INTERIM REPORT

ON

TRANSIENT, HIGH CURRENT ARCS IN EXTREMELY DENSE AIR

by

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ABSTRACT

The objective of the study of quarter-million-ampere, high pressure arcs is to obtain information useful in the design of arc chambers for hypersonic wind tunnels. Initial experiments indicated that the arc properties were dominated by gas contamination due to electrode erosion. This interim report describes exploratory studies in which magnetically driven arcs were used to minimize electrode erosion. The use of a controllable, externally applied magnetic field to drive an arc inside a chamber is experimentally very convenient for the scientific study of low contamination plasmas at high pressures and temperatures. For wind tunnel usage the desired motion of the arc spots can apparently be produced by utilizing the inherent instability of the arc column due to its self-magnetic field.

The experiments described in this report used a 200,000-joule inductive energy storage power supply which was capable of producing 250,000 amperes with a maximum potential limitation of 800 volts. Future experiments will be made with a 6-megajoule power supply designed for voltages up to 20 kv at currents of 300,000 amperes.

INTRODUCTION

This study of transient electric arcs at currents up to 300,000 amperes and high gas pressures is directed towards the engineering problems associated with heating air for a Hot-Shot type of hypersonic wind tunnel. The objective is to obtain a better understanding of arc characteristics at high temperature and pressure in order to assist in the design and improvement of wind-tunnel arc chambers and power supplies. The work is thus a combination of both basic and applied science.

This interim report discusses an exploratory investigation of methods of producing a low contamination, homogeneous plasma at very high temperature and pressure. The miscellaneous topics herein discussed are all related to the general objective of producing and measuring the characteristics of such a plasma and correlating experimental data with theory.

The initial experiments on this contract at currents of 300,000 amperes indicated that the rate of erosion from the electrodes was so large that the properties of the arc were dominated by the properties of the metal vapor present. The work, so far, has been directed primarily towards exploring methods of reducing air contamination which is important to both the wind tunnel objective and the basic science objective. One approach to the erosion problem is to study the erosion process in detail from a quantitative, energy balance standpoint, and another approach is to consider only the gross, qualitative phenomena and explore various methods of using moving arc spots to reduce the erosion. This project has proceeded in both directions, but the emphasis has been on the exploratory work of finding effective methods of reducing erosion.

The experiments have been performed with an energy-storage power supply which will deliver half-megampere current pulses, but the available voltage has been a limiting factor. A much larger, 6-megajoule power supply, financed by the University of Michigan Institute of Science and Technology, has been under construction for the past year. It is estimated that this new power supply will be in operation by January, 1961, and future experiments on this contract will be conducted at substantially higher energy levels.

POWER SUPPLY

The transient arcs discussed in this report were produced by means of a transformer type of energy-storage inductance coil. The high impedance primary winding of the coil was energized by a d-c current of 5000 amperes from an ignitron rectifier, and approximately 200,000 joules of energy could be stored in the magnetic field. The secondary consisted of a two-turn winding of aluminum sheets which was tightly coupled to the primary. With the two secondary turns connected in parallel, the power supply would deliver pulses of current at 500,000 amperes (maximum) at 400 volts maximum. By reconnecting the two secondary turns in series, the load current was reduced to 250,000 amperes and the voltage was doubled. The maximum available voltage was limited by a protector spark gap across the primary winding. Typical discharge time constants were 1 to 3 milliseconds.

A general description of the power supply and switching technique will be found in References 1 and 2. A related discussion of inductive energy storage is given in Ref. 3.

INSTRUMENTATION

All experimental data were recorded by means of oscilloscopes and Polaroid cameras which were located about 200 feet from the arc chamber in order to reduce extraneous interference. Triggering of the scopes was accomplished by a special triggering switch which was attached to the fast mechanical switch which opened the primary circuit of the energy-storage coil.

Voltage curves were obtained by resistive voltage dividers , and arc current curves were obtained by integrating the $L\frac{di}{dt}$ voltage curves of the voltage across the energy storage coil.

Pressure curves were obtained with an Atlantic Research Corporation lead zinconate pressure transducer which was calibrated against a dead weight tester. The calibration appeared reliable for pressures up to 7000 psi. Above this pressure the response became somewhat non-linear, and the calibration was not considered reliable.

ARC CHAMBER No. 1

For this investigation, it was not necessary that the arc chamber be equipped with the rupture diaphragm and dump valve associated with wind tunnel usage, and therefore a closed chamber was used.

The first high current arc tests were made with the chamber arrangement shown in Fig. 1 which was designed to withstand 1000 atmospheres. An axial electrode geometry was chosen so that there would be no magnetic force on the arc column tending to deflect it sidewise. The wall of the beryllium copper chamber acted as a symmetrical return path for the current so that the self-magnetic field of the arc was also symmetrical. It was believed that if a stationary arc column could be obtained in this manner, such factors as column diameter, temperature distribution, and pinch pressures could be measured more satisfactorily than if the arc were unstable and fluctuating.

The electrodes consisted of tungsten tips attached to the ends of 1-inch diameter beryllium copper rods. The lower rod was electrically connected to the chamber, while the upper rod was free to slide inside a guide which was electrically insulated from the chamber. At the beginning of the current pulse, the air cylinder held the electrodes in contact with a loading force of 600 pounds.

Having the electrodes in solid contact at the beginning of the current pulse was desirable in that the load impedance on the secondary of the energy storage coil was low during the switching. Without this low value of load impedance the switching process in the primary of the coil was difficult.

A gas-tight seal around the sliding electrode was achieved by means of a combination of an "O"-ring seal and a packing of viscous grease between the electrode and the electrode guide. The "O" ring was adequate to withstand the pre-firing pressure in the chamber, but it might have extruded if subjected to the high-transient pressure during the firing. To prevent possible extrusion and binding, the "O" ring was placed very close to the outside end of the electrode guide. The retraction of the electrode after arc initiation moved this "O" ring outside the guide. During the remainder of the transient pulse, the viscous grease was adequate to prevent leakage.

Electrical contact to the moving electrode was obtained by 4 flexible braided copper straps similar to the braided copper strap used for the ground connection to a car battery. These braided straps were connected to the edge of a 5-inch diameter beryllium copper plate attached to the moving electrode as shown in the figure. The geometry of the braid and plate is such that the magnetic field of the current acts on the plate and retracts the electrode. At a current of 300,000 amperes, the magnetic force tending to retract the upper electrode was calculated to be approximately 5000 pounds. This force was adequate to separate the electrodes a distance of 1.0 inch in 3 milliseconds.

The electrode motion was arrested after approximately 1 inch of travel when it hit a massive iron plate. Wood and rubber shock absorbers were used to cushion the blow when the electrode struck the iron plate.

The cross-sectional drawing in Fig. 1 shows the quartz pressure window designed to withstand 1,000 atmospheres which was located in the chamber wall; the window had a useful diameter of 1/2 inch. By using a special lens adjacent to the surface of this window, a photographic field of view was obtainable inside the chamber representing a solid angle of 35 degrees.

ELECTRODE EROSION

All attempts to obtain a satisfactory light sample from the No. 1 chamber failed. At the very beginning of each current pulse, the window was rendered completely opaque by metallic tungsten which was sprayed about the chamber. The inside walls of the chamber were also coated with a red-brown powder which was tentatively identified as a mixture of cupric oxide, CuO, and tungsten dioxide, WO_2. Tungsten trioxide, WO_3, a yellow-green powder, was also found but only when the arc duration was accidentally cut very short because of a flash-over in the protective system of the power supply. The powdery dust was deposited almost uniformly throughout the chamber and probably did not settle out until later in the cycle.

The metallic tungsten was deposited so quickly that no useful light sample was obtainable through the window. The deposits on the chamber walls indicated that, while the maximum amount of tungsten traveled radially outward from the point of contact of the two electrodes, the tungsten was sprayed in virtually all directions. There was little to be gained by moving the window to some other position.

In transient arcs having lower currents and/or shorter duration, most of the material is lost by evaporation. Also in low current, steady state arcs, most of the material is lost as vapor. Under such conditions, an approximate energy balance can be obtained by equating the power delivered to the cathode or anode fall of potential to the power expended in melting and vaporizing the eroded metal.[4, 5] As the current level (or pulse length) is increased, part of the metal leaves the electrode as droplets of a molten liquid, as in the case of a welding arc in which the filler metal for the weld is provided by consuming the electrode. When the temperature of the electrode tip exceeds the boiling point, the expanding gas bubbles spatter the droplets of molten metal away from the electrode tip.

The production of molten metal is a combination of joule heating (which is greatly accentuated by the high resistance of the hot metal) and the energy delivered to the surface by ion and electron bombardment. An analytical explanation of the transient energy balance under these conditions is being prepared, but will need experimental verification.

The importance of joule heating is indicated by the curves of Figs. 2 and 3, which illustrate the fast temperature rise in tungsten and copper for current densities comparable to the conditions in the electrodes of 1/3-megampere arcs. These curves were calculated (Appendix A), using handbook data for the resistivity of copper and tungsten as a function of temperature and assuming a constant specific heat which actually varies less than 5 per cent. The curves are useful in determining the upper limit of pulse handling capacity for these metals.

With the No. 1 arc chamber, a test was made in which the electrodes were clamped together under a heavy clamping pressure, and the metal erosion per coulomb at the junction of the two electrodes was comparable to the conditions where the electrode separation was 1/2 to 1 inch and an arc was known to be present. If the actual area of intimate and complete contact of the clamped electrodes was 0.5 cm^2, a 300,000-ampere arc would have theoretically brought the tungsten at the interface to the boiling temperature in 300 microseconds. With an area of 1.0 cm^2, the melting point would be reached in 1.2 milliseconds.

In several tests, the initial contact resistance between the electrodes was reduced by a very thin "shim" of deformable, soft metal between the electrode tips which increased the area of contact. The resulting benefit, if any, was not large and the results were inconclusive.

Fig. 4 is a photograph of a pair of 3/4-inch diameter tungsten electrodes after one firing at 300,000 amperes. This photograph does not provide information as to the actual diameter of the arc spot except (in this case) to indicate that it was smaller than the 3/4-inch diameter of the tungsten. Fluctuations in the voltage trace (Fig. 5) suggest the possibility that the arc column and arc spots may have been undergoing rapid changes due to "sausage" and/or "kink" instabilities.

Fig. 6 is a photograph of two 1-1/2-inch diameter tungsten electrodes which illustrates the explosive pressure of the gas from the vaporizing tungsten. As the electrodes pulled apart, molten or plastic metal was blasted out in a radial direction and flow lines were left in the remaining metal on the electrode surface.

A listing of data from 12 tests is given in tabular form in Table 1, and a brief description of these tests is given below.

No. 1 and No. 2. Tungsten electrodes 1.5 inches and 0.75 inch in diameter were used. The faces were slightly covex for No. 1 and flat for test No. 2, and in order to increase the area of initial contact and decrease contact resistance, a thin shim 0.01 inch thick of soft solder was placed between the electrodes.

