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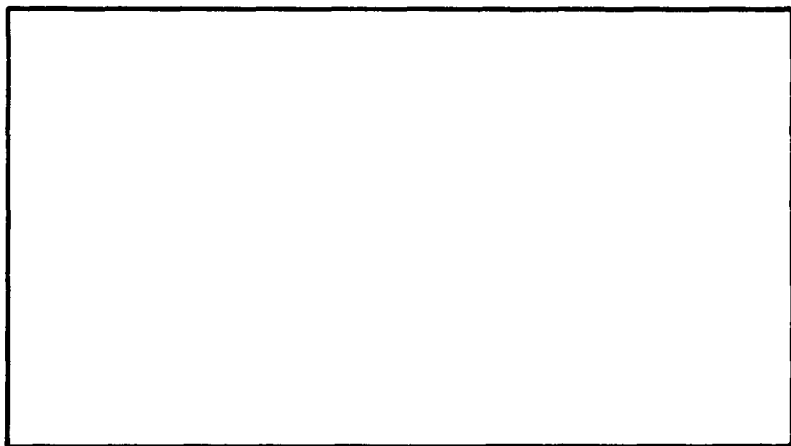
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WRIGHT-PATTERSON AIR FORCE BASE, OHIO

THESIS

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AN EXPERIMENTAL EXAMINATION OF
RETROGRADE MOTION OF AN ELECTRIC ARC

by

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GE/EE/62-10

Graduate Electrical Engineering

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Preface

Although the investigation of the phenomenon known as retrograde motion is currently being made largely by physicists, it still holds an interest for the electrical engineer.

I have attempted to contribute data in a small corner of the area to be investigated. However, these data cannot be regarded as anything approaching conclusive. They should, however, supplement those of other experimenters. Singly, or as a whole, these investigations have given many clues about what must be explainable by any wholly acceptable theory. I have attempted to summarize these necessary points, without formulating an explanation of my own. The problem is far too complex to be solved by a student except through a phenomenal accident.

Almost anyone who undertakes to write a thesis incurs unpayable obligations to people who have assisted him, but when one wanders far from his own training the size and number of the obligations become staggering. Enumerating all the persons from whom I have received encouragement, suggestions, favors, and physical aid would be prohibitively long. I must hope, therefore, that I have been able to verbally express my deep felt gratitude to the many individuals in the Thermo-Mechanics Branch, and the Machine Shop of the Aeronautical Research Laboratory who have given so unstintingly of their aid in the many facets of the research project. I must especially thank my sponsor, Mr. E. E. Soehngen, Chief of Thermo-Mechanics Branch of ARL, and my Faculty Adviser, Professor J. H. Johnson, of the AFIT Electrical Engineering Department for their guidance, support, and academic assistance.

David R. James

Abstract

Under certain conditions, particularly under reduced pressures, electric arcs in a transverse magnetic field move in a direction opposite to that predicted by conventional electromagnetic formulae. This phenomenon is called retrograde motion. Several widely varying theories have been made to help confirm or refute the proposed theories. Additional data is presented here in an area not previously investigated. Implications of these and other observations as they pertain to a comprehensive theory are discussed together with an analysis of what a truly quantitative investigation must encompass.

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AN EXPERIMENTAL EXAMINATION
OF RETROGRADE MOTION OF
AN ELECTRIC ARC

I. Introduction

One of the earliest results of the investigation of the inter-relation of electric currents and magnetic fields was the formulation by Andre' Ampere (1775-1836) of an expression for the force exerted by a magnetic field on a current carrying element. This expression,

$$\vec{F} = \vec{J} \times \vec{B} ,$$

was formulated in 1820, and for over eighty years received additional verification from experimenters throughout the field of Physics. In addition, this equation was used for further investigations and for certain practical applications, such as the protection of electric equipment from "blowback" of the electric arc associated with opening switches.

In the early 1900s, physical experimenters (Refs 15:440 and 16:95-124) observed instances where, under certain conditions, resultant motion was completely contrary (Retrograde direction) to that predicted (Amperian direction). If additional confirmation was needed outside the experimental range, it came rapidly from damaged equipment contained in aircraft and supposedly protected by transverse magnetic fields. These practical phenomena, and the many forthcoming experimental phenomena, were performed under many varying conditions. There was, however, one

common denominator for all of these instances. In each case the retrograde motion occurred under conditions of reduced pressure.* This correlation has naturally caused universal acceptance of pressure as a contributing factor to the occurrence of retrograde motion. The wide variance of pressures under which the phenomena occurred made it equally obvious that pressure alone did not control the "wrong" motion. The other possible contributing factors are limited only by the imagination of the theoreticians, and the number of explanations proffered can be estimated from a partial summary by Eidinger and Rieder, (Ref 3:109-113) which indicates at least thirteen distinct theories along with some duplicate or similar theories.

Although a multidimensional "space" for Amperian-retrograde motion may be considered possible, in the last analysis the phenomenon must be explained by one of the following:

- (1) The force is not as indicated by Ampere.
- (2) The currents and magnetic fields have components other than the obvious ones which have significant effect.
- (3) Other forces are present that can override the Amperian force under certain conditions.
- (4) Some combination of (2) and (3).

Although no one has proposed explanation (1), the other three each have their proponents, with the majority favoring (4) where the other force

*There have been subsequent reports of retrograde motion occurring under atmospheric pressure. (Refs 8:15-16 and 9:Appen.)

is associated with cathode emission phenomena. These theories will be examined more closely in section III.

Eidinger and Rieder also list some conditions observed to favor retrograde motion. This list is repeated here. The number of reports demonstrating each instance is given in parentheses following the condition. The actual references are contained in the Eidinger and Rieder Bibliography.

- 1) Decreasing pressure (28)
- 2) Decreasing current (6)
- 3) Decreasing electrode gap (5)
- 4) Increasing magnetic field (10)

(Himmler and Cohn (Ref 5:1151) have indicated an opposite relationship between magnetic field and retrograde tendency.)

- 5) Certain types of gas which increase the cathode fall (6)

In addition to these favorable conditions, there are three reports that when the cathode was heated to a temperature high enough to maintain the arc by thermionic emission alone, retrograde motion did not occur under any conditions.

Conflicting reports are listed as to whether cathode material has any effect on the occurrence of retrograde motion. Also, while the surface condition has a definite effect on arc performance, opinions vary as to whether this is directly connected with the cause of retrograde motion or merely determines the overall arc stability.

It seems obvious, therefore, that any totally acceptable theory must account for these observations in some way.

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At the present time, many persons are concerned with trying to develop quantitative measurements in all aspects of electric arcs, particularly those that might help to demonstrate the actual cathode emission mechanism. Accurate experiments may hasten the development of a theoretical understanding and will certainly be necessary to confirm any proposed theory.

II. Objectives

There are three separate, although inter-related, objectives of this thesis:

- 1) To provide additional data in one segment of the large range of conditions where the phenomenon of retrograde motion occurs.
- 2) To provide future AFIT students with an introduction to an intriguing problem not covered in an already crowded curriculum.
- 3) To provide the Thermo-Mechanics Branch of the Aeronautical Research Laboratory with sufficient practical data to indicate possible areas of attack, mechanical problems, and limitations that would be involved in a more comprehensive investigation.

When this thesis was first conceived, each objective was of relatively equal weight, however, subsequent events have dictated that the degree to which each objective was fulfilled varied considerably.

Every effort was made, within the limited scope of the attack, to specify parameters and results in such a way that significant quantitative results would be obtained. While numerical values have been attached to the results, later sections will show why this data is really only qualitative, or at best, quantitative within the order of magnitude. It is, in fact, the author's opinion that certain data already in the literature on the problem may be suspect unless there was attention given to the control of parameters not specified.

As the accomplishment of the first objective has declined, the accomplishment of the third objective has significantly risen. Many

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of the observations and problems involved have exhibited clear trends that can be extrapolated to a more comprehensive approach to the problem. Equipment design and attack plans are already underway for this project.

The results of this investigation, therefore, are analyzed with heavy accent upon the problems and limitations encountered and the conclusions and recommendations emphasize what attributes the equipment and procedures of further experiments must have in order to obtain significantly improved quantitative data.

III. Theory

Introduction

In most theses, the section on theory consists of an accepted background for the area involved, plus any extensions or exceptions that are advanced by the author. In this instance, however, one is confronted by many varying theories, some related, some mutually exclusive. Certain portions of arc theory are universally accepted, but when the phenomenon of retrograde motion is involved, the point where individual theoreticians diverge is soon reached. The exact point where general acceptance ends is not very clear, but in order to try and distinguish them this section will be divided into two subsections, General and Proposed. This division is made on the conservative side and all the material in the Proposed portion is not controversial. It is, in fact, stressed that in many cases the argument is not over the principle itself, but over whether it is applicable in this case. In some instances the question is not even whether some circumstance is likely, but only whether the magnitudes involved are sufficient to constitute the reason for the arc reversal.

General

Ampere's Law. Although the physical picture of the electric arc will be shown more fully later, it can be regarded as a flexible conductor for the purpose of examining Ampere's Law.

This law states that a current carrying element in a magnetic field will experience a force proportional to the vector cross product of the current density, $\vec{J}$, and the magnetic flux density, $\vec{B}$. Specifically:

$$d\vec{F} = \vec{J} \times \vec{B} dA$$

In the case where the magnetic field is completely transverse to the current, this relationship has the form shown in Figure 1,

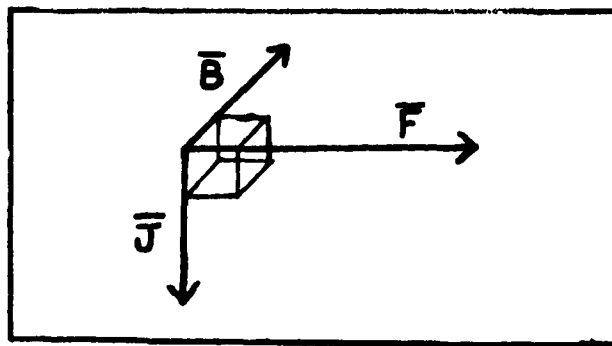


Figure 1

where the force is exerted in the direction shown and its magnitude is $\propto JB$. Any motion in the direction of this force will be referred to as Amperian. Motion in the opposite direction is called retrograde.

Arc Characteristics. Electrically the arc discharge differs from the glow discharge in that it can support a larger current with a smaller voltage drop, and exhibits a negative volt-ampere characteristic. Physically it differs in that it has a definite shape and a high light intensity. The shape is roughly that of a round column, usually, although not always (Ref 2:27), with a slight constriction at the anode and a more pronounced one at the cathode. This column always exhibits a random lateral motion,

often superimposed on a definite "bowing out" from the straight line between the electrodes.

The voltage drops along the length of the arc takes the form shown in Figure 2. Notice the higher voltage gradients in the areas immediately

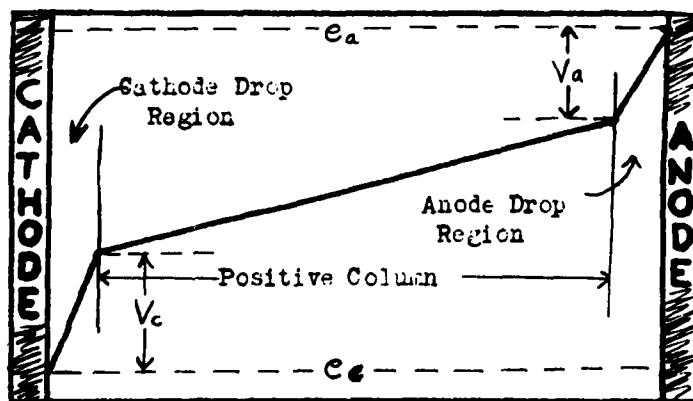


Figure 2

adjacent to the electrodes. This relative relationship is always maintained although the actual magnitudes involved vary considerably.

The cathode drop is associated with a sheath of positive ions around the cathode where the high velocities of escaping electrons prevents a canceling density of free electrons. The cathode drop is in the order of the ionization potential of the gas used and the thickness is in the order of the mean free path of the electrons although considerable variation from these values has been measured. The variations have been "explained" in several ways, all of which involve various assumptions as to the cathode emission mechanisms and modifying actions from the cathode materials, etc.

Similarly, the anode drop is associated with an electron space charge from incoming electrons supplemented by those emitted from the

anode itself due to its elevated temperature. The drop in this region can be more closely explained by use of classical heat transfer equations and the Stefan-Boltzman Law to give the formula

$$V_a = \frac{a \sigma T^4}{j} - \phi_0$$

where a is the emissivity of the anode relative to a black-body, σ is the radiation constant, T is temperature in degrees Kelvin, j is the current density at the anode surface, and ϕ_0 is the work function of the anode material. This formula ignores certain conduction and convection losses and involves the knowledge of the area actually involved in current transfer and the actual temperature at the points of transfer. Even ignoring these losses, using the general anode surface temperature for T , and assuming that the area involved is exactly that of the incandescent spot, the predicted anode voltage drop is very close to that shown by experimental measurements.

The remaining portion of the arc is the general plasma area or positive column. It is made up of relatively equal components of electrons and positive ions whose drift toward the electrode of the opposite potential constitutes the current flow. The portion of the current made up of positive ion flow varies from as much as 10% to a small fraction of 1%, depending on conditions. The voltage drop through this region is a function of column length and voltage gradient, which is in turn determined by the current, the pressure and the gas which makes up the plasma.

