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AN INVESTIGATION OF THE MAGNETOHYDRODYNAMICS OF THE POSITIVE COLUMN OF A DIRECT CURRENT ELECTRIC ARC MOVING AT HIGH VELOCITY UNDER THE IMPETUS OF A STRONG EXTERNAL MAGNETIC FIELD—PHASE I

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I. INTRODUCTION

In today's electric arc chambers, magnetic fields are being used to move arc columns at speeds from the subsonic well into the supersonic regime. Though a number of studies have been made of arc motion under the driving influence of magnetic fields (particularly studies of retrograde motion), most of these studies are concerned with, and the results are heavily influenced by, the mechanisms for arc root motion.[1-10] There has been little experimental work on arc column phenomena under the influence of high speed convection.

There is a clear need for experimental information on the convected arc column, for it is in the column where the major interaction between electric, magnetic, thermal and velocity fields occurs. There are even situations where the column mechanisms alone probably determine the speed of motion of the arc in a transverse field--for example in the arc chamber with a central white-hot thermionic carbon cathode and a concentric annular anode. In these situations, information from a study of the convected column could be put to direct practical use in calculating, for example, the magnetic field strength necessary to move the arc at the speed required for sufficiently uniform heating of the gas or sufficiently distributed electrode heat transfer.

Completely aside from practical applications, the study of the convected arc column represents a challenging problem in aerothermomagnetics. It lies in the realm of problems defined by Ecker[11] where, although the phenomena are governed by well-known laws of physics, the theory is still incomplete due to the complexities involved in handling simultaneously a large number of physical laws connecting a larger number of significant variables. These complexities account for the scarcity of generally applicable experimental results and make it difficult to design experiments to show the effects of independent variation of the significant parameters. This report is conerned with the first phase of an investigation of the effects of variations in velocity, pressure, and external magnetic field strength on the characteristics of the convected arc column. Such a study should lead to some definitive insight into the mechanisms involved.

The experimental setup consists of two rail electrodes mounted within the free stream of a wind tunnel. An electric arc is initiated between the two by means of an exploding wire. The arc column is held stationary by the combined effects of the electric field and an external magnetic field directed normal to the free stream and the electric field.

The six months of work during Phase I was mainly design, fabrication, installation, and shakedown of power supply, electromagnets, ballast resistors, electrode components, wind tunnel modifications, and instrumentation. This

report outlines that work and the experimental approach planned for Phase II. Phase II will be directed toward the use of this equipment and approach for experimental measurements, and toward the analytical investigation of convected arc theory in the light of these experimental measurements. A final report will present these data and analyses and a review of the literature.

II. PHASE I WORK SUMMARY

The purpose of Phase I of the contract (Item 6, Exhibit A) was the design and installation of apparatus and instrumentation and of the switches, circuit breakers, conduit, cables, and control system necessary to supply power from the 1100 KW DC generator to the 4 x 7 in. supersonic tunnel area. (To the latter end a special fund of $7900 was granted by the University.)

Any time remaining of the six months was to be devoted to preliminary tests. Unfortunately there was no time remaining for tests other than the shakedown tests mentioned below. However, it can be reported that tests during the early weeks of Phase II have shown that the arc can be held in the test-section at M = 2.5 by the methods outlined herein, and have given some hope that an observed sidewise motion of the arc can be reduced.

The hardware design and installation is best summarized in the figures.

Figure 1 shows the 1100 KW DC generator and its synchronous drive motor. In order to use this power supply for the present project it was necessary to install the double 1500 MCM cables and double-pole double-throw switch, also visible in Fig. 1. This switch allows the generator output to be routed through either the arc circuit or the low-speed wind-tunnel drive motor to which the generator was originally connected.

Figure 2 shows the generator armature switch and the two 1600-ampere circuit breakers and connecting 1500 MCM cable which are in the arc circuit. Also visible in Fig. 2 is a four-pole double-throw switch which is used for the arc circuit to modify the generator field connections in two ways: (1) to change the field coil hook-up from parallel to series; and (2) to change the field excitation from external to self excitation. Changing the generator output from the subsonic wind tunnel to the arc circuit or vice versa is thus a simple matter of shutting down the generator and throwing two switches.

From the breakers in the power house the two sides of the arc circuit pass through 5 in. conduit supported by a new truss structure to two knife switches in the tunnel room (Fig. 3). These switches are mounted overhead and operated by long wooden handles. A glance at these switches indicates to the tunnel personnel whether the arc circuit is energized.

One side of the arc circuit then passes through the ballast resistor assembly (Fig. 4). This assembly can be set at values of resistance between about .008 ohms and .80 ohms. The time required to change ballast is from 0.5 man-hours to about 20 man-hours depending on the change desired.

Each side of the arc circuit passes through one of the external field coils. Figure 5 shows one of these coils mounted on the west side of the tunnel. Cooling water is carried to the coil through nylon tubing. The coil construction is outlined in Section V. The breaker control circuit contains an interlock which allows the breakers to be closed only when there is sufficient cooling water flow.

From the field coils the two sides of the arc circuit pass through Plexiglas windows on opposite sides of the tunnel about 1-1/2 ft downstream of the coils. Inside the tunnel single 4/0 cables carry the current to carbon electrodes mounted on opposing walls. The electrode, cable, and support are shown in Fig. 6.

Figure 7 shows these electrode components mounted on the phenolic wall block. The phenolic walls will be used for initial tests to reduce the likelihood of formation of a double arc configuration anode-to-wall and wall-to-cathode. The possibility of a single arc to the wall from one electrode is eliminated by the use of an externally ungrounded circuit.

Figure 8 shows the cathode mounted on the east wall.

Figure 9 shows the approximate location of the anode as it is when mounted on the west wall.

Figure 10 gives electrode dimensions.

The circuit diagram for the arc control system is given in Fig. 11.

The arc control panel is shown in Fig. 12. This panel is located on a platform about 20 ft from the 4 x 7 in. wind tunnel and separated from the tunnel by a sheet of tinted 1/4 in. Plexiglas. The panel contains controls for the following:

1. Tunnel downstream-valve, power
2. Tunnel downstream-valve, open
3. Schlieren picture, take
4. Arc run timer
5. Arc operate

6. Synchronous motor, off

7. DC generator field interrupt (not yet complete)

8. Visicorder drive, remote synchronization.

The panel also contains meters indicating generator voltage, arc voltage, arc current, and arc run time, as well as various indicator lights.

III. SUMMARY OF SHAKEDOWN TESTS

Numerous shakedown tests were made of the safety and operation of various components of the power supply system, some of which are mentioned in the monthly progress reports. While such tests are very important to the success of the investigation, they relate mainly to details of operation and will not be enumerated here.

It seems appropriate however to list some of the results.

1. The initial cable-electrode configuration prevents the establishment of supersonic flow at M = 1.5, but not at M = 2.5. (Free stream flow uniformity at M = 2.6 is illustrated in Fig. 13; see also Ref. 12.)

2. The maximum power drawn from the generator was 2400 amperes at 580 volts; the minimum was 430 amperes at 185 volts. The power supply characteristics were as shown in Fig. 14.

3. The external field strength at the electrodes was about 2 gauss/ampere. A preliminary check of the distribution in transverse field strength is shown in Fig. 15.

IV. INSTRUMENTATION

The goal of initial tests must be the assessment of the relative magnitudes of the difficulties involved in stabilizing the arc in high speed flow by use of magnetic fields. It does not appear advisable to seek precision until this first assessment of difficulties is made. It is therefore planned, for example, that the design of the force balance to support the electromagnets will not be frozen until first experiments indicate the rough magnitude of the forces to be measured as well as the field strength, weight, and size of electromagnet required. The selection of the more specialized instruments is also to be deferred until these initial observations are made. The instru-

mentation system to be employed initially will allow immediate study of the simultaneous variations in current, voltage, pressure, etc., which occur during a given run so that the initial determination of points within the envelope of stable convected-arc operating conditions can proceed rapidly.

