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SURVEY OF INVESTIGATIONS OF ELECTRIC ARC INTERACTIONS WITH MAGNETIC AND AERODYNAMIC FIELDS

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Project No. 7063

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OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

FOREWORD

This report presents a survey of investigations of electric arc interactions with magnetic and aerodynamic fields.

This survey of investigations was conducted by the Thermomechanics Research Laboratory of the Aerospace Research Laboratories as part of a program to investigate the interactions between electric arcs and external aerodynamic and magnetic fields.

The authors wish to thank Mr. E. E. Soehngen for his direction and helpful suggestions.

ABSTRACT

This report summarizes and evaluates the existing literature related to the interaction of an electric arc at pressure levels of one atmosphere or greater with magnetic fields and/or aerodynamic fields which are transverse to the arc column. The scope of this survey does not include the subject of retrograde motion.

For the purposes of this survey, the subject is broken up according to whether or not there is net arc motion with respect to the electrodes. When motion occurs, the arc is designated a travelling arc; this is the type of arc which occurs in rail accelerators, arc heaters utilizing magnetically rotated arcs and electric switchgear circuit breakers. When the arc undergoes no net motion with respect to the electrodes it is designated a stationary arc; this type occurs when the arc is balanced in a transverse gas flow by an appropriate transverse magnetic field.

This report summarizes the results of the various investigations and presents them graphically for easy comparison. General conclusions which may be drawn from the investigations are presented.

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THE TRAVELLING ARC

SECTION I

INTRODUCTION

The purpose of this report is to summarize and evaluate the existing literature related to the interaction of an electric arc with transverse aerodynamic fields, transverse magnetic fields or both at pressures of one atmosphere or greater. Part 1 is concerned with the "travelling arc", as defined below, while Part 2 discusses investigations of an arc stationary with respect to the electrodes and subjected to either transverse aerodynamic or transverse magnetic fields, or both.

THE TRAVELLING ARC

Sections II through VI are concerned with arc motion over electrode surfaces at pressures of one atmosphere or greater. The scope of this survey does not include the subject of arc retrograde motion, as this type of motion has been reported at atmospheric pressure only in the special case of very narrow gaps and low currents.* (However, for completeness, the Appendix contains a chronologically arranged list of the retrograde investigations.) Thus, the arc motion considered here will always be in the amperian direction over the electrode surfaces ---such an arc will be designated as a "travelling arc" for the purpose of this survey. Due to its motion over the electrode surface through the ambient gas, there will always be an induced gas flow with respect to the column of the travelling arc. However, it should be emphasized that the travelling arc differs from the arc held stationary in an imposed transverse gas flow in which there is no net motion of the arc with respect to the electrodes. Thus, to fit the present definition of a "travelling arc", the arc must have a net motion with respect to one or both electrodes and, furthermore, the arc motion must be in the amperian direction.

The motion of the travelling arc may be caused by the self-magnetic field, an external magnetic field or a combination of the two. The self-magnetic field is that field which is created by the current flowing through the electrodes to the arc. By proper routing of the current leads, this self-field may be eliminated, and the arc made to move only under the influence of an applied external magnetic field. As shown in Figure 1, the arc may travel between: (a) parallel rails, (b) diverging rails, (c) the ends of parallel cylinders, or (d) concentric cylinders. For geometries (c) and (d) the arc travels over the electrodes repeatedly after it has been initiated; for the rail cases it travels over the electrodes only once each time it is initiated, with the arc being extinguished at the ends of the rails. The geometry of configuration (d) requires that the opposite ends of the arc travel at

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*Robson, A.E. & A. von Engel, Phys. Review 104-1, 15 (October 1, 1956)

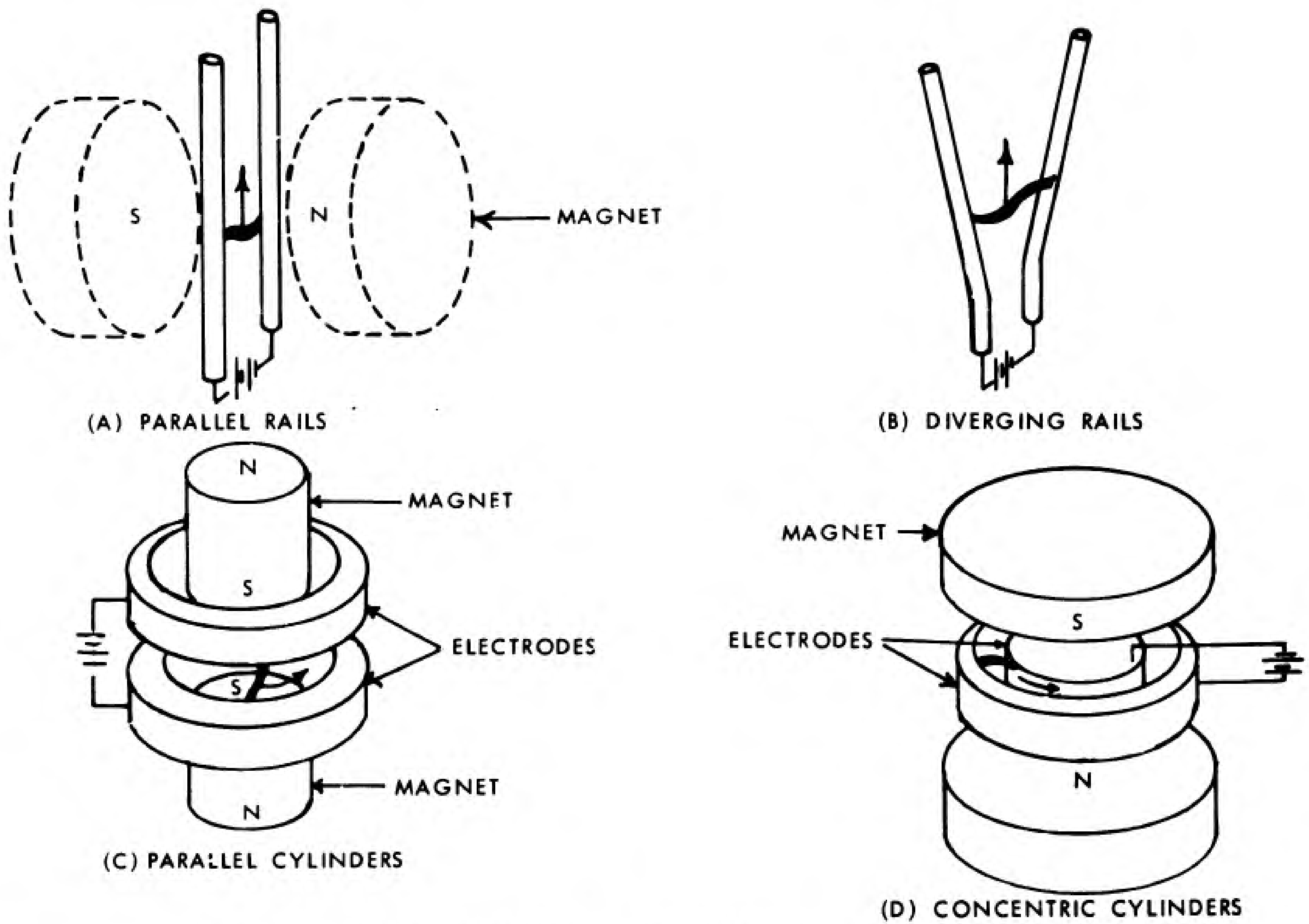


FIGURE 1 - CONFIGURATIONS FOR TRAVELLING ARC STUDIES

different speeds to complete a cycle, while that of configuration (b) requires the arc to change its length as it travels along the electrodes. In addition to these different electrode geometries, the arc motion may be affected by the orientation of the arc electrodes with respect to a gravitational field. Because the arc is hotter and less dense than the surrounding gases, there is a buoyancy force on the arc.

In addition to the primary variables (the arc current, the gas pressure, and the magnetic field) there are many other parameters which affect the motion of the travelling arc. These include the electrode parameters, the geometric and orientation factors, and the channel variables. The electrode parameters include the material, shape, surface condition, and the previous history of the electrodes (whether or not they have been used before). As defined here, the geometric and orientation factors include the electrode gap, as well as the effect of the electrode geometries mentioned above. The term channel variables, as used here, includes the effects due to insulating side walls of various materials and configurations which may be used to enclose the arc in a channel; i.e., two opposite walls containing the electrodes and the other two opposite walls being the insulating side walls.

The applications of the travelling arc are centered in two areas: high-current switchgear and electric arc gas heaters. The switchgear applications produced the first engineering studies of the travelling arc. These studies started in the middle 1920's and the majority of the work was done in Germany, although significant work was also done in the U.S.S.R. and the U.S. In the switchgear applications, the travelling arc is utilized to open a high-current electrical circuit as rapidly and with as little destructive effect as possible. Therefore, the primary objective in these studies was to cause the arc voltage to rise as rapidly as possible, until the circuit voltage is no longer sufficient to maintain the arc. The arc voltage may be caused to rise by lengthening the arc, moving the arc at a high velocity, or by driving the arc against a stack of plates which divide it into a series of arcs having a total voltage drop significantly higher than that of the original arc. An important factor in all of these methods is that the velocity of the travelling arc should be as high as possible within the space, cost, and external power supply requirements. Even though an external magnetic field would increase the travelling arc velocity, it introduces extra size, cost, and power requirements such as to make it prohibitive for intermittent switchgear operation. Thus, the switchgear travelling arc is usually driven by its self-magnetic field.

The travelling arc is utilized in arc heaters which provide high temperature gases for wind tunnel simulation of the conditions encountered in aerospace technology. These arc heaters operate at extremely high power levels (50 megawatt units are now being tested) and introduce severe problems in electrode heat loads. The arc must be rapidly moved over the electrode surface to prevent electrode melting. Thus, for this application, just as for switchgear applications, the velocity of the travelling arc should be as high as possible. External magnetic fields are used extensively in arc heaters to drive the arc as rapidly as possible. The power required for the magnetic field is usually a small portion of that used to power the arc heater. Even though the final arc heater design must be such as to allow continuous running [geometries (c) and (d)], many experiments have also been made with rails to define the dominant parameters with arc heater applications in mind. In addition, most of the work has been done at atmospheric pressure even though projected arc heater specifications require up to 200 atm pressure operation. There has been great interest in arc heater applications of the travelling arc during the past 10 years, with the design requirements outstripping the fundamental knowledge. Much of this work has taken place in Great Britain and the U.S. The present survey will include only those studies in which the travelling arc velocity was determined as a function of the operating variables, and will consider the arc heater design and lifetime feasibility tests as outside its scope.

Sections II through VI will discuss the travelling arc studies with respect to the different electrode geometries and the presence or absence of the external magnetic field. Most of the studies have been made in air at atmospheric pressure and this will be understood to be so unless stated otherwise. The separate studies will be discussed under the following headings: parallel rails without external magnetic fields; parallel rails with external magnetic fields; parallel cylinders; and concentric cylinders. In Section VI, the dominating parameters for such a travelling arc and their effects will be summarized.

THE STATIONARY ARC

Sections VII through X are concerned with the interaction of transverse magnetic and/or transverse aerodynamic fields on a stationary arc. The term "stationary arc" refers to an arc which undergoes no net motion with respect to the electrodes and is subjected to either transverse blowing, a transverse magnetic field or both. The transverse blowing may arise either from an external source or from natural convection. The transverse magnetic field is always due to an external source.

The studies of the stationary arc have been, in general, more nearly directed toward solving fundamental problems in arc physics than those performed on the travelling arc for which the approach has been more nearly from an engineering viewpoint. From a strictly geometric point of view, the interaction of the arc positive column with the transverse fields (aerodynamic or magnetic) should be independent of whether the arc moves through the field or the field is caused to move past the arc. However, as will be pointed out, the interactions taking place at the electrode surfaces have a much greater effect on the travelling arc than on the stationary arc. Thus the stationary arc configuration is more often used when it is desired to neglect the effect of the arc attachment regions or to study the arc column plasma interaction with the transverse fields. This interaction is quite complex and the trend has been toward experimental investigations to give redirection to theoretical analyses.

The first section of the stationary arc survey presents the historical development of the area and gives a brief summary of what has been done. The subsequent sections (VIII and IX) divide the subject into the theoretical and experimental investigations, respectively. Each of these sections is subdivided according to whether the investigation included transverse blowing only, transverse magnetic field only, or both transverse blowing and a transverse magnetic field. When both fields are used the orientation is always such that the magnetic force on the arc opposes the aerodynamic drag force of the transverse blowing. Section X presents a general summary of stationary arc phenomena.

PART 1

THE TRAVELLING ARC

SECTION II

PARALLEL RAILS WITHOUT EXTERNAL MAGNETIC FIELDS

Even though the influence of most of the parameters on the travelling arc is quite similar whether or not an external magnetic field is used, a distinction will be made between these two cases for the purposes of this survey. This distinction is necessary primarily because of the nature of the tests made when no external magnetic fields were imposed. In these tests, the primary objective was to obtain the arc current-velocity relationship and the effect of the other parameters on this relationship. Because of the variation of the self-magnetic field across the electrode gap, and the difficulty in measuring this field during an actual test, little work has been done to relate the self-magnetic field values to the external magnetic field values discussed in the next section. Since the primary application of the tests in this section was to high-current switchgear, the experiments were often at higher current levels than those in the next section and, hence, the results are not entirely comparable. The papers will be grouped according to the parameters investigated. In the final section, the results will be presented graphically and the effect of the various parameters will be summarized.

THE ELECTRODE PARAMETERS

The effects of the electrode material, size, shape, and previous history will be included under the term electrode parameters. A preliminary study on the movement of the arc roots over an electrode surface was reported by Kouwenhoven and Jones (35). Observations were described on an arc which was maintained between a stationary electrode and an electrode consisting of a rapidly moving steel tape. Direct currents in the range of 50-160 A were used and the moving tape speeds were between 5 and 11 m/sec. Electrode spacings between 0.16 and 0.33 cm were used. Little difficulty was encountered in maintaining the arc in atmospheric pressure air, argon and helium with the moving tape as the anode. However, with the moving tape as the cathode, stable arcs could be maintained only in argon and helium atmospheres. The primary contribution of this study was that in the range studied, the anode spot did not move continuously, but in a series of intermittent jumps with a new anode spot being formed before the arc left the old one. This type of anode motion was in direct contrast to the continuous motion of the cathode root which was reported.

The effects of the electrode parameters on a.c. arcs up to 3,000 A and d.c. arcs up to 500 A were studied by Guile and Mehta (24). Rail electrodes were fed current from one end and were made of 0.951 cm diameter, 0.61 m long rods with electrode spacings from 0.127 to 19.05 cm. The velocities of the different portions of the arc were obtained using a 960 frames/sec camera. The a.c. tests were made on mild steel, copper, and brass electrodes. The velocities were about

50% higher on the mild steel electrodes than on copper or brass ones. An approximately linear relationship between the velocity and the current was found, with the maximum velocity in the tests reaching about 60 m/sec at 3000 A. In other tests with alternating current, the rail apparatus was placed in a wind tunnel to find the necessary wind speed to hold the arc stationary. This wind speed was approximately equal to the travelling arc velocity previously observed at the shorter gaps, but it was significantly less than the travelling arc velocity at gaps greater than 10 cm. In all of the tests, both with alternating and direct currents, there was considerable statistical deviation between successive test runs. For the direct current tests, to obtain reproducibility of the results, new electrodes were used on each test. It had earlier been found that the cathode velocity was lower on new clean rods than used pitted ones. Comparison tests were made for different electrode materials at an electrode gap of 3.17 cm. It was found that the arc cathode velocity was highest for mild steel; approximately 1/5 of this value on brass, copper, aluminum, duralumin, and zinc electrodes; and about 1/40 of the mild steel value on carbon electrodes. The majority of the tests were made on mild steel electrodes on which the velocities of the anode and cathode varied considerably with the prevailing conditions. Four different kinds of cathode tracks were observed as the arc current was increased, changing from continuous with melting, to random (small jumps), to random with intermittent large jumps, to a high speed continuous track with no melting. Velocities up to about 15 m/sec were observed in the mild steel tests. It was concluded that the arc column influenced only the random movement and not the continuous motion. The anode movement tended to be less regular than that of the cathode and was largely controlled by the arc column. Thus, it appeared that the motion of the travelling arc was largely determined by cathode processes.

Other experiments conducted at about the same time by Guile, Lewis and Mehta (22,23) further verify that for the range of variables studied the motion of the travelling arc was determined by cathode processes. In these tests 1 cm diameter electrodes, 3.2 cm apart, were fed direct currents up to 400 A. In addition to the magnetic field due to the arc current being fed from one end of the rails, axial magnetic fields (parallel to the rail electrodes) were applied both by means of permanently magnetized electrodes and by external windings. It was found that the track left by the arc on the cathode with an axial magnetic field took the form of a helix. For the permanently magnetized mild steel and stainless steel cathodes there is a change in the direction of the magnetic field at the electrode surface, while only a discontinuity is present for the electrode in an external field. By comparing the motion of the arc on the cathode under these conditions, it was determined that the direction of the helix was determined by the internal cathode field whether it was produced by external windings or by permanent magnetism. The circumferential self-magnetic field at the electrode surface due to the arc current was calculated and it was found that the relationship between the axial velocity and circumferential magnetic field at the cathode surface was quite similar to the relation between the circumferential velocity component of the helical motion and the internal axial magnetic field. The tests were made only for the lower current range where the cathode track was continuous; the maximum velocities were less than 5 m/sec. Helical motion was also observed at the anode in the direction determined by the internal axial magnetic field, but the anode motion appeared to be dominated to a much greater extent by the arc column. As in the preceding paper, the arc motion was observed with a drum camera operating at 960 frames/sec.

Even though there are some shortcomings in an aerodynamic-drag conducting cylinder model, it can be said in a general way that the driving force on a travelling arc is proportional to BI, while the retarding force is proportional to V^2. Since the electrode self-field B is directly proportional to I, a linear relation between the velocity, V, and the current, I, can be expected. This was indeed observed in the tests described above for the nonferrous electrode materials. However, V increased much more rapidly with I than a linear relationship for the ferrous electrodes. The reason for this enhanced arc velocity on magnetic electrodes was discussed in papers by Secker (49) and Secker, Guile and Caton (52). It was shown that the greater velocity on the magnetic materials could be explained by a skin effect due to the high-frequency movement of the cathode micro-spots. As the travelling arc velocity increases due to an increase in arc current, the skin depth decreases which causes an increase in the transverse magnetic field because of the compression of the current lines in the narrower skin depth. Thus, when this skin depth effect becomes dominant, the velocity increases more rapidly with the current than a linear relation would indicate. The skin depth effect will be present on both magnetic and non-magnetic electrodes, but as the current is increased it will appear on the former first because of their higher magnetic permeability. This will effect the motion on magnetic materials at currents above about 50 A, while it will influence the motion on non-magnetic materials at currents above about 400 A if the mechanism by which the travelling arc motion is controlled does not change. Tests at direct current levels up to 275 A were made on mild steel hollow electrodes of 1 cm diameter at an electrode spacing of 0.63 cm and wall thicknesses from 0.005 to 0.05 cm. These tests, at velocities up to 5 m/sec, verified that there was indeed a skin effect. As the wall thickness was decreased at a constant arc current, the velocity remained constant until a certain wall thickness was reached. Below this thickness, the velocity increased as the thickness was further decreased. The wall thickness at which the skin effect first became noticeable was about 0.015 cm at 270 A and increased to about 0.025 cm as the current was decreased to 120 A. The skin effect would be expected to contribute to the arc motion only in the continuous modes of cathode root travel and have negligible effect in modes where the cathode motion is intermittent with frequent sticking.

Extensions of the above studies were described by Guile, Lewis and Secker (25). Electrodes 1 cm in diameter and 3.2 cm apart were made of various materials. Currents up to about 500 A were used to drive the arc in its own self-field. Cathode velocities up to 4 m/sec were reported with the velocities being the highest on the magnetic materials. In general, the velocities decreased with electrode materials in the following order: stainless steel, silver steel, mild steel, molybdenum, tungsten, duralumin, aluminum, lead, bronze, zinc, and brass. In view of the dependence of the motion of the travelling arc on the electrode material, it is clear that in the regime investigated, electrode phenomena must be quite important. Since, as before, it was found that the anode root motion was predominately controlled by the arc column, it appears that the cathode root is the seat of the travelling arc motion. This paper presented a preliminary interpretation of the cathode proccesses which determine both the amperian travelling arc motion and the retrograde arc motion. The model proposed suggests that oxide layers at the cathode site are important in maintaining the cathode spot. Thus, the motion would be dependent on the electrode material, as observed, and such a model explained the observed difficulty of maintaining an arc on an oxide-free surface. The model also helped to explain the observed increase in arc velocity with running time in an oxidizing atmosphere and the decrease in arc velocity with time in a reducing atmosphere. However, as stated, the model is incomplete, and will probably remain so; at least until the very complicated processes taking place in the cathode region of the arc are better understood.

A significantly different view of the effect of the electrode regions on the travelling arc motion was presented by Mosch (38). The travelling arc was considered to be acted upon by buoyancy, aerodynamic, electrical and self-magnetic field forces with a frictional retarding force (called an inertial resistance) present at the arc roots. This inertial resistance of the arc roots depended upon the electrode material and increased in the following order for the materials studied: copper, iron, brass, and aluminum. Thus, the arc velocity was greater on copper than on iron, conflicting with the results of Guile, et al. The experiments of Mosch were made with currents up to 50 A. Velocities up to 4 m/sec were measured photographically. The electrodes were 1 cm apart and were 0.05 cm and 0.833 cm diameter in different test runs. A considerable difference was found in the arc behavior with the different electrode diameters because of the effect of the electrode diameter on the self-field. The surface condition of the electrodes also had a significant effect on the motion of the travelling arc. If the surface of the copper electrodes was worked with sandpaper parallel to the direction of motion the cathode track was reasonably continuous while the anode track was discontinuous; sandpapering perpendicular to the direction of motion caused intermittent sticking motion of both arc roots.

Studies were made on round rods by Gonenc (21) at alternating currents up to 1000 A. Parallel, horizontal electrodes of iron, copper and aluminum were used with diameters of 0.5, 1.0, 2.0 and 4.0 cm and electrode gaps from 2 to 20 cm. Average travelling arc velocities up to 40 m/sec were obtained by measuring the time elapsed between the electrical signals from two coils located adjacent to the rails which were energized as the arc root passed by them. The velocity decreased as a function of the electrode material in the order of iron, copper and aluminum. For example, at a gap of 2.5 cm and an electrode diameter of 0.5 cm, the travelling arc velocity on iron was 33% greater than on copper, while on aluminum it was 95% of the copper value. There was no arc motion below a certain "adhesive current". This adhesive current varied between 50 and 200 A, depending on the electrode diameter and gap. It was noted that at the lower arc velocities (1 to 2 m/sec) the arc motion was intermittent with considerable sticking. The travelling arc velocity dropped off with increasing electrode diameter even more than would be expected due to the self-field effect alone. The difference in the measured and calculated dependence of the velocity on the electrode diameter was thought to be due to an incomplete consideration of the configuration of the arc near the electrodes. Different arc configurations were observed at different velocities. At low velocities, the arc column led the arc roots while at high velocities the column lagged behind the arc roots. The complex shape of the arc column at all velocities again points out the difficulty in applying the conducting cylinder model with aerodynamic drag to such a situation. However, for lack of a better model this was done in this paper. It was experimentally found that the velocity was proportional to $I^{0.85}$ rather than directly proportional to I. This difference was thought to be largely due to the dependence of the arc diameter on the current, although there were other complicating factors.

Hesse (30) compared the calculated and measured values of the self-magnetic field of an arc travelling along rails of rectangular cross-sections. The characteristic arc field was calculated assuming the arc to be a conducting cylinder of finite size. The field due to the current in the rails was calculated to several different degrees of approximation and the different results of these procedures were compared. These calculations showed that assuming the current to be concentrated along the electrode centerline produced considerable error (as much as 40% for a gap of 0.7 cm) in the calculation of the self field at narrow gaps, while a procedure which displaced the arc current line concentration a specified distance toward the arc root gave much better agreement with the exact and much longer calculation. Using this procedure, the effects of the rail width, thickness and spacing on the rail self-field were calculated. By adding this field to the characteristic arc field, the total self-field was obtained. These calculated values were found to agree well with experimental self-field values obtained with a copper cylinder substituted for the arc. However, the experimental self-field values for a 1230 A arc travelling at 90 m/sec did not show such close agreement. (In both of these experimental studies a Hall element was used to measure the magnetic field.) The differences between the calculated and the experimental arc self-field values appeared to be due to the lack of an axially symmetric travelling arc, a diffuse arc boundary, and the effect of multiple arc roots. The results indicated that the current distribution was more concentrated at the leading than at the trailing edge of the arc. Photographs of the arc appeared to confirm this current distribution. The above calculations of the travelling arc self-field would only apply when the arc forms the shortest connection between the two rails. For the configuration used this was true for current values greater than 600 A.

Hesse (29) also studied the effect of the rail dimensions on the travelling arc velocity at direct currents between 100 and 1400 A. Vertical copper rail electrodes of rectangular cross-section, 0.7 cm apart were used. Rail widths (the dimension perpendicular to the arc column) between 0.06 and 0.10 cm and rail thicknesses between 0.5 and 5.0 cm were used. The arc velocity was measured photographically (1600 frames/sec), with photoelectric cells, and by means of the voltage drop in the arc rails. All three methods of measurement agreed well. Depending on the rail dimensions and the arc current, three modes of arc travel were noted. At velocities greater than a certain value (typically 50 m/sec) the arc shape was symmetric with respect to the plane through the rails and was primarily determined by the aerodynamic effect. There was negligible electrode melting in this mode. The arc cross-section appeared to be much wider transverse to the flow direction than parallel to it, with the downstream arc cross-section boundary being quite concave. Using a measured arc diameter, the drag coefficient was calculated to be about 0.34, independent of the current. For intermediate velocities (typically between 50 and 25 m/sec) the arc shape was unsymmetric with respect to the plane through the rails, aerodynamic forces as well as those in the arc roots determined the arc shape, and there was some electrode melting, more on the anode than on the cathode. The calculated drag coefficient increased from 0.34 to 0.6 as the current decreased. At the lowest velocities (typically below 25 m/sec) the arc motion was intermittent and the arc roots appeared to be diffuse in this mode. As long as the arc had only one anode root, it travelled along the edge of the rail. In other tests with the anode rail divided axially by an insulating strip, the current was approximately equal in the two segments. When the cathode rail was split, however, the current was either carried in one half or the other at any specific time. Tests were also made in which the minimum current required to cause arc motion was determined. These results did not agree with those of Eidinger and Rieder (46); currents approximately 20 times greater than those given by the Eidinger and Rieder empirical equation (see page 31) were required. The arc velocity as a function of the electrode width at a constant current, had a relative maximum at about 0.2 to 0.3 cm and then slowly decreased as the width increased. The velocity at a constant current decreased as the rail thickness was increased. The effects of these rail dimensions on the travelling arc velocity were largely explicable in terms of the changes caused in the self-magnetic field due to the current flowing in the rail electrodes.

In a subsequent paper(31), Hesse discussed in detail the effect of the electrode material in the experiments with the 0.7 cm gap at currents between 100 and 1400 A and compared his results with those reported by others. Results are reported for tests with rails which had been broken-in (run 5 to 20 times, depending on current level). The arc velocity was approximately twice as high on broken-in electrodes than on new ones. Three types of anode tracks were observed on copper. At velocities of several m/sec there was a broad uniformly melted intermittent trail usually leading toward the edge of the rectangular electrodes. As the velocity was increased up to 50 m/sec the distance between the spots making up the above trail became less and the melting was less severe. Above 50 m/sec, the anode root simultaneously struck to numerous (up to 25) small (≈ 0.045 mm^2) base points with only very slight melting. Two types of cathode tracks were observed on copper: a continuously melted trail at velocities less than about 25 m/sec and a high speed track with no evidence of melting, only a decomposition of the oxide layer. The effect of the oxide layer and the presence of oxygen in the cathode region was discussed and it was concluded to be responsible for the low arc velocities on the initial test runs. Only after most of the cathode oxide layer had been removed, was the arc motion controlled by processes in the column or anode region. Tests were made with many different rail materials with identical geometric dimensions. The materials studied were: silver, silver-cadmium, copper, brass, steel, aluminum, tungsten, and carbon. When the anode and cathode rails were of different materials, the cathode material definitely had the predominate influence on the arc motion. Some tests were also performed on round rails with diameters between 0.08 and 1 cm and a spacing of 0.7 cm. The velocity decreased as the diameter increased, as expected, due to the decrease in the magnetic field at the rail surface. Hesse's literature survey discusses and compares the works of 11 other authors. From this survey, as well as from his own work, Hesse concluded that the rail materials can be divided into five groups according to their influence on the arc motion. No ordering of the materials within the groups was possible. The groups (in the order of decreasing velocity) were as follows: (1) silver, gold; (2) copper, brass, steel; (3) tungsten, molybdenum, zinc, bronze, nickel, cobalt, new-silver, lead, cadmium, tin; (4) aluminum; (5) carbon. The highest velocities occurred with group (1), whereas for group (5) the arc moved irregularly and with the lowest velocities. The low velocities on carbon were due to the different cathode mechanisms occurring with carbon and the metals. It was impossible to explain the relative velocities for the different metals on the basis of physical properties such as melting point, specific heat, electron emission work functions or ionization potential.

The form that the arc takes near the electrode was studied by Fehling (19). The arc was established between parallel vertical rails. One rail was divided into halves by an axial insulating panel and the alternating current fed into each half was monitored up to 16,500A. The results indicated that at high current intensities, both the anode as well as the cathode spots become dissociated and there are several parallel and simultaneous focal spots on both rails. It was observed that the cathode roots glide continuously while the anode roots move intermittently, apparently being appreciably influenced by the arc column motion.

GEOMETRIC AND ORIENTATION FACTORS

The primary factor to be included under this heading is the electrode gap. However, the effect of the orientation of the travelling arc with respect to gravity and the effect of magnetic materials near the travelling arc region, will also be included here. The latter two effects will be considered first.

The relationship between the self-magnetic field force and the buoyancy force due to gravity on a travelling arc was discussed theoretically and examined experimentally by Hochrainer (32). Even though the calculations based on a cylindrical arc column model indicated that in most cases the self-field forces would be larger than the buoyancy forces, this was not observed experimentally. Tests were conducted on parallel rails, 2.5 cm in diameter, inclined 60° to the horizontal, 1.1 m apart, and 3.15 m long. Direct currents between 1400 and 8400 A were used for a time duration of approximately one second. The arc motion was observed photographically. In some tests the arc was initiated at the top of the sloping rails and in others, at the bottom. The current was always fed in from the top. It was found that even at low currents the arc roots were pressed downward, while in the middle of the arc column, thermal buoyancy forces appeared to predominate. This was expected due to the relatively greater self-field in the electrode regions. At a current of 2800 A an arc initiated at the bottom remained at the bottom while for currents above 3000 A,, the arc always travelled downward regardless of where it was initiated. Thus, for this particular configuration, the self-magnetic field forces appear to predominate for arc currents greater than about 3000 A. Experiments were also described in which a horizontal arc was caused to move in a circular path (in a vertical plane) in a "carrousel" fashion. At a three-phase current of 35,000 A an arc velocity of 3000 m/sec was observed.

The effect of buoyancy was also discussed by Mosch (38) (also see page 9), who used a straight, conducting cylinder model identical to that used by Hochrainer. Tests were performed on parallel rails oriented in all possible ways with respect to the earth's gravitational field. The primary objective of this study was to develop a model by which the effects of the various parameters on high current switchgear arcs could be studied at much lower currents. As previously mentioned, currents up to 50 A were used. The model assumed that for identical ratios of the length of the "arc stems" (the stiff regions near the electrodes) to the electrode gap, similar arc behavior would result. In view of the various factors which affect the arc motion and the changes they undergo at different current levels, the validity of this model is questionable. However, the experimental portion of this study is of value whether or not the results can be applied to high current arcs. The tests showed, as expected, that the most rapid lengthening of the arc column was obtained with vertical, bottom-fed electrodes, while the slowest elongation was obtained with horizontal electrodes located one above the other. The current value at which the arc motion ceased to depend on the rail orientation (self-field force predominant) was found as a function of the arc gap and electrode radius. For a gap of 1 cm and an electrode radius of 0.05 cm this minimum value was approximately 42 A. This minimum current value was extrapolated using the preceding model and expressed graphically for gaps up to 100 cm, electrode radii up to 20 cm and currents up to 2000 A.. The current at which an arc travels downward in opposition to buoyancy forces on top-fed, vertical parallel rails was found experimentally. For a gap of 1 cm and an electrode radius of 0.05 cm a current of 8 A was required; at the same gap and a 0.833 cm electrode radius 30 A were required. These results were also extrapolated to high current regimes graphically and successfully described the results of Hochrainer. Tests were made on the effect of a horizontal iron plate on an arc burning in another horizontal plane. A length parameter called the "range of influence" was obtained as a function of the arc current, beyond which the iron plate no longer had an effect.

Mosch extended his discussion in another paper (39). In addition, further studies concerned with arc motion on a flat plate are described. These studies indicated that for a finite number of supply points the arc will always migrate to a plate edge. This is due to the paths followed by the current which produces the driving self-field force. This analysis was extended to parallel rails and indicated that the arc will always tend to move to an outer edge of the electrodes.

The relation between the self-field force and the buoyancy force on the travelling arc was further discussed with application to arc extinction by Hochrainer (33). This paper was concerned with design requirements to prevent damage due to the heat radiation and overpressure resulting from a short-circuit switchgear arc.

The experiments of Fehling (19) also included a study of the motion of the travelling arc under a buoyancy force. A needle anode was located perpendicular to a vertical copper or silver plate. Thus the cathode root moved vertically upward. The self-field was eliminated by the current routing used. A higher cathode travelling velocity was obtained on a rough than on a smooth plate. No difference in behavior was reported for the two different cathode materials. With speeds of several hundred m/sec there was hardly any trace left on the cathode plate. At the lower speeds (currents between 6 and 34 A), cathode current densities between 5000 and 10,000 A/cm^2, increasing with current, were estimated from the traces on the cathode. Multiple cathode spots occurred at currents of 60–100 A and above, and it appeared that the current density remained constant above this current level. This is in approximate agreement with the results of Secker and Guile (51) who reported dissociated cathode spots above 40 A.

The effects of placing magnetic material around or near the travelling arc electrodes have been reported by three other authors in addition to Fehling. Wegesin (59) performed experiments directly related to circuit breaker application. A stationary cathode was used adjacent to the bottom of a vertical rail anode. The anode rail was located inside iron cylinders of different configurations. The anode root velocity was then measured photographically as a function of the insulation thickness between the anode and the iron core and as a function of the axial slit width through the iron cylinder down to the anode rail. Currents of 400, 1200, 3600 and 7200 A were used to produce anode velocities up to 320 m/sec. The anode velocity was considerably greater than that observed by other experimenters when the self-field was not augmented by enclosing the electrode in a magnetic material. The arc velocity was approximately proportional to the square root of the arc current in all of these tests.

In the study reported by Büchner (12), iron electromagnets, series-excited by the arc current, were placed around the electrode regions. The specific application in mind was an improved circuit breaker. Therefore, an insulating plate was located between the parallel electrodes to provide for more rapid arc lengthening. Arc root velocities up to 250 m/sec were reported at currents up to 4000 A. Additional tests were made at currents up to 30,000 A. Several different electromagnet shapes were used. Of the shapes tried, it was found that a hollow cylinder with an axial slit along one side (the electrode being located in this slit) produced the highest velocity. The arc motion was studied with high-speed photography (five microsecond exposure times at 360 frames/sec). In the discussion it was pointed out that if the increase in arc length was a function of the force BI only, then at low currents, before the iron saturates, the velocity (and the arc lengthening) should be proportional to the square of the arc current. At higher currents, when the iron saturates, it was expected that V may be proportional to I. However, the experimental results indicated that V was more nearly proportional to the square root of I, agreeing with Wegesin. The observed form of the dependence was thought to be due to the aerodynamic drag on the arc and the presence of the insulating plate which complicated the path of the arc. The travelling arc velocities observed were greater than those reported at a similar current level without the presence of the series-excited electromagnets.

