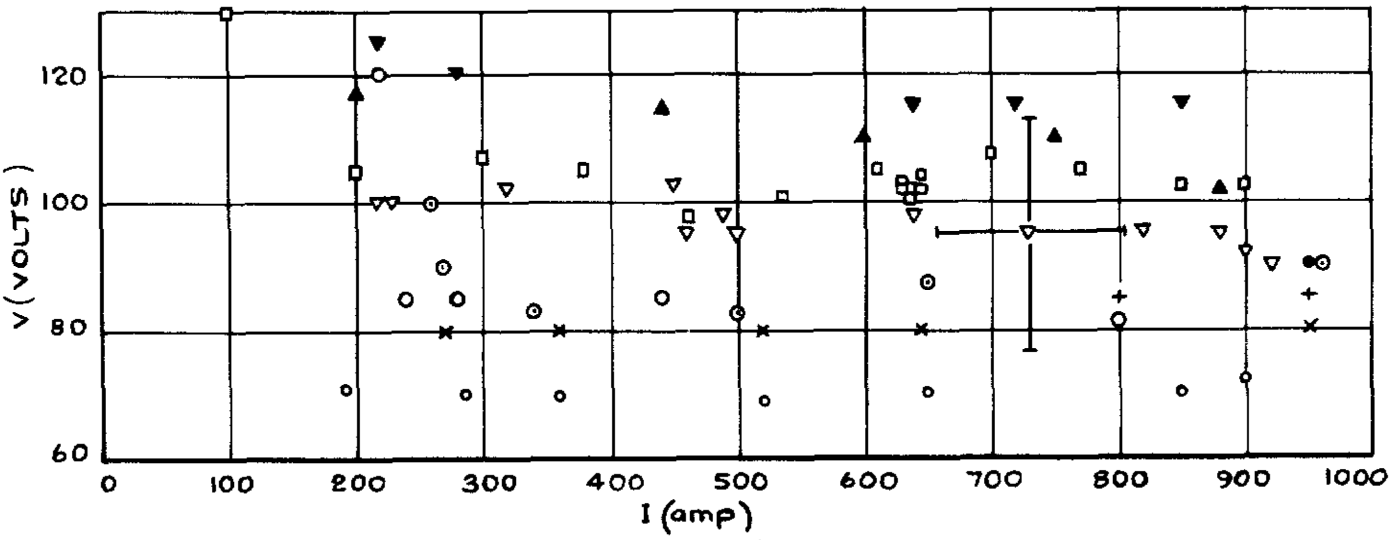


FIG. 14 MIMIMUM ARC VOLTAGES FOR DOUBLE END CONNECTIONS TO COPPER ELECTRODES

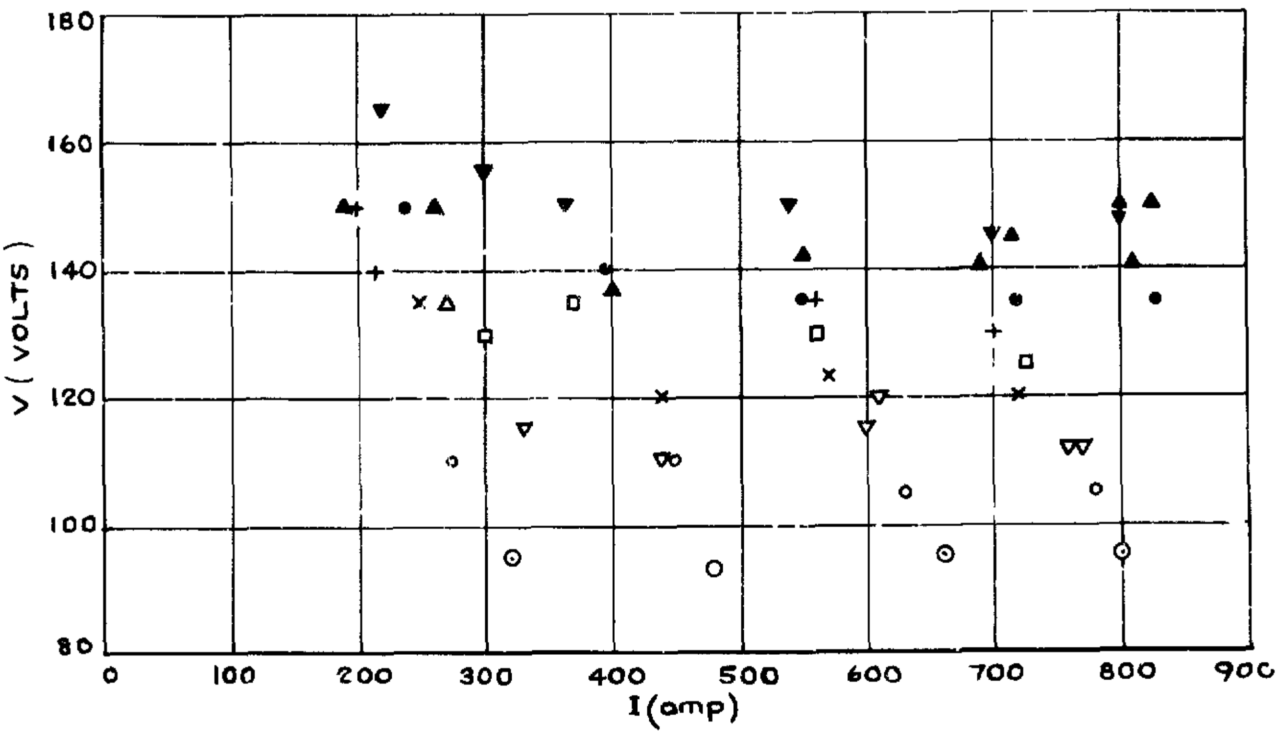


SYMBOL	⊙	×	+	•
B (Wb/m²)	0.0255	0 053	0·081	0·1055

d = 1·27 cm

SYMBOL	⊙	▽	□	▲	▼
B (Wb/m²)	0·014	0·025	0·0525	0·082	0·109

d = 2·54 cm



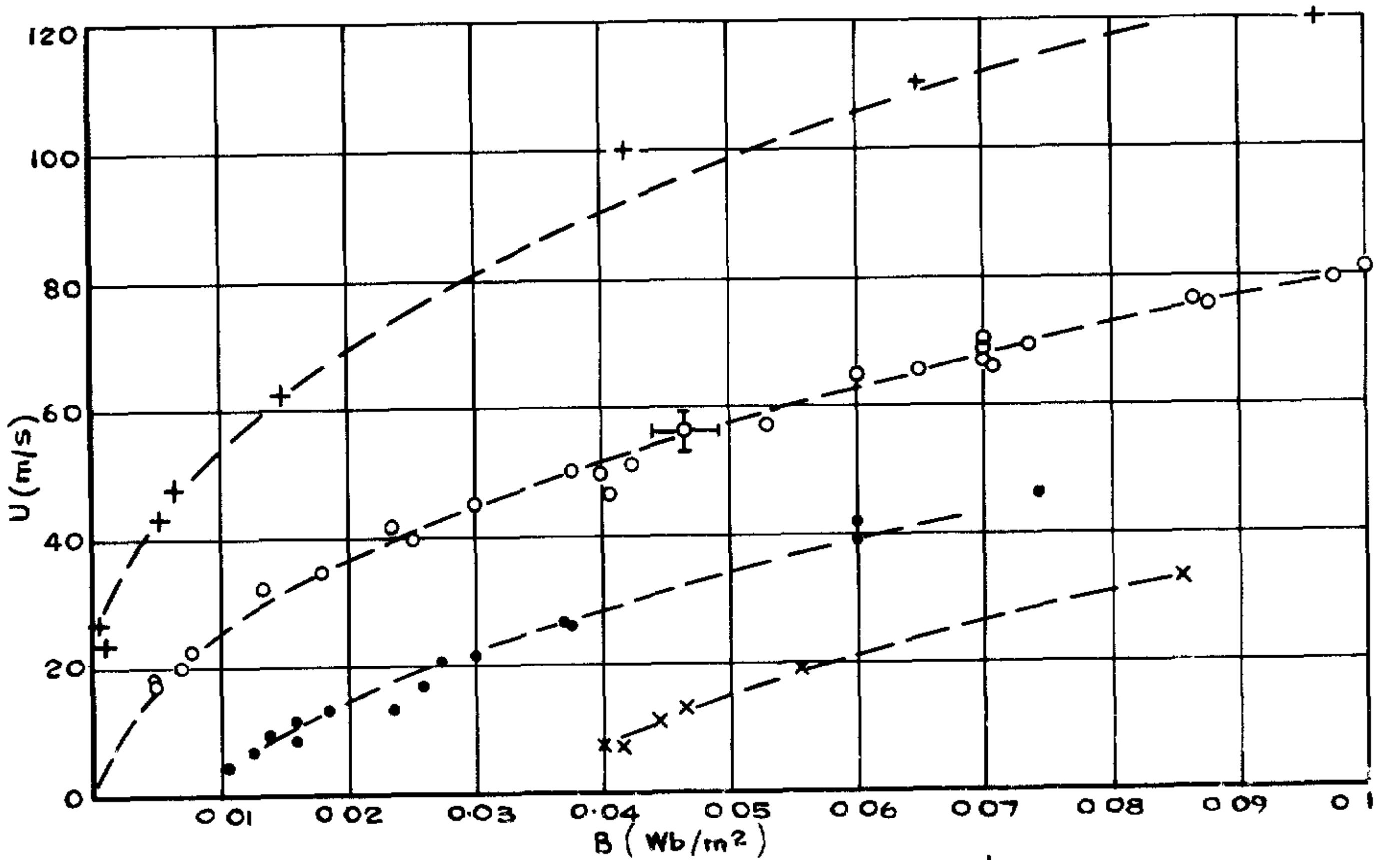
SYMBOL	⊙	o	×	+	•
B (Wb/m²)	0·014	0 026	0·053	0·080	0 108