The central component of this system is a direct-recording, light-beam oscillograph (Visicorder model 1508). Due to the voltage surges inherent in circuits powered by rotating machinery it was necessary to modify this instrument slightly so that it will accommodate galvanometers, manufactured by Hathaway Instruments, Denver, which can withstand up to 2500 volts channel-to-ground and channel-to-channel. The instrument can record 6 channels with Hathaway galvanometers, or 12 channels with standard galvanometers.

The measurement of magnetic field strength will be accomplished by use of a Bell model 120 gauss meter. This model was chosen over cheaper models because it provides superior accuracy in measuring magnetic field strengths just over 3000 gauss.

A Kelvin Bridge (Minneapolis-Honeywell Catalog No. 1622) will be used for the measurement of ballast and coil resistances.

It is felt that a considerable amount of valuable information on arc behaviour can be inferred from the measurement of voltage and current changes during stabilization tests. For example, if the arc voltage first remained constant for a time, then increased to generator terminal voltage, it might be assumed that the arc has travelled down the rails during the time of relatively constant voltage and then extinguished. From this time interval the speed of arc-movement could be determined. From two such determinations the effect of field on velocity could be estimated to a first approximation. On the other hand, an uninterrupted increase in arc voltage to the terminal value could be interpreted as either a divergent lengthening of the arc column or as excessive convective cooling. In either case two observations of the variation of voltage with time would allow an estimation of the effect of, say field strength on arc collapse and point the way to an improved combination of values of the significant variables—velocity, field strength, current, electrode separation, etc. High speed photography will of course be a great aid in interpreting the measured variations.

V. EXTERNAL FIELD COILS

The first configuration of electromagnet was designed to produce a transverse field of up to about 5300 gauss at the saddle point with a current of 2000 amperes. Figures 16 and 17 show the theoretical distribution in transverse field strength, calculated from the graphs in Ref. 13. Preliminary measurements indicate that the actual field strength will be up to 20% less

than this (see Fig. 15).

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 amperes of continuous current without overheating. The copper tubing is insulated with plastic tubing and each pancake is held in shape by epoxy resin. The segmented design offers the following advantages: (1) it allows the introduction of cooling water every 50 ft of coil length; (2) it allows easy step-changes in field strength; and (3) it reduces the extent of repair necessary in the event of any unforeseen damage to the coil.

VI. ARC STABILIZATION

Of crucial importance to the present investigation is the problem of arc stabilization. Measurements of the effects of forced convection on the positive column cannot be made until it is possible to attain steady-state or at least quasi-steady-state conditions. A stabilized arc, in this context, is one which persists for the required length of time in the space where measurements must be made.

One well-known requirement for DC arc stabilization is given by the Kaufman stability criterion. A second requirement is that arc movement must be properly confined so that the arc roots and the positive column are constrained at the proper location. These two general requirements for arc stabilization are inseparably coupled, since all methods of arc confinement affect the voltage—current characteristic of the arc and, on the other hand, changes on the external circuit characteristic will affect the arc current and thus confinement.

Arc confinement in the present case will be based initially on the interaction of forced convection with an externally applied magnetic field (see Section VII). Among the defects which can be anticipated in arc stabilization are the following.

1. Electrode burnout—the catastrophic melting of a metal electrode. Since initial stabilization tests will be made using carbon electrodes, no trouble is expected from this source.

2. Electrode attrition and gas contamination—excessive erosion of electrodes. Since for the present program the arc roots dwell at one place, it

can be expected that there will be considerable electrode erosion. The gas contamination resulting therefrom will probably not enter the positive column but be convected away near the roots.

3. Electrode fracture—cracking of refractory electrodes. This could give serious problems. Electrodes were fabricated from four different grades of carbon to provide some control over this factor.

4. Arc mislocation. This problem could be particularly severe. Here not only must the arc roots strike at the desired location, but the arc column should not bow out significantly.

5. Arc collapse—extinguishment of the arc due to increasing arc characteristic beyond the power supply capability.

6. Excessive current fluctuation.

All these phenomena are strongly influenced by the conditions of operation such as geometry, pressure, mass flux, arc current and voltage, and magnetic field strength.

VII. ARC CONFINEMENT

The essential mechanism to be employed for constraining the electric arc to strike between the electrodes is the Lorentz force $\underline{j} \times \underline{B}$. In principle of course this requires merely the provision of a uniform magnetic field of proper strength directed such that $\underline{B}$, $\underline{j}$, $\underline{V}$ forms a positive orthogonal triple. But as with all forms of confinement one must provide not just a balance of forces, but a stable balance. Thus there must be some mechanism to oppose any upset in the balance caused by perturbation in the significant variables.

In the present case the initial balance of forces and the stabilizing mechanism will both be effected through use of electric and magnetic fields. The Lorentz force $\underline{j} \times \underline{B}$ from the transverse external field will be used to balance the aerodynamic forces. Stability in the axial direction is provided by placing the rail electrodes such that there is a monotonic increase in magnetic field strength as the arc moves toward the trailing edge (see Fig. 16).

Stability in the transverse direction will be provided by the combined effects of the electric field and a transverse gradient in the strength of the transverse field (see Fig. 17). The transverse magnetic field near the electrodes increases in strength about 10% one inch to either side. Any tendency for the arc to bow out to either side should be reduced since a balance of forces on the arc at the electrodes would mean an imbalance of forces on the arc column when displaced appreciably to the side.

It is by no means certain of course that the arc will not bow out to the side with this field configuration. The rail-accelerator experiments (none of which has been conducted with a significant transverse gradient in external field) have indicated a considerable tendency toward arc bowing.[3-6] In most cases this tendency has been counteracted by the use of guide walls. But the effects of these guide walls on arc behavior has been shown to be profound.[4] The use of guide walls would severely limit the present investigation in the range of test conditions, in the nature of the information which could be obtained, and in the general applicability of the results. Present plans therefore are based on the use of the magnetic field configuration described above for arc confinement.

As no data are available on the magnitude of the aerodynamic resistance force, so there is little to go on in estimating the magnitude of the electromagnetic field strength which might be required for arc stabilization. In such cases a first attempt must be made, based in part on intuition. In the present case, based in part on unpublished observations by the author, of arc motion between concentric electrodes, it was decided that the first electromagnetic field design should have a capability of 4000 gauss at 1500 amperes.

VIII. ELECTRODE GEOMETRY

The choice of rail electrodes for the first experiments is necessary to allow the use of the stabilization techniques described herein and to provide longer run times for moving arcs. It might be reasoned that coaxial point-electrodes for example might give data less affected by the velocity boundary layer. Still other electrodes geometries might be dictated by the results of initial tests. Any changes in electrode geometry must be tempered by consideration of their effect on arc stabilization.

IX. FIELD-COIL CURRENT SUPPLY

For initial tests the arc and the field coils will be connected in series. Although a separate power supply might be somewhat more convenient, this does not appear to justify the additional cost of an 800 KW power supply.

It should be noted that the inconvenience of the present method is very slight for the case of an arc stabilized between rail electrodes as described herein, since a range of values of B is available for any given choice of the number of field-coil segments.

X. ARC IGNITION SEQUENCE

Arc ignition will be accomplished by the exploding wire technique. The sequence of events at the start of a given run will have to be carefully controlled. If the arc is fired before the tunnel is started, the unbalanced Lorentz force will cause the arc to move in the upstream direction and collapse. Thus the tunnel must be started before the arc. But since the magnetic field coils are in series with the arc itself, the time constant of the arc power supply is high (over 5 msec) compared to the time required for a gas particle to travel the length of the rail electrode (under 1 msec). A time delay is needed to allow the current in the field coils time to build up so that the external field will be strong enough to hold the arc against the aerodynamic forces. This can be accomplished by the proper choice of starting wire diameter. A rough calculation of the diameter necessary to produce a time delay of 10 msec indicates that the starting wire diameter should be on the order of .025 in. for copper.