In the experiments of Menke (37), parallel electrodes were entirely enclosed first with 0.3 cm thick plexiglass and then with 2 cm thick iron plate. Thus the arc was constrained to move within a closed channel. The complicating effects of adding both side walls and iron cladding made it difficult to study the effect of the iron cladding separately. The electrodes were copper bars 0.5 cm wide, 1.45 cm thick and 84 cm long. The electrode spacing was 14.5 cm. The d. c. arc current was varied between 2000 and 14,000 A. It was found that addition of the iron cladding approximately doubled the velocity over that which was observed with no cladding. The maximum velocity observed was about 450 m/sec at 14,000 A. It was also observed that when the iron cladding was added the shape of the arc changed from arc column lagging the arc roots to arc column leading the arc roots.

There have been a number of papers which have examined the effect of the electrode spacing on the travelling arc. Freiberger (20) used three phase currents up to 30 KA on three parallel aluminum rods. Velocities up to 60 m/sec due to the self-magnetic field were observed photographically for electrode spacings of 25 cm. The rails were 0.277 cm in diameter. Electrode spacings between 5 and 30 cm were used. The velocities reported in this work are considerably lower than those reported elsewhere due to the larger electrode spacing and the use of aluminum as the electrode material.

Guile and Mehta (24) (also see page 6) found that on 0.951 cm diameter mild steel rods at direct currents up to 500 A there was no simple explanation of the way in which the regular cathode velocity varied with electrode spacing. There was a general tendency for the regular cathode velocity at a given current to decrease as the electrode spacing was increased from 1.27 to 7.6 cm, but at 19 cm the velocity rose again. As the electrode spacing increased, there was more of a tendency for the cathode movement to be regular. It was noted that the cathode root portion of the arc did not change much as the spacing was varied. Thus the obvious explanation for the increased regular movement at increased spacing was the additional freedom to bend without intermittent anode jumping that is now available to the arc. This is in contrast to the relatively straight arc which is maintained at the short gaps due to the stiff electrode roots. For the a. c. arc tests on steel electrodes at currents up to 1500 A, it was found that the arc velocity was approximately inversely proportional to the electrode spacing for spacing between 5.7 and 7.6 cm.

The effect of electrode spacing on the travelling arc with and without the presence of insulating side walls has been examined by Müller (41). Parallel copper rails, 1 cm square cross-section, were used with gaps between 0.2 and 10 cm. Alternating currents from 100 to 20,000 A were used in the tests. The arc velocity was determined photographically. The tests were sufficiently short that the arc current was essentially a direct current. Without the presence of side walls, the arc velocity at a given current steadily decreased as the electrode gap was increased from 0.2 to 1.0 cm. For instance, at a current of 15,000 A the velocity decreased from about 480 m/sec to 300 m/sec over the above range of electrode spacings. When insulating asbestos side walls were added the velocity at a given current and gap increased. With the side walls it was found that, as before, the velocity at a given current steadily decreased as the gap was increased from 0.2 to 10 cm. Electrodes of different widths were used at a constant current of 10,000 A to observe the effect of changing the wall spacing. With wall spacings of 0.5 and 0.2 cm relative maxima in the velocity vs. electrode spacing curves were observed at gaps of about 0.5 and 0.6 cm, respectively. The velocity decreased quite rapidly for larger or smaller electrode spacings.

Gonenc (21) (also see page 9) used electrode gaps from 2 to 20 cm with currents up to 1000 A. For this range, the velocity at a given current decreased approximately inversely proportional to the electrode spacing for the three electrode materials used: iron, copper and aluminum. However, the decrease was greater than that predicted solely from a consideration of the decrease in the average self-field with increasing electrode gap. This deviation was, as mentioned before, thought to be due to the complicated shape of the arc column.

Guile and Spink (55) studied electrode spacings between 0.32 and 10.2 cm. The experiments were performed with 0.96 cm diameter brass electrodes at currents up to 10,000 A. Velocities up to 250 m/sec were measured using a streak camera. The results show that the travelling arc velocity continually decreased as the electrode spacing was increased. These tests were compared with similar tests performed with an external magnetic field imposed. The self-magnetic field was calculated at both midway between the arc electrodes and immediately outside the electrodes. At a spacing of 0.32 cm both of these field values compared closely with the external magnetic field at the same velocity. This is because the self-field does not vary much between the electrodes at narrow gaps. However, at the 10.2 cm spacing the self-field midway between the electrodes agreed with the external magnetic field required to give the same velocity much better than the field immediately outside the electrodes. Thus, it appeared that in this regime, the motion was column dominated. When the arc velocity was plotted as a function of the self-field midway between the electrodes, there was little effect of the electrode spacing. Thus, the velocity in this regime depended primarily on the field at the center of the electrode gap regardless of the electrode spacing. This compared well with the results of Gonenc who found that by using the average self-field between the electrodes, the calculated velocity did not decrease with spacing as rapidly as the observed velocity. Using the centerline (minimum) self-field would bring the calculated values closer to the measured ones.

CHANNEL VARIABLES

In this section, the effects of adding insulating side walls on either side of the arc electrodes will be discussed. The side wall material, the distance between the walls, and whether or not there are slits or vents in the side walls all affect the behavior of the arc.

The studies performed by Müller (41) (also see page 15) were concerned with the effects of adding asbestos side walls. With the side walls added, velocities up to 1200 m/sec were photographically observed at currents up to 20,000 A. The addition of side walls to the 1 x 1 cm cross-section parallel copper rails caused roughly a 70% increase in the travelling arc velocity. The wall spacing was 1 cm, the same as the electrode width, and there were no vents in the side walls. With this wall spacing, tests were made with electrode spacings between 0.2 and 10 cm. The velocity steadily decreased as the electrode spacing increased. In another series of tests, the wall spacing was set at different values for a constant current of 10,000 A. Wall spacings of 0.2 and 0.5 cm were also used with a range of electrode spacings between 0.2 and 2 cm. These data showed a relative maxima in the velocity vs. electrode spacing plots as discussed previously. At spacings greater than these maxima, the velocity at wall spacings of both 0.2 and 1 cm was less than the velocity at 0.5 cm. However, in the region of the maxima (electrode spacings between 0.4 and 0.8 cm) the velocity steadily increased as the wall spacing decreased. This indicated a complicated interaction between the arc diameter, which would be expected to increase at larger electrode spacings, and the wall spacing. It seems reasonable that when the arc fills out the channel as closely as possible its velocity would be greatest while wider channels would increase the aerodynamic drag and narrower ones would exert a drag on the arc column itself. With the side walls, the voltage gradient in the arc column was increased and the arc motion was more regular than without side walls.

Kuhnert (36) introduced the additional variable of vents in the travelling arc channel. Initial tests were made in a closed channel with an electrode spacing of 0.5 cm at currents from 10,000 to 200,000 A. A maxima occurred in the plots of travelling arc velocity vs. wall spacing at a constant current. The position of this maxima did not appear to change from a wall spacing of about 0.5 cm as the current level changed. However, this maxima was much more pronounced at the lower current levels than at the higher currents. Vents of widths up to 0.6 cm were located in the center of the electrode walls of the channel along the entire length of the rails in another series of tests. Each rail then consisted of two separate rails. These tests were made at an electrode spacing of 4 cm and, therefore, could not be directly compared with the previous closed channel tests. Plots of velocity vs. wall spacing do not, in this case, show maxima in the range of wall spacing between 2.2 and 2.6 cm, but rather very shallow minima whose positions are a function of the arc current. The position of the minima moved to smaller wall spacings as the current was increased. Measurements of the arc voltage indicated that at a constant current the arc gradient (obtained by dividing the arc voltage by the electrode spacing) increased as the electrode spacing increased and as the wall spacing decreased. The arc motion was discussed qualitatively in terms of the conducting cylinder model. The electromagnetic (self-field) and the gasdynamic (aerodynamic drag) forces were discussed. In order to justify the use of the conducting cylinder model, it was argued that the pressure within the arc column is much higher than outside (about 500 atm) and that the hot arc column plasma has a much higher viscosity than the surrounding gas. However, no quantitative calculations were made using this model.

Neumann (42), included the effects of channel vents and insulating wall material in his studies. Experiments were performed both with parallel rails and diverging rails. Only the parallel rail work will be discussed here. The travelling arc velocity was measured by means of electrical pickups located along the rails. Velocities up to 600 m/sec were measured by this means at currents up to 10,000 A. The electrode spacing remained constant at 2.5 cm in these tests. Increasing the spacing between sipa side walls from 0.3 to 0.5 cm increased the travelling arc velocity at a constant current, both with and without the presence of vents. Vents were located in the electrode walls of the channel; the rails were located at one side of this wall and an open vent to the atmosphere along the entire channel length was located between the rail and the opposite wall. When these vents were opened the arc velocity at a constant current roughly doubled and, surprisingly, was higher at the 0.3 cm wall spacing than at the 0.5 cm spacing. This was a reversal of the effect of the wall spacing with closed vents. At a wall spacing of 0.3 cm the travelling arc velocity decreased as a function of the wall material in the following order: sintered corundum--closed vents, sintered zircon--closed vents, sipa--open vents, sipa--closed vents, mycalex--closed vents. The effect of wall material appeared to be explicable in terms of the different thermal conductivities of the various materials. The effect of the wall material was greater with closed vents than with open ones.

The work reported by Schütte (48) was performed at the peak phase of alternating currents up to 20,000 A. Thus the tests were essentially carried out with d.c. excitation. As in the above study, the travelling arc velocity was measured using electrical pickup probes located along the electrodes. A pressure transducer was located in the arc channel to measure the similarity between the travelling arc and a shock wave. One series of tests was made in a closed channel with square copper electrodes 4 cm apart. The side walls were made of zircon at spacings of 0.3, 0.5 and 1 cm. As the wall spacing decreased, the velocity and overpressure at a constant current increased. Tests on a 4 cm long arc located between ceramic side walls 0.5 cm apart with and without vents showed that open side vents 0.1 cm wide located on either side of the electrodes (in the electrode side wall) increased the velocity by roughly 20%. Velocities up to 750 m/sec were observed with the open vents. However, with the same configuration and using zircon side walls, the velocity decreased about 10% when the vents were opened. With plexiglas the velocity decreased about 15% when the vents were opened. The pressure transducer measurements showed that the peak overpressure in the channel always varied in the same direction as the arc velocity. Thus, it was higher for open vents with ceramic side walls, but lower for open vents with zircon and plexiglas side walls. Peak overpressures up to 18 atm were observed. The pressure peak corresponded to the arrival of the arc at the transducer location. When the arc velocity was supersonic, the pressure peak became quite steep and slightly preceded the arc front. Schlieren photographs taken of the supersonic arc front revealed a shock front ahead of the arc with a region of turbulence between the shock and the arc. Both the cylindrical conductor model and the propagation of state model were discussed by the author. It was concluded that neither model is adequate and suggested that a combination of the two models might be used to give a more adequate picture of the processes determining the arc motion. The theoretical relationship between overpressure and velocity for a shock wave model gave approximate agreement to that observed for the travelling arc, especially at the higher velocities.

SUMMARY

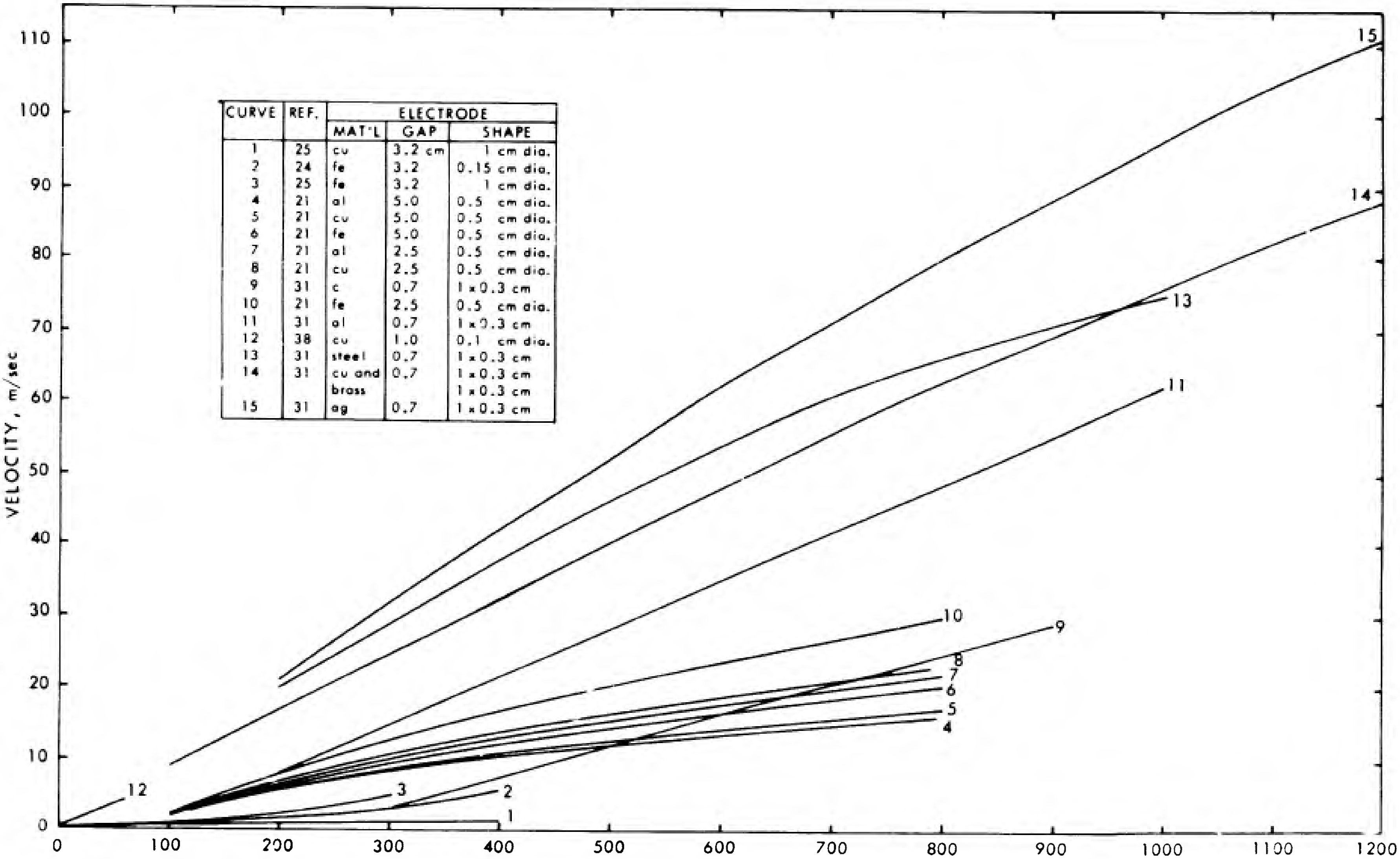
Figures 2 and 3 present the results of travelling arc studies on parallel rails without external magnetic fields at the low and high current ranges, respectively. Above a velocity of about 10 m/sec the curves indicate a linear velocity vs. current relationship, as is to be expected from the conducting cylinder analogy. The decrease in travelling arc velocity with increased electrode spacing is also evident.

Although there are some conflicting results, the travelling arc velocity is highest on steel (due to the skin effect), followed by copper, brass, and aluminum. There is always an electrode effect even though its relative magnitude appears to lessen as the arc velocity increases (21, 24, 25, 38). The previous history and surface condition of the electrodes has an effect on the arc velocity, especially at the velocities below 10 m/sec. Used electrodes, oxidized surfaces, and roughened electrode surfaces all tend to increase the travelling arc velocity (25, 38), apparently because the arc roots (especially the cathode) find it easier to move over such electrodes. The different modes of arc root motion observed at different electrode spacings and currents do not appear to have a significant effect on the travelling arc velocity (until immobility occurs), but represent the most convenient method of root motion available to the arc under the prevailing conditions.

Below a certain velocity (10-50 m/sec) the arc velocity appears to be largely controlled by processes at the arc roots (22, 23). The magnetic field at the electrode surface, especially at the cathode, appears to control the arc velocity in this regime. With velocities above 10-50 m/sec, the drag on the arc column appears to determine the velocity (21, 29, 55) and the conducting cylinder model may be applicable. The magnetic field in the center of the electrode gap appears to determine the motion at these higher velocities (54), further indicating a predominant controlling mechanism in the arc column. However, because of the different velocities observed with different electrode material over the entire range, electrode effects are never completely eliminated. The effects of varying the electrode dimensions (excluding the electrode spacing) appear to be largely explicable in terms of the resulting effect on the electrode self-field (29). However, the substitution of a cylindrical conductor for the arc does not reproduce the self-field in the arc region (30).

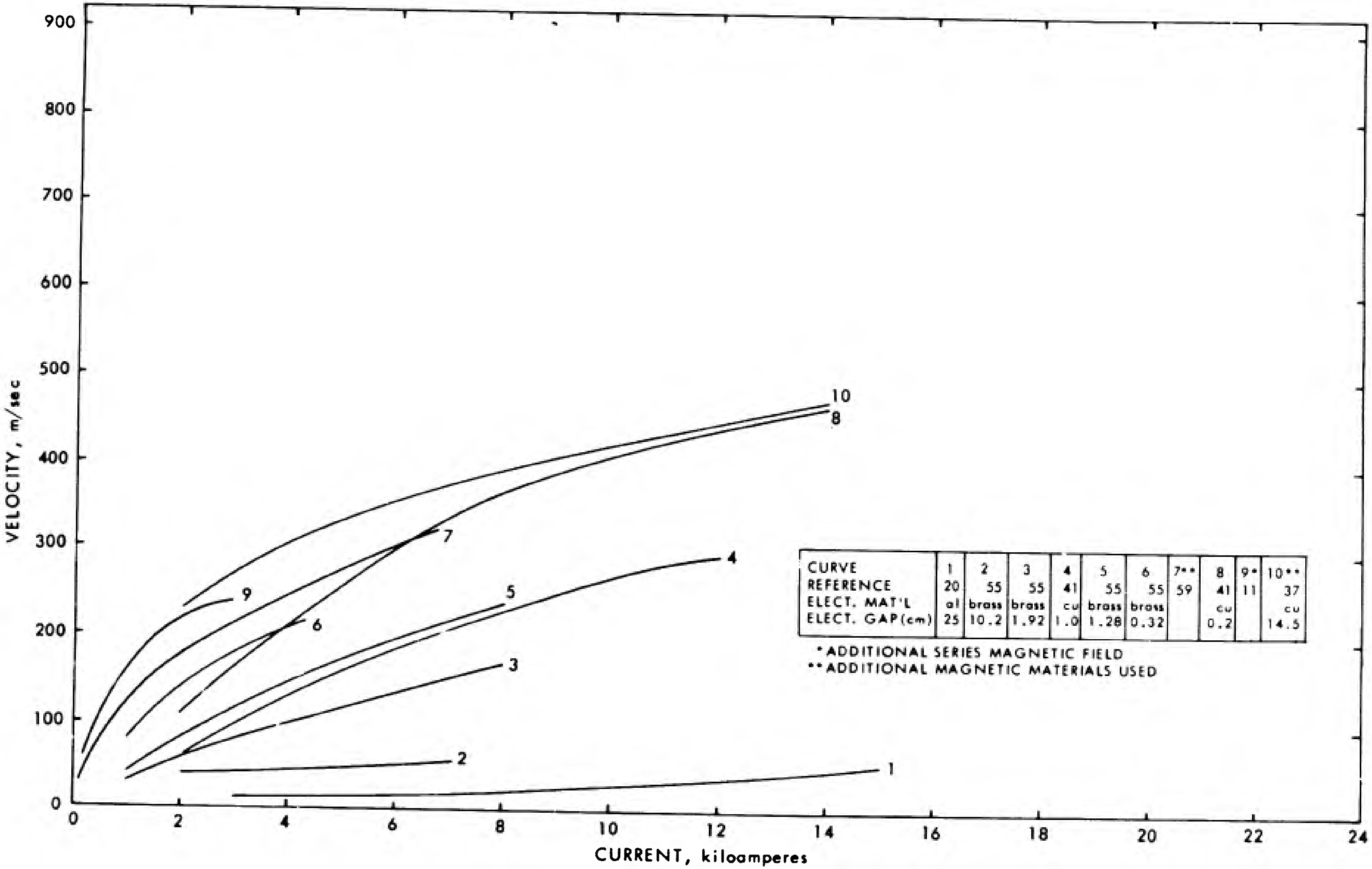
Magnetic materials in the region have the effect of increasing the travelling arc velocity above what it would be in the absence of such material. However, for some unexplained reason, with magnetic materials present the velocity is proportional to the square root of the current, indicating that at high currents (above those currently reported) either the V vs. I dependence will change or that the magnetic material will reduce the velocity below its value in their absence.

Even though there have been only a few studies made, the relationship between the buoyancy forces and the self-field forces appears to be satisfactorily determined by experiments (32, 38). However, no theoretical explanation of this relationship is currently available, largely due to the difficulty of calculating the



CURVE	REF.	ELECTRODE MAT'L	GAP	SHAPE
1	25	cu	3.2 cm	1 cm dia.
2	24	fe	3.2	0.15 cm dia.
3	25	fe	3.2	1 cm dia.
4	21	al	5.0	0.5 cm dia.
5	21	cu	5.0	0.5 cm dia.
6	21	fe	5.0	0.5 cm dia.
7	21	al	2.5	0.5 cm dia.
8	21	cu	2.5	0.5 cm dia.
9	31	c	0.7	1 x 0.3 cm
10	21	fe	2.5	0.5 cm dia.
11	31	al	0.7	1 x 0.3 cm
12	38	cu	1.0	0.1 cm dia.
13	31	steel	0.7	1 x 0.3 cm
14	31	cu and brass	0.7	1 x 0.3 cm 1 x 0.3 cm
15	31	ag	0.7	1 x 0.3 cm

FIGURE 2 - DEPENDENCE OF TRAVELLING ARC VELOCITY ON CURRENT AT CURRENTS UP TO 1200 AMPERE--SELF-FIELD ONLY.



CURVE REFERENCE	1	2	3	4	5	6	7**	8	9*	10**
	20	55	55	41	55	55	59	41	11	37
ELECT. MAT'L	al	brass	brass	cu	brass	brass		cu		cu
ELECT. GAP (cm)	25	10.2	1.92	1.0	1.28	0.32		0.2		14.5

*ADDITIONAL SERIES MAGNETIC FIELD

**ADDITIONAL MAGNETIC MATERIALS USED

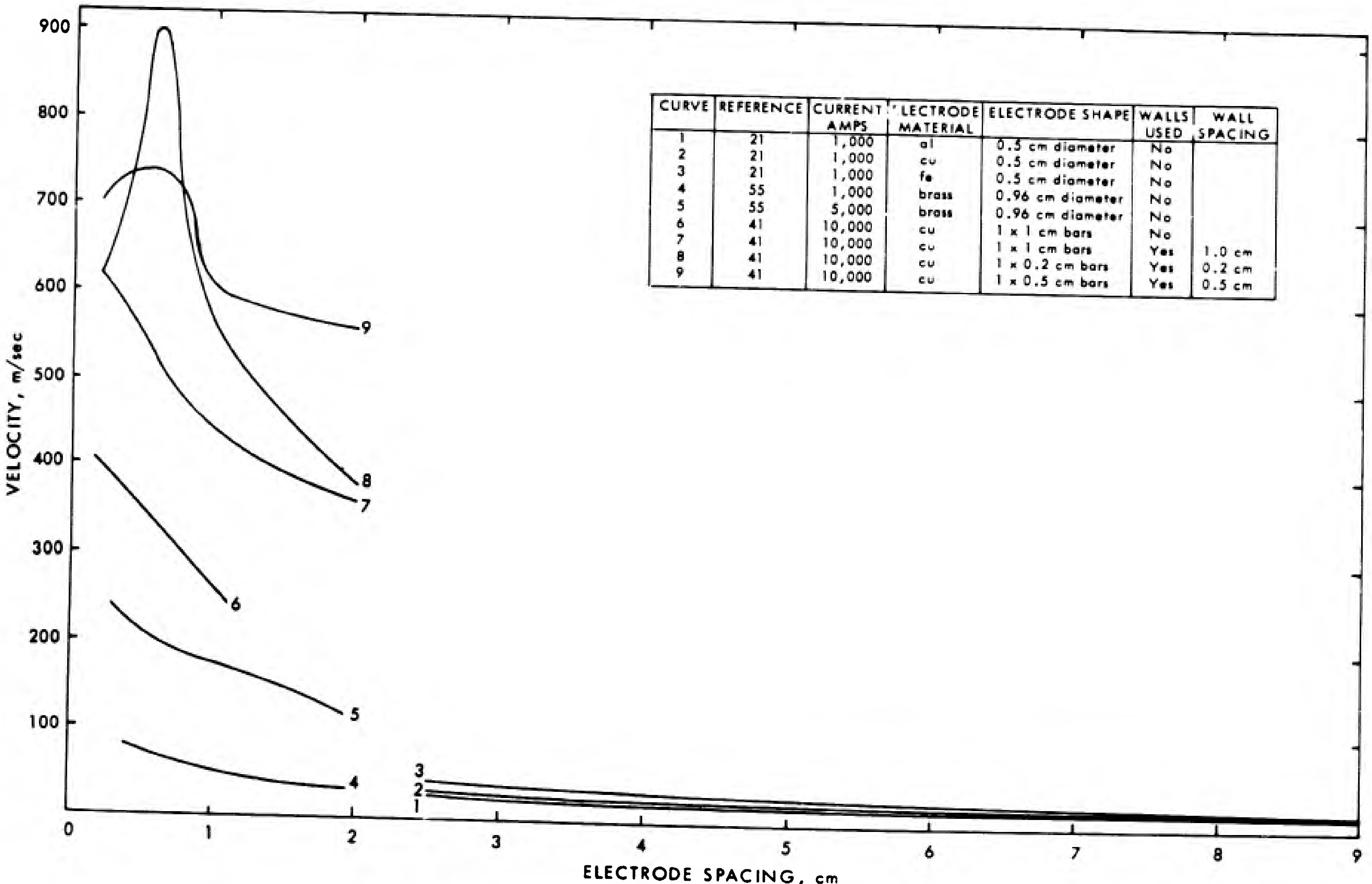
FIGURE 3 - DEPENDENCE OF TRAVELLING ARC VELOCITY ON CURRENT AT HIGH CURRENTS -- SELF-FIELD ONLY

self-field forces due to the arc column itself (30).

The effect of the electrode spacing on the travelling arc velocity is shown in Figure 4. In general, especially at gaps greater than about 1 cm, it can be said that increasing the spacing decreases the velocity for a given current, largely due to the reduction in the self-field. However, there are many significant complicating factors. These factors include the stiffness of the arc column, i.e., the relative strength of the anode and cathode jets, which determines if the two roots move independently of each other or not (24,55). If partially independent motion occurs, the shape of the arc column may become quite complex, invalidating a conducting cylinder analogy. Since the electrode spacing directly affects the relative length of the arc which is made up of root dominated and column dominated regions, it will have an effect on whether the motion is root or column dominated. Decreasing the electrode spacing may cause the arc motion to be controlled by processes at the electrode surfaces rather than by the aerodynamic drag on the arc column. Thus the multitudinous effects of the electrode spacing may combine to produce the different velocity dependencies shown in Figure 4.

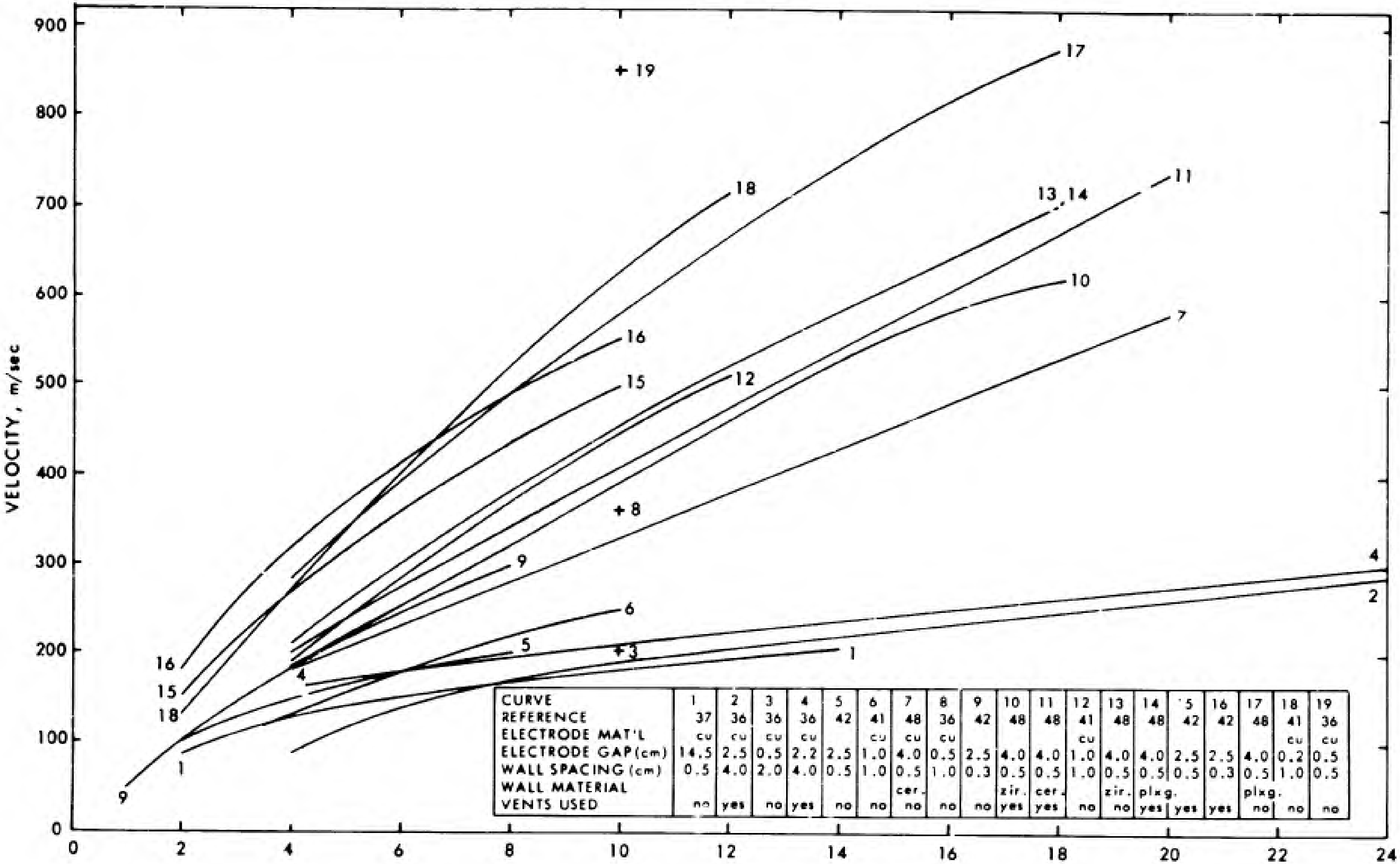
Adding insulating side walls produces quite varied results. In general, travelling arc velocities are higher if the walls are present. The V vs. I curves remain linear as shown in Figure 5. Usually, there is a relative maximum in the arc velocity as the wall spacing is varied (36,41), which is thought to result from a minimum in the sum of the aerodynamic and wall drag forces. At wider wall spacings, the arc has more freedom to move back and forth transverse to the channel, and the column may form loops or helixes, encountering more aerodynamic drag. At narrower wall spacings the arc is constricted and is retarded by friction on the insulating side walls. As yet there is no completely satisfactory explanation for the dependence of arc velocity on the wall material. Often the presence of vents in the arc channel will cause the velocity to increase, as might be expected due to the gas leaving the channel, resulting in lower pressure in front of the arc. However, at times, this expected trend is inexplicably reversed.

In conclusion, it appears that the conducting cylinder model with aerodynamic drag is successful in explaining the linear form of the relationship between the travelling arc velocity and the arc current. However, the complicating effects of the electrode material and condition, presence of magnetic materials, electrode spacing and orientation, and insulating side walls with and without vents, cannot be satisfactorily explained at present, but the trends can be indicated from the experiments.



CURVE	REFERENCE	CURRENT AMPS	'LECTRODE MATERIAL	ELECTRODE SHAPE	WALLS USED	WALL SPACING
1	21	1,000	al	0.5 cm diameter	No	
2	21	1,000	cu	0.5 cm diameter	No	
3	21	1,000	fe	0.5 cm diameter	No	
4	55	1,000	brass	0.96 cm diameter	No	
5	55	5,000	brass	0.96 cm diameter	No	
6	41	10,000	cu	1 x 1 cm bars	No	
7	41	10,000	cu	1 x 1 cm bars	Yes	1.0 cm
8	41	10,000	cu	1 x 0.2 cm bars	Yes	0.2 cm
9	41	10,000	cu	1 x 0.5 cm bars	Yes	0.5 cm

FIGURE 4 - DEPENDENCE OF TRAVELLING ARC VELOCITY ON ELECTRODE SPACING -- SELF-FIELD ONLY



CURVE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
REFERENCE	37	36	36	36	42	41	48	36	42	48	48	41	48	48	42	42	48	41	36
ELECTRODE MAT'L	cu	cu	cu	cu		cu	cu	cu				cu						cu	cu
ELECTRODE GAP (cm)	14.5	2.5	0.5	2.2	2.5	1.0	4.0	0.5	2.5	4.0	4.0	1.0	4.0	4.0	2.5	2.5	4.0	0.2	0.5
WALL SPACING (cm)	0.5	4.0	2.0	4.0	0.5	1.0	0.5	1.0	0.3	0.5	0.5	1.0	0.5	0.5	0.5	0.3	0.5	1.0	0.5
WALL MATERIAL							cer.			zir.	cer.		zir.	plxg.			plxg.		
VENTS USED	no	yes	no	yes	no	no	no	no	no	yes	yes	no	no	yes	yes	yes	no	no	no

FIGURE 5 - DEPENDENCE OF TRAVELLING ARC VELOCITY ON CURRENT WITH INSULATING SIDE WALLS USED -- SELF-FIELD ONLY

SECTION III. PARALLEL RAILS WITH EXTERNAL MAGNETIC FIELDS

With the introduction of an external magnetic field, the travelling arc motion is subject to two independent variables: the arc current and the magnetic field. In the previous section, the magnetic field was coupled to the arc current so that these two parameters could not be varied independently. By providing an external field, the magnetic field can be more uniform over the arc column and a situation results which is somewhat easier to analyze. In some of the studies, the self-field due to the arc current was not completely eliminated and had some effect on the arc motion. However, as long as the arc current is less than 100 A, the electrode spacing is greater than 1 cm, and the external magnetic field is greater than several hundred gauss, the external field is approximately an order of magnitude larger than the self-induced field. If the self-field is reduced by means of proper routing of the arc current, these limits may be safely exceeded.

The organization of this section is very similar to that of the previous one. The investigations will be discussed according to the parameters investigated, and then chronologically within the groupings: electrode parameters, geometric and orientation factors, and channel variables. Most of the investigations have been made in atmospheric pressure air between parallel rails and this will be understood to be so unless stated otherwise. The final part of this section will graphically present the results of the various parameters on the travelling arc.

THE ELECTRODE PARAMETERS

The effect of the electrode parameters, i.e., the material, shape, surface condition, and previous history of the rail electrodes, is discussed in this section. One of the earliest studies of the changes in the behavior of the travelling arc with the electrode parameters was performed by Burghoff (13). Electrodes made of brass, silver, aluminum, copper, and chromium-nickel were used at alternating currents up to 135 A. Magnetic fields up to 1000 G were provided by a separately powered electromagnet. Velocities up to 60 m/sec were observed with a camera utilizing a slotted disk. Electrode spacings between 3 and 5 cm were used. The electrodes were oriented vertically and fed from one end, therefore, the effect of the self-field was not eliminated. No information was given on the electrode shape or cross-section. The tests showed that the travelling arc velocity depended on the electrode material. On highly polished electrodes the anode root travelled faster than the cathode root. After the electrode surface was oxidized (requiring approximately 30 minutes of running time) there was little change in arc behavior with time. After the electrodes had been broken in it was noted that: for silver and brass the anode velocity was greater than that of the cathode; for aluminum and chromium-nickel the two velocities were approximately equal; for copper the cathode velocity was greater up to 300 G, above this value both velocities were approximately equal. The velocity was independent of electrode spacing over the range studied. The travelling arc velocity was quite sensitive to the electrode surface roughness, increasing as the surface became smoother. There was considerable scatter in the data. Double anode and cathode spots were observed, with double anode spots being an order of magnitude more prevalent than double cathode spots. Double anode spots were observed about 4% of the time. The cathode movement was more uniform than that at the anode. As the magnetic field was increased, a discontinuity was observed in the cathode root velocity. For instance, with copper electrodes, at a constant current of 81 A the cathode velocity dropped from 32 m/sec to 27 m/sec as the magnetic field increased from 220 to 290 G. Above this discontinuity the anode and cathode velocities were approximately equal, increasing to 36 m/sec at 800 G. Below this discontinuity, the cathode velocity was higher than that of the anode. The author suggested that this discontinuity was due to a laminar to turbulent transition.

