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I. Summary

First results are presented of an experimental investigation of the effects of supersonic convection on the positive column of a direct-current electric arc. The experimental setup consists of two rail electrodes mounted in a supersonic wind tunnel and oriented parallel to the tunnel free stream. External coils provide a transverse magnetic field which is mutually perpendicular with the arc current and free stream. The coils are placed such that there is a monotonic increase in flux density from the upstream to the downstream ends of the rails. The arc is initiated by means of an exploding wire between the upstream ends of the rails. The plasma column generated is then convected downstream along the rails by the supersonic flow until a point is reached where aerodynamic and electromagnetic forces come into balance. The arc remains in the vicinity of this point until the current is shut off.

Initial experiments have demonstrated that the arc can be successfully held in the supersonic flow by two distinct mechanisms. With both mechanisms confinement is achieved primarily through dynamic processes in the positive column and for a given current and magnetic field, arc location is independent of root phenomena. The first mechanism requires sufficient external magnetic induction to hold the arc at locations where the electric field is essentially two-dimensional, remote from the rail ends. In this case confinement is due to the magnetic Lorentz force, and stability in the streamwise direction results from the increase in Lorentz force with downstream displacement. With the second mechanism the arc is held at the downstream ends of the electrodes by a much weaker magnetic field than is necessary for pure magnetic confinement. In this case, though some external magnetic field is necessary for confinement, large changes in magnetic flux density can be made without affecting arc root location. Indications are that arc curvature and a "fringing" electric field, as well as the magnetic field, are essential to this mode of confinement.

A simple derivation shows that heat-blocking imposes a limitation on possible combinations of arc power W, Mach number M, and free stream stagnation pressure, P_{t_1} which depends only on M and W/P_{t_1}. This limitation is observed experimentally to occur at higher values of W/P_{t_1} than calculated, probably due to heat loss at the walls and electrodes.

II. Introduction

Investigations[1-11] of the convected electric arc which involve motion of the arc relative to the electrodes are complicated by a coupling between the mechanisms for root motion with those for motion of the positive column. Arc velocity is found to vary not only with cathode surface conditions but also with parameters such as arc length and circuit inductance which are essentially operative through the positive column.

The integrity of the arc is maintained principally through the ability of the column to change in length and shape readily. As a result the arc column is forced into extremely unpredictable and complicated shapes and fluctuations in shape.

Experiments under conditions where arc motion is independent of root phenomena would not only reveal the role played by dynamic processes in the positive column in determining overall arc behavior, but might also produce a column sufficiently stationary and long-lasting to allow the diagnostic measurements necessary for detailed analyses of the role played by convection in the column mechanism.

Such an experiment might be performed by holding an arc column in the free stream of a conventional wind tunnel. In this case the arc would not be required to move over the electrodes, and hence the roots, once established, might have no effect on the convected column. The wind tunnel would provide the additional feature of being itself a precision instrument capable of producing very uniform flow conditions over a wide range of Mach number and pressure.

Use of the wind tunnel for arc studies hinges on solution of the problem of arc confinement. This paper presents a discussion of some of the problems peculiar to wind tunnel arc research and describes a method which has been devised for the magnetic confinement of a high current d-c electric arc in the free stream of the 4 x 7 in. Supersonic Wind Tunnel of The University of Michigan.

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Only such results are discussed as pertain to the problem of confinement. A forthcoming report[12] will include a more extensive discussion of results of the overall investigation, as well as some observations of arc behavior which have a bearing on confinement, but which are beyond the scope of the present paper.

III. Experimental Setup

The experimental setup consists of two rail electrodes mounted in a supersonic wind tunnel—oriented in a vertical plane and parallel to the free stream (Figure 1).

External coils provide a transverse magnetic field essentially perpendicular to the plane of the electrodes (Figure 2). The arc is initiated by means of an exploding wire between the upstream ends of the rails. Energy is supplied through the electrodes to the resultant plasma by an external circuit consisting of a large d-c generator connected in series with a ballast resistor (Figure 3). The same generator supplies power to external field coils which are energized 3 sec prior to arc ignition.

A. Electrodes

Each electrode is a cone-cylinder about 6 in. long with a 7-1/2° half-angle cone and 1/2 in. diam cylinder (Figure 4). The electrodes are connected electrically to insulated standard cables which carry the current downstream from the electrodes and out through Plexiglas ports in opposing sides of the tunnel (Figure 5).

The cone angle of 7-1/2° was chosen to limit the disturbance to the flow. It produces a very weak conical shock at $M = 2.5$, the shock angle being within about 1° of that for an infinitesimal disturbance. The length of the electrodes was made roughly equal to the test rhombus length. The electrodes are uncooled; and electrode diameter was, consistent with structural considerations, minimized to allow tunnel starting at low Mach numbers.

B. Electrode Sleeves

A 1 in. brass sleeve separates the base of the electrodes from the support strut (Figure 4). This sleeve is insulated with Teflon and serves to prevent damage to the struts caused by multiple arcing.

C. Electrode Support Struts

The support struts have leading-edge half-angles of 5°, and will therefore maintain shock attachment down to $M \sim 1.3$. The struts are mounted from Plexiglas windows and are insulated from the tunnel and the electrodes.

D. Wind Tunnel

The 4 x 7 in. supersonic wind tunnel is a blow-down type with Mach number variable between 1.4 and 4.0 and with run times around 2 min.[13] It has a 4 x 4 in. test section which exhausts into the top portion of a 4 x 7 in. channel (Figure 1).

This wind tunnel has been used for studies of supersonic jet mixing,[14] for which a second supersonic stream exhausts into the lower portion of the 4 x 7 in. channel. For the present investigation this lower channel has been plugged (Figure 1).