d = 3·2 cm

SYMBOL	▽	□	▲	▼
B (Wb/m²)	0 0235	0·053	0 815	0·1075

d = 3·7 cm

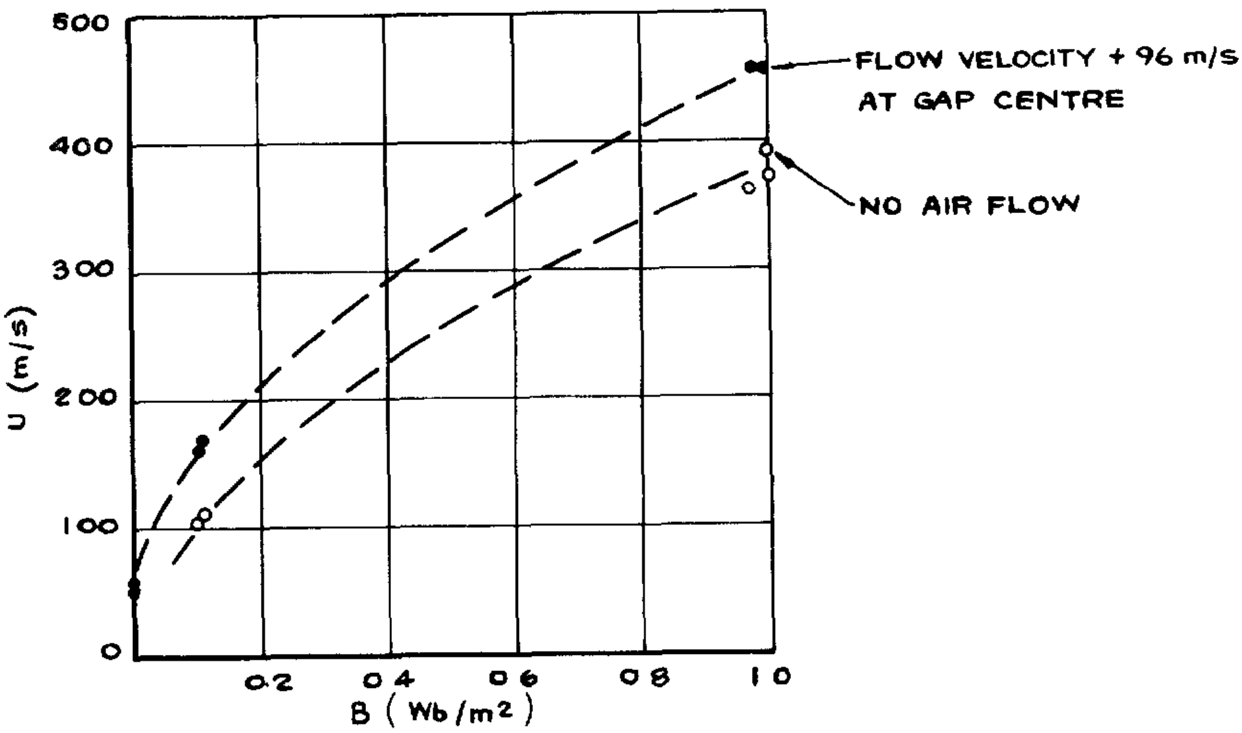
FIG.15 MINIMUM ARC VOLTAGES FOR DOUBLE END CONNECTIONS TO ALUMINIUM ELECTRODES



a

I = 290 ± 30 amp
d = 1·59 cm

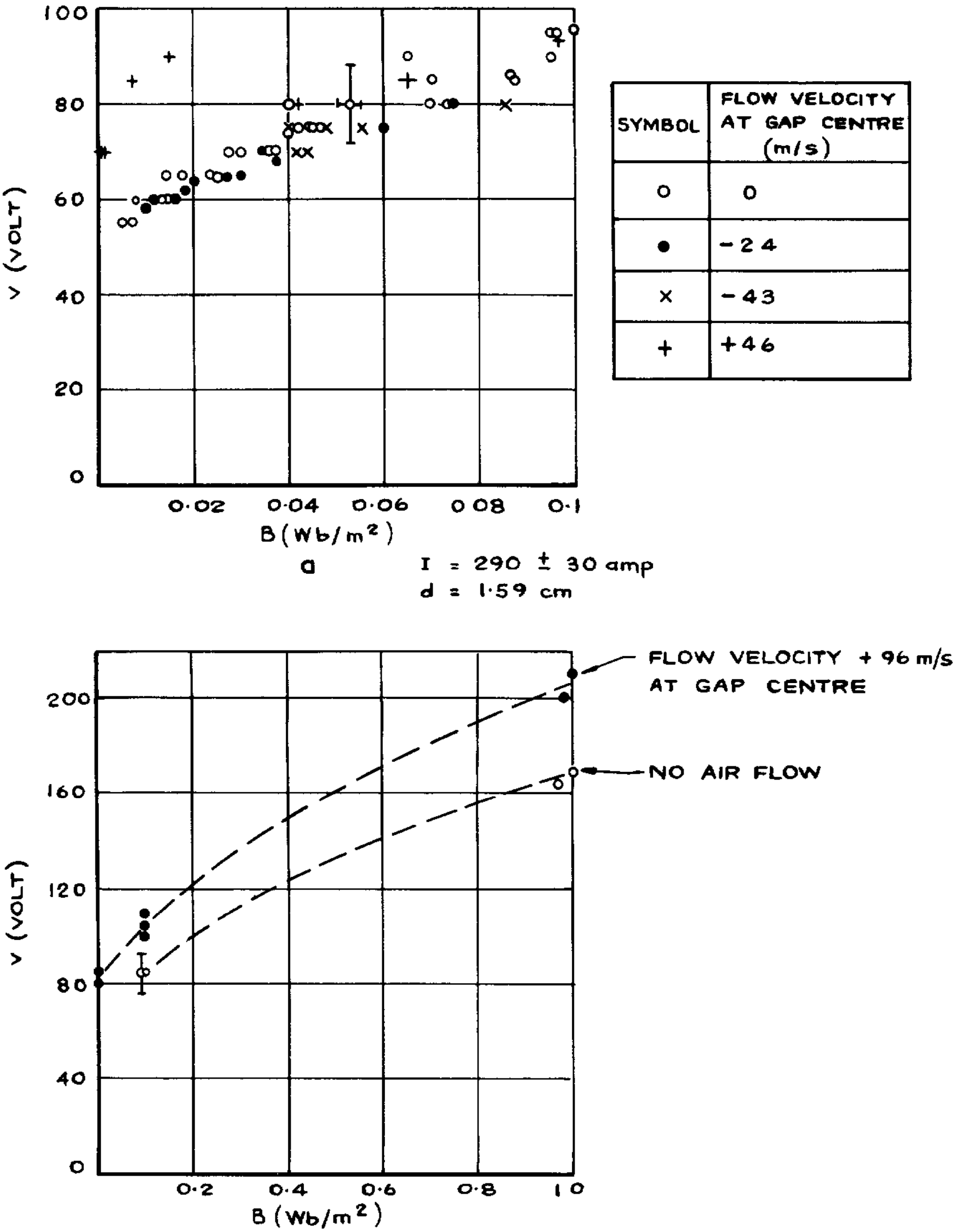
SYMBOL	o	•	x	+
AIR FLOW REL TO DIRECTION OF ARC MOTION (m/s) (AT GAP CENTRE)	0	-24	-43	+46



b

