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The Influence of Gas Streams and Magnetic Fields on Electric Discharges

Part 5. Arcs at Pressures up to 18 Atmospheres in Annular Gaps

by

V. W. Adams

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THE INFLUENCE OF GAS STREAMS AND MAGNETIC FIELDS ON ELECTRIC DISCHARGES

PART 5. ARCS AT PRESSURES UP TO 18 ATMOSPHERES IN ANNULAR GAPS

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SUMMARY

Experimental results are presented for electric arcs rotating round an annular gap between carbon electrodes in a pressure vessel with a throughput of nitrogen. The arc velocity, U, is shown to depend on the ambient pressure, P, in the following way i.e., $U \propto P^{-0.44}$, for pressures up to 18 atmospheres.

Some results for arcs rotating in an annular gap at atmospheric pressure with additional air flows through the gap are also given. In this case water-cooled brass electrodes are used. The rotational arc velocity is shown to be reduced by small flows to about $\frac{1}{2}$ the value with no flow.

Initial difficulties at high pressure and the effects of small axial flows are regarded as significant for arc heaters and are described in some detail.

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* Replaces R.A.E. Technical Report No.67089 - A.R.C. 29311

CONTENTS

1 INTRODUCTION

This paper is the fifth in a series which reports the results of experiments on the behaviour of direct current arcs in transverse magnetic fields, and refers specifically to the motion of arcs in annular gaps using,

(i) carbon electrodes with ambient pressures up to 18 atmospheres and a flow of nitrogen through the pressure vessel,

(ii) brass electrodes at one atmosphere with an axial flow of air through the annular gap.

The amount of basic data published on the motion of arcs at pressures above one atmosphere is limited[1,2], so that it is thought the present results, although preliminary in nature, are worth recording. Walker and Early[1] give data for helium and air using a pair of copper rod electrodes at pressures up to 30 atmospheres, arc currents up to 4 amp and transverse magnetic fields from 0.35 to 0.68 Wb/m^2. Blix and Guile[2] give data for air up to 15 atmospheres with some results for nitrogen, hydrogen and sulphur-hexa-fluoride up to 4 atmospheres. They used two circular brass electrodes of equal diameter arranged to work with a radial applied magnetic field up to 0.106 Wb/m^2, an electrode gap of 0.2 cm and arc currents up to 275 amp for air.

The present results give

(i) data for nitrogen at pressures up to 18 atmospheres using carbon electrodes with arc currents in the range 200 to 500 amp, electrode gaps from 0.325 cm to 1.9 cm and magnetic fields of 0.040 Wb/m^2 and 0.051 Wb/m^2.

(ii) data for air at one atmosphere with small measured air flows through the annular gap, (1.27 cm), using brass electrodes. Arc currents are between 360 amp and 490 amp, with a magnetic field of 0.047 Wb/m^2 and air flows of 5×10^3 cm^3/s to 19×10^3 cm^3/s, corresponding to velocities of about 2.0 m/s to 7.5 m/s in the arc gap.

2 APPARATUS AND EXPERIMENTAL PROCEDURE

2.1 High pressure

The electrodes consisted of a 1.27 cm diameter carbon rod (cathode) mounted axially through an anode disc with inner and outer diameters of 2.5 cm and 15 cm respectively, as shown in Fig.1, and were similar to those used for experiments at one atmosphere[3]. Rotation of the arc round the annular gap resulted from the interaction of the arc current with an applied axial magnetic field. A general view of the apparatus is shown in Fig.2. A cylindrical, stainless steel pressure vessel (0.61 m × 0.3 m diameter), with steel end plates and a small quartz window fitted centrally in one of them, housed the electrodes. The magnetic field was provided by an external coil constructed from copper bar (10 × 0.6 cm) and intended for use up to 10 kamp for short running times, see Fig.2. The apparatus was designed[4] for experimental work on arcs rotating in annular gaps employing magnetic fields up to 0.8 Wb/m^2, arc currents up to 1000 amp and ambient pressures up to about 65 atmospheres. A high pressure reservoir of nitrogen was exhausted through the vessel and controlled by the inlet and outlet nozzle sizes and a pressure control valve. The reservoir capacity was sufficient for several arc runs. Bourden gauges were fitted to the vessel for measurements on the upstream side of the inlet nozzle and of the steady chamber pressure. The vessel was also fitted with a capacitor type transducer for oscilloscope recording of the chamber pressure.

Electrical connections to the electrodes were made through insulated and sealed studs in one of the vessel end-plates. The arc current was fed into the central electrode equally from both ends, Fig.1, to eliminate as far as possible the magnetic effect of the arc current in this electrode. Arc starting was provided by means of a simple mechanism which moved the central electrode until it touched the outer electrode, and a return spring then restored it to the concentric position thus "drawing out" an arc. The central electrode was fitted with flexible connections and the starting mechanism was manually operated by an insulated handle brought outside the pressure vessel, Fig.1.

Measurements of the frequency of arc rotation, total arc voltage and arc current were made for a period corresponding to many cycles of the arc using the apparatus and methods described for arcs in annular gaps in an earlier report[5].

The frequency of rotation was measured from the frequency of voltage pulses provided by an optical probe consisting of a miniature photo-diode mounted in one end of a short length of tubing, as described in Ref.5. In order to align the probe to a position midway between the electrodes a simple projection system was used in conjunction with the quartz window, as shown in Figs.2 and 3. This also enabled high speed photographs of the arc to be made using a Fastax rotating prism camera with speeds up to 10000 frames/second.

The accuracies of the measuring techniques have been given in the earlier note[5]; typical observation errors are shown in the plotted experimental results and a list of errors for all parameters used is given with the list of symbols. In plotting experimental results of total arc voltage a correction has been made for the voltage drop in the central carbon rod electrode.

2.2 Atmospheric pressure with measured air flows through gap

This work is an extension of that already published using a pair of water-cooled circular brass electrodes, (Fig.3 of Ref.5), in an open-ended solenoid 0.45 m inside diameter.

Provision was made for an axial flow through the annular gap using air from the laboratory compressed air supply. An air inlet manifold and standard orifice plate with manometer connections for differential pressure measurement was connected to an insulating (resin bonded paper) duct. This duct was in turn connected to the outer electrode by means of a diverging brass tube, as shown in Fig.4. Electrical connections to the inner electrode (cathode) were made via equal stabilising resistances to each end of the central tube (used for both support and cooling water), so that there was no resultant magnetic field due to the arc current. The connection on the upstream side of the arc was passed through the wall of the air duct at about one metre from the electrode plane in order to avoid interrupting the flow near the arc gap. Electrical connections to the outer anode were made to both ends of the three equally spaced tubes used for cooling water to this electrode. The arcs were started by means of a piece of folded metal foil acting as a fuse between the electrodes.