The expansion fan from the channel enlargement crosses downstream of the electrodes, which are mounted in the uniform supersonic flow of the test rhombus (Figure 6). The channel enlargement probably serves a useful purpose in allowing the heated air additional expansion (see Section V).

The side walls of the tunnel consist of large 3/4 in.-thick windows which extend from the throat downstream past the test rhombus, allowing optical observations of the flow in any part of the nozzle not obscured by external apparatus (Figures 1, 5, and 7).

For the present investigation, the walls(or windows) are made of Plexiglas to allow simple installation of pressure orifices when needed, to facilitate installation of electrode support struts, and to avoid problems which might result from thermal stresses in glass walls. The Plexiglas windows reduce the effectiveness of Schlieren photography (although not completely—see Figure 8), especially in areas which have ablated slightly due to heating.

For normal photography, the Plexiglas is quite satisfactory, and Fastax observations of the arc over a fairly wide angle are made possible by the large windows (Figure 5).

The tunnel is so constructed that it is possible to mount the 13 in. diam field coils flush with the outside surfaces of the windows (Figure 5).

E. Field Coils

The electromagnet consists of two coaxial coils, located on opposite sides of the tunnel. Each coil contains 11 pancake segments. Each pancake is 1 in. thick, about 12 in. in diam with a 3 in. hole through the center. The pancakes are connected in series electrically but are connected to the cooling water supply in parallel. Each consists of 20 turns of 3/8 in. x .065 in. copper tubing and is capable of carrying at least 2400 amp of continuous current without overheating. The copper tubing is insulated with plastic tubing and each pancake is held in shape by epoxy resin.

The distance between the two external field coils, including end plates, is about 6 in. The maximum flux density on the tunnel centerline is about 6400 gauss with 2000 amp flowing through the coil. The flux density was found to be proportional to the coil current over a wide range of current and at several points in the test section; a sample curve is given in Figure 9.

The calculated variation of B_y, the transverse component of magnetic induction, is given in Figure 10. Measured values of B_y are given in Figure 11.

The field coils are so mounted that they can be placed in various streamwise locations. Thus the location of the peak induction can be moved relative to the electrodes and/or test rhombus.

F. Generator

The arc power supply is a d-c generator rated at 600 v and 1600 amp. For the present investigation it is connected for self-excitation. Its characteristic is quite flat out to 2400 amp at 600 v terminal.[15] The generator field rheostat provides fine control on terminal voltage in the arc circuit.

G. Ballast Resistors

The ballast resistors for the arc and coil are identical.[15] Their grids are cooled by radiation and convection. Possible values of resistance are from about .01 ohm to about 1.3 ohm. These resistors provide a simple means for changing arc current and coil current independently.

H. Arc Power Circuit

The arc power circuit is shown schematically in Figure 3. Since the wind tunnel is grounded, the power circuit is left ungrounded to lessen the likelihood of arcing to the upper and lower tunnel walls.

IV. Arc Confinement

A. Approach

Although confinement is only one factor in arc stabilization,[15] it is the added instrumentality essential to making arc research in the wind tunnel possible. Smith and Early[16] observed a dominant tendency for a low-current arc to follow the low density, low velocity boundary layer around a supersonic mainstream, in some cases forming a column of length many times the distance between electrodes.

In addition to the boundary-layer question there is also the problem of avoiding excessive sidewise fluctuation of the column. Some investigators using the rail-accelerator approach have made use of guide walls which prevent sidewise bulges in the column. The effects of these guide walls on arc behavior has been shown to be profound.[2]

Magnetic fields have been employed in a variety of cases for the stabilization of moving arcs.[17-20] Moreover, for a high-current electric arc, even without magnetic stabilization, there can be profound magnetic effects due to the field from the input power cables.[17]

In principle the use of magnetic fields for wind tunnel confinement of an electric arc requires merely the provision of a magnetic field directed such that B, j, v forms a positive orthogonal triple. The magnetic Lorentz force on the column can then balance the aerodynamic resistance force. There are two basic difficulties in the application of this principle.

First, unlike the rail accelerator approach, where a balance between aerodynamic forces is achieved through the mechanism of column acceleration, the wind tunnel approach requires that the balance of forces be achieved through provision of the correct flux density. At present, however, the required flux density cannot be calculated, and is in fact one of the items under investigation.

Second, as with all forms of confinement, there must be more than a balance of forces; there must be a stable balance.

The approach which was taken to the solution of the foreseeable confinement problems mentioned above can be itemized as follows:

1. To prevent arcing through the tunnel boundary layer, the electrodes are completely within the supersonic free stream—having no contact with the tunnel boundary layer. The electrodes are insulated from the supporting struts (Figure 4), and the supporting struts are mounted on opposite tunnel walls (Figure 1).

2. It was decided to observe the effectiveness of sidewise decreases in electric field strength and increases in magnetic field strength in preventing excessive sidewise bowing of the column. The electric field from the electrodes will appear, looking downstream, similar to that of an electric dipole, with greatest intensity between the electrodes. Since the arc column tends to follow lines of maximum intensity,

this field should exert a restraining influence on sidewise excursions of the positive column. It had been shown [3,8,9,21] that this restraining influence does not prevent sidewise bowing, bulging, and looping of the column in the rail-accelerator experiments; but the causes of this behavior had not been found and there was no certainty that bowing would be observed in the wind tunnel experiment.

The changes in magnetic field as the column moves to the side could have a stabilizing or destabilizing effect, depending on the column mechanism. The slight axial component of induction at points off the electrode plane (Figure 2) would tend to hold the column away from the center plane. On the other hand, the increase in the magnitude of the transverse component of the induction with distance from the electrode plane (Figure 10) make it unlikely that the column could bulge very far to the side and still maintain a stable balance of forces all along its length. Since guide walls would defeat most of the aims of the investigation, their use was ruled out.