I = 600 ± 100 amp
d = 1·59 cm

FIG. 16a & b ARC VELOCITY AGAINST MAGNETIC FIELD FOR ARCS WITH IMPOSED AIR FLOW



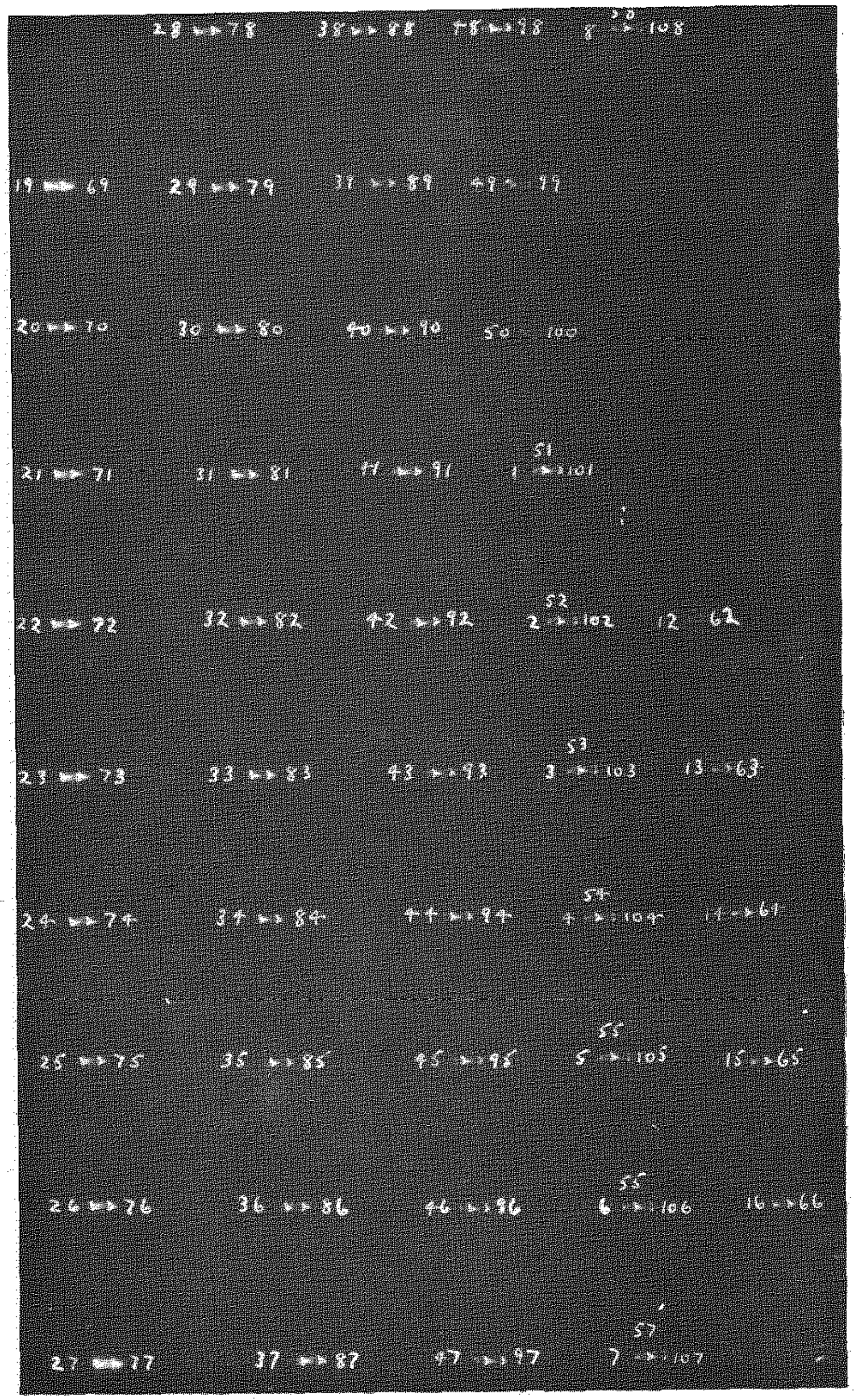
a

I = 290 $\pm$ 30 amp
d = 1·59 cm

b

I = 600 $\pm$ 100 amp
d = 1·59 cm

FIG. 17a & b MINIMUM ARC VOLTAGES FOR ARCS WITH IMPOSED AIR FLOW



$B = 0$

$I = 635$ amp

$U_a = 96$ m/s

$U = 60$ m/s

Nos. indicate sequence of images.