More detailed examinations of the electrical and physical makeup of electric arcs are available from many sources. One excellent source is

Cobine, (Ref 1:290-352) who includes the derivation of the formulas used, several tables of experimentally determined values, and an estimation of the merits of proposed formulas and their assumptions.

Proposed

The phenomenal number of theories purporting to explain retrograde motion could not possibly be covered in a paper of this scope. If the reader wishes to peruse them all, the paper by Eiding and Rieder (Ref 3:109-112 and Biblio.) gives a short summary of, and references for, all theories advanced up to 1957. Four widely varying theories have been selected for discussion here to indicate the divergences. The first three papers are covered by Eiding and Rieder, while the fourth has been published subsequent to their survey.

Electrodynamics. The theory of A. E. Robson and A. von Engel (Ref 7:1121-1122) is unique among the theories presented in that it is the only theory that attempts to explain retrograde motion entirely by additional electromagnetic forces opposing the obvious force. The observed deflection of an arc in a transverse magnetic field is shown in Figure 3.

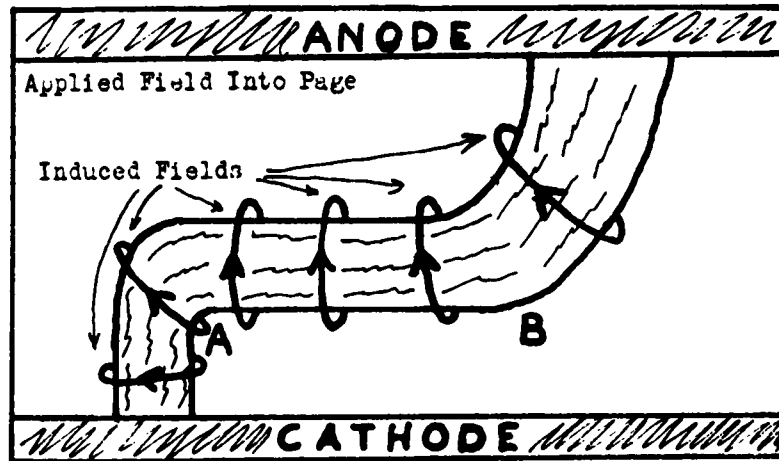


Figure 3

This deflection is as would be predicted from the knowledge that more deflection can be experienced in areas where the electric field is smaller than it is in the cathode fall area (i.e. the positive column). The normal Amperian motion occurs in a "stepping" manner as the potential between the cathode and point B of the arc becomes high enough to break down the gas at that point. The arc then establishes itself on the new spot, and the process repeats.

There is, however, an additional magnetic field in the picture. The current flow also induces its own magnetic fields. In the sharp bend at point A the self-induced fields from the vertical and horizontal elements reinforce one another in a stronger field directed out of the page close to the cathode arc root. This field is of the order i/R , where i is the arc current and R the effective radius of curvature of the arc, determined by the several parameters involved. If the applied field is H_0 then the resultant field H is given by

$$H = H_0 - i/R$$

If the second term can be made large enough, the resultant field may be directed out of the page. The cathode root will move in the retrograde direction "dragging" the rest of the arc with it.

While an increase in H_0 tends to increase the Amperian field component, it also decreases R through increased deflection of the positive arc column. The increase in the i/R term may exceed the increase in H_0 and yield an increased tendency toward retrograde motion.

If the pressure is reduced, the vertical column will be less "stiff". The bend (and the resulting negative field) will occur closer to the

cathode spot, increasing the retrograde tendency.

A decrease in electrode gap will compress the arc. If the gap approaches the diameter of the unobstructed arc, the anode will act as a wall for the column near the cathode. The resultant movement of the arc away from the restricting wall will cause a sharp decrease in R and again increase the probability of retrograde motion.

Cycloidal Electron Paths. G. J. Himler and G. I. Cohn (Ref 5:1150-1151) propose to explain retrograde motion by certain assumptions as to the manner of electron emission and the subsequent paths.

The electrons emitted from the cathode spot exert a force of mutual repulsion, causing initial motion to have a radial diffusion. This diffusion is supplemented by the fact that electron emission is not directly perpendicular to the cathode surface but has a random distribution. When a magnetic field is applied, the electrons will start to curve in the correct direction in a cycloidal path as shown in Figure 4. At normal pressures, the concentration of gas molecules is such as to make the mean

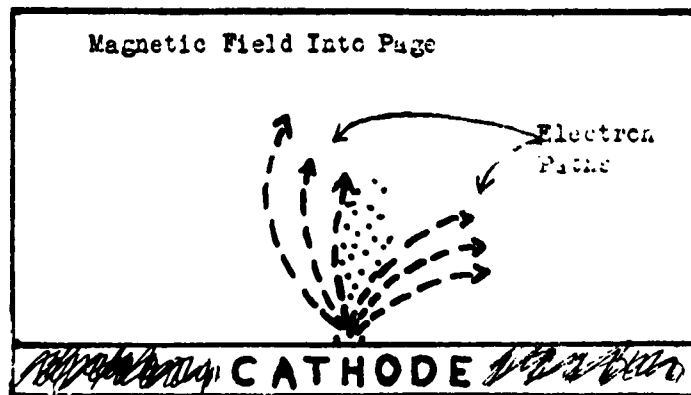


Figure 4

free path $\sim 9.6 \times 10^{-6}$ centimeters. The collisions so experienced keep the amount of electron diffusion small. As pressure is reduced, the

increase in mean free path allows greater curvature and diffusion of electrons. At some critical pressure the dispersion of the electrons will reach the extent shown in Figure 5. The electrons on the right

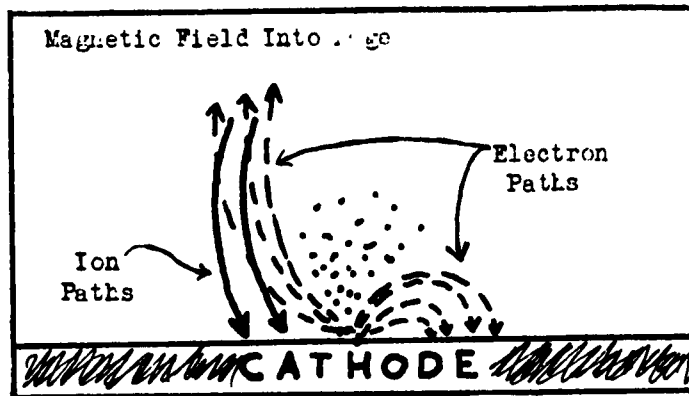


Figure 5

are forced back to the surface of the cathode where they form a dense electron cloud, reducing further electron emission on this side. The electrons on the left will continue curving toward the anode until they eventually collide with molecules of gas. The positive ions caused by the collisions will be drawn to the cathode on the side of the arc where the collision occurred, bombarding the cathode to the left of the cathode spot. The energy of the bombardment will cause this area of the cathode to come heated so that emission can take place, and the cathode spot will migrate to this new area. This sequence is repeated and total arc motion is in the retrograde direction.

Summation of Coulomb Forces. A theory similar to that of Himler and Cohn, but not depending on initial diffusion of electrons, was proposed by R. M. St. John and J. G. Winans (Ref 10:1097-1102). It was reasserted by them (Ref 11:1664-1671), and additional observations were presented to reinforce this theory by D. Zei and J. G. Winans (Ref

The mechanism is demonstrated in Figure 6. The cathode has a

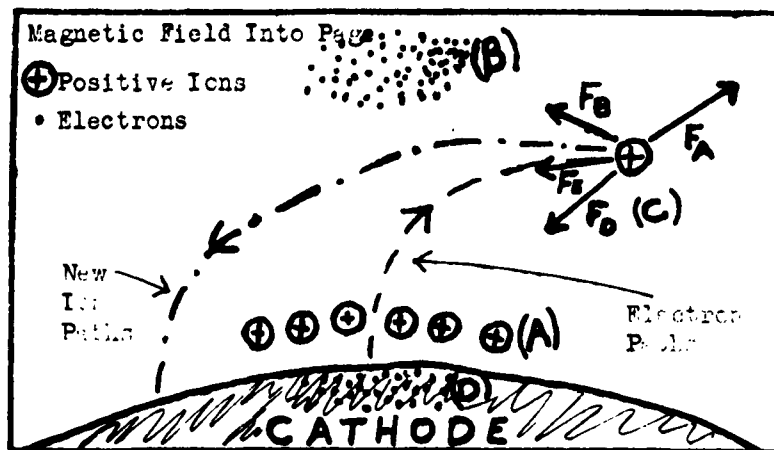


Figure 6

sheath of positive ions (A) much thinner than the electron free path for ionization. Under certain conditions, spectrographic evidence indicates the presence of doubly and triply ionized atoms. This would indicate a cathode drop greater, in many instances, than the drop along the entire arc. This could only be true if a minimum potential, in the form of an electron cloud (B), were present some distance out from the cathode surface. Electrons are accelerated by the ion sheath as they leave the cathode and deflected to the right by the magnetic field. After traveling the length of their ionization free path they collide with atoms, producing new positive ions (C). Four forces act upon these ions. They are attracted by the electrons (D) in the cathode (F_D), repelled by the ions in the sheath (F_A), attracted by the electron cloud (F_B), and attracted by new electrons proceeding along the emission path (F_E).

Because the electrons in the cathode and the ion sheath are image charges and close together compared with the distance to the new ion, the resultant force of F_A and F_D is close to zero. F_B and F_A exert a force with a component in the retrograde direction, and the new ion starts in this direction.

As the ions gain speed, a fifth force from the magnetic field comes into play. Once the ion has passed the area of the cathode spot, this force predominates. The ion is then driven into the cathode on the retrograde side of the cathode spot and forms a new spot.

An increase of the magnetic field causes a smaller radius of curvature for the emitted electrons. This means the new ions will be formed nearer the cathode outside the range of the ion sheath. They will then have an additional resultant force away from the cathode. This will cause the ion to follow a path of larger arc and strike the cathode further along the retrograde side than before, with a resultant increase in retrograde velocity. The rapid velocity rise observed at certain magnetic field strengths is explained by hypothesising that at that field strength, collisions would produce some critical density of doubly ionized atoms. The forces on these atoms would be sufficiently stronger to cause them to impact the cathode substantially further on the retrograde side.

Increased current would increase all coulomb forces involved and hence tend to increase retrograde velocity, however, the extra ionization would tend to cause the positive ions formed further from the cathode to experience an increase in F_A from the ions formed closer to cathode. This

is consistent with observations that increased current sometimes encourages, and sometimes opposes, retrograde velocities.

Pressure reduction would lengthen the probable path before collision and more electrons would form positive ions far enough from the cathode surface to enhance the effect described.

Force Transfer. One of the biggest names in plasma physics, G. Ecker, has undertaken a comprehensive examination of the electric arc, including an explanation of retrograde motion (Ref 2:104-111). This theory is tied intimately with an overall examination of the cathode components, rendering impossible a complete development in a paper of this scope. Very loosely, the explanation says that retrograde motion occurs only with an arc of a certain type within Ecker's classification. In any type of arc, energy balance for a stationary state requires a radial potential fall to exist, in the cathode region, to hold back the electrons and partially compensate the ion space charge.

In this particular type of arc, an ion stream of high density enters the potential fall zone. This uncompensated charge sets up its own electric field, with a portion of the field lines leaving the discharge area to form a potential tube of at least several electron volts depth. Electrons emitted with little energy must then follow this potential tube.

This radial coupling of ions and electrons is such that in a transverse electric field the force experienced by the electrons is transferred to the ions.

The Lorentz and Poisson equations are combined and certain simplifications are made, based on the proposed model. The result is a series

of differential equations solvable by analog computer.

The presence, in the Ecker arc model, of several parameters whose numerical values are not known, requires that the resulting curves be fitted to experimental results at one point. Once this "fitting" has been made, the theoretical curves closely follow the experimental curves of St. John and Winans (Ref 11:1100).

Additional. The most recent theory put forward was that of Hull (Ref 6:1605-1607). In addition to being the most recent, it has the distinction of having perhaps the most quantitative explanation to date. Unfortunately, it deals with a mercury arc and has certain computations based on the deformation of the surface of the mercury pool. Since no adaptation to solid electrodes is given, little confirmation could be forthcoming from this experiment. It is, therefore, not included here.

IV. Description of Equipment

Introduction

One of the objectives of this thesis was to gain information for the Aeronautical Research Laboratory to use in further research in this area. The development of suitable equipment and an understanding of some of its limitations are therefore an important part of this paper. While this information actually comprises a portion of the results of this project, it seems more fitting that it be included with the equipment description. Hence, the subsections on the electrodes, instrumentation and starting contain a short history of unsuccessful attempts and some commentary on the weaknesses of the final equipment.

General

The physical layout of the equipment used is shown by block diagram in Figure 7 and by photograph in Figures 8 thru 11. A more detailed arrangement of the test section is shown in Figure 12.