3. To discourage arcing to the wind tunnel walls the external arc circuit was kept electrically ungrounded. Although double arcing from anode to tunnel and tunnel to cathode is still conceivable, it is much less likely than would be a single ground-loop arc from one electrode to the tunnel which could occur if the external circuit were grounded.

4. To increase the likelihood of correct choice for the magnitude of B_y, a range of values for B_y is provided by the use of rail electrodes in a region of changing B_y.

5. To provide a balance of forces stable to streamwise perturbations in arc location, the rail electrodes are placed relative to the external field coils such that there is a monotonic increase in B_y in the downstream direction.

With this scheme of confinement the hope was that the plasma column generated by the exploding wire between the upstream ends of the electrodes, where the magnetic field is weakest, would be convected downstream to a point where the magnetic induction would be sufficient to provide a (stable) balance between the aerodynamic force and the Lorentz force.

B. Arc Establishment

The conditions, if any, under which the above approach to arc confinement would be efficacious could not be predicted a priori because they depend upon the unknown column mechanisms which are under investigation. Initial tests, therefore, were concerned with experimental study of the transient processes which occur during the establishment of an arc.

These initial tests of arc establishment were made with the arc electrodes connected in series with the external field coils. For series operation the starting fuse-wire must be sufficiently large to allow the current to build up before arc initiation to a point where the external field is sufficient to prevent convective extinguishment of the nascent arc. The three types of initial arc behavior observed are described qualitatively below.

(a) Arc collapse or blowout. For many runs arc collapse occurred at the beginning of the run—that is, the arc was never fully established. For a few runs the arc was extinguished after seemingly stable conditions had been attained. Arc collapse in almost all cases could be obviated by lowering the free stream stagnation pressure, or strengthening the external magnetic field. (It was later found that arc collapse can result from the use of an insufficiently large fuse-wire even when the external field is completely established by a parallel circuit before arc initiation.)

Figure 12a shows the voltage-current time history for arc collapse. The current through the field coils is seen to be only about 500 amp when the voltage buildup signals arc initiation. The external field is too weak to prevent arc blowout. The arc current goes to zero while the electrode voltage goes to the terminal valve.

(b) Arc confinement. For the proper conditions the arc will be established and confined. Figure 12b shows a voltage-current time history for this case. It is seen in this figure that there is an initial buildup of arc (and coil) current to about 1000 amp with little increase in electrode voltage. During this buildup the firing wire remains intact while the magnetic induction increases with the current. Next there is a rapid buildup in arc voltage, signaling arc initiation. The arc voltage increases to a value very near the characteristic of the external circuit. After this the arc evidently traces out a portion of its static voltage-current characteristic until it intersects the characteristic of the external circuit at the point of Kaufmann stability.

(c) Arc mislocation. For the arc just discussed, the power input was great enough to cause flow reversal in the boundary layer on the lower tunnel wall. Figure 12c shows the characteristic of an arc where this reversed flow caused the arc to strike momentarily from electrode tip to the lower tunnel wall. In this case it can be seen that the arc at first traced out a voltage-current path similar to that for arc blowout, Figure 12a. But here the arc is blown in the upstream direction, finally striking to the lower tunnel wall. It then begins to trace out a portion of the characteristic for a new arc configuration. This new configuration however, apparently results in changes in the velocity field which extinguish it, causing a final portion of the voltage-current trace which is again similar to that for arc blow-out. (Damage to the tunnel was slight and reparable.)

C. Modes of Arc Confinement

Initial test runs established that currents over about 1200 amp result in levels of arc energy addition too high for undisturbed tunnel flow (see Section V). In order to operate at lower arc currents and yet maintain high currents through the external field coils, the arc power circuit was revised to allow operation of the arc in parallel with its field coils. This revised circuit has been described in Section III and shown in Figure 3. With the parallel circuit the external field is established a few seconds before the arc breaker is closed so that firing-wire size is not as critical as with the series circuit.

Initial tests also led to several changes in the design of the electrodes, electrode mounts, and windows. The design described in Section III incorporates these changes.

Figure 12d gives the voltage-current history of an arc with a steady-state current around 300 amp between electrodes of the latest design. Here the power is low enough so that there is no disturbance to the supersonic free stream ahead of the arc. Current to the field coils is about 2000 amp. Runs such as this which resulted in arc confinement in undisturbed supersonic flow can be divided into three categories according to root location.

(1) Root strikes to electrode tip. Fastax film shows these runs to be characterized by sidewise fluctuations in column location which are accompanied by large fluctuations in arc voltage (±15%) and by acoustical noise which can be heard above the wind tunnel noise. Figure 13a illustrates the appearance of the anode tip after such a run.

It is found that if the field coils are moved downstream sufficiently, or if the free stream stagnation pressure is increased sufficiently, the arc roots will both strike downstream of the shoulder of the electrode cone tip.

(2) Root strikes to the electrode base. These runs are also characterized by fluctuations in the column location, arc voltage (±20%), and by acoustical noise. Figure 13b shows the appearance of a cathode after such a run. If Teflon washers are placed around the cathode (Figure 13c), the root location will remain at the base. This indicates that root convection is not the cause of the downstream root location. If saw-tooth ridges are cut in the cathode (Figure 13d), the root will remain at the base. This indicates that electric field concentration at the base is not the cause of the downstream root location. The magnetic flux density can be varied over a wide range, for example from about 700 to about 3000 gauss, without causing either the roots to move upstream or the arc to extinguish. If the flux density is zero, the arc cannot be established. If the flux density is raised enough or the pressure lowered enough, the roots will strike upstream of the electrode base.

These observations indicate that arc confinement in this mode is based on dynamic processes in the positive column. The mechanism is probably related to arc curvature and dependant upon the "fringing" electric field in the base region in a manner similar to that treated by Rother[22] and Thiene.[23] In this case however a magnetic field is also present and exerts a stabilizing influence on the column.