Measurements of the frequency of arc rotation, total arc voltage, arc current and applied magnetic field were made as before[5], the optical probe being mounted at the downstream side of the electrodes and pointing at a position midway between them. The probe signals were superimposed on the arc voltage signal by making use of the differential input to the oscilloscope, so that arc voltage, current and frequency of rotation were recorded on a common time-scale using a two-beam oscilloscope.

The axial volume air flows were calculated from the differential pressure measurements across the standard orifice, and where flow velocities are quoted, these were obtained by dividing the calculated volume flow by the area of the annular gap ($25.3\ cm^2$).

3 DISCUSSION OF RESULTS

This section is divided into three parts dealing with

(i) experimental results at different ambient pressures above one atmosphere using carbon electrodes;

(ii) experimental results at atmospheric pressure with measured air flows through the arc gap using water-cooled brass electrodes;

(iii) collation of data on arcs moving in transverse magnetic fields using non-dimensional parameters.

3.1 Experiments in nitrogen at pressures above one atmosphere

Initially, experiments with electrode gaps of 1.2 cm and 1.9 cm and chamber pressures up to 7 atmospheres were made, but due to severe electrode erosion and difficulty in starting arcs the results were unreliable. The arc could not be struck at pressures higher than 7 atmospheres with these gap widths, (whereas this presented no difficulty at one atmosphere[3]). It was also found that severe erosion of the anode occurred at the arc starting point presumably because of persistent attempts to strike an arc. After several runs of approximately 2 to 3 minutes total running time the cathode rod diameter in the region of the arc was eroded from 1.27 cm to about 0.5 cm. The amount of erosion appeared to be greater than in the earlier work with air at one atmosphere[3] but this was difficult to estimate with certainty. These difficulties may have been the result of either the gas flow through the vessel and consequent flow in the annular gap, or an effect of the ambient pressure. When an inlet manifold for the ambient gas (nitrogen) was fitted in the vessel so that the incoming gas was distributed around the chamber periphery, it was still difficult to start an arc at a moderate pressure (5 atmospheres) with a 1.9 cm gap. We note that the arc operating voltage increases with both electrode spacing[3] and ambient pressure (see later, Fig.6) so that higher overall starting voltages are required in the vessel than at one atmosphere. Thus it appears that the difficulty experienced in starting an arc was an effect of the high ambient pressure for the particular electrical circuit conditions used.

High speed photographs were obtained but these were marred by rapid obscuring of the window with eroded carbon dust. However, photographic evidence of arc rotation was obtained, showing a highly luminous region rotating round the annular gap.

In order to overcome the difficulties above and to obtain more reliable arc starting and operation the electrode gap was reduced from 1.2 cm to 0.325 cm. The inlet manifold intended to reduce the flow through the arc gap, was retained. In spite of this precaution observations through the window at the inlet end of the chamber indicated that the arc intensity was reduced soon after it was started. This may have been the result of the arc being blown downstream and out of the field of view, which was restricted by the outer electrode. It was however, possible to obtain measurements with the smaller gap for pressures up to 18.4 atmospheres and the arc could be started quickly, thus avoiding uneven erosion of the anode. It was found that an increase of the electrode spacing from 0.325 cm to 0.4 cm due to erosion after several arc runs had a negligible effect on the arc behaviour.

The frequency of arc rotation, ω, and cathode root velocity, U_c, calculated from the cathode circumference (4 cm) are plotted against pressure, P, in Fig.5. Total arc voltages, V, are given in Fig.6 for the range of pressures used, the variation in the recorded voltages also being shown. The results for one atmosphere in air are taken from Ref.3 for similar electrodes and conditions. By plotting either $\log_{10} U_c$ or $\log_{10} U$ (U is the mean circumferential velocity) against $\log_{10} P$ (Fig.7) it may be shown that

$$U_c \text{ (or } U) \propto P^{-0.44} \qquad (1)$$

where the arc current is between 440 amp and 500 amp, the applied field is 0.051 Wb/m^2 and the arc gap is between 0.325 cm and 0.4 cm. This relation (1) may be compared with those obtained by Blix and Guile[2] for brass electrodes with smaller currents (20 to 275 amp) and gap (0.2 cm), and similar magnetic fields (0.034 Wb/m^2 to 0.106 Wb/m^2), who found that the power of P in a relation similar to (1) was between -0.38 and -0.49, depending on the arc current and magnetic field. Thus, the above two cases for different electrodes and conditions give indistinguishable relations between arc velocity and pressure. The experimental results may also be compared with a theoretical analysis by Lord[6] for a uniform arc column held at rest in a transverse gas stream by a magnetic field mutually perpendicular to the arc current and gas stream. This analysis, in which radiation losses are neglected and the radial heat conduction is equated to the convection loss, yields

$$U \propto P^{-0.42} \qquad (2)$$

in close agreement with the experimental relation (1).

The model used to derive equation (2) is compatible with the simple model used in the previous reports of this series where a value is assigned to the effective frontal area, A, of the arc presented to the surrounding gas, and the drag force is equated to the electromagnetic force;

$$\tfrac{1}{2}\,\rho\, U^2 A \;=\; B\, I\, d \quad . \qquad (3)$$

Now, assuming a constant temperature, T, of the surrounding gas, $P \propto \rho$, so that at constant B, I, d and T equation (3) gives:-

$$U \;=\; \text{constant}\;(A\,P)^{-\frac{1}{2}} \quad . \qquad (4)$$

By comparing this equation with the experimentally derived equation (1) between U_c (or U) and P, we may deduce that,

$$A \propto (P)^{-0.12} \qquad (5)$$

for constant B, I, d and T i.e., a small dependence of A on P.

3.2 Experiments at one atmosphere with measured air flows through gap

Comparative experiments were made with and without an air flow through the annular gap. The effect of an air flow was to produce a plume of luminous gas downstream of the arc gap. Uneven operation of the arc sometimes occurred because the arc roots left the working edges of the electrodes and pierced the refractory coating, with which the remaining electrode surfaces were covered, Fig.4. When this happened no results were recorded. Two unexplained phenomena were also noticed:-

(i) The arc rotational frequency was steadier with an air flow than with no flow, but the arc running time was restricted and arcs only operated for periods up to ten seconds. With no axial flow the arc could be made to run for at least twenty seconds, but was more erratic.

(ii) When the arc was started with no flow and the flow gradually increased, the arc was invariably extinguished after only small flows had been established

(3.9×10^3 to 5.5×10^3 cm^3/sec corresponding to velocities of about 1.5 m/s to 2.2 m/s through the arc gap). On the other hand, when experiments were made by first establishing the air flow and then starting the arc, air flows up to 1.88×10^4 cm^3/sec or about 7.5 m/s were possible with arc running times sufficiently long to obtain measurements.