Winsor and Lee (58) used electrodes of silver, copper, carbon, tungsten, molybdenum, nickel, and titanium. Direct currents up to 100 A and magnetic fields up to 200 G were used to obtain velocities up to 28 m/sec. The electrodes were made of 0.635 x 0.635 cm square rods mounted horizontally with the cathode above the anode. The current leads were connected to the end of the cathode at which the arc was initiated and to the downstream end of the anode. Thus the self-field was somewhat reduced. The usual electrode spacing was 0.318 cm. Several modes of arc motion were observed photographically. Continuous motion of both the anode and cathode occurred at low currents and high field strengths. In this mode the arc velocity appeared to be independent of the electrode material. This mode occurred at currents less than 40 A and magnetic fields between 100 and 200 G. In the second mode intermittent motion of the anode occurred, while the cathode motion remained continuous. In this mode the anode remained in one spot, while the cathode and the arc column moved ahead until a new anode spot was formed ahead of the old one. This mode occurred at currents between 50 and 109 A and over the entire magnetic field range studied. The anode spots left peaks on the electrodes which were highest for copper and less pronounced for the refractory materials. A third mode occurred when both the anode and cathode motion became intermittent. This mode appeared at low magnetic field strengths and high currents. Reproducible results could not be obtained for this mode of motion. Sometimes the arc extinguished itself by blowing out sideways when in this mode. The current at which transition to this mode occurred depended on the electrode material. It was highest for copper, then silver, and relatively low for the other materials. The transition to this mode appeared to be controlled by the cathode material rather than that of the anode. In the third mode the travelling arc velocity was considerably lower than in the other modes. The transition current increased with an increase in field strength. A highly oxidized cathode caused the motion to tend to remain in the first mode rather than changing to the third mode. Due to the non-reproducibility of the third mode data and little correlation between the transition points for different materials and magnetic fields, little can be concluded from this portion of the study.

Only two modes of motion were reported by Secker and Guile (50): regular cathode and anode movement and regular cathode movement with intermittent anode movement. The experiments were conducted with 1 cm diameter electrodes mounted horizontally with the anode above the cathode. The electrode spacing was constant at 0.32 cm. Direct currents from 40 to 700 A were fed in equally from both ends of the electrodes, eliminating the self-field effect. Magnetic fields from 50 to 1000 G were utilized. The arc motion was recorded photographically with a 960 frames/sec camera. New, clean electrodes were used for each test. The electrode materials used were brass, mild steel, aluminum, and carbon. Considerable scatter was found in the regular cathode velocity for a given magnetic field; this appeared to be due to the cathode surface layers. Perhaps the most unusual finding of this study was that the travelling arc velocity in both modes was independent of the arc current. Thus the dependence of the velocity on the magnetic field could be expressed as $V = KB^n$, where the constants K and n vary with the cathode material.

An extension of the above work has been reported in another paper by Guile and Secker (26). The self-magnetic field was again eliminated by feeding the electrodes equally from both ends. Tests were made on mild steel electrodes 1 cm in diameter, 0.3 cm apart, at arc currents between 40 and 670 A and magnetic fields up to 550 G. Up to 550 G the cathode motion was continuous, but above this field the cathode motion was discontinuous. The cathode velocity in the continuous mode was independent of the arc current in the range given. The cathode velocity was also independent of the current for brass electrodes over the same range. At currents below 40 A, however, the cathode velocity on brass was highly dependent on the current. When the cathode moved in the discontinuous mode (i.e., in a stepping process with random jumps between electrode spots) the cathode velocities were reproducible and again independent of the current. This was confirmed for this mode on electrodes made of brass, aluminum, copper, mild steel and carbon at velocities up to 30 m/sec. The cathode velocity in both modes was highly dependent on surface condition and only one test was made per electrode set to reduce this variation. The authors suggested that the reason the cathode velocity was independent of the current at currents above 40 A was because the mechanism responsible for the travelling arc motion was dependent on the cathode current density, rather than the cathode current. Since above 40 A multiple cathode spots have been reported to occur with approximately constant current density, this may be the reason for the change in behavior at 40 A.

A continuation of the above work to magnetic fields of 1400 G has been reported by Secker and Guile (51). In these studies 0.95 cm diameter electrodes were located horizontally with the anode above the cathode. The current was fed from both ends of the electrodes. Velocities up to 10 m/sec were observed with direct currents from 40 to 670 A. The arc motion was again observed with a 960 frames/sec camera. A continuous cathode track with slight surface melting was observed on unused mild steel electrodes 0.32 cm apart 90% of the time, the rest of the time the motion was discontinuous. The continuous cathode velocity was independent of the current for currents above 40 A. On brass the continuous cathode velocity was higher than for steel and again the velocity was independent of the arc current above a current of 40 A. On copper electrodes continuous cathode tracks occurred below 50 G, and above this value the high-speed continuous track (negligible electrode melting) was observed. Tests on carbon and aluminum electrodes gave hardly any continuous tracks. The travelling arc velocity in both the discontinuous mode and the continuous mode was quite dependent on the electrode surface condition. Again the dependence of the velocity could be expressed in the form $V = KB^n$. In general, the tests showed that as the arc current was increased the arc passed through the following modes: discontinuous or sticking track, high-speed continuous track and a random track where the cathode spot appeared to dwell at a few points only. As the magnetic field strength was increased the arc passed through the same modes as for increasing arc current.

Increasing the electrode spacing decreased the amount of continuous track motion in favor of random jumping. The arc velocity increased as the electrode spacing on aluminum was increased from 0.64 to 4.8 cm. The fact that the velocity was greater on non-ferrous than on ferrous electrodes, while the opposite effect was observed with only the self-magnetic field present was explained by means of the model whereby the cathode velocity was determined by the field at the cathode surface. The self-field would be greater for magnetic materials than non-magnetic ones, while the external field would be distorted by the magnetic material so that it would be greater at the electrode surface for the non-magnetic materials.

A summary of the above experiments as well as the tests using only the self-magnetic field is found in the paper by Guile, Lewis and Secker (25) which was discussed in the previous section (see page 8). Additional interesting experiments were performed at low pressure (25 torr) in which the amperian arc velocity was measured as a function of the oxidation time of brass electrodes. These tests were made at an electrode spacing of 0.64 cm and at a magnetic field strength of 240 G. The velocity initially increased with oxidation time and then decreased thus indicating the influence of the thickness of the cathode oxide layer on the arc velocity. When a reducing atmosphere such as hydrogen was introduced into the test chamber during a test the travelling arc could no longer be maintained on stainless steel until air or oxygen was again introduced into the chamber. Thus it was concluded that for an arc operating in air the arc track will tend to become more heavily oxidized and the arc will follow the same path in subsequent operation. In hydrogen or nitrogen the opposite effect will tend to occur.

In two subsequent papers (27, 28), Guile and Spink indicate somewhat of a new view of the processes controlling the travelling arc. In their preceding work conditions were such that the velocities were low--always less than 50 m/sec. In the work now described arc velocities up to 250 m/sec were obtained and measured with a streak camera. This was done utilizing currents (the peak of a single phase of a 50 cps alternator) up to 20,000 A and magnetic field strengths up to 1280 G. As in the previous work, the arc electrodes were equally fed from both ends to eliminate the self-field. Brass electrodes of 0.96 cm diameter were situated horizontally 0.3 cm apart. At these higher currents the cathode surface condition exerted relatively less influence on the travelling arc velocity than at the lower currents. In contrast to the earlier results which indicated the velocity was independent of the arc current up to 670 A, these tests showed that above 300 A the velocity increased with the current. This relation was empirically expressed as $V = K_1 BI^{(0.42-B)}$, (B is in w/m^2) which held for magnetic fields between 100 and 1280 G and currents from 1000 to 10,000 A. A different form of the dependence of the velocity on the prime variables could be expressed as $V = K_2 B^{(0.445 - 3.3 \times 10^{-3} I)}$, which fit the data satisfactorily for currents between 200 and 3000 A, and magnetic fields between 300 and 1280 G. Below the 200-300 A current range the velocity was proportional to the magnetic field strength and independent of the current. In view of these results it was suggested that the seat of control of the arc motion changes at a velocity of about 50 m/sec. Below this velocity the previous experiments had verified that the motion was due to the field in the cathode region and not that in the arc column region. However, above a velocity of 50 m/sec the aerodynamic drag forces on the arc column became so great as to control the travelling arc velocity. The view was still held that interactions in the cathode region are the cause of the motion, but below 50 m/sec the travelling arc velocity is limited by the rate at which new emitting sites are formed, while above 50 m/sec column retardation limits the velocity. Thus, above 50 m/sec it was thought that the cylindrical model which results in the equation $BI = 1/2 C_D \rho DV^2$, with D representing the arc diameter and ρ the ambient gas density, may be approximately valid. By using a drag coefficient of 0.63 (solid cylinder, turbulent boundary separation) for C_D the value of D was estimated to be between 1 and 2 cm at 20,000 A, a reasonable value. Nevertheless, comparison with the above empirical equations shows that this model falls short of an adequate description of the travelling arc.

Results of an extensive series of tests by Spink and Guile (55), which also included some of the preceding work indicated a further clarification of the conditions for which the travelling arc was column controlled and for which it was cathode controlled. These tests were conducted with electrode spacings between 0.16 and 10 cm, currents up to 20,000 A equally fed in both ends of the electrodes, and magnetic fields from 320 to 1280 G. The rails were mounted horizontally with the anode above the cathode. Arc velocities up to 250 m/sec were measured with a streak camera. With the external magnetic fields used the arc velocity was dependent on the current for currents greater than 100 A. Over the entire range of currents the travelling arc velocity was dependent on the electrode material. When both electrodes were of the same material, spaced 0.32 cm apart, and in a 320 G external field, the velocity decreased as a function of the electrode material (new electrodes for each test) in the following order: ground brass, polished drawn copper, polished phosphor bronze, polished tungsten (0.48 cm diameter), polished drawn brass, polished duralumin, unpolished duralumin, polished stainless steel (1.12 cm diameter), and mild steel. Unless otherwise indicated the electrodes were 0.96 cm in diameter. These data confirmed the previous results that the velocity in an external field was lower on magnetic than on nonmagnetic materials. In other tests at an electrode spacing of 10.2 cm with brass, duralumin and mild steel electrodes the large differences in the velocity due to the electrode material was not present. By changing anode materials it appeared that an anode effect was present at the lower currents and velocities. This effect reduced the velocity at small spacings and increased it at large spacings when a duralumin or mild steel anode was substituted for a brass anode with a brass cathode being used in all cases. There was also a cathode material effect; that is, replacing a brass cathode by a duralumin or mild steel cathode decreased the velocity nearly to that which occurred when both electrodes were duralumin or mild steel. The cathode track was almost entirely continuous over the entire test range and for the electrode materials used. The electrode surface condition had a pronounced effect over the entire range of velocities and currents. For instance, with brass electrodes 0.32 cm apart in a 320 G field the velocity was greatest for a polished and longitudinally scratched cathode, less for a cathode that was only polished, and reduced even more for an unpolished cathode. Repeated tests were also made with the same 0.96 cm diameter electrodes spaced 0.32 cm apart in a 320 G external field. For an unpolished copper cathode the velocity was initially very low and then increased until it approached the velocity for a polished copper cathode. Repeated tests with initially polished brass electrodes showed that the velocity first decreased and then increased back to approximately the original value. The variation of velocity with run time also depended on the current level. These repeated tests mainly serve to point out reasons for the great deal of scatter found in the published results. The relation between the velocity and the prime variables was expressed as $V = K(B) I^{n(B)}$ where the factors K and n depend on the magnetic field and have different forms above and below a velocity of approximately 50 m/sec. The conclusions reached by the authors were that short arcs (below 5 cm) travelling less than 50 m/sec are root (primarily cathode) controlled, short arcs travelling greater than 50 m/sec are cathode influenced but column retarded, and long arcs (above 5 cm) travelling at more than 50 m/sec are column controlled. This latter point was supported by the observation that at large spacings and with only self-field excitation, photographs of the arc column showed that its shape approximately followed the magnetic field strength variation across the electrode gap. Thus, the evidence suggested that at velocities above 50 m/sec the aerodynamic retarding forces on the arc column restrict the velocity to a value below that which the cathode processes would allow.

GEOMETRIC AND ORIENTATION FACTORS

The primary variable which is considered in this section is the electrode gap. The orientation with respect to gravity is of less significance in the experiments with external magnetic fields because the magnitude of the buoyancy force is usually small in comparison to the electromagnetic forces acting on the arc.

Electrode spacings between 10 and 40 cm were used in the experiments reported by Bronn (7). The arc was driven upward on parallel vertical copper rails with the current fed from one end. Thus, the self-magnetic field was not eliminated. Direct currents up to 1000 A and magnetic fields up to 1000 G, provided by an air core solenoid, were used to produce travelling arc velocities up to 130 m/sec. The arc motion was analyzed photographically with a 1300 frames/sec camera. The travelling arc velocity increased both with increasing current and with increasing magnetic field. The velocity decreased as the electrode spacing increased due both to the decrease in the self-magnetic field and the increased arc column drag. The arc column lagged the electrode portions of the arc. This column lag was more pronounced at larger gap spacings. Experiments were also performed with travelling arcs on diverging rails.

The travelling arc tests were extended over a current range from 1 to 265,000 A and a magnetic field range from 1 to 10,000 G in a later work by Bronn (8). The parallel rail portions of these tests were quite similar to that above, being performed on vertical parallel copper bars 40 cm long located inside a solenoid over a current range of 100 - 1000 A and a magnetic field range of 100 - 1000 G. The electrode spacing range was extended to include gaps from

0.15 to 4 cm. There was a relative maximum in the velocity vs. electrode spacing plot at a constant magnetic field strength of 250 G. This maximum moved to slightly higher spacings as the current increased, going from about 0.4 cm at 100 A to approximately 0.9 cm at 1000 A. The change in the self-magnetic field was not entirely responsible for the velocity dependence on the electrode spacing. The initial increase in velocity as the spacing was narrowed was thought to be due to less of a tendency of the arc to twist and coil which would decrease the aerodynamic resistance to its motion (i.e., the arc was more controlled by its root portions). The drastic decrease in arc velocity as the spacing was further reduced could not be satisfactorily explained. The arc voltage increased linearly with the normal component of the arc velocity; the effect decreased as the electrode spacing became narrower.

The variation of the travelling arc velocity with the electrode spacing at currents of 100 and 400 A and with external magnetic fields from 100 to 930 G was studied by Babakov (4). Velocities up to 100 m/sec were observed with a 10,000 frames/sec camera. Vertical parallel copper rail electrodes were used with spacings between 0.01 to 0.3 cm. The electrode shape was not given although the figures indicate that they were circular in cross-section. The arc velocity dropped off strongly at spacings less than 0.06 cm. The velocity appeared to be nearly constant for electrode spacings between 0.1 and 0.3 cm. The author concluded that at 100 A for gaps less than 0.16 cm the arc attachment points retard the arc significantly and for gaps less than 0.03 cm the cathode spot mobility in the controlling factor. Thus, at gaps less than 0.03 cm the travelling arc velocity is strongly dependent on the cathode oxide layers and the cathode material. At these short gaps it was thought that the arc current was conducted by a melted filament of electrode material. The approximate analysis included the magnetic force, the aerodynamic drag, and the wall friction. In order to study the effect of the wall friction further, experiments were performed on an arc between parallel copper plates 0.2 and 1 cm apart and 0.1, 1.0, 2.2 and 4 cm wide. Currents of 100 and 400 A were used with a constant field of 200 G. The velocity was independent of the plate width. With these same currents at 800 G the velocity depended on the electrode width, increasing with decreasing width. The greater the arc velocity, the greater was the influence of the electrode width. This indicated that the frictional drag of the gases against the electrode walls retarded the arc.

Experiments at magnetic fields from 1.6 to 400 G produced by a Helmholtz coil were performed by Rieder and Eidinger (46) with application to circuit breakers. The direct current levels were varied up to 60 A to produce velocities up to 30 m/sec. The arc travelled between vertical plate-shaped parallel copper electrodes with spacings between 0.16 and 4 cm. The arc motion was observed photographically. The dependence of the travelling arc velocity on the prime variables was expressed as $V = C I^{0.61} B^{0.74}$, as long as $B d^3$ (d is the electrode spacing in cm and B is in gauss) was greater than three. Measuring the current in amps and the velocity in m/sec, the constant C was equal to 0.045. The velocity was independent of the electrode spacing in this range. Using the cylindrical arc column model; the form of the above equation would be expected to be

$V = \left(\frac{2}{DC_D}\right)^{0.5} I^{0.5} B^{0.5}$. However, the arc diameter D increases with increasing I and thus the power on I must be smaller than on B as was observed. Also the arc diameter would be expected to decrease with increasing velocity thus causing V to increase more rapidly than $I^{0.5} B^{0.5}$ as was also observed. If the above parameter Bd^3 was less than three the velocity was also a function of the electrode spacing: $V = C_1 I^{0.61} B^{1.4} d^{2.22}$, with the constant C_1 being 2.3×10^{-4} for the same units as above. No influence of electrode material on the arc motion was observed. In other portions of this study a criterion was developed to designate when arc motion would start on electrodes of a specified material. It was found that if the product BId^2 was greater than a certain constant, depending on the electrode material, motion would occur. Other tests were made in which the thermal convection uplift (buoyancy force) on an arc between vertical electrodes was balanced with a magnetic field. This balancing magnetic field was found to be a function of the arc current and electrode spacing. This function was $B = B_o \frac{d - d_c}{d} \ln \frac{I_o}{I}$, where B_o was 7.5 G, d_o was 0.35 cm and I_o was 45 A.

Further description of the above work is found in other papers by Eidinger and Rieder (14, 15, 16). In addition to the above, it was reported that on clean electrodes which had not yet been used (presumably run-in electrodes were used in the above tests), small scratches may considerably slow the arc motion. Empirical equations were presented which described the travelling arc characteristic as a function of magnetic field, the arc length and the potential gradient of the undisturbed arc. The empirical equations were developed from measurements over a fairly narrow range of variables and are probably not applicable to conditions outside of this range.

A different variation of the travelling arc velocity with electrode spacing than that given by Bronn was reported by Secker and Guile (51) (also see page 27). For a similar current range (40-670 A) and magnetic field range (0-1400 G) the arc velocity on 0.96 cm diameter aluminum electrodes increased from 5 to 13 m/sec as the electrode spacing increased over the range from 0.25 to 5 cm. This velocity was recorded for the discontinuous mode of cathode motion. The electrode spacing had a pronounced effect on the mode of arc movement. As the spacing was increased the percentage of regular movement became less until finally only random jumping occurred.

Bronfman (9) summarized and discussed the effect of the electrode gap on the travelling arc velocity. Drawing data from his own studies (not described) and the published results of other authors he concluded that for the current range 50-500 A the dependence of the velocity on the electrode spacing can be divided into three regimes. In regime A, for spacing greater than about 0.2 cm, the motion is governed by arc column processes and the conducting cylinder with aerodynamic drag model is applicable. The velocity steadily increases as the electrode spacing decreases. In regime B, occuring between regime A and spacings greater than about 0.03 cm the velocity continues to increase as the spacing decreases, although to a lesser degree than in regime A, and it increases with increasing magnetic field and current. As in regime A, the motion is practically independent of the electrode material. In this regime cathode root sticking occurs and the motion is dependent on the electrode surface condition. In regime C, occuring at spacings less than about 0.03 cm, the travelling arc velocity is quite low, less than 2 or 3 m/sec, and the motion is practically independent of current and magnetic field strength. The velocity is controlled entirely by electrode effects in this regime.

The travelling arc in transverse magnetic fields has been studied with magnetic fields up to 3500 G, produced by an air core solenoid, and currents to 600 A by Roman (47). Velocities up to 150 m/sec were observed. Electrode spacings of 0.72, 1.44 and 2.16 cm were used. The electrodes were 30.5 cm long, made of copper and mounted horizontally with the cathode above. The current was fed in from one end of the electrodes so that the self-field effect was present. In a few tests the current was fed in opposite ends of the anode and the cathode with no change in results. Photographic equipment was used to take high-speed pictures of the arc at 7,000, 14,000 and 26,000 frames/sec from both the side and the upstream end of the rails. These photographs showed that the arc shape was very complex with the formation of loops and helixes so that its length might be several times the electrode spacing. Stepping motion took place at both the cathode and the anode roots of the arc. The travelling arc velocity decreased with increasing electrode spacing and approached a limiting value at larger gaps. This indicated that the arc motion in small gaps may be dominated by electrode effects while at gaps greater than 2 cm interactions in the arc column dominate the motion. Two different electrode widths were used: 0.32 cm and 0.95 cm. The velocity was always less with the wider electrode width. The arc root tracks were observed, from microscopic examinations, to wander back and forth across the electrodes. Since there was more room for this transverse motion on the wider electrode this may have been the reason why the velocity was less for this case. The travelling arc velocity increased with both arc current and magnetic field. The form of this dependence was empirically expressed as $V = CI^{0.33}B^{0.61}$, where C is a constant depending on configuration. The arc voltage increased almost linearly with arc velocity. The arc characteristic (arc voltage vs. arc current) curves had a slightly negative slope. Other tests were made with an a.c. arc in a d.c. magnetic field, and a d.c. arc in an a.c. magnetic field.

Although most of the study was performed at reduced pressures, some of the tests of Rauchschindel (45) were performed at atmospheric pressure and are discussed here. Copper electrodes with spacings between 0.2 and 1.5 cm were used with direct currents from 10 to 150 A in external magnetic fields from 100 to 1000 G. The current was fed into both ends of the electrodes to eliminate the self-field. The average arc velocity was measured using photocells. The velocity decreased as the electrode spacing increased over the range studied. At atmospheric pressure the dependence on the prime variables was expressed as $V = KI^{a}B^{0.631}$, where K depended on the electrode spacing and had a value between 0.10 and 0.14 if I was in A, B in G and V in m/sec. The parameter "a" was a function of the arc current, decreasing from 0.55 to 0.45 as the current was increased from 20 to 150 A.

In the experiments of Spink and Guile (55) (also see pages 16 and 29) electrode spacings between 0.16 and 10.2 cm were used. The travelling arc velocity on polished brass electrodes generally decreased as the electrode spacing increased. However, above about 50 m/sec, where the travelling arc controlling processes appear to move from the arc roots to the arc column, there was a change from a decrease in velocity as the spacing was decreased from 6 to 2 cm, to an increase in velocity as the spacing was decreased. Thus, the decrease in velocity as the spacing increased occurred only in the column dominated arc. For currents less than about 3000 A with an external field of 320 G these effects produced a relative minimum in the velocity vs. spacing curves. (see Fig. 14) At spacings greater than approximately 6 cm the velocity was independent of the electrode spacing. Quite complex empirical equations were required to fit the data in these tests. The equations found were: $V = (1.5 + 86B)\ I^{(0.47 - 0.96B)}$, which was valid for $100 < I < 2000$ A for B = 0.021 w/m^2 and $100 < I < 800$ A for B = 0.128 w/m^2; and $V = (1.5 + 246B)\ I^{(0.36 - 1.18B)}$, which was valid for $800 < I < 6000$ A for B = 0.128 w/m^2 and $1,200 < I < 20,000$ A for B = 0.032 w/m^2. The velocities are in m/sec when I is in amperes and B in w/m^2.

CHANNEL VARIABLES

The effect of side walls on the motion of the travelling arc in an external magnetic field has been studied in three different experiments. The results of experiments on a travelling arc in different gases at pressures above atmospheric are also presented in this section.

Travelling arc studies at pressures above atmospheric were performed by Walker and Early (57). This preliminary series of tests was performed at pressure levels of 1, 10, 20, and 30 atmospheres in air and helium. The arc current was quite low--between 1 and 5 A. Magnetic field strengths between 3000 and 7000 G were produced by an iron-core electromagnet. Copper electrodes, 16.5 cm long, were mounted horizontally, anode above the cathode, and curved toward each other at one end to facilitate initiating the arc. Their straight portions were parallel and 5.08 cm apart. Although a high-speed Fastax camera was used to photograph the arc in some of the tests, the arc velocity was measured from oscilloscope traces of the arc current on which the time between arc ignition and extinction could be measured. Thus, only an average travelling arc velocity was obtained. Atmospheric pressure tests in air produced a velocity of 24.4 m/sec at I = 0.3 A, B = 3500 G and a velocity of 44.3 m/sec at I = 4.9 A and B = 6000 G. The high pressure tests were made inside a 8.25 cm diameter pressure cylinder. Results in helium at current levels of 2 and 4 A at three different magnetic field strengths (3500, 6000, 6800 G) appeared to show a linear increase of velocity with increasing magnetic field strength. Velocities up to 180 m/sec were observed. The travelling arc velocity decreased as the pressure increased. The arc in helium travelled in a much more uniform manner than in air. In air the arc behavior was so erratic that it was difficult to obtain satisfactory data. The results in air showed velocities 5 to 10 times less than in helium and a decrease in velocity with increased pressure. Some tests were attempted at higher current levels but were difficult to interpret and were therefore abandoned.

Angelopoulos (3) performed experiments on arcs moving upward between vertical, parallel, copper rails with and without side walls. The current was fed in one end of the electrodes so that the self-field effect was present. The electrode spacing was not given. The travelling arc velocity was measured photographically at 3600 frames/sec. In the portion of the study in which no side walls were used, direct currents between 85 and 980 A were used and an iron-core electromagnet of special design produced magnetic field strengths from 1000 to 4000 G. It was observed that the arc roots travelled more irregularly at lower currents, with the arc column forming loops and deviating greatly from the shape of a right circular cylinder. The polarity influence was small with the cathode root only slightly lagging the anode root. A maximum velocity of 250 m/sec was observed at 980 A and 4000 G. Repeated arc ignitions on the rails occurred at higher currents, preventing extension of the tests to higher velocities. In the tests with side walls, one wall was made of fiber and the other of plexiglass to facilitate observation. The wall spacing was 0.4 cm. These tests were performed over a current range of 80 to 1800 A and magnetic field strengths from 500 to 5000 G. The presence of the walls caused the arc column to be nearly straight, but caused the cathode root to lag the anode root more than without walls. The walls caused the roots to move much more continuously and prevented sticking. Repeated arc ignitions did not occur below a current of 1800 A when side walls were used. At this value of current with a magnetic field strength of 3800 G a maximum velocity of 530 m/sec was observed. The travelling arc velocity increased with either an increase in current or magnetic field strength and was approximately 50% greater than without side walls. The arc potential gradient (including the electrode potential drops) increased somewhat more rapidly than the linear dependence on velocity which was reported by Bronn and Roman. The conducting cylinder with aerodynamic drag model was used to analyze the results. A value for the self-magnetic field was added to the external magnetic field value to give an approximate correction for this effect. The arc diameter was not photographically measured. The arc diameter was assumed to be equal to the wall spacing, resulting in a drag coefficient between 6.7 and 10.1. This is higher than most others reported and does not agree with the values of von Engle and Steenbeck* (C_D between 0.4 and 0.9) as was reported by Angelopoulos. By assuming that the drag coefficient remained constant, it was concluded that the arc diameter decreased as the current decreased and the velocity increased.

The experiments of Féchant (18) were performed on a travelling arc between 1 m long, vertical, parallel, copper electrodes. Currents between 300 and 6000 A were used with magnetic fields between 20 and 5000 G to produce

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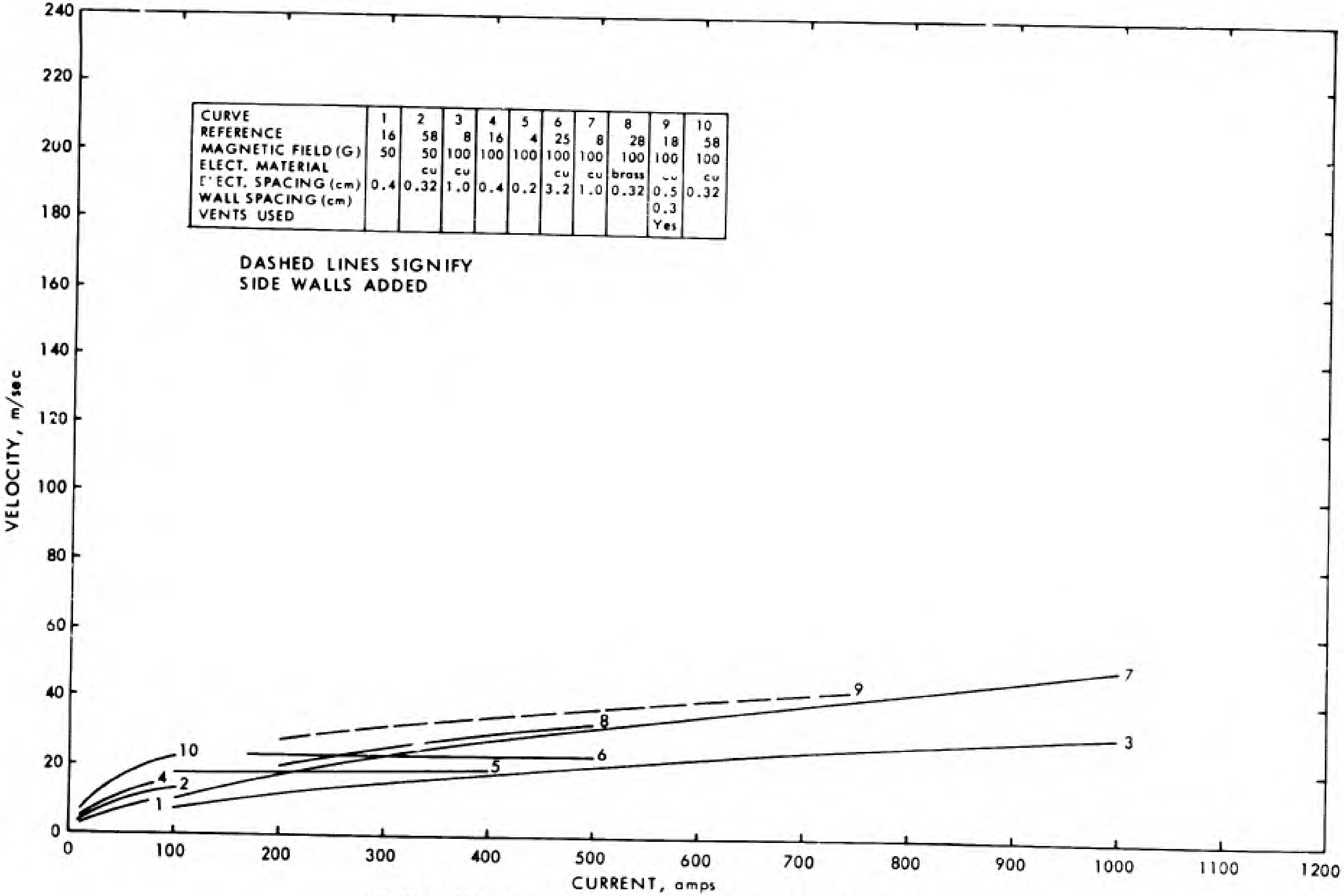
*von Engel, A., and M. Steenbeck, Elektrische Gasentladungen, Vol. 2, Springer-Verlag, Berlin, p. 151 (1934).

travelling arc velocities up to 500 m/sec. The electrode spacing was variable between 0.09 and 1.3 cm. The velocity was measured by means of an electric pickup located along the electrodes. The self-field was eliminated so that only the external magnetic field had an effect on the arc motion. With a completely closed arc channel the arc movement was not very regular and there was considerable sticking at an electrode spacing of 0.5 cm. However, by increasing the electrode spacing to 0.55 cm, providing a 0.05 cm vent between the walls and one electrode, regular movement occurred. In subsequent tests the channel walls were made of spaced partitions such that each wall consisted of three slabs of insulating material with vents located on either side of the center wall slab. Wall widths between 0.15 and 0.5 cm were used in this configuration. Decreasing the spacing between the walls increased the travelling arc velocity significantly. The travelling arc velocity was not as sensitive to changes in the electrode spacing at the longer electrode spacings although the velocity was less at the longer spacings. The conducting cylinder model was used to analyze the arc motion in spite of its limitations. By assuming the arc diameter equal to the wall spacing, drag coefficients between 1.5 and 5 were estimated, increasing with increasing current and decreasing wall spacing.

While Angelopoulos noted an increase in velocity when walls were added and Féchant noted that the velocity increased with narrower wall spacings, Roman (47) (also see page 33) found that the addition of side walls caused a uniform downward displacement of about 10 m/sec in the travelling arc velocity. Vycor side walls spaced 0.95 cm (3/8 in.) apart had the effect of making the arc appear more diffuse. The cause for the difference in behavior with the addition of side walls may have been due to the much wider wall spacing used by Roman. However, no single investigator has examined the effect of varying the wall spacing over a wide range. The results of these three investigators make it appear that wide walls reduce the velocity below what it would be without side walls while narrow walls increase it. Thus for a certain wall spacing, depending on the operating conditions, the addition of side walls might have no effect.