The system will be discussed by a breakdown into the following components:

- 1) Electrodes
- 2) Pressure system
- 3) Magnetic coil
- 4) Power and cooling supplies
- 5) Instrumentation
- 6) Starting

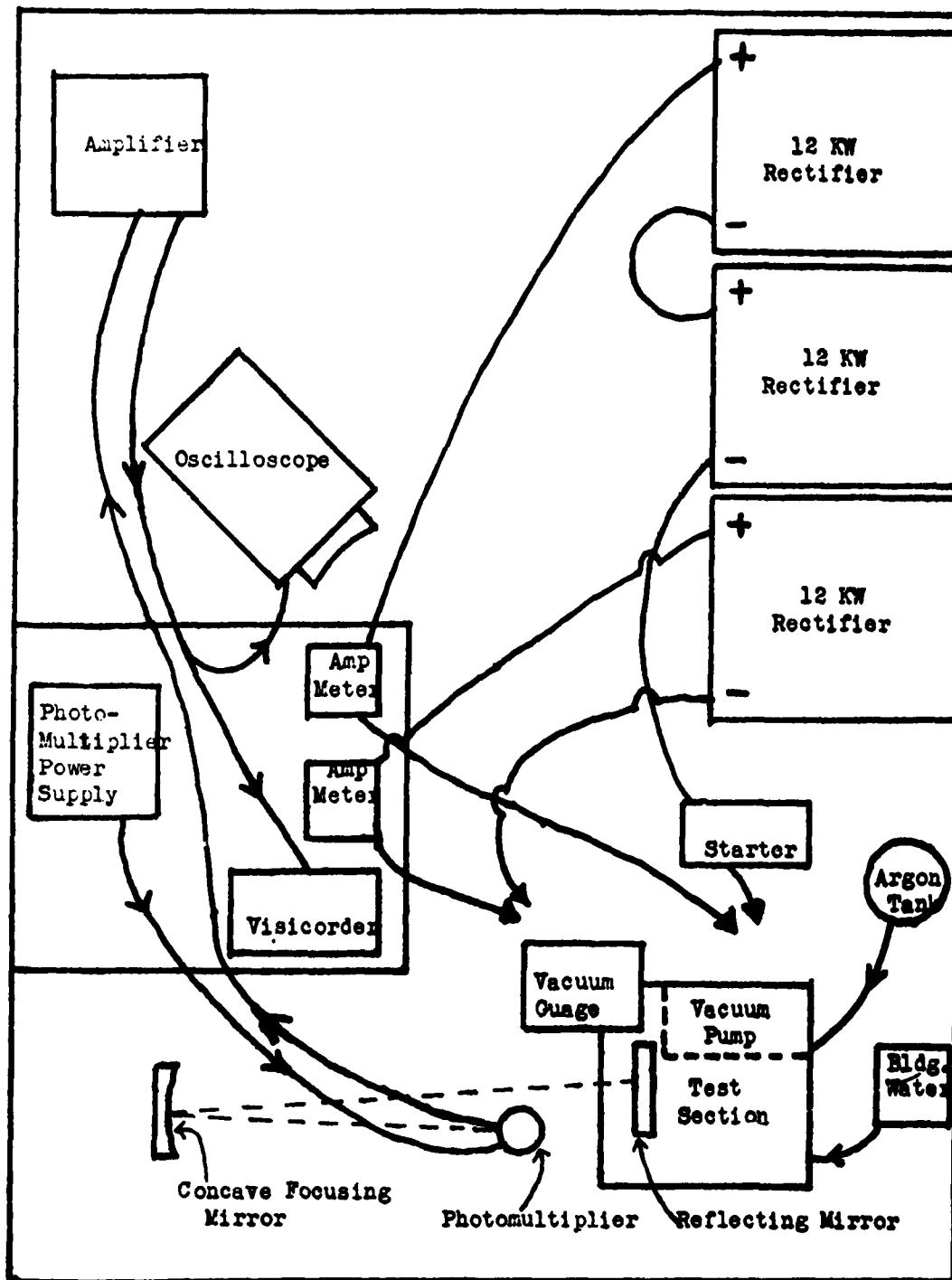


Figure 7. Block Diagram of Physical Test Set-up.

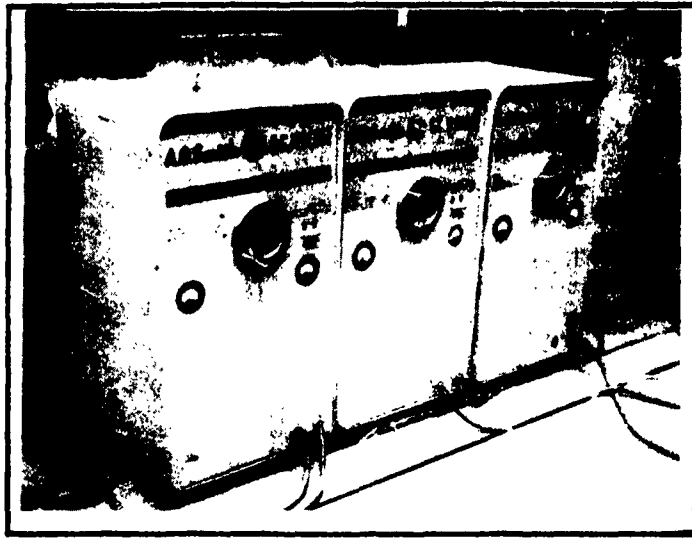


Figure 8. Power Supplies.



Figure 9. Test Section, Gas Pressure System and Starter



Figure 10. Mirror system and Photomultiplier.
(Showing relation to test section.)

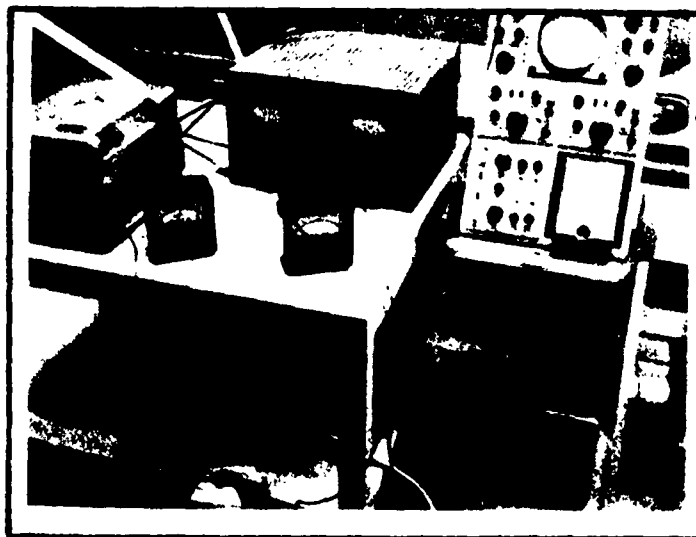


Figure 11. Instrumentation.

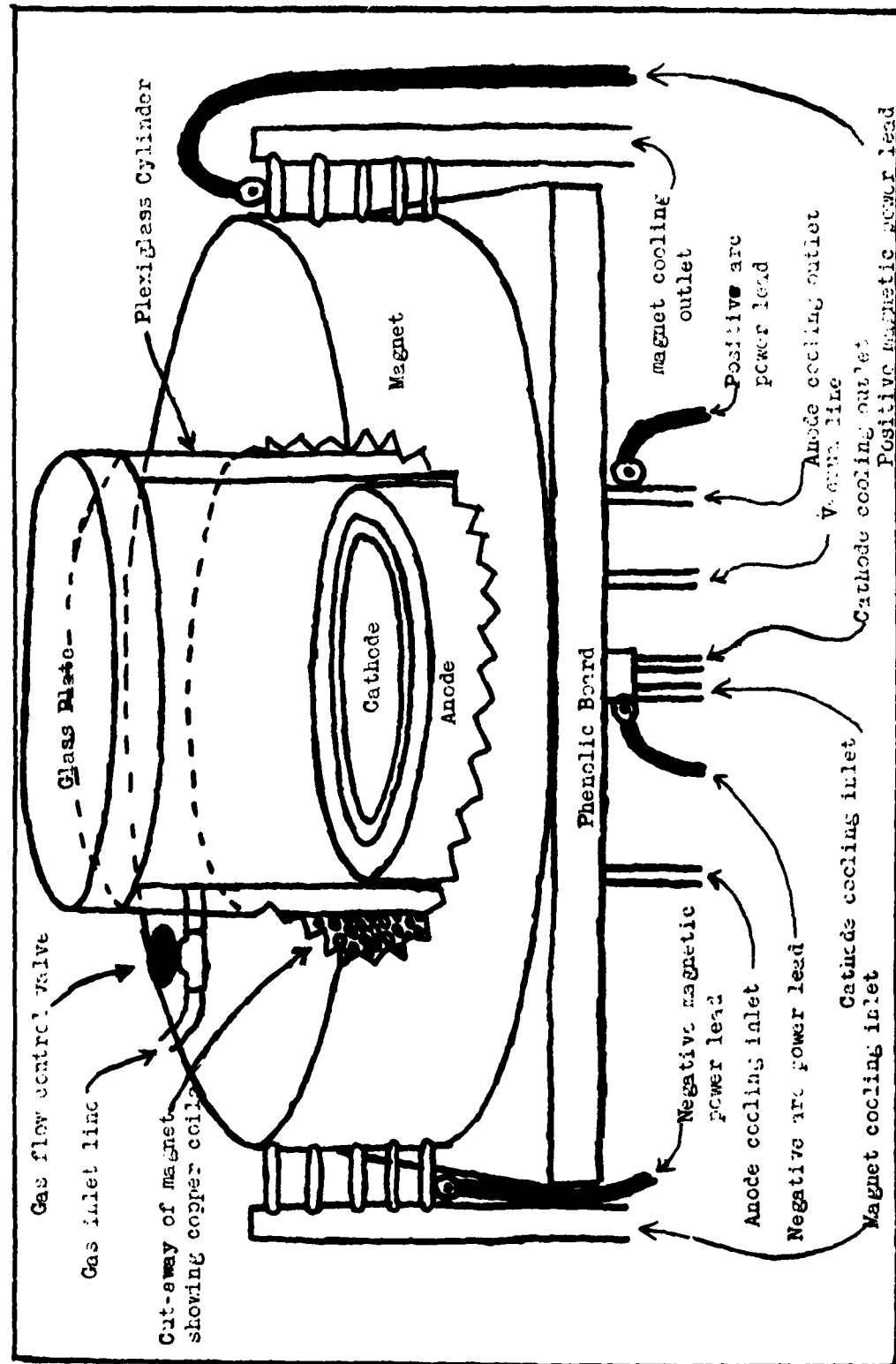


Figure 12. Test Section Arrangement

Electrodes

In order to allow sufficient time for arc stabilization and accurate readings of all parameters, it was necessary to provide a continuous track for the arc. This was adapted from a design used by C. G. Smith (Refs 13:217A and 14:1329 and personal communication of C. G. Smith to E. E. Soehngen). Smith used circular copper electrodes mounted above one another and provided his magnetic field from below the electrodes.

In order to provide a less distorted magnetic field and better photographic coverage, it was decided to mount the electrodes as horizontal concentric circles within a larger concentric magnetic coil (See Figure 12). Also, the power range being investigated required that the electrodes be water cooled.

The initial electrode design is shown in Figure 13. The soldered joints, necessary to allow a continuous cooling water flow around the electrode perimeters, presented a great operational problem. In spite of the cooling, soft solder heated enough to "bubble" small holes; and silver solder would, under certain pressures, provide a preferred arc path, in spite of the much greater gap involved. The water leaks from these events would, when major, extinguish the arc and pollute the vacuum system. This pollution required extensive periods of pumping and flushing to restore the system to working order.

Although continual "patching" was attempted, the rate of data collection was prohibitively slow and extreme fluctuation of data indicated that smaller leaks had frequently altered test conditions even before their effects became apparent.