The results are shown in Fig.8 where the frequency of arc rotation, cathode root velocity (calculated from the cathode circumference, 16 cm) and mean circumferential velocity (calculated from the mean gap circumference, 20 cm) are plotted against the air flow for different values of mean arc current. Arc voltages are shown in Fig.9, the total variation in recorded voltage being given.

The experimental results show that the initial minimum flow (5.5×10^3 cm^3/sec) of air through the annular gap reduces the arc frequency of rotation and hence velocity by about 50% and increases the mean arc voltage by about 15%. Over the complete range of flows used (5.5×10^3 to 19×10^3 cm^3/sec) the variation in the mean arc velocity at constant current and magnetic field was only 49 m/s to 39 m/s while the corresponding range of average axial velocity through the arc gap was 2.2 m/s to 7.5 m/s. Thus, it appears that a small air flow transverse to the arc motion has a retarding effect on the arc, and this retardation is not much increased by further increases in the air flow, Fig.8. This could possibly be accounted for in terms of the removal of the arc wake from the annular gap by the axial flow. Consider the minimum flow usable, 2.2 m/s, and the corresponding mean circumferential velocity of 47 m/s. Now, since the mean gap circumference is 20 cm the ratio air velocity/arc velocity gives a value of 0.9 ± 0.1 cm for the axial displacement of the wake in one revolution of the arc. This would completely clear the arc wake from the gap if its width in a direction transverse to the rotation was not greater than 1.0 cm. A wake of this size is of the same order as the luminous arc widths recorded photographically[3,5]. We are also able to compare the value this gives for the effective area i.e., $A \leqslant 1.0 \times d \leqslant 1.27$ cm^2, with that calculated using equation (3). By assuming ρ to be for air at $300^{\circ}K$ and substituting the same experimental conditions ($U = 47$ m/s, $I = 340$ amp, $B = 0.047$ Wb/m^2 and $d = 1.27$ cm) into (3), we obtain $A = 1.56 \pm 0.22$ cm^2 for an axial air flow of 2.2 m/s. The difference between the above two values for A could be accounted for if the retardation of the arc by the axial flow is effective when the arc wake is only partially removed from the gap during one revolution.

It should be noted however, that the arc velocity on a pair of parallel, straight brass electrodes[5] for the same conditions as above (340 amp, 0.047 Wb/m^2 and a 1.27 cm gap) but where the arc moves through undisturbed air, is about the same as for an arc rotating round an annular gap with no axial flow of air. Thus, it appears that the removal of the arc wake by an axial flow in the annular gap experiment does not give results equivalent to an arc moving through undisturbed air.

3.3 Use of dimensionless similarity parameters

We now consider the dimensionless similarity parameters given by Dautov and Zhukov[7] for arcs moving in transverse magnetic fields on the same electrodes and in the same gas. It has been shown elsewhere[8,9] that a wide range of data from twelve different authors for arcs moving on parallel straight or circular brass or copper electrodes in air at one atmosphere may be approximately collated by these parameters;

i.e., $$U d \rho^{\frac{1}{2}}/I \mu_o^{\frac{1}{2}} = \phi \, [\mu_o I/B d \, , \, B^2/\mu_o P] \quad . \qquad (7)$$

Now, since the present results for carbon electrodes at nearly constant B, I and d may be represented by equation (1),

i.e., $$U_c = (128 \pm 6) \, P^{-0.44} \quad , \qquad (1)$$

they are also in accordance with equation (7), and

$$U d \rho^{\frac{1}{2}}/I \mu_o^{\frac{1}{2}} = (B^2/\mu_o P)^{0.44} \, \phi_1 \, (\mu_o I/B d) \quad . \qquad (8)$$

It should be noted that the results for annular carbon electrodes in air at one atmosphere[3,5] at a constant value of d may be represented by the equation[5]

$$U_c \simeq 143 \pm 10 \, I^{0.33} \, B^{0.60} \, m/s \quad . \qquad (9)$$

Thus, since these results are for constant ρ, d and P they are also in accordance with equation (7) but where ϕ is now a different function. The function ϕ is different since it may be shown that equations (8) and (9) are inconsistent indicating that either equation (9) does not apply at pressures above atmospheric or, the situation is more complicated. The results of

Blix and Guile[2] for brass electrodes show that the powers of I and B in an equation similar to (9) vary with the ambient pressure. Thus, one would not expect equation (8) for high pressures to be consistent with equation (9), which applies at one atmosphere.

In addition, it may be noted that the results of Blix and Guile[2] for constant B, I and d may be represented by an equation where U is proportional to an inverse power of P. Again, these results are in accordance with (7) where ϕ is also a different function. In view of the different forms that appear to hold for the function ϕ under different conditions it must be concluded that simple power law relations such as (9) can only have a limited range of validity. They may perhaps be used as a guide to the order of magnitude of a particular parameter to be expected in a given experiment that belongs to the class of experiments used in deriving the relation, but should not be used for experiments outside that class.

SYMBOLS

A	effective drag area of arc	(m^2)
B	magnetic field	(Wb/m^2)
d	electrode gap width	(m)
I	mean arc current	(amp)
P	ambient pressure	(atmos) or (Nt/m^2)
U	mean circumferential arc velocity	(m/s)
U_c	cathode root velocity	(m/s)
V	total arc voltage	(volt)
ρ	gas density	(Kg/m^3)
μ_o	magnetic permeability of free space	(Henry/m)
ϕ, ϕ_1	functions between dimensionless parameters	
ω	frequency of arc rotation	(c/s)

Estimated experimental errors

A	± 14%
B	± 5%
d	± 0.05 cm
I	± 10%
P	± 5%
ω, U, U_c	± 5%
V	± 10%

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9	V.W. Adams A.E. Guile W.T. Lord K.A. Naylor	Correlation of experimental data for electric arcs in transverse magnetic fields. (To be published.)