XI. AERODYNAMIC RESISTANCE MEASUREMENTS

In order to measure the forces exerted on the arc by the air stream, the external magnetic field coils will ultimately be mounted on a force balance. The design of this balance cannot begin until the size, shape, and weight of electromagnet required for stabilization is determined. Balance design also requires some estimate of the order-of-magnitude of the forces to be measured. This estimate can be made once the current and field strength necessary for arc stability are known.

Assuming the force to be of order $IB\ell$ and that stabilization is achieved with the equipment built during Phase I, this estimate will not exceed 10 lb_F. The force will thus be small compared to the weight of the magnets (about 150 lb each) and the force of attraction between the magnets (up to about 2000 lb). Some care must therefore be taken in balance design, as well as in procedures for tare measurements.

The tare measurements will be performed with the electrodes shorted at the point where the arc is to strike. The force from the current in this conductor will be calculated and subtracted from the tare readings. All current paths and cooling-water flow conditions must of course be the same during tare measurements as during the run.

XII. CONVECTION VELOCITY

Initial tests with the arc will be conducted at a Mach number of 2.5. The 4 x 7 in. tunnel can be run at subsonic Mach numbers as well as supersonic Mach numbers between 1.5 and 4.0, and it is reasonable to ask why the initial tests should not be conducted at low subsonic speeds. There are two significant reasons for this choice. First, it is felt that the development of stabilization techniques for subsonic flow would not lead to the achievement of supersonic stabilization any earlier than the direct approach. Second, in supersonic flow it is possible to assure a flow field which is uniform upstream of the arc column. In the subsonic case the flow field is difficult to predict because flow approaching the arc has already deflected to accommodate the arc, the electrodes, the supports, the cables and any other obstructions downstream of the arc.

XIII. COMPARISON OF APPROACHES

Information on the convected arc can be obtained either by moving the arc through the gas or by moving the gas through the arc. We shall call the first approach the rail-accelerator approach since apparently all such experiments to date have used fixed electrodes, usually in the form of rails, over which the arc is forced to move by the external field. We shall call the second approach the wind-tunnel approach since the wind tunnel offers the best method for obtaining in the laboratory a high speed stream of gas of known flow uniformity.

There are important ways in which the wind-tunnel approach to the study of convected arc phenomena differs from the rail-accelerator approach. One of the most important of these is in the root phenomena. With the rail accelerator the roots must move over the electrodes. The results will therefore be highly dependent on electrode surface conditions. For the thermionic cathode, root motion is limited by the time required to heat the cathode surface; on metal cathodes root motion is greatly affected by surface oxides and roughness (see Ref. 14, p. 285). For the general case the mechanism for root motion will differ from that for column motion and this difference will manifest itself as a tendency toward irregular motion of the arc. With the wind-tunnel approach the arc roots ideally do not move over the electrodes. Thus with carbon electrodes, for example, thermionic emission will be established from one location of the cathode. Once this is done the column behavior should be virtually independent of root phenomena.

Another important difference in these two approaches is the difference in the run time available. For example, with a 1-ft rail accelerator and an average arc velocity of from 200 to 2000 ft/sec this time is only from .5 to 5 msec. More time than this would be desirable for allowing transients in

arc current to die out and for determining how the velocity varies with time. With the wind-tunnel approach run, times can be easily 1000 times greater, affording an opportunity for measuring the static voltage-current characteristic for the convected arc.

Another difference between the wind tunnel and rail-accelerator approach is the absence of a back emf with the wind-tunnel setup. This would require a correction to the arc voltage readings obtained with the rail accelerator of at most only a few percent.

With the wind-tunnel approach the convection velocity can be controlled. This will be of great importance for example in isolating the effects of velocity on measurements of the arc characteristic.

In summary the rail accelerator seems most suitable for obtaining information on root motion whereas the wind tunnel seems best suited to the study of convected-column phenomena.

XIV. MODELS FOR ARC BEHAVIOR

The need for a mathematical model for arc behavior under the influence of forced convection is so great that there has been a tendency toward mathematical analysis of admittedly questionable physical models. The use of a solid cylindrical conductor as a physical model for the electric arc is an example of this. This model has received wide consideration (see Ref. 3, 4, 9, 10) and even some support.[5] But the inadequacy of this physical model becomes clear when it is compared to a real arc—even a cylindrical real arc. Most of these inadequacies are suggested by the simple fact that the gas is free to flow through a real arc. Others are suggested by the fact that for an electric arc there will be considerable coupling between the energy equation and the momentum equations, or between the velocity fields and the thermal field.

A fortuitous adjunct of the present investigation would be a physical model for the variation of current density distribution with the significant independent parameters such as geometry, velocity, current, external field, etc. Conceivably such a model could be induced from the measurements of the effects of these parameters on total arc force in conjunction with photographs showing the distribution of arc luminosity.

In order to treat the force on the arc it will be necessary to define precisely what is meant by "arc" under these conditions. The arc could be defined as a region with electrical conductivity greater than some arbitrary limit. This region constitutes a control volume.

The Lorentz force is

$$\underline{f} = \int_{\tau} (\underline{j} \times \underline{B}) d\tau$$

where the integral is performed over the volume of significant conductivity. In the language of fluid dynamics, the Lorentz force constitutes a body force exerted (via the charge carriers) on the fluid instantaneously contained in the control volume. It is precisely this force which is balanced by the aerodynamic force and results in a momentum deficit in the gas passing through the control volume or arc.

The problem then is one of determining, perhaps by iterative procedures, the current density distribution for the field-stabilized arc. Where thermal equilibrium can be assumed this determination can be accomplished by means of the macroscopic equations of aerothermomagnetics without detailed consideration of the equations of motion for individual species.

Any mathematical analysis must be classed as only an exercise unless it is based on a physical model which takes into account all the essential mechanisms of arc behavior. The complexity of arc behavior under the conditions of the present investigation increases the number of possible physical models to the point where it becomes mandatory that the choice of one model be made only after sufficient experimental data are at hand.

Dimensional analyses have been performed[15] for convected-arc phenomena, but experimental data are necessary to isolate the significant dimensionless parameters. Order-of-magnitude analyses must be based on some mathematical model for the phenomena being analyzed. A similarity analysis of the thermal boundary layer caused by a diffuse sheet arc, for example, would be of little use if the arc is later found to be highly constricted. The research must therefore be directed toward a careful experimental determination of actual arc behavior with the goal of building anew, if need be, a physical model which expresses the essential mechanisms of arc behavior under the conditions pertaining. Then can follow mathematical model, solution of the mathematical equations, and back-comparison with experiment.

XV. PHASE II EMPHASIS

Details of the program of experimentation during Phase II of the investigation will depend heavily on the magnitude of the practical problems encountered in following the approach outlined above. It seems advisable here only to list three areas of interest which will receive major attention.

A. ARC STABILIZATION

The stable confinement of a motionless electric arc in a supersonic stream by means of electromagnetic fields is a formidable task. An important part of this investigation will be a study of the effects of the independent variables on arc confinement and the development of reliable experimental techniques for stabilization under a wide range of conditions.

B. ARC CHARACTERISTIC

Once stabilization techniques have been perfected the experimental setup will offer an unparalled opportunity for the measurement of the effects of forced convection on the static voltage—current characteristic of the arc. Such measurements would in themselves constitute a valuable contribution to basic knowledge of arc phenomena. They are also necessary for the planning of other fruitful areas of the present investigation.

C. AERODYNAMIC RESISTANCE

The measurement of aerodynamic resistance to the motion of the arc is of prime interest for practical applications, and a major goal of the present investigation.

