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ELECTRODE BREAKDOWN AND SHIELDING OF INTENSE DISCHARGES ACROSS THE MAGNETIC FIELD

J. W. Flowers

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J. W. Flowers*

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ABSTRACT

PIG discharges have been operated in a uniform magnetic field of 5000 gauss and over a path length of 6 feet with currents ranging from 5 to 180 amperes for argon. Electrode failure, initially encountered, required the development of improved electrode shields which enabled grading of potentials near the electrodes. Potential distribution possibly afforded by multiple shields in a plasma-magnetic field environment is discussed in relation to plasma conductivity transverse to the magnetic field. An anode breakdown condition was attained at high power of operation and provided a limit of the gas discharge for the anode position and dimensions.

INTRODUCTION

Difficulties with electrode breakdown were experienced in attempting to produce high power gas discharges of a PIG[1] or reflex class operating over a longer path than previously attained.[2] This work had in view a study of the ion energies in the expected intense discharges running as arcs from self-heated hollow tungsten cathodes and across the magnetic field.

Discharges operating across the magnetic field at relatively high potentials and current seem particularly susceptible to electrode failure due to shunting discharges of higher conductance. For the particular electrode arrangement used, breakdown initially occurred over wide pressure ranges due to several different mechanisms not immediately separable. Two distinct classes of breakdown were found to occur. For each the gas discharge, during operation at considerable power, was supplanted by some electrode vapor arc or breakdown.

The prevention of one class of breakdowns was made possible by the use of suitably developed shielding. This shielding enabled the electrodes to hold the required potentials and prevented discharges from the electrodes in all undesired directions and over wide pressure ranges.

The second and more unusual breakdown was found to occur on lowering gas pressure during operation at considerable power input. It was found to be independent of electrode shielding and, in nature, it consisted of a transition to a new discharge between cathode and anode in which an anode spot formed. This anode spot always formed most remote from the cathode with the metal vapor ensuing from it then determining the arc behavior.

Since the electrode shields developed may be applicable to other arcs or discharges with possible adverse voltage and pressure conditions, a description of this shielding seems worthwhile. Also since the second

class of breakdown or transition appears to be the result of a discharge mode developing as the pressure is reduced, it seems likely that this breakdown defines some limit of operation of the gas discharge for the electrodes used. For the electrode geometry used this limit prevented operation of the arc in the low pressure regions of most interest. Expected operation toward high voltage and low conductance was limited and as a consequence little study of the discharge was made. The overall results indicate some electrode configurations and shielding requirements likely necessary to achieve high voltage and high power operation in coaxial discharges where the space is adequate.

Electrode Arrangement and Gas Control

The essential electrode configuration for the discharges under consideration is shown in Fig. 1. All electrodes were water cooled and