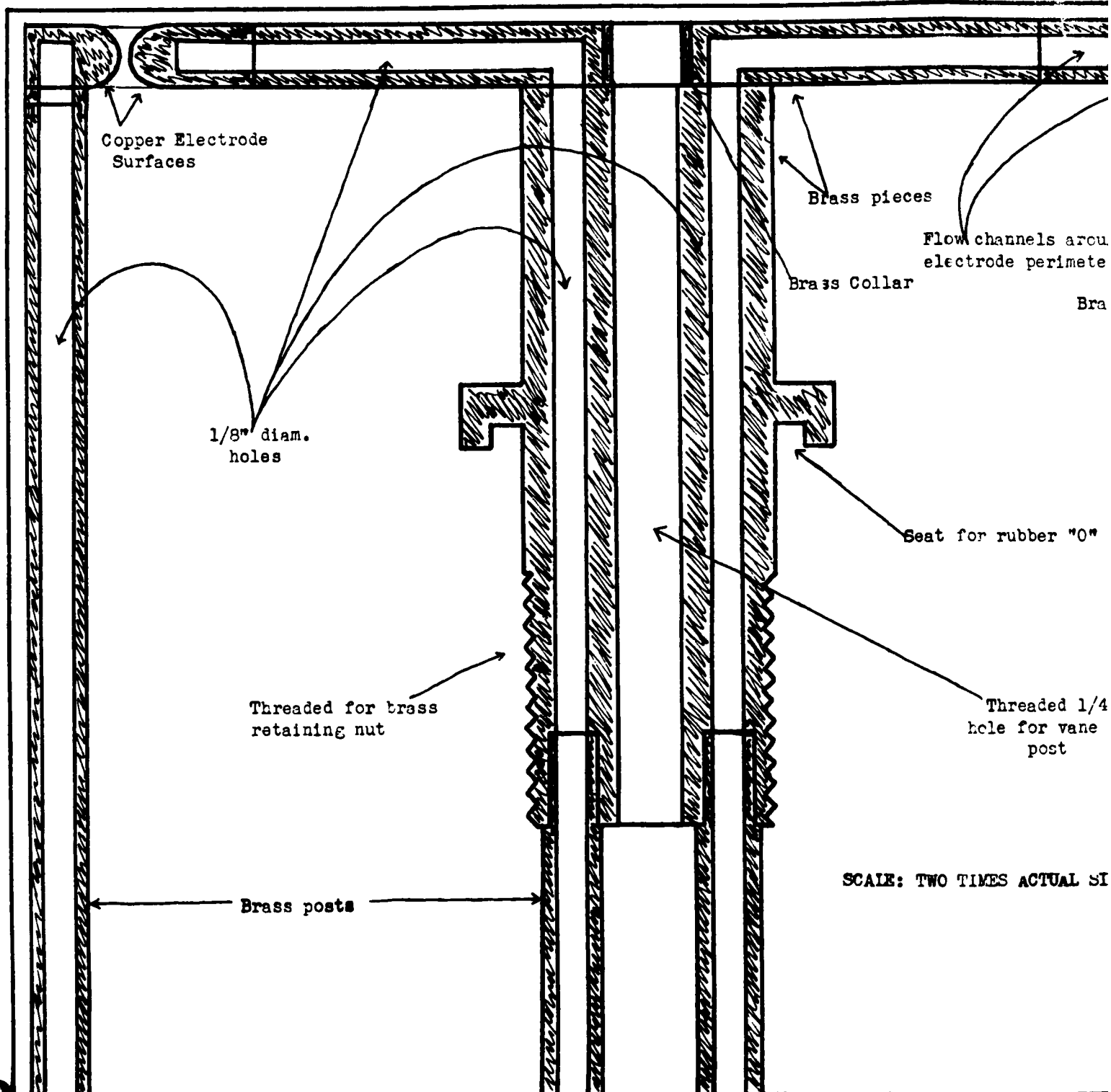


Figure 13. Original Electrode Design

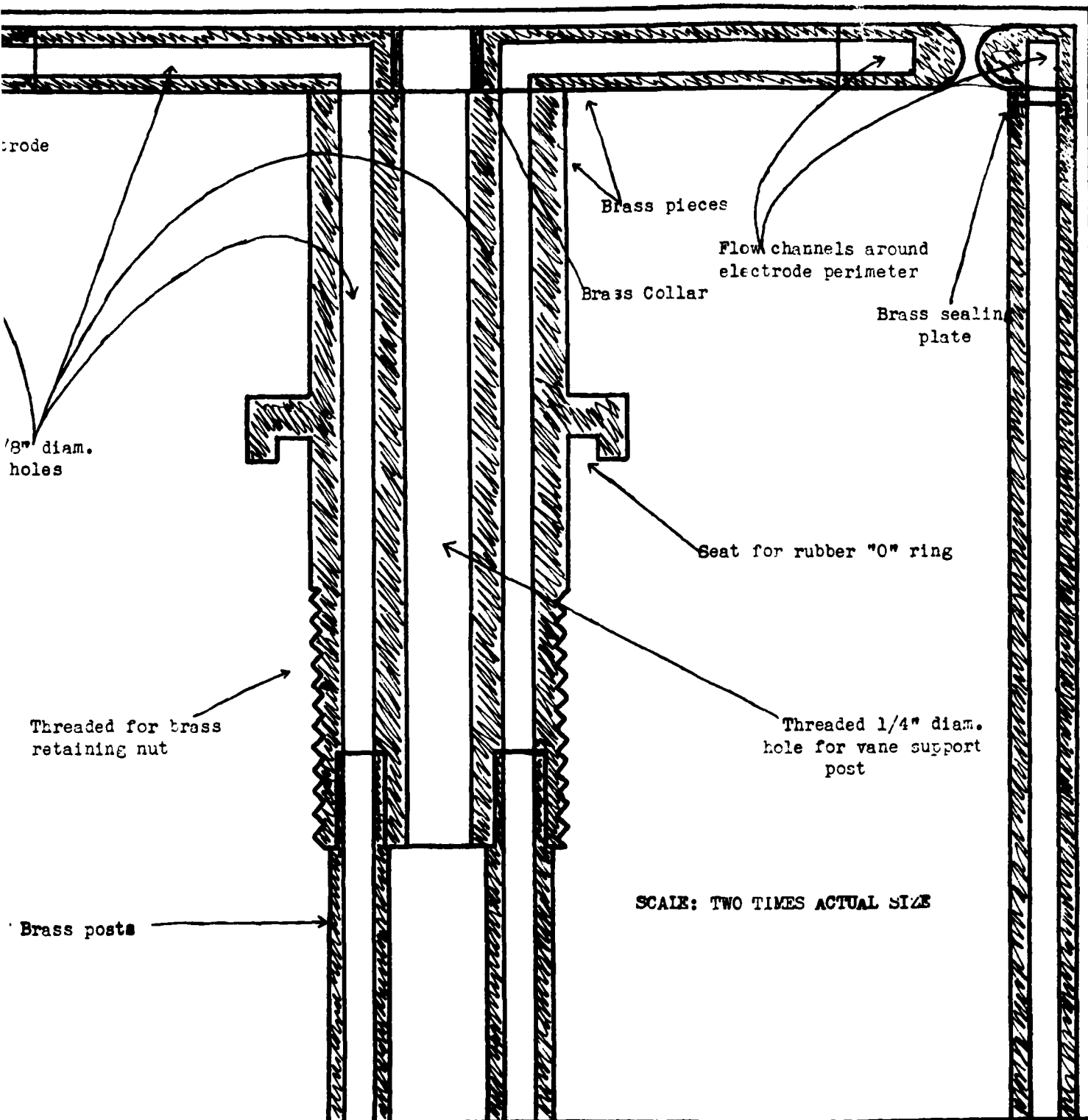


Figure 13. Original Electrode Design

Two major modifications were tried before the final design was adopted. This design is shown in Figure 14 (Photographs Figures 15 thru 19). The soldered joints on the anode were placed far enough away from the source of heat to allow the use of soft solder. The silver solder required for the hotter cathode was protected from the arc by moving it farther from the anode and lengthening the undesired arc path by the addition of a protecting lip. Note also the filleted corners in every case close to the electrode gap to combat the preference of the arc for sharp angles. In addition, electrode surfaces outside the gap area were coated with commercial auto dent repair compound.

The supporting posts (which also served as water connections) of the anode pierced the 5/8" phenolic board which served as the base for the entire test section. The point of entry was made vacuum tight with epoxy resin. Since the cathode had to be removable for inspection of the surface condition it was necessary to install a permanent brass bushing in the phenolic board and make the cathode vacuum seal with an "O" ring. The ring was seated in a flange on the cathode stem and smeared with vacuum grease. It was drawn tight against the surface of the bushing by a brass nut which fitted the threaded section of the cathode stem below the phenolic.

Pressure System

The electrodes were contained within a plexiglass cylinder, 4" high with 6" outer diameter and 3/8" wall thickness. This cylinder fitted snugly within the magnetic coil and around the electrodes, allowing enough clearance for a thin metal shield to protect the cylinder from molten

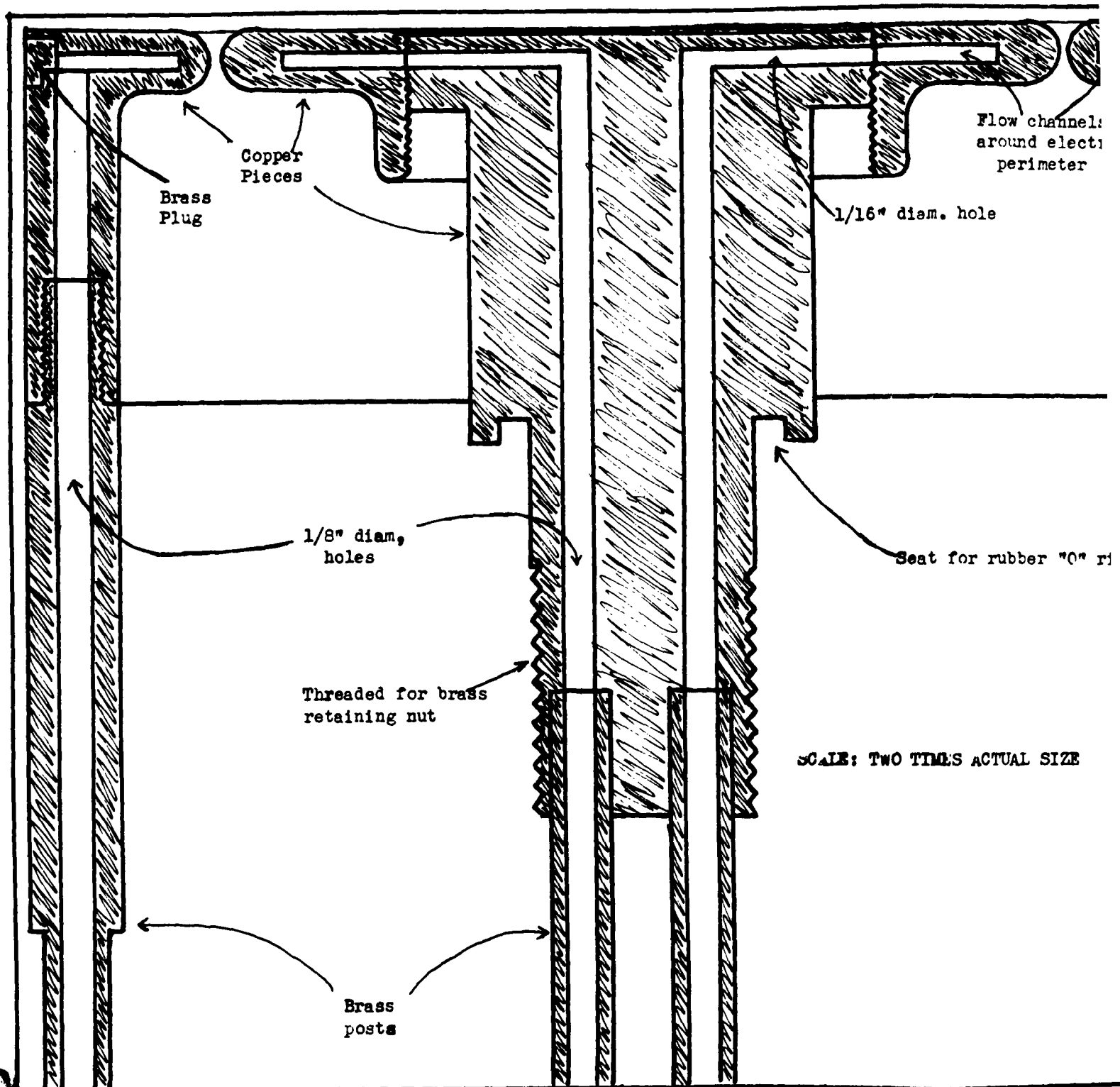


Figure 14. Final Electrode Design

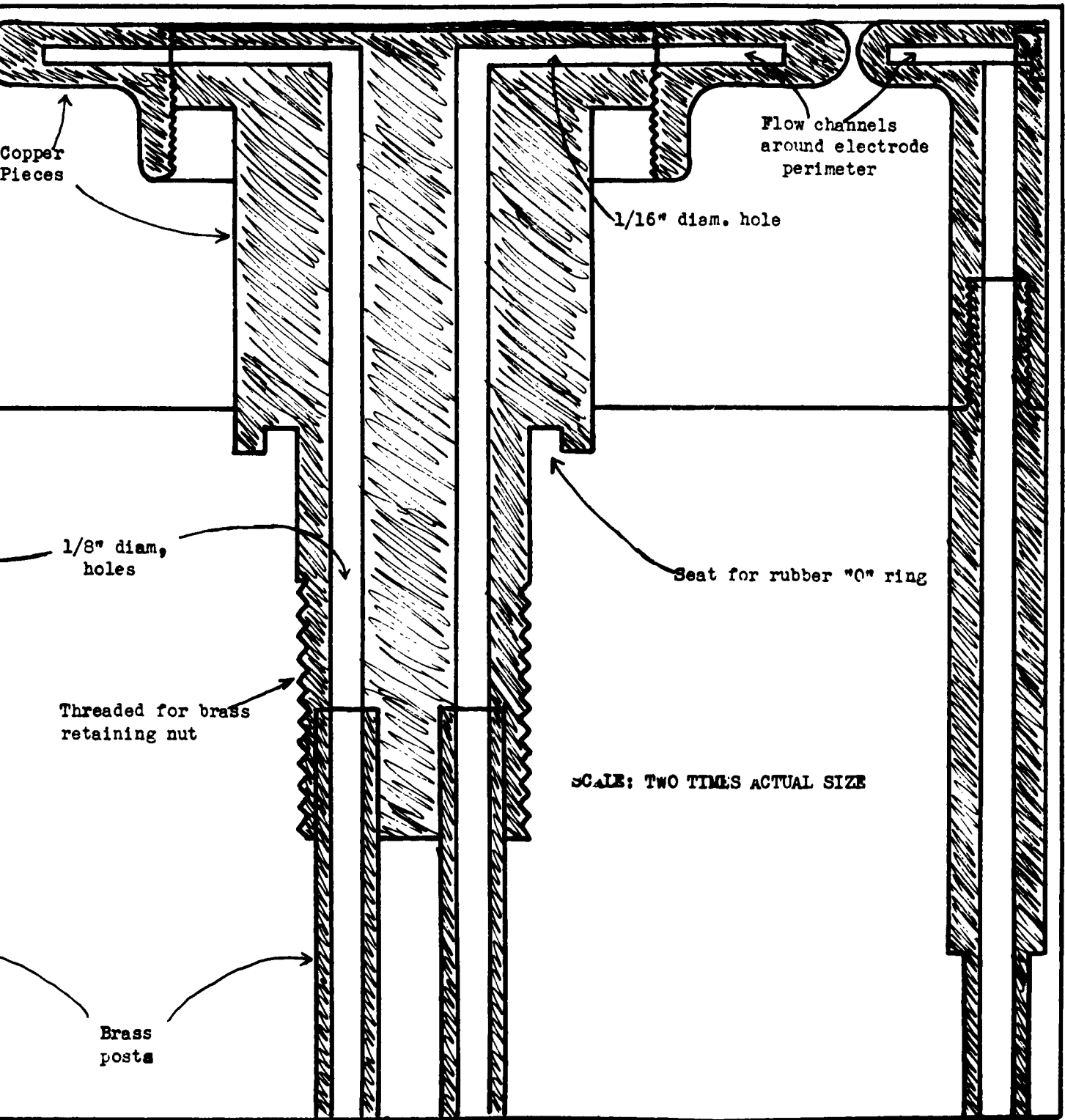


Figure 14. Final Electrode Design

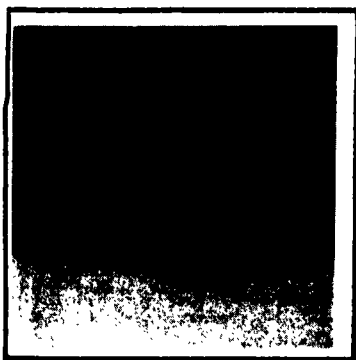


Figure 15. Anode,
bottom view.