Fig.18. High speed photographs of arc moving with air stream (arc motion left to right)

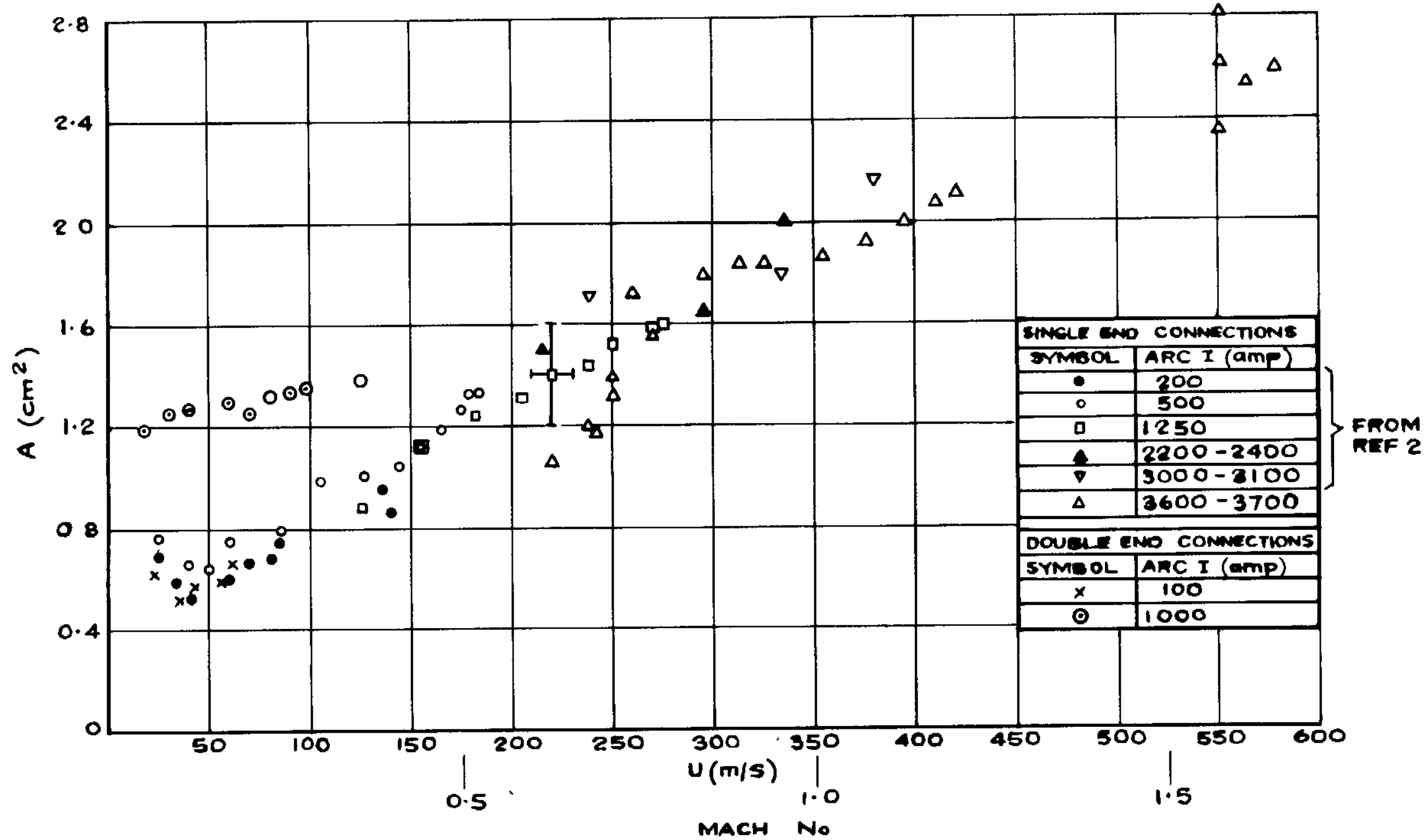


FIG. 19 A AGAINST ARC VELOCITY FOR BRASS ELECTRODES (d= 1·27cm)