No. 3. At the time this test was made, it was believed that the principal cause of erosion was the energy delivered to the surface of the anode and cathode spots and the importance of ohmic heating of the metal was not appreciated. It was reasoned that if the erosion were related to the gaseous conduction mechanism at the anode and cathode spot, then the presence of a metal vapor having a very low ionization potential, as compared to tungsten, would have a significant effect on the rate of erosion. Tungsten has an ionization potential of 8.1 volts as compared to 5.96 volts for aluminum and 5.19 volts for barium. A special insert was placed between the electrodes which consisted of barium held in place by an aluminum retainer. The electrode loading pressure (previous to the current flow) was approximately 600 pounds. The arc voltage exceeded the 400-volt

Table 1. Erosion Data.

No.	Diameter of electrodes (inches)	Peak current (amps)	Cathode erosion (grams)	Anode erosion (grams)	No. of coulombs	Total grams eroded per 100 coul.	Initial pressure	Remarks
1	1.5	325,000	2.3	2.7	500	1.00	600	Initial contact area increased by .14 gm. shim of soft solder.
2	0.75	300,000	1.8	1.5	300 (est.)	1.10	600	Discharge arrested by arc-over across primary overvoltage protector gap after 1.8 ms. 0.14 gm. solder shim used.
3	0.75	150,000	0.4	0.6	100 (est.)	1.00	600	Discharge arrested by flash-over. Shim of barium and soft aluminum.
4	0.75		1.5	1.5			400	Asymmetric electrode to produce magnetic blow-out.
5	0.75	300,000	0.8	0.9	200	0.85	600	Asymmetric electrode to produce magnetic blow-out.
6	0.75	300,000	1.2	3.9	400	1.27	600	Parallel arcs, only one carried current.
7	0.75	325,000	1.9	1.6	500	0.70	600	Same as above.
8	0.75	250,000	5.8	3.2	1100	0.85	600	Clamped electrodes
9	---	300,000	-1.6	2.5	400	0.22	600	Concentric copper electrodes. Spoke arc moving in z direction.
10	0.75	275,000	0.7	1.1	360	0.50	600	Mallory G-14 tips.
11	0.75	300,000	0.8	1.2	400	0.50	600	Same as above.
12	0.75	300,000	1.6	2.3	400	0.95	600	Mallory G-12 tips.

limitation when the current reached a value of only 150,000 amperes.

No. 4 and No. 5. The axial symmetry of the magnetic field inside the arc chamber was destroyed by machining the support to one electrode so as to put a "kink" in the current path. The lack of symmetry caused a radially directed blow-out force and increased the voltage in the arc column. This increase caused a larger proportion of the total energy to go into heating the gas and a smaller portion to go into melting the electrodes. However, even a relatively small deviation in axial symmetry caused such a pronounced increase in the voltage requirement that the arc could not be maintained with the available power source.

No. 6 and No. 7. Since the electrode erosion per coulomb for very large arc currents was very much larger than for smaller arc currents, it appeared that the total erosion for a given total arc current would be reduced if two or more arcs could be operated in parallel. Familiar types of arcs have a negative slope on the volt-ampere characteristics and operation of two arcs in parallel requires stabilizing resistances or balancing reactors. In this particular case, there appeared to be a theoretical argument that the volt-ampere characteristic might have a positive slope and parallel operation might be possible. The experiments indicated that this theory was wrong and that one or the other of the arcs would take all of the current and the other arc would extinguish.

No. 8. The electrodes were clamped together under heavy pressure to prevent the formation of an arc column. The duration of the current pulse was 7 milliseconds. The results of this test seemed to indicate that the erosion is primarily due to ohmic heating of the electrode metal. The tabulated data indicates that the erosion per 100 coulombs for this test is consistent with other tests using tungsten electrodes.

No. 9. This was an experiment to determine if an arc spot moving rapidly over the surface of an electrode would significantly reduce erosion. The arc was driven between the parallel surfaces of copper electrodes spaced 0.25 inch apart. The electrodes were made of copper because of the difficult machining problem with tungsten. The geometry and magnetic force configuration are rather complicated to explain without going into considerable detail. The arc moved in an axial direction and the driving force was less violent than if a straight rail geometry had been used. The erosion measurement, based on loss of electrode weight, is misleading, since most of the material lost by the anode was collected by the surrounding cathode. The arc traces, however, indicated that erosion was probably reduced by the moving arc.

No. 10, No. 11, and No. 12. The electrodes were tipped with 0.75-inch diameter Elkonite discs, 0.125 inch thick. This material, produced by Mallory, is sintered tungsten and tungsten carbide with the interstitial voids filled with silver. The G-12 material has more silver, higher conductivity and lower strength properties than the G-14 material. The tests indicate that the G-14 Elkonite is significantly better than pure tungsten.

EROSION REDUCTION BY MAGNETICALLY DRIVEN ARCS

Experimental information from various sources indicates that an effective method of reducing erosion is to magnetically drive the arc spot along or across the electrode surface. When this is done, the arc will dwell on any one area only a very short time, and therefore the thermal capacity of the metal surface layer will be sufficient to minimize heating and melting. This method has been utilized for many years in the design of circuit breakers and more recently in the design of arc air heaters for plasma research.

The advantage of reducing the dwell time of the arc spot on any one area is also illustrated by thermonuclear research apparatus where spark gaps are operated repetitively with very high current sparks in the microsecond range and the electrode erosion is unimportant. The amount of electrode erosion per coulomb produced by very high current sparks is small if the individual current pulses are short enough. Since both the amount and rate of erosion increase very rapidly with pulse duration, the thermal capacity of the metal surface layer appears to be the important factor in the low erosion caused by sparks in the microsecond range.

The rate at which an arc spot must move to sufficiently limit the erosion in a high pressure arc chamber is not known, but let us assume that an "exposure" time of 50 μseconds does not cause excessive erosion. If an arc spot is assumed to have a diameter of 1 cm, and if it moves one diameter in 50 microseconds, the resultant velocity is 20,000 cm/sec, or approximately 660 feet/sec. Velocities of this order are presumably attainable even at very high air densities, although published data as to the velocities of magnetically driven arcs seem to be limited mostly to observations at atmospheric pressure.

The calculation of the arc velocity in a magnetic field is not a simple task. The force on the arc column can be calculated, and it might seem, at first thought, that a knowledge of the gas properties and the column diameter would enable the velocity to be approximately calculated. This has been done with some success with arcs at current levels low enough so that heat convection forces are the predominant forces on the arc column. However, the motion of a magnetically driven arc through a gas is not the motion of a solid cylinder through a viscous fluid, but is much more complex. The mobility of electrons is greater than the mobility of ions, so that electrons are displaced slightly out of the arc column on one side, causing new ionization into which the column will move. The column motion involves both the creation of new charged particles and the small, but significant, motion of the charged particles in the direction of the arc motion. The rate of motion is difficult to predict quantitatively.

Walker and Early[6] measured the velocity of magnetically driven arcs in air at 30 atmospheres pressure. A 6000-gauss field moved a 2-ampere arc along rail electrodes at 200 feet/second. The rate of motion is very dependent on the gas density and temperature.

Fig. 7(a), reproduced from Ref. 6, illustrates an experiment (at atmospheric pressure) with a rotating arc. One electrode was a 1/4-inch-diameter, copper rod located in the center of a 1-3/4-inch-diameter hole in a copper sheet which served as the other electrode. The axial magnetic field was 5600 gauss, and the current was 12 amperes. The arc column did not rotate like a radial spoke in a wheel, but was bent into a spiral because the angular velocity was greater near the center electrode. This spiral effect presumably also exists under conditions where both the air density and the current density are scaled up by large factors.

Fig. 7(b) is a single frame of a Fastex motion picture taken with the center electrode as the anode. The rate of rotation, as measured from the Fastex film, was 2700 revolutions per second. The arc voltage was 1400 volts. Fig. 7(c) was taken under identical conditions, except that the center electrode was the cathode. The arc voltage was 1200 volts, and the rate of rotation was 2000 revolutions per second.

The velocity of air motion, as observed by smoke tests, was at least one or two orders of magnitude slower than the velocity of the arc. The electrode erosion, after 15 minutes of operation, was too small to be noticed by visual inspection, although the power into the arc was 15 kw.

MOTION OF ARCS DUE TO SELF-MAGNETIC FIELD

At high currents, the forces on the arc column due to its self-magnetic field become very important. In any loop of current, the forces from the self-magnetic field of the current in the loop are in such a direction that the loop will tend to enlarge or stretch in a direction which will increase its inductance. At arc currents of many thousands of amperes, the effects of the self-magnetic field of the arc will completely overshadow the thermal convection effects. For example, even if an arc column were assumed to be straight and the self-magnetic field were symmetrical, and the magnetic forces were balanced, a small perturbation would tend to grow forming kink (sidewise movement) and sausage (pinching) instabilities.

Blow-Out Arcs

An arc across the ends of two parallel electrodes or across the end of a coaxial line can be termed a blow-out arc because the self-magnetic field of the arc current forces the arc to expand outward into a loop until the voltage becomes high enough to cause the arc to re-ignite near the electrodes. If the arc is free to expand in all directions with no convection or wall effects, the arc column will tend to blow out into a circle. Where there are metal chamber walls present, the arc current induces image currents in the metal wall which tend to repulse the arc from moving towards the wall. This effect is well described in the literature pertaining to thermonuclear research where a copper "mirror" is used outside dielectric cylinders and toroids to help keep the "pinch" stabilized.[7,8] This image current thus acts to reduce "kink" instabilities.

At currents of hundreds of thousands of amperes, a dominant effect associated with a blow-out arc is the huge magnetohydrodynamic force which causes convection air flow in the gas and increases the rate of heat transfer to the walls of the arc chamber. To illustrate the magnitude of this "pumping force" in the gas and the resultant acceleration of the air, a numerical example is of interest.

Assume that the electrode tips are relatively close together, and that the magnetic forces are such as to blow the arc out into a loop. Since the actual effect of the tips is not significant, it can be assumed for simplicity that the arc is in the shape of a toroid and the force is expanding the toroid in a radial direction. If it is assumed that the minor diameter remains constant as the major diameter expands, the total radial force outward on the circle is given by the relation[9]

$$F = \frac{1}{2} I^2 \frac{dL}{dR}$$

where F = force in newtons

I = current in amperes

L = inductance in henrys

R = major radius of toroid in meters.

The inductance of a toroid as a function of the major and minor diameters is given in Ref. 10.

If the calculation is carried out for a million-ampere arc having a major diameter of 16 cm and a minor diameter of 3 cm, the total MHD force on the gas is 1.7×10^6 newtons, or approximately 380,000 pounds. An order-of-magnitude conception of the effectiveness of this force in accelerating air can be obtained by assuming that the force is acting to accelerate 6.4 pounds of mass in a linear, non-viscous manner. After 20 milliseconds, the mass would attain a final velocity of 12,000 meters/sec and would travel a distance of 120 meters. Even if allowances are made for the fact that the motion is reduced by a large factor inside an arc chamber, and for the tapering off of the current pulse, there is a significant circulation which pumps the hot plasma from the arc against the far end of the chamber and circulates it back along the walls of the chamber as illustrated in Fig. 8(a).