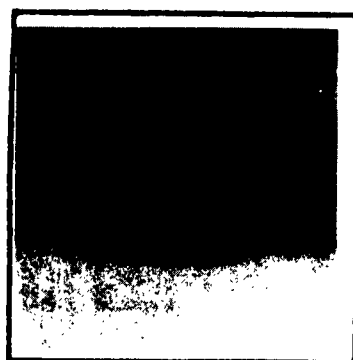


Figure 16. Anode,
side view.

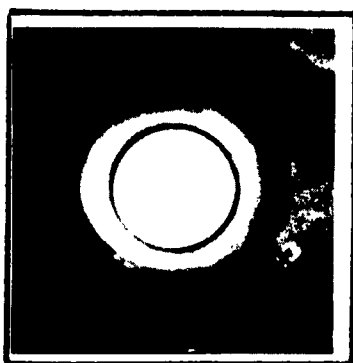


Figure 17. Electrodes,
mounted with plexi-
glass cylinder in
place.

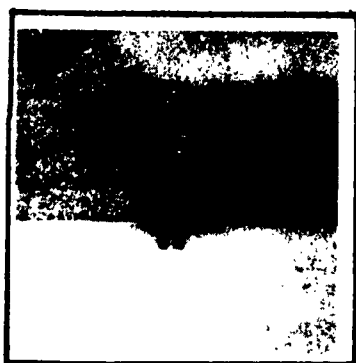


Figure 18. Cathode,
bottom view.



Figure 19. Cathode,
side view.

copper thrown from the cathode. The top and bottom edges of the cylinder were lapped smooth for better sealing. A 3/4" thick optically flat glass plate formed the top of the cylinder. Before operation the bottom and top of the cylinder were liberally smeared with vacuum grease. As the chamber was evacuated the glass plate was drawn tight against the top of the cylinder and the bottom of the cylinder drawn against the phenolic board, effecting a pressure seal.

Argon passed from a tank through a standard Airco reducing valve and flow meter into a controlling needle valve leading through the wall of the cylinder just above the top of the magnet.

Vacuum line connections were threaded through the phenolic bottom, inside the cylinder and sealed with epoxy resin. These lines led to a Wallace and Tiernan 0 to 200 millimeter vacuum gauge and a Welch Duo Seal vacuum pump, rated to 1 micron. The gauge was calibrated against a standard gauge and found accurate to within reading error. (± 0.2 mm.)

Magnetic Coil

The magnetic coil used was fabricated in the Aeronautical Research Laboratory for use in two previous experiments. The coil was made from 100 turns of $\frac{1}{4}$ " by 0.065" copper tubing, which served as its own cooling water passage. Individual turns were insulated from each other by strips of fiberglass cloth impregnated with epoxy resin. The coils were baked in a compound of 65% epoxy resin and 35% polamid resin. The entire magnet assembly formed a cylinder of 12" outer diameter, 6" inner diameter and 3 1/8" height.

The availability of this custom-wound, water-cooled coil determined the diameter of the plexiglass cylinder, the outer electrode and ultimately the arc path. The electrodes were designed so that the arc would run in the exact vertical center of the coil in order to render the field as perpendicular to the arc as possible.

The field strength in the electrode gap was calibrated by use of a Bell, model number 110, gaussmeter. The plot of magnetic field strength versus current to the coil is shown in Figure 20.

Power and Cooling Supplies

Power for the magnetic field was supplied by one 12 KW output, A. O. Smith Rectifier, Model 3001. The inherent limitations of the rectifier and the resistance of the coil, leads, and meter shunts restricted the variation of field current to from slightly less than 60 to slightly over 300 amps.

Power for the arc itself was produced from two other rectifiers of the same type, connected in series. The variation of arc resistance with gap length and pressure, as well as cooling system capacity, limited the range of arc current that could be used at all pressures and gaps to 50-250 amps.

Cooling water was taken from the building supply at 75 psig and run into a common manifold. Standard valves were used to distribute this water between the anode, cathode and magnet in accordance with their cooling needs. Since the temperature at the electrode surface is a function of the arc itself, no attempt was made to control temperature beyond closing down operation below the temperature level that threatened the plexiglass cylinder or vacuum hoses.

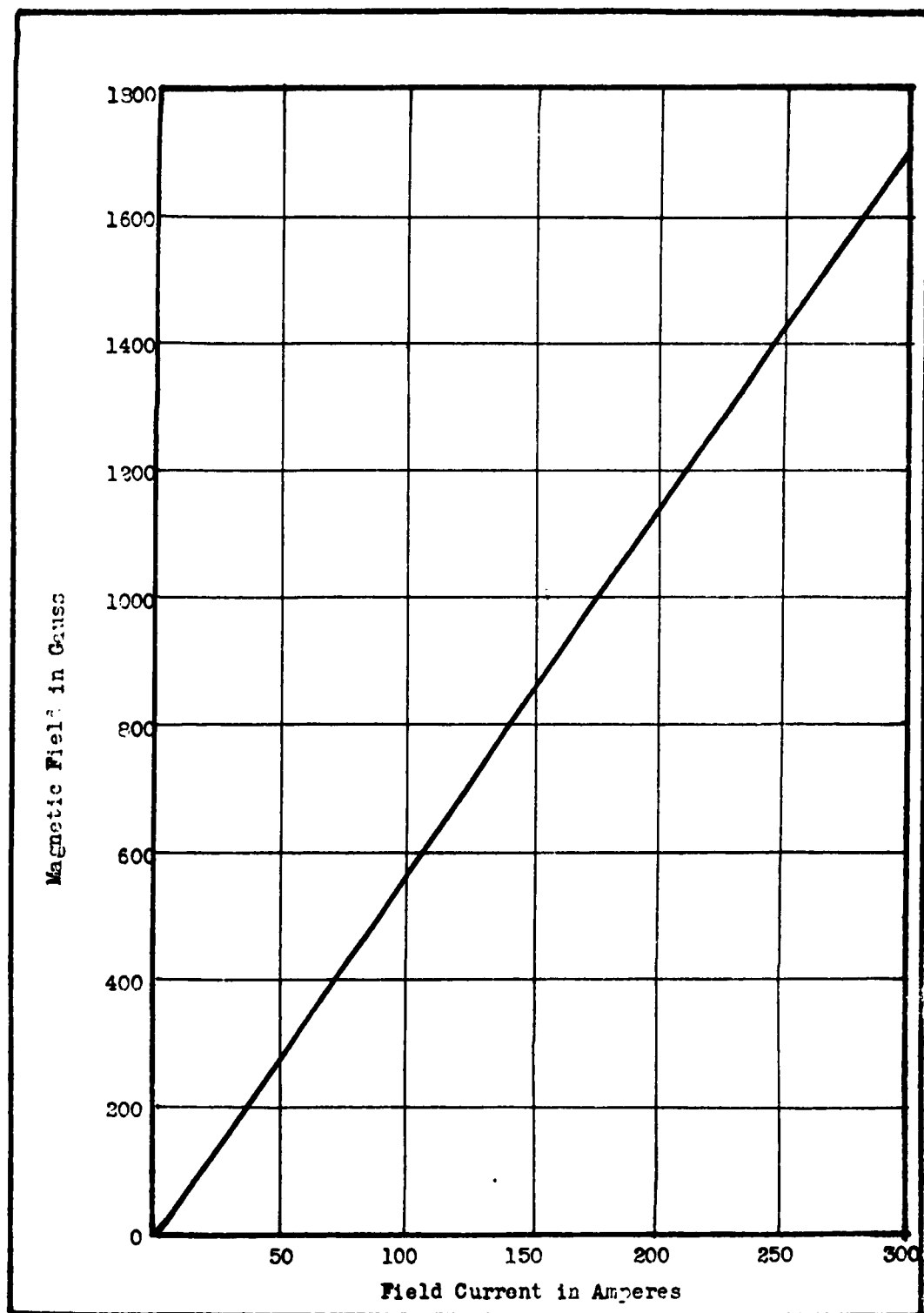


Figure 20. Magnetic Field Calibration

In order to isolate the components from one another electrically, Tygon or rubber water connections were used in all cases.

Instrumentation

Arc and magnetic field currents were measured with Weston Electric Co., Model 430, D. C. Ammeters, using calibrated leads and appropriate shunts to give 75, 150, or 300 amp full-scale deflection. The least accurate readings (300 amp scale) were within ± 1 amp.

Recording arc velocity presented another problem area. Initial runs were shot using a 16mm Wollensak Fastax camera and associated timing gear. Camera speed was 7200 frames per second and timing marks were made on the film each 1/10 second. These films provided excellent information on the speed and uniformity of arc travel; however, the camera shot the entire 100 ft. roll of film in 0.6 seconds. This caused three difficulties. First, reloading time required would necessitate excessive arc running time or shut-down after each data point. Second, as the arc slowed down, the motion became quite uneven and the motion caught in that short time might be far off the average. Third, even assuming that each attempt provided good data, the cost would be prohibitively high. The camera was, therefore, abandoned as the principle velocity measure, but all other systems were checked against the camera for accuracy.

Next a directed photoelectric cell was placed on top of the glass cover over one segment of the arc and passages were counted on a Hewlett-Packard Electronic Counter. A much too high count was found, and

attributed to reflections from the arc when it became brighter at spots other than under the photo-electric cell.

A sharper focus was arranged in the following manner. A 2" high by 21" wide mirror was placed approximately two feet above the arc at a 45° angle from the horizontal. It was then moved forward until only a very small segment of the arc was reflected. This reflection was then focused by a concave $5\text{-}3/4$ " diameter mirror, approximately five feet away, and directed into the photoelectric tube. Counts thus obtained were good only for a fraction of a minute after the arc was ignited because light combustion deposits on the glass lid cut down the signal rapidly.

The photoelectric cell was replaced with a photomultiplier using a Sorenson Nobatron Rectifier, Model 560, to supply 500 volt d. c. power to the tube. This arrangement, however, failed during slower arc speeds when changes in brightness of the passing arc were counted separately.

In order to be able to interpret passage in spite of multiple pulses, the output of the photomultiplier was amplified with a Consolidated Engineering Oscillator Power Supply and fed into a Honeywell Visicorder with speeds of 0.2, 1, 5 and 25 inches per second. Two recordings from the Visicorder are reproduced in Figures 21 and 22 for fast and slow arc movement respectively. Note the many secondary pulses (which caused the false count on the electronic counter) associated with arc passage at the slower speed.