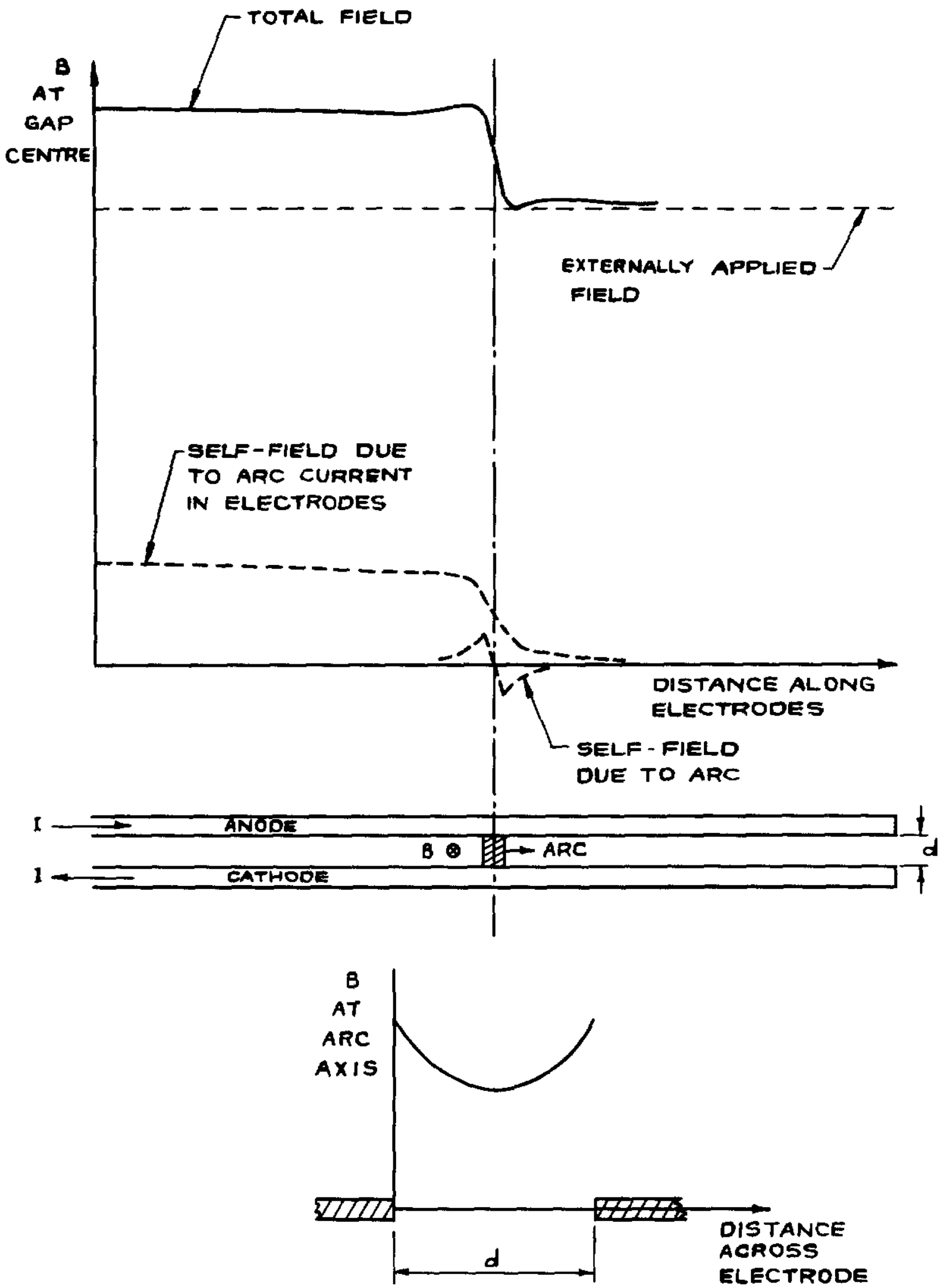


FIG.20 DIAGRAM OF VARIATION OF MAGNETIC FIELD IN ELECTRODE GAP DUE TO SELF-FIELD

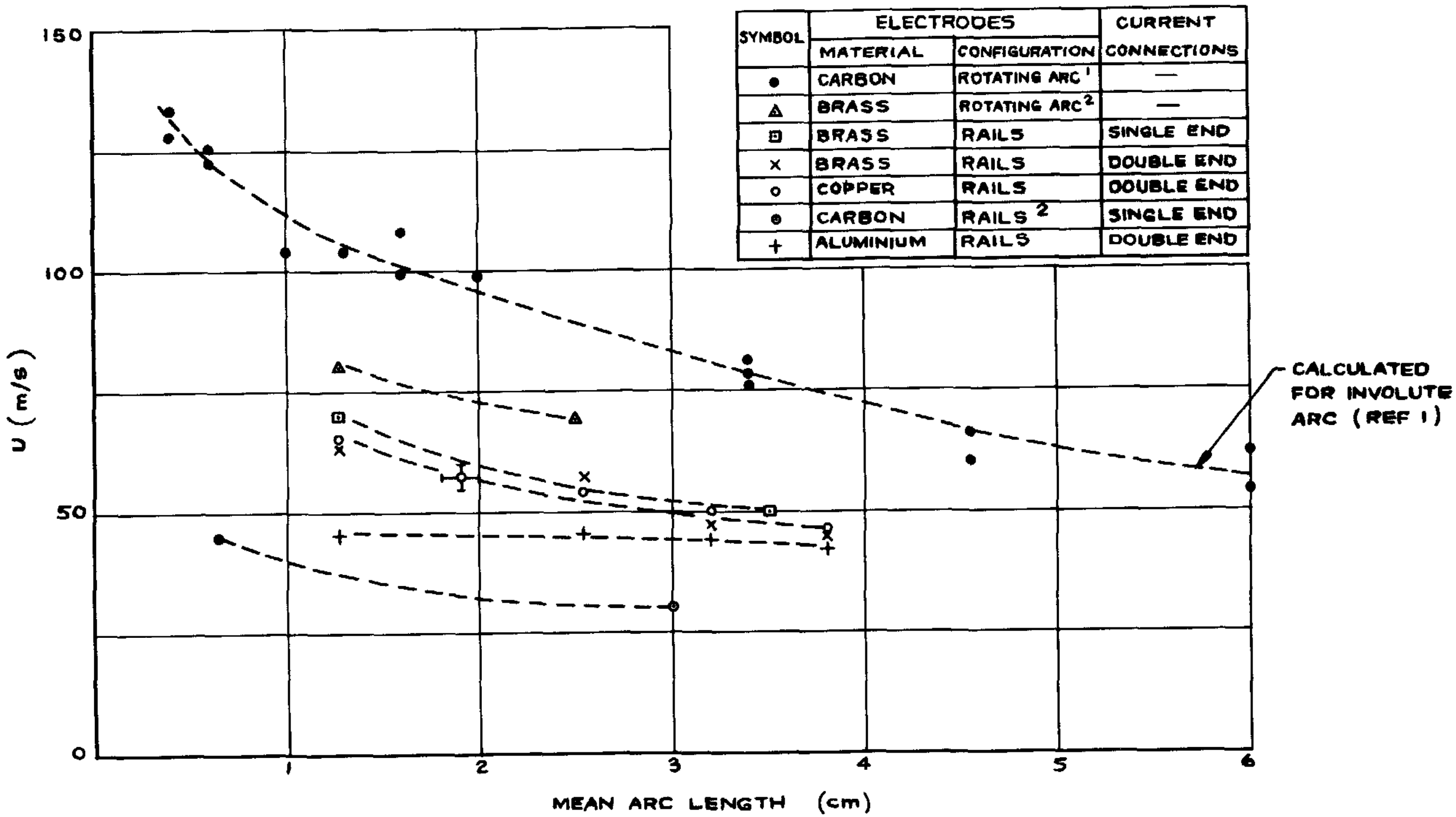
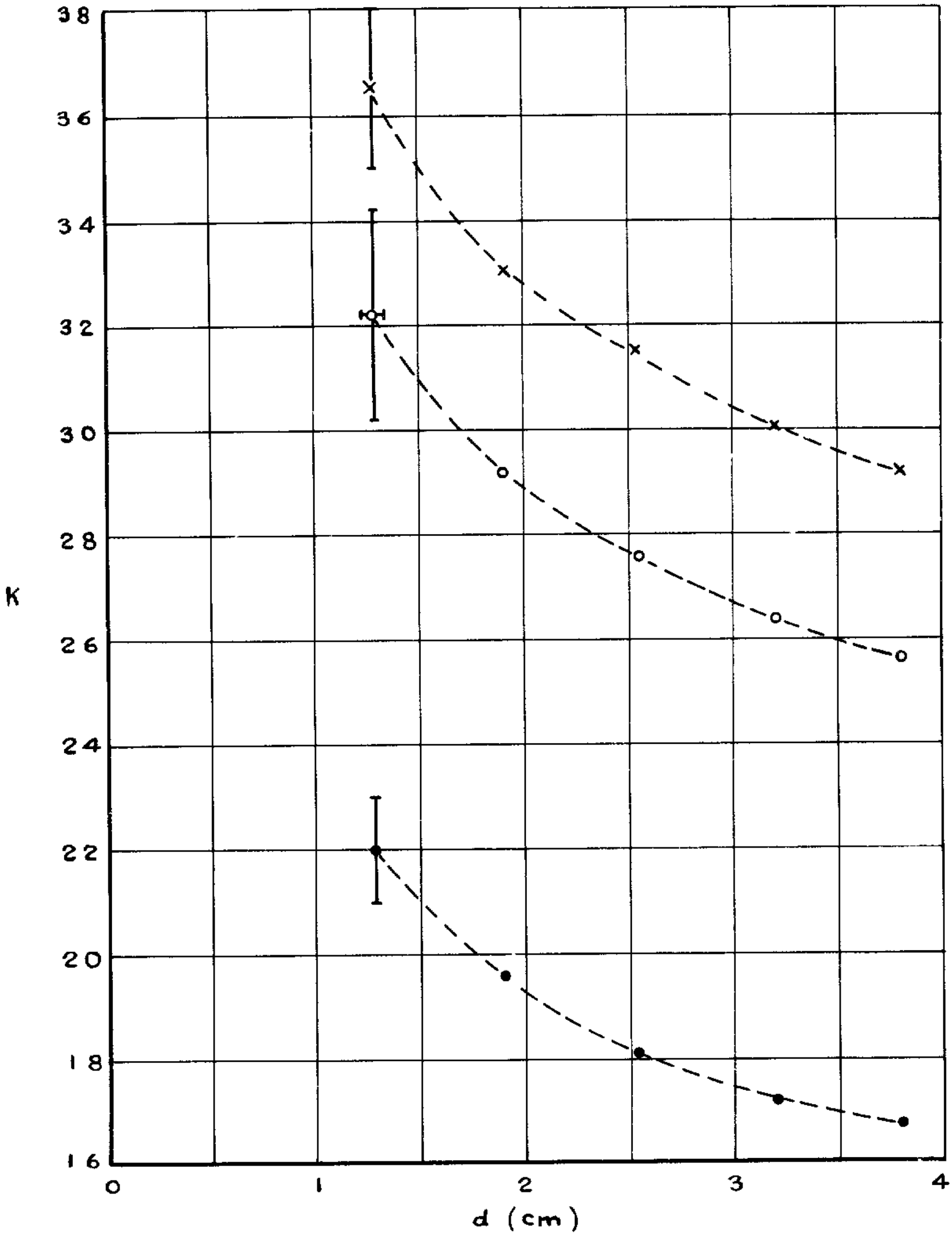