From measurements in this mode of arc confinement no inference can be made of the relation between magnetic induction and the velocity of an arc column moving through a two-dimensional electric field.

(3) Root strikes along electrode cylinders, upstream of base and downstream of cone. In this case the arc column shows little or no lateral fluctuation, little voltage fluctuation (±4%), little current fluctuation, and no audible noise. Teflon flow baffles have no effect on cathode root location, indicating that confinement is due to column processes. If the external coils are moved in the streamwise direction, the arc roots will follow that motion, provided they can do so without striking to the electrode tip or base. This indicates that confinement in this mode is based purely on the external magnetic field. Changes in electrode material have no measurable effect on arc location (Figure 14). Figures 13e, 13f, and 13g show typical marks left by the arc roots in this mode.

For copper electrodes the cathode root usually occurs at spots (points B and C, Figure 15) near the "far side" of the cathode, away from the anode. Figure 13h shows the cathode appearance after the run. A tendency for the cathode root to strike on the far side is also noticeable for other electrode materials. For carbon cathodes the root can be seen to occasionally move around to the far side only to be immediately re-established at a thermionic site on the near side (point A, Figure 15).

It is believed that the tendency to strike to the far side of the cathode is due to the slight streamwise component of the magnetic induction which exists at points to the side of the center plane (Figure 2). When the cathode root makes an excursion to either side of this plane, it moves into a region where the streamwise component is finite. There is then a force on the root tending to move it farther toward the far side of the cathode (Figure 15). This same induction component also exerts a force on the column, tending to hold it away from the electrode (Figure 15).

In the case of carbon the near proximity of the column eventually results in sufficient heating of the near side of the cathode (point A, Figure 15) to establish a thermionic site there. For copper there seems to be a similar tendency though it is seldom manifest. In this case the new root moves, perhaps aided by an oxide layer, from B past A to an opposite far-side point C. Motion of the root around the cathode is accompanied by fluctuations in the column.

Figure 14 shows the measured variation with P_{t_1}, the free stream stagnation pressure, of B_c, the magnetic induction at the cathode root, for pure magnetic stabilization. It is to be noted that this figure includes data obtained using four cathode materials, and three inter-electrode gap distances. Data obtained with electrode polarity (and external field direction) reversed are also included. The fact that these points define a single curve offers strong confirmation of the conclusion that confinement in the pure magnetic mode is independent of root phenomena.

V. Limits on Experimental Conditions

Many of the limits on experimental conditions for the wind tunnel approach to convected arc research can be derived in advance. These include (1) limits related to the performance of the wind tunnel alone,[13] (2) limits related to the capability of the electrical power supply and control system,[15] and (3) limits imposed by the union of the tunnel and arc facilities.

Limits of types (1) and (2) for the present investigation are discussed in the cited references; they are outlined in the following table:

Mach number: 0.1 to 0.5; 1.4 to 4.0
Free stream stagnation pressure: 0 to 30" Hg
Arc current: 0 to 2400 amp
Arc voltage: 0 to 600 v
Arc power: 0 to 1.5 megawatts

Limits of type (3) include these due to simple geometrical considerations:

1. A maximum electrode gap (about 1-1/4 in.) to avoid interaction with the tunnel boundary layer.

2. A maximum electrode length (around 6 in.) to keep within the test rhombus.

3. A maximum magnetic induction (about 15000 gauss) due to the tunnel width and structure.

4. A maximum permissible magnitude of column fluctuation (about 2 in.) to avoid arcing to tunnel walls.

5. A maximum area for the cross section of electrode and strut (about 0.7 in.^{2} at M = 1.4 in 4 x 4 in. section) to allow tunnel starting.

Perhaps the most important limitation peculiar to wind tunnel arc research is due to thermal blocking or choking of the tunnel flow. This phenomenon limits the ratio (W/P_{t_1}) of arc power to free stream stagnation pressure for a given M. This can be shown as follows: Assume that the energy from the arc is added uniformly to the free stream.

Then

$$Q = \frac{W}{\dot{m}} = C_p(T_{O2}-T_{O1})$$

where

W = arc power
$\dot{m}$ = mass flow
Q = heat added
C_p = specific heat
T_{O1} = initial stagnation temperature
T_{O2} = final stagnation temperature

The maximum heat addition permitted by the Rayleigh relation for the undisturbed free stream is that given by

$$\left(\frac{W}{\dot{m}}\right)_{max} = C_p(T_O^{*H}-T_{O1})$$

where T_O^{*H} is the stagnation temperature at the point where the Mach number is unity due to heat addition. For a given test-section size the mass flow is a function of Mach number and stagnation pressure. For a 16 in.^{2} test section and T_{O1} = 530°R, the above equation becomes

$$\left(\frac{W}{P_t}\right)_{max} = 0.024\left[\frac{(T_O^{*H}/T_{O1})_{M'}-1}{(A/A^*)_M}\right]\ \frac{MW}{"Hg}$$

Where $(A/A^*)_M$ must be evaluated at the design test-section Mach number in order to give the proper relation between $\dot{m}$ and M, but where $(T_O^{*H}/T_{O1})_{M'}$ must be evaluated at the section where uniform heating is assumed to occur. For rates of heat addition greater than that given by this equation, the nozzle flow can no longer remain undisturbed by the arc, and must in fact shock down to a subsonic Mach number where T_O^{*H} is great enough to accommodate the given rate of heat addition. The occurrence of thermal blocking would therefore be expected to cause dramatic changes in the flow configuration.

In the present case thermal blocking is preceded somewhat by separation of the flow from the lower tunnel wall, as can be seen from Figure 8b. This is probably due to feedback of the static pressure in the heated stream, which for near-maximum heat addition exceeds that required[24] to cause separation at the free stream Mach number.