XVI. SYMBOLS

$\underline{B}$	magnetic induction
$\underline{f}$	force
I	current
$\underline{j}$	current density
ℓ	electrode separation
M	free stream Mach number
x	distance along tunnel axis from centerline of field-coils, positive upstream
y	distance along field-coil axis from tunnel centerline, positive east
z	vertical distance from tunnel axis, positive down

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XVIII. ACKNOWLEDGMENTS

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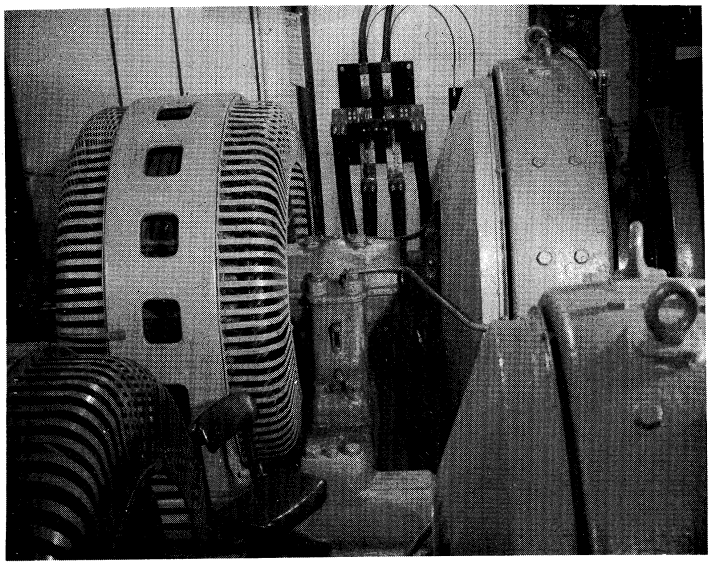


Fig. 1. Synchronous motor (left background), 1100 KW DC generator (right background), and generator-armature switch (center background).

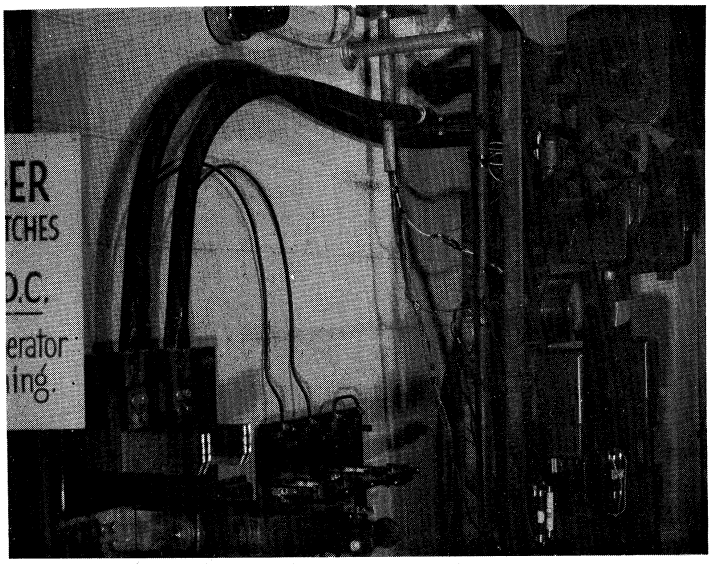


Fig. 2. Generator-armature switch and arc circuit breakers.

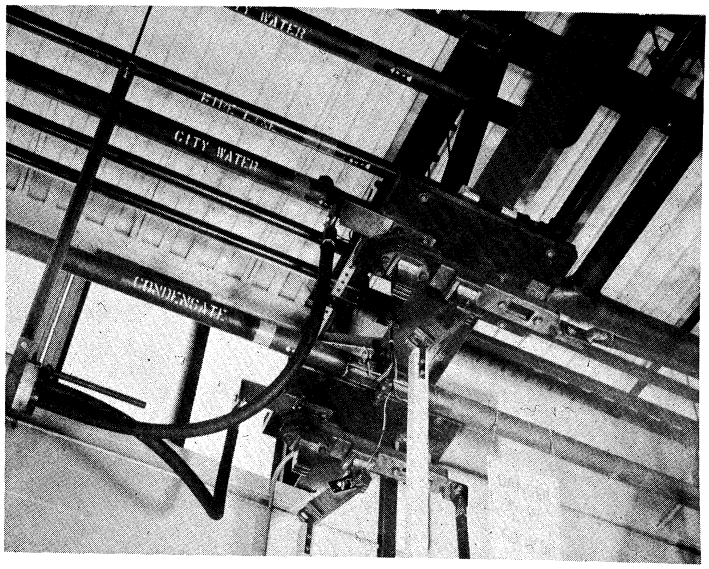


Fig. 3. Tunnel-room arc safety switches.

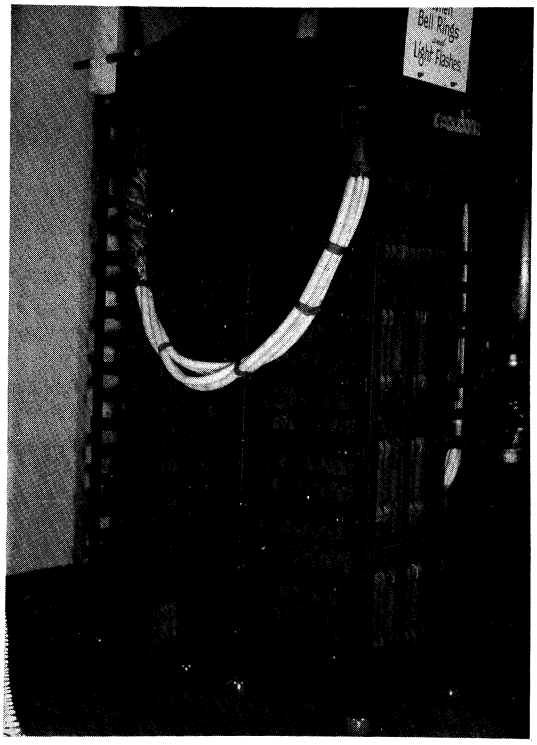


Fig. 4. Ballast resistor assembly.

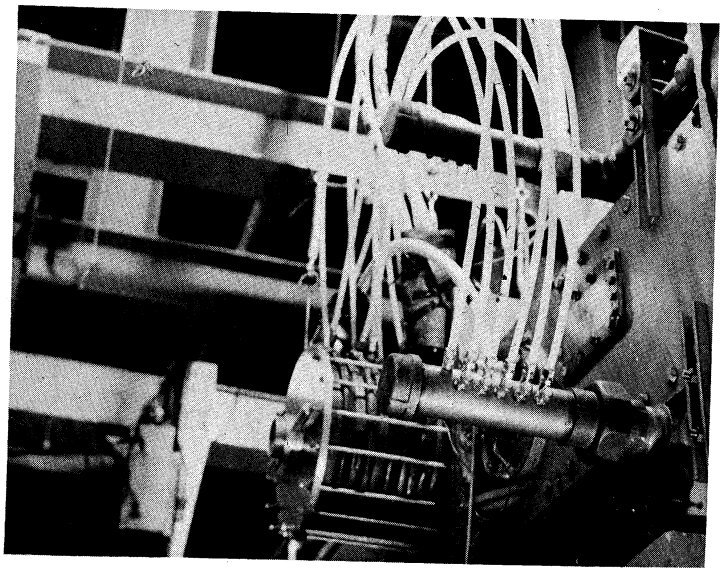


Fig. 5. West field-coil and cooling system.