Finally a Tektronix, type 555, dual beam oscilloscope was added in parallel with the Visicorder to determine that the arc was stable and

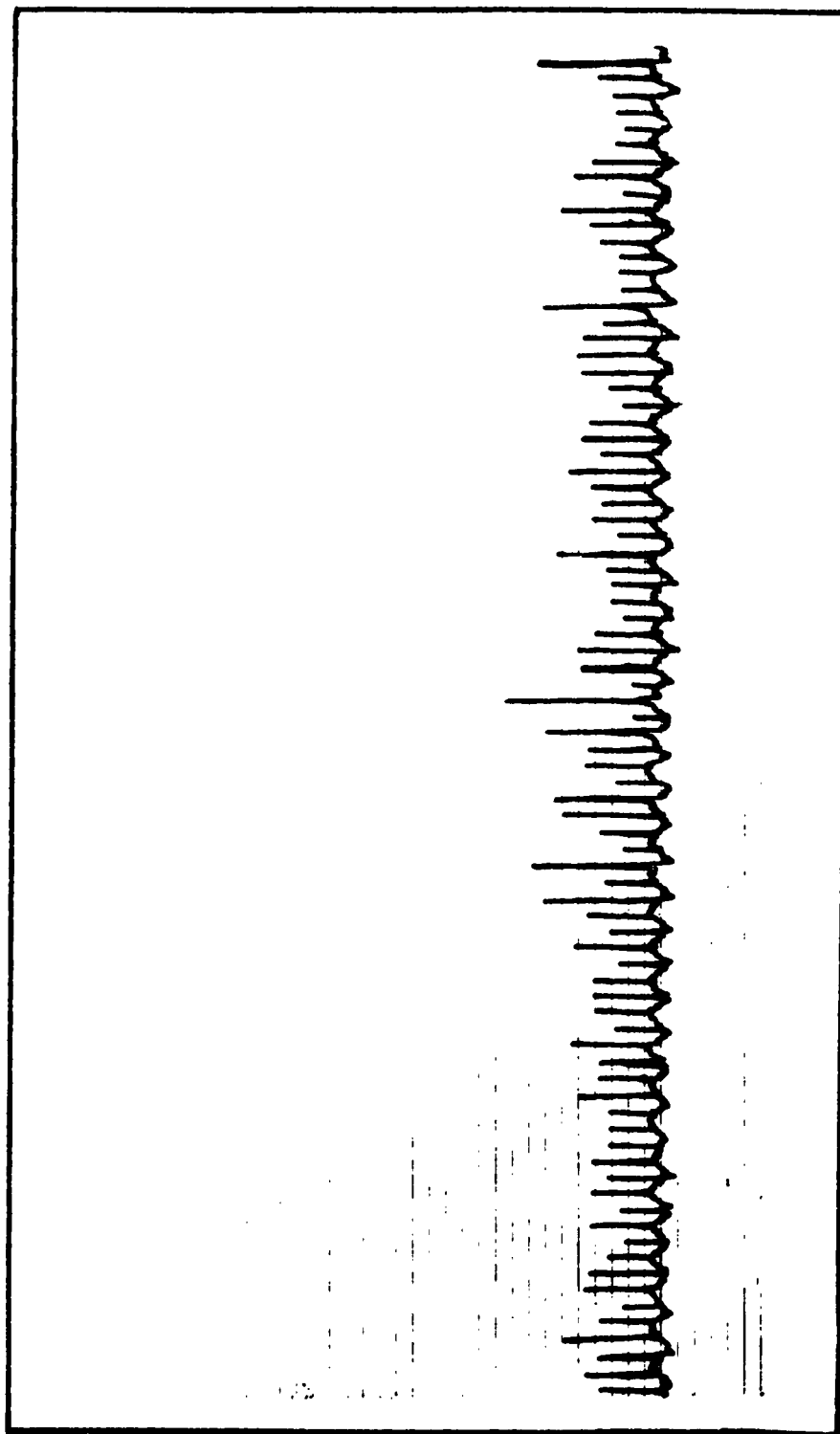


Figure 21. Visicorder Trace for Fast Arc Speeds.
(Moderate signal. Paper speed 25 in./sec)

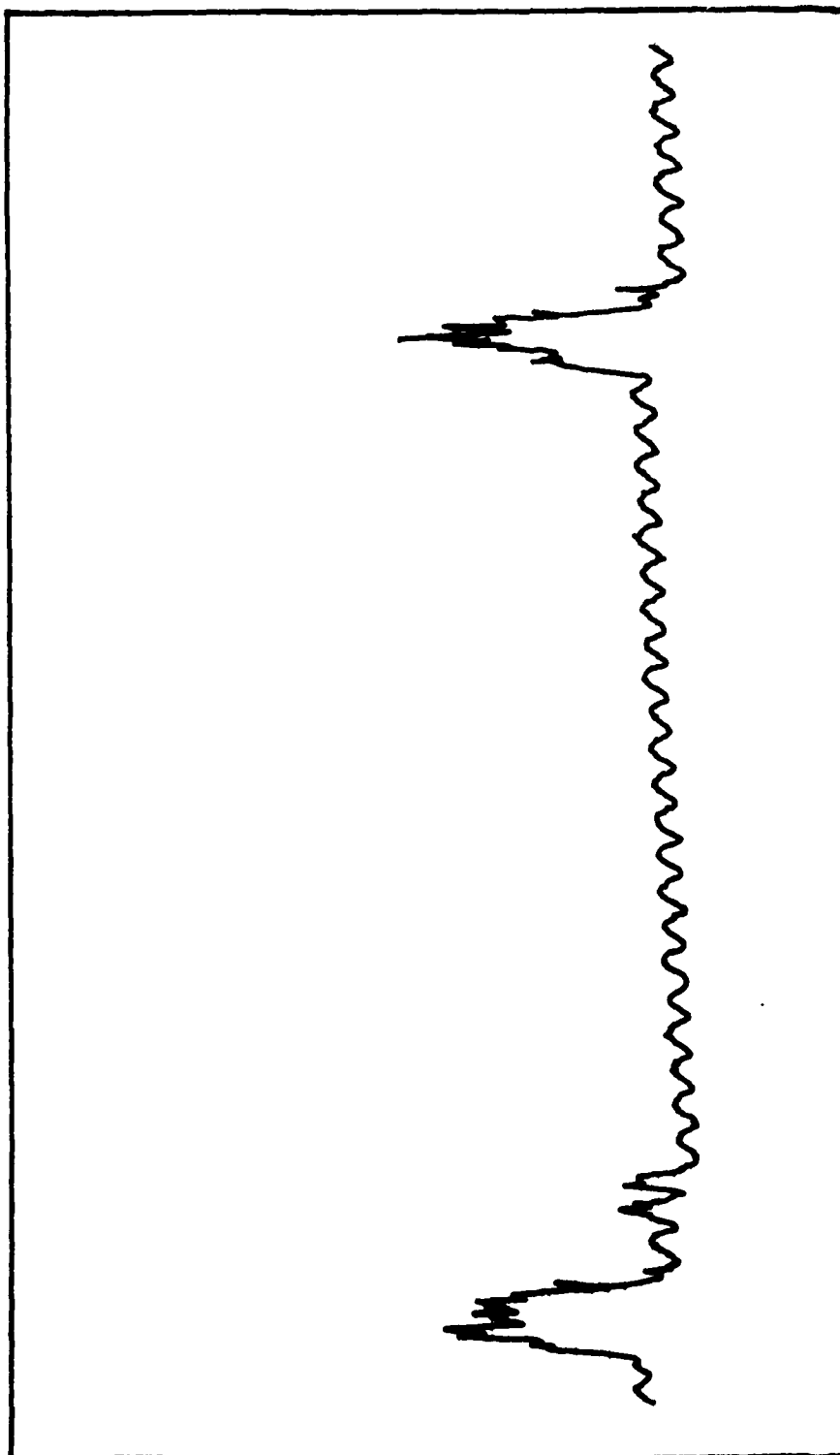


Figure 22. Visicorder Trace for Slow Arc Speeds.
(Strong signal. Paper speed 5 in./sec)

signal strength adequate before the recording.

Starting

Each time the plexiglass cylinder was opened, certain cleaning and regreasing was required to renew the vacuum seal and a lengthy purging process and pressure readjustment followed. It therefore seemed desirable to devise an external automatic starter.

Attempts were made to ionize the gas in the electrode gap by use of energy applied through a point electrode centered in and slightly below the gap. 20,000 volt, low power, r. f. energy was tried from a Tesla coil. This resulted only in a glow discharge around the third electrode with no apparent ionization in the electrode gap. The discharge of a 600 volt capacitor between the cathode and third electrode similarly produced a spark but no arc ignition.

Attempts at automatic starting were abandoned and starting was achieved by placing a small ball of steel wool between the electrodes before closing the cylinder. When voltage was applied to the electrodes, arc ignition ensued. Often the steel wool was not consumed on starting but merely blew to the side. Occasionally when the arc went out, shutting down and restarting the magnetic field would replace the steel wool between the electrodes and reignite the arc, but this was a random thing and very seldom of value.

Lately the Aeronautical Research Laboratory has acquired, after observing the difficulties in this experiment, a commercial arc starter. This is the Airco, Model HF-15-1, 500 Ampere High Frequency Oscillator

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which was designed to add an h. f. component to either a. c. or d. c. arc welders. However, this unit can be used to start an arc and then be removed from the line. This starter was available for gathering about the last 5% of the data presented in this report.

V. Approach

General

The second and third objectives outlined in section II must come as matter of course from the design of equipment, theoretical research, and the degree to which the first was satisfied. The approach to the experiment was, therefore, directed toward examining as many as possible of the parameters known, or suspected, to influence retrograde motion while keeping the others as constant as possible. The parameters to be varied independently were:

- 1) Gas pressure
- 2) Magnetic field strength
- 3) Arc current

The measurements taken during testing were:

- 1) Gas pressure
- 2) Magnetic field current (Later converted to field strength.)

(See Figure 20)

- 3) Arc current
- 4) Arc velocity

Although the electrode gap could not be measured during the actual runs, it was measured at various intervals between runs.

It has been originally intended to also vary electrode materials, type of gas, and electrode gap. The difficulties encountered in obtaining data eliminated the possibilities of using different electrodes and gas, due to time considerations. The machine work required for the final

electrode design (necessitated by the range of variables) lent additional fiscal considerations to the abandonment of trying several electrode materials. The erosion that took place at the cathode (discussed in section VI) did lend some information as to the effect of gap variation, however, this variation cannot be considered as controlled.

Range of Variables

The area of operation was initially selected to add data outside the range of experiments already well publicized. (See Figure 23) Actual variable ranges were then determined by the capabilities of the equipment available and the power limitations imposed by the size and cooling of the electrodes. Pressures used varied from ≈ 5 to 200 mm of mercury in steps of ≈ 25 mm. Magnetic field current was varied from 60 to 300 amps (345 to 1720 gauss) in steps of 30 amps (steps of 172 gauss). Arc current was varied from 50 to 250 amps in 25 amp steps. Electrode gap was originally machined to 1 mm, however, initial difficulties in achieving arc stability and determining operating ranges allowed cathode erosion prior to the taking of data. All significant data was taken for gap widths from ≈ 1.75 to 3.0 mm.

Test Procedure

Prior to each recording run, all recording equipment was warmed up and checked for spurious signals. A "no signal" run was made to indicate the present noise pattern on the visicorder. This was necessary because some feedback from other building equipment changed the noise pattern

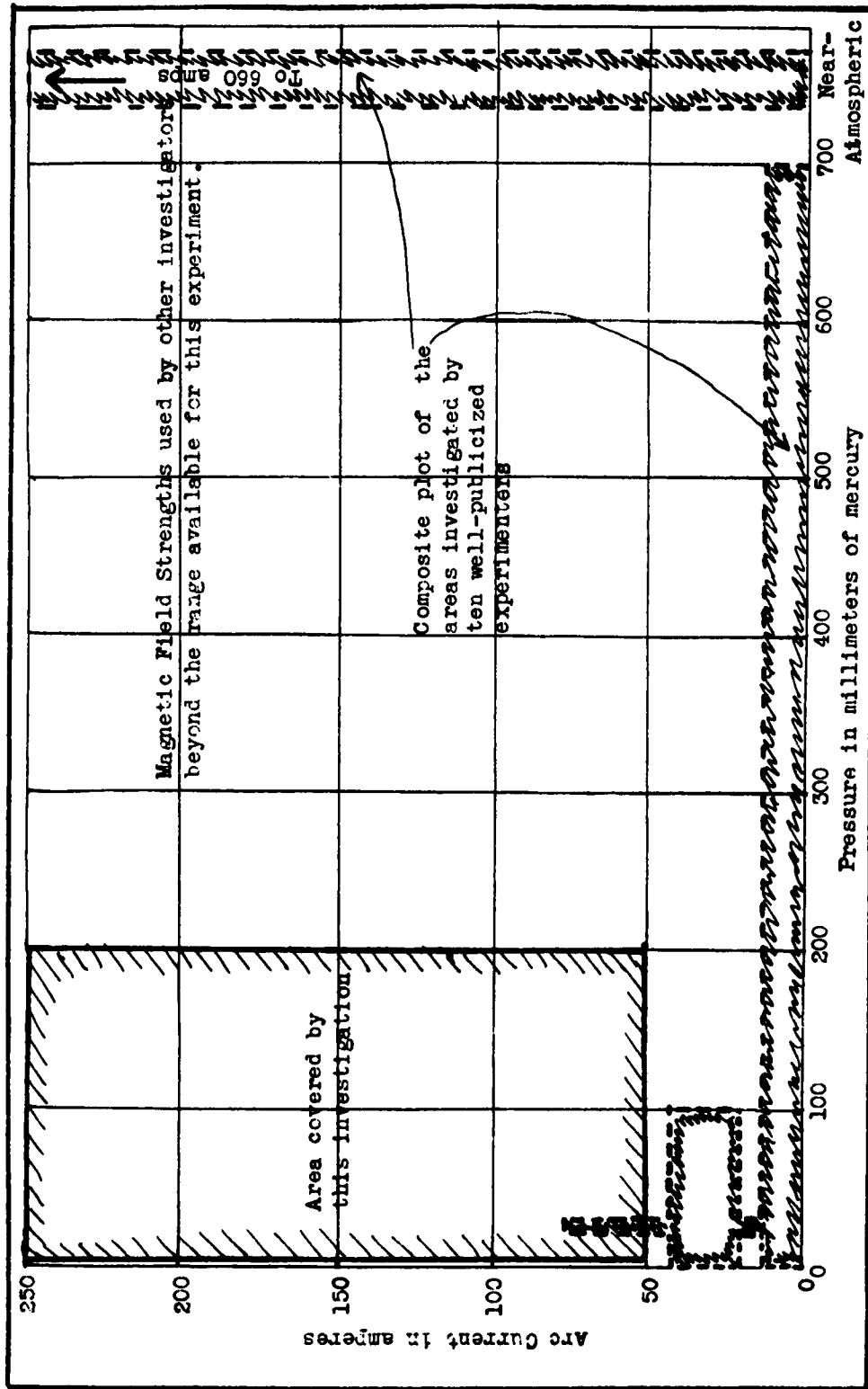


Figure 23. Area of Investigation vs. those of Other Investigators.

slightly and occasionally caused difficulty in trace interpretation. Electrode and magnet cooling water was then turned on and the system checked for leaks and adequate flow. The vacuum pump was started and taken to minimum pressure to check for significant vacuum leaks in the test cylinder and/or lines. The test cylinder was then purged of air by alternately pumping down and flushing with argon. At all times after purging, sufficient argon flow was kept going into the test cylinder to insure that leaks associated with the very low pressures were not allowed to influence gas purity.