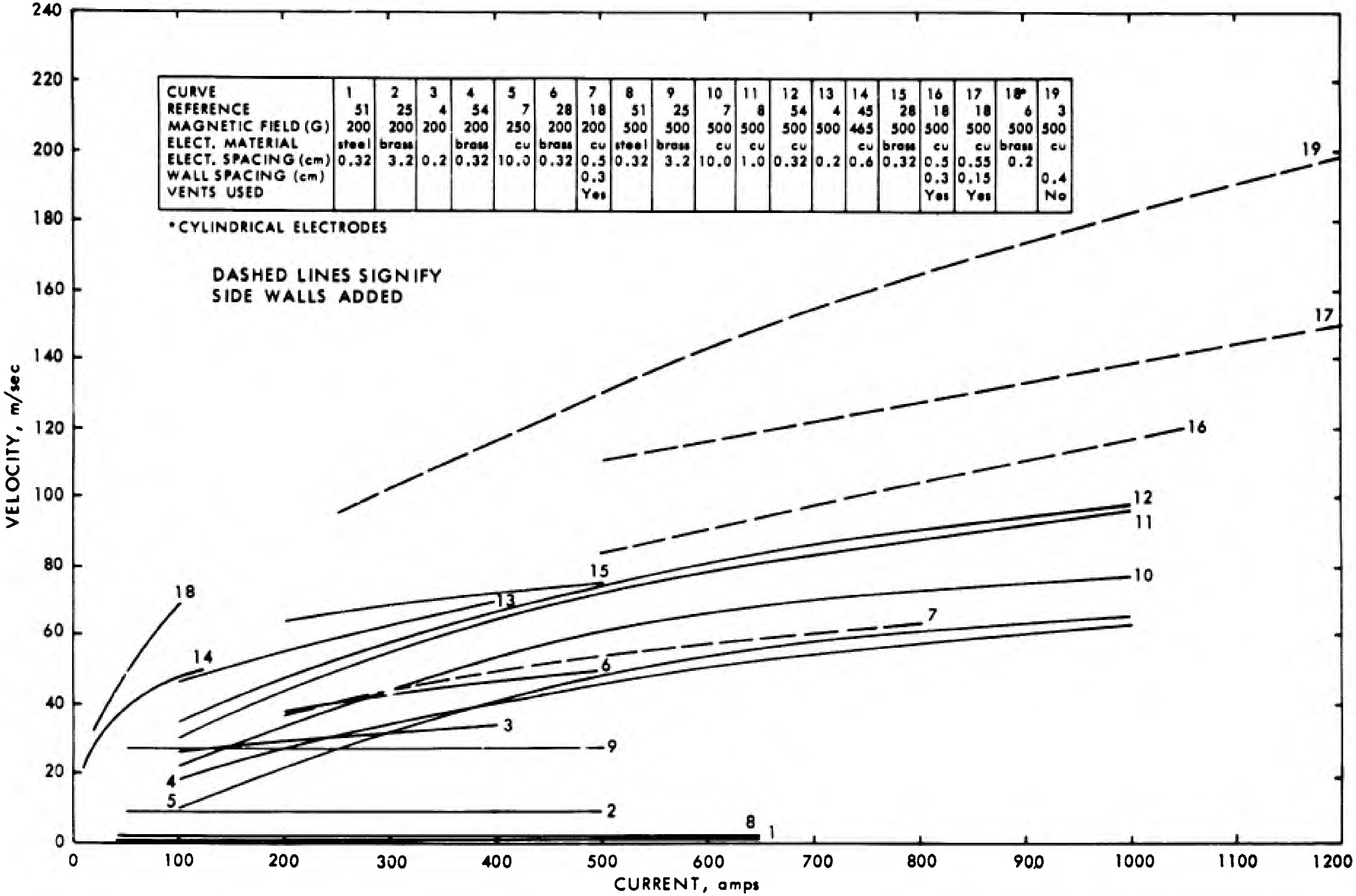
SUMMARY

The experimental results of the investigations of a travelling arc on parallel rails in an external magnetic field are graphically condensed in Figures 6 through 14. Figures 6 through 8 show the travelling arc velocity as a function of the current with the magnetic field as a parameter, while in Figures 9 through 13 the velocity is plotted as a function of the magnetic field with the current as a parameter. Although the results of different experiments differ considerably due to the different conditions imposed, several generalizations can be made from these data. The V vs. I curves are more nearly parabolic than they were for the self-field results in which V was linearly dependent on I. On a log-log plot of the V vs. I curves, nearly all of the data appear as straight lines with the majority of the slopes falling between 0.40 and 0.50. The early results of Secker and Guile (26, 50, 51) in which V was found to be independent of I are in variance with this dependence; however, these results are probably in error due to the relatively slow photographic speeds used to determine the arc velocity. Later measurements



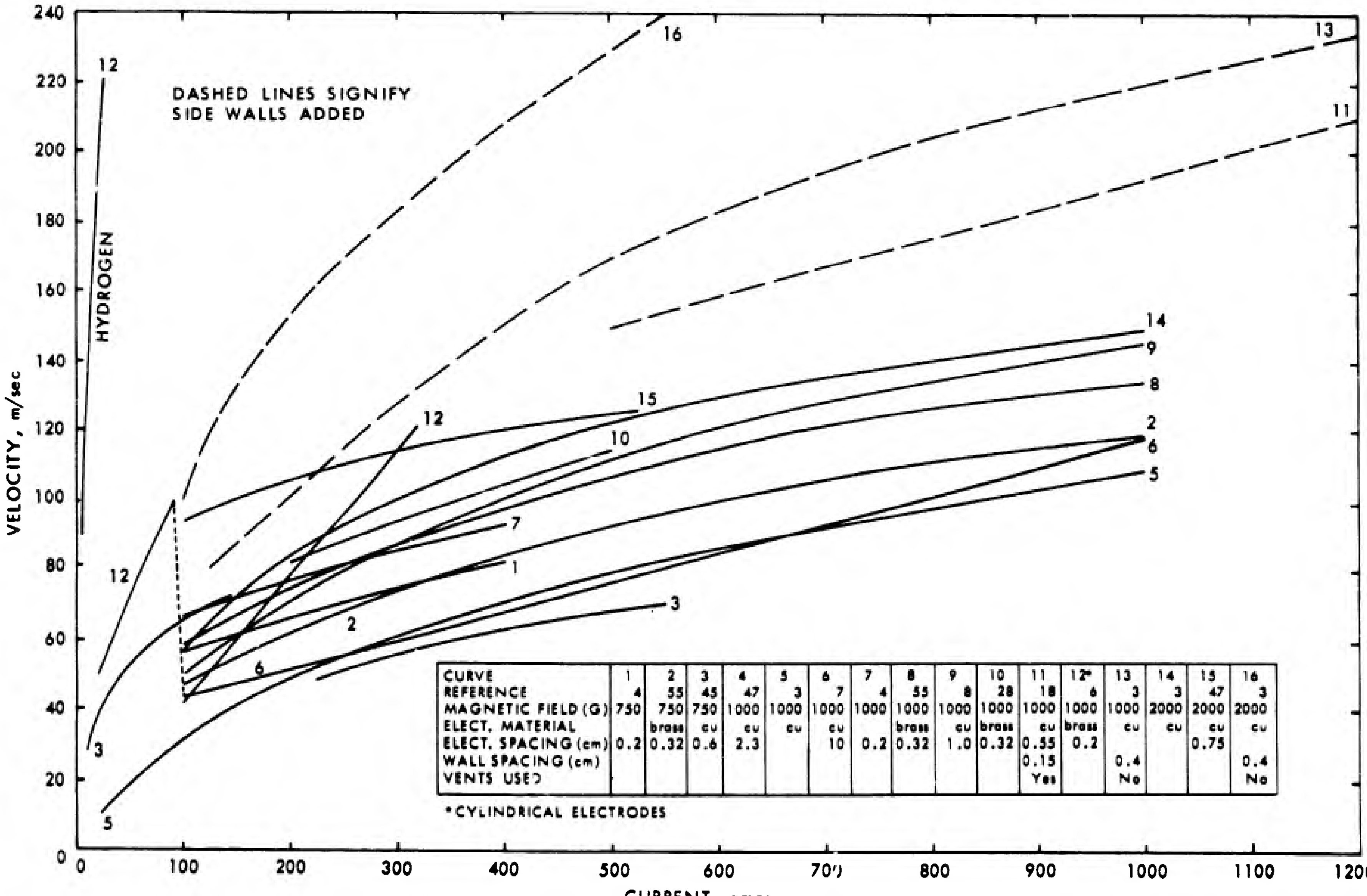
CURVE	1	2	3	4	5	6	7	8	9	10
REFERENCE	16	58	8	16	4	25	8	28	18	58
MAGNETIC FIELD (G)	50	50	100	100	100	100	100	100	100	100
ELECT. MATERIAL		cu	cu			cu	cu	brass	cu	cu
ELECT. SPACING (cm)	0.4	0.32	1.0	0.4	0.2	3.2	1.0	0.32	0.5	0.32
WALL SPACING (cm)									0.3	
VENTS USED									Yes	

FIGURE 6 - DEPENDENCE OF TRAVELLING ARC VELOCITY ON CURRENT FOR MAGNETIC FIELDS OF 50 AND 100 GAUSS



CURVE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18*	19
REFERENCE	51	25	4	54	7	28	18	51	25	7	8	54	4	45	28	18	18	6	3
MAGNETIC FIELD (G)	200	200	200	200	250	200	200	500	500	500	500	500	500	465	500	500	500	500	500
ELECT. MATERIAL	steel	brass		brass	cu	brass	cu	steel	brass	cu	cu	cu		cu	brass	cu	cu	brass	cu
ELECT. SPACING (cm)	0.32	3.2	0.2	0.32	10.0	0.32	0.5	0.32	3.2	10.0	1.0	0.32	0.2	0.6	0.32	0.5	0.55	0.2	
WALL SPACING (cm)							0.3									0.3	0.15		0.4
VENTS USED							Yes									Yes	Yes		No

FIGURE 7 - DEPENDENCE OF TRAVELLING ARC VELOCITY ON CURRENT FOR MAGNETIC FIELDS OF 200 AND 500 GAUSS



CURVE	1	2	3	4	5	6	7	8	9	10	11	12*	13	14	15	16
REFERENCE	4	55	45	47	3	7	4	55	8	28	18	6	3	3	47	3
MAGNETIC FIELD (G)	750	750	750	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	2000	2000	2000
ELECT. MATERIAL		brass	cu	cu	cu	cu		brass	cu	brass	cu	brass	cu	cu	cu	cu
ELECT. SPACING (cm)	0.2	0.32	0.6	2.3		10	0.2	0.32	1.0	0.32	0.55	0.2			0.75	
WALL SPACING (cm)											0.15		0.4			0.4
VENTS USED											Yes		No			No

*CYLINDRICAL ELECTRODES

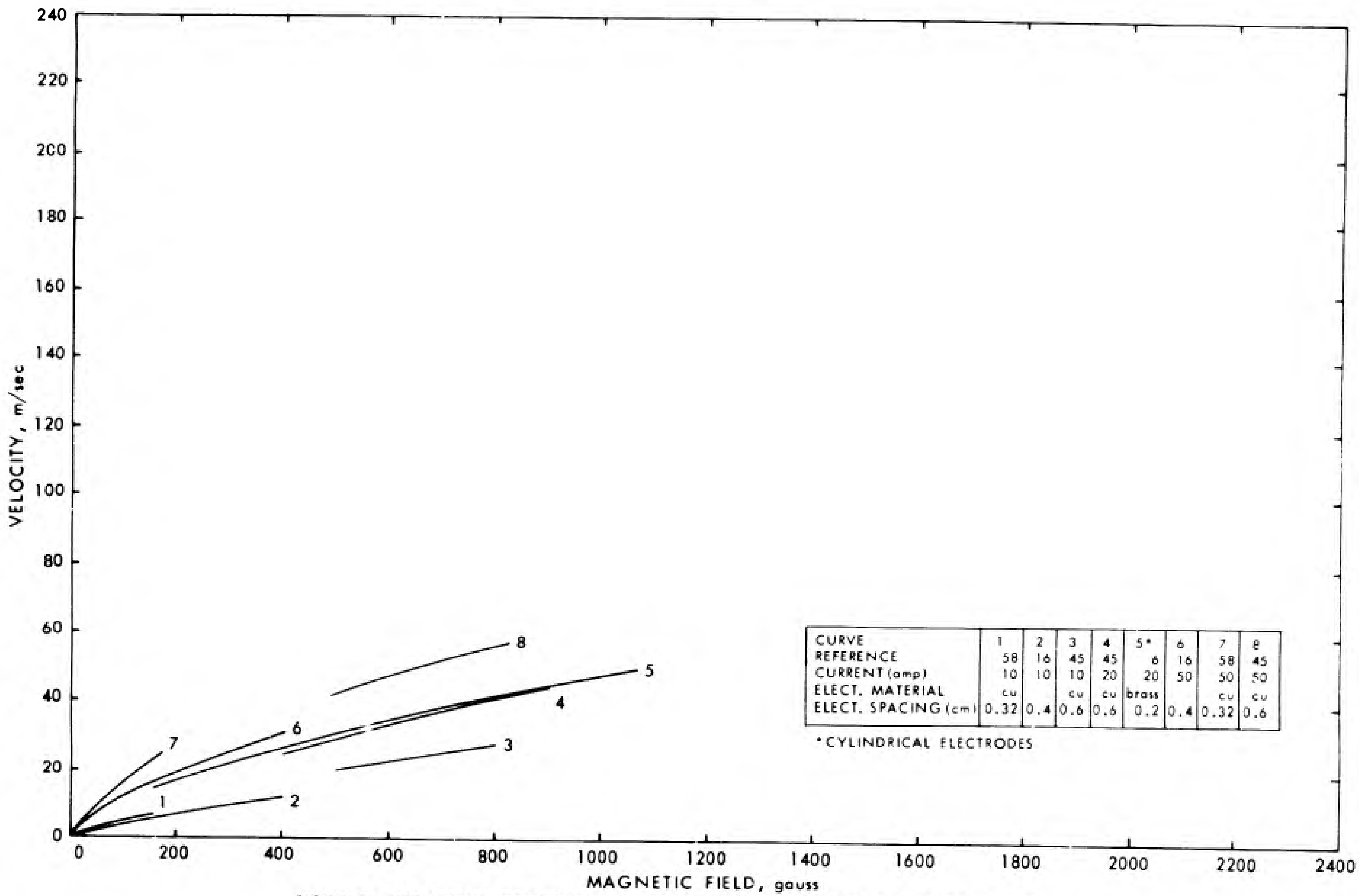
FIGURE 8 - DEPENDENCE OF TRAVELLING ARC VELOCITY ON CURRENT FOR MAGNETIC FIELDS OF 750, 1000 AND 2000 GAUSS

utilizing streak photography were felt to be much more accurate (27, 28, 55).

The plots of the velocity as a function of the magnetic field are quite similar in shape to the V vs. I curves. The considerable variance between the different V vs. B curves is due to the different conditions imposed. A log-log plot of these data shows an approximately constant slope between 0.55 to 0.65 for the majority of the results. Thus, the approximate overall behavior of the travelling arc appears to be given by the conducting cylinder with aerodynamic drag analogy. As was discussed by Rieder & Eidinger (46) the power on I would be expected to be smaller than on B since the arc diameter increases with increasing I. Of course, if the diameter was independently measured and used in the conducting cylinder model equation, the velocity would be expected to be more nearly proportional to the square root of the BI product. Use of this model, however, gave cross-flow drag coefficients nearer to 5 than the unity value which has been obtained for a cold cylinder (laminar boundary layer) in cross-flow (3,18). It must be emphasized that the conducting cylinder analogy would only be expected to apply where the arc column is fairly straight. Shapes such as those photographed and described by Roman (47) would certainly invalidate the model. Also, the considerable work of Guile, et. al., indicates that below a certain travelling arc velocity (about 50 m/sec) the conducting cylinder model is invalid due to the processes which control the arc motion shifting from the arc column (above 50 m/sec) to the electrode regions (below 50 m/sec).

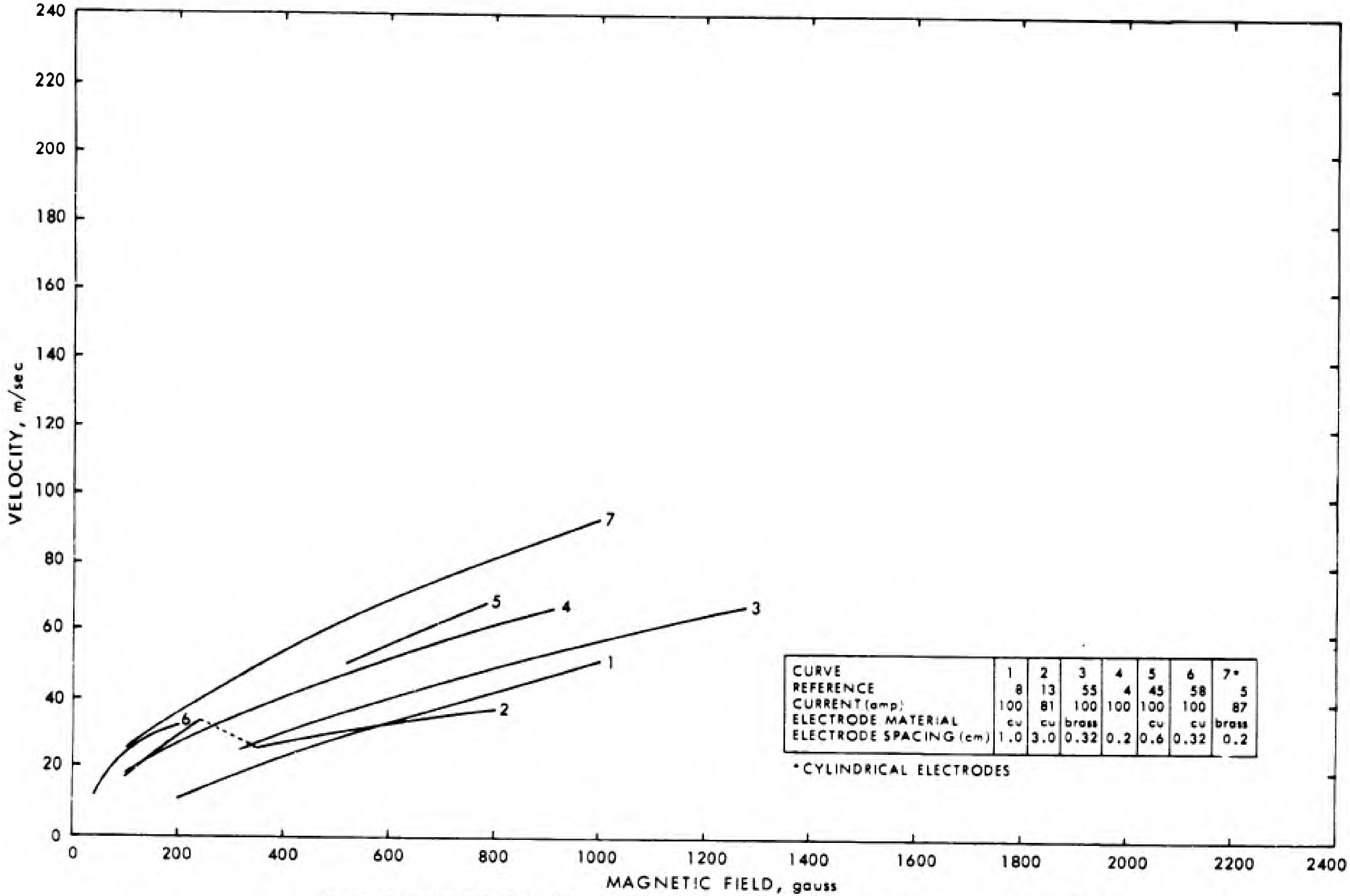
Conditions at the electrodes affect the arc motion over its entire range, but their influence becomes significantly less at higher velocities. The velocity is greater on non-ferrous materials than on ferrous materials (51,55), indicating that the field at or immediately outside the electrode surface has the predominant effect on the arc motion. The cathode material appears to have a greater influence on the arc behavior than the anode material (55). More than one attachment spot often occurs at both electrodes, with multiple anode spots being more prevalent (13, 47). The velocity is dependent on the surface condition, increasing as the electrode surface is polished, or longitudinally scratched (13, 55). The velocity of the arc increases with the oxidation time of the electrodes, indicating the importance of the cathode oxide layer in determining the arc root motion (25, 55). The mode of motion of the arc roots over the electrodes changes as the velocity changes. In general, as the velocity increases, the mode of arc root travel changes from continuous with sticking, to intermittent with sticking, to high-speed continuous with little electrode erosion, to high-speed intermittent (or random) motion with little erosion (50, 51). The changes from mode to mode do not necessarily occur at the same velocity on both electrodes.

The effects of the geometric and orientation factors are quite similar to those for the arc driven by its self-field. Above a certain electrode spacing (about 0.5 cm) the velocity decreases with increasing electrode spacing. This variation appears to be primarily due to an increase in column drag because of a greater arc diameter and the tendency of the arc to form loops and helixes at the wider electrode gaps (7, 8, 9, 47). (In some of the tests the self-field and its dependence on the electrode spacing were not completely eliminated, causing part of the de-



CURVE REFERENCE	1	2	3	4	5*	6	7	8
	58	16	45	45	6	16	58	45
CURRENT (amp)	10	10	10	20	20	50	50	50
ELECT. MATERIAL	cu		cu	cu	brass		cu	cu
ELECT. SPACING (cm)	0.32	0.4	0.6	0.6	0.2	0.4	0.32	0.6

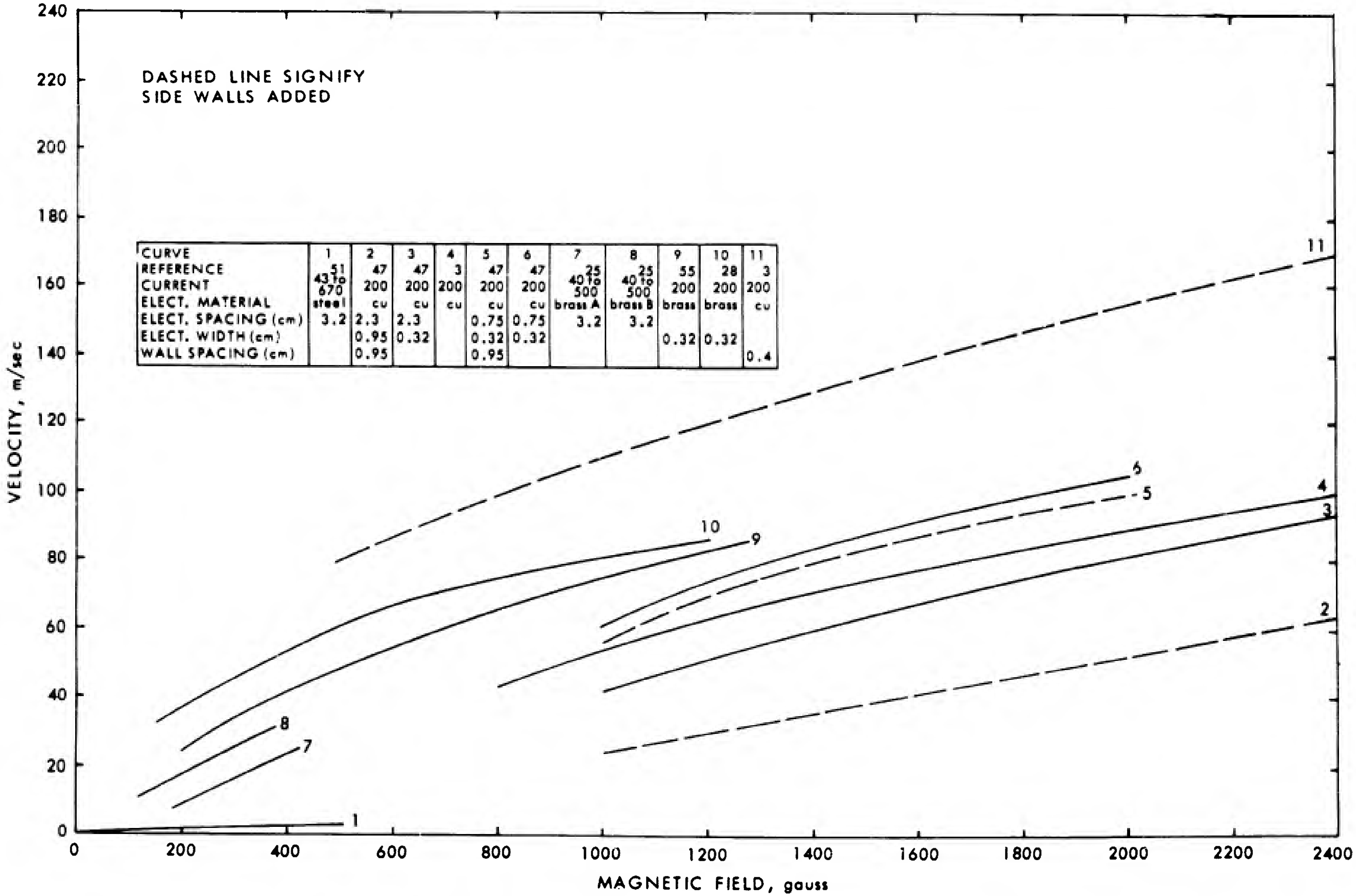
FIGURE 9 - DEPENDENCE OF TRAVELLING ARC VELOCITY ON MAGNETIC FIELD FOR CURRENTS OF 10, 20 AND 50 AMPERES



CURVE	1	2	3	4	5	6	7*
REFERENCE	8	13	55	4	45	58	5
CURRENT (amp)	100	81	100	100	100	100	87
ELECTRODE MATERIAL	cu	cu	brass		cu	cu	brass
ELECTRODE SPACING (cm)	1.0	3.0	0.32	0.2	0.6	0.32	0.2

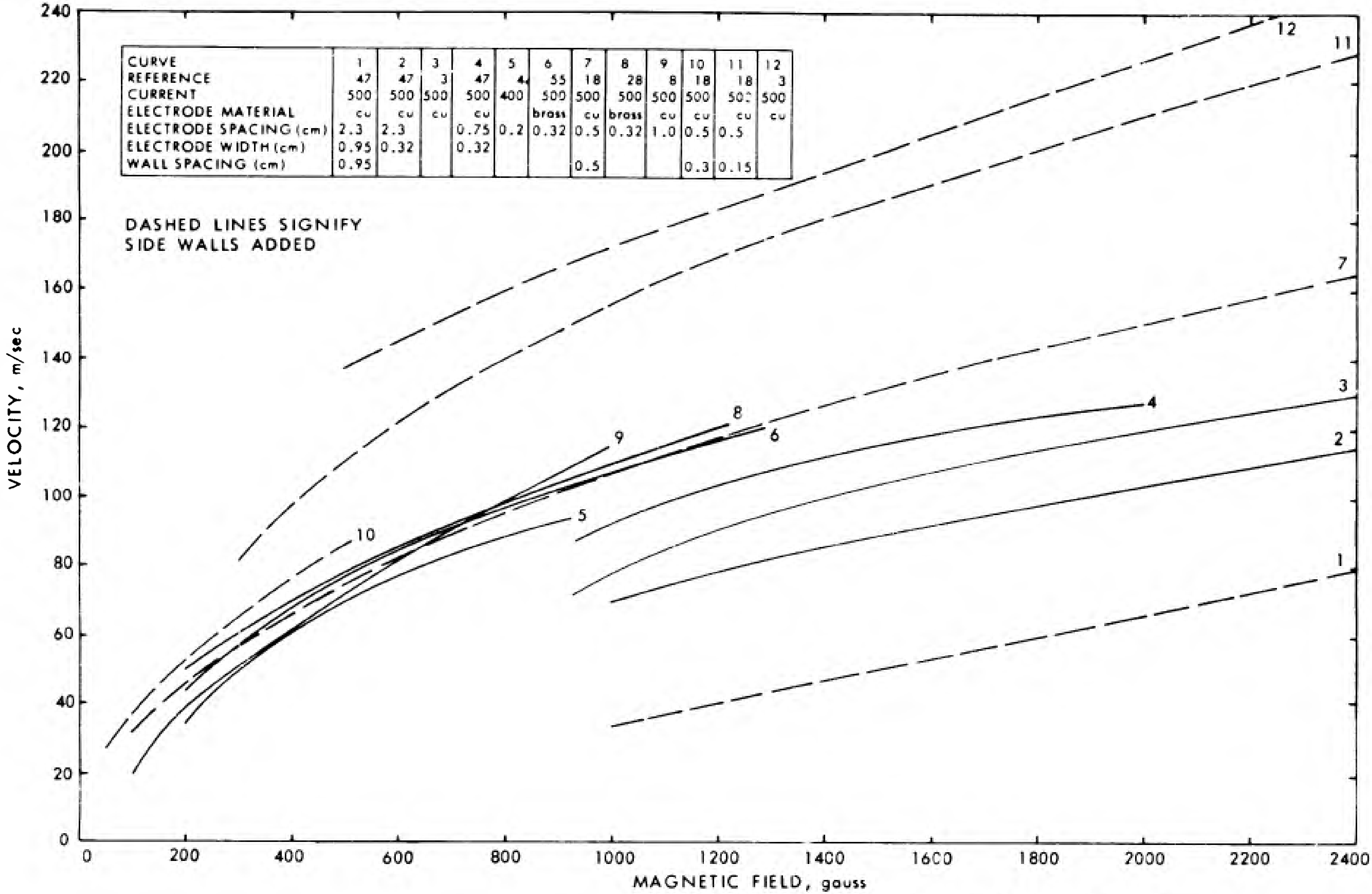
*CYLINDRICAL ELECTRODES

FIGURE 10 - DEPENDENCE OF TRAVELLING AF 'ELOCITY ON MAGNETIC FIELD FOR CURRENTS OF APPROXIMATELY 100 AMPERES



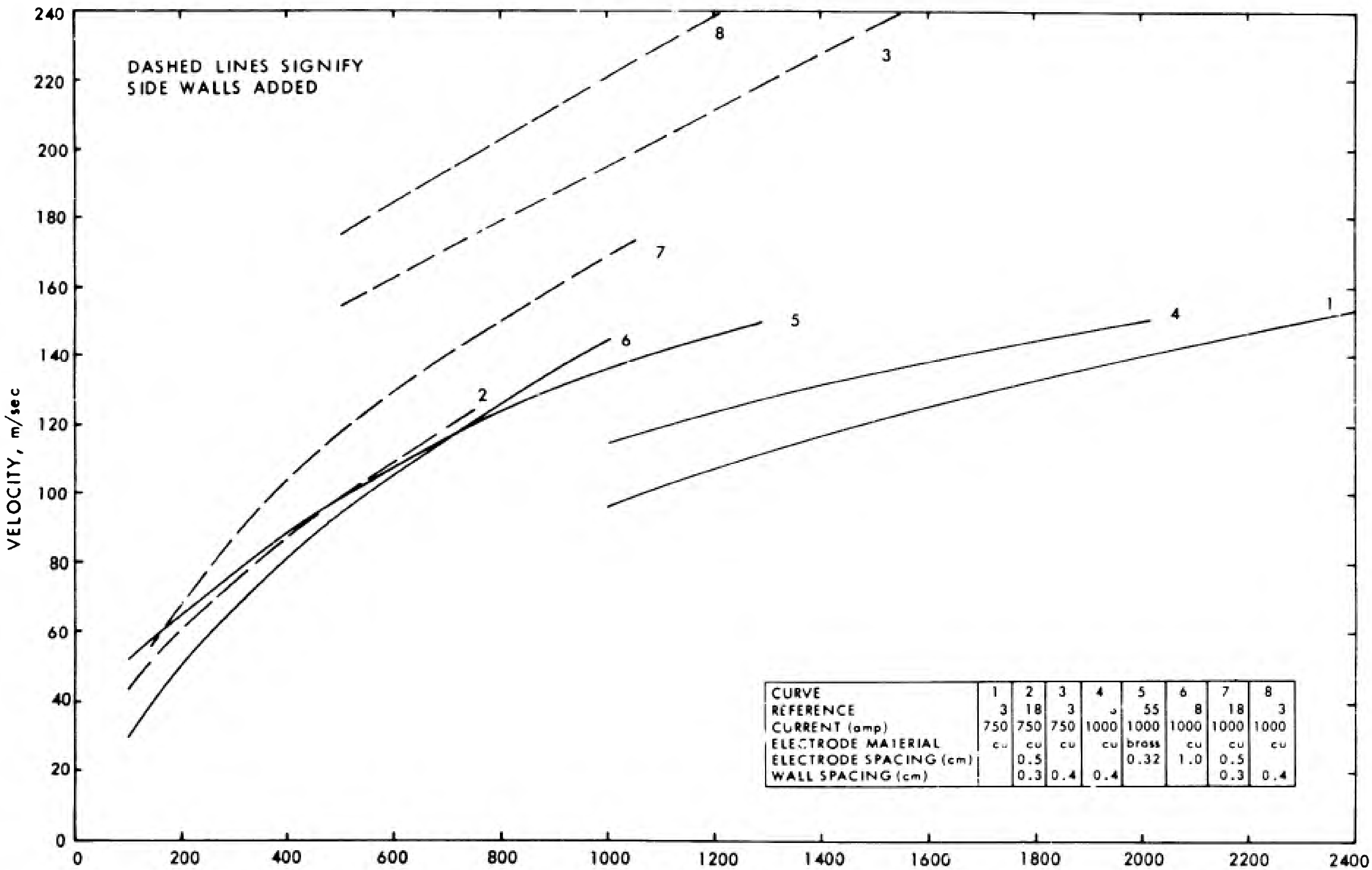
CURVE	1	2	3	4	5	6	7	8	9	10	11
REFERENCE	51	47	47	3	47	47	25	25	55	28	3
CURRENT	43 to 670	200	200	200	200	200	40 to 500	40 to 500	200	200	200
ELECT. MATERIAL	steel	cu	cu	cu	cu	cu	brass A	brass B	brass	brass	cu
ELECT. SPACING (cm)	3.2	2.3	2.3		0.75	0.75	3.2	3.2			
ELECT. WIDTH (cm)		0.95	0.32		0.32	0.32			0.32	0.32	
WALL SPACING (cm)		0.95			0.95						0.4

FIGURE 11 - DEPENDENCE OF TRAVELLING ARC VELOCITY ON MAGNETIC FIELD FOR CURRENTS BETWEEN 43 AND 670 AMPERES AND AT CURRENTS OF 200 AMPERES



CURVE	1	2	3	4	5	6	7	8	9	10	11	12
REFERENCE	47	47	3	47	4	55	18	28	8	18	18	3
CURRENT	500	500	500	500	400	500	500	500	500	500	500	500
ELECTRODE MATERIAL	cu	cu	cu	cu		brass	cu	brass	cu	cu	cu	cu
ELECTRODE SPACING (cm)	2.3	2.3		0.75	0.2	0.32	0.5	0.32	1.0	0.5	0.5	
ELECTRODE WIDTH (cm)	0.95	0.32		0.32								
WALL SPACING (cm)	0.95						0.5			0.3	0.15	

FIGURE 12 - DEPENDENCE OF TRAVELLING ARC VELOCITY ON MAGNETIC FIELD FOR CURRENTS OF 400 AND 500 AMPERES



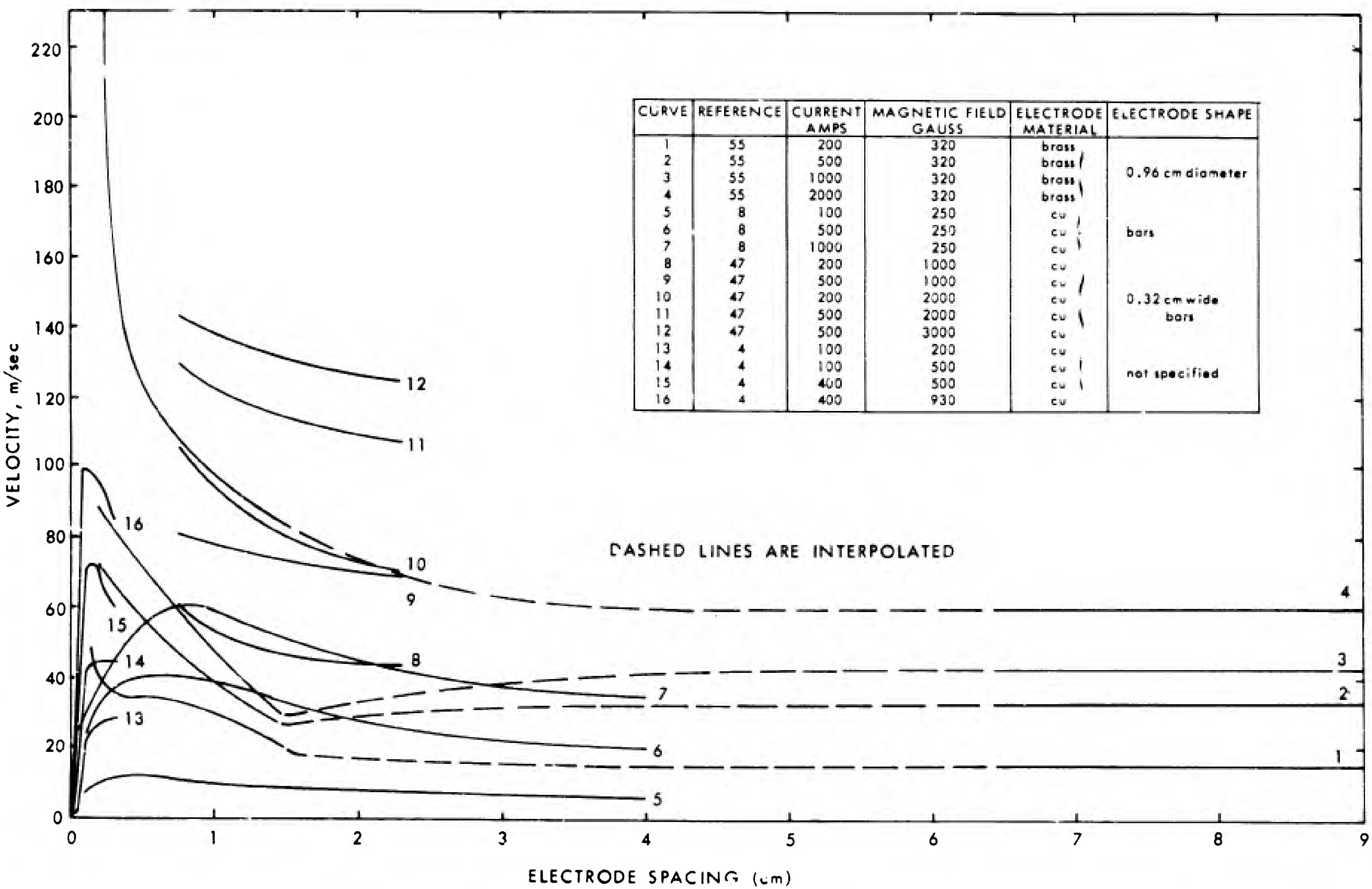
MAGNETIC FIELD, gauss

FIGURE 13 - DEPENDENCE OF TRAVELLING ARC VELOCITY ON MAGNETIC FIELD FOR CURRENTS OF 750 AND 1000 AMPERES

crease in velocity with increasing spacing). The dependence of the arc velocity on the electrode spacing is shown in Fig. 14. For gaps greater than about 3 cm the effect of the electrode spacing appears to be negligible. At gaps less than about 1 cm electrode effects are more dominant in determining the arc motion at any velocity and may entirely control the motion at spacings less than 0.2 cm (4, 47). The arc velocity increases as the electrode width is decreased (4,47). The arc voltage has been reported to increase approximately linearly with the arc velocity (3, 8, 47).