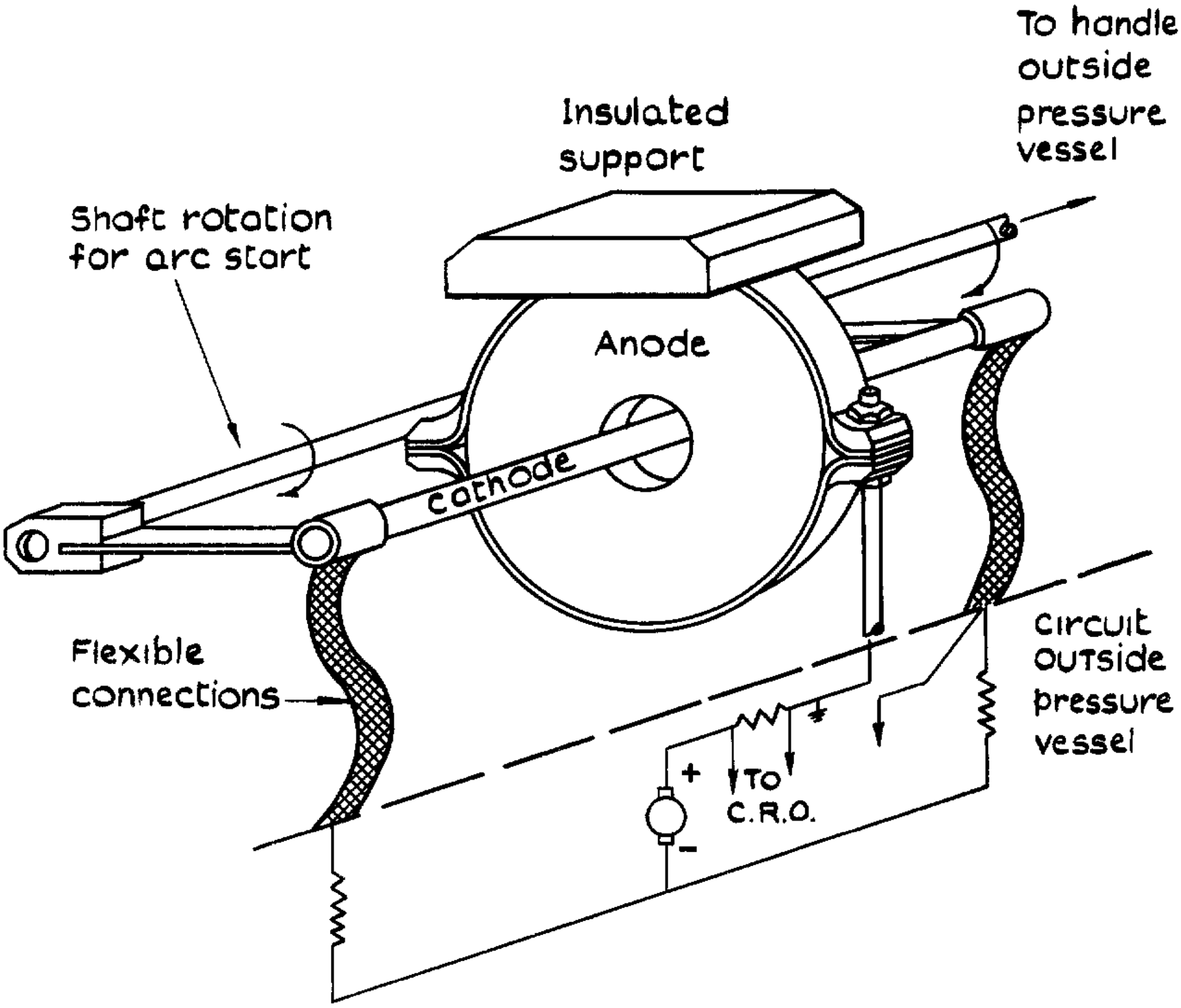


Fig.1 Carbon electrodes
(see R.A.E. drwg. No. Gas 41626)