FIG. 21 ARC VELOCITY AGAINST MEAN ARC LENGTH. $B = 0{\cdot}047\ \mathrm{Wb/m^2}$ $I = 360$ amp



× BRASS (DOUBLE END CONNECTIONS)
○ COPPER (DOUBLE END CONNECTIONS) $U \simeq K I^{n_1} B^{n_2}$
● BRASS (SINGLE END CONNECTIONS)

FIG 22 VARIATION OF K WITH d

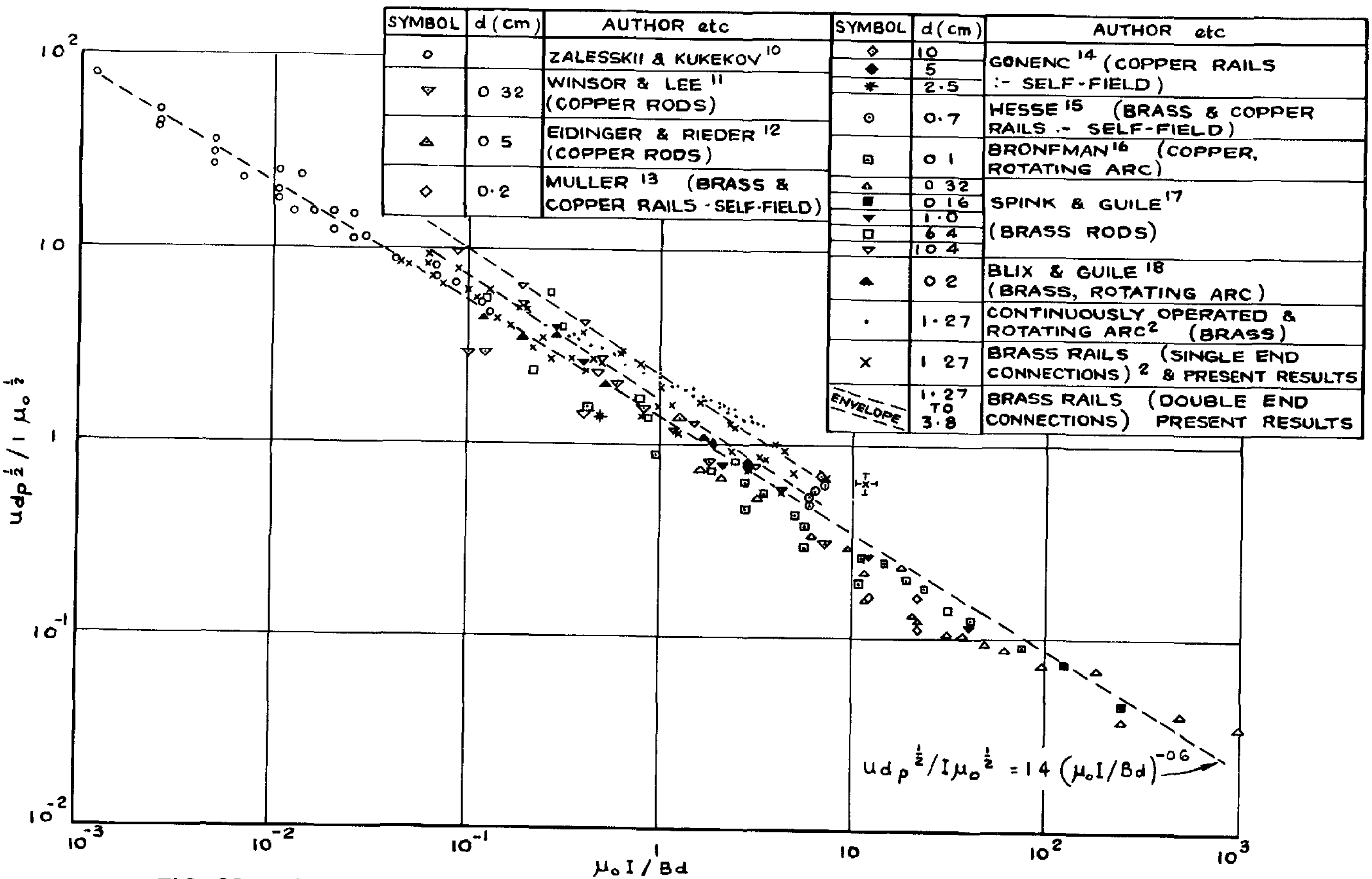


FIG. 23 COLLATED DATA ON ARCS MOVING IN AIR AT ONE ATMOSPHERE (COPPER AND BRASS ELECTRODES)