Adding insulating side walls may increase the arc velocity by about 50% (3). The velocity also increases as the wall spacing is decreased (18). These results appear to be because the narrow wall spacings (less than 0.5 cm) kept the arc column straighter, lessening its aerodynamic drag. These results agree, in general, with the effect of the walls on the arc driven by its self-field. The slight decrease in velocity with the addition of walls reported by Roman (47) was at a wider wall spacing (1 cm).

In the one test where its effect was studied, the arc velocity decreased as the pressure increased (57).



CURVE	REFERENCE	CURRENT AMPS	MAGNETIC FIELD GAUSS	ELECTRODE MATERIAL	ELECTRODE SHAPE
1	55	200	320	brass	
2	55	500	320	brass	0.96 cm diameter
3	55	1000	320	brass	
4	55	2000	320	brass	
5	8	100	250	cu	
6	8	500	250	cu	bars
7	8	1000	250	cu	
8	47	200	1000	cu	
9	47	500	1000	cu	
10	47	200	2000	cu	0.32 cm wide bars
11	47	500	2000	cu	
12	47	500	3000	cu	
13	4	100	200	cu	
14	4	100	500	cu	not specified
15	4	400	500	cu	
16	4	400	930	cu	

FIGURE 14 - DEPENDENCE OF TRAVELLING ARC VELOCITY ON ELECTRODE SPACING--EXTERNAL FIELD USED

SECTION IV. CYLINDRICAL RING ELECTRODES

One of the configurations which may be used to investigate the continuous motion of the travelling arc is that obtained by causing the arc to run between the ends of two opposed cylinders of the same size (Fig. 1-C). The transverse magnetic field necessary to move the arc is created by two opposed magnet poles located inside the cylinders. This produces a radially diverging magnetic field which is approximately constant across the width of the cylindrical electrodes and always perpendicular to the arc column and the direction of the arc motion. Except for the continuous arc motion which is now possible, this configuration is geometrically similar to that of the travelling arc on parallel rails.

Stolt (56) discussed the travelling arc experiments performed previous to 1924. He examined the travelling arc between cylindrical electrodes at low values of the direct current (0.5 to 12 A) and magnetic field (15-150 G). Velocities up to 2.2 m/sec were observed. Electrodes of copper, gold, silver, aluminum, and carbon were used. The electrode spacings were varied from 0.2 to 0.67 cm with the top electrode being the anode. In each test the electrode surface was first polished with fine sandpaper. The average arc velocity over one revolution was obtained photographically. The anode root appeared larger than the cathode root and the arc tended to run on the outer edge of the cylindrical electrodes. The motion was quite sensitive to electrode irregularities and the travelling velocity increased with running time (runs up to 5 minutes were made). For low velocities the arc was inclined to the electrodes with the cathode root leading. An arc could not be obtained with both electrodes of aluminum or carbon, but could be obtained with these materials as anodes if other materials were used for the cathode. The results indicated that the travelling arc velocity is determined by the anode material at currents above 2 A, conflicting with the rail results described in the previous sections. Below this current the velocity was independent of the electrode material. The velocity decreased as a function of anode material in the following order: carbon, silver, gold, copper, and aluminum. The velocity with an aluminum anode was considerably lower at the same magnetic field and current than for the other materials. The travelling arc velocity decreased as the electrode spacing increased. The arc characteristic curves (voltage-current plots) show a positive slope in contrast to the negative slope of a free-burning arc characteristic curve.

Ramberg (44) performed studies on an arc rotating between the ends of opposed cylinders. A magnetic field of 85 G, currents up to 2.5 A, and copper electrodes with spacings between 0.2 and 0.3 cm, were used. Velocities up to 2.5 m/sec were deduced from the voltage fluctuations. Arc characteristic curves at different conditions constitute the main body of data taken. These characteristic curves had a negative slope in contrast to the positive slope reported by Stolt. The arc voltage appeared to be independent of the velocity above 1 m/sec. Experiments were also performed using a 3.9 cm diameter rotating copper disc as the cathode opposite a stationary anode which was oriented perpendicular to the axis of the rotating disc. The arc was maintained between the edge of the rotating cathode and the anode. For the same cathode rotational velocity as for the travelling arc the arc voltage was found to be about 25% less. This extra power required for the travelling arc represented the sum of the convection losses from the arc column and the power required to move the anode attachment region.

Sodtke (54) used a cylindrical carbon cathode and a water-cooled copper anode spaced 1.1 cm apart with direct currents up to 25 A. The cathode inner and outer diameters were 1.0 and 1.2 cm, respectively. Magnetic field strengths up to 100 G were used. An iron-core electromagnet was located only inside the cathode, rather than inside both the cathode and anode as shown in Fig. 1-C. The rotational frequency of the arc was determined photographically (16 frames/sec). The travelling arc velocity depended on the number of cathode spots. (Actually only the rotational frequency is given in this paper, but by using the cathode dimensions, the maximum average velocity was calculated to be about 4 cm/sec.) The velocity increased approximately linearly with the arc current and the external magnetic field, but only if the number of cathode spots did not change. There was always a drop to a lower velocity (other variables constant) when an additional cathode spot was formed. Curves of rotational frequency vs. magnetic field were obtained for 1,2,3 and 4 cathode spots, with the above behavior always present. The arc voltage decreased as each additional cathode spot was formed. The empirical relation found for the velocity was $V = \frac{I \cdot B}{n \, \Phi(n)}$, where n is the number of spots and $\Phi(n)$ is a function which depended on the number of spots. The low velocities and the use of a carbon cathode make it difficult to compare this work with other experiments.

The travelling arc between cylindrical brass electrodes was studied by Blix and Guile (5,6) at pressures from 0.26 to 14 atmospheres in air, with a few tests also being run in hydrogen, nitrogen, and sulphur hexaflouride. The electrodes had a 16.2 cm mean diameter, a 1 cm square cross-section and were 0.2 cm apart in all of the tests. Direct currents up to 400 A and magnetic fields up to 1060 G produced travelling arc velocities up to 150 m/sec. The average arc velocity over one revolution was measured using photocells. The results obtained were for well "run-in" electrodes. These tests showed a new result not reported elsewhere. At a current of about 80 A, irregardless of pressure, the travelling arc velocity suddenly dropped with an increase in current. The magnitude of this drop was quite large. For instance, in atmospheric air the velocity dropped from 100 to 40 m/sec at this transition. More than one transition was noted for this short arc. An earlier transition from a diffuse arc to a cored arc at magnetic fields between 340 and 1060 G occurred at about 5 A (as the current was increased) in nitrogen and air. This transition was thought to be due to the increased heat conduction loss from the arc at higher velocities and the axial conduction losses from the arc to the electrodes. The second transition back to a diffuse arc at about 80 A was thought to be due to the arc core in air and nitrogen reaching a high enough temperature (about 20,000°K) that the electrical conductivity increased relatively little with temperature. This caused the arc radius to increase much more rapidly as the current was increased, creating a larger or more diffuse arc. The behavior of the arc was compared to theories based on the conducting cylinder arc column model. The relation between the velocity and the current, magnetic field, and pressure for air, nitrogen, hydrogen and sulphur hexaflouride was $V = I^a B^b p^{-c}$, where "a" (except for SF_6 for which it was between 0.13 and 0.18) varied between 0.30 and 0.96, "b" between 0.44 and 0.68 and "c" between 0.38 and 0.57. The dependence on the relative gas density for the 4 different gases was checked. The velocity was proportional to the density to the exponent -0.57, which compares well with the theoretical -0.50 dependence. From this approximate agreement with the conducting cylinder model, it was concluded that even though the electrode spacing was quite small, the arc motion was column dominated. This was thought to be because the repeated motion over the electrodes suppressed the cathode effect. However, applying the conducting cylinder model to calculate the arc radius, r, from $BI = C_D \rho V^2 r$, using C_D for a cylinder (0.63), produced surprisingly small values for r for currents below 80 A. For instance, in atmospheric pressure air, the arc radius was about 0.1 cm before the cored to diffuse transition at 80 A and 1 cm after it. This may be due to the arc travelling in its own wake or it may be an effect peculiar only to an arc operating at these narrow electrode spacings. The results of Blix and Guile are shown in Figures 7 through 10 along with the parallel rail data.

SECTION V. ANNULAR GAPS

The other configuration which may be used to study the continuous motion of the travelling arc is obtained by causing the arc to rotate in the annular gap between two concentric cylinders (Fig. 1-D). An external magnetic field is applied along the direction of the axis of the two cylinders. If the cylinders are short, the external field may be created by an electromagnet located on either side of the annular test region with its axis along the axis of the concentric electrodes. If the cylinders are long, the external magnetic field may be produced by a solenoidal winding around the cylindrical electrodes. Thus the field is always perpendicular to the direction of arc travel as well as the axis of the arc column. This configuration introduces one complication not present in those discussed previously, i.e., different portions of the arc must travel different distances to complete a cycle about the annular gap. This will produce complex arc shapes. When the arc shape is different from that of a radial spoke in the annular gap, the travelling arc velocity is not perpendicular to the arc column axis. This non-orthogonality was not present in the other configurations as a necessary consequence of the geometrical configuration. It only arose when the arc column took a complex shape of loops and helixes. Due to these factors, which somewhat complicate the analysis of the travelling arc in an annular gap, fewer studies have been performed than on the arc between parallel rails. However, the annular gap configuration has the advantages of continuous running and smaller size, as well as being more applicable to the design requirements of high-temperature gas heaters.

Walker and Early (57) (also see page 34) performed experiments on a travelling arc in an annular gap. The center electrode was a 0.635 cm diameter copper rod and the outer electrode was a copper plate with a 4.44 cm diameter hole. The external magnetic field of 5600 G was produced by an electromagnet. A 7800 frames/sec Fastax camera was used to photograph the arc. Direct currents of 7 and 12 A were used. With the center electrode positive (anode) the arc took a spiral shape (could also be described as the involute of a circle) and, for a current of 12 A, rotated at 2700 revolutions/second. This corresponded to a circumferential velocity of about 300 m/sec at the outer electrode. When the inner electrode was the cathode the arc column was somewhat straighter and travelled at only 2000 revolutions/second at a current of 12 A. This difference in behavior with polarity appeared to be due to the jet being more prominent at the cathode root than at the anode root.

Adams (1) performed an extensive set of experiments on the travelling arc in an annular gap between carbon electrodes. By changing the diameter of the electrodes, gap widths between 0.3 to 3.2 cm were obtained with a mean radius from 0.95 to 5.2 cm. The center electrode was the cathode in most of the tests. Direct currents from 100 to 750 A were used with magnetic fields from 60 to 940 G to produce rotational frequencies up to 4700 revolutions/second and cathode velocities up to 187 m/sec. The arc motion was studied photographically with a 16,000 frames/sec camera. With a constant annular gap of 0.65 cm, the empirical relationship between the principal variables was $V_c = 0.57\ B^{0.6}\ I^{0.33}$, where V_c is the cathode root velocity in m/sec, B is in G, and I is in A. With this constant annular gap the rotational frequency was inversely proportional to the mean radius of the gap, r, and V_c was proportional to $r^{-0.3}$. In tests with a 1.3 cm diameter cathode, gaps between 0.3 and 3.2 cm were obtained by varying the diameter of the outer electrode (anode). In this case, the rotational frequency was inversely proportional to r and thus the average velocity was independent of the gap width. By estimating the combined electrode drops to be 15 V and measuring an average arc length from the photographs, the potential gradient of the arc column was estimated to be proportional to $B^{0.27}$. This dependence of the gradient on the magnetic field might be due to several factors: increased convective energy loses at the higher velocity associated with the higher B, an increase in the arc length with B, and the effect of B on the arc column conductivity. It was concluded that the first effect was predominant. The studies of the arc shape revealed that the cathode led the anode and there was discontinuous anode motion with more than one anode spot often observed; the cathode motion was continuous. A conducting cylinder model was suggested and it was mentioned that the dependence of the arc diameter on the current and magnetic field would cause the exponent on B to be larger than on I as was found in the above empirical equation. The complication due to the travelling arc velocity being measured with respect to the electrodes rather than the gas in the annular gap was expected to cause deviations from the conducting cylinder model.

In a subsequent paper Adams (2) used the conducting cylinder model to calculate the shape of the travelling arc in an annular gap. The calculated arc shape was the involute of a circle. This compared very well with the arc shape photographed in the preceding tests. The departures from the involute shape were thought to be due to the arc rotating in its own turbulent wake, the plasma jet at the cathode root (estimated to be an order of magnitude higher than the travelling arc velocity), and the unsteadiness or intermittent motion at the anode. Because of the effect of the jets at the arc roots, an annular gap greater than 2 cm was necessary to experimentally obtain the involute shape. By estimating the travelling arc diameter from photographs, the drag coefficient, C_D, in the conducting cylinder model was estimated to be between 1 and 5. In a few tests, the electrode polarity was reversed to make the inner electrode the cathode; this had little effect on the overall shape.

The above theoretical analysis was extended by Shaw (53) to include the variation of the magnetic field strength over the annular gap. The variation of the magnetic field was taken to be of the form $B = a + br^n$, where r is the radius from the axis of the concentric cylinders and a, b and n are constants. The conducting cylinder model was used for the arc column. The involute shape was obtained if B was constant. For $B = br^n$, $(a = 0)$, the general solution gave two families of arc shapes depending on whether n was greater or less than two. For the case of $B = a + br^n$, no general solution was found, but there were again two families of arc shapes. For this general form of the magnetic field with certain values of a, b, and n the analysis indicated that part of the arc travels in one direction and part travels in the opposite direction around the annular gap. This type of motion has never been observed experimentally.

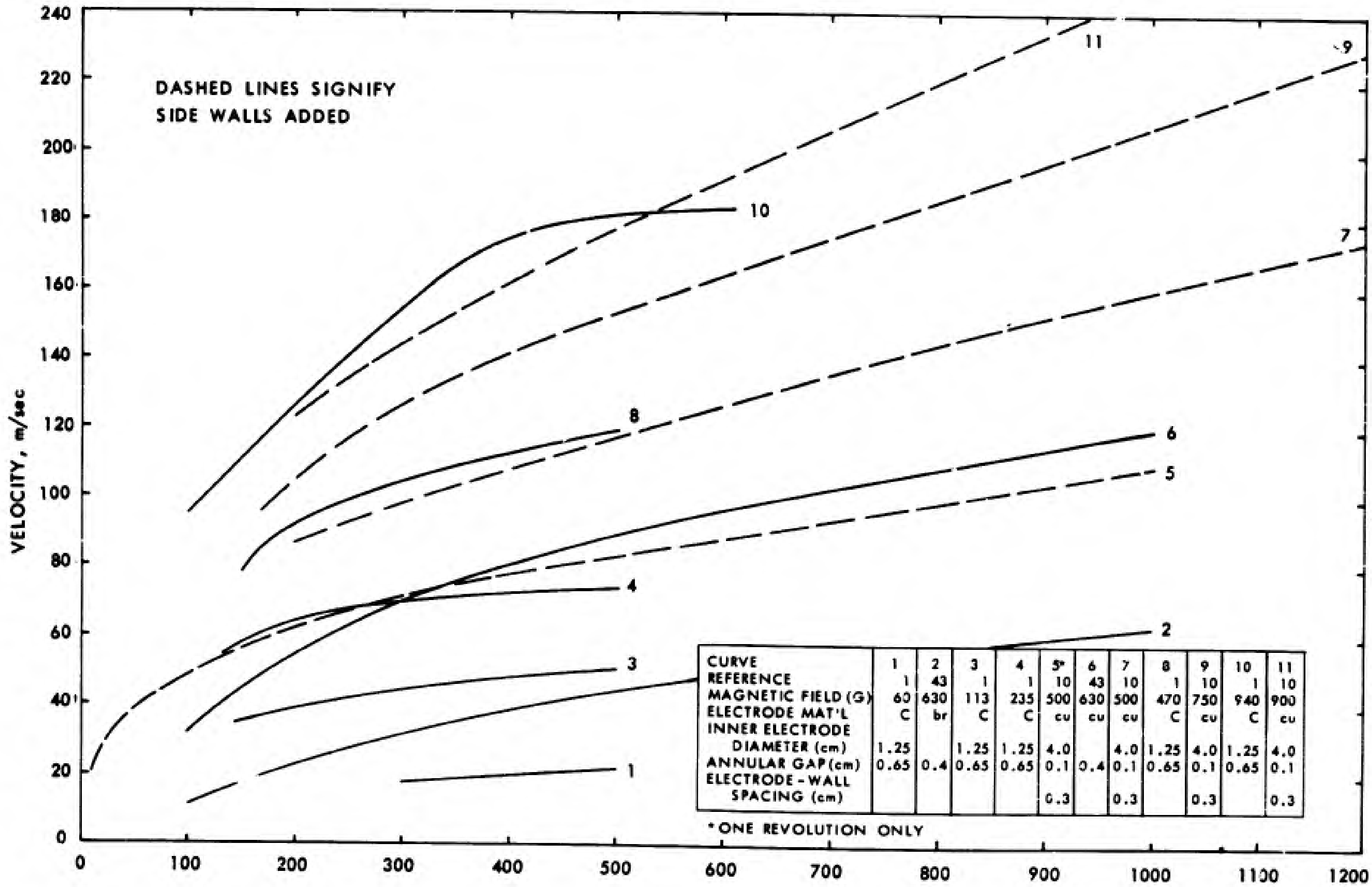
A similar theoretical analysis of the travelling arc in an annular gap was made by Jedlicka (34). With assumptions which were essentially the same as those used by Adams, the involute of a circle shape was obtained. These assumptions were: (1) the arc column may be represented as an impenetrable aerodynamic body having a cross-flow drag coefficient, C_D, and a diameter which is invariant with arc length, (2) electrode effects are negligible, (3) at steady state the arc rotates as a solid body having a constant angular velocity, (4) the magnetic field and the gas density are constant outside the arc column, (5) the electric field effect is small compared to the effect of the magnetic field, and (6) the fluid viscous effects are negligible except for the cross-flow drag. The travelling arc probably deviates most seriously from the first three of these assumptions. However, the experimentally observed arc shape shows that there is considerable merit in this model of the travelling annular arc, especially in the regions somewhat removed from the electrodes.

Pratt and Rieder (43) measured the velocity of a travelling arc in an annular gap between 0.2 and 0.5 cm. At these narrow gaps the arc column was essentially in the radial direction and no involute shape occurred. Alternating currents between 100 and 1000 A were used with homogeneous magnetic fields between 100 and 630 G. Photoelectric cells were used to measure the average arc velocity. The inner electrode was segmented and fed current from both ends so that the arc would remain centered in the device. This was done to keep the arc from running on the edge of the inner electrode where velocities 4 times greater had been observed. "Run-in" electrodes of copper or brass were used. During a current half-wave, the maximum velocity was attained after the current maximum. This phase shift between the velocity maximum and the current maximum decreased with increasing current and was larger for brass than copper. At a magnetic field of 630 G, the travelling arc velocity decreased with increasing gap for copper, but increased with increasing gap for brass. The reason for this puzzling variation was not understood. With 0.5 cm gap, the experiment confirmed the empirical formula of Eidinger and Rieder (16) to within 20%, i.e., the relation between the prime variables was $V = 0.045\ B^{0.74}\ I^{0.61}$, where V is in m/sec, B in G, and I in A. Travelling arc velocities up to 120 m/sec were observed in this experiment.

Experiments on a travelling arc in a narrow annular gap were also performed by Bronfman (10). The tests were made at a.c. levels from 100 to 2000 A and magnetic fields from 200 to 1300 G. Copper electrodes were used; the inner electrode had a diameter of 4.0 cm, while the outer electrode diameter was varied from 4.2 to 4.48 cm. The inner electrode was slightly eccentric with respect to the outer one so that for the continuously running tests the rotational frequency of the arc could be obtained by monitoring the voltage fluctuations of the arc. In most of the tests, the electrodes were 0.3 cm wide and enclosed between insulating side plates located at distances of either 0.3 or 0.15 cm from the electrodes. The nature of the arc motion depended on the current amplitude. It was intermittent for the first several runs from 100 to 200 A; above 300 A the arc moved continuously. The arc velocity was higher during current fall than during current rise over one half-cycle, as reported by Pratt and Rieder. After once making a revolution, the arc continued to move over the same track again and again. In some of the tests, the arc was allowed to make only one revolution and the arc velocity was obtained using streak photography. The arc velocity was less than the velocity observed in the continuously rotating tests by a factor of 2 or 3. For a magnetic field of 460 G, the velocity in these one revolution tests was proportional to $I^{1/3}$. For these tests, the velocity compared well with that reported in the literature for a travelling arc between parallel electrodes. In the continuous tests with a mean gap of 0.1 cm and a wall spacing of 0.3 cm, the empirical relationship was $V_m = (1.24 \times 10^{-2})\ I_m^{0.4}(B + 440) - 20$, where V_m is the maximum arc velocity in m/sec, I_m is the maximum arc current in A and B is in G. When the mean electrode spacing was less than 0.05 cm the arc did not move. After motion started, the arc travelled slower as the electrode spacing increased, independent of the arc current. When the distance between the electrodes and insulating side plates was decreased from 0.3 to 0.15 cm, the arc velocity (continuous) decreased about 15% at a current of 250 A, and decreased about 36% at 1500 A. The electrode width was changed from 0.3 to 0.15 cm; with this change, the velocity did not change for currents from 200 to 500 A, but the velocity decreased about 10% for currents from 1200 to 1500 A.

The experiments of Fabri (17) were performed with an apparatus similar to that which might be used in an arc heater. A flat-topped cylindrical copper cathode, 2.4 cm o.d., was centered inside a 3 cm i.d. copper anode. The cathode root located itself on the top portion of the cathode, thus the arc configuration was not exactly that of an annular arc as in the prior experiments. A coil was connected in series with the arc current to provide the driving magnetic field. The gas (air) to be heated was passed through the annular region between the cathode and the anode and out through a nozzle. A photoelectric cell was used to measure the time per arc revolution and thus obtain the arc velocity. The arc chamber was run at pressures between 2 and 13 atmospheres. The experimental analysis was based on the conducting cylinder model. The data was presented parametrically, using this model. Insufficient information was given to allow calculation of the magnitude of the different parameters (e.g., current, pressure, flow rate.) The velocity was directly proportional to the current and the square root of the pressure, and inversely proportional to the square of the annular gap. Velocities up to 170 m/sec were observed. Calculations for the device acting as an arc heater indicated that efficiencies between 10 and 40% were achieved.

The results of the studies on a travelling arc in an annular gap are shown in Figures 15 and 16. With similar conditions imposed, the arc in an annular gap travelled at higher velocities than an arc between parallel rails. This is to be expected due to the arc travelling in its own wake, which is not necessarily stationary, and because the arc continually returns to electrode sites which have been recently used and therefore preconditioned. These conclusions are supported by the fact that the velocity was 2 to 3 times less in a single run around the annular gap (10). The approximate validity of the conducting cylinder model with aerodynamic drag was indicated by the success of the theoretical analysis based on this model which predicted the involute shape taken by the arc column (2, 34, 53). However, the cross-flow drag coefficient calculated from this model (C_D values between 1 and 5) appear to be somewhat larger than those for a cylinder. Usually the velocity decreased with increasing annular gap spacing (10, 17), just as would be expected from the parallel rail studies. However, some results indicated the velocity was approximately independent of the gap (1) and that the electrode material had an effect on the velocity-gap relationship (43). Decreasing the spacing between insulating side plates decreased the velocity (10) conflicting with most of the parallel rail results.



CURVE	1	2	3	4	5*	6	7	8	9	10	11
REFERENCE	1	43	1	1	10	43	10	1	10	1	10
MAGNETIC FIELD (G)	60	630	113	235	500	630	500	470	750	940	900
ELECTRODE MAT'L	C	br	C	C	cu	cu	cu	C	cu	C	cu
INNER ELECTRODE DIAMETER (cm)	1.25		1.25	1.25	4.0		4.0	1.25	4.0	1.25	4.0
ANNULAR GAP (cm)	0.65	0.4	0.65	0.65	0.1	0.4	0.1	0.65	0.1	0.65	0.1
ELECTRODE - WALL SPACING (cm)					0.3		0.3		0.3		0.3

*ONE REVOLUTION ONLY

FIGURE 15 - DEPENDENCE OF TRAVELLING ARC VELOCITY ON CURRENT IN AN ANNULAR GAP AT VARIOUS MAGNETIC FIELDS

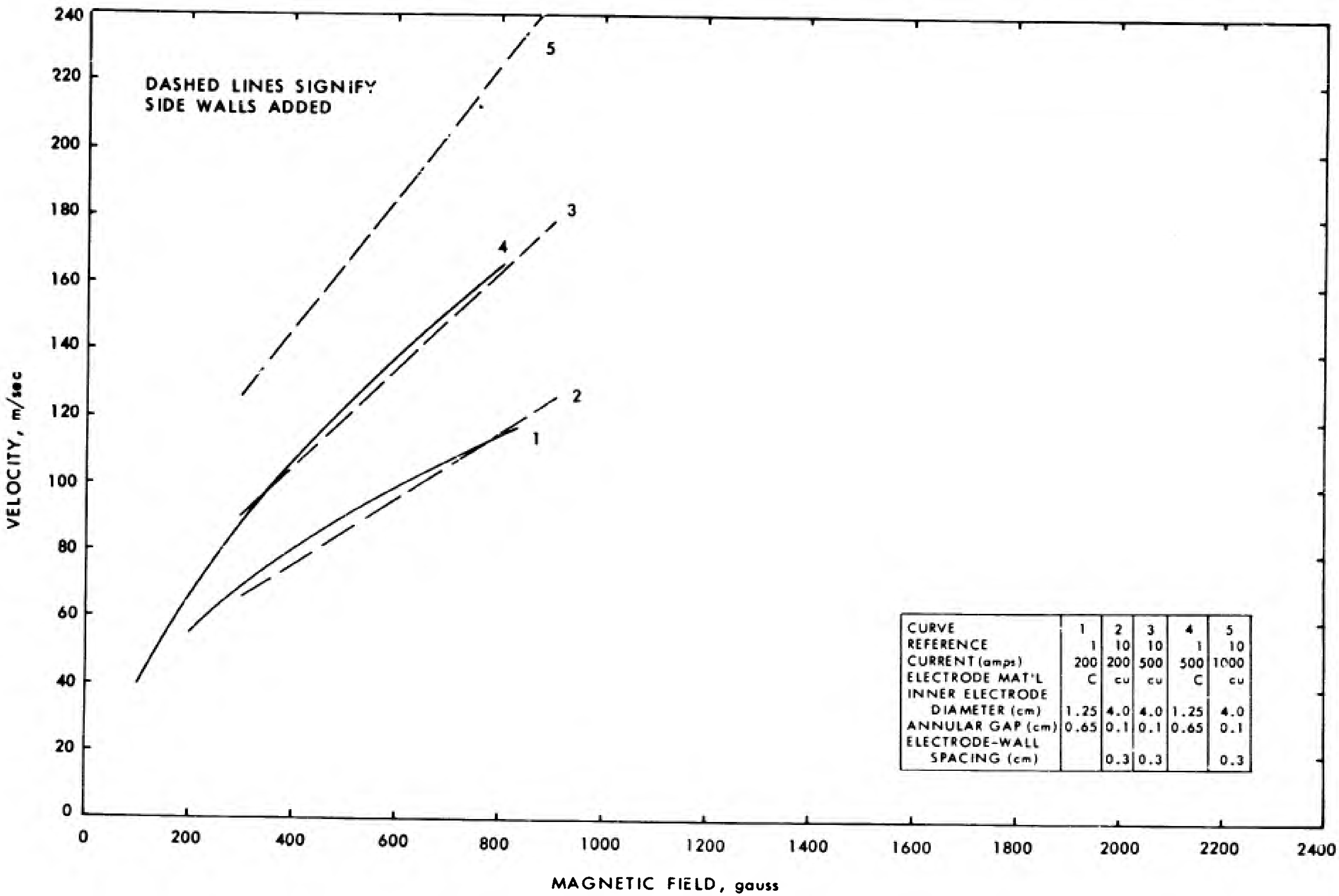


FIGURE 16 - DEPENDENCE OF TRAVELLING ARC VELOCITY ON MAGNETIC FIELD IN AN ANNULAR GAP AT VARIOUS CURRENTS.

SECTION VI. SUMMARY OF EFFECTS OF TRAVELLING ARC PARAMETERS

In this section general conclusions will be drawn from the preceding survey of travelling arc investigations. Since the results have been quite varied and have often conflicted because of the unknown complex interactions between the parameters, there are often exceptions to these conclusions. It is quite difficult and may be impossible to pick out one parameter and say what effect changing it in a specified way will have on the arc without knowing the effects this change will produce on the other arc parameters. Nevertheless, some conclusions may be drawn from this mass of experimental data to give an indication of what is now known and the direction in which future studies should proceed. These items have been discussed in the summaries at the ends of the preceding sections and their supporting references specified. Therefore, no references will be given for these conclusions.

The travelling arc behavior is dependent on conditions at the electrode roots over the entire range of velocities studied, although the effects of the electrode conditions lessen at higher velocities (greater than about 50 m/sec) and wider electrode spacings (greater than 1 cm).

When the electrode effects are dominant, the magnetic field at the electrode surface is the controlling field.

For a travelling arc under the influence of only its self-magnetic field, the velocity is higher on ferrous than non-ferrous materials; for an arc in an external field the velocity is lower on ferrous than non-ferrous materials.

The arc velocity is greater on electrodes which have been previously used, have been polished, have been longitudinally scratched or roughened, and which have been exposed to an oxidizing atmosphere than for electrodes which are new and unused.

The arc may not move satisfactorily in a reducing atmosphere; it appears to be difficult to form new electrode sites in such an atmosphere and severe sticking may result.

Repeated runs over the same electrodes produce higher velocities than is obtained with a single run.

The self-field produced by the arc column differs considerably from that of a cylindrical conductor.

As the travelling arc velocity is increased, the mode of arc root travel changes from sticking to intermittent (both with local electrode melting) to high-speed continuous to high-speed intermittent (both with little electrode erosion).

Multiple arc attachment points may occur at both the anode and the cathode.

Conditions at the arc cathode are more dominant in controlling the arc motion than those at the anode.

The anode motion is often controlled by the arc column motion.

Magnetic materials near the electrodes which concentrate the magnetic field in the electrode region increase the arc velocity above what it would be in their absence.

The arc velocity increases as the electrode width is decreased.

For electrode spacings greater than about 1 cm, the travelling arc velocity decreases as the spacing is increased due to both the decreasing self-field and the tendency of the arc to form loops and helixes which increase the arc column drag.

For gaps greater than 3 cm the effect of the electrode spacing is negligible for the external field case.

As the electrode spacing is reduced below about 1 cm, the velocity reaches a maximum and then decreases.

At shorter electrode spacings (less than about 1 cm) processes in the electrode regions have a dominant effect on the arc motion; these processes may completely control the motion at spacings less than 0.02 cm.

The arc shape may deviate considerably from a straight plasma conductor representing the shortest connection between the two electrodes.

The conducting cylinder with aerodynamic drag represents the best model developed to date to describe the dependence of the relatively straight arc column behavior on the arc current and magnetic field; it may be applicable at velocities above 10-50 m/sec and electrode spacings above about 1 cm.

The shape of an arc column in an annular gap when electrode effects are negligible is an involute of a circle.

The velocity of an arc driven by its self-field increases linearly with the arc current.

The velocity of an arc driven by an external field is approximately proportional to the current raised to powers between 0.4 and 0.5 and to the magnetic field raised to powers between 0.55 and 0.65.

The drag coefficient obtained from the conducting cylinder analogy may vary over the range 0.3 to 10.1, compared to the value of 1.2 for a solid cylinder with a laminar boundary layer.

At velocities greater than 50 m/sec and electrode spacings greater than about

1 cm the magnetic field at the center of the electrode gap controls the arc motion.

Travelling arc velocities are often higher with insulating side walls than without them.

As the spacing between the side walls is decreased, the velocity of the arc increases and then decreases; the position of the relative maximum occurs at a wall spacing of the order of the arc diameter but also depends on the other arc parameters.

The travelling arc velocity decreases as the pressure is increased; the velocity is inversely proportional to the square root of the pressure.

The travelling arc velocity decreases as the gas density is increased; the velocity is approximately inversely proportional to the square root of the density.

PART 2

THE STATIONARY ARC

SECTION VII

HISTORICAL DEVELOPMENT OF STATIONARY ARC LITERATURE

Over the past 17 years many valuable and interesting investigations have been conducted related to the interaction of an electric arc with transverse aerodynamic and/or magnetic fields. The first related cross-flow investigation was done in Leipzig, Germany, and reported in 1949 in the classic article by Weizel and Rompe (91). This theoretical investigation, however, was directed primarily at the effects of free convection on a free burning horizontal electric arc. The possibility of balancing a convective velocity on an arc with a magnetic field in order to cause it to remain a straight body was mentioned.

Little if any work was reported during the next five years until a report was published in 1954 by Smith and Early (87). This was an experimental investigation to determine the feasibility of heating an air stream in a wind tunnel using an electric arc. This was the first reported experimental study where an external magnetic field was used to oppose the aerodynamic forces of a supersonic flow on the arc column. An unusual characteristic slant angle of the column, with respect to the electrodes, was observed.

In 1957, Rother (83), in Germany, applied the energy equation to a horizontal electric arc subject to an upward convection to gain information on the arc curvature and temperature distribution. This was the first paper to question the validity of the work of Weizel and Rompe.

In 1959, Thiene (88) published an extensive experimental and analytical study of the flexure of an electric arc under forced convection. An analogy was made between the convected arc and the distributed load on a structural beam. An energy balance analysis provided arc curvature, temperature distribution, a so-called flexural rigidity, and blowout criteria. This investigation set the pattern both theoretically and experimentally for much of the work that followed.

A Russian article by Serdyuk (85) concerned with a welding arc in a transverse magnetic field appeared in 1960. This was comprised of both an experimental and an analytical portion. A force balance was applied to a deflected arc column and this was used to calculate the stability limit of the arc and the magnitude of the bowing due to the external magnetic field.

In 1961 some preliminary work was done by Chen (68) on a theory for an arc positive column subjected to a transverse gas flow. The column was assumed to behave as a solid cylinder and by applying the steady state energy equation, it was shown that the arc may be stable or unstable depending on the perturbation introduced. At this same time, Sherman and Yos (86) conducted an analysis of scaling laws for electric arcs subject to forced convection. Numerous assumptions were made and the analysis was tested experimentally. The results indicated the importance of certain parameters on the forced convection arc.

From 1961 until the latter part of 1963 little was reported until Lord (75) in England, published a theoretical investigation of some magnetofluiddynamic problems involving electric arcs. A portion of this report included a magnetically balanced arc in cross-flow. A solid body analogy was made and by applying conservation equations, Ampere's law and Ohm's law, the arc characteristics were obtained in non-dimensional form.

Toward the end of 1963 two Russian scientists, Alferov and Bushmin (60), conducted an experimental investigation of an arc discharge across the exit of a convergent-divergent nozzle at both subsonic and supersonic flows. The results included photographs of the form of the discharge as well as current and voltage characteristics.

By 1964 keen interest had been aroused and focused on the electric arc interacting with both aerodynamic and magnetic fields. This was primarily motivated by the immediate aerospace applications. The first reported research in 1964 was that of Kalachev (73) in Russia. His investigation was an extension of the work of Alferov and Bushmin with the same apparatus being used. This was again mainly a photographic study of a pulsed arc discharge.