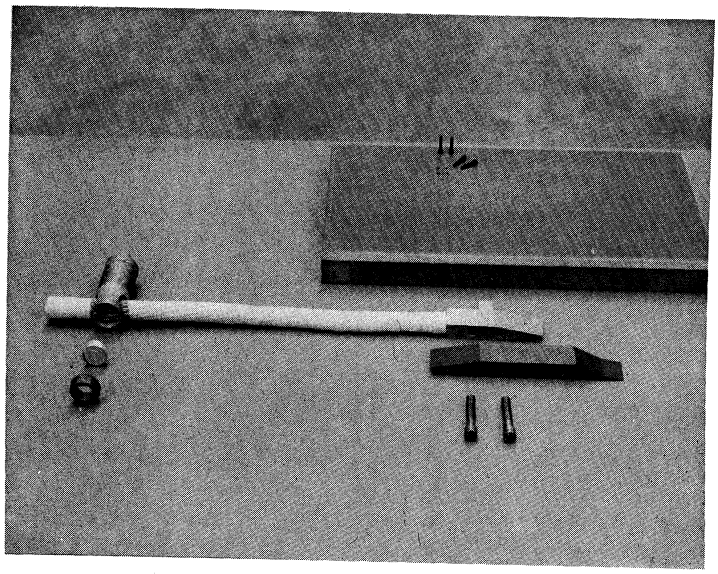


Fig. 6. Electrode, cable, support wedge, and phenolic window inse

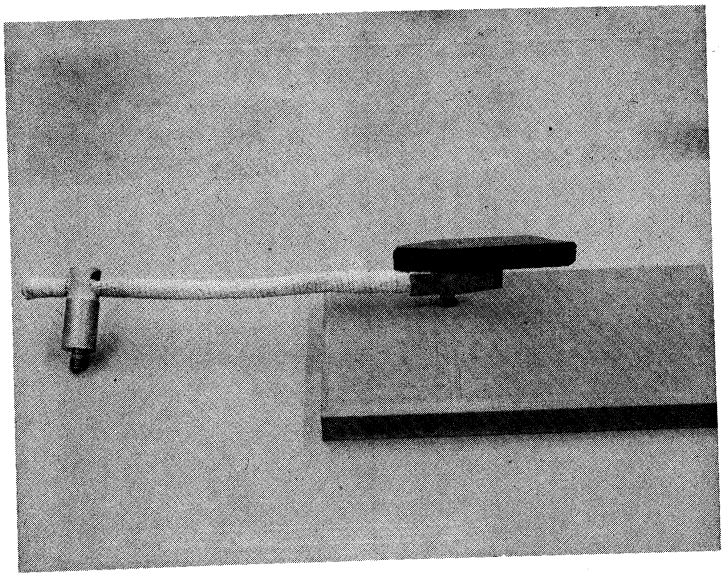


Fig. 7. Electrode assembly.

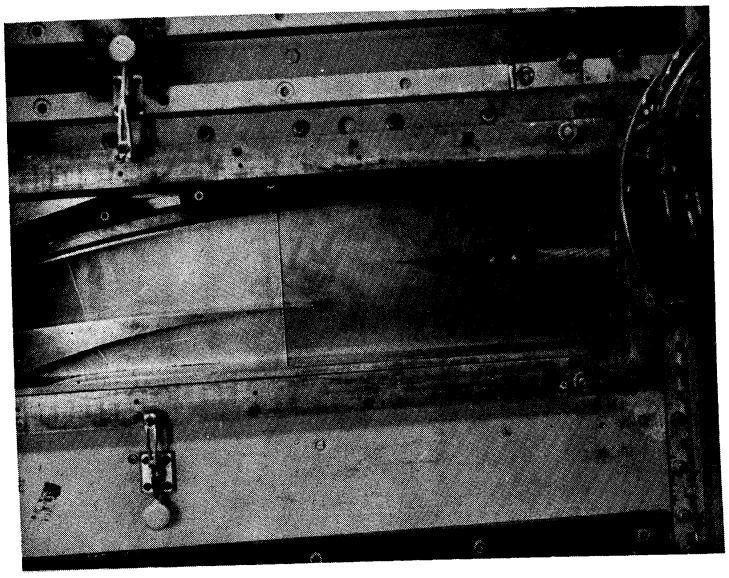


Fig. 8. Electrode assembly installed in tunnel.

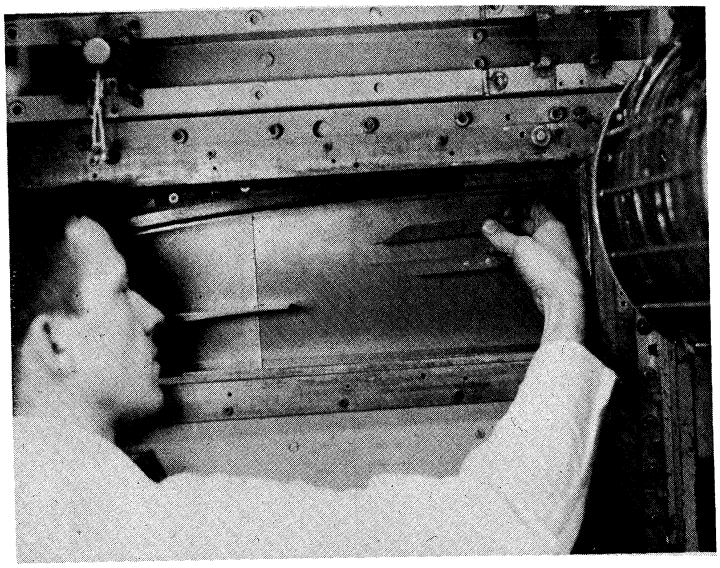
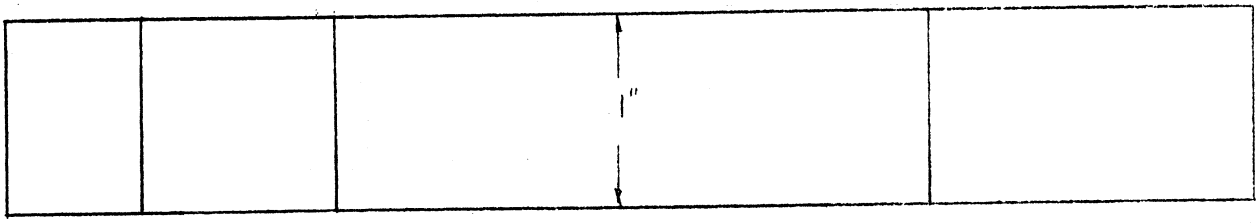


Fig. 9. Electrode orientation.



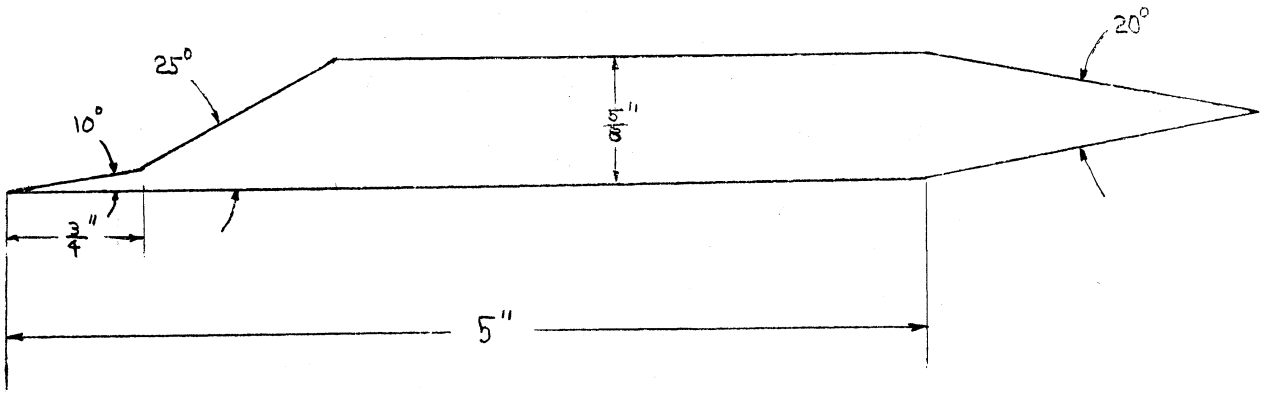


Fig. 10. Electrode dimensions.