Suggested Chamber Geometries

The chamber design illustrated in Fig. 8(b) uses the end of the chamber for one electrode and the chamber wall for the other electrode. This appears to have a reduced pumping action and the systematic circulation of plasma from the center of the chamber to the walls would be expected to be greatly reduced. Fig. 8(c) is similar to Fig. 8(b), except that the current is brought into the chamber on parallel plates instead of a coaxial line, and hence it is easier to locate the dump valve opening in the end of the chamber. Fig. 8(d) is a chamber design which uses half of the copper chamber liner for the cathode and the other half for the anode. This design has been tested at a current level of 400 amperes at atmospheric pressure, and the results support the theory that the arc and the arc spots move continuously due to the inherent instability of the arc column. Also, there is apparently no pumping action in this design. There is, however, a great deal of small scale turbulence in the gas which causes the gas to mix more rapidly. A further investigation of the relative merits of the design of Fig. 8(c) as compared to Fig. 8(d) is planned on this contract.

POSSIBILITY OF PRODUCING A HOMOGENEOUS, HIGH DENSITY PLASMA FOR SCIENTIFIC MEASUREMENTS

If the properties of a very high density plasma are to be experimentally measured, it seems essential to be able to produce a small volume of the plasma which is in thermal equilibrium and at a uniform temperature. The conductivity of such a plasma as obtained by theoretical calculations is only an approximation and may represent substantial error.[11] Measurements on such an "ideal" plasma would assist in predicting the arc impedance under various conditions in arc chambers for Hotshot wind tunnels. Such a plasma can possibly be produced inside an arc chamber by a rotating arc.

It is logical to assume that if a rotating arc is in a closed chamber, and if the rate of heat loss from the chamber is low enough, the cooling and deionization of the gas between successive passes of the arc column become insignificant, and the plasma tends to assume uniform temperature and conductivity. This assumption is also consistent with the behavior of a stationary arc column operating on alternating current where the temperature fluctuation may be thousands of degrees at 60 cycles but gradually decreases at higher currents and frequencies.[12,13] The cyclic temperature fluctuation of an a-c arc is always reduced at high currents where the arc column diameter is larger and the volume-to-surface ratio of the plasma is greater. Likewise, the temperature fluctuations produced by a rotating arc inside a large arc chamber would be less than in the case of a small chamber. In the large chamber, the ratio of heat stored to the heat lost per second may be much greater than in a small chamber. Hence, the thermal time constant is longer.

Ref. 14 describes a rotating arc at high current levels used for thermonuclear research. A discussion with the authors of this paper indicated that they found no evidence of a spoke-like arc column.

The heat loss due to convection currents set up in the gas by a 1/3-megampere rotating arc can be made very small in comparison with a blow-out arc at the same current. As described in the next section of this report, an external magnetic field of a few hundred gauss is sufficient to cause the arc to move rapidly, and yet the magnetic force on the gas is one or two orders of magnitude less than in a blow-out arc at a comparable current level.

An alternative method of producing a low contamination, homogeneous plasma is the system shown in Fig. 8(d), which requires no external magnetic field. The attractiveness of using the split chamber design was not fully appreciated at the time the decision was made to design chamber No. 2 for a rotating arc.

ARC CHAMBER No. 2

The design of the No. 2 arc chamber was chosen with two objectives in mind:

(1) To demonstrate that rapidly moving arc spots greatly reduce electrode erosion even at current levels of hundreds of thousands of amperes.

(2) To obtain a plasma of high density gas, a portion of which would be homogeneous as to temperature and current density, or at least determine the size of the chamber and the energy level necessary to achieve this condition.

It was believed that a chamber which used an externally applied magnetic field to rotate an arc at a controllable rate would offer the best probability of meeting the above objectives. It also appeared that experiments with a blow-out arc would yield empirical data applicable to a particular piece of apparatus but would not be amenable to scaling or similitude relationships or interpretation in terms of gaseous conduction theory. Various considerations led to the prediction that the production of a plasma of uniform current density and temperature by a blow-out arc geometry would be so difficult that measurements with such a chamber would probably be limited to the conditions of a transient "dying plasma" after the current had been turned off. Measurements in a dying plasma would be of basic-science interest, but the most important measurement of all, plasma conductivity, to be directly useful in an engineering application, should be made under conditions where the plasma has a high uniform current density.

Although the use of an externally supplied magnetic field is attractive from a basic-science point of view, there is a disadvantage of major significance in that the design is not easily adapted to the requirements of a Hotshot wind tunnel.

Fig. 9 is a cut-away drawing of the No. 2 arc chamber. The total volume was 41.0 cubic inches. Because of the limitations of the power supply, the energy density in the chamber was increased by filling the ends of the chamber with ceramic inserts which decreased the volume to 18 cubic inches. The chamber was made of beryllium copper and designed for 15,000 psi. An axial magnetic field was produced by a winding of copper cable around the chamber which would supply fields up to 8000 gauss inside the chamber for periods of several seconds without overheating the cable. The part of the chamber wall which served as the anode was protected by two replaceable metal rings which were held in place by a press fit.

In order to prevent the blow-out effects caused by the self-magnetic field of the arc current from overshadowing the effect of the applied field, the current was brought into the chamber symmetrically from both ends as illustrated in Fig. 10. With this arrangement there was no average net blow-out force on the arc towards either end of the chamber, and the dominant magnetic effect was the rotation caused by the reaction of the arc current on the axial magnetic field.

If a 300,000-ampere arc column is assumed to be 1 cm in diameter, the self-magnetic field at the surface of the column is approximately 100,000 gauss. Since the magnetic pressure is $\frac{B^2}{8\pi}$ (in cgs units), and thus varies as the square of the field strength, the addition of an externally supplied magnetic field of a few thousand gauss has little effect unless the forces on the arc column caused by the self-magnetic field are approximately balanced. Otherwise, the effect of the self-magnetic field will predominate over the effect of the externally applied field.

The limited voltage obtainable from the power supply required that the spacing between the concentric electrodes be kept small. With the inductive storage transformer reconnected so that the two secondary turns were in series, the maximum available voltage was 800 volts, which seemed to be more than enough to sustain the arc, once it was established. The average arc voltage was 250 to 500 volts, depending on current and air density, but short voltage "spikes" occurred when the required voltage would exceed the available voltage, and the arc would extinguish. The voltage spikes were apparently caused by some form of arc instability.

Arc initiation was accomplished by a small third electrode inside the chamber which was connected to the high voltage primary winding of the coil through a resistance. About 50 amperes of current would flow to this third electrode throughout the discharge, and this current not only initiated the main discharge but also helped somewhat to prevent extinguishing when transient "spikes" occurred in the arc voltage.

Tests at 250,000 amperes indicated that the erosion was greatly reduced. The anode rings could be weighed before and after each test, and the amount of material lost was usually too small to measure, certainly less than 0.1 gram per 100 coulombs which was down by a factor of at least 10 from the previous chamber, even though copper was used instead of tungsten.

A 1/4" diameter quartz rod was successfully used as a "light pipe" to bring a sample of light from the center of the arc region, out through the wall of the chamber, and this indicated that spectral measurements of temperature are probably possible by this method.

Fig. 11 illustrates typical curves of voltage, current, power and pressure which were obtained on several successful firings at approximately 1/4 megampere. Several tests were also made with the arc chamber connected in the primary circuit of the inductance coil, and good, repeatable results were obtained at peak currents of 2000 to 12,000 amperes, but these results are not particularly relevant to the objective of this contract. Repeatable operation could also be obtained at 1/4 megampere when the magnetic field was very low, but with a magnetic field of about 1000 gauss which was required to move the arc fast enough to control the erosion, the power supply peak voltage limitation was serious.

Theory showed that a considerable amount of energy was lost in the switching operation whenever the secondary arc voltage was high at the instant of switching. Since the arc voltage was rapidly fluctuating, the energy lost in switching and the energy into the chamber would vary considerably from one experiment to the next. In addition, the arc voltage requirement was not met with a satisfactory safety factor, and the value of 800 volts on the secondary, which corresponded to 50,000 volts on the primary, was not enough to consistently maintain the arc. Each time there was a severe transient in the arc, the primary voltage would exceed the allowable voltage, and the protective spark gap on the primary of the coil would arc over, shorting out the system. The operation was not reproducible, nor scientifically satisfactory.

PRESENT STATUS OF INVESTIGATION

In July, 1959, the University of Michigan Department of Aeronautical and Astronautical Engineering negotiated a contract with the Office of Naval Research to build a Hotshot wind tunnel. The tunnel was to be constructed and operated under the Office of Naval Research contract, and the energy storage power supply was to be financed by the University of Michigan Institute of Science and Technology.

The power supply, now nearly completed, is to be an interdepartmental facility and will be used for arc and plasma studies by the Department of Electrical Engineering, for thermonuclear work by the Department of Nuclear Engineering, and for hypersonic wind tunnel work by the Department of Aeronautical and Astronautical Engineering. This energy storage supply will use a unipolar generator and flywheel in conjunction with a large inductance coil similar to Hotshot II at AEDC. The flywheel will store 20 megajoules of kinetic energy, and 6 megajoules will be stored in the inductance coil at peak current. Fig. 12 is a photograph of the inductance coil.

Since the high current arc investigation sponsored by AEDC required a better power supply, it was decided to suspend the experimental program approximately one year, until approximately June, 1960, when the new power source was scheduled to be completed. Delivery of the unipolar generator was originally scheduled for April, 1960, but the delivery date was subsequently moved up to August, 1960, by mutual agreement. This unit has not yet been received. The supplier reports that the time extension was used to incorporate improvements into the system, based on information obtained from similar generator units. It is reported that the generator is nearly completed (as of November, 1960), and will be shipped in the very near future.

APPENDIX A

Transient Temperature Rise in a Metal at High Current Density

The power dissipated per unit volume in a metal is given by the formula

$$\frac{P}{V} = J^2 \rho$$

where J = current density

ρ = resistivity.

When the current density is uniform and the temperature rise is sufficiently rapid so that thermal diffusion effects can be neglected, the following relationship holds:

$$J^2 \rho dt = C\ m\ dT$$

where C = specific heat

m = density.

Since the resistivity and specific heat are functions of temperature, by separating variables,

$$dt = \frac{m\ C(T)\ dT}{J^2\ \rho(T)}$$

Solving this equation by integration yields the temperature implicitly as a function of time.

$$t = \frac{m}{J^2} \int \frac{C(T)}{\rho(T)}\ dT + \text{constant}$$

Values of specific heat and resistivity at various temperatures are available in handbooks, and integration may be carried out numerically. An approximate empirical equation for $\rho(T)$ for tungsten derived from handbook data is $\rho = 4.16(T^2 + 5T)$ μohm-cm, where T is in kilodegrees Kelvin.

The specific heat of tungsten varies less than 5 per cent over the range from room temperature to 1800 $^{\circ}$K, and in the curves plotted in Figures 2 and 3 it was assumed to be constant.