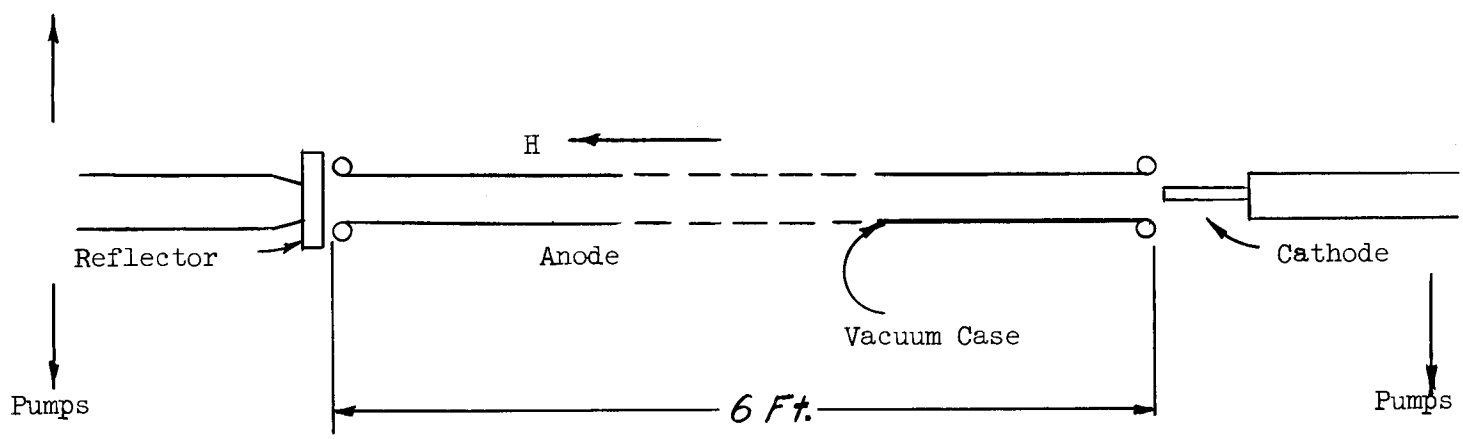

Fig. 1 ELECTRODE ARRANGEMENT, SHIELDS NOT SHOWN

situated coaxially within a long solenoid.[3] This solenoid provided an essentially uniform magnetic field and a field value of 5000 gauss was usually employed. Anode and reflector were made of copper while the cathode was a tungsten rod machined into a hollow tube and extending approximately 6 inches beyond the cooled copper cathode holder in which it was seized. The outside diameter of the cathode was approximately 0.75 inches with a bore of 1/4-inch diameter. A hole size of .5 inches used for a short time seemed to be more erratic in operation and raised the low current point at which the discharge would be extinguished from 5 amperes to 25 amperes. This was opposite to expectation on a simple assumption of the heating.

In operation gas was fed into the discharge through the hollow cathode at a controlled rate while simultaneously pumping from the vicinity of the cathode and the reflector. Four diffusion pumps of 6 inches diameter were used at the reflector end of the system and two at the cathode end and all backed by a large mechanical pump. Gas pressures were measured at each end and in the center of the system by ion and thermocouple gauges. Essential characteristics of these discharges are very likely associated with the cathode gas feed and the pumping rate which together produce pressure differences and pressure gradients. Also the breakdown characteristics of necessary shielding likely depend upon pressures in their vicinity and pressure gradients that can be maintained. Gradients were not measured but consideration indicates relative difficulty in achieving the advantages of lower pressures near shields within a restricted solenoid with pumping confined end wise. As a consequence, compared to other field situations,[2] improved shielding was necessary.

Cathode Shielding

With the anode connected to the vacuum case, as shown in Fig. 1, the shielding of the electrodes concerns the cathode and reflector insulation relative to the case and anode. Negative cathode potentials as high as 750 volts were available from a supply consisting of ten rectifier type arc welders series connected. Other combinations of the welder supplies were also used.

In Fig. 2 is shown a plane shield which was expected to serve as an electron reflector for the discharge as well as an insulator or discharge interrupter preventing the shoulder and face of the cathode support from acting as a cathode. The insulating sleeve prevented the formation of

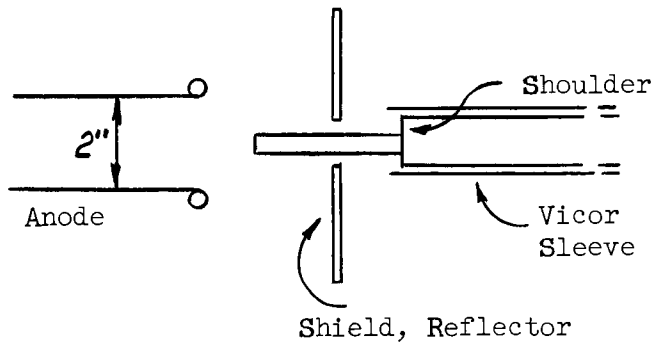

Fig. 2 PLANE CATHODE SHIELD

discharges along the holder and outward to an end plate. This plane shield failed in several different ways depending upon the supporting insulation. In common with each failure a discharge was evident at the inner edge of the shield surrounding the cathode, and on the holder face. In addition various combinations of failures took place from the outer edge of the shield to the solenoid case. These were in part across the magnetic field and along insulating supports, and in part along the magnetic field. In

the case of a water cooling attempt, similar breakdown occurred at the water line entrance bushing.