Pressure and power supplies were set in a combination known (by prior investigation) to be favorable to arc starting and rapid stabilization, and the arc was ignited. The arc was left running in this condition long enough to stabilize, reach a constant heat balance with the cooling system, and burn off any oxidized layer that might have formed between runs. The last two items were insisted on in order to remove, as far as possible, any deviations of surface conditions from former runs. During this stabilization period, the mirror system was checked and adjusted to insure a proper focus on the photomultiplier tube and a trial run was made to insure a proper signal on the visicorder trace.

Parameters were then adjusted to the test conditions. This adjustment was accomplished gradually by whatever steps visual and Tektronix scope observations showed to be maintaining the most stable arc. In spite of these precautions, the arc frequently extinguished and the procedure had to be repeated.

Once the test area was reached, steps between recording points were taken as evenly as possible. However, the rather insensitive pressure control and the interdependence of pressure and current necessitated the taking of readings at somewhat unequal spacing. The variation of stability already described necessitated that the test points be taken in a more random order than was desired.

The lengthy pre-recording procedure made it desirable to obtain as many points as possible during the run. To save time, recording runs were continued as long as temperature remained within reasonable bounds and the arc remained on and stable.

Modifications

No modifications of the test procedure were made other than the obvious ones occasioned by equipment changes. These changes were discussed in the previous section.

Velocity Measurement

The only measurement not taken directly was that of arc velocity. The number of arc cycles per second were taken from number of pulses shown on the visicorder paper. The errors in speeds of the visicorder paper ejection were negligible compared to measuring the cycles per second to only 0.1 cycle.

The c. p. s. readings were then converted to meters per second from the physical dimensions of the electrodes.

VI. Discussion of Results

Introduction

Prior to beginning data runs, several trial runs were taken. The purpose of these runs was to investigate general arc behavior, determine areas of interest and discover the limits of parameter variation possible with available equipment. Additional runs were taken to develop an adequate velocity measurement system as described in Section IV. Observations made during this period not only provided certain qualitative information, but also determined the requirements for valid data runs.

Extreme variations of velocity, under conditions that were apparently the same, showed that it would be necessary to take complete sets of data under almost continuous runs if they were to be compared. Several runs, terminated because of water leaks or extreme arc instability, were discarded. The two data sets presented are considered to be consistent.

Constant Field Cross-Section

A set of data taken for pressure versus arc current is shown in graphical form in Figure 24. This graph is in the form of a velocity contour map with positive values indicating amperian motion and negative values showing retrograde motion.

The plane of the paper represents a constant magnetic field value of 345 gauss. Velocity values were taken at approximately every 25 amperes

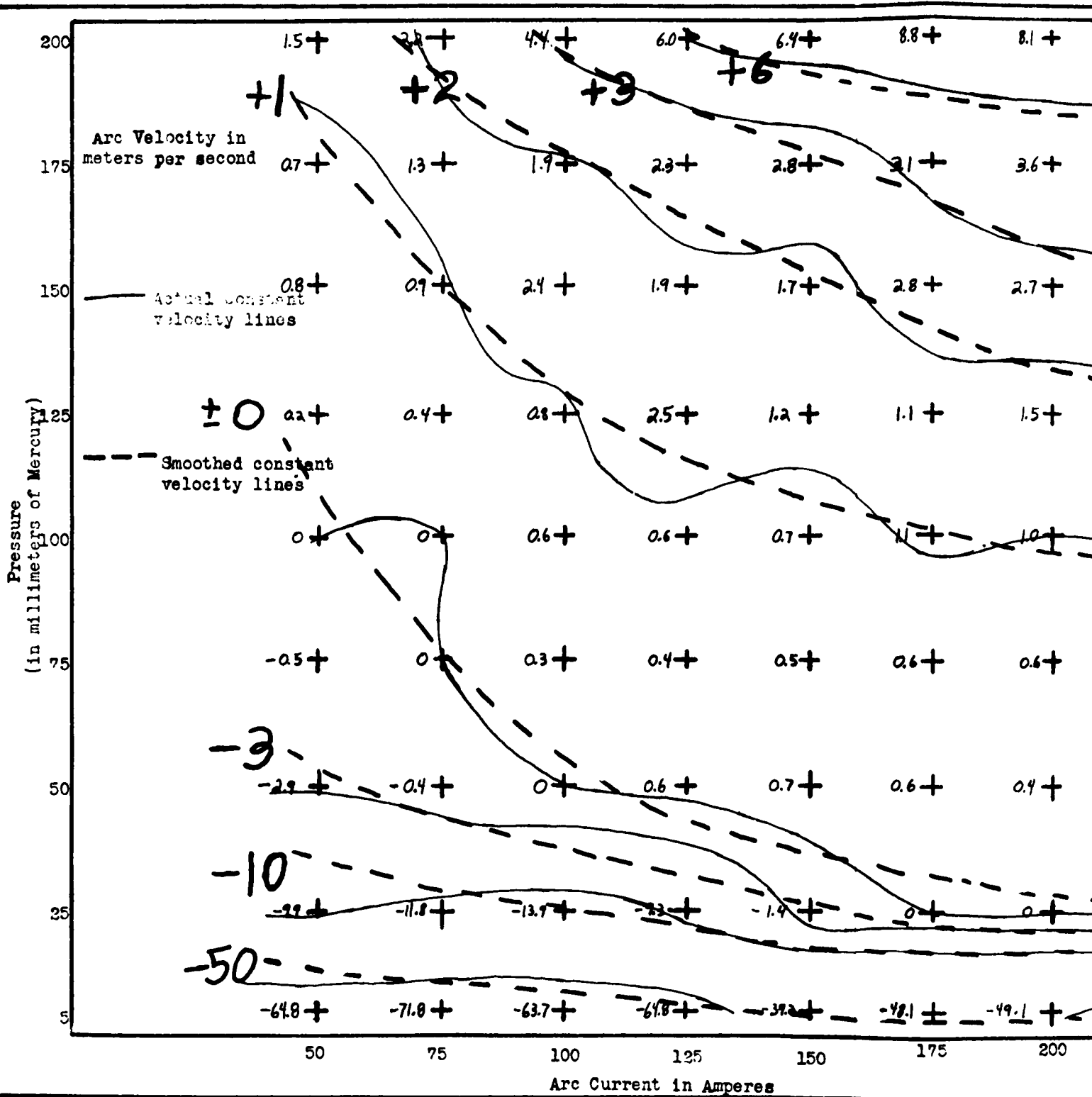
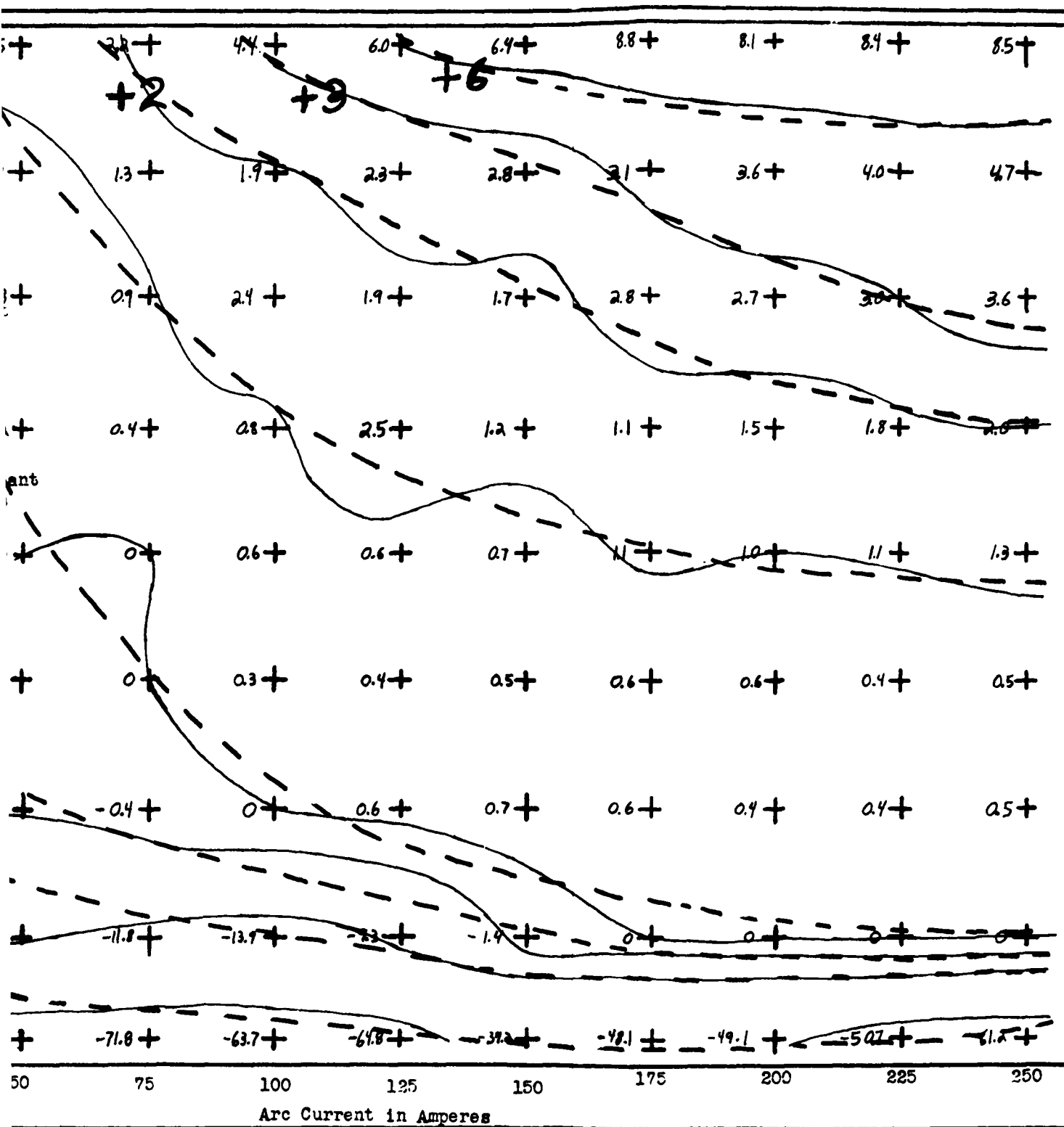


Figure 24. Arc Velocity Plotted for Pressure vs. Arc Current. (Magnetic Field constant at



Velocity Plotted for Pressure vs. Arc Current. (Magnetic Field constant at 345 gauss)

Table of Data for Figure 24.

Magnetic field constant
at 345 gauss

Pr = Pressure in mm Hg I = Arc Current in amperes
Vel = Velocity in meters per second

Pr ≈ 5			Pr ≈ 75			Pr ≈ 150		
Pr	I	Vel	Pr	I	Vel	Pr	I	Vel
5.5	51	-64.8	73.2	54	-0.5	147.4	54	0.8
5.8	73	-71.8	73.8	74	0.0	149.3	73	0.9
5.5	104	-63.7	73.8	101	0.3	149.6	101	2.4
5.7	127	-64.8	74.1	127	0.4	148.8	124	1.9
4.2	151	-37.2	74.5	151	0.5	149.2	148	1.7
4.2	174	-48.1	74.6	178	0.6	149.2	176	2.8
4.3	200	-49.1	74.7	197	0.6	149.0	199	2.7
4.3	223	-50.7	75.8	225	0.4	147.7	224	3.0
4.3	252	-61.2	77.6	252	0.5	148.6	250	3.6

Pr ≈ 25			Pr ≈ 100			Pr ≈ 175		
Pr	I	Vel	Pr	I	Vel	Pr	I	Vel
23.1	52	- 9.9	101.3	49	0.0	174.8	54	0.7
23.2	75	-11.8	99.8	73	0.0	174.7	74	1.3
23.2	100	-13.9	99.6	99	0.6	175.3	101	1.9
23.6	124	- 9.3	99.6	126	0.6	175.8	123	2.3
24.4	153	- 1.4	99.7	153	0.7	176.3	150	2.8
25.0	175	0.0	99.8	176	1.1	176.3	175	3.1
25.5	202	0.0	100.2	200	1.0	176.0	200	3.6
26.0	225	0.0	100.1	226	1.1	177.0	227	4.0
26.0	250	0.0	100.1	252	1.3	177.3	252	4.7

Pr ≈ 50			Pr ≈ 125			Pr ≈ 200		
Pr	I	Vel	Pr	I	Vel	Pr	I	Vel
50.3	51	- 2.9	124.3	55	0.2	196.8	53	1.5
51.3	76	- 0.4	124.8	77	0.4	197.3	73	2.2
51.8	100	0.0	125.5	101	0.8	198.2	99	4.4
51.0	127	0.6	125.9	123	2.5	198.8	124	6.0
51.0	151	0.7	124.0	153	1.2	198.8	152	6.4
51.0	177	0.6	120.7	177	1.1	199.7	176	8.8
51.0	207	0.4	126.5	198	1.5	197.8	197	8.1
53.6	224	0.4	127.1	225	1.8	199.3	225	8.4
54.3	254	0.5	127.8	254	2.0	198.3	252	8.5

Figure 25. Constant Field Data

of arc current from 50 to 250 amperes and every 25 mm of pressure from 25 to 200 mm, plus a value near 5 mm. Due to scale considerations the velocities on the graph are plotted at the nominal values of pressure and current; however, the actual parameter values are given in tabular form in Figure 25.