Figure 8 gives examples of Schlieren pictures for two values of W/P_{t_1}. In 8b it is clear that the flow is separated from the lower tunnel wall. In 8c it is just as clear that the flow is not separated. Yet for 8c, with attached flow, the power level exceeds the maximum for heat blocking and one would expect a normal shock to occur somewhere in the nozzle.

Figure 16 gives a plot of the experimental measurements of the separation limit. It is seen that the experimental maximum is considerably above that given by theory even when A' is taken to be the maximum value possible in the first 30 ft of diffuser length, and even though the calculation does not account for diffuser friction. This discrepancy is probably due to heat losses to the electrodes and walls.

VI. Conclusions

1. It is possible to magnetically confine within the free stream of a supersonic wind tunnel a stable arc discharge sustained by an electric field essentially normal to the flow vector.

2. Root location for the confined arc is determined by processes in the column and is independent of material or flow conditions at the surface of the cathode.

3. With weak external magnetic fields, confinement is due to a column mechanism for which a fringing electric field and arc curvature are important. In this mode the arc occurs at the electrode base.

4. With strong external magnetic fields, confinement is due to a column mechanism for which the external magnetic field plays the dominant role. In this pure-magnetic mode of confinement, the arc occurs between the rails in a region where the electric field is essentially two-dimensional, at points determined by the streamwise location of the external field coils.

5. For pure magnetic confinement, a stable balance of forces on the column is provided by an external magnetic field with monotonic increase in transverse component from electrode tip to electrode base.

6. Pure magnetic confinement is characterized by high column stability.

7. Care must be exercised in applying data obtained from convection experiments where a curved arc is subject to the effects of a fringing electric field, such as that between the tips of colinear electrodes, to cases where the arc must move through a two-dimensional electric field.

8. Fluctuations in column characteristics which indicate that no steady balance of column forces is possible characterize arcs which strike to the electrode tip or base.

9. Sidewise column fluctuations which have been observed by investigators using rail accelerators are probably caused by differences between the equilibrium velocities of column and roots, which force accommodation through column fluctuation.

10. Heat blocking places a limitation on experimental conditions which can best be expressed in terms of W/P_{t_1} and M. The experimental value for this limit considerably exceeds the theoretical value, due to differences between assumptions of the theory and conditions of the experiment.

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BOWD-6

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VIII. Acknowledgements

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He would also like to acknowledge valuable discussions of the work with J. L. Amick, Professors H. C. Early, A. F. Messiter, J. A. Nicholls, and R. A. Wolfe, the laboratory assistance of J. Bennett, and the many helpful suggestions of Mr. Eric Soehngen and Mr. Ward C. Roman of the Aerospace Research Laboratories.

BOND-8

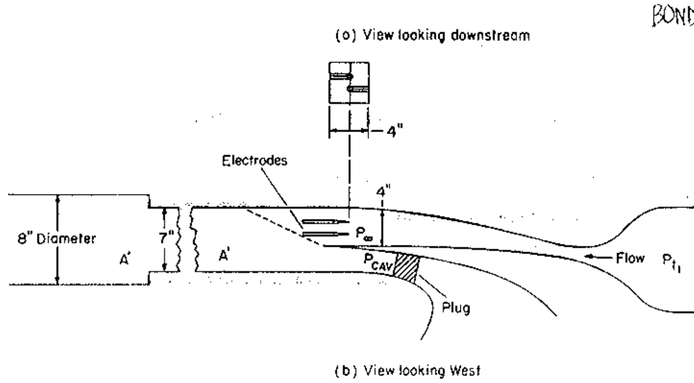


FIGURE 1. SCHEMATIC DRAWING OF TEST SETUP.

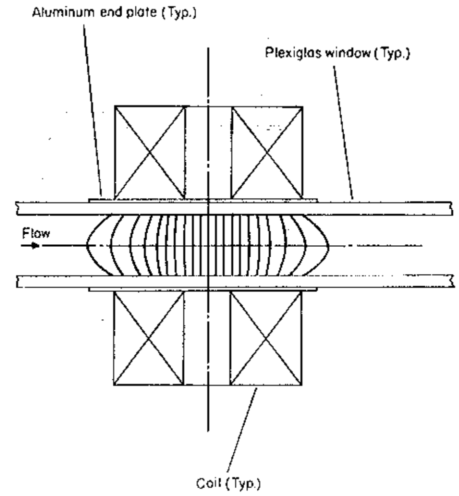


FIGURE 2. SCHEMATIC DRAWING OF LINES OF INDUCTION FROM EXTERNAL FIELD COILS.
(Top View)

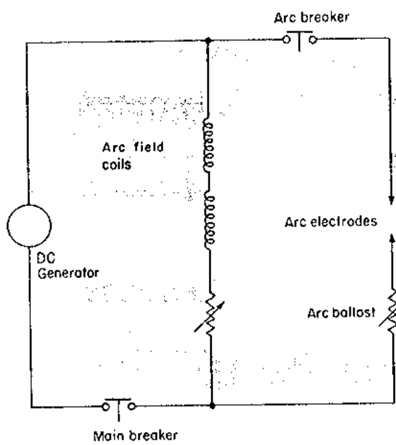


FIGURE 3. SCHEMATIC DIAGRAM OF PARALLEL POWER CIRCUIT.