Temporary operation with gas control of the discharge was obtained by sealing a quartz glass disc in the end of the sleeve with a hole through which the cathode protruded. Failure occurred after several minutes with the hole in the disc enlarged. The addition of one or two plane shields to Fig. 2, and with these supported upon the quartz sleeve, did not prevent failure. The discharge in each case developed to the outer edge of the additional shielding with indications of sputtering on the shield surfaces which faced together. Some limited operation was indicated with the additional shields of 7 inches and 8 inches diameter equally spaced upon the sleeve and with a copper ring 3 inches in diameter providing a radial extension at the face and shoulder of the cathode support. In this case the quartz sleeve terminated close to the ring away from the cathode. Rings of smaller or large outside diameter failed more easily and in each case a discharge, distributed in nature, developed across the magnetic field.

From these observations of various failures it seemed likely that the various paths involved in any one breakdown had a common electron source. Thus the potential distribution and division expected in several regions, presumably separated by shields, did not take place. A single discharge was probably being formed over a devious path, instead of two or more discharge regions separated by a shield, or shields, each with its own cathode mechanism and potential fall.

The effective separation of two regions by a shield was achieved by the configuration shown diagrammatically in Fig. 3. For this situation

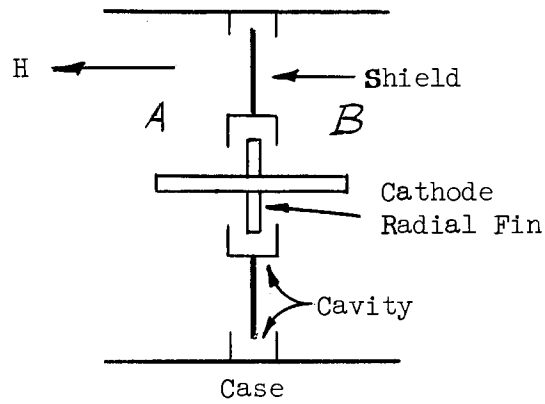

Fig. 3 SCHEMATIC CATHODE SHIELD PROVIDING EDGE DRAIN OF ELECTRONS

electrons from region A cannot as readily enter region B and tend to be collected by the shield cavity as they attempt to propagate around the cathode and its radial extension. A similar situation exists at the outer edge of the shield with a cavity connected to the case. Cavity dimensions may be related to maximum pressures of operation but this was not investigated. The experimental cathode with a successful shield is shown in Fig. 4