Constant Arc Current Cross-Section

An additional velocity contour map for pressure versus magnetic field is shown in Figure 26. Here the plane of the paper represents a constant arc current value of 175 amperes. Magnetic field current was varied between 30 and 300 amperes in steps of 30 amperes for pressure values of approximately 5, 25, and 50 mm. The somewhat larger scale shown here did allow the plotting of actual values. The pressure differences are not evident, however, in proportion to their effect on arc velocity. Hence the actual values are again shown in tabular form in Figure 27.

Observations

Blast Movement. In his original experiment (Ref 13:217(A)), C. G. Smith observed that the "air blast" associated with the arc continued in the amperian direction regardless of the direction of arc movement. The initial electrode design for this investigation included a provision for movable glass vanes located over the electrode gap. The impossibility of obtaining quantitative information from this arrangement, plus the additional vacuum and water leaks it engendered, led to its abandonment in later models; however, Smith's observations were confirmed.

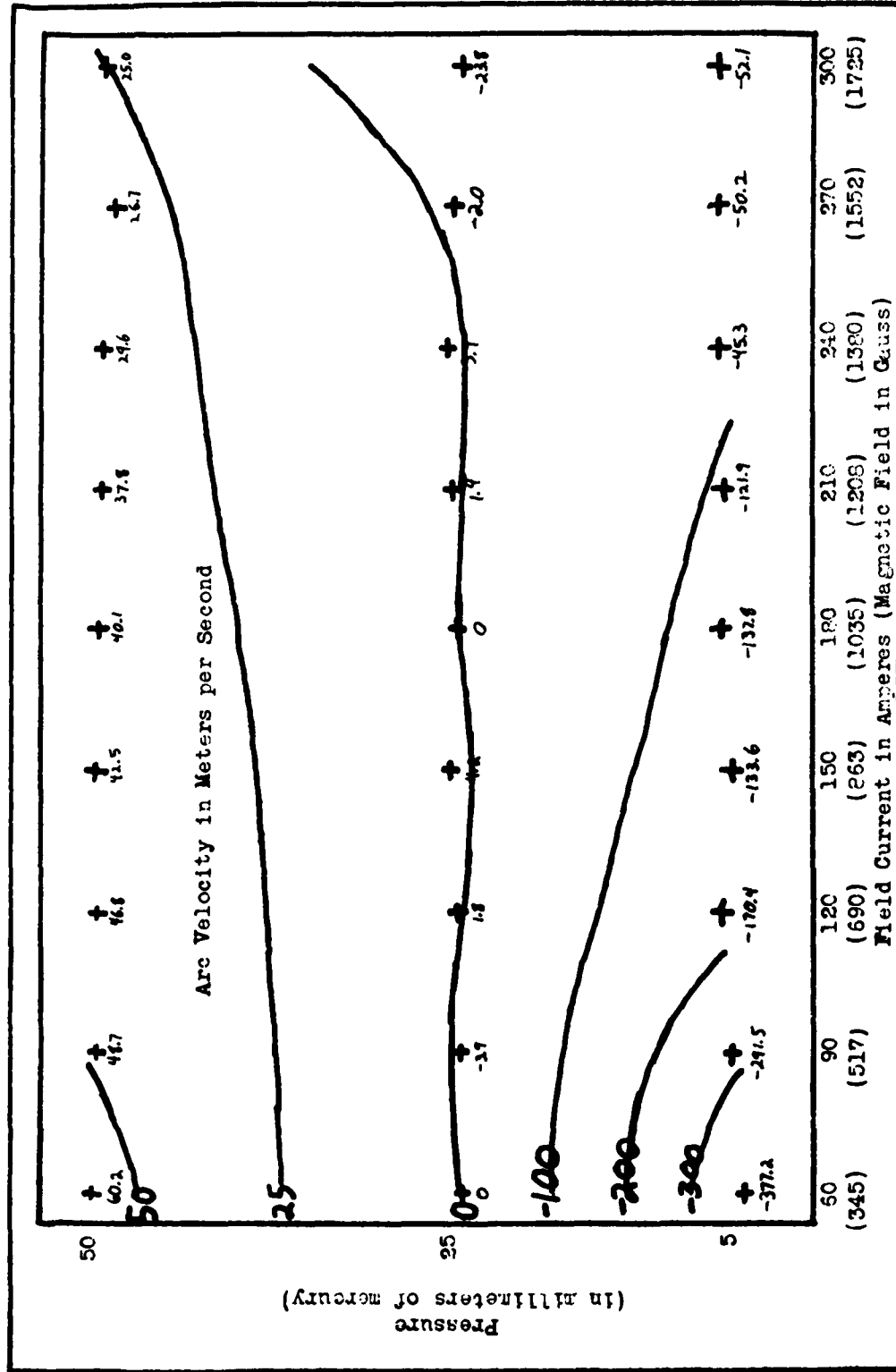


Figure 25. Arc Velocity Plotted for Pressure vs. Magnetic Field. (Arc current constant at 175 amperes)

Table of Data for Figure 26.

Arc Current Constant
at 175 amperes

Pr = Pressure in mm Hg

B = Magnetic Field in gauss

Vel = Velocity in meters per second

Pr ≈ 5			Pr ≈ 25		
Pr	B	Vel	Pr	B	Vel
5.6	345	-377.2	23.8	345	0.0
5.6	517	-291.5	23.8	517	- 3.9
6.2	690	-170.4	24.1	690	1.8
6.5	863	-133.6	24.4	863	4.2
6.2	1035	-137.8	24.1	1035	0.0
6.1	1208	-121.9	24.4	1208	1.4
6.6	1380	- 45.3	24.8	1380	3.9
6.6	1552	- 50.2	24.2	1552	- 2.0
6.5	1725	- 52.1	23.8	1725	-23.8

Pr ≈ 50

Pr	B	Vel
48.8	345	60.2
48.3	517	48.7
48.5	690	46.8
48.5	863	42.5
48.3	1035	40.1
48.0	1208	37.8
48.0	1380	29.6
47.2	1552	26.7
47.8	1725	25.0

Figure 27. Constant Arc Current Data

Gap. Not enough evidence was gathered in this experiment to constitute concrete confirmation as to the effect of varying gap width. The random variations described in the introduction to this section were of greater magnitude than any actual gap effect. Under this masking effect of this variation there did appear to be a general trend discouraging retrograde motion as gap increased.

Stability. The most noticeable manifestation of the random variation was in arc stability. Upon certain occasions the arc would not maintain itself even under conditions formerly very favorable to stability. At other times the arc was extremely stable under all conditions.

Glow Discharge. Associated with instability of the arc at low pressures was an occasional drop from the arc discharge state to a glow discharge. This was often followed by a cease of all visible discharge.

Arc Appearance. The necessity for showing the entire arc path in the motion pictures of arc movement precluded a close enough view of the arc to determine the physical appearance of the arc column. Several features were noted about general visual appearances.

- (1) Arc color varied from a very bright green to almost white.
- (2) At arc speeds where the arc appeared continuous, apparent cathode "hot spots" moved slowly in the amperian direction.
- (3) Flaming gases around the arc tended to increase with instability and also with the greener arc colors.
- (4) The arc tended to move more evenly with increasing speeds.

- (5) Faster arc speeds, both amperian and retrograde, and sharper zero velocity lines were associated with the whiter arcs.

Discussion of Data

Figure 24 shows clearly that both decreasing arc current and decreasing pressure favor retrograde motion. Variation from the general pattern shown at the lowest pressures can be explained quite easily. The "packing" of the lines of constant velocity in this region shows that a very slight change in pressure will cause a large change in velocity. Pressure control in this area was very difficult because the gas flow was more sensitive to valve manipulations and slight deviations in vacuum pump rhythm had more effect. Since there was no compensating improvement in gauge scale or gauge lag, pressure readings, and hence velocity plots, are less reliable in this range.

Figure 25 shows a lesser effect from magnetic field change. While an enlarged scale drawing in the 25 mm pressure area is meaningless in itself, it would show a slight increase in retrograde tendency with increasing magnetic field even prior to the noticeable break near 1500 gauss. Perhaps the most significant point in this data is around 50 mm pressure. This shows the arc speed in the amperian direction decreasing with increasing magnetic field. This would indicate that any theory of retrograde motion would have to account for a reversal of the magnetic field effect at some point above the critical pressure for zero velocity. Any comprehensive investigation of retrograde motion should also include this crossover point.

The numerical values associated with the data must be regarded as questionable. The best indication of this can be seen by examining the three points common to Figures 24 and 26 (i.e. Magnetic field = 345 gauss; Arc Current $\approx$ 175 amps; Pressure $\approx$ 5, 25, and 50 mm). These three points are consistent with each other and taken under similar conditions for each graph. Gap widths are also consistent within each set of data. Disregarding gap effect, which should be the same in each case, the minor variations of arc current and pressure from the nominal values would predict the following relation between the common points:

Pr $\approx$ 5: Figure 24-More retrograde tendency than Figure 26.

Pr $\approx$ 25: Figure 24-Less retrograde tendency than Figure 26.

Pr $\approx$ 50: Figure 24-Less retrograde tendency than Figure 26.

The actual measurements show:

Pr $\approx$ 5: Figure 24-Less retrograde tendency than Figure 26.

Pr $\approx$ 25: Equal retrograde tendencies for the two figures.

Pr $\approx$ 50: Figure 24-More retrograde tendency than Figure 26.

The obvious conclusion is that data contained in this report should only be regarded in a qualitative sense.

Comparison With Theories

None of the theories discussed accounts for the observed random fluctuations apparently connected with the electrode surface conditions. While this observation is not definitely established, the evidence points strongly to the need for consideration of this point. If surface condition is not actually a criteria for retrograde motion, its modifying effect must be explained.

The theory of Robson and von Engel (Ref 7:1121-1122) is the only one to take into account the observed dependency on electrode gap. It does, however, seem to contradict the observation of increased retrograde tendency with decreased arc current. Since this theory depends on self-induced magnetic fields to explain retrograde motion, it follows that current decrease should reduce the retrograde tendency. The theory has also been questioned on the possible magnitudes involved by C. G. Smith (Ref 14:1328-1329) and Guile and Secker (Ref. 4:1666). No data was obtained in this investigation to support either side.

The explanation of Himler and Cohn (Ref 5:1148-1152) was one of the earlier theories offered and has since been generally discredited on many grounds, particularly the proposed diffusion of emitted electrons. It is supported only by the pressure effect and the magnetic field effect. It is interesting to note that their own data on magnetic field effect is the only observation failing to support their theory in this area.

The St. John and Winans theory (Ref 10:104-111) fails to predict any general pattern associated with the effect of arc current. It is probable that the isolated instances where they quote data contrary to the general observations are a function of the cathode surface condition. The observation that, "at some value of magnetic field a critical density of doubly ionized atoms may be produced," may be true; however, they have proposed nothing tangible to show why this relationship exists.

The apparent agreement of the Ecker theory (Ref 2:110) with certain experimental results does not eliminate the possibility of dependence on

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electrode gap and cathode surface conditions. The technique of matching one experimental point with one theoretical point, to allow for unmeasurable parameters, could easily obscure these effects and many others.

No wholly satisfactory theory for retrograde motion or completely quantitative experimental data appear to be available at the present time.

VII. Conclusions and Recommendations

Data contributed by this investigation can be only regarded as qualitative but do agree with that of other investigators in the field. The points of specific confirmation were the increase of retrograde tendency with decreasing pressure, decreasing arc current and increasing magnetic field.

Observational agreement was found with the increase in retrograde tendency with decreasing electrode gap. Agreement was also found concerning amperian motion of the "air blast" regardless of the direction of arc travel.

The wide variations of velocity discovered, when all parameters were the same as far as could be discerned, lends confirmation to the assertion of Secker and Guile (Refs 4 and 12) that retrograde motion is highly dependent on cathode surface condition. The question as to whether this might not be merely a function of stability cannot be answered completely; however, these variations were noticed when oscilloscope and visual observations indicated complete stability.

An additional observation was made that has not been explicitly mentioned in the literature researched. Even above the critical conditions for retrograde motion, increasing magnetic field may sometimes act in a manner opposite to that predicted by Ampere. Not enough information was obtained to discover how far above critical conditions this effect extended.

No specific confirmation or refutation of proposed theories was attained; however, the observations of apparently unexplainable variations of velocities indicates that a fully successful theory must be intimately connected with cathode emission. This theory should also explain changes in cathode emission as a function of surface condition.

Any investigation that is to yield quantitative results in this area must effect careful control of all known or suspected parameters. The equipment involved in such an experiment must be highly refined and electrodes must be easily replaceable for close control of gap width and surface condition.

No specific recommendations are made for further AFTT thesis work in this area since the Thermodynamics Branch of the Aeronautical Research Laboratory is currently sponsoring a doctoral dissertation utilizing the experience gained from sponsoring this thesis.

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