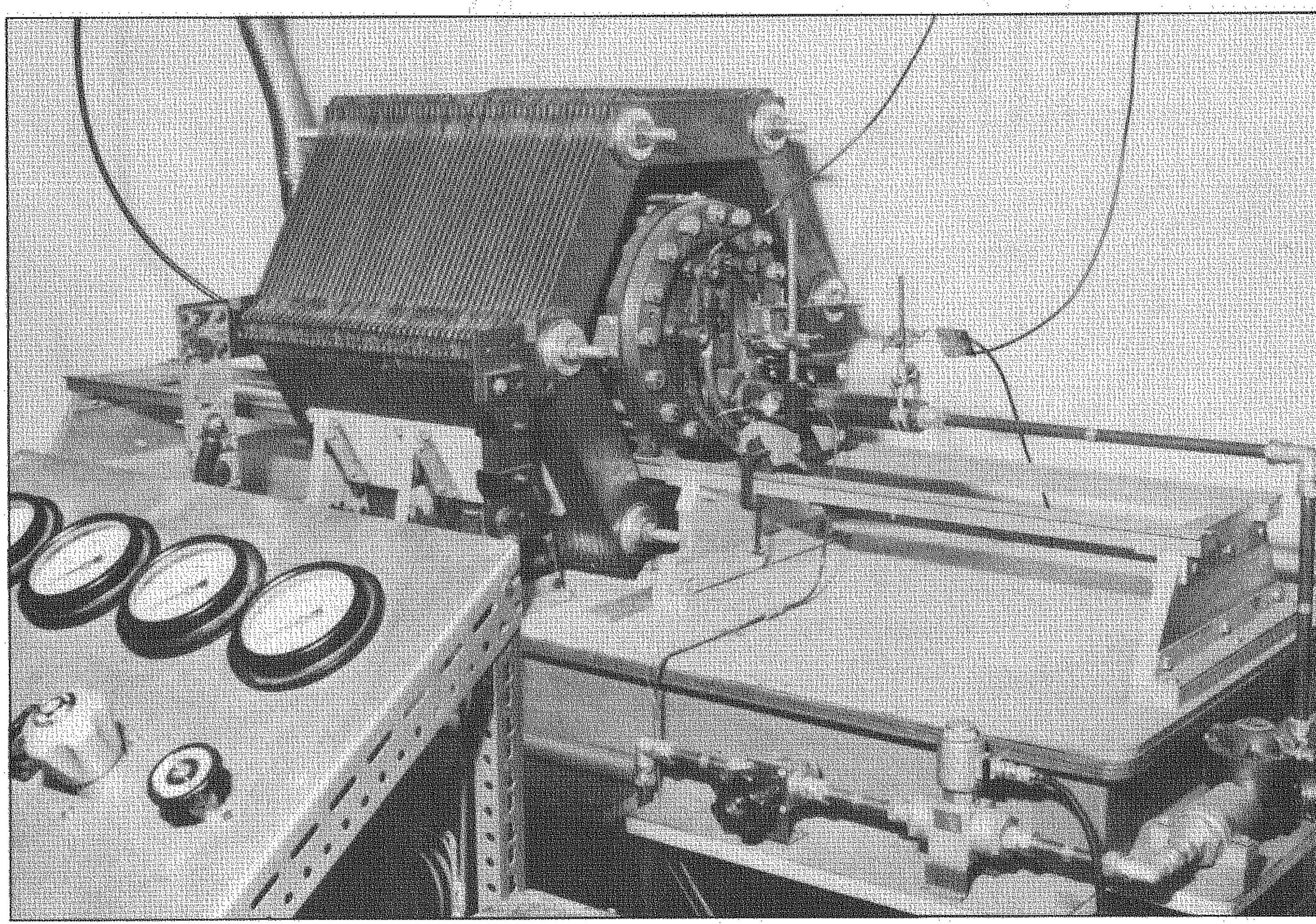
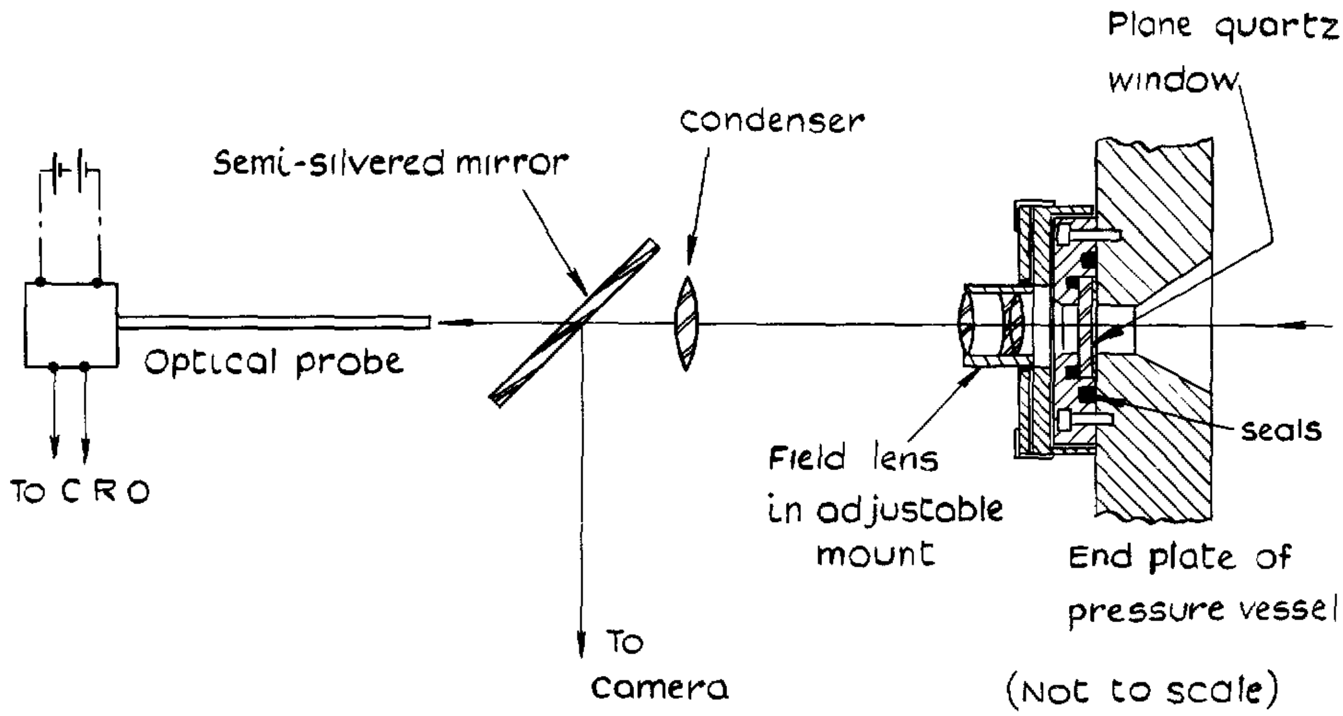
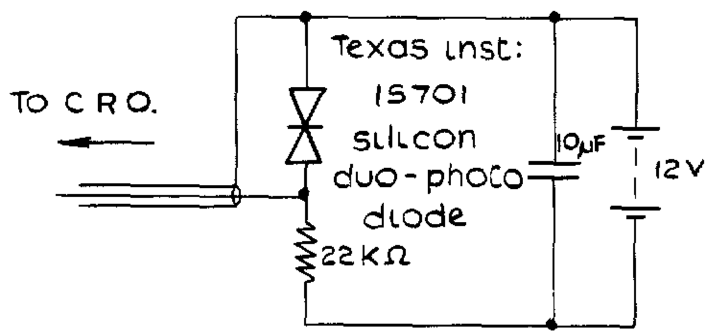