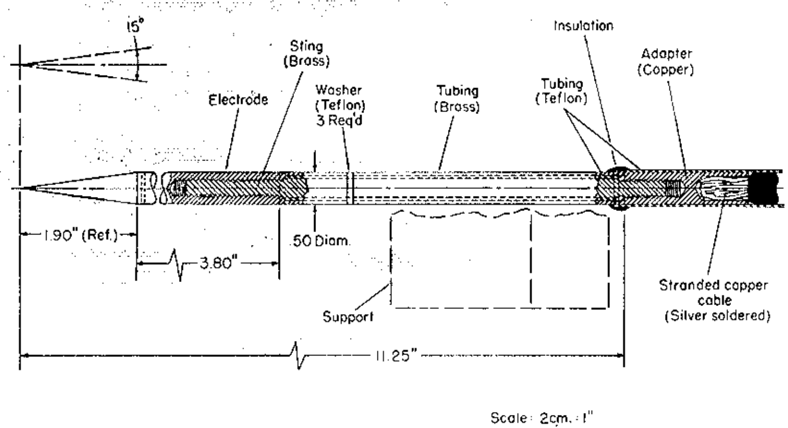


FIGURE 4. ELECTRODE AND STING ASSEMBLY.

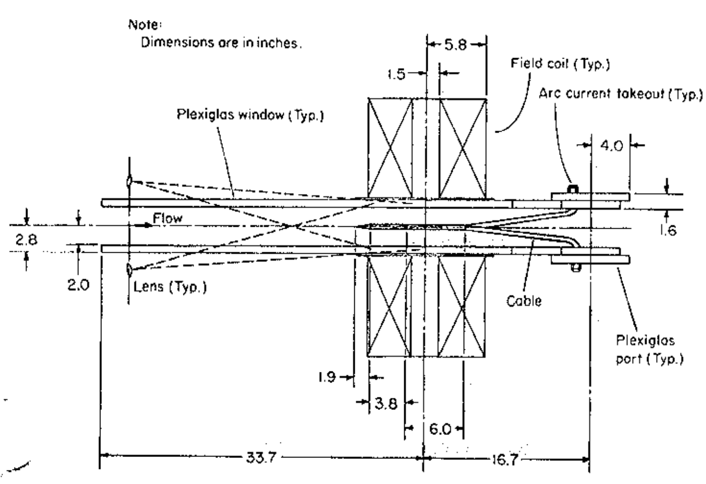


FIGURE 5. TOP VIEW OF EXPERIMENTAL SETUP.

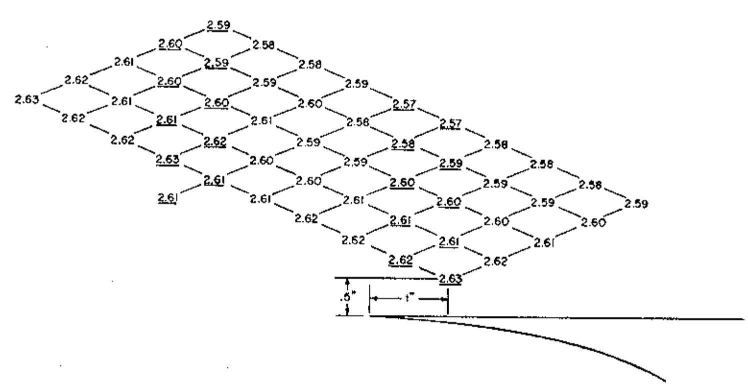
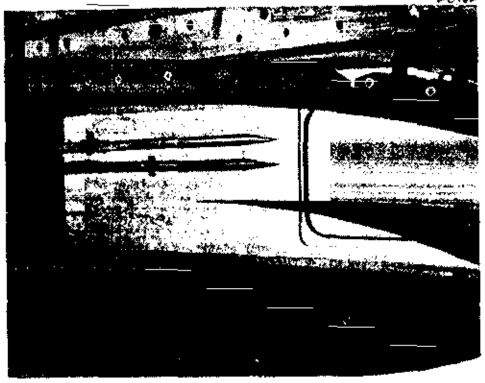


FIGURE 6. MACH NUMBER DISTRIBUTION AT M = 2.6.

BOND – 9



7

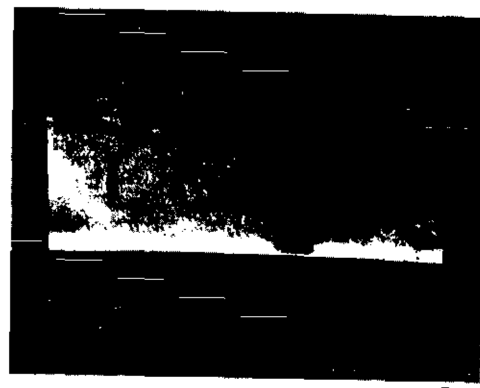
8A

Figure 7. Electrode installed in tunnel (field coils removed).

Figure 8a. Schlieren photograph of test section flow without arc (M = 2.5).

Figure 8b. Flow separation caused by arc, $W/P_t = 0.014$, M = 2.5.

Figure 8c. Attached flow with arc, $W/P_t = 0.009$, M = 2.5.



8B

8C

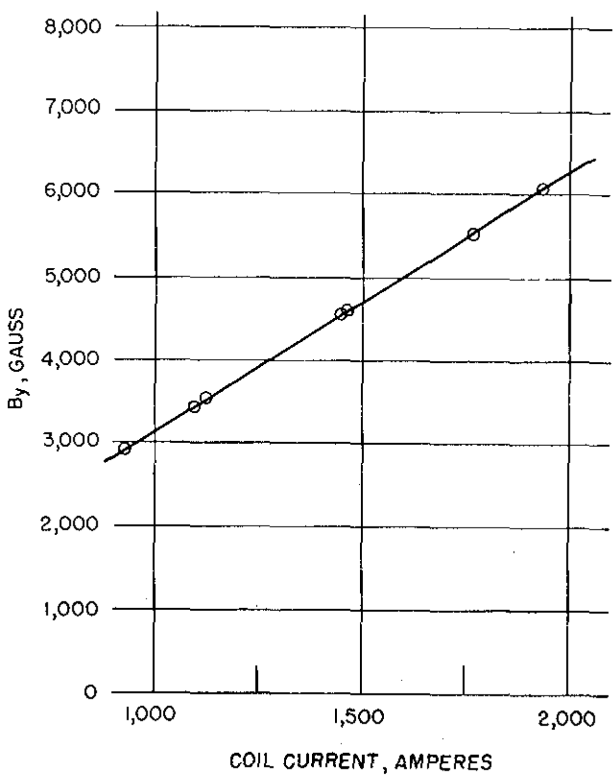


FIGURE 9. VARIATION OF TRANSVERSE COMPONENT OF MAGNETIC INDUCTION WITH COIL CURRENT, AT CENTER OF COIL.