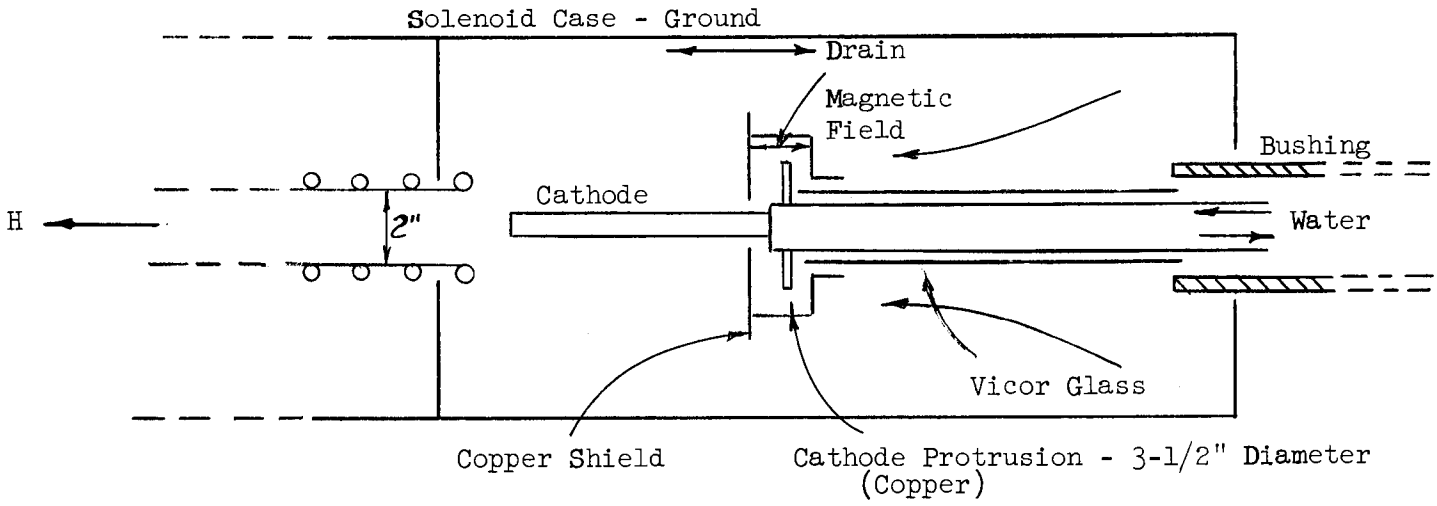

Fig. 4 DRAIN-TYPE CATHODE SHIELD

with the shield supported upon the glass sleeve around the cathode support. Long periods of high current operation were possible with this cathode shielding after similar shielding was made at the reflector electrode.

Reflector Shielding

The reflector, shown in Fig. 1 and isolated in the electrical circuit, developed a high negative potential causing breakdown similar to that at the cathode. This occurred after the cathode was properly operating. Two breakdown paths were observed, and each was composed of two parts. One path in part extended from the reflector along the magnetic field outward from the solenoid end to ground. Associated with this, the other part of the path was established along the field between the cathode and the reflector center with melting in a local spot at the center. The second breakdown path extended in part from the reflector to the adjacent anode end along the magnetic field. This was associated also with a cathode to reflector center path. Figure 5 shows a reflector shield successfully employed. This development followed considerations similar to those of the

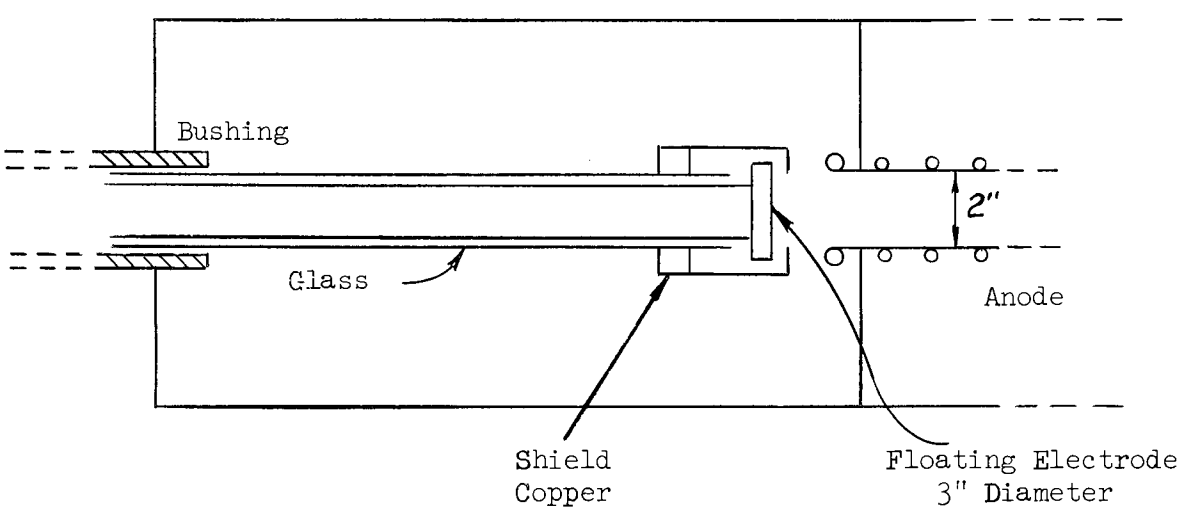

Fig. 5 SINGLE REFLECTOR SHIELD

cathode. With shielding of both cathode and reflector steady operation then became possible over a range of current, limited by extinction at small current and cooling conditions at large current.