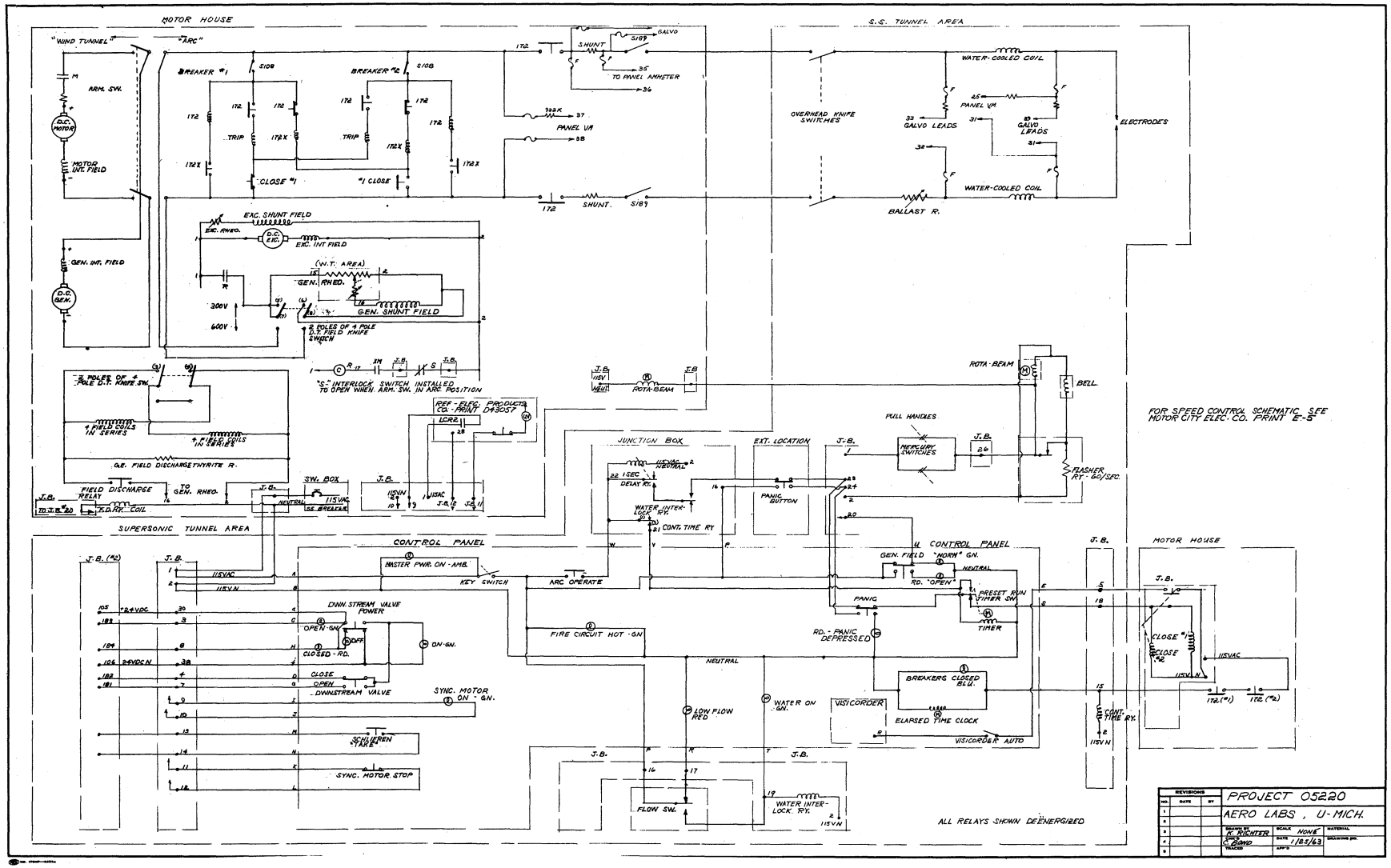


Fig. 11. Circuit diagram for arc power supply and control system.

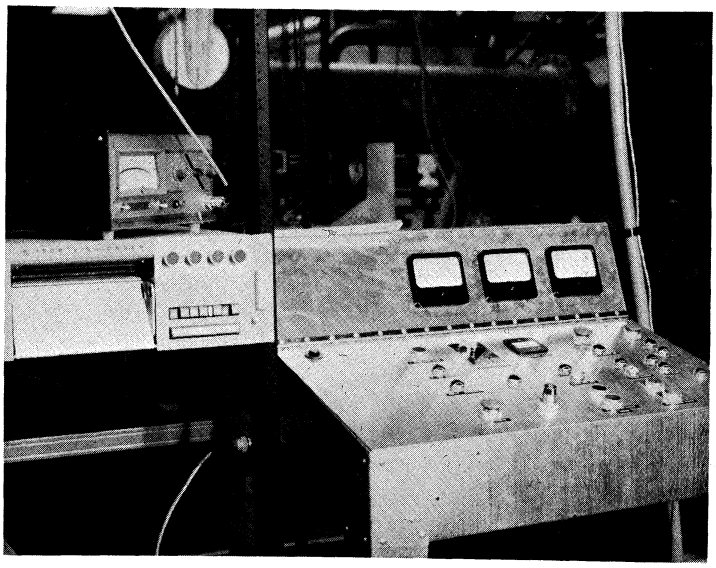


Fig. 12. Arc control panel, visicorder, and gaussmeter.

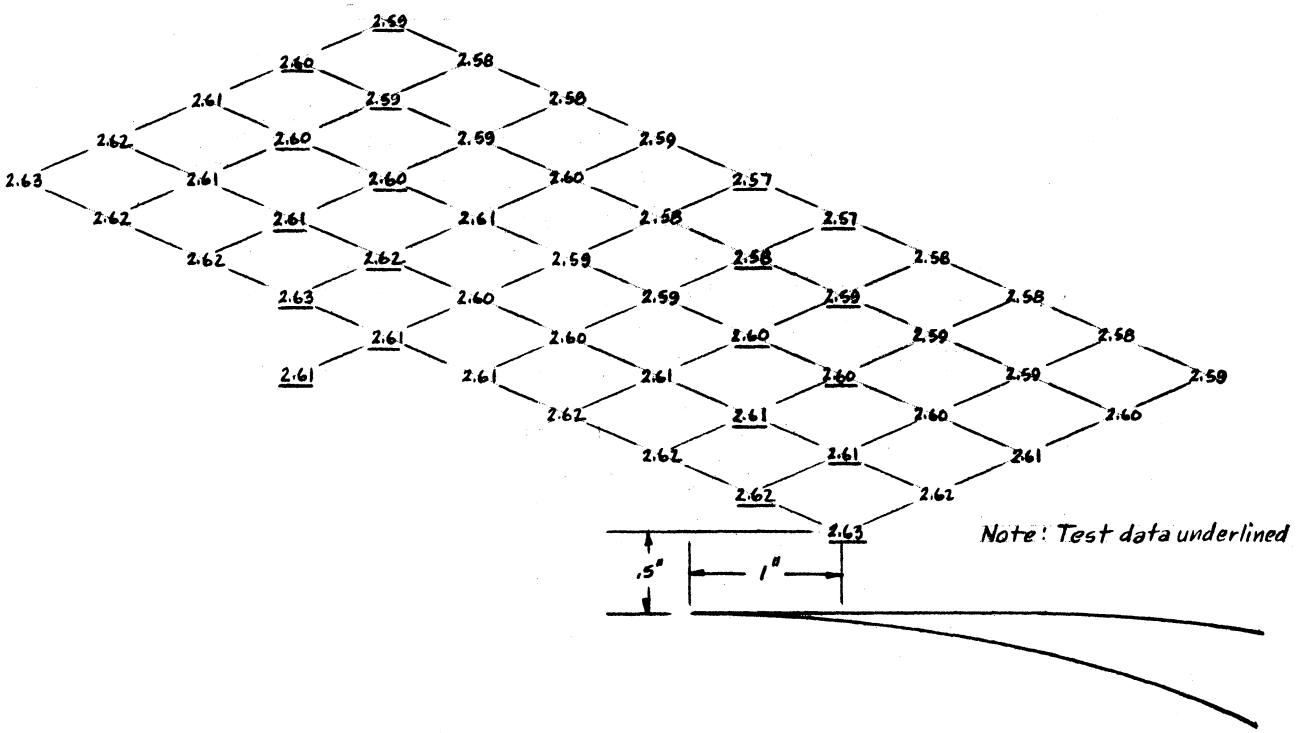


Fig. 13. Test-rhombus Mach number distribution at M = 2.6.