BOND-10

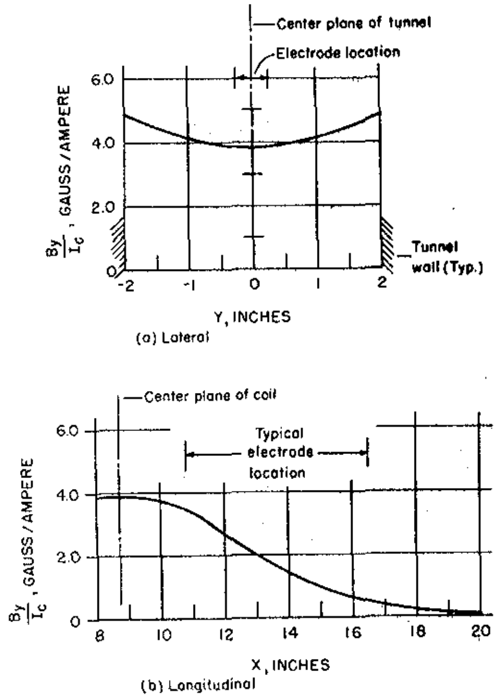


FIGURE 10. CALCULATED SPATIAL VARIATION IN TRANSVERSE COMPONENT OF MAGNETIC INDUCTION.

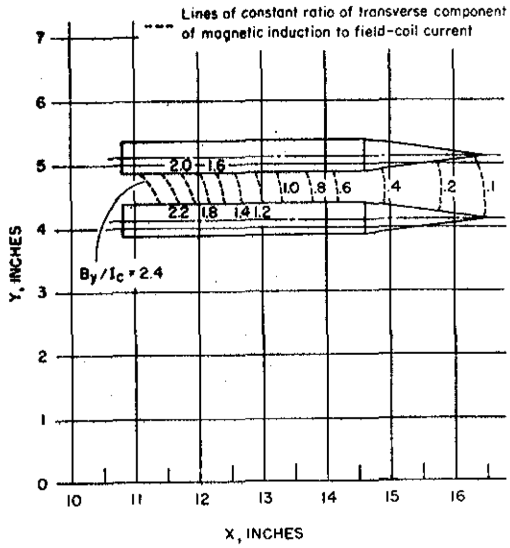


FIGURE 11. MEASURED SPATIAL VARIATION IN TRANSVERSE COMPONENT OF MAGNETIC INDUCTION AT ELECTRODES.

NOTE: FIGURE 13 APPEARS ON THE NEXT PAGE

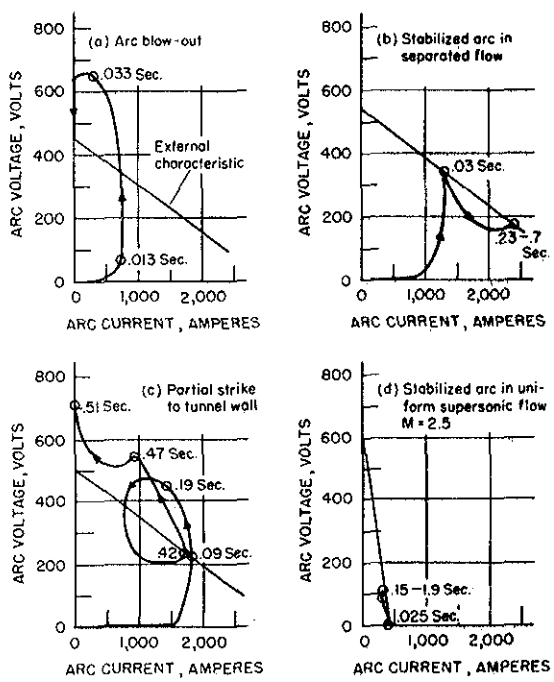


FIGURE 12. VOLTAGE-CURRENT TIME HISTORIES; M = 2.5.

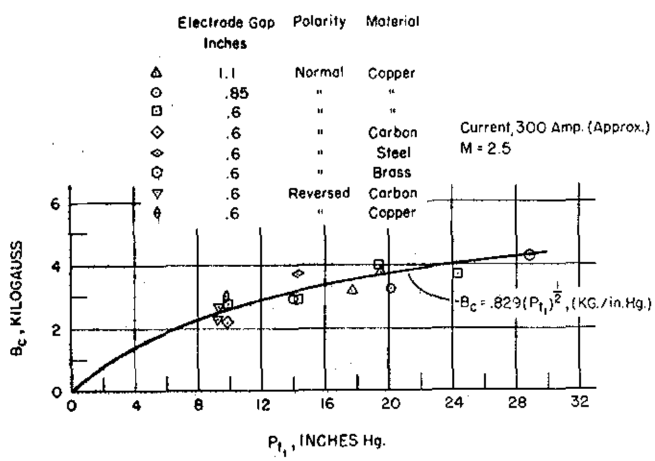


FIGURE 14. VARIATION OF MAGNETIC INDUCTION AT CATHODE ROOT WITH FREE STREAM STAGNATION PRESSURE. (Pure-magnetic confinement)

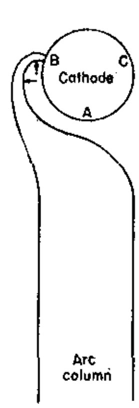


FIGURE 15. LORENTZ FORCES DUE TO B_x.