Fig.2. General view of high pressure apparatus





circuit of optical probe

Fig. 3 Arrangement for viewing arc

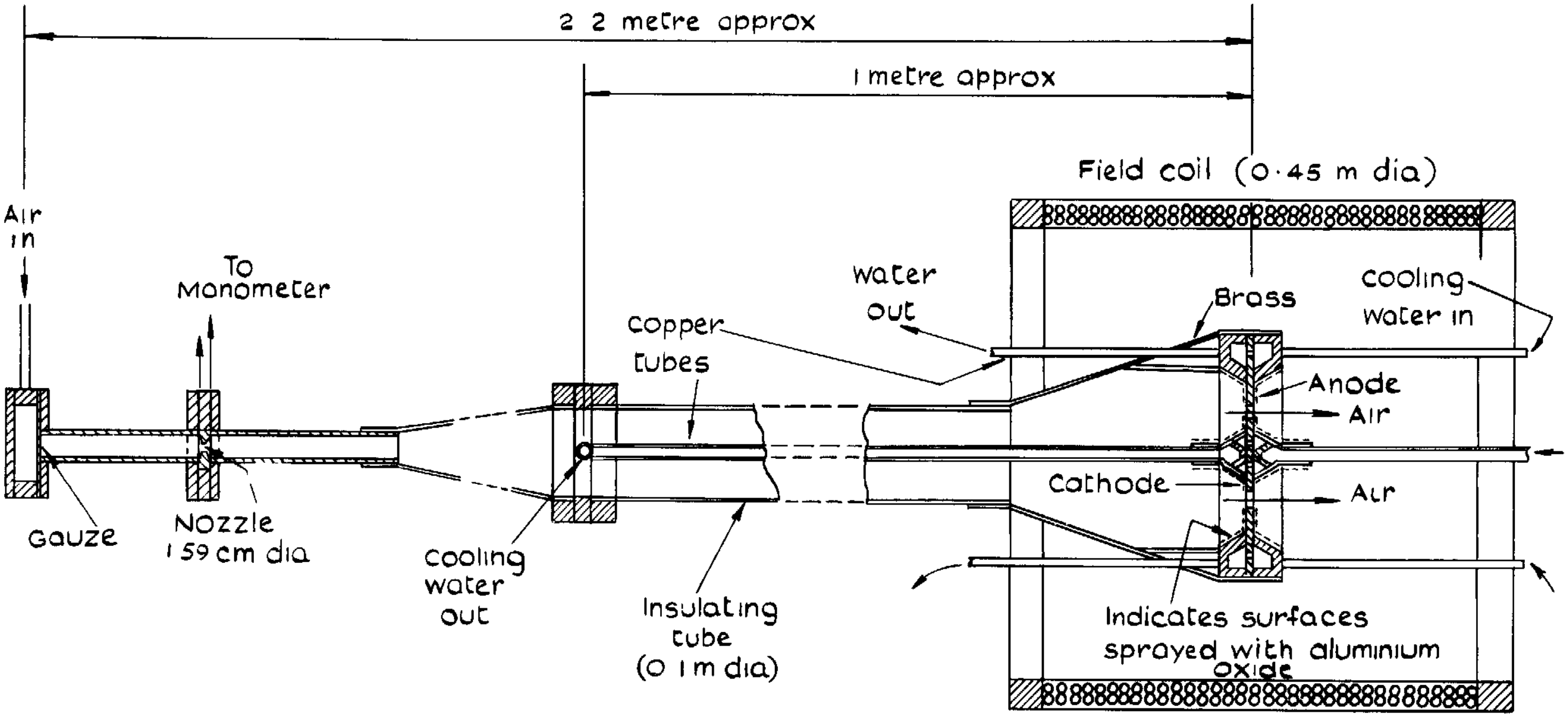


Fig. 4 Brass electrodes in simple wind tunnel (not to scale)
(Electrodes shown in Fig. 3, ref. 5)

SYMBOL	d (cm)	I (amp)	B (wb/m²)
○	0·325 to 0·4	500	0 051
●		490	0·051
×		480	0 051
+		470	0 051
△		440	0·051
◬	1·2	300	0·040
▲	1·2	270	0 040
⊗	1·9	260	0·040
⊙	1·9	200	0·040