An interesting closed form solution may be obtained by making two simplifying approximations. First, assume that the specific heat is a constant. Next, assume that the resistivity varies linearly with absolute temperature. This is inferred by the Wiedemann-Franz law for all metals. For tungsten, this is quite reasonable an assumption, since the resistivity rises only slightly more rapidly than linearly. The resistivity can be written as

$$\rho = \frac{\rho_0}{T_0} T$$

where ρ_0/T_0 is merely a constant, but the use of this notation maintains the dimensions. The term ρ_0/T_0 may be interpreted as the slope of a straight line that is used to approximate the resistivity-vs.-temperature curve.

The advantage of these latter assumptions can now be shown, since

$$dt = \frac{m\ C}{J^2}\int\frac{dT}{\rho} = \frac{m\ C}{J^2}\int\frac{T_0 dT}{T\rho_0} = \frac{m\ C\ T_0}{J^2\rho_0}\int\frac{dT}{T}$$

$$\text{or } t = \frac{m\ C\ T_0}{J^2\rho_0}\ \ln T + \text{constant.}$$

This can be re-arranged, and if T_0 is defined as room temperature,

$$T = T_0\left[e^{\left(\frac{J^2\rho_0}{m\ C\ T_0}\right)t}\right]$$

The temperature rises exponentially with time.

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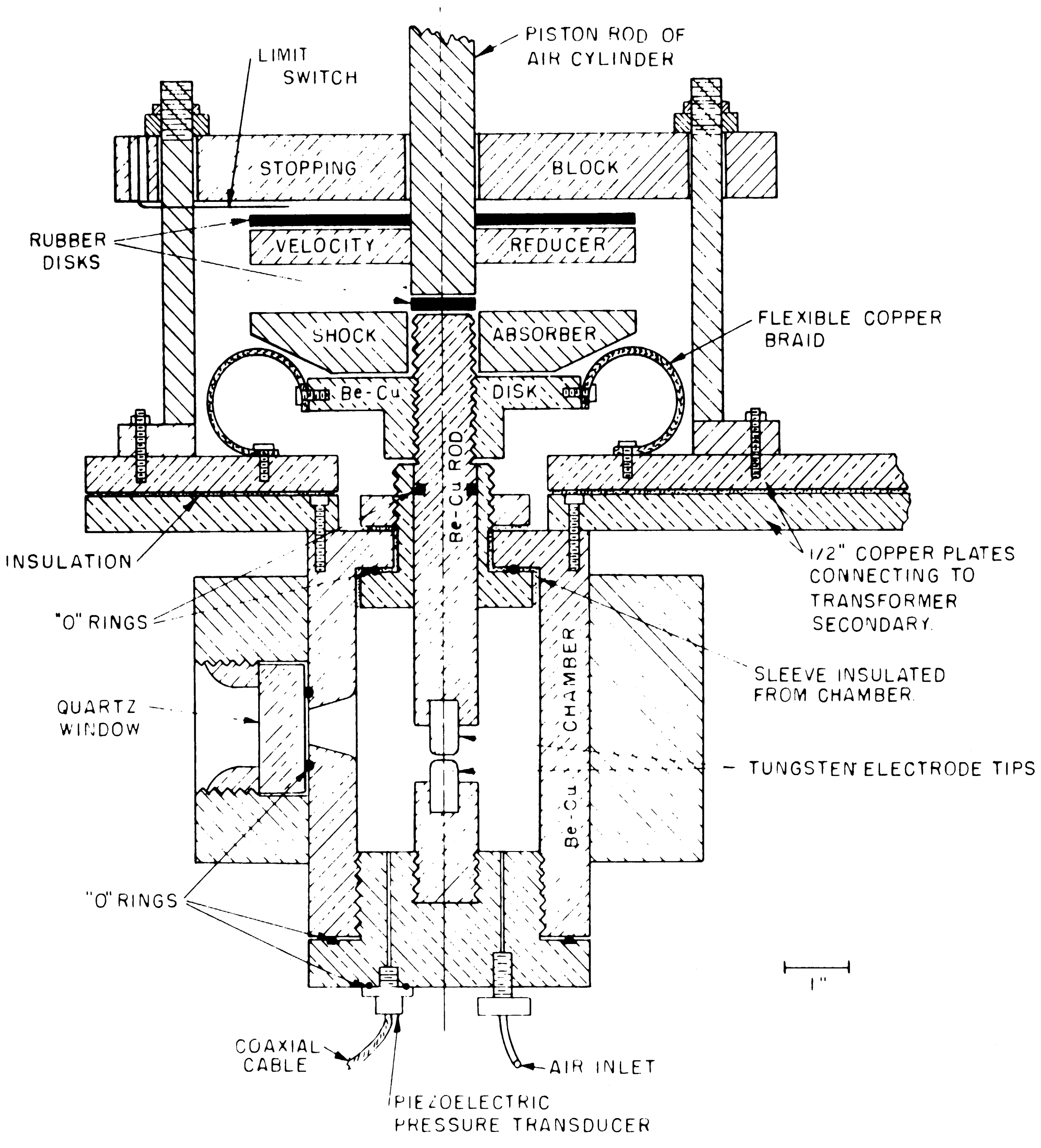

FIG. I ARC CHAMBER AND ELECTRODE ACTUATING MECHANISM.