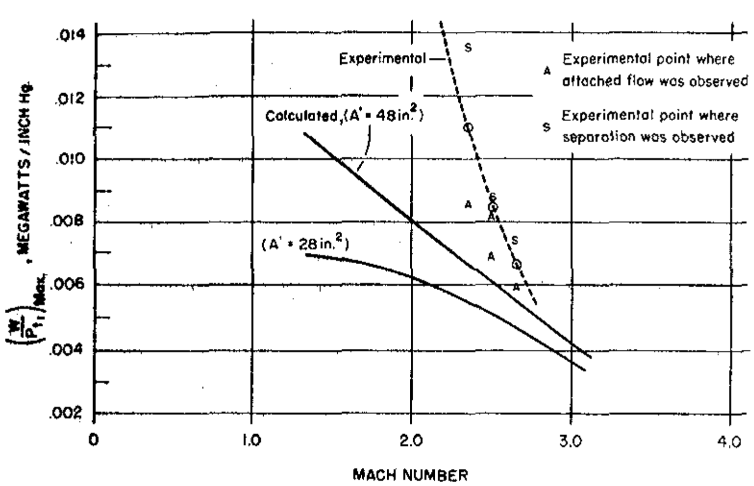


FIGURE 16. LIMIT ON TEST CONDITIONS DUE TO THERMAL BLOCKING.

BOND-11

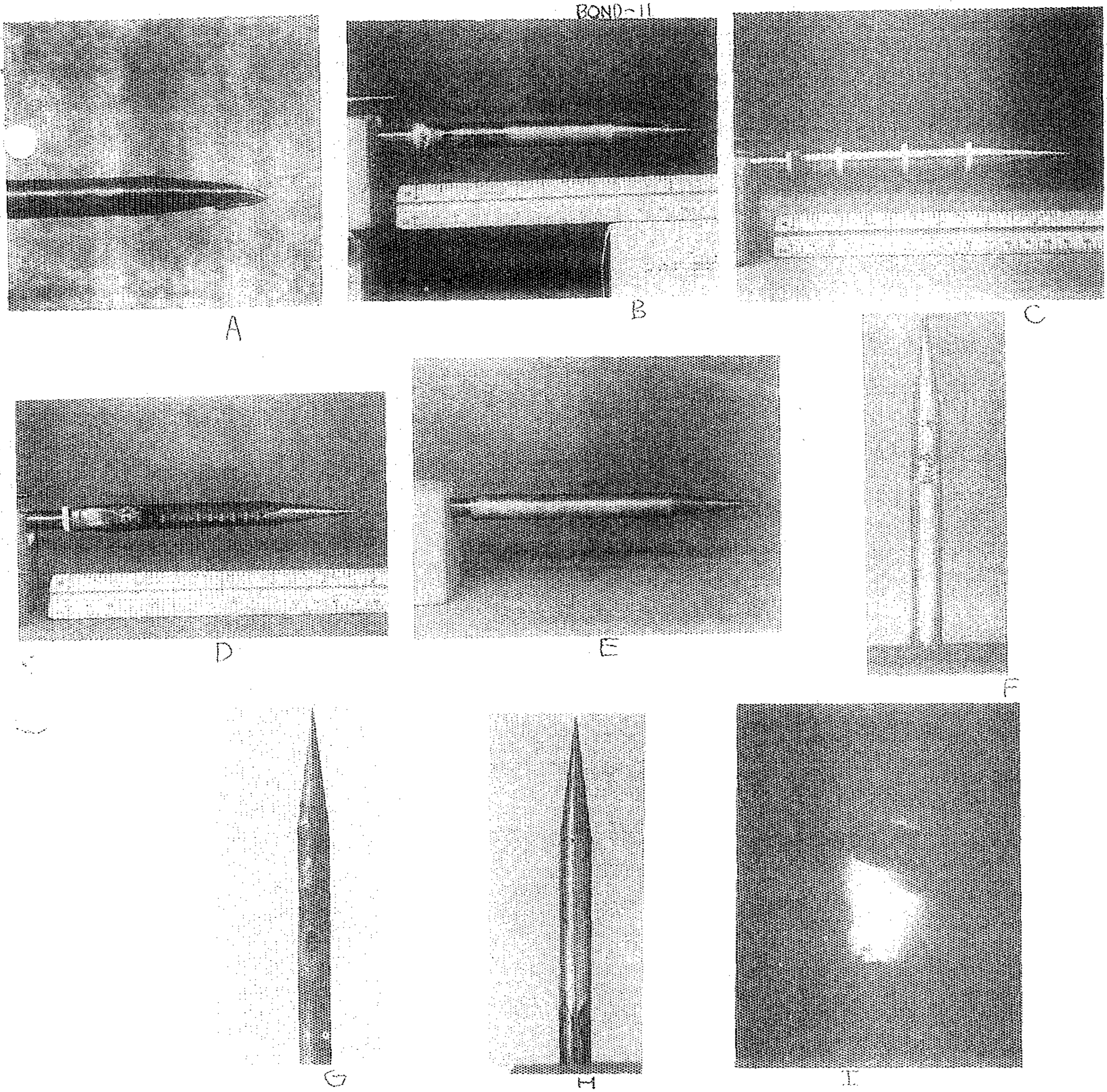


Figure 13. Examples of electrode markings left by arc.

(a) Mark at tip (anode)

(b) Mark at base (cathode)

(c) Mark at base of cathode with Teflon flow baffles

(d) Mark at base of cathode with saw-tooth-edge facing anode

(e) Mark on cylinder of copper anode

(f) Mark on cylinder of brass anode

(g) Mark on cylinder of carbon cathode

(h) Mark on far side of cylinder of copper cathode

(i) Fastax photograph of arc with root at far side of copper cathode