Multiple Shields

Lack of complete isolation of the regions separated by the cathode shield of Fig. 4 was indicated by the behavior with a second plane shield shown in Fig. 6. With this second shield breakdown occurred while without

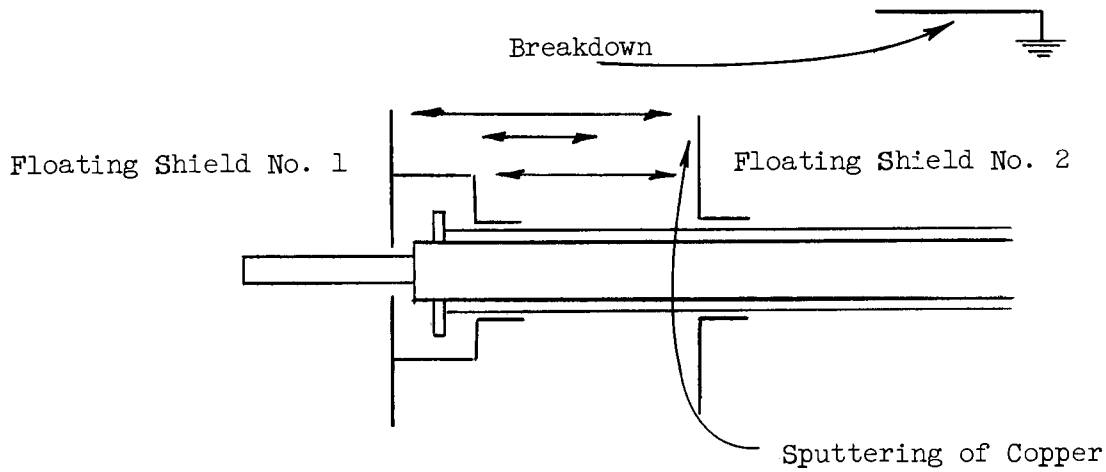

Fig. 6 BREAKDOWN CAUSED BY FLOATING SHIELD

it none could be attained. In this case coupling of the regions likely occurred around the outer edge of the first shield. This is supported by behavior of a second shield enclosing the first, as shown in Fig. 7, which

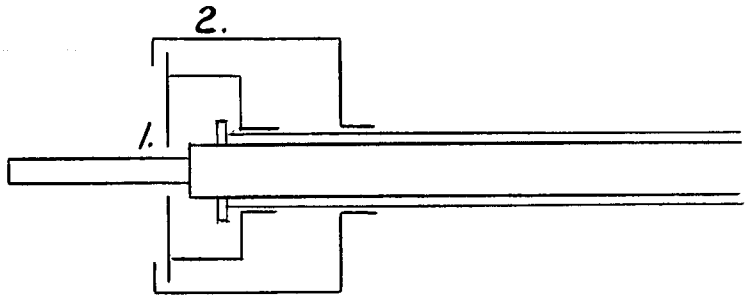

Fig. 7 DRAIN-TYPE DOUBLE SHIELD

showed no breakdown tendency. With this arrangement of two shields, and with argon entering near the cathode end of the system instead of through the cathode, no discharge could be obtained until a pressure of 20μ was reached. At this pressure and at a starting potential of 750 volts the discharge struck between the cathode and a limited nearby region of the anode. This would seem to be an essential test for electrode shielding for more severe conditions.

Multiple shielding would appear to offer the distribution of DC potentials across the magnetic field; for example, over a large radial space in a manner not attainable by a continuous conducting surface, an insulating surface, or simple combinations. Such a suggested schematic set of end shields is shown in Fig. 8 for a negative central electrode in

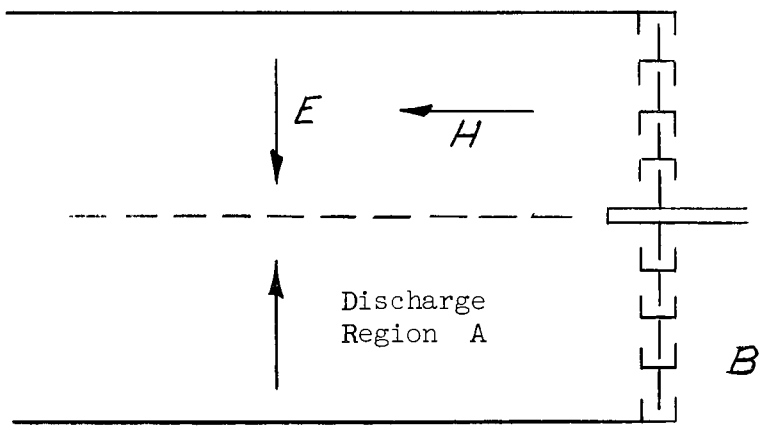

Fig. 8 SCHEMATIC END SHIELDS FOR RADIAL POTENTIAL DISTRIBUTION

coaxial geometry. Each shield zone in Fig. 8 should assume a potential determined mainly by the discharge in a corresponding cylindrical shell in region A. Conduction between zones should be small compared to that in the discharge region between discharge shells. Finally, electron feeding