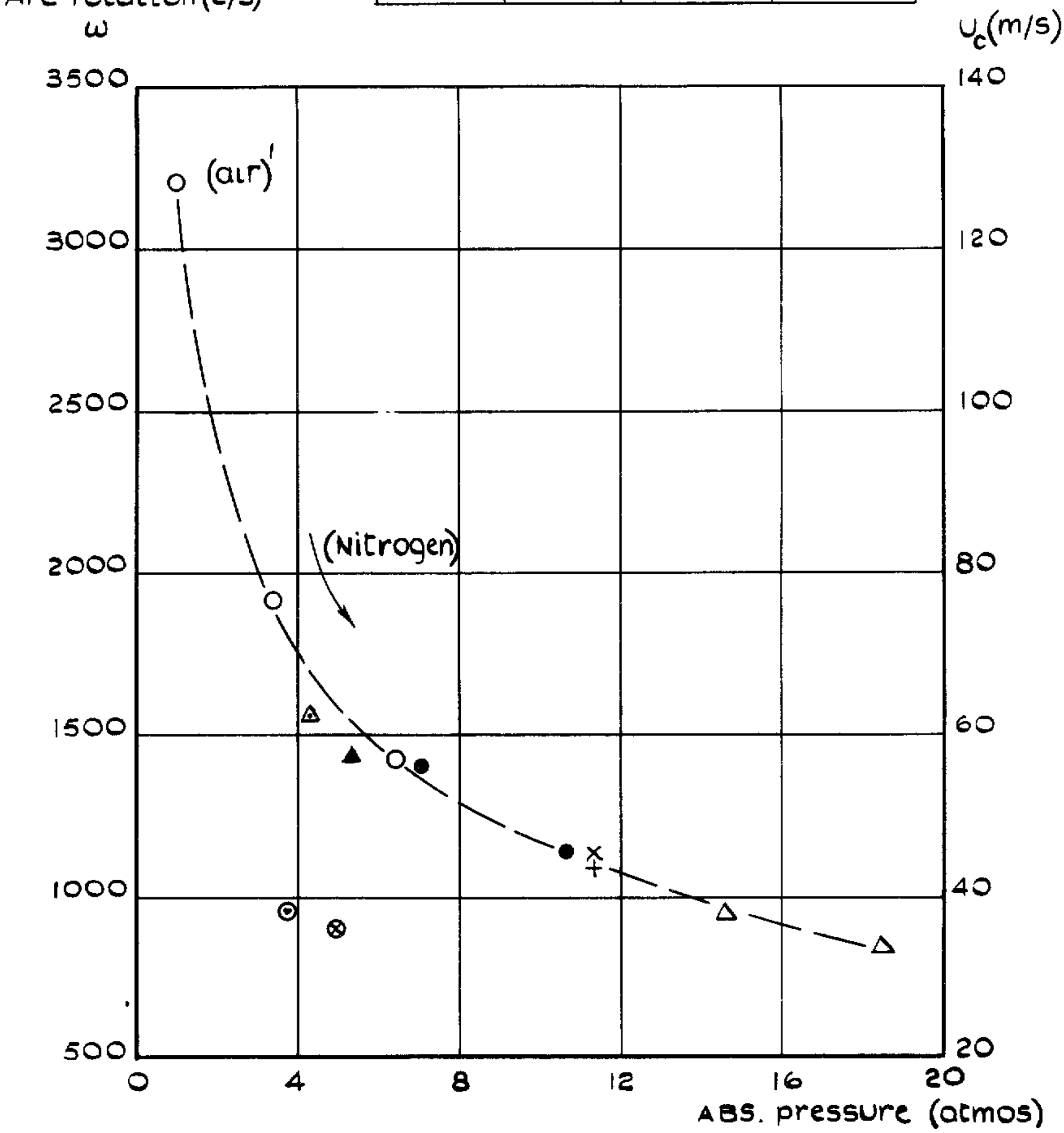


Fig.5 Arc rotation against pressure for carbon electrodes

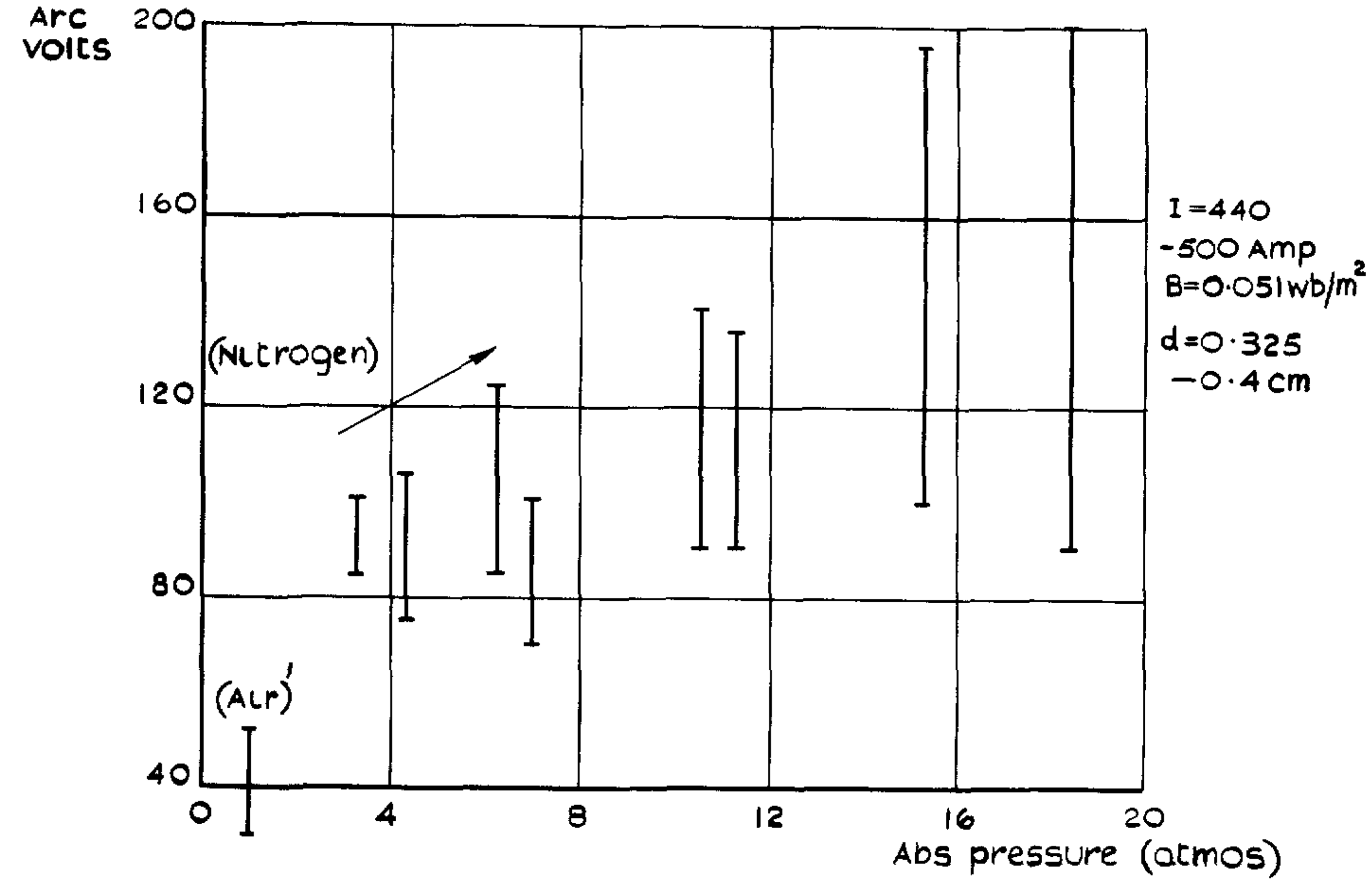


Fig. 6 Arc voltage against pressure for carbon electrodes

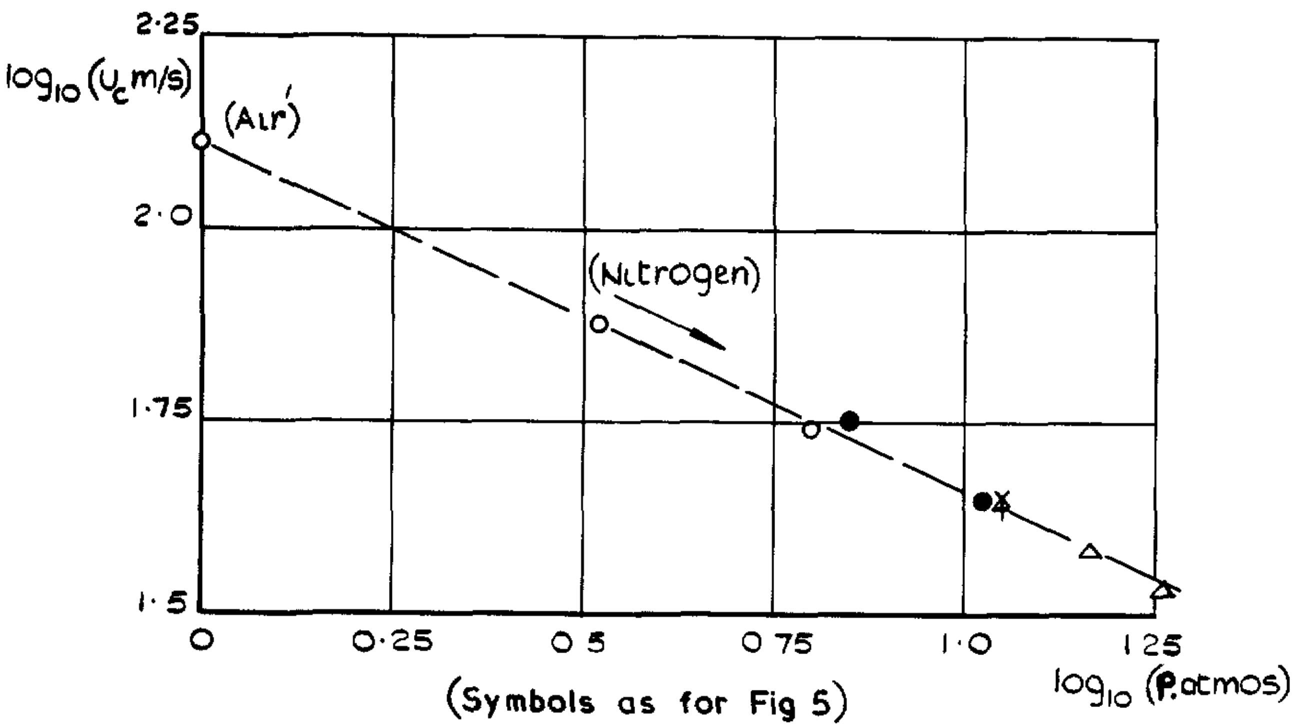


Fig.7 Arc velocity against pressure for carbon electrodes