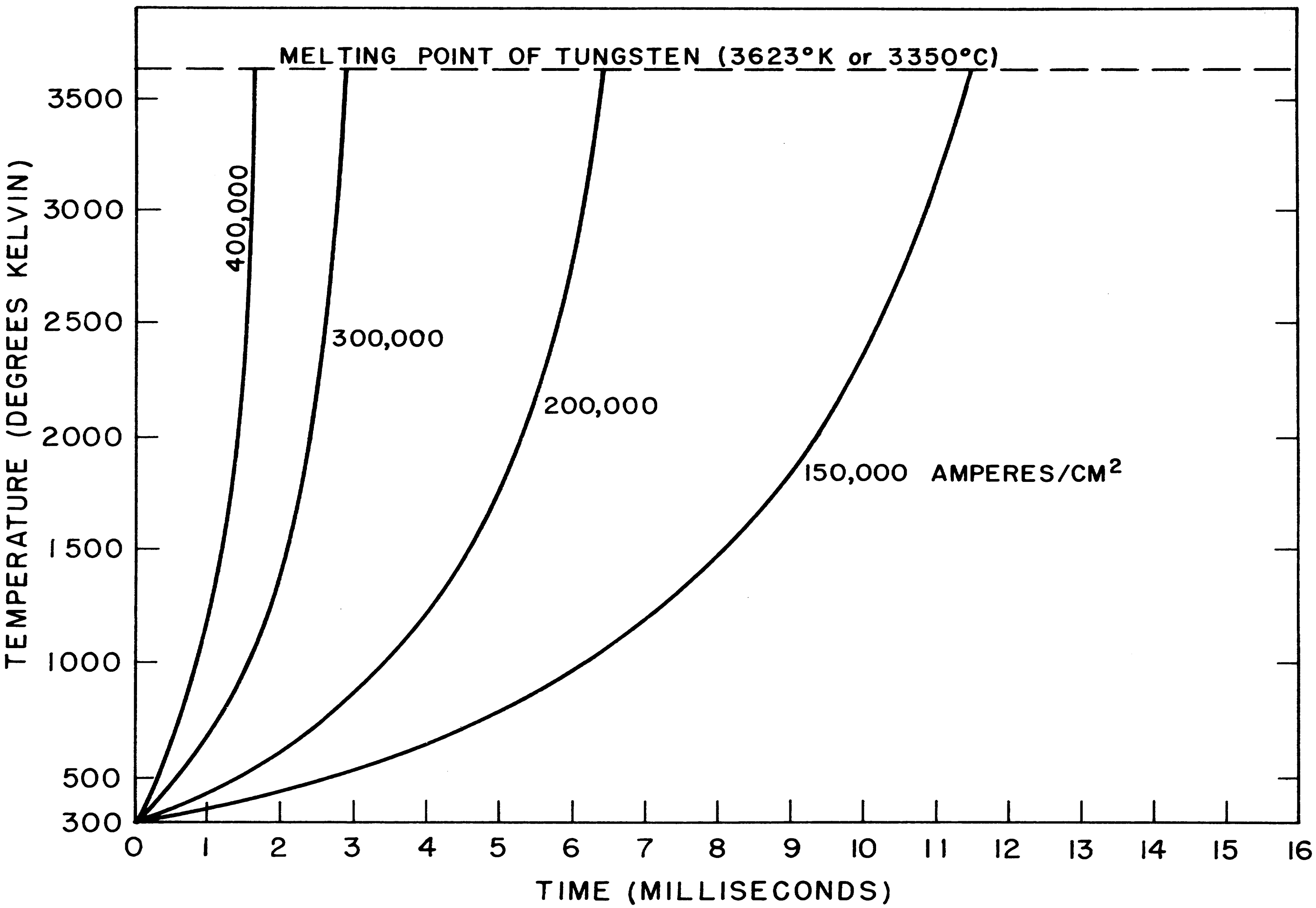

FIG. 2. THE TEMPERATURE RISE IN TUNGSTEN FROM OHMIC HEATING AT CONSTANT CURRENT DENSITY

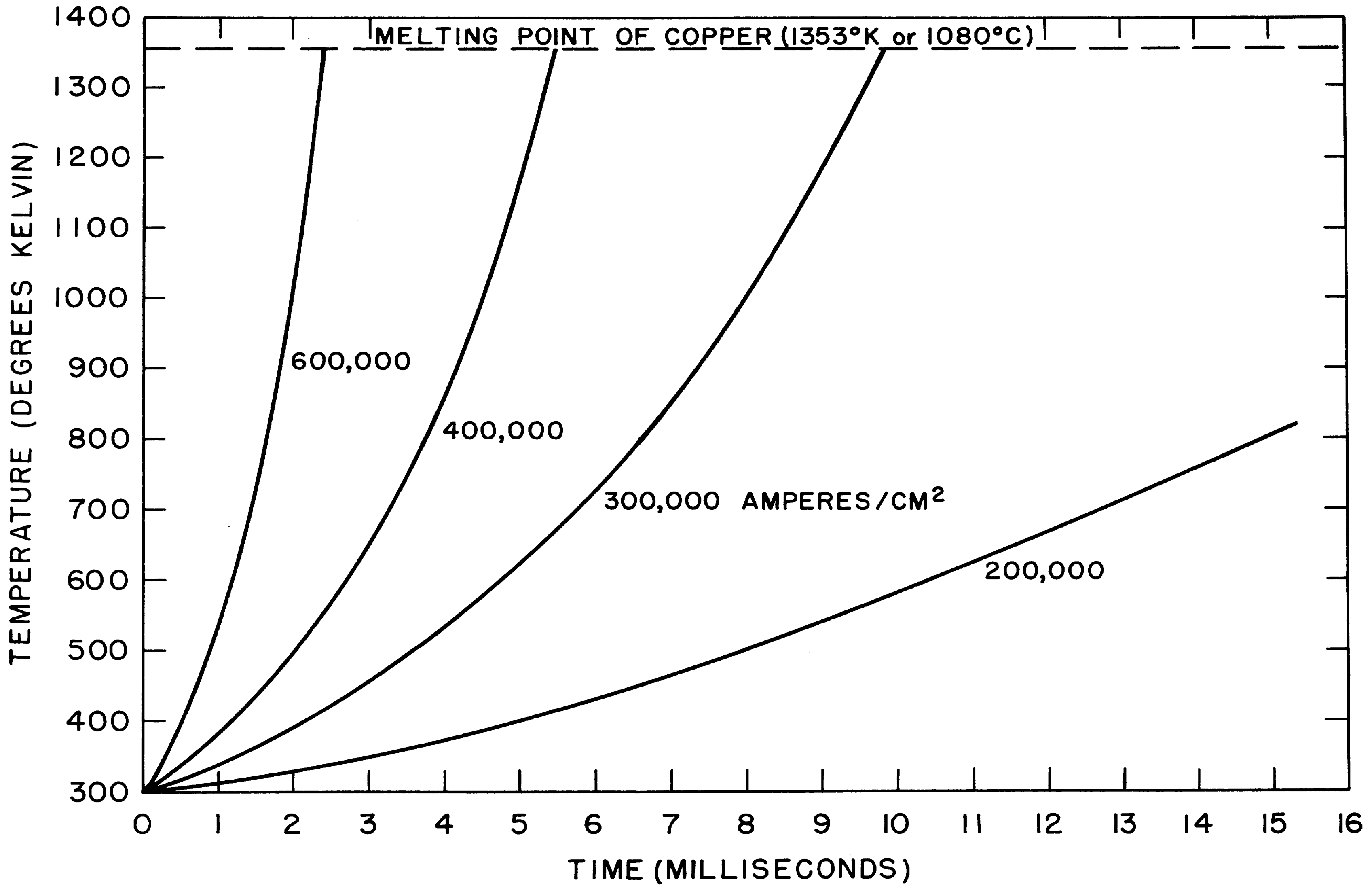

FIG. 3 . THE TEMPERATURE RISE IN COPPER FROM OHMIC HEATING AT CONSTANT CURRENT DENSITY

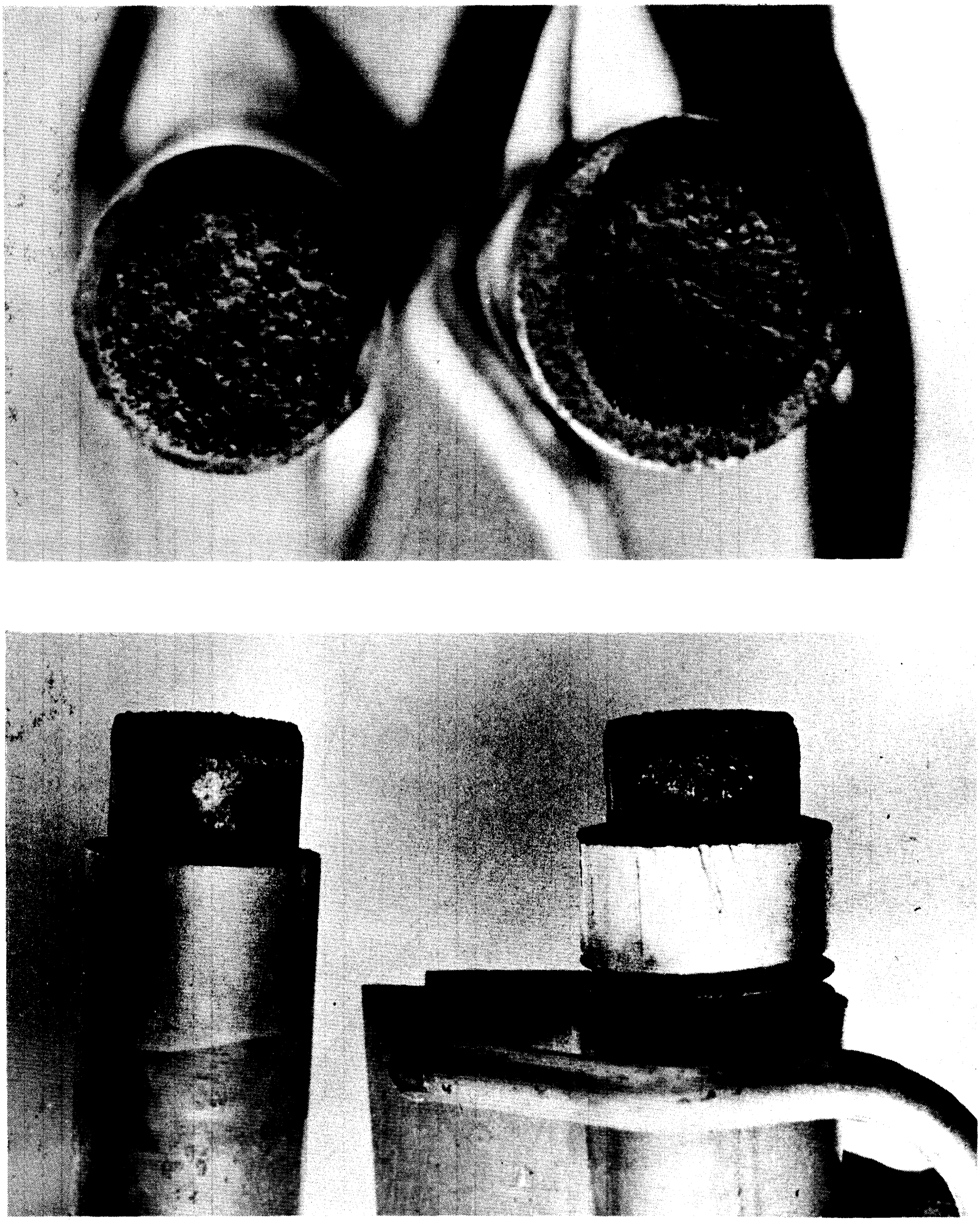

FIG. 4. **TUNGSTEN ELECTRODE TIPS, 0.75 INCH DIAMETER, AFTER ONE FIRING AT 300 KILOAMPERES.**

Molten tungsten flowed away from the flat end surfaces of the electrodes and solidified on the sides. Arc spot diameter was evidently less than the 0.75 inch diameter of the end surface.

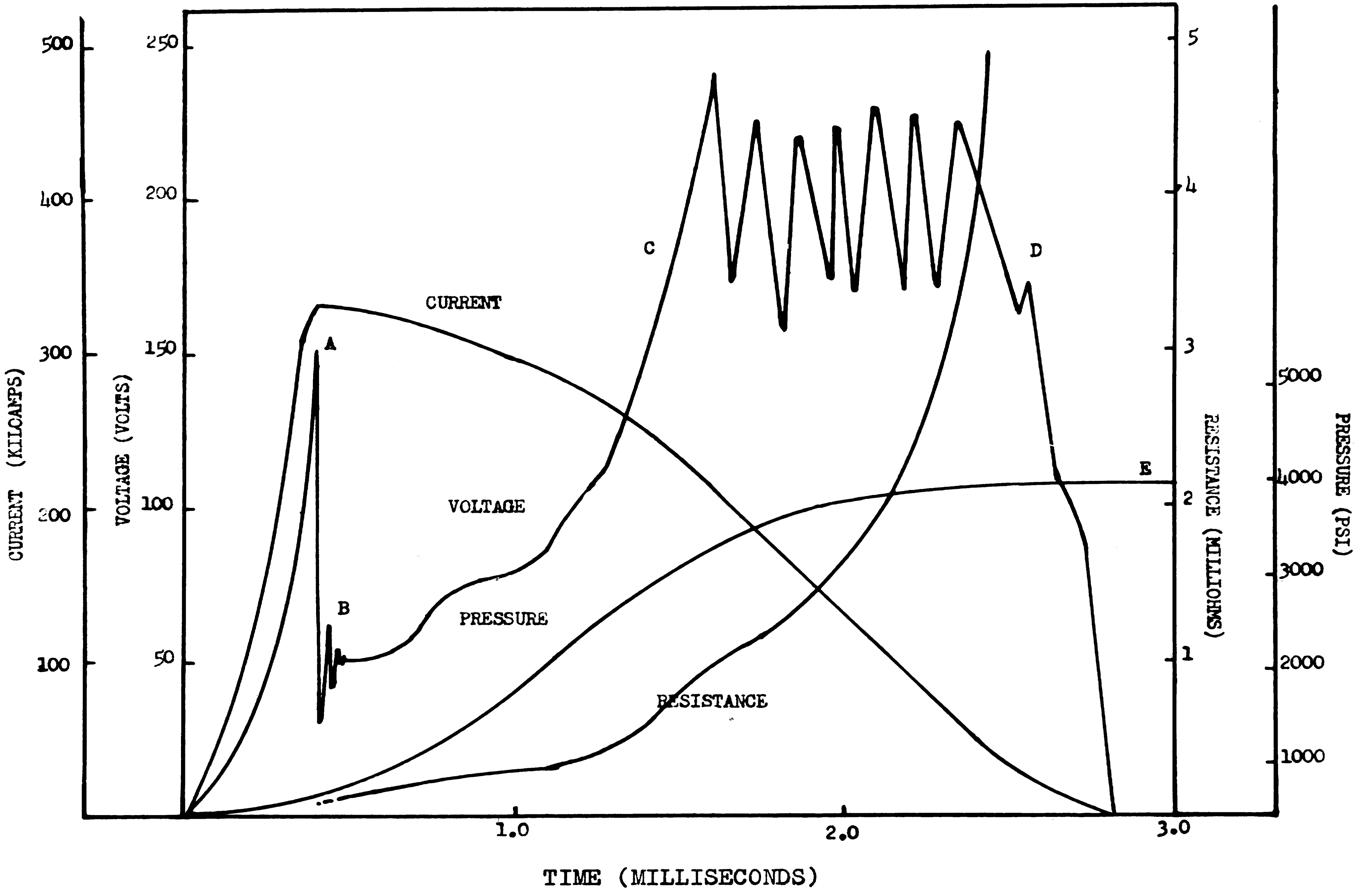

FIG. 5. TYPICAL DISCHARGE CHARACTERISTICS FOR ARC CHAMBER NO. 1.