Fay (70) published a short note as a comment on the previously reported work of Thiene.

Bond (65) published a series of papers concerning the magnetic stabilization of an electric arc in supersonic flow. These were primarily experimental observations of the arc column configuration. One interesting observation was that the arc had a characteristic slant angle between the electrodes with the anode root always upstream of the cathode root. Unfortunately, the explanations given for this slant were quite speculative and no final conclusions could be reached.

An investigation was started by Hogan and later continued by Malliaris (78) on an experimental and analytical study of the fundamental interaction and energy exchange process between electric arc discharges and cross-flow fields of pre-ionized gases both with and without the presence of external transverse magnetic fields. The objective was to examine the phenomena taking place in the J x B region and obtain information on the appearance and behavior of the discharge under varying conditions.

Baranov and Vasil'eva (62) of the USSR published a report on an electric arc struck across a high velocity cross-flow of argon. They suggested application to a non-equilibrium magnetohydrodynamic generator. Velocity, shape of the luminous region, and other arc characteristics were experimentally measured by high-speed photography.

Lord (76) of England published a paper concerned with the effects of a radiative heat sink on the voltage-current characteristics of a cross-flow arc stabilized by an external magnetic field. The characteristics were expressed in a non-dimensional form which showed the importance of different parameters. Numerical examples, based on some published magnetically driven arc rail-type experiments showed the heat loss from the arc bore little resemblance to that due to forced convection from a heated solid cylinder.

Anderson (61) reported an analytical and experimental study on the Hall effect and electron drift velocities in the plasma of a positive column under the influence of an external transverse magnetic field. The arc column was confined within a cylindrical tube in which probes were used to measure the Hall voltage and column gradient.

Following Anderson was a purely theoretical investigation by Ecker and Kanne (69), in Germany, of a cylindrical plasma conductor in a transverse magnetic field. This investigation was limited to small magnetic fields which allowed linear perturbation theory to be applied to the two cases of a collision dominated and collision free plasma.

By the start of 1965 there appeared to be on an average of almost one publication every few months treating the cross-flow arc problem both with and without external magnetic fields. The first of these was Broadbent (66) in England, who theoretically explored the flow about an electric arc transverse to an air stream using potential flow methods. The conservation equations were applied to the arc which was treated as a source and a heat sink was assumed in the flow downstream. This model, however, gave unrealistic temperature distributions.

Paralleling this work, Lord and Broadbent (77) published a report on an electric arc across an air stream. The paper discussed an electric arc in a transverse subsonic air stream held stationary by an external transverse magnetic field. Non-dimensionalized arc characteristics were obtained and the theory was compared with the experimental annular gap travelling arc data of Adams (1). The conclusion reached was that the solid cylinder analogy is not very satisfactory.

Olsen (81) published a report concerning a series representation method for inverting externally measured asymmetrical spectral intensity distributions of the emission coefficients for optically thin sources. The method was successfully applied to both analytical and experimental data. The experimental portion dealt with the interaction of a pre-ionized transverse gas flow with an electric arc.

Broadbent (67) published another report concerning electric arcs in cross-flow. The experimental apparatus was a rail accelerator, but the analysis of heat transfer aspects and comparison with the solid cylinder analogy links the results closely to the cross-flow category. Useful similarity laws were also derived.

Noeske (80) presented analytical work on the behavior of an arc in cross-flow.

The porosity of an arc in cross-flow was examined as a function of temperature and properties of the gas. Temperature fields were compared with solid hot cylinders and horizontal free-burning arcs with natural convection. Analytical expressions and a stability criterion were developed which related the geometrical, electrical and thermodynamical parameters of the arc current-sheet model.

Myers (79) investigated a magnetically balanced electric arc in a transverse argon gas flow. This was an experimental study of an electric arc in crossed convective and magnetic fields. The arc was found to behave similarly to a solid cylindrical drag body. The application to non-equilibrium conductivity was also discussed.

Kookekov (74) in Russia treated the mechanism of heat transfer in transverse blown arcs. The motion of an electric arc with transverse blowing and a perpendicular magnetic field was studied. Experimental data were obtained on the arc velocity and characteristics. A theoretical analysis was included using conservation of energy, Ohm's law, and the minimum principle. The results indicated that by excluding radiation and heat conductivity, the energy transfer is primarily by means of turbulence, i.e., there is turbulence within the transverse blown arc.

Schrade (84), presented a paper on arc pumping and the motion of electric arcs in a transverse magnetic field. This was a theoretical study concerned with calculating the transverse forces which act on an arbitrarily curved current-carrying conductor in a transverse magnetic field. The arc motion was concluded to depend on the external magnetic field, the self-magnetic field, and the curvature of the discharge axis.

Roman (82) performed experiments on a magnetically balanced electric arc in an open-flow type facility. The open-flow configuration allowed various diagnostic probes to be used in the flowing gas stream adjacent to the arc. The heat transfer aspects and aerodynamic drag of the arc were found to be quite similar to that of the heated solid cylinder model. An interesting optical observation was that the balanced-arc diameter increased transverse to the flow direction as compared to the no-flow condition.

To complete the historical development of the investigations up to 1966, three other studies, which are currently being conducted, shall be included. Benenson (64) is investigating the effects of low velocity forced convection upon the characteristics of electric arcs. Of prime interest is the arc shape, curvature, voltage gradient, and temperature distribution (asymmetrical) within the arc. An experimental technique is being employed to determine the arc shape and local integrated intensity of the arc's radiation. Following this phase will be an analytical determination of the asymmetrical temperature distribution within the arc column using information gained from the experimental phase.

Fischer (71) in Germany, is investigating interactions of an electric arc with transverse magnetic and gas flow fields. This is an analytical study of the arc discharge cross-section, temperature distribution and mass flow distribution in transverse external fields. Work to date has been on a confined arc in a transverse magnetic field and on an arc under transverse convection. Preliminary calculations have provided temperature distributions and flow fields.

Han (72) is presently investigating the convective heat transfer and arc curvature in cross-flow. This is an analytical study directed between the two asymptotic cases of a solid cylinder (no penetration) and a completely porous cylinder (full penetration). The first portion of the study deals with establishing the asymptotic size of the vertical arc core based on a heat dissipation viewpoint. The convective heat transfer correlations are solved using a numerical integral method. Other portions of the study are concerned with establishing the radiation loss from the arc column and an approximate analysis of the asymptotic column growth for turbulent flow.

TRANSVERSE BLOWING ONLY

Weizel and Rompe (91) primarily concerned themselves with the problem of why an arc discharge channel straightens if it accidentally assumes a curved form. This straightening occurs as soon as the arc channel is no longer subject to any disturbing influence such as free or forced convection or external magnetic fields. The straightening tendency has occasionally been interpreted as a tensile stress in the longitudinal direction. In contrast to this, however, is the experimentally verified fact that the electrodes are repelled, instead of attracted, by the discharge. If one blows continuously on an arc with a cross-flow, the arc is displaced by this blowing. If this cross-flow velocity is below the magnitude required to extinguish the arc, an equilibrium state may be established whereby the arc remains in a curved configuration. The tendency of the arc to straighten is balanced by the flow forces. For a horizontal arc, this cross-flow is induced by the buoyancy effect of the highly heated gas of the arc. Because of gravitational forces the hot gas rises and is replaced by cold gas flowing in from below. The highest flow velocity should therefore exist in the center of the column. Thus, a continuous stream of gas flows through the arc column vertically. Since the electric current prefers to pass through the highest conducting area, the column distorts upward until a stable condition is reached. Thus, assuming the arc does not extinguish, an equilibrium may be established between restoring forces (which increase with arc curvature) and the upward displacement of the arc. In this manner, the free convection, horizontal arc acts like a pump. Cold gas is sucked in from below and hot gas is ejected above. A certain similarity exists between the deflected arc due to cross-flow and a deflected arc due to a transverse external magnetic field. In both cases an equilibrium state results in which the tendency of the arc to straighten and the influence of the external field balance each, other.

The calculations of Weizel and Rompe were based on the differential energy equation relating ohmic heating, radiation, heat convection, diffusion, and conduction losses:

$$E\cdot J - S = \frac{\partial}{\partial t}\left(\rho c_v T + \frac{\rho V^2}{2}\right) + \nabla\cdot\left[V\left(\rho c_v T + \frac{\rho V^2}{2}\right)\right] + \nabla P\cdot V + \nabla\cdot(k\nabla T).$$

The terms on the left side of the equation are the ohmic heating and radiation; the terms on the right side are the total energy density of the gas, change of energy density of the flow, energy deformation and heat conduction, respectively. The results indicated that the velocity, V, with which a curved element of arc moves toward its curvature center increases with the power per unit length and with the cross-sectional area of the channel and decreases with radius of curvature and internal energy per unit length. Thus, $V = \frac{2LR^2}{u\rho}$ where L = power per unit length, R = arc channel radius, u = internal energy per unit length, ρ = arc radius of curvature. This is in partial agreement with some experimental observations, especially with regard to cross-sectional area of the arc channel. Discharges with small cross-sectional area are much more susceptible to bending through convective flexure than those with a large cross-sectional area. The velocity which the horizontal arc channel achieves due to its own buoyancy was equated to the velocity calculated for the curved arc channel moving toward its curvature center at the equilibrium condition to yield a parameter which indicated the range of stability of the arc. Exceeding a calculated value of this parameter indicated that the arc would blow out and would not be capable of straightening itself. This parameter A was found to be equal to $K \frac{S T_o u d^3}{4 \sigma U^2 R^2 \eta}$, where K = a constant based on geometrical shape, S = gas density, T_o = maximum arc temperature, u = energy/unit length, d = electrode gap, σ = electrical conductivity, U = discharge voltage, R = arc channel radius, and η = viscosity. Weizel and Rompe gave no consideration to the arc's self-magnetic field influence, the possibility that the arc may not actually assume a sector of a circle for its shape, electrode region effects and the $p \nabla \cdot V$ term in the energy equation.

Rother's analysis, (83) like that of Weizel and Rompe, primarily considered the curvature and range of stability of a horizontal arc perpendicular to a gas flow. The arc was found to bend to the point where the unsymmetrical cooling of the column due to convection was exactly compensated by the unsymmetrical heating on the concave side due to the curvature and increased electric field. The Heller-Elenbaas differential energy equation was used together with an assumed radial temperature distribution in the arc of the form $T = T_o - (a)(x^2 + y^2)$ where T_o is the centerline arc temperature and (a) is a constant. By initially assuming a uniform velocity field which was not affected by the arc, the resultant decoupled approximate energy equation was solved, assuming constant conductivities, by finding the appropriate Green's function. Whereas Weizel and Rompe assumed that the constant (a) in the radial temperature distribution could be determined from the radius at 1/2 of the maximum temperature, leading to the result that the radius of curvature was proportional to the power input, Rother claimed this to be erroneous and that there is no connection between (a) and the radius. The relation obtained by Rother was of the form $\frac{1}{\rho} = \frac{V}{4} \frac{C_p}{K_o} (1 - \frac{S_o}{L_o})$, where ρ = radius of curvature, V = convection velocity, S_o = radiation in the middle of the arc, C_p = specified heat, K_o = heat conduction coefficient and L_o = power density in the middle of arc. That is, the radius of curvature is practically independent of the power. The theory of Rother predicts the dependence of arc curvature on the arc pressure and arc power and was said to agree quite well with his experimental results for carbon arcs in air and argon arcs. However, no description of the experimental conditions, measurement techniques, or range of parameters was given. Again, like Weizel and Rompe, no consideration was given to the effects of the self-magnetic field or electrode region effects.

The main difficulty which occurs in any simple theory for predicting the flexure of an electric arc column under forced convection is how to account for the flow field around and through the column. Thiene (88,89) investigated this using the same configuration as Weizel, Rompe, and Rother. By assuming that the flow through the column was essentially two-dimensional, a qualitative analogy was made between the convection-loaded arc and the flexure of a structural beam under a distributed load. The simple assumption was that the curvature at any point, x (y), where the y-axis is the original undeflected column and the x-axis is perpendicular to the y-axis in the plane of flexure, was proportional to the mass flux. The constant of proportionality was defined as the "flexural rigidity" of the arc column. Thiene's analysis included the energy balance, equation of motion, continuity equation, Maxwell's equations, and entropy changes. It was assumed that the isotherms within the arc were parallel to the electric field lines. Thiene justified this assumption by stating under steady state conditions, conservation of charge and Ohm's law require that $\nabla \cdot j = E \cdot \nabla \sigma + \sigma \nabla \cdot E = 0$, where σ = the electrical conductivity. In addition, Poisson's equation and charge neutrality require that $\nabla \cdot E = 4\pi e (n_i - n_e) = 0$. Therefore, $E \cdot \nabla \sigma = 0$ or the isotherms (lines of constant conductivity) are parallel to the electric field and current lines.

The temperature distribution in the zone of ohmic heating was derived by assumming the following linear conductivity variation $\sigma = a(T - T_b)$ with $T > T_b$, where T_b is the arc boundary temperature at which σ is effectively zero. All other properties were assumed independent of T. Because of Thiene's low blowing velocities, the stagnation enthalpy was assumed equal to the free-stream enthalpy. In addition, radiation and viscous losses were neglected.

Thiene's results indicated that the flexural rigidity of the column should decrease with the specific heat of the gas and increase with the thermal conductivity, radiation, and ambipolar diffusion. Thiene's analysis omitted boundary conditions at the electrodes, electrode effects, and no consideration was given to the possibility that the mass flux through the column may differ from the free-stream mass flux upstream of the column. The change in mass flux within the column due to its change in curvature was included.

Fay (60) offered a comment on Thiene's assumption that the electric field is divergence-free because the plasma is neutral. Fay pointed out that although $\nabla \times j$ is perpendicular to both ∇T and j, it cannot be concluded that the latter two vectors are necessarily mutually perpendicular. Therefore, the current does not necessarily flow in the isothermal surfaces, as Theine had assumed, but since the current always has a tendency to flow through regions of the highest electrical conductivity, it may approximately follow such a path, except in the electrode regions.

Since the many different processes occurring in the arc positive column are each affected differently by changes in arc dimensions, pressures, velocities, etc., a study of arc scaling laws may furnish a powerful tool for establishing which of the processes are most important in determining arc operating characteristics. Sherman and Yos (86) dealt with a dimensional analysis of scaling laws for electric arcs subject to forced convection. The important processes considered for viscous, compressible flow were: heat conduction and convection, ohmic heating, and radiative heat transfer. The effects of natural convection, non-equilibrium, electrodes, and external and self-magnetic fields were excluded. The resultant scaling expression was

$$\Phi = \frac{I}{L\sigma} F\left[\left(\frac{\mu c_p}{k}\right)\left(\frac{p}{\rho V^2}\right)\left(\frac{\rho V L}{\mu}\right)\left(\frac{I^2}{L^2 \mu \sigma h}\right)\left(\frac{q \rho^2 L^2}{\mu h}\right)\right].$$

This equation includes the effect of the electrical conductivity, σ; density, ρ; pressure, p; velocity, V; viscosity, μ; specific heat, c_p; thermal conductivity, k; enthalpy, h; power radiated per unit volume, $q\rho^2$; and a typical length, L; on the arc column voltage, ϕ. Even though some effects which apply to many of the most important processes in the arc column-flow interaction are excluded, scaling laws do include a number of effects which may be important in the interaction mechanism of the arc column with external flow. It should be noted, however, that if natural convection, non-equilibrium, electrode, external and self-magnetic field, or induced current effects are important, or if other effects not considered in the analysis are important, then the scaling law will not hold.

Chen (68) applied the steady state energy equation to a positive column subjected to a transverse gas flow to show that the arc may be stable or unstable. The following assumptions were made:

1) MHD effects were neglected.
2) The pressure was uniform everywhere.
3) Chemical and thermal equilibrium exists everywhere in the arc column. The important consequence of this assumption is that for a given pressure, the physical properties and composition are functions of temperature only.
4) Radiation was neglected. (This assumption may not be valid, especially at higher pressures.)
5) The gas is incompressible.

A temperature perturbation was introduced and a stability criterion derived. This estimated the arc diameter to be $D = \frac{\pi}{E}\sqrt{\frac{k}{\left(\frac{d\sigma}{dT}\right)}}$ The conductive heat loss equation for a hot cylindrical rod was applied to determine that 97% of the energy transfer from the arc column is by means of conduction through the arc boundary layer. Therefore little flow, if any, goes through the arc. The numerical results indicated the column temperature is not greatly affected by pressure. Since radiation was neglected, the pressure effect may be exaggerated since the significantly increased radiation losses at higher pressure may result in lower temperatures than those predicted.

Broadbent (66) applied the energy, continuity, and momentum equations together with the assumption that pressure variations are small to explore the flow about an electric arc. Outside the arc the flow was assumed inviscid and incompressible. A circular cross-section was assumed for the arc, which acted as a heat source in a potential flow. An iteration procedure was required to obtain the complete solution of the equations. This led to the result that the stream tubes which pass through the arc column change density, whereas those that pass around the arc column remain incompressible. This method involved guessing a velocity and density distribution within the arc. The model is somewhat unrealistic, since it results in a negative arc drag, as long as the flow field is deduced solely by potential methods. In the actual case of viscous flow, a wake originates that induces vortices and lends to a positive drag. Mathematically, Broadbent obtained a positive drag by introducing a velocity discontinuity and a heat sink in the downstream flow. The heat source and the heat sink were of equal magnitude. The models used were somewhat questionable, since they gave unrealistic temperature distributions. A more reasonable temperature distribution could be realized by introducing an inner region with an impenetrable boundary which would act as a line heat source for the external convection.

Noeske (80) analytically derived the amount of mass flux which actually crosses the arc boundary by using a current-sheet model and making the following assumptions:

1) Electrode regions are excluded.
2) No conduction or radiation in direction perpendicular to the current and the flow.
3) The current lines are concentric circles (with the model only valid for bending up to a half-circle).
4) The flow is incompressible and inviscid.
5) The electrical conductivity was defined as: $\sigma = 0$, $T < T_o$; $\sigma = \theta(T-T_o)$, $T \geq T_o$.
6) Estimated average values of C_p and k were taken.

The perviousness was given by $\frac{\dot{m}_x}{\dot{m}_\infty} = \frac{-1 + \sqrt{1 + 2\left((Ti/To)-1\right)}}{(Ti/To)-1}$ where $\dot{m}_\infty$ = initial flow flux, $\dot{m}_x$ = mass flux actually crossing arc column, T_o = temperature outside arc, and T_i = maximum arc temperature. The derived equations represented relations between the voltage, current, curvature and thickness of the current sheet, the thermodynamic properties, the mass flux of the fluid which penetrates the boundaries, and the temperature distribution within the discharge. The temperature field in the vicinity of an arc in cross-flow was compared with the temperature field of a heated solid cylinder, and a horizontal free-burning arc subjected to natural convection. The plots of arc characteristics and the effect of current and cross-flow blowing on arc diameter indicate that the arc voltage increases with mass flow rate and decreases with increasing initial gas temperature and the arc diameter increases with increasing current, decreasing flow rate, and increasing initial gas temperature. A stability criteria was developed on the basis of two assumptions:

1) The maximum temperature in the column must be upstream of the arc center, and
2) $dq/di_o = 0$,
   where q = heat flux and i_o = arc column current.

Compared to previous investigations, this was the first to consider the difference between the mass flux through the column compared to the mass flux upstream of the column.

Han (72) is analytically studying the convective heat transfer and arc curvature in cross-flow. The first phase of the investigation deals with establishing the model for the growth of the column radius of a vertical arc. The analysis is not valid at the electrode because of a strong singularity existing there. Three basic models of the arc column are being considered for numerical solution:

1) A solid cylinder with internal heat generation (Conduction is the primary mode of heat transfer within the cylinder, radiation is being neglected),
2) A solid cylinder surrounded by an annulus of ionized gas (Conduction and

radiation are the primary modes of heat transfer), and

3) A completely fluid cylinder with internal heat generation (Conduction, convection, and radiation are the primary modes of heat transfer. It is planned to determine the convection-originated flexure by analyzing the "fringe-shift" of the isotherms due to the asymmetrical cooling of the arc column).

TRANSVERSE MAGNETIC FIELD ONLY

The investigations of Anderson (61) and Ecker and Kame (69) concerning transverse magnetic field effects on the plasma column deal with the very low pressure, low current regime (electron temperature >> neutral gas temperature). The discussions are limited to very low magnetic fields, which allow introduction of linear perturbation theory. Therefore, the results are not directly applicable to this survey and will not be discussed further.

Fisher (71) analytically determined the influence of a transverse force field for two types of arcs: 1) a wall-stabilized arc where the force is caused by a uniform weak external transverse magnetic field and , 2) a free-burning arc where the force is caused by an external transverse gas flow. The energy, momentum, and continuity equations were applied. For case 1) a double-vortex type flow appears with the arc core displaced in the J x B direction as shown in Fig. 17. The calculations yielded the temperature distribution, electrical conductivity, and the flow field. For case 2) the arc column shifted in the direction of the flow. It was assumed that the electric field and isotherms were parallel and heat conduction along the arc axis was negligible. A perfect gas relation, a radially symmetric arc profile with temperature distribution of the form $T = T_o + \dfrac{T_a - T_o}{\left(1 + \dfrac{r^2}{r_o^2}\right)^{\alpha}}$ (necessary to determine the flow field), and a small dynamic pressure, compared to the static pressure were the additional assumptions made. In this equation T_A is the arc centerline temperature, T_o is the gas temperature, r_o is the arc boundary radius, and α is a constant. The flow field was calculated from the momentum equation, continuity equation, and equation of state. Typical results are shown in Fig. 18. The results were only valid in the upstream half of the column and not in the wake region, because there the temperature profile is no longer radially symmetric and the inertial forces become important. The results indicated that the per cent of flow going through the arc increases with increasing gas temperature and decreasing arc temperature, in agreement with Noeske (80).

Schrade (84) conducted an analytical investigation of the transverse forces which act on an arbitrarily curved current-carrying plasma channel in a transverse magnetic field. This study was primarily motivated by the arc retrograde motion problem and deals with low current arcs at low pressure ($<$ 1 atm.). The transverse forces consist of the Lorentz force in the Amperian direction and an electromagnetically induced gas-dynamic thrust in the retrograde direction. This gas-dynamic thrust is due to the gas being expelled from the low pressure side of the arc (to the left in Figure 19b) and being replaced by gas drawn in from the side where the magnetically induced pressure is greatest. The balance of the forces

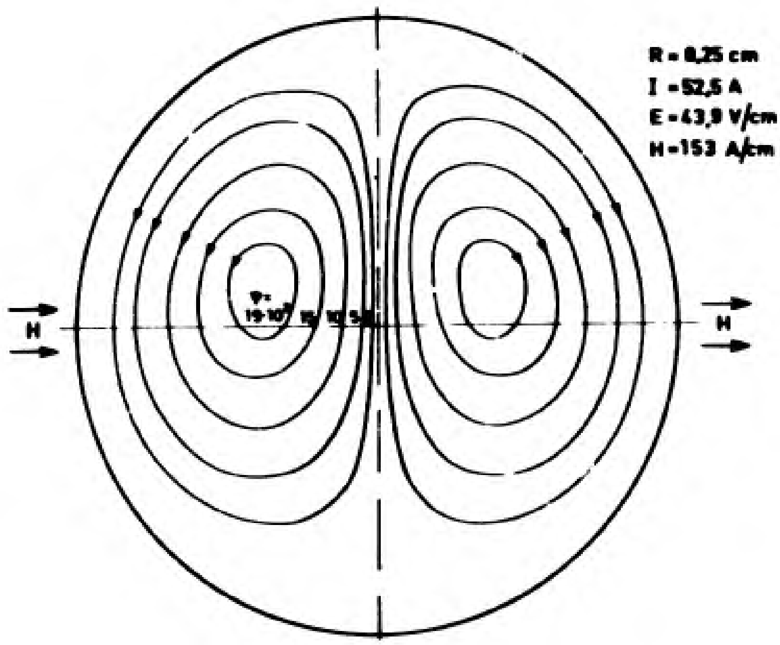


FIGURE 17 - STREAMLINES OF THE FLOW IN A WALL-STABILIZED ARC EXPOSED TO A TRANSVERSE MAGNETIC FIELD (71).

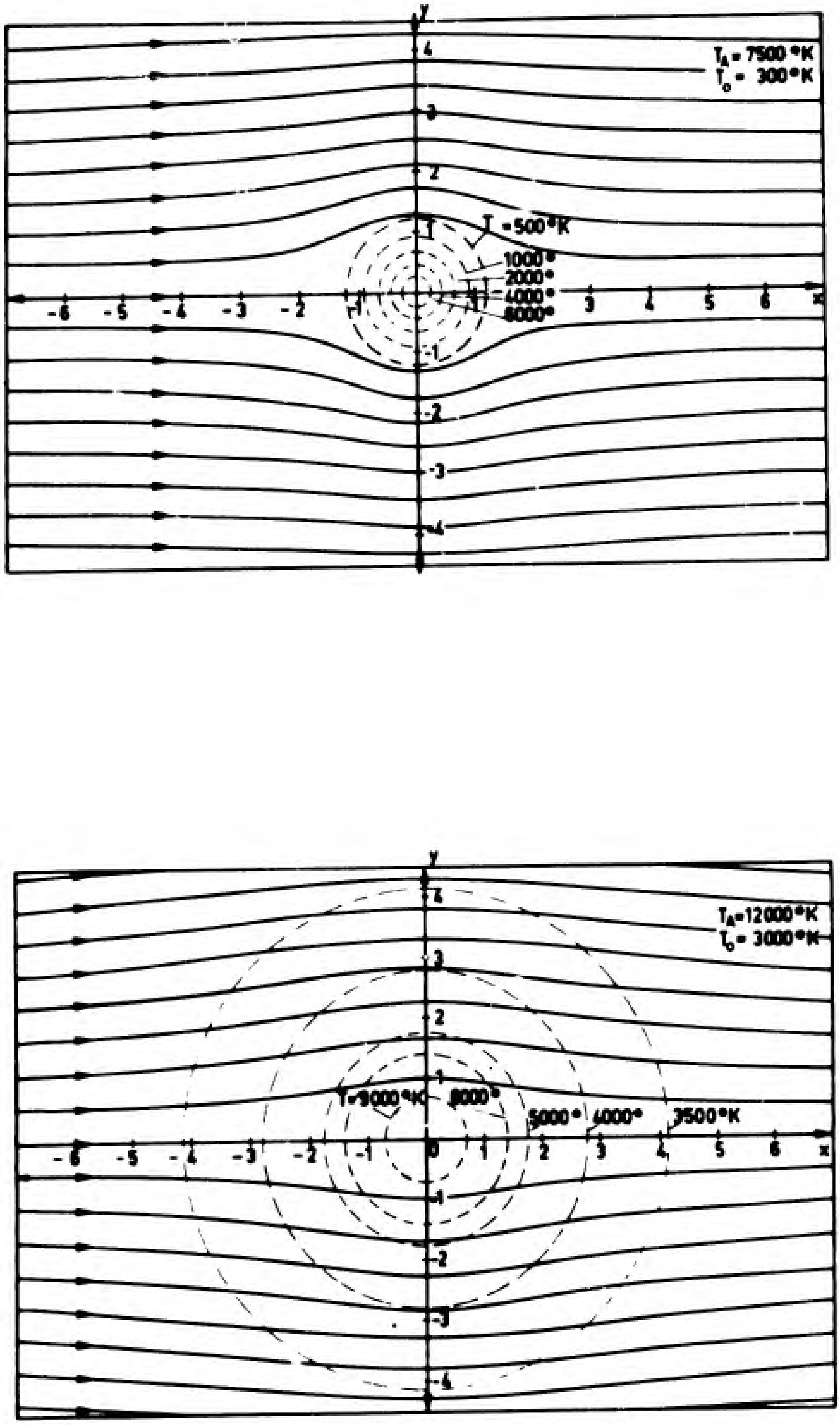


FIGURE 18 - DISTURBANCE OF A HOMOGENEOUS STREAM OF COLD (TOP) AND PREHEATED (BOTTOM) GAS BY AN ARC (71).

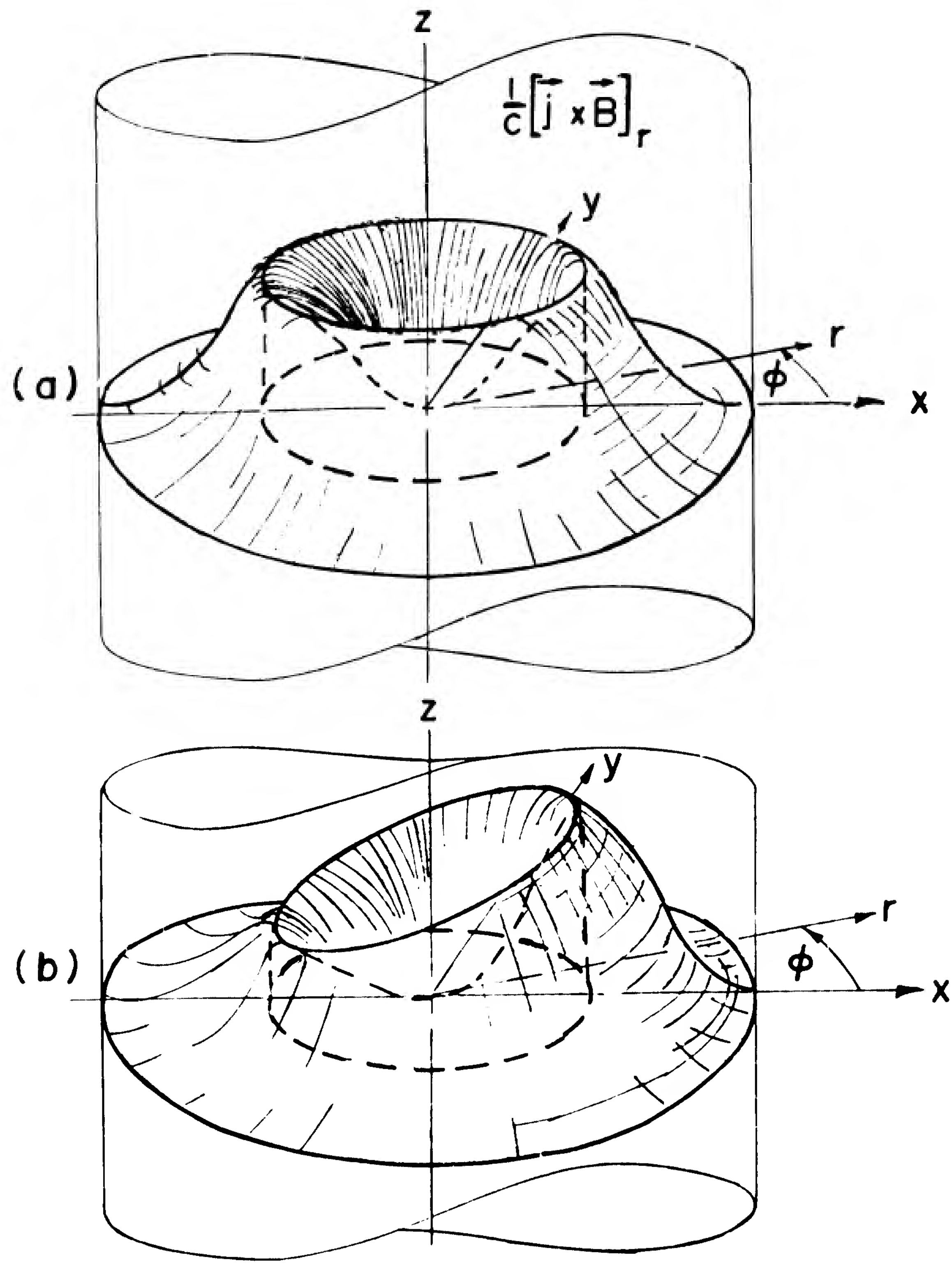


FIGURE 19 - QUANTITY OF THE RADIAL LORENTZ FORCE DRAWN UPON THE CROSS SECTION OF THE DISCHARGE CHANNEL FOR A CURRENT DENSITY DISTRIBUTION: $j_z = j_o \, e^{-(\frac{r}{r_c})^2}$ (a) WITHOUT AN EXTERNAL MAGNETIC FIELD. (b) WITH AN EXTERNAL MAGNETIC FIELD ($\vec{B}_o$) in Y - DIRECTION.

and, therefore, the motion of the arc was found to depend on the relation between the outer magnetic field B_o, the self-magnetic field $2I/cr_o$ and the curvature of the discharge axis. When the discharge channel moves relative to the outer cold gas, an additional transverse force corresponding to the drag of a heat source in a flow field must also be considered. The balance of these forces led to an equation which, in general, permitted the calculation of the curvature of the discharge channel.

TRANSVERSE BLOWING AND TRANSVERSE MAGNETIC FIELD

Thiene's (90) analytical investigation was predicated on the assumption that an external transverse magnetic field applied to the arc column so as to oppose the convective force would give rise to an internal double-vortex flow pattern due to the J x B body force acting on the arc plasma. A stagnation point was assumed to exist within the column in order for the arc to be stationary in the transverse gas flow. The steady-state momentum equation was applied, neglecting the viscous forces. Thiene assumed that along the external flow axis within the column, some fraction of the J x B force was balanced by the pressure gradient. It was also assumed that outside the column, the pressure gradient was balanced primarily by the inertia effect. Integrating the equations along a streamline to the stagnation point gave the same result that would be obtained by equating the magnetic force to the aerodynamic force on a conducting cylinder (i.e., $BI = (1/2)\rho C_D V^2 D$). By measuring the arc radius the drag coefficient was found to be approximately 6, compared to a value near unity for a solid cylinder.

Lord (75) analytically treated the convected arc held at rest by an applied transverse magnetic field. The following assumptions were made:

1) There are no effects on the arc from the external circuit.
2) The electrodes were in the same plane as the jet sides.
3) Uniform flow exists upstream of the arc.
4) The external magnetic field is applied such that a perfect balance is achieved at each arc segment.
5) The arc center is a straight line perpendicular to the electrodes.
6) Outside the arc column $\sigma = 0$, and k, ρ, ν, and c_p are constant and equal to the value at the free stream condition.
7) Inside the arc column σ, k, ρ, c_p, ν are constant and equal to the value at the temperature and pressure of the arc center. Only the uniform column portion of the arc was considered, therefore, the following additional assumptions were made:
8) The arc periphery is circular in cross-section.
9) The column radius varies with the velocity of imposed flow.
10) The arc periphery is non-porous.
11) Partial matching of the various properties at the arc periphery is permissible.
12) There is no convection within the arc.
13) The arc periphery can withstand tangential stress.
14) The total magnetic field is the sum of the induced plus internal magnetic field.

15) The pressure distribution inside the arc is the sum of the static pressure plus magnetic pressure.

16) The heat flux and temperature distribution are the same as for the corresponding static arc.

The momentum and energy equations, Ampere's and Ohm's law and $BI = (1/2) \rho C_D V^2 D$ were applied to the arc with the following quantities continuous at the arc periphery:

1) P at forward stagnation point,
2) total force,
3) temperature, and
4) total heat transfer.

Thus, P, T, B_r, B_Θ and j_z were obtained inside and P and T on the periphery. The arc characteristics were also obtained in non-dimensional form. The following general conclusions were reached. The major effects of increasing the current at constant magnetic field are to decrease the voltage gradient and to increase the size of the arc. The relative velocity of the arc and the flow, and the temperature of the arc, are only slightly affected by increasing the current. The major effect of increasing the magnetic field at constant current is to increase the relative velocity of the arc and the flow; the voltage gradient, the size of the arc, and the temperature of the arc, are affected to a lesser extent.

Lord (76) analytically derived equations for the arc characteristics and the fraction of input power lost by radiation using a radiative heat sink model. The following assumptions were made:

1) radial symmetry (circular arc boundary),
2) thermal equilibrium,
3) no convection inside arc and
4) constant conductivity inside arc.

The effects of the applied external magnetic field, particularly on the conductivity, were not considered although the magnetic field was used to stabilize the arc. The theoretical results were derived by means of an analogy with a wall-stabilized static arc combined with the Nusselt-Reynolds relationship for convective heat transfer. The results indicated that the fraction of the input power lost due to radiation decreases as flow velocity is increased or as pressure is increased. This latter conclusion is reached because the arc decreases in size as the pressure increases. Therefore, even though radiation loss per unit volume does increase with pressure, the decrease in cross-sectional area is such that the radiation loss per unit length of column decreases with increasing pressure.