through effects between region A and a conducting surface in region B should be minimized. One objective of the distribution of potential across the magnetic field would be the study of plasma and ion energy associated with initial lower conductivity across the magnetic field. This cannot be achieved with free streaming to conducting end walls, a condition likely to dominate, and by which the diffusion of low energy plasmas across the magnetic field has been shown to be largely determined.[4] This is because of the anisotropic conductivity with the much higher conductivity along magnetic lines and free streaming to conducting ends. With free streaming the conductivity in any direction is likely determined by that along the field. Multiple shielding suggested in Fig. 8 should offer a way toward freedom from end streaming and thus a study of the plasma in relation to its conductivity across the magnetic field.

Some Gas Arc Characteristics, Anode Breakdown

During the shield development attempts were made to obtain some arc conduction characteristics by measurements of current and potential at constant pressure. Uncontrolled pressure changes made this difficult near breakdown. Undetected changes in vapor pressure contribution were likely of influence. A few measurements were made before new breakdown aspects became apparent.

Figure 9A shows a characteristic at constant gauge pressure obtained with the cathode support enclosed in vicor glass as previously mentioned and while in the process of progressive failure. The cyclic behavior would seem to be likely associated with vapor changes due to current and heating changes. Figure 9B shows a similar positive slope which also increases as the current increases. For this case the shielding was improved but not in