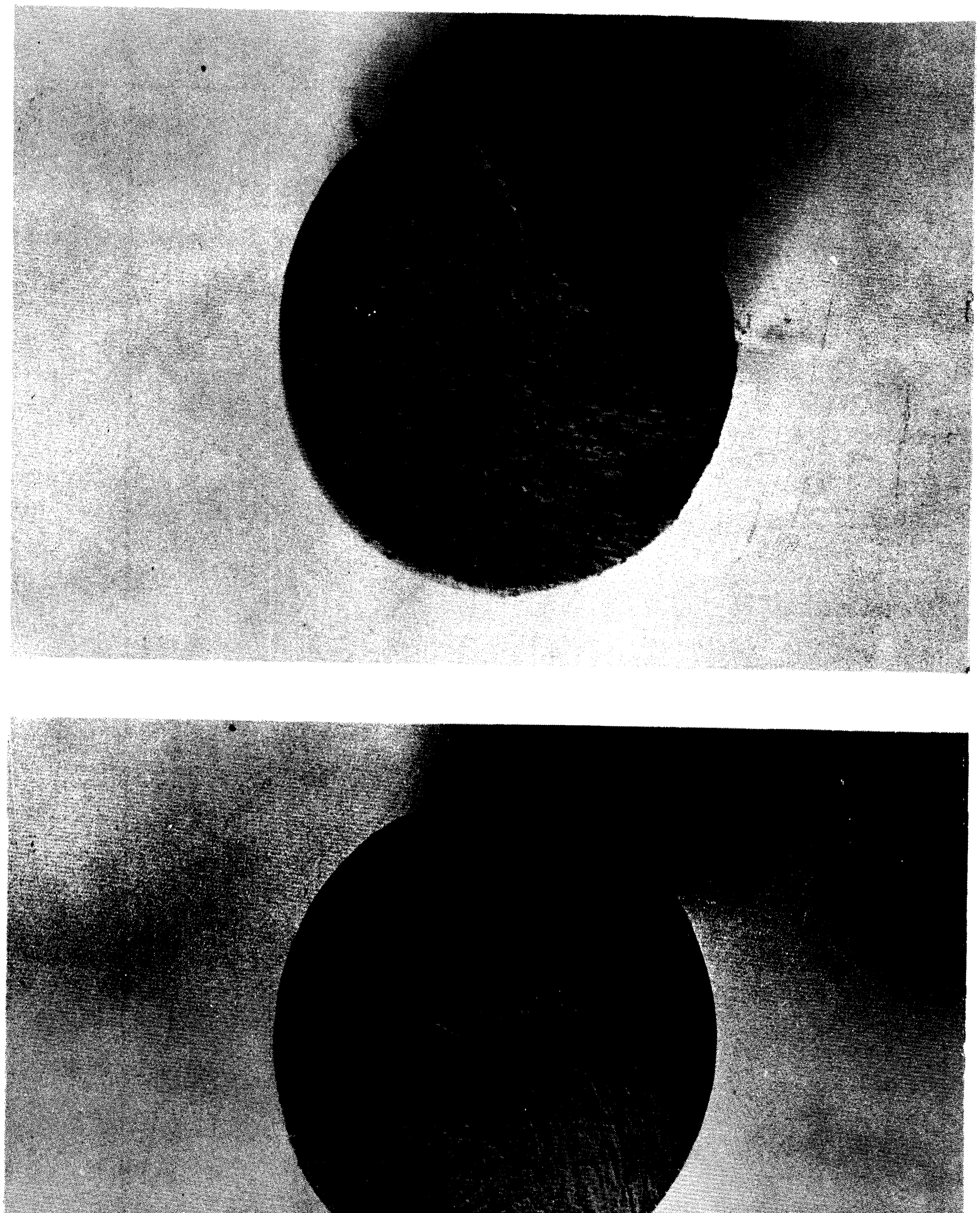

FIG. 6. EROSION OF 1½-INCH DIAMETER FLAT TUNGSTEN ELECTRODES.

The markings illustrate the flow lines of molten metal caused by the vapor blast while the electrodes were separating.

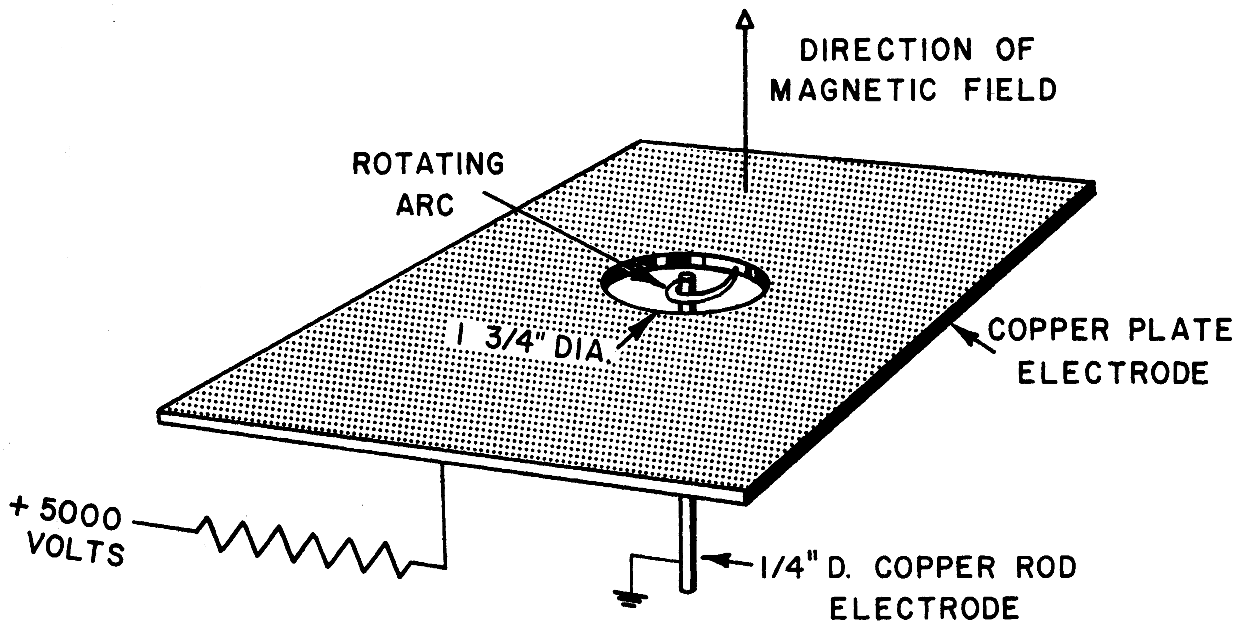

FIG. 7(a) ELECTRODE STRUCTURE FOR ROTATING ARC AT ATMOSPHERIC PRESSURE

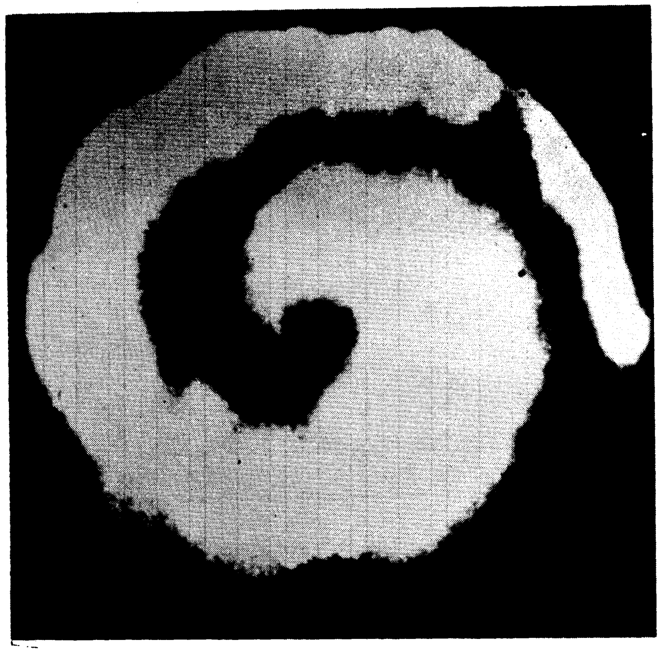

Fig. 7(b). SINGLE FRAME FROM FASTEX PHOTO OF ROTATING ARC WITH CENTER ELECTRODE AS ANODE.

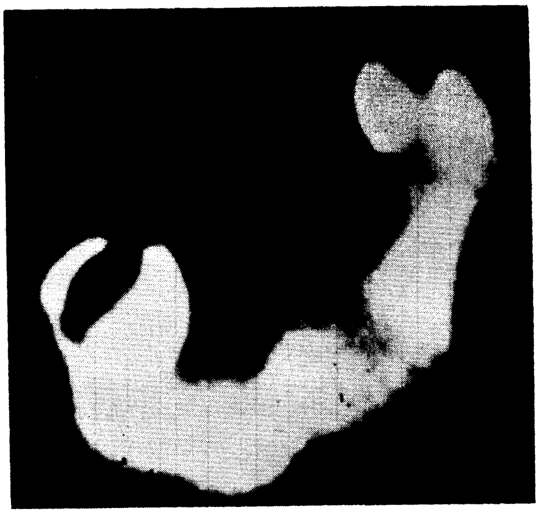

Fig. 7(c). FASTEX PHOTO SIMILAR TO Fig. 7(b) WITH CENTER ELECTRODE AS CATHODE.

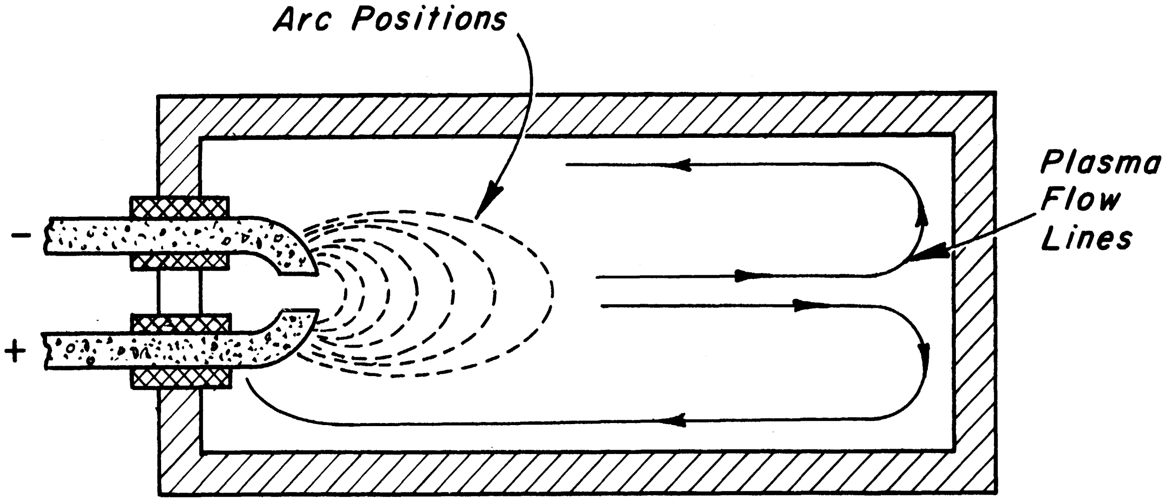

FIG. 8(a) BLOW-OUT ARC CHAMBER WITH BOTH ELECTRODES INSULATED FROM CHAMBER. STRONG CONVECTION COOLING OF PLASMA.