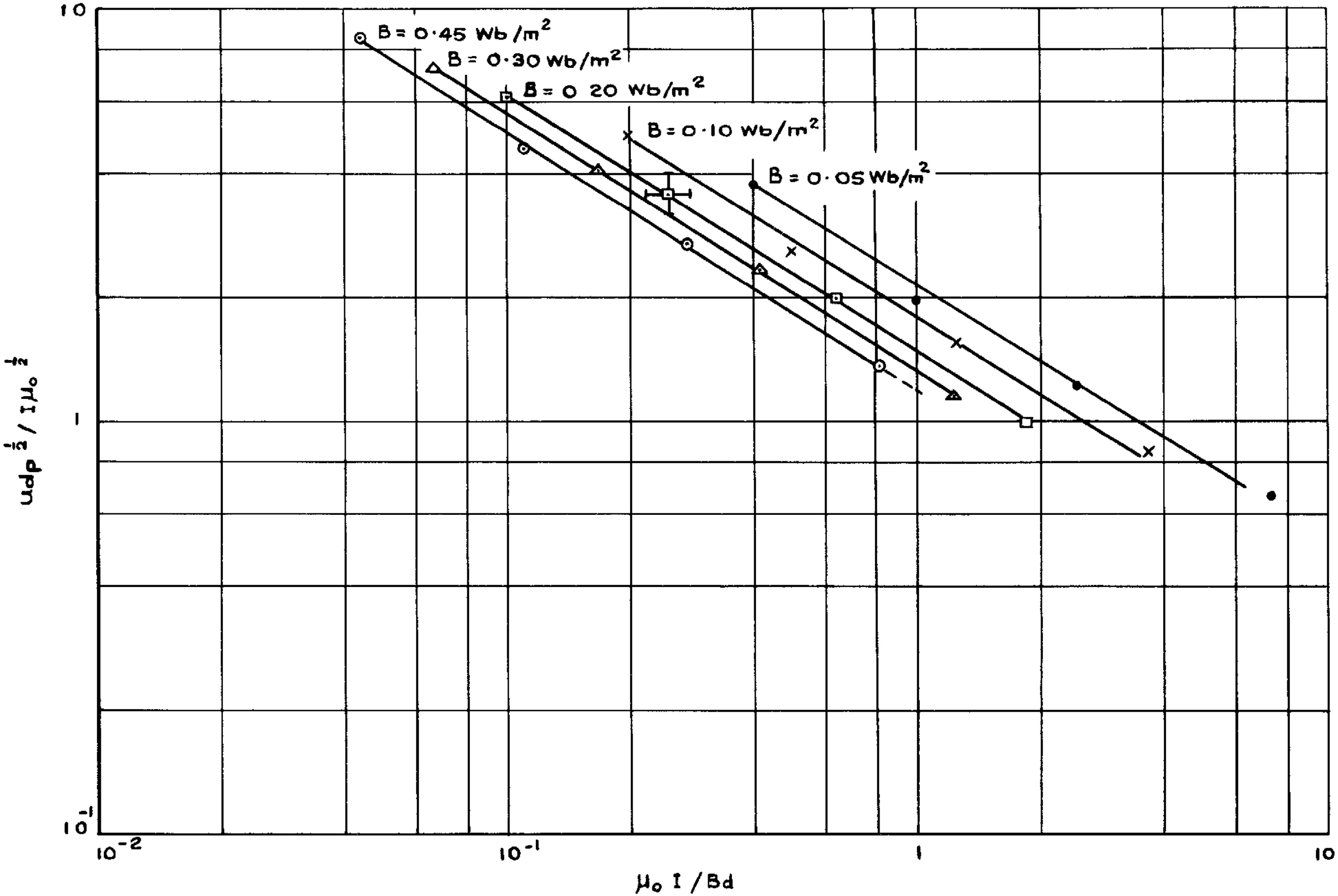


FIG. 24a Ud/I AGAINST I/Bd FOR BRASS ELECTRODES WITH SINGLE END CONNECTIONS (d = 1 27cm)

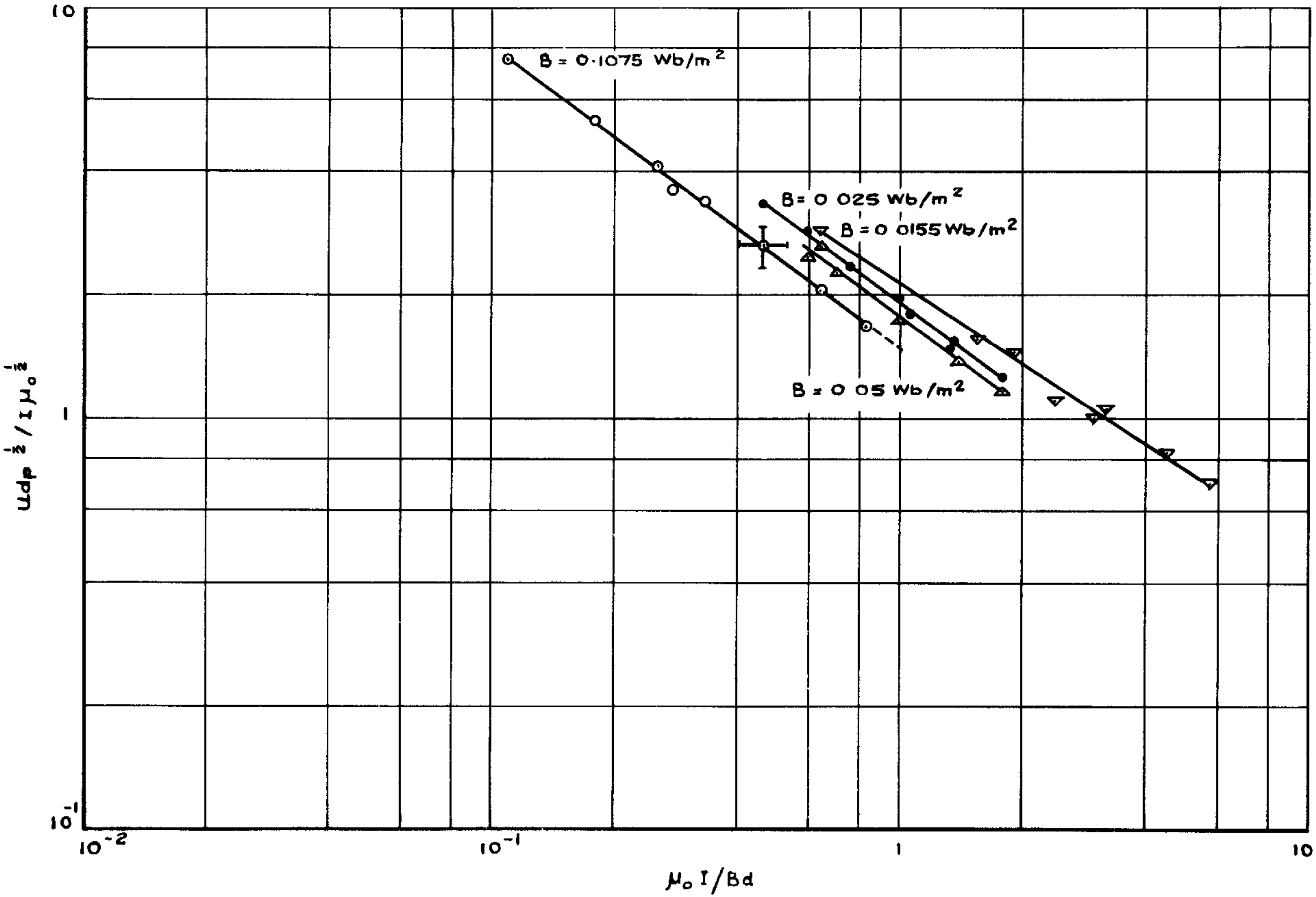


FIG. 24b Ud/I AGAINST I/Bd FOR BRASS ELECTRODES WITH DOUBLE END CONNECTIONS (d = 1·27 – 3 8cm)