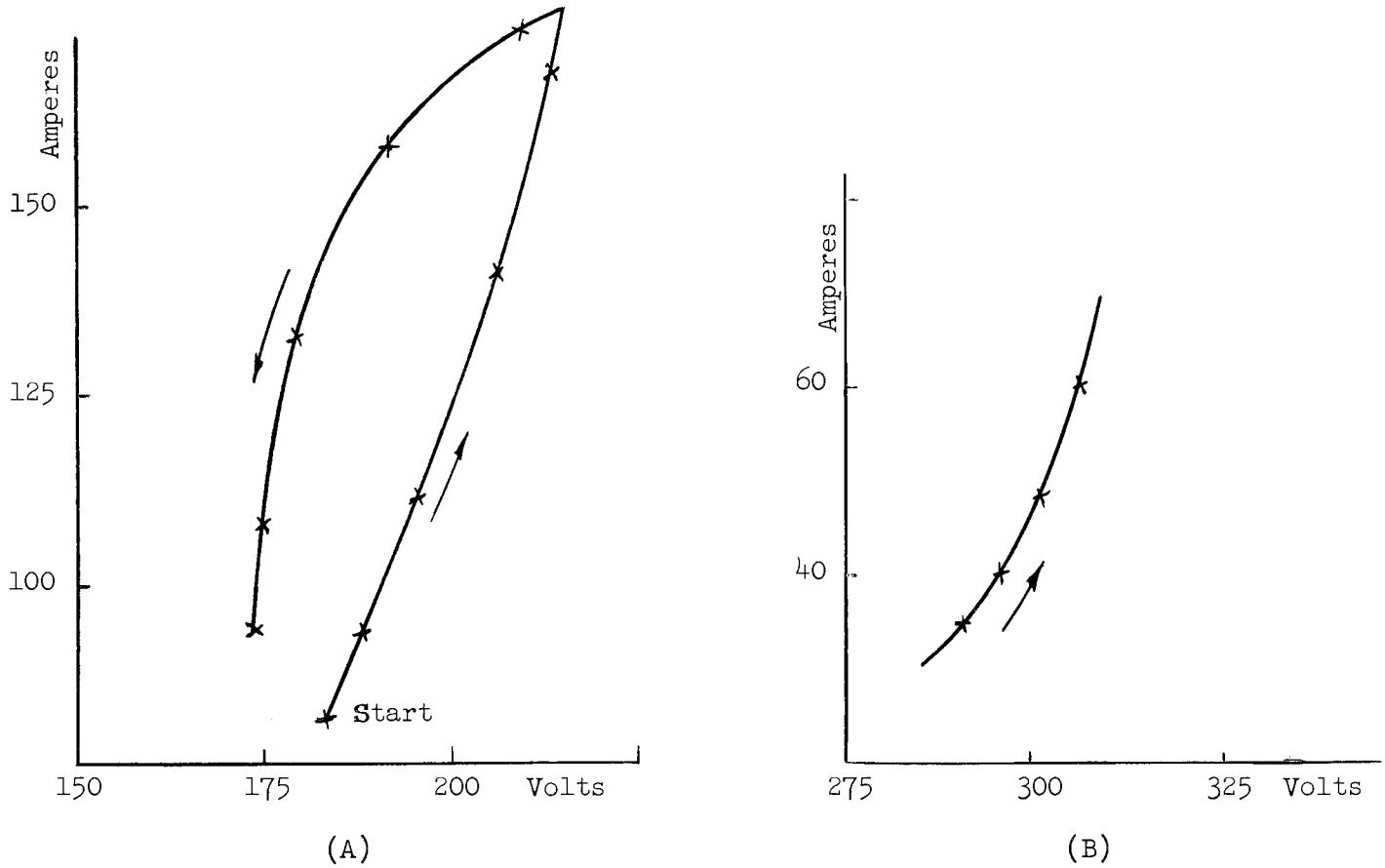

Fig. 9 CONDUCTION CHARACTERISTICS IN ARGON AT CONSTANT GAUGE PRESSURE

(A) $p \sim 3 \times 10^{-4}$ mm, .25 ID Cathode, Known Failure in Development.

(B) $p \sim 3 \times 10^{-5}$ mm, .5 ID Cathode, Arrows Show Order of Measurements Obtained in Rapid Changes of Welder Settings.

the final situation. However, it seems less likely that vaporization due to shielding failure was involved in this measurement. No measurements of arc characteristics were obtained for the optimum shielding conditions since anode breakdown then was found and the proximity to breakdown appeared likely of influence on the characteristic. However, the rising characteristic is similar to other measurements obtained for small PIG discharges.[5] Figure 10 shows a power supply characteristic for five welder units in series and control settings at maximum for an argon arc acting a variable load and operated over the pressure range from 2×10^{-5} to 3×10^{-4} mm Hg.