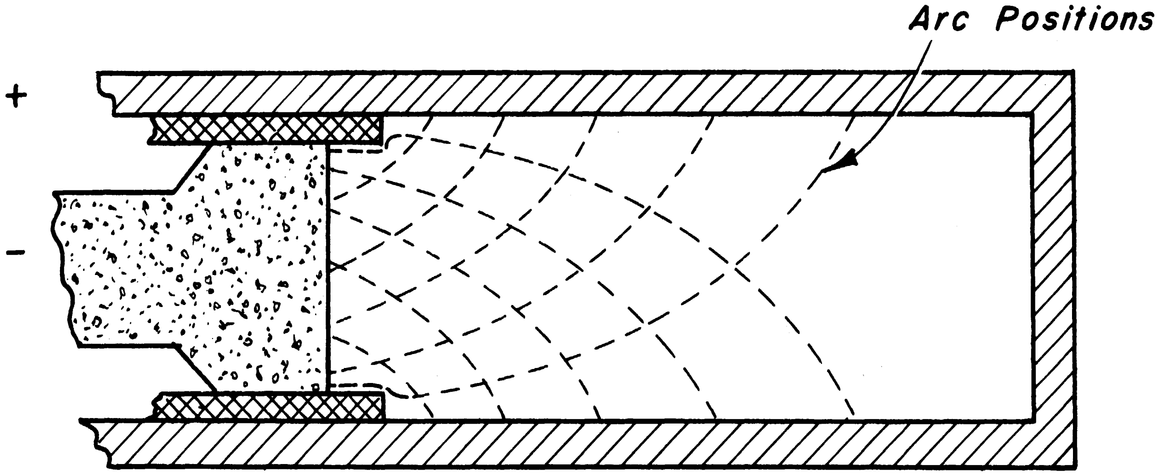

FIG. 8(b) ARC CHAMBER DESIGN WITH COAXIAL INPUT. LESS "PUMPING" AND CONVECTION EFFECTS THAN IN FIG.-(a).

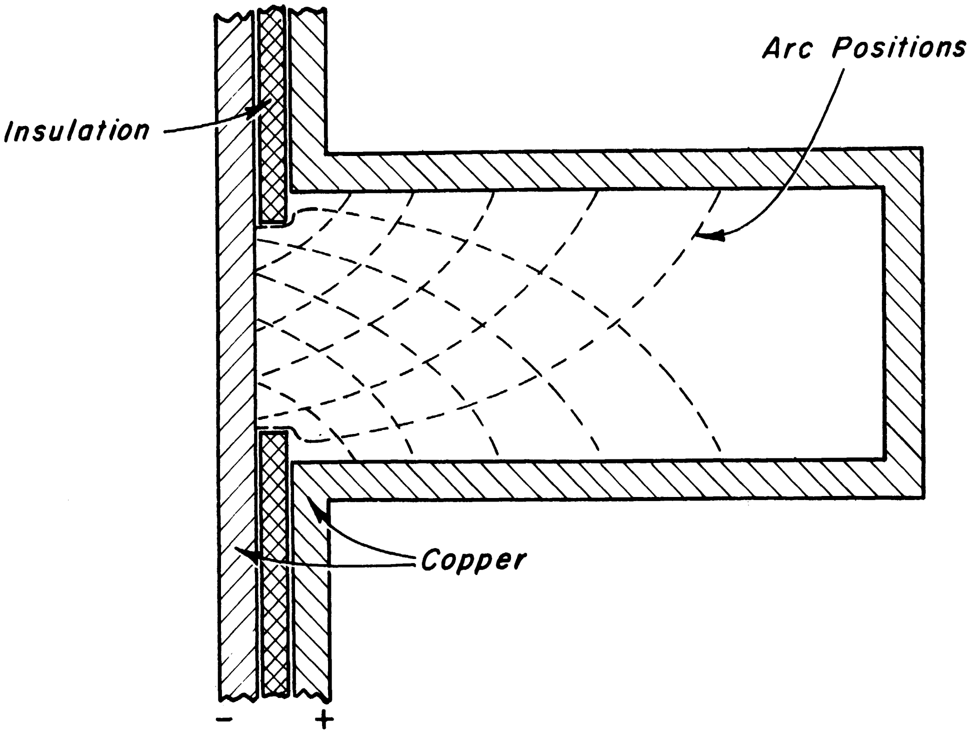

FIG. 8(c) DESIGN WITH ELECTRICAL INPUT ON PARALLEL PLATES, TO FACILITATE USE OF DUMP VALVE. ARC ACTION SIMILAR TO FIG.-(b)

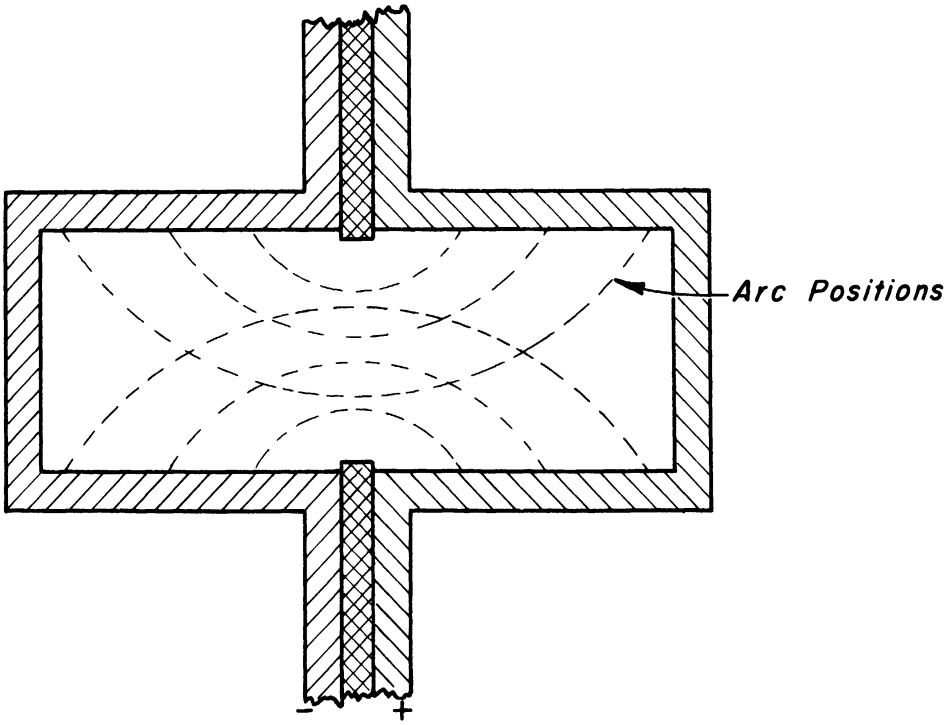

FIG. 8(d) SPLIT CHAMBER DESIGN. ARC DOES NOT EXTINGUISH AND RE-IGNITE AS IN ALTERNATE DESIGNS ABOVE. NO PUMPING ACTION.