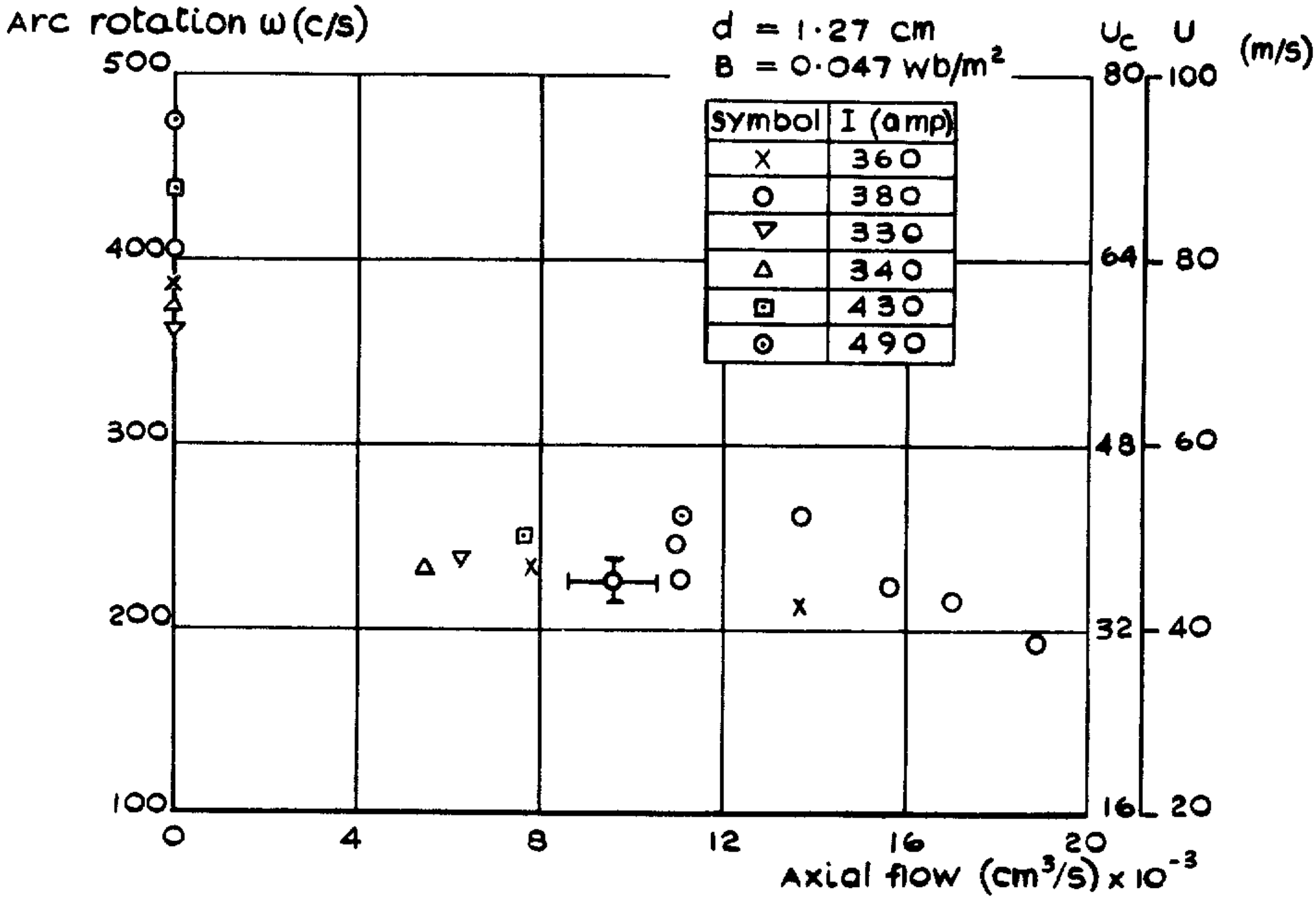


Fig. 8 Arc rotation against axial flow for brass electrodes

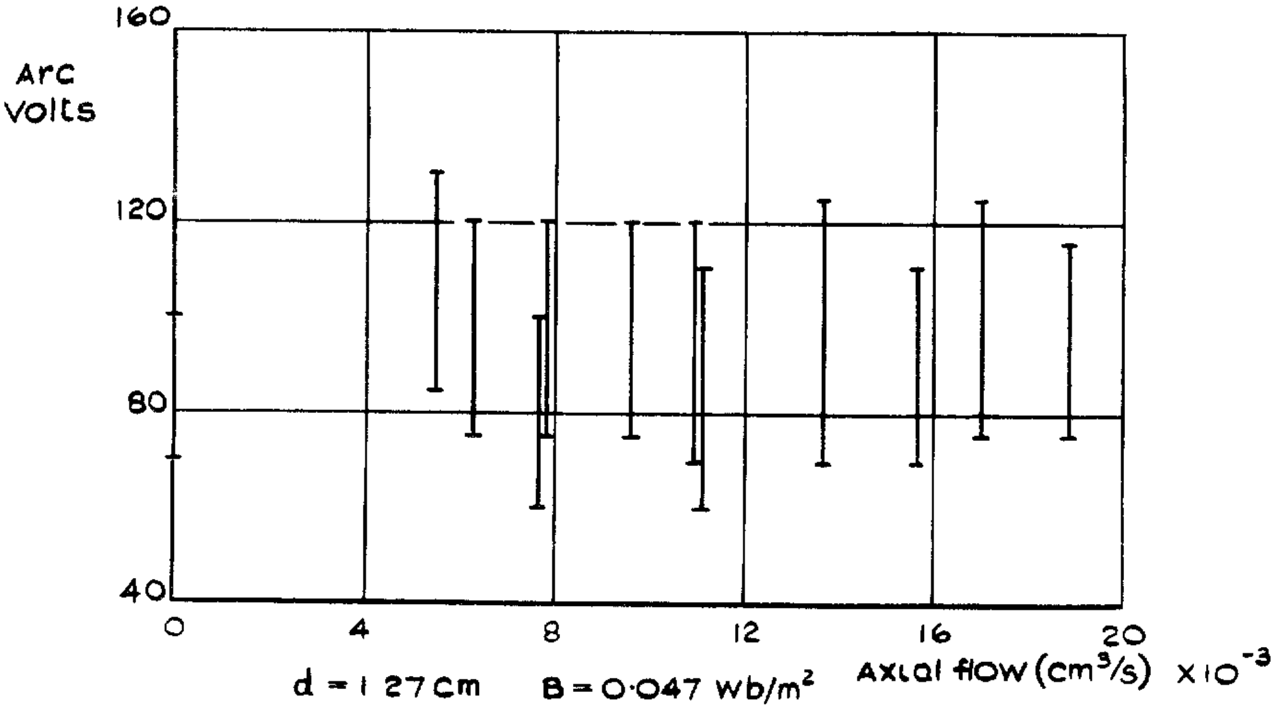


Fig. 9 Arc voltage against axial flow for brass electrodes

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DETACHABLE ABSTRACT CARDS

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