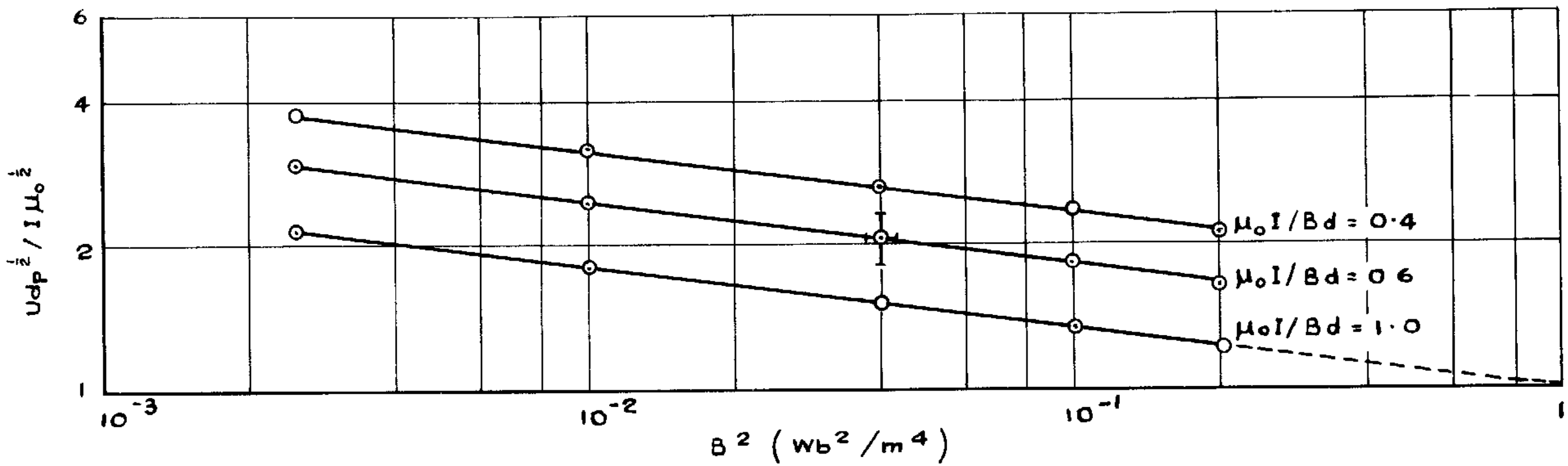


FIG 25a Ud/I AGAINST B^2 FOR BRASS ELECTRODES WITH SINGLE END CONNECTIONS

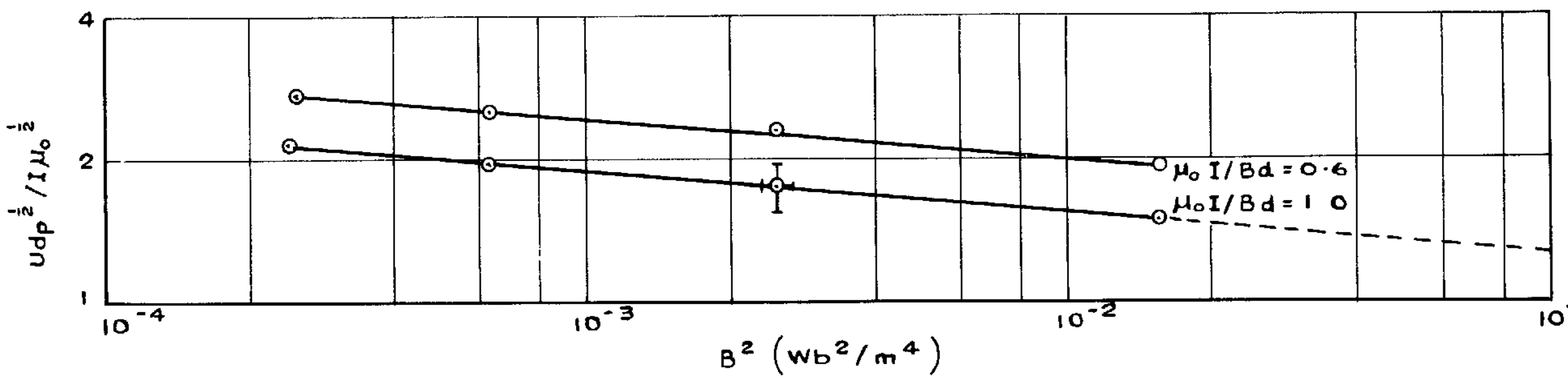


FIG 25b Ud/I AGAINST B^2 FOR BRASS ELECTRODES WITH DOUBLE END CONNECTIONS

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A.R.C. C.P. No.987
March 1967

537.523 :
538.6 :
621.3.032.2

Adams, V.W.

THE INFLUENCE OF GAS STREAMS AND MAGNETIC FIELDS ON ELECTRIC DISCHARGES. PART 4. ARCS MOVING ALONG STRAIGHT PARALLEL ELECTRODES

This report is a continuation of the experimental work in air at one atmosphere on the motion of d.c. arcs along straight open-ended electrodes already reported in Part 3 of this series. The earlier work with the slef-field due to the arc current in the electrodes in the same direction as the applied magnetic field has been extended to include results with fields up to 1.0 Wb/m^2. Results are also given for three electrode materials with electrical connections arranged so that the self-field is eliminated, and are shown to differ from those where the self-field is present and approximately calculated.

(Over)

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(Over)

DETACHABLE ABSTRACT CARDS

A method, employing similarity parameters given by Dautov and Zhukov of collating data on arc motion in transverse magnetic fields is used to compare results for the present series of reports with other published data, and is shown to be effective for a wide range of parameters from eleven different papers, including the present results.

Arc motion with a low-velocity imposed air flow along and relative to the electrodes has been studied, and the simple notion that the algebraic difference between the arc velocities relative to the electrodes in still and moving air is equal to the imposed air velocity is found to be only approximately true when the air stream acts against the arc motion.

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Arc motion with a low-velocity imposed air flow along and relative to the electrodes has been studied, and the simple notion that the algebraic difference between the arc velocities relative to the electrodes in still and moving air is equal to the imposed air velocity is found to be only approximately true when the air stream acts against the arc motion.

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