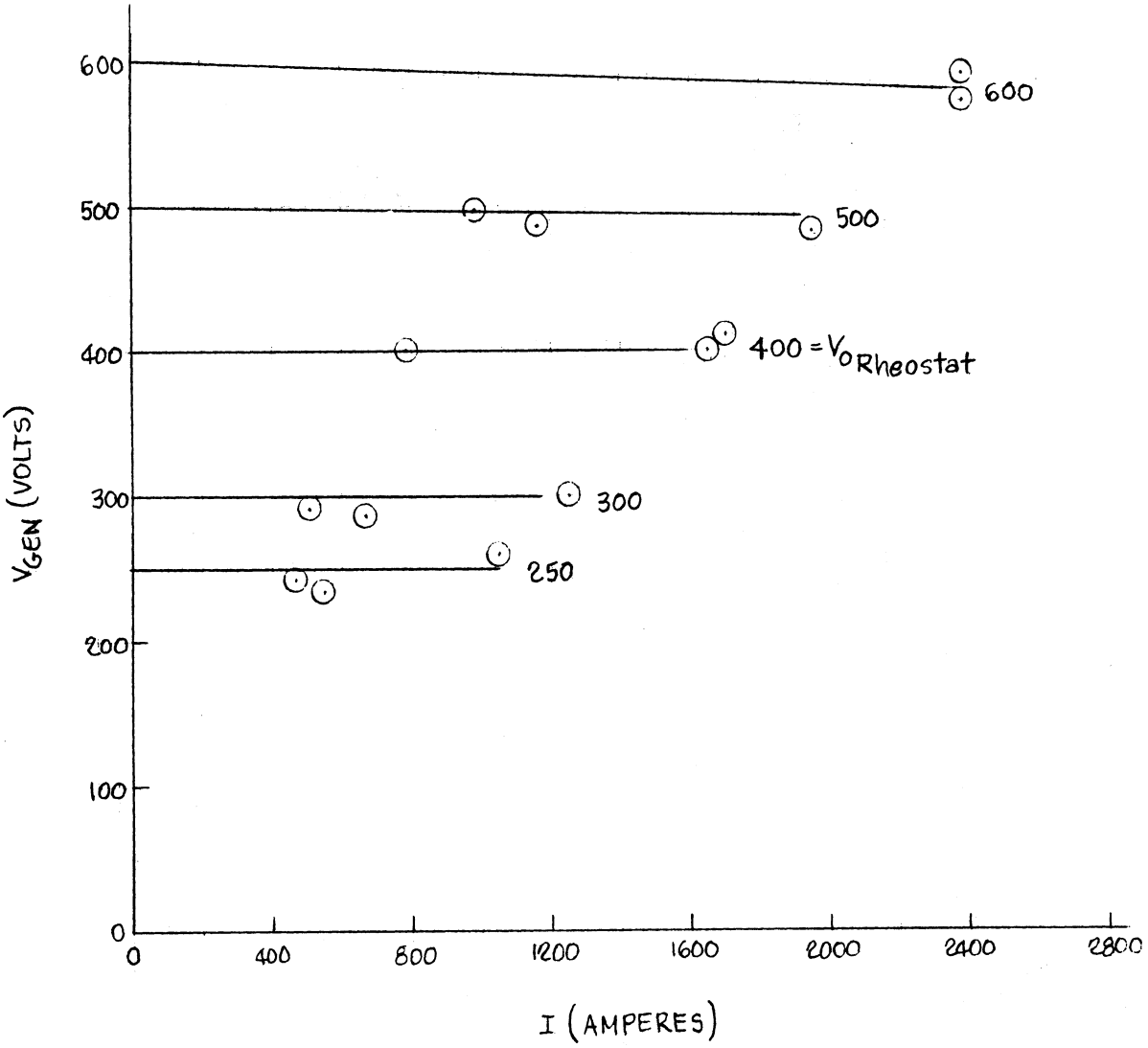


Fig. 14. DC generator characteristics for various field-rheostat settings.

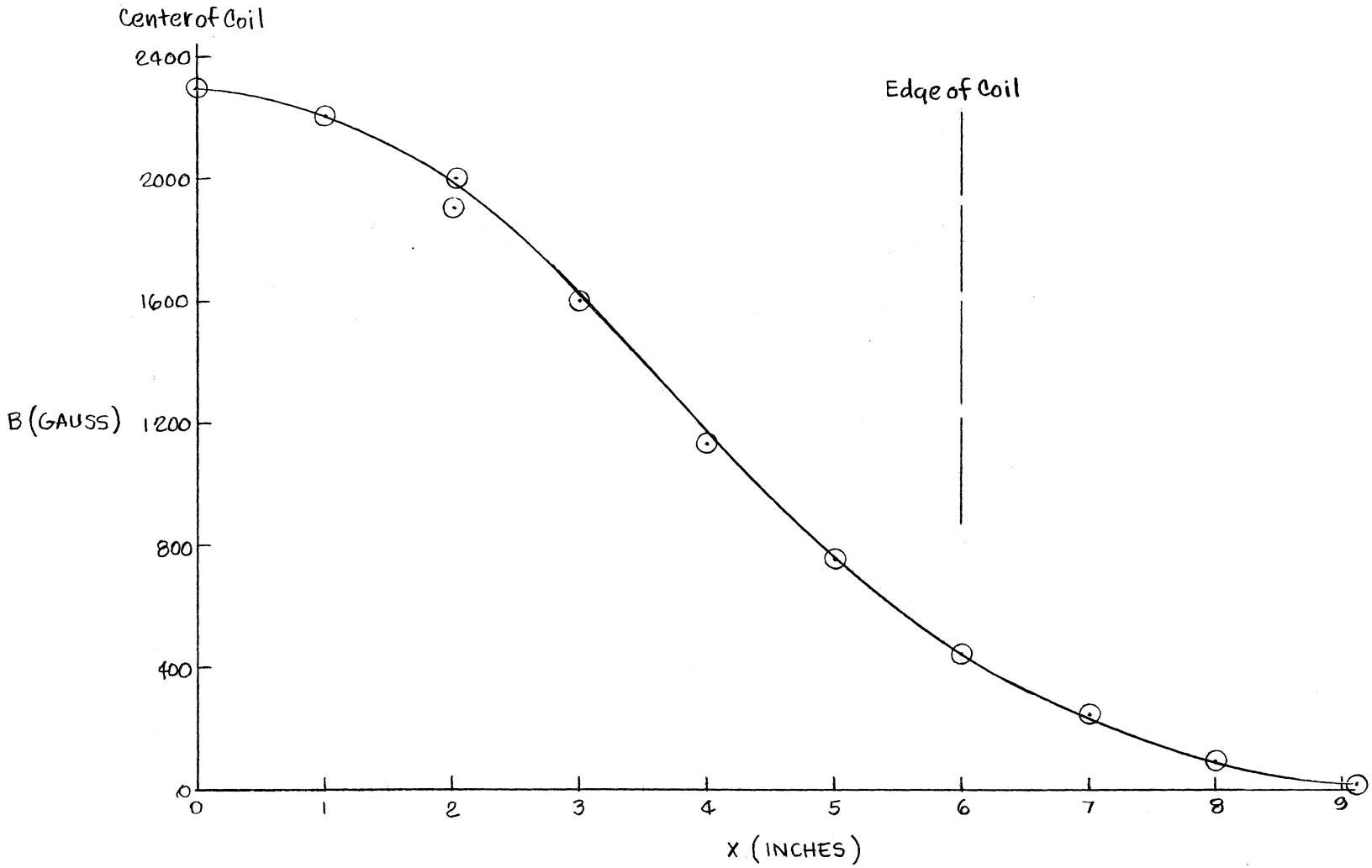


Fig. 15. Measured variation in transverse field B_y along $Z \cong 0$; $Y \cong 1/2$-inch; $I \cong 1200$ amperes (preliminary data).