Lord and Broadbent (77) semi-empirically analyzed an electric arc in a transverse subsonic air stream held stationary by an external magnetic field. A simple model was put forth by making an analogy with an equivalent arc of circular cross-section which carried the same current but was free from convection within the column. The following assumptions were made:

1) Charge neutrality exists in the plasma column.
2) The gas inside the arc is in thermal equilibrium.
3) A definite boundary exists outside of which the electric current is zero.

4) There is no variation of properties along the column axis.
5) Steady two-dimensional flow exists.
6) The arc boundary is of circular cross-section.
7) σ inside arc is constant corresponding to centerline temperature.
8) There is no convection inside the arc.
9) The radiated power density is constant.

The energy equation, Ohm's law, momentum equation and Maxwell's equations were applied to obtain expressions for the heat flux and arc radius as a function of E, I, and arc properties. The results were compared with the annular gap, travelling arc experimental data of Adams (1). Lord and Broadbent concluded that a model based on a heated solid cylinder analogy is not valid. One may indicate possible sources of discrepancy:

1) The boundary layer difference with regard to laminar and turbulent flow between solid cylinders and arcs.
2) The extrapolations necessary due to lack of experimental data for cross-flow on very highly heated cylinders.
3) The application of the rotating arc results to a stationary balanced arc condition. (The effects of small electrode gaps, effect of induced swirl in the wake of the arc due to vortices, departures of the arc shape from a uniform cylinder stream velocity and power supply fluctuations, electrode jet effects, and contamination of arc by electrode vaporization are neglected.)

Broadbent (67) semi-empirically analyzed the behavior of a magnetically driven electric arc in cross-flow. The assumptions were that

1) a uniform column exists where electrode effects are not important and
2) the drag law $BI = \rho C_D V^2 r_o$ is valid. Broadbent compared his data with the experimental annular gap travelling arc experiment of Adams. The heat transfer was compared with that for a heated solid cylinder. The results indicated that at comparable Reynolds numbers, the arc Nusselt number was greater than 10 times that of the heated solid cylinder. The Nusselt number was calculated from experimentally measured arc properties. To verify the observed heat transfer future spectroscopic temperature measurements throughout the arc were planned. Broadbent also derived similarity laws which indicated that the parameters EI, BI/V, and V^2I/E (E = voltage gradient, I = current and V = velocity) are quite important in describing the stationary arc behavior.

SECTION IX. EXPERIMENTAL ANALYSES OF THE STATIONARY ARC

TRANSVERSE BLOWING ONLY

Thiene (90) reported experimental measurements of the deflection of a small horizontal electric arc between collinear tungsten electrodes in the presence of subsonic, laminar, forced convection. Studies were conducted for arc currents from 2-6 amps, arc voltages between 30-50 volts, electrode gaps from 4-8 mm and blowing velocities up to 200 cm/sec. Argon gas was used at atmospheric pressure and the tunnel test section was 1-3/4" square. Photographs of the deflected column as functions of various parameters were taken and analyzed. A typical photograph is shown in Fig. 20. The effect of the cathode jet was noticed and numerous attempts were made to eliminate or reduce it. Although the occurrence of such a jet was not unexpected, it was presumed that at sufficiently low arc currents, the effect of the cathode jet would be negligible. The compromise design finally adopted was a pointed thoriated tungsten rod surrounded by an electrically floating tungsten sleeve. The sleeve provided the necessary boundary condition and appeared to significantly reduce the jet effect. An interesting observation made by Thiene was that as the flow velocity was increased beyond the maximum value used for recording data, the column became increasingly "horseshoe" shaped and pulsated upstream and downstream at several cycles per second. If the blowing velocity was further increased, arc blowout resulted. This pulsation may have been due to the interaction of the electrode-tip vortices. The stiffening effect on the column exerted by the electrode sleeves was observed from the photographs. Thiene postulated that the increased electric field on the concave side of the column when in the convection-bowed shape contributed to the flexural rigidity. Numerous effects were neglected by Thiene in the experimental evaluation which may have had a significant influence such as:

1) The difference between a horizontally burning arc exposed to natural convection and an arc in a forced cross flow.
2) The difference of mass flux through the arc column compared to free-stream mass flux of the undisturbed flow.
3) The "horseshoe" shape effect compared with a small arc deflection. (This severely deflected arc case actually consists of two separate problems with regard to flow pattern. One dealing with axial flow and the other dealing primarily with true cross-flow.)

Alferov and Bushmin (60) studied arc discharges drawn across the exit of a closed wind-tunnel convergent-divergent nozzle. The air flow Mach numbers investigated were 0, 0.5, 1.5, 3.0 and 4.5, which were obtained by using interchangeable nozzles. The stagnation temperature was maintained constant at T_o = 283° K and the static pressure was varied (in the range of 15 - 330 mm Hg) in order to have the same gas density at the various Mach numbers. The electrodes were solid molybdenum, 5 mm in diameter, which extended into the tunnel. They were surrounded by a teflon sheath and were variable to gaps of 10, 15, 20, and 25 mm. The discharge was investigated using two electric circuit variants: (1) a stabilizing ballast resistor and (2) a shunted ballast resistor. Photographs were taken of the form and behavior of the discharge. In the first variant the discharge was in

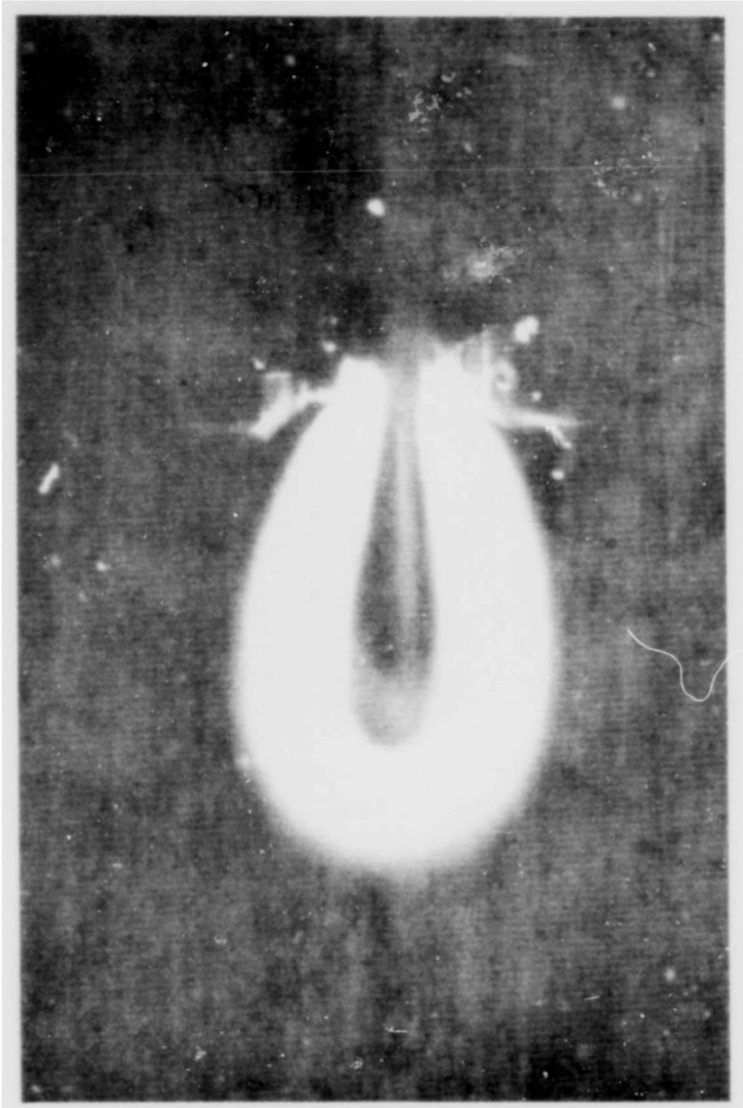


FIGURE 20 - COLUMN DEFLECTION PHOTOGRAPH, GAP = 0.6 CM, CURRENT = 6 AMP, VELOCITY = 1.92 M/SEC (90).

the form of a series of flashes in the absence of gas flow, but in the presence of gas flow the discharge exhibited high stability which increased with increase of flow velocity. The discharge had a falling current-voltage characteristic, indicative of a stable arc discahrge. Voltages of approximately 8 KV and currents of 0.5 - 3 amperes were typical. Comparison of the current both with and without air flow showed that the gas flow considerably reduced the duration of the current pulses. In the second variant, the discharge breakdown of a discharge gap and was characterized by a prebreakdown glow and an increase of the breakdown voltage with increase of the Mach number of the gas flow, other conditions being equal. Paschen curves were obtained for the various Mach numbers.

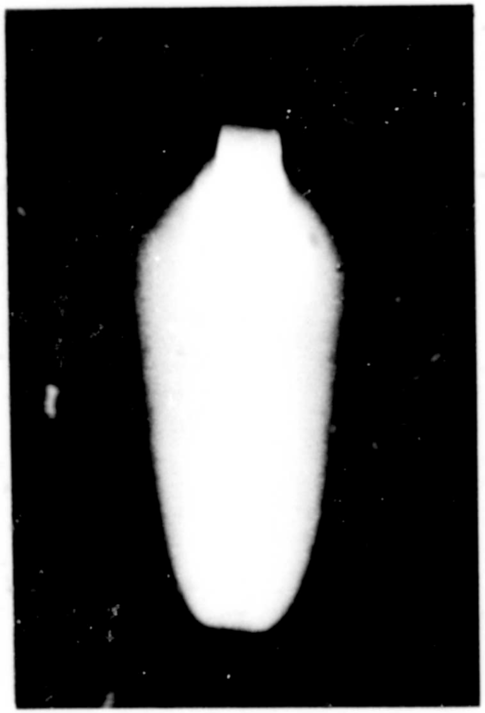
Baranov and Vasil'eva (62) experimentally investigated a low current arc drawn across a high velocity flow of argon. The arc currents varied from 0.4 - 20 amps, gas pressure ranged from 0.1 - 60 mm Hg and flow speeds from $10^2 - 10^4$ cm/sec. A closed circuit system was used in which a J x B arc accelerator upstream of the 4 cm diameter glass tube test section provided the flow. Steel or covar anodes were used together with oxide cathodes (indirectly heated). The electrodes were approximately 2.5 cm in diamèter and mounted flush with the tube walls. High-speed photography was used for the diagnostics. The velocity was measured by the transverse displacement of a spark. The gas pressure, flow speed and arc current all affected the shape and displacement of the arc. A critical flow speed ($\approx 3 \times 10^3$ cm/sec) was determined, which increased with current. When the flow speeds were below this critical value, the luminous region followed the curved contour of the laminar Poiseuille flow in the tube, thereby causing the arc to tend to follow the walls of the tube. When the flow speeds were greater than or equal to the critical value, luminous streaks extended between the electrodes and across chords of the curved contour. This indicated that an ionized path had been formed in the flow near the front of the arc where the electric field strength was highest. It was noted that low frequency voltage fluctuations accompanied the breakdown. At higher speeds, the entire arc region became diffuse. It appeared to be made up of a series of breakdowns whose frequency increased with flow speed.

Kalachev (73) experimentally studied a pulsed discharge in a high velocity air stream. The apparatus was identical to that used by Alferov and Bushmin. The same air flow Mach numbers were used but the static pressures were limited to the range of 15 - 252 mm Hg. The discharge, produced by a capacitor bank, was investigated using high-speed photography, oscillograms of the discharge current and voltage, and conventional photography. The results indicated that luminescence precedes the breakdown followed by an initially straight discharge which drifts downstream. A comparison of the photographs of the luminescence with the flow pattern of the electrodes obtained by Alferov and Bushmin showed shock waves on the background of the luminescence. It was concluded that the high-velocity air flow has a significant effect on pre-breakdown phenomena in the discharge gap; in particular, it modifies the shape of the discharge channel. However, the electrical characteristics such as the time dependence of the current and voltages are not significantly affected by the air stream.

Benenson (64) is presently investigating the effects of low velocity forced convection upon the steady-state characteristics of electric arcs. The objective is to determine the arc characteristic shape, temperature distribution within the arc (asymmetrical) and the voltage gradient as a function of the arc current, gas velocity, and electrode gap. The experimental apparatus consists of a 15 - 100 ampere electric arc established across a 1-3/4" square test section of a small wind tunnel. Argon gas blowing velocities in the 0-5 ft/sec range are used and the pressure is approximately atmospheric. The electrode gap can be varied between 1/16" and 1-1/4". A 0.040" diameter tantalum cathode and a 0.187" diameter copper anode are used. The electrodes (both unshielded) are collinear with the gravitational field, with the convective blowing oriented in the horizontal plane. The test facility may be rotated so that the influence of gravity (which may have a significant effect at the low blowing velocity, low arc current, and large gap regime) may be determined. A vertical, relatively stable arc has been achieved. Gross instabilities (both visually and in the arc current and voltage output) were found to exist in the initial experimentation, but these were significantly reduced by using a cylindrical, tantalum cathode together with a cylindrical copper anode. Two stable modes have resulted with accompanying voltage ripple less than 2% and are shown in Fig. 21 along with the arc with no blowing. For $I \leq 20$ amps a bow-shaped arc results. For $I > 20$ amps a cusp-shaped arc results. Both modes were found with the same electrode arrangement, and therefore are associated with the cathode electrode material, its properties, its shape, and the jet effect. At the low current range, local melting of the cathode tip occurs forming a spherically shaped tip. A diffuse spot attachment appears to occur, therefore a reduced electrode jet effect. At the higher current operating range, a transition occurs wherein the cathode attachment spot region appears to be more highly localized at a point, thus promoting the jet effect. The jet effect then produces the cusp-shaped formation. The experimental technique being devised to determine the arc's characteristic dimensions and local integrated intensity of arc radiation will consist of small mirrors located along one side of the wind tunnel test section at different azimuthal locations. The images of the arc will be reflected from these primary mirrors to a secondary set of mirrors which then reflect the light to two cameras. Each camera is simultaneously triggered and contains a different narrow band interference filter. From the data obtained, the arc dimensions may be determined together with details on the arc radiation intensity using a 2-line or absolute intensity method.

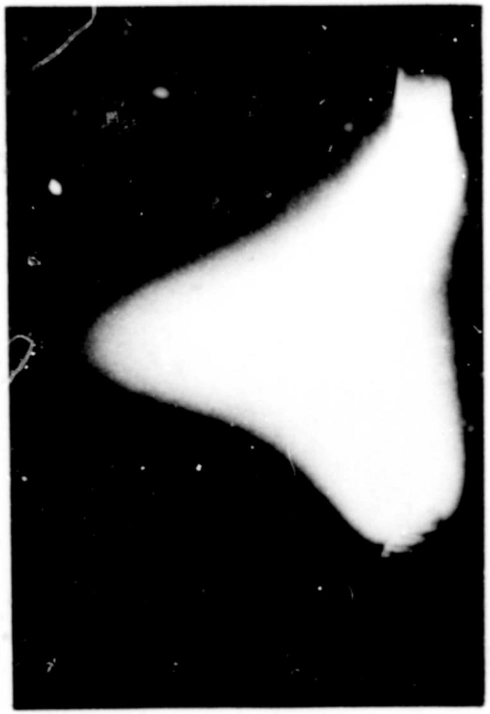
TRANSVERSE MAGNETIC FIELD ONLY

Serdyuk (85) investigated a welding arc under the influence of an external transverse uniform magnetic field. Two cases were considered: An arc with magnetic deflection (shifting of anode and cathode spots together with the column) and an arc with magnetic deformation (stationary cathode spot, movement of anode spot and deformation of the column). The latter was much more difficult to obtain experimentally. The first case was empirically described by $B = 4C \rho \sqrt{V^3/I}$ (where C = dimensionless coefficient) for arc currents of 100-1000 amperes. The influences of electrode material, electrode jets, self-magnetic field and configuration effects were not included. The second case was investigated using a 310



33.6 amperes 1/2" gap — 16.4 volts 0 velocity

16.4 amperes 1/2" gap — 21.0 volts 76.1 cm/sec



60 amperes 1/2" gap — 16.5 volts 69.6 cm/sec

FIGURE 21 - BOW-SHAPED AND CUSP-SHAPED ARC PHOTOGRAPHS (64).

ampere carbon arc of 15 mm length in a uniform external transverse magnetic field with the aid of a high-speed camera. The high-speed pictures showed that the cathode remained fixed while the arc column and anode spot were free to move. An increased deflection at increasing distance from the cathode was observed. The nature of the deformation was explained by the effect of the forced gas flow of the arc column, directed under normal conditions from the cathode to the anode. Consequently, deformation began at the cathode and increased on its way toward the anode depending upon the rate of motion of the arc column plasma. Such a phenomena was also observed during the application of a variable external transverse magnetic field. In this case, the arc column was continuously deformed by the time changing magnetic field. A delay was noted, and attributed to the resistance of the medium to the movement of the arc column. An interesting phenomenon was observed in the case of employing a copper anode. As the arc column was being deformed by the transverse magnetic field, the gas stream (i.e., cathode jet) from the cathode to the anode changed its direction relative to the surface of the anode accompanied by a decrease in its component rate in the direction of the anode. This facilitated the conditions for the origination of a visible stream of gases from the anode spot (an anode jet), which is suppressed under ordinary conditions by the slower initial rate of its formation and the cathode stream. The observations showed that the predominant role was played by the vapors coming from the copper anode as compared to other tests using aluminum or iron anodes. These data are in agreement with the evaporation energy values of the particular metallic materials. An equation of dynamic equilibrium was applied to the deflected arc column. This included the inertia force, resistive force of the medium, elastic (i.e., restoring) force, and the magnetic driving force. A non-linear differential equation was formed from the force balance and analyzed by creating approximate expressions for the individual members. The equation could not be solved in general form through elementary functions; however, a solution was obtained for the simplest case of an arc in a constant uniform external transverse magnetic field. The obtained formulae could be used for calculating the stability limit of the arc in a transverse external magnetic field in addition to the magnitude of the deformation due to the magnetic field.

Olsen (81) is presently investigating the interaction of an external transverse magnetic field with an electric arc. (He is also investigating the interaction of a transverse pre-ionized gas flow with an electric arc.) The apparatus consists of a free-burning, 1.1 atm, 400 ampere argon arc drawn between a 1/8" diameter thoriated tungsten rod cathode and a copper plate anode. The electrode separation is varied from 5 to 15 mm with the cathode always the top electrode. Enclosing the arc is an octagonal aluminum housing with eight ports for viewing or probe insertion. During the portion of the investigation concerned with the transverse pre-ionized gas interaction with the vertical free-burning arc, an F-40 Thermal Dynamics plasma arc torch is mounted in one of the ports. Contamination level, which is extremely important for maintaining free-burning arc stability and minimum electrode erosion, is carefully monitored and held to a minimum. This investigation is part of a long-range research effort directed at a fundamental understanding of interacting plasmas in an external magnetic field. Two stumbling blocks for such a basic research effort have been the unavailability of plasmas with independently well-known properties, and the lack of a method for making detailed local measurements of internal properties of the asymmetrical plasma produced by the interaction. During 1965 Olsen succeeded in developing a series representation method for precisely inverting externally measured asymmetrical spectral intensity distributions to true radial distributions of the emission coefficients for optically thin sources. The method has been successfully applied to experimental and analytical data under the condition of an assumed mirror plane of symmetry. The inversion method has been tested on numerous assumed models (formed from both symmetric and displaced distributions) with greater than 0.1% accuracy. Olsen's free-burning argon arc has been operated in an external magnetic field of up to 100 gauss. Photographs were taken of the distorted arc at angular positions of 0°, 45°, and 90° with respect to the mirror plane of symmetry in the plasma. From these photographs the asymmetrical plane of symmetry was confirmed. A cross-flow induced by the field interaction was also noted. With the maximum external magnetic field for which stable operation can be maintained ($\approx$ 100 gauss), the plasma was deflected from the cathode with a radius of curvature such that the gas stream developed a component in the reverse direction to that of the cathode jet. This observation was also made by Serdyuk (85). Work is presently proceeding in the direction of verifying the inversion method for a magnetically distorted plasma.

TRANSVERSE BLOWING AND TRANSVERSE MAGNETIC FIELD (PRE-IONIZED FLOW)

As part of a long-range Air Force sponsored research program, Hogan (78) initiated an experimental investigation of the fundamental interaction and energy exchange process between electric arc discharges and cross-flow fields of pre-ionized gases with and without the presence of transverse magnetic fields. The objective was to examine the phenomena taking place in the J x B region and obtain information on the appearance and behavior of the discharge. The diagnostics included high-speed photography of the discharge, measurement of the electrical characteristics and measurement of the heat transfer to the electrodes. The experimental apparatus consisted of a rectangular 2" x 4" test section. The source of the pre-ionized flow of nitrogen was a 3/4" diameter unconfined plasma jet with an enthalpy of approximately 5000 BTU/lb. The pressure range was 3-760 mm Hg, currents used were 500 and 1000 amperes, the external magnetic field was 1000 gauss and the electrode gap was 1/2". Five different electrode configurations were tried varying from flat to semi-cylindrical to conical. The results indicated that a stable discharge was not obtained over the above range of test conditions. A filament type discharge repetitively moved downstream over the electrodes. Malliaris (78) is presently doing a continuation study of the phenomena taking place within the J x B region. This new effort includes studies of the radiation emitted by the discharge, current distribution within the J x B region, principal mode of energy transport from the discharge to the gas, the effect of the applied external magnetic field on the discharge and the effect of varying the incident flow parameters. The experimental conditions are approximately the same with the exception that the external magnetic field is varied from 0 to $\pm$ 5000 gauss. An approximate theory is being developed which when correlated with the data is only partially satisfactory at present. So far the main conclusions reached were these:

1) The electrical discharge had arc-like characteristics.
2) The column occupied a small fraction of the cross-sectional area in the flow.
3) The fraction of the input power used for acceleration was small.
4) The predominant mode of energy transport from the discharge was by convection.
5) Conduction and radiation were negligible.
6) The input power increased in the presence of the magnetic field but the electrical conductivity was independent of the magnetic field up to 5000 gauss. The increase of power is thought to be a result of the increased convection through the arc by electromagnetic pumping rather than a result of plasma acceleration or decrease of the electrical conductivity in the presence of the applied magnetic field.

TRANSVERSE BLOWING AND TRANSVERSE MAGNETIC FIELD (COLD FLOW)

Smith and Early (87) conducted an experimental feasibility study of heating an air stream in a wind tunnel by an electrical discharge. The experimental apparatus consisted of a small, 1" x 1" cross-section, approximately four second run-time, blow-down wind tunnel. Both dry nitrogen and air in the Mach number range of 3 to 5 were used. The static pressure was approximately 5 mm Hg, the arc current was less than or equal to 15 amperes, and the externally applied transverse magnetic field varied from 0 to 6000 gauss. The anode and cathode electrodes formed the divergent portion of a wedge nozzle as shown in Fig. 22a. Various other geometries were used including horn-shaped and pin type electrodes. Up to 5 kw of electrical power were dissipated. One of the more important observations was that the arc showed a strong tendency to concentrate in the tunnel boundary layer region near the walls, i.e., away from the higher velocity free stream, and thereby filled only approximately 1/2 of the tunnel cross-section. Two possible reasons for the arc's strong preference for the boundary layer are the reduced density in the boundary layer and the reduced cooling there (due to the lower velocity). In addition, the arc assumed a skewed orientation (a slant angle of 20-70°), with the cathode spot always downstream of the anode spot. The arc width was also observed to be 3 to 4 times as great in the dimension parallel to the flow as in the transverse direction. Numerous unsuccessful attempts were performed in trying to eliminate the arc slanting. It was also noted that slight changes in the thickness of the top or bottom boundary layer or in the orientation of the magnetic field made the discharge jump all the way from one dielectric tunnel wall to the other. These rapid fluctuations in the arc location were observed with high-speed motion pictures (7000 frames/sec). Pulsed discharge experiments of up to 1500 amps were also conducted, but the arc was still concentrated near the boundary layer. The arc was also observed to become more diffuse as the external magnetic field increased. Smith and Early concluded that the arc slanting did not necessarily depend upon phenomena occurring at the electrode sites; but was more a result of the momentum transfer mechanism in the arc column itself. It is interesting to note that when the flow went subsonic, the arc im-

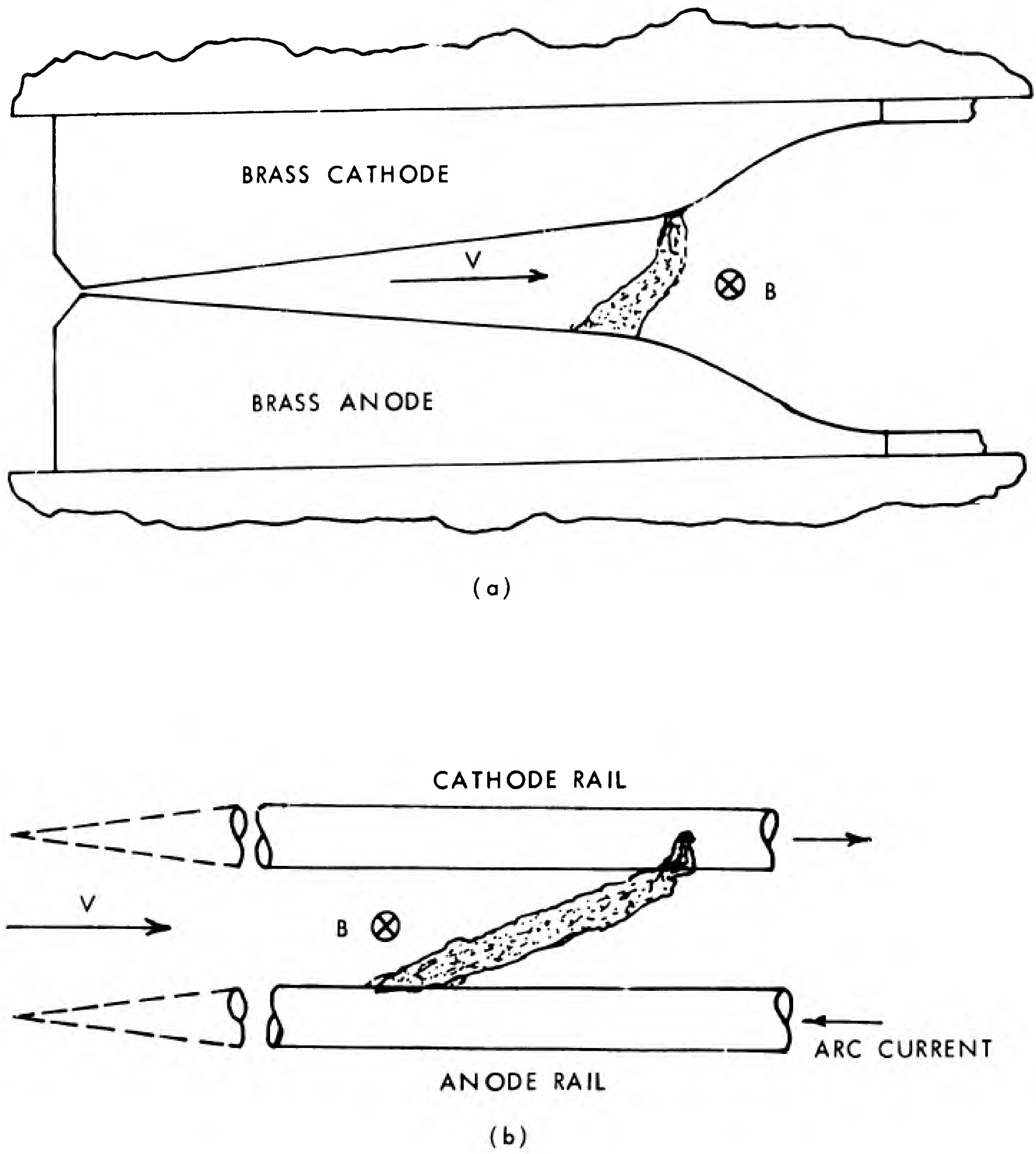


FIGURE 22 - CONFIGURATIONS FOR SUPERSONIC BALANCED-ARC STUDIES (a) REF. 87 (b) REF. 65.

mediately localized on the tips of the horn electrodes and located itself in the center of the tunnel away from the boundaries. However, it still maintained the characteristic "S" shape with the anode attachment again upstream. Possible areas of uncertainty include the effects of:

1) non-uniform flow condition in the boundary layer,
2) flow separation,
3) strength and fringe effect of the magnetic field for the various geometries used,
4) amount of non-uniform heating into the tunnel walls and electrodes,
5) distinguishment between electrode spot and column interaction phenomena,
6) true equilibrium being reached in the approximate 4-second run time,
7) turbulence level in the flow, and
8) after-glow radiation persisting in the flow downstream.

Thiene (90) conducted some exploratory investigations with a weak external magnetic field applied to the blowing apparatus previously discussed under the transverse blowing only section. A magnetic field of up to 1.4 gauss was applied transverse to the column so as to oppose the forced convection. Thiene postulated that this magnetic field would give rise to a circulatory convection due to the J x B body force acting on the arc plasma. A stagnation point was assumed to exist within the arc boundary. The arc current used was 4 amperes and the blowing velocities reached a maximum of 5 ft/sec. The momentum equation (neglecting viscous forces) was applied in an analysis of the phenomena. Thiene assumed that within the column, some fraction of the J x B force was balanced by the pressure gradient. The equation was integrated along a stream line from a free-stream position to the stagnation point. Outside the column, it was assumed that some fraction of the pressure gradient was balanced principally by the inertial reaction. Because of the low blowing velocities used, it was assumed that the static and stagnation pressures were approximately equal. The resulting equation was the same relationship that would have been obtained by equating the aerodynamic drag force to the magnetic restoring force (i.e., $BI = (1/2)\, \rho\, C_D V^2 D$).

The following conclusions were reached by Thiene:

1) The magnetic field required to balance the arc was directly proportional to V^2.
2) The force due to the self-field was of the same order of magnitude as the externally applied force.
3) The contribution of the magnetic field to the enthalpy flux due to ambipolar diffusion was negligible.
4) The effect of the magnetic field on the current density was negligible.
5) The contribution of the magnetic field to the rate of energy production term $[(E + V \times B) \cdot j]$ was negligible.
6) The use of scalar transport coefficients was justified since the cyclotron frequency was small compared with collision rates.

Some possible sources for error were:

1) the effect of the earth's magnetic field,
2) the effect of stray fields from electrode leads,
3) the effect of ferromagnetic materials in the vicinity of the test section,

4) determination of the voltage gradient and power in the positive column,
5) neglect of radiation,
6) tunnel wall effect at the low blowing velocities (super-imposed effect of free convection) and
7) the effect of the electrodes protruding into the tunnel test section.

Bond's (65) dissertation, similar to the research effort of Smith and Early (87) dealt with the experimental investigation of magnetically stabilizing an electric arc in a supersonic flow. The experimental setup is shown schematically in Fig. 22b and consisted of two parallel cylindrical uncooled rail electrodes mounted in a supersonic blow-down wind tunnel and oriented with the electrode axes parallel to the tunnel flow direction. The electrode gaps used varied from 0.6 - 1.1 inches. The arc was initiated by exploding a wire at the upstream end of the electrodes. Electrode materials of carbon, brass, steel, copper and oxygen-free high-conductivity copper were used. The average tunnel run time was 0.8 seconds during which time the data were obtained. Throughout the majority of the tests the Mach number was 2.5 (corresponding to V = 1800 ft/sec), P_{stag} was 20.2 in. Hg, and arc currents were between 300 and 1000 amperes. External field coils provided a non-uniform transverse magnetic field in the range of approximately 1000 to 4000 gauss. The magnetic field was oriented such that the magnetic field increased in the flow direction. This helped to stabilize the arc from streamwise displacements. Typical values of magnetic field were 1300 gauss at the anode root and 4300 gauss at the cathode root. The following observations were made:

1) The cathode root was always located downstream of the anode root (also noted by Smith and Early (87).
2) The positive column assumed a slanted orientation with respect to the electrode axis (angle of 60 to 70° measured from the vertical). No change was observed in the slant angle with different electrode materials or shapes. Therefore it is doubtful that slant was primarily due to an electrode phenomena (as noted by Smith and Early).
3) The angle of slant did not vary with current (within the range 130 to 1000 amperes) or P_{stag} (within the range 10 to 24 in. Hg), but changed sign with electrode polarity reversal.
4) The slant angle was in the correct direction for the Hall angle, but it did not show dependence on B or I which would be expected if slant was primarily due to the Hall effect.
5) The slant angle was approximately equal to the Mach angle (lines along which infinitesimal pressure disturbances must propagate) at Mach numbers of 2 and 2.5.
6) Slanting took place at approximately the angle where $E_{||}/P_{stag}^*$ was a maximum. (P_{stag}^* is the stagnation point pressure of a solid slanted cylinder and $E_{||}$ is the component of the electric field parallel to the column.)
7) The aerodynamic force increased with increasing arc current. Bond therefore assumed the arc diameter increased with current. (High-speed photographs, 7000 frames/sec, indicated this to be approximately true.)
8) The arc had a characteristic curve with a negative slope.
9) The average transverse magnetic field required to balance the arc was in-

dependent of I_{arc} (over the range 150-700 amps) but increased from approximately 2000 gauss at P_{stag} = 10 in. Hg to approximately 3500 gauss at P_{stag} = 25 in. Hg.

It was found that the arc could be held stationary in two modes. In the first the arc was confined to the downstream portion of the electrodes. It had considerable curvature and this mode occurred at weak external magnetic fields. The arc balance in this mode was postulated to be due to the arc curvature and a fringing electric field. In the second mode the arc was confined to the cylindrical portion of the electrodes. The arc was skewed but relatively stable. The balance in this mode was postulated to be due to arc column fluid-mechanical interaction mechanisms.

Using the length of the slanted column, the voltage gradient E was estimated to be 14 volts/cm at M = 2.5 and P_{stag} = 20 in. Hg. It was independent of arc current from 200 to 700 amperes. The electrical conductivity σ was estimated to be 10 mho/cm. For the arc in the balanced mode at M = 2.5 and I_{arc} = 300 amperes Bond obtained the empirical relationship

$$B_{ext} = 0.829\,(P_{stag})^{1/2} .$$

For supersonic flow $P_{stag} \propto \rho$ (assuming T_{stag} = constant), therefore $B \propto (\rho)^{1/2}$. Comparing this to $BI = (1/2)\,\rho_\infty C_D V^2 D$ for subsonic flow one would expect $B \propto \rho$. This difference may be due to differences between subsonic and supersonic flow regimes. Questionable aspects of the experiment included:

1) the short run times (question of true equilibrium being reached),
2) flow separation effects,
3) effects of non-uniform heating into electrodes and tunnel walls,
4) electrode region and column coupling interaction phenomena,
5) after-glow radiation persisting in the downstream direction,
6) data taken at one Mach number, thereby not explicitly relating external magnetic field and velocity, and
7) the large external magnetic field gradient along column.