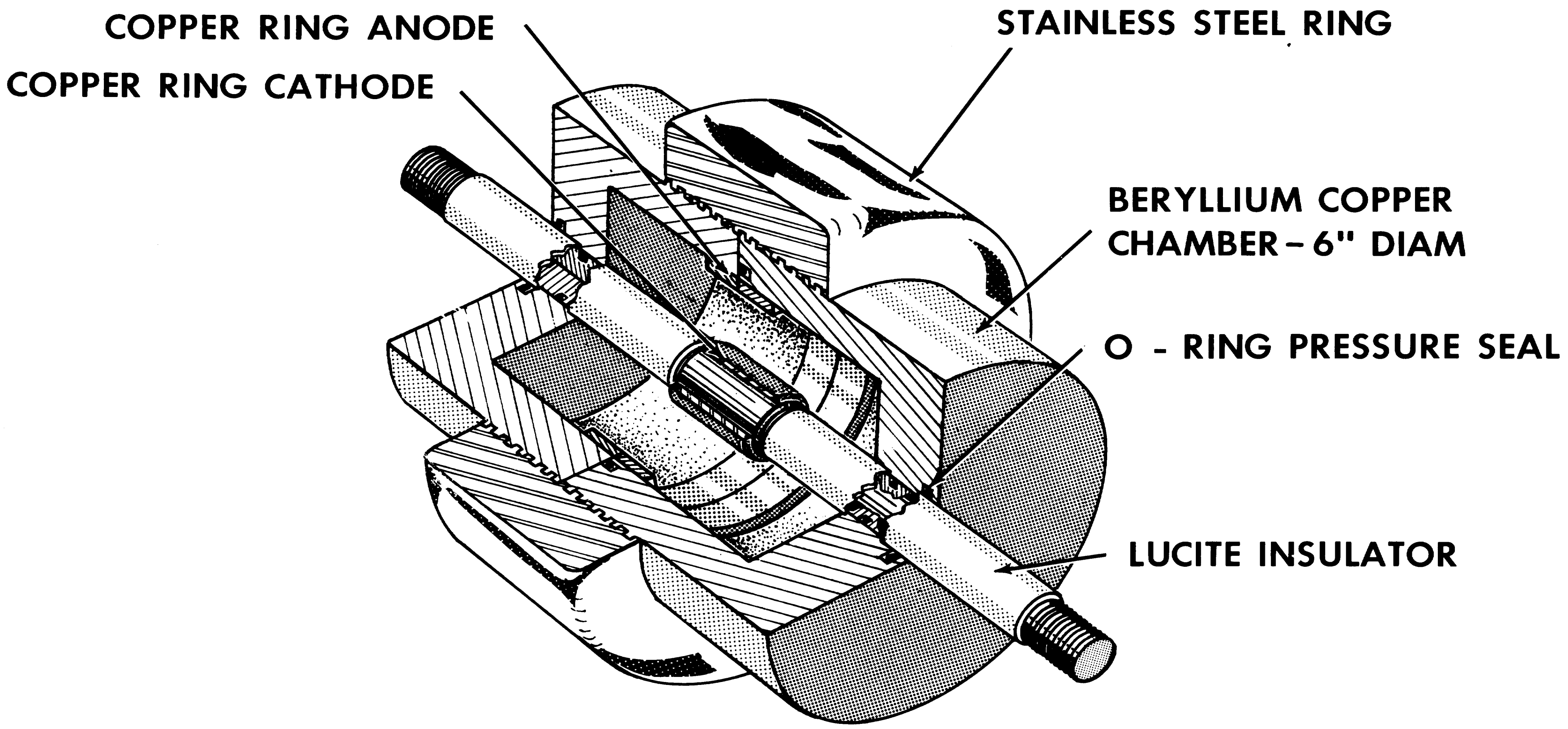

FIG. 9. CHAMBER #2. THE ARC ROTATION WAS PRODUCED BY AN EXTERNAL MAGNETIC FIELD

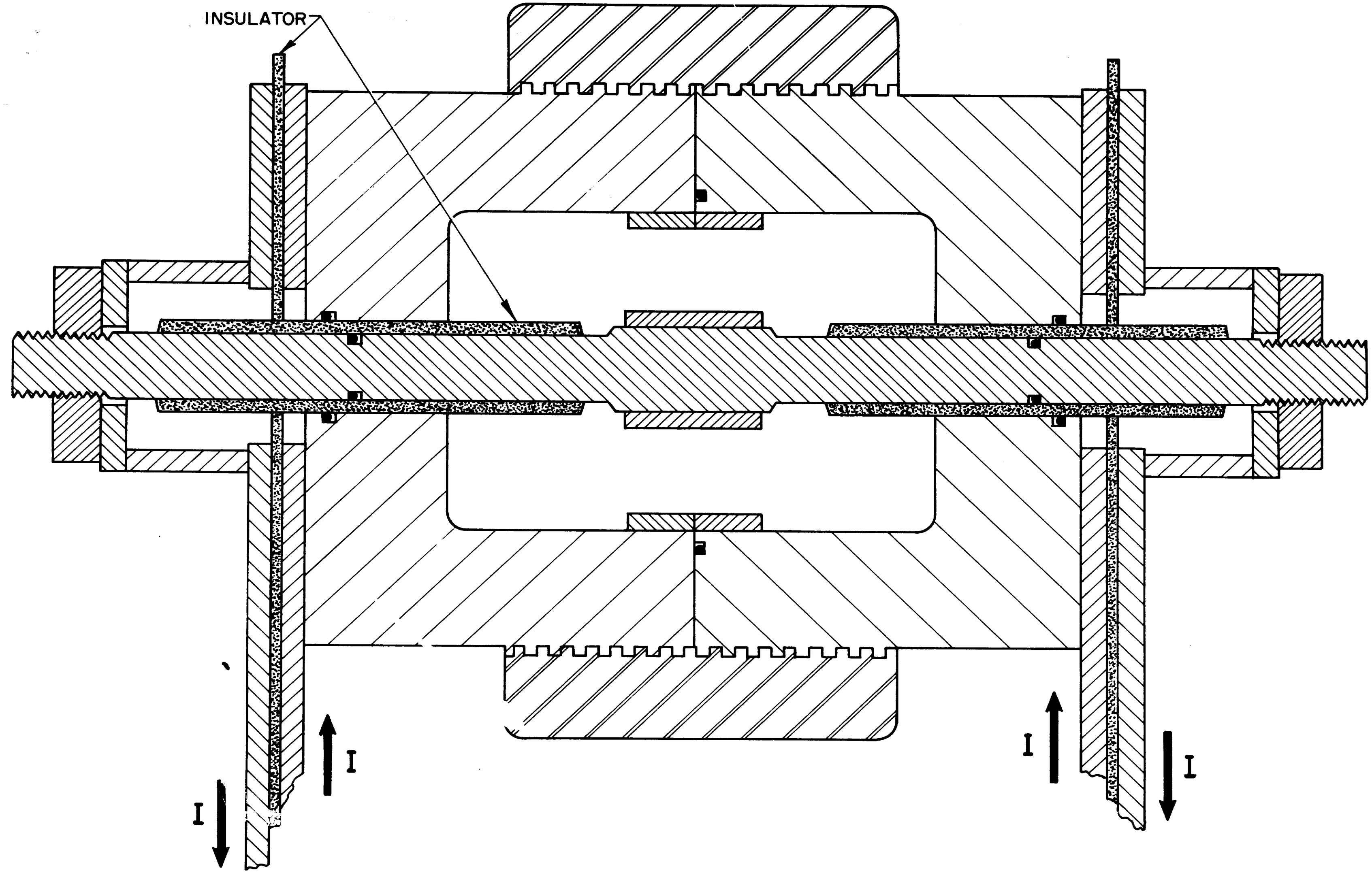

FIG. 10. ELECTRICAL CONNECTIONS TO ARC CHAMBER NO. 2. CURRENT WAS BROUGHT INTO CHAMBER ON PARALLEL COPPER PLATES AT BOTH ENDS OF CHAMBER TO CANCEL THE BLOW-OUT FORCE ON ARC COLUMN.

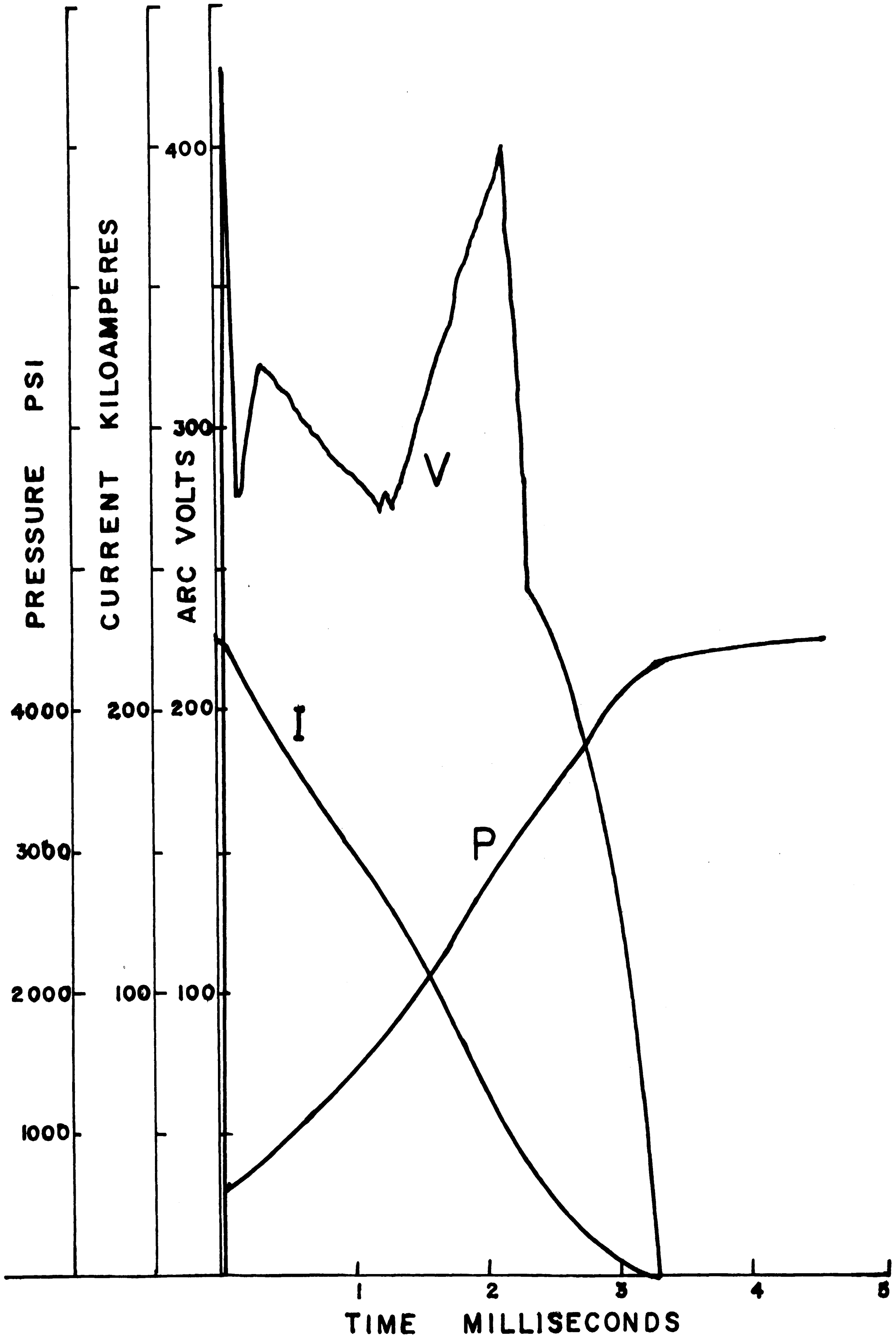

FIG. 11. TYPICAL DISCHARGE CHARACTERISTICS
FOR ARC CHAMBER # 2

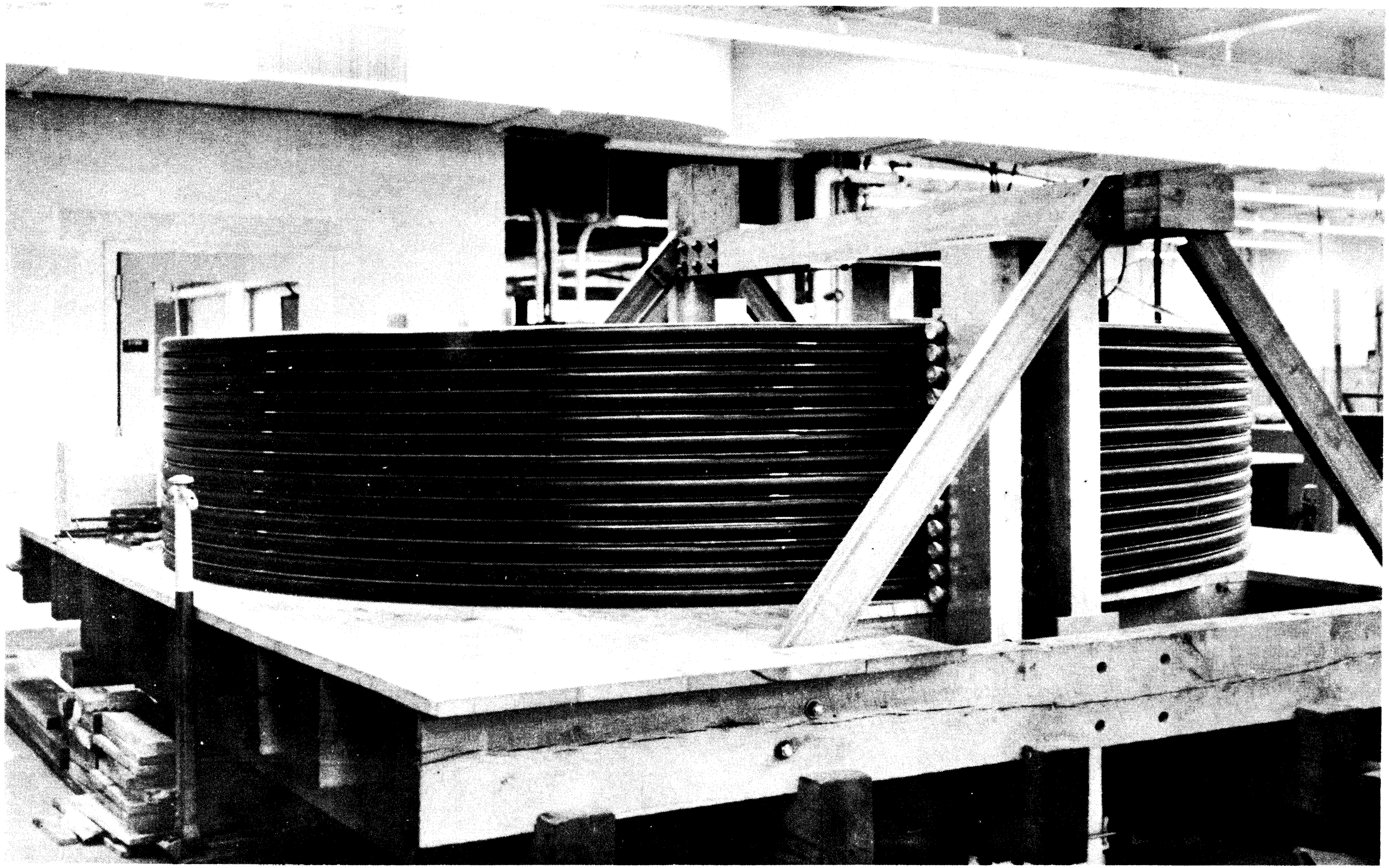

FIG. 12. NEW ENERGY STORAGE COIL

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