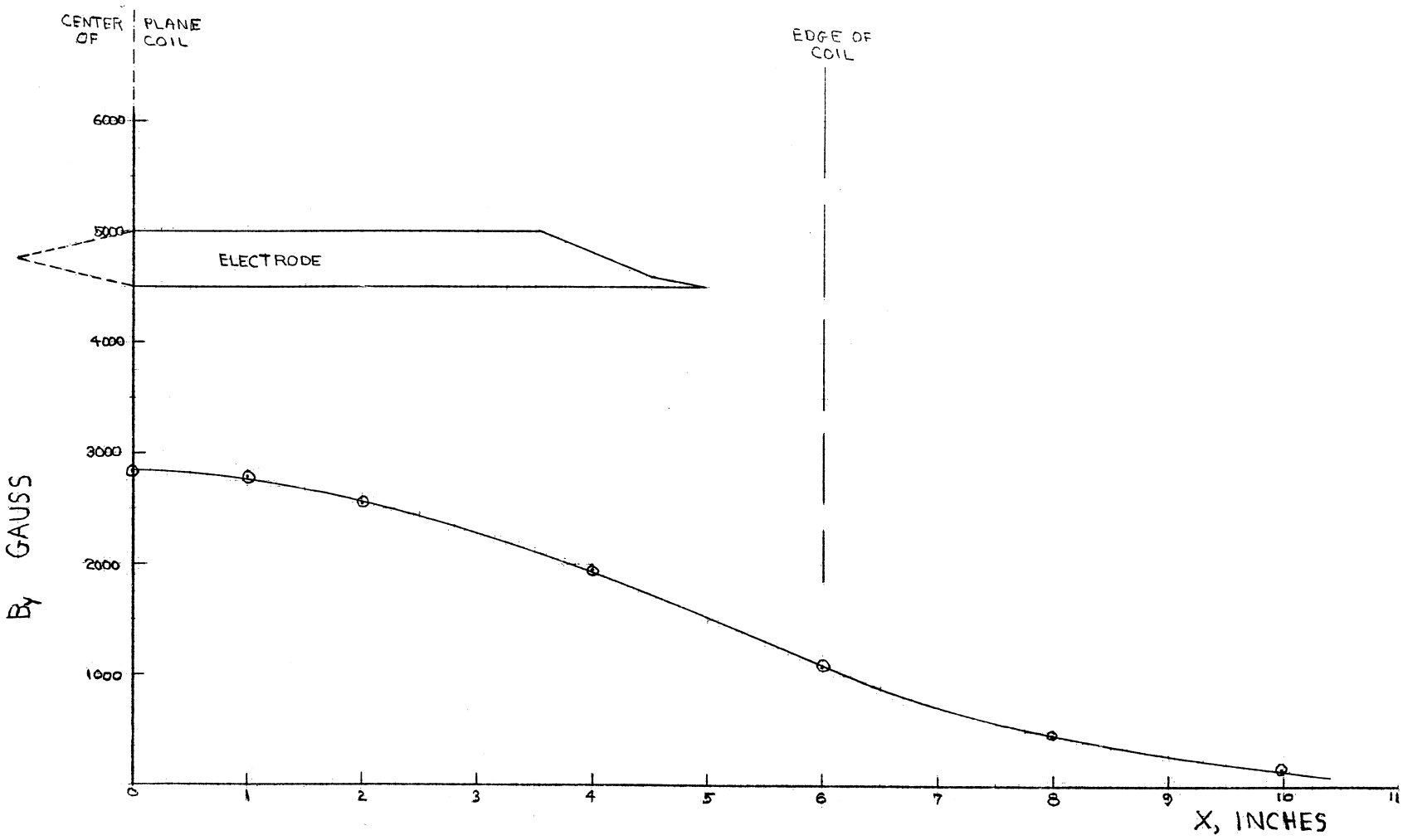


Fig. 16. Theoretical variation in transverse field strength B_y along tunnel centerline (I = 1000 amperes).

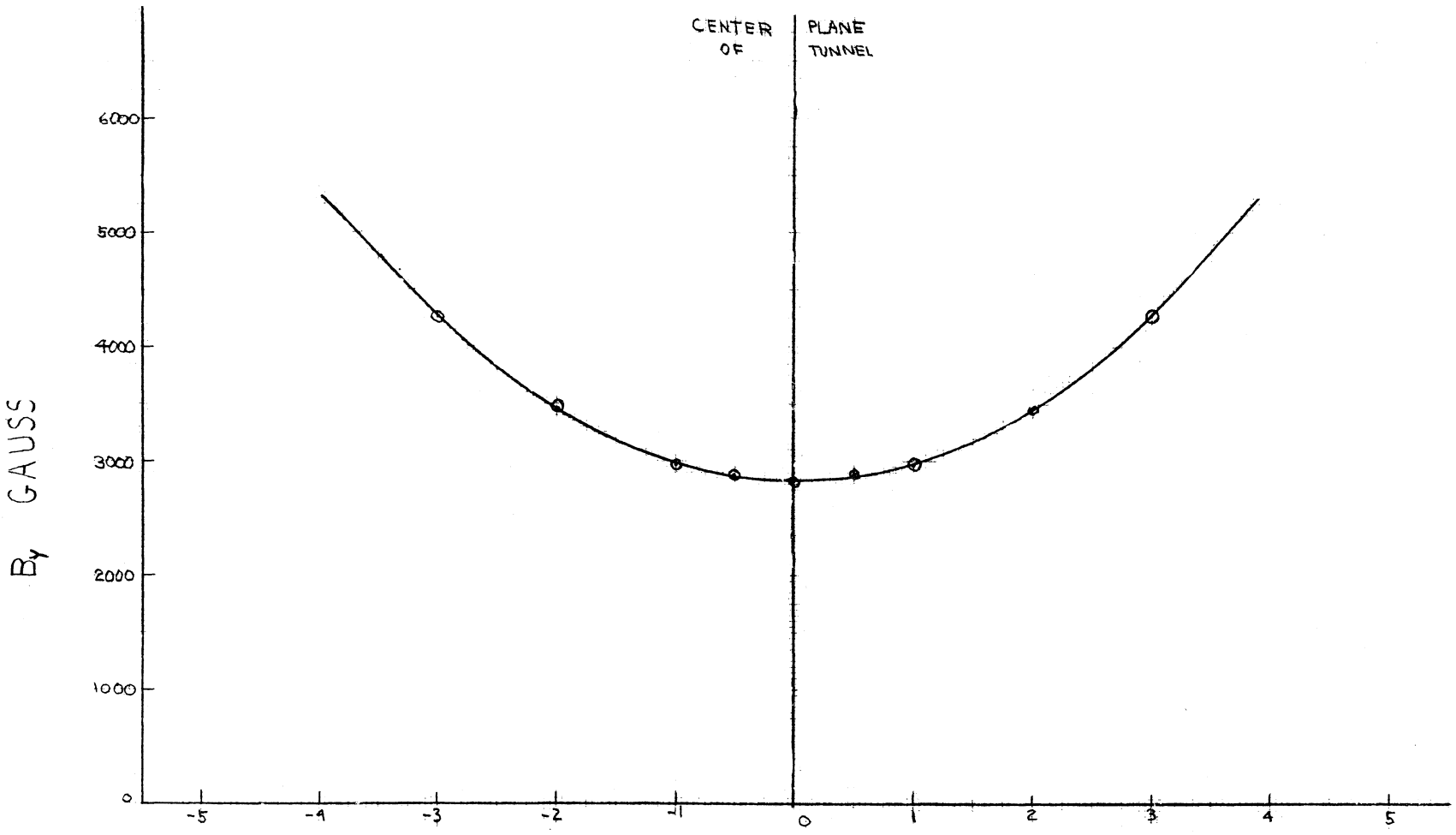


Fig. 17. Theoretical variation in transverse field strength along coil centerline (I = 1000 amperes).

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