Myers (79) investigated a magnetically balanced electric arc in a transverse subsonic gas flow of argon with the configuration shown in Fig. 23. The objective was to extend the range investigated by Thiene from the very low velocity and magnetic field range to higher velocities and extremely high magnetic fields. The possibility of significantly increasing the electrical conductivity by heating the electrons to a significantly higher temperature than that of the positive ions and atoms was also investigated. The experimental apparatus consisted of a small blow-down type wind tunnel with a 1-1/4" x 3/4" rectangular test section. Argon gas was used at static pressures of approximately 1.3 atmospheres and velocities of 0-300 ft/sec. The arc current ranged from 20-100 amperes and the external magnetic field from 2000-28,500 gauss. Myers used unshielded electrodes similar to Benenson (Thiene (85) on the other hand, used shielded electrodes) composed of 3/32" diameter 2% thoriated tungsten rods. (Ground flat at the tip as compared to Benenson's conical shaped tips.) The electrode gap was varied from 5/32" to 7/8". The average run time was approximately 5 seconds. The convective force on the arc was found to be quite similar to the aerodynamic force of a sub-

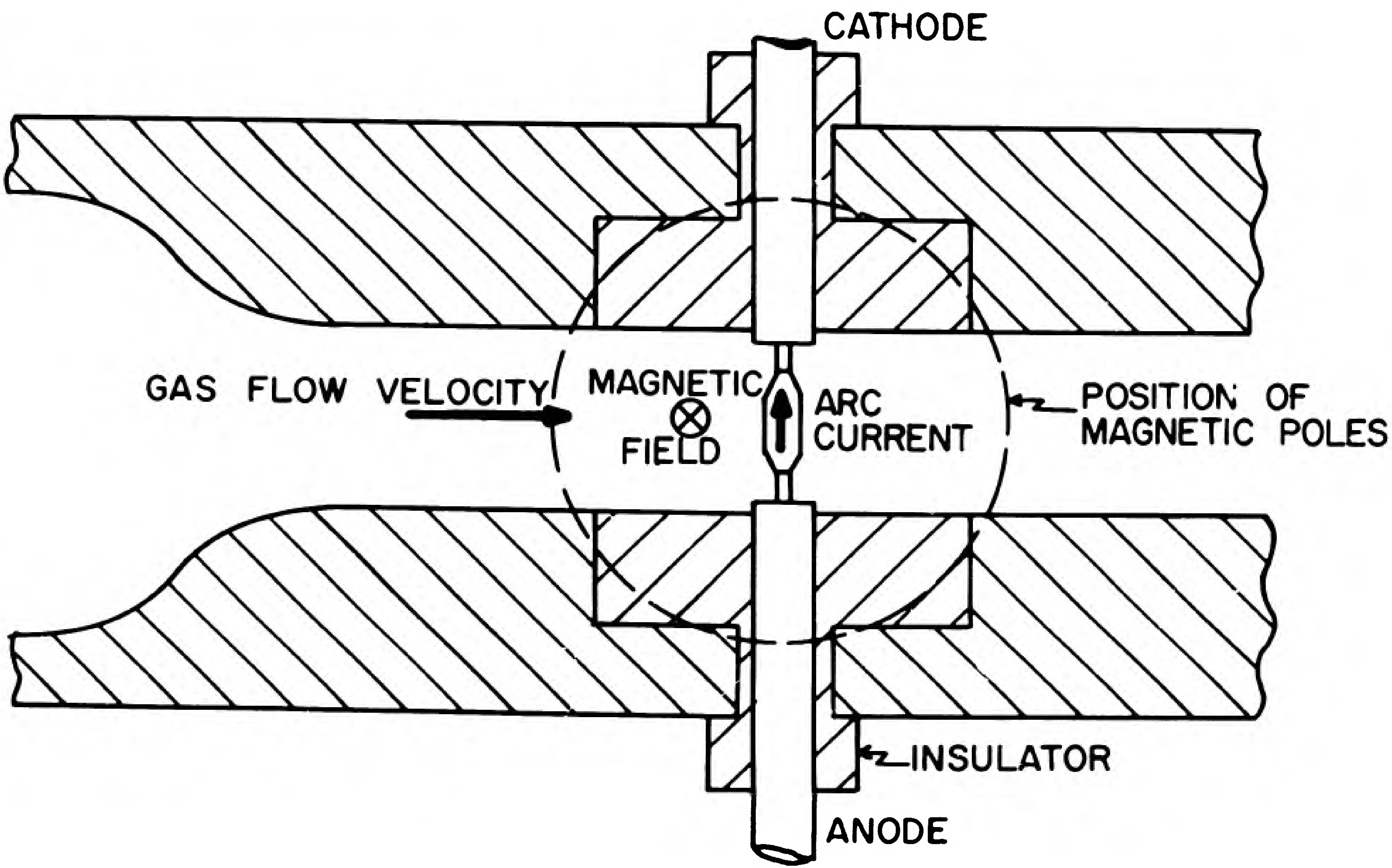


FIGURE 23 - CONFIGURATION FOR SUBSONIC BALANCED ARC STUDIES (79).

sonic gas flow on a solid cylinder. The assumption that the arc could be replaced by a solid cylinder with a diameter varying directly as the current satisfactorily explained the relation between the gas flow velocity and the external magnetic field required for balancing. The balancing was found to be proportional to the velocity squared and independent of the arc current. The arc characteristic curves were found to be typically negative with the arc voltage increasing as the magnetic field was increased. An analysis was made to predict the dependence of the column voltage gradient on the magnetic field. This compared favorably with the experimental data points. The results indicated that the column voltage gradient increased nearly linearly with increasing external magnetic field (constant arc current). An analysis similar to that of Thiene's was applied to give an estimation of the electric arc cross-sectional area. (Thiene's C_D value was used to obtain the arc diameter.) Because of the positionment of the electromagnet and tunnel configuration used, no high-speed pictures were possible, however, the discharge was visually observed to pulsate intermittently in the stream direction (similar to Smith and Early). From the assumed arc cross-sectional area, the theories of non-equilibrium conductivity were applied to estimate the dependence of the arc's average electrical conductivity on the magnetic field in addition to an estimate of the electron temperature.

The data obtained experimentally best fit the equation $\sigma_{B_\perp} = \frac{1}{1+\beta^2}\sigma_o$ where $\beta = \omega t$, ω = electron cyclotron frequency, t = electron collision time, $\sigma_{B_\perp}$ = electrical conductivity perpendicular to the magnetic field and σ_o = electrical conductivity before the external B field is applied. Therefore, the conductivity decreased by a factor of $1 + \beta^2$ upon applying the external transverse magnetic field. Questionable aspects of the experiments were:

1) the applicability of conductivity equations,
2) the electrode effects combined with magnetic field effects in the electrode region,
3) temperatures assumed for heat transfer and energy calculations,
4) neglect of heat loss to electrodes (especially for such short test times),
5) method of estimation of positive column voltage gradient and electrode drops, and
6) questions concerning arc shape, stability, and behavior during test data measurement.

Kookekov (74) studied the motion of an electric arc with transverse blowing under the influence of an external, transverse magnetic field. The objective was to obtain experimental data on the arc current, voltage gradient, and velocity relationships. No description of the experimental set-up, measurement techniques, or range of parameters was reported. A semi-empirical analysis was made based on the conservation of energy, Ohm's law, and the minimum principle to obtain the relation $E = A\sqrt[3]{V^2/I}$, where A was found from the experimental data. By assuming that the energy input to the arc was equal to the convective heat transfer losses, along with independence of ρ, h, σ and r on I and V, the relation $EI/V = A\,(I^2/V)^{1/3}$ was obtained. This, combined with empirical data led to the final result $V = 0.595\sqrt{B/M}\,\sqrt[3]{I/\rho^2}$. (M was undefined.) From the experimental results and the fact that the ionized particle density was found to be

4 to 5 orders of magnitude lower than the values for an isolated arc led Kookekov to the conclusion that there is turbulence in the transverse blown arc. Questionable aspects of the investigation were these:

1) neglect of radiation and conduction heat transfer and
2) independence of ρ, h, σ, and r on I and V.

Roman (82) investigated a magnetically balanced arc in the open-flow configuration shown in Fig. 24. Argon injection was used around the thoriated tungsten cathode. A coiled copper anode was used. A two-inch square nozzle was used to blow a subsonic stream of air at atmospheric pressure and at velocities up to 60 ft/sec against a central two-inch portion of a vertical electric arc column of 200 to 400 amperes. The electrode regions were partially isolated from the section of the arc column under study by water-cooled copper locators. The arc was held stationary against the flow by external magnetic fields up to 50 gauss produced by an iron-core electromagnet.

Miniaturized pitot, enthalpy, and heat flux probes were used to determine the velocity and energy distribution in the region downstream of the arc. Other probe measurements determined the electrical potential distribution along the arc positive column. Flow visualization with a micron-size particle injection scheme was used in conjunction with high-speed 7000 frames/sec photographic techniques to study the gas flow pattern near the arc boundary and in the wake region. Typical photographs are shown in Fig. 25. The photographs are oriented such that the camera is looking upward along a line at a slight angle to the arc column. The flow visualization studies showed a distinct wake, symmetric on both sides. The arc appeared impervious to the transverse flow. The velocity profiles measured downstream of the arc showed the wake structure to be similar to that of solid bluff bodies. However, the arc wake was considerably wider than that of a similarly sized circular or elliptical cylinder. Increasing the arc current distinctly broadened the wake, whereas increasing the transverse blowing velocity had little effect. Distinct vortex shedding was observed, photographed by high-speed cameras, with frequencies comparable to those of bluff bodies under similar Reynolds number conditions ($4 \times 10^2 - 4 \times 10^3$).

Simultaneous photographs of the arc column were taken along the flow axis and the magnetic field axis. The results indicated that the arc width in the direction transverse to the external flow become wider with increasing arc current and transverse blowing velocity. The arc dimension in the flow direction decreased approximately linearly with blowing velocity. The arc cross-sectional area remained practically constant.

The magnetic field strength required to balance the arc was proportional to the square of the blowing velocity. A drag coefficient was defined analogous to that of a solid cylinder. This coefficient had values between 0.7 and 1.1, agreeing closely with those of a cylindrical rod in the $4 \times 10^2 - 4 \times 10^3$ Reynolds number range.

As a result of the energy distribution measurements, the Nusselt number -

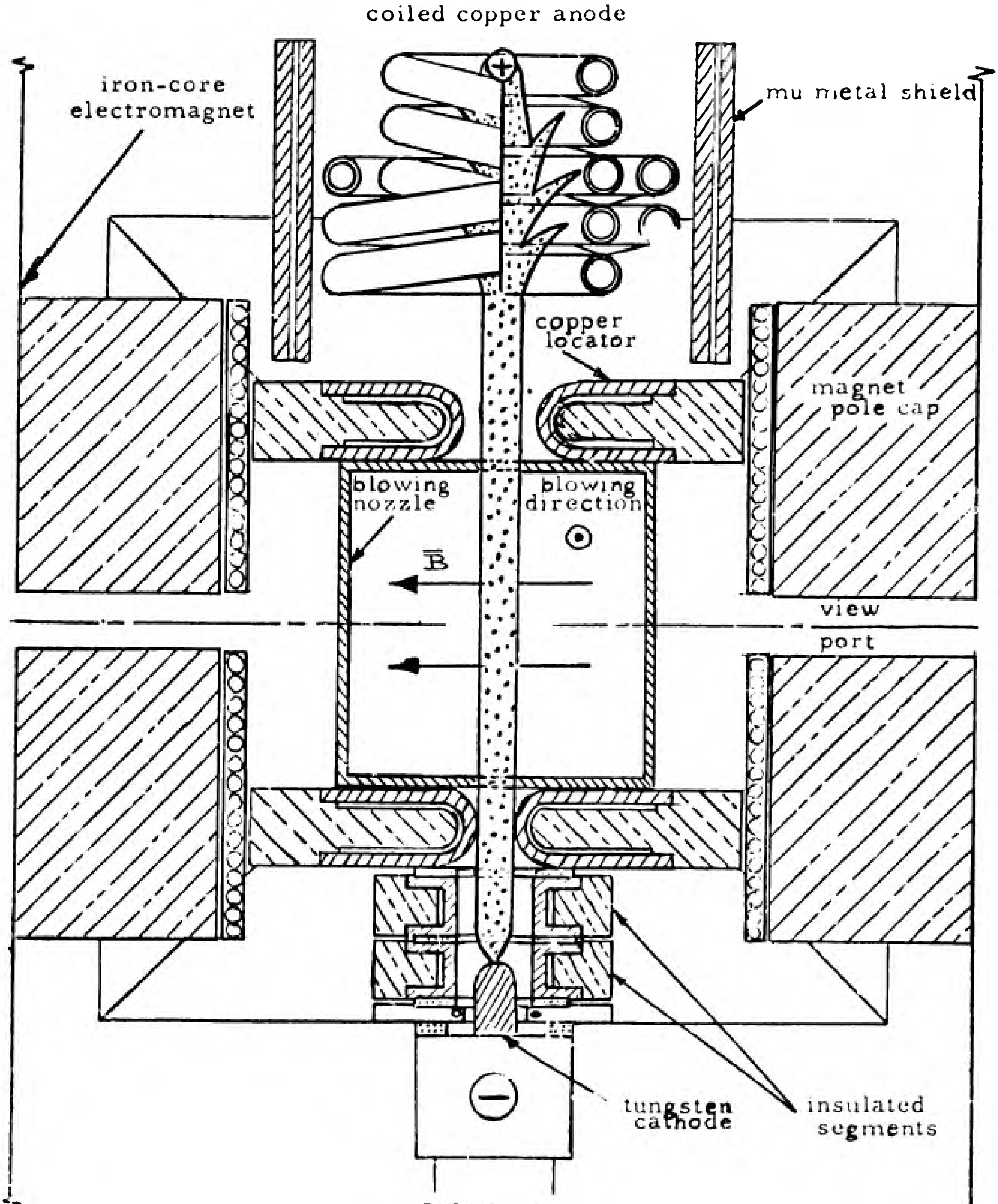


FIGURE 24 -

UPSTREAM VIEW OF CROSS-FLOW ARC TEST SECTION (82)

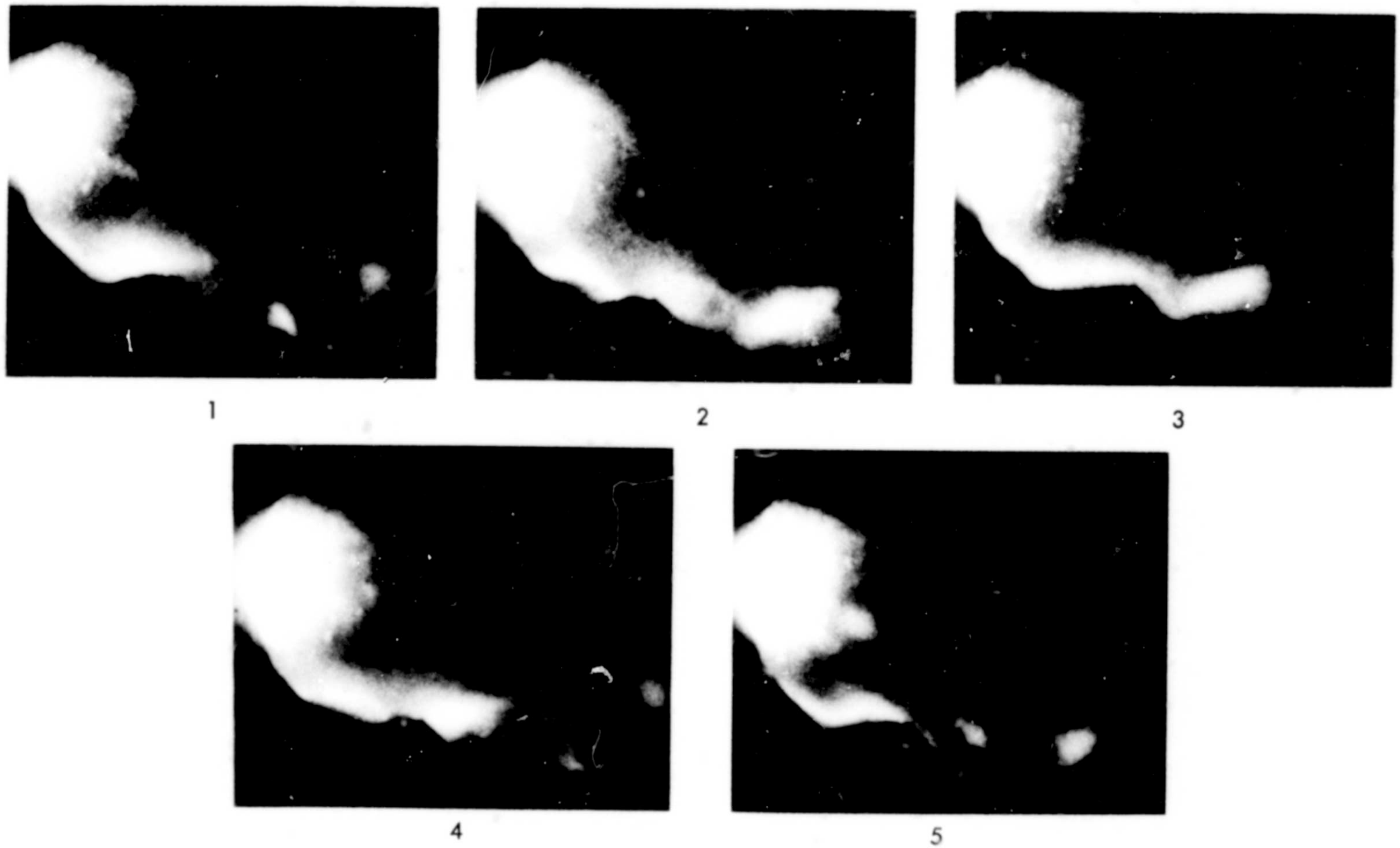


FIGURE 25 - WAKE FLOW VISUALIZATION , PARTICLE INJECTOR 3/8" OFF ARC CENTERLINE, I = 300 AMPERES, V = 35 FT/SEC. LEFT TO RIGHT, 7000 FRAMES/SEC.
(82)

Reynolds number plot shown in Fig. 26 was obtained and compared with Hilpert's curve for solid cylinders in a cross-flow. The only other comparable data, that of Lord and Broadbent (77), lies approximately an order of magnitude above Hilpert's curve. Roman's data were found to be reasonably near Hilpert's curve when an arc boundary temperature of 6000° K was used and the properties were evaluated at the mean or film temperature. Comparison of the energy distribution results with the voltage gradient results showed that the convective energy transfer per unit arc length was approximately equal to the additional energy per unit arc length above what was required in the free-burning mode.

It was impossible to extend the tests to higher blowing velocities and magnetic fields due to erratic arc behavior near the top locator and in the anode region. Some questionable aspects of the experiment were:

1) the effect of the relatively strong vertical jet from the cathode region,
2) the injection of argon in the cathode region and blowing with air; i.e., which gas properties should be used in the various regions and
3) the effect of the magnet walls and other adjacent boundaries on the arc wake.

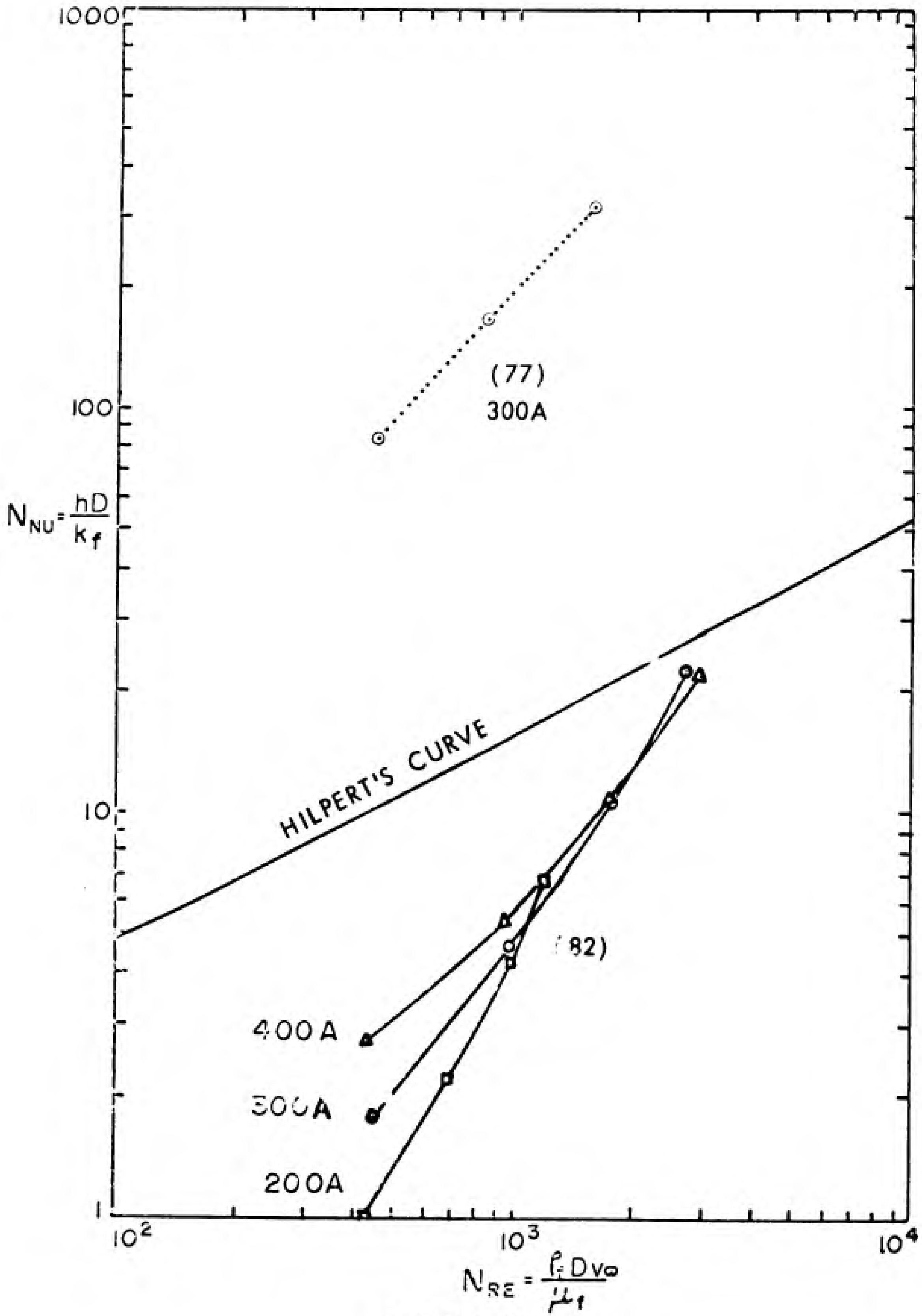


FIGURE 26 -

LOG - LOG PLOT OF NUSSELT NUMBER VS. REYNOLDS NUMBER

SECTION X. GENERAL SUMMARY OF STATIONARY ARC PHENOMENA

EXPERIMENTAL STUDIES

The number of experimental studies which have been made on the stationary arc is too few to allow definite conclusions to be reached, but only trends to be indicated. The investigations of the stationary arc in supersonic flow have generated more questions than they have answered. For instance, why does the arc assume a characteristic slant and why does it show the strong preference for the boundary layer of a supersonic tunnel? Little progress has been made toward understanding the nature of the stationary arc's interaction with the supersonic flow. No localized property measurements have been made in the arc or in the gas stream near the stationary arc region.

Similarly, the stationary arc in subsonic flow has been the subject of only a few investigations. However, relatively more trends can be indicated than for the supersonic case. As shown in Fig. 27 the three studies to date have spanned a large range in velocity and magnetic field strength and all indicate that the velocity is approximately proportional to $\sqrt{B}$. Thus, the analogy of the conducting cylinder with aerodynamic drag appears to be the best model for the stationary arc at present. This model is also indicated by the heat transfer measurements (Fig. 26) and the flow visualization work of Ref. 82.

Broadbent (67) suggested that use of the parameters EI, BI/V and V^2I/E (E = voltage gradient, I = current and V = velocity) may reduce the stationary arc data. He found that these parameters reduced the data of Adams (1) reasonably well even though Adam's work was not performed with a stationary arc, but with an arc in annular gap. Such a parametric plot of the data of Myers (79) and Roman (82) is shown in Fig. 28 along with Broadbent's reduction of Adam's data. The BI/V vs. V^2I/E data shows a better collapse than the EI vs. V^2I/E data. It appears that at least in the latter case, these parameters do not effectively collapse the arc data.

All of the stationary arc studies in subsonic flow have been of a preliminary nature and no measurements have yet been made at the boundary between the arc and flow to show the energy exchange mechanisms or inside the arc to determine its internal structure. Reason compels one to expect the stationary arc interactions in these regions to differ significantly from the conducting cylinder analogy. Considerable work is also needed at different pressure ranges and with different gases.

Even though the conducting cylinder analogy for the stationary arc and the column dominated travelling arc is the most satisfactory to date, its use results in a wide variation in drag coefficients. The range of drag coefficients is shown in Table 1, which also serves to summarize the parameter range of several of the travelling arc and stationary arc investigations. Some of the differences in the value of the drag coefficient, C_D, may be due to the experimental methods used. The C_D values obtained from wall width measurements are open to question. Even

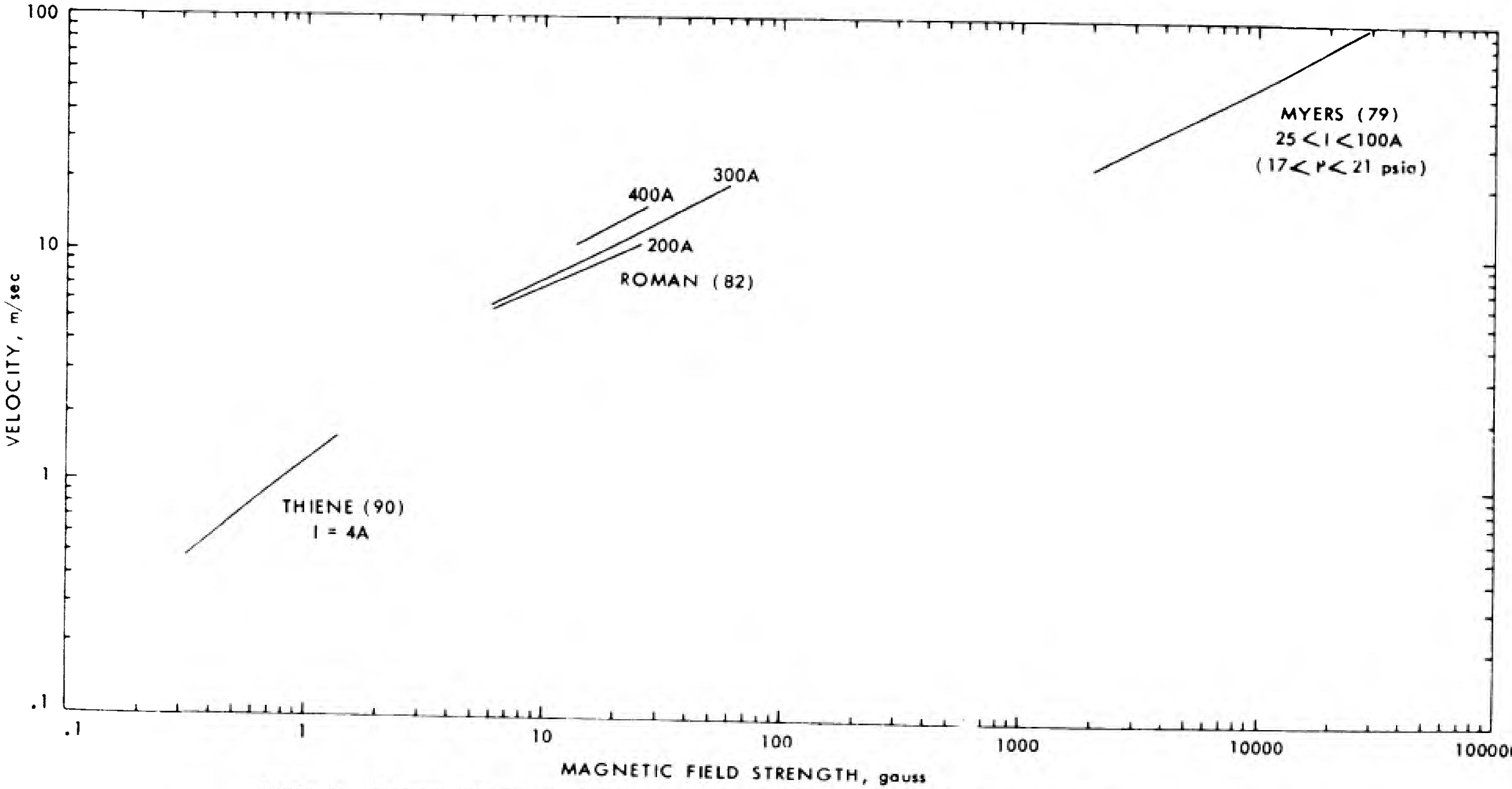


FIGURE 27 - BLOWING VELOCITY-MAGNETIC FIELD DEPENDENCE FOR BALANCED, ATMOSPHERIC PRESSURE ARGON ARCS.

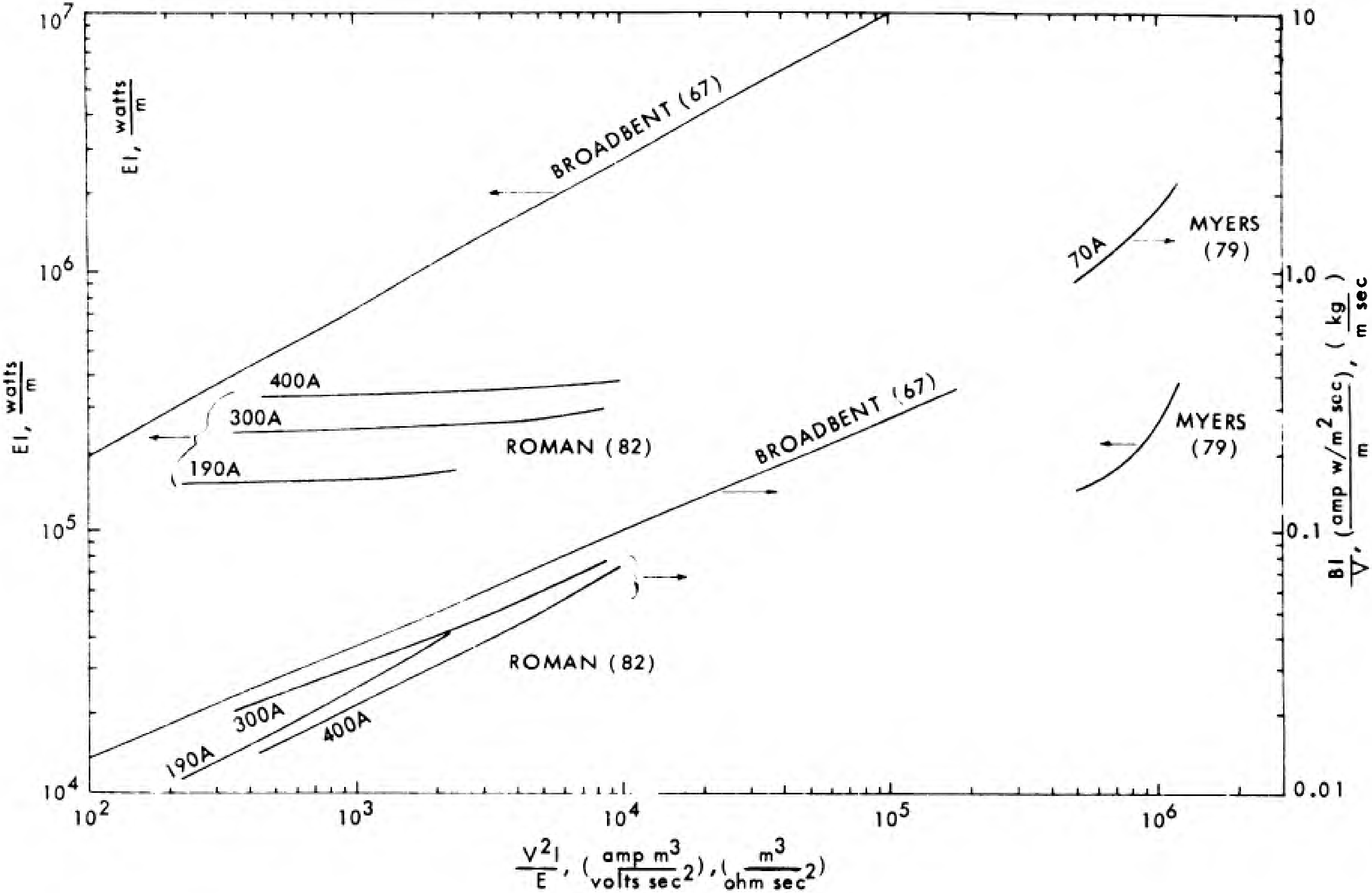


FIGURE 28 - EXPERIMENTAL RELATION BETWEEN BI/V, EI AND V^2I/E.

INVESTIGATOR	CONFIGURATION	I_{arc} (amps)	B_{ext} (gauss)	V (m/sec)	C_D	DETERMINATION
Steenbeck and Von Engel (see p. 35)	Parallel rail electrodes	2	10	1	0.4-0.9	From measured arc diameter
Angelopolos (3)	Parallel rail electrodes	85-980	0-800	$\leq$ 250	6.7-10.1	Arc diameter was estimated from the side wall spacing
Blix and Guile (6)	Ring electrodes in two planes	80-400	340-1060	$\leq$ 200	0.63	Postulated from solid cylinder analogy
Féchant (18)	Vertical parallel rail electrodes (with side walls)	300-5000	20-5000	$\leq$ 500	1.6-[illegible].5	From wall width measurement
Adams (1)	Annular ring electrodes	100-760	60-940	$\leq$ 187	1-5	Photographically measured arc diameter
Jedlicka (34)	Concentric cylindrical electrodes	Purely theoretical investigation			0.63	Postulated from solid rod analogy in turbulent flow regime
Hesse (29)	Parallel rail electrodes	95-800	none - driven by self-magnetic field	$\leq$ 130	0.344	Photographically measured arc diameter
Thiene (90) $P \approx$ 1 atm. - argon	Horizontal opposing pin electrodes within vertical wind tunnel	4	$\leq$ 1.4	$\leq$ 1.55	6.3	Photographically measured arc diameter
Lord and Broadbent (77)	Concentric cylindrical electrodes	150-700	60-940	28-270	0.7-1.5	Photographically measured arc diameter
Myers (79)	Vertical opposing pin electrodes within horizontal wind tunnel	20-100	2000-28500	$\leq$ 100	6.3	From Thiene
Roman (82)	Vertical arc subjected to transverse air flow	200-400	0-50	$\leq$ 20	0.7-1.1	Photographically measured arc diameter

TABLE 1 - C_D ESTIMATION BY VARIOUS INVESTIGATORS

the photographic measurements of an appropriate arc diameter is subject to considerable interpretation.

THEORETICAL STUDIES

As a consequence of reviewing each of the directly pertinent investigations in detail, some general features and effects of the cross-flow phenomena (both with or without external transverse magnetic fields) which any generally acceptable complete theory should explain for the high pressure case are listed below. In some parameter ranges, several of these effects may be neglected. (It should be re-emphasized that the cross-flow arc interaction phenomena, both with or without external transverse magnetic fields, which have been reported in the literature were determined with a variety of electrode and external field configurations and also under vastly different parameter ranges. Therefore, any correlation between the many different investigations is extremely difficult.)

Cross-Flow Only

1) arc curvature (including blowout criteria)
2) arc cross-sectional shape
3) electrode material effect
4) electrode shape and arrangement effect
5) electrode jet effects (with corresponding induced axial gradients)
6) free-convection effect
7) drag effects
8) heat transfer effects
9) temperature distribution
10) property variations as a function of temperature
11) effect of enclosing the arc with channels of different geometry.

The theory, in addition to describing the above effects, should then clarify some of the following areas:

1) pervious versus solid body model (or a combination of the two)
2) occurrence of internal double-vortex (including shear effects at boundary)
3) laminar or turbulent flow (both within and surrounding arc column) and
4) mechanism of heat transfer inside the arc, through the boundary, and to the external flow.

Cross-Flow with External Transverse Magnetic Field

In addition to those effects listed under cross-flow only, the following are present:

1) external magnetic field interaction,
2) self-magnetic field interaction and
3) the electrode field interaction effect.

Travelling Arc

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4 Babakov, N.A., "Speed of Motion of a Short Electric Arc", Elektrichestov 7, 74 (1948).

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APPENDIX

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13 ABSTRACT

This report summarizes and evaluates the existing literature related to the interaction of an electric arc at pressure levels of one atmosphere or greater with magnetic fields and/or aerodynamic fields which are transverse to the arc column. The scope of this survey does not include the subject of retrograde motion.

For the purposes of this survey, the subject is broken up according to whether or not there is net arc motion with respect to the electrodes. When motion occurs, the arc is designated a travelling arc; this is the type of arc which occurs in rail accelerators, arc heaters utilizing magnetically rotated arcs and electric switchgear circuit breakers. When the arc undergoes no net motion with respect to the electrodes it is designated a stationary arc; this type occurs when the arc is balanced in a transverse gas flow by an appropriate transverse magnetic field.

This report summarizes the results of the various investigations and presents them graphically for easy comparison. General conclusions which may be drawn from the investigations are presented.

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