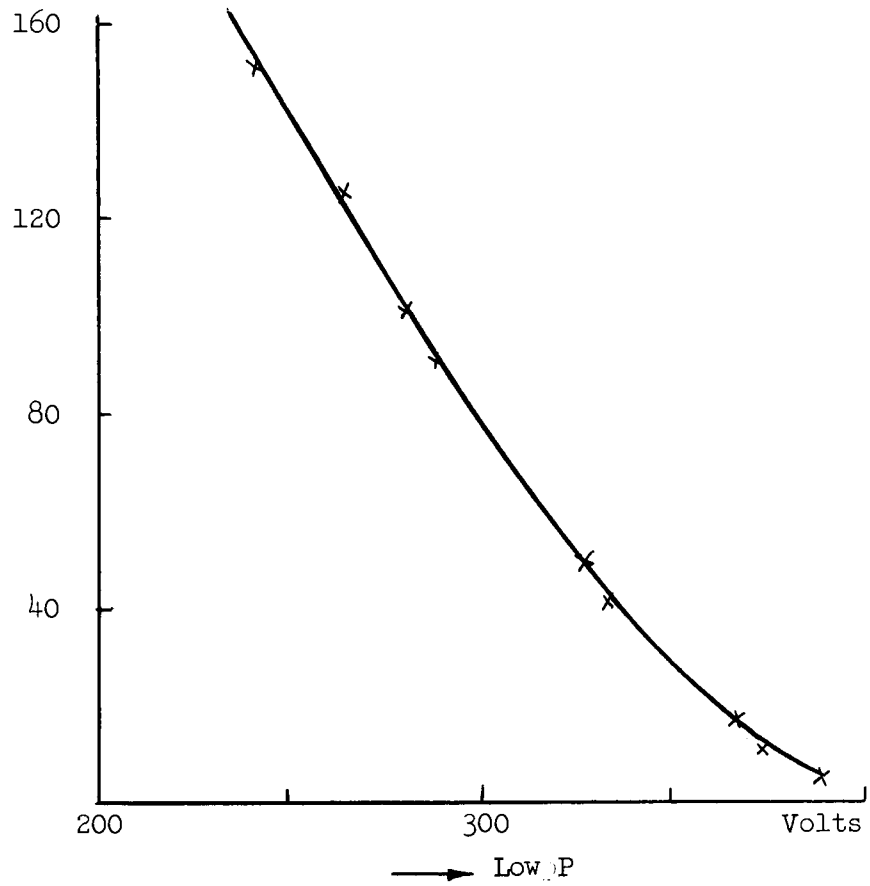

Fig. 10 ARC CURRENT AND VOLTAGE AVAILABLE FROM FIVE SERIES WELDERS FOR ARGON ARC, PRESSURE RANGE 2×10^{-5} mm TO 3×10^{-4} mm.

With suitable shielding at the cathode and reflector it became possible to operate the gas arcs over extended periods and transfer from argon to other gases. With a power supply of ten welder units in use breakdown with argon was again encountered, but not of the nature of a shield failure. This breakdown occurred in the course of reducing pressure and current after initiating an arc. The rapid onset and extensive damage to the anode did not allow close determinations of the breakdown conditions.

Repeated examinations of the electrodes for several anode failures showed only a local melted spot on the anode at its end adjacent to the reflector. No corresponding spot was found as in the case discussed for

the reflector failure. As an indication of electrode alignment and failure spot origin, the discharge was operated below breakdown and the reflector was suddenly grounded by a switch for a period comparable to the failure duration. The reflector was then found to have a melted spot located on the center and of approximately the same damage extent as the failure spot in the anode of the same material.

The anode failure made it appear that the argon discharge was limited by a discharge condition which developed at high voltage and fairly high current. For this condition the current concentrated at a region on the anode end remote from the cathode in a manner suggesting that a considerable electron stream was able to pass directly from the cathode to the far anode region and across the magnetic field. Such an electron stream would be expected to cause intermittent effects. It is likely associated with the development of oscillating electric fields about the discharge axis, such as observed[6] for another discharge having some possible similarity. Oscilloscope observations on the reflector electrode showed potential variations of the order of 100 volts during operation with principle frequencies in the region of 100 KC. Radial drifting of electrons would occur for suitable components of the oscillating electric fields if they were present, and the direct crossing of a long anode would be favored over a short anode. A test with a short tungsten anode 12 inches in length and placed near the cathode with reflector unchanged showed no difference in starting behavior in argon. The conductance of the discharge decreased by a factor of about 10. No breakdown occurred and lack of cooling allowed a short duration.

Helium and deuterium arcs were difficult to run without gradual extinction. They required higher pressures and potentials, and current

drain. The discharges were initiated in argon after which a transfer was made to helium or deuterium. An RF welding starter was used in parallel with the arc supply on initiation. An increase of potential during operation with helium showed an increase of ionization from relative spectrum measurements. For deuterium minimum conditions of operations were 50 amperes and 400 volts at a pressure of 4.6×10^{-4} mm. In view of anode difficulties with argon the direction indicated toward higher voltage and lower pressure did not seem feasible without major electrode changes requiring additional radial space and additional power.

CONCLUSIONS

1. In the intense magnetic field plane shields for gas discharge electrodes become ineffective above some pressure-voltage limit and fail to separate discharge regions effectively by failure to distribute potentials.

2. Multiple plane shields show essentially the same limitations with a single overall discharge failure enveloping shield edges and with such a failure probably comprised of portions which both cross the magnetic field and travel along it.

3. The most effective step in electrode shielding is that which traps and removes electrons which attempt to pass around the shield edges and apertures. This can be accomplished by forming a cavity at the shield edge and perpendicular to the magnetic field and into which electrons are obliged to enter and drain.

This enables a shield to divide more effectively the discharge regions and thus divide potentials.

4. In a long gas arc of limited radial space and with the discharge across the magnetic field, an anode breakdown appears to provide a limit of operation unrelated to shielding of the electrodes. At some intense operation the anode fails at a spot in such a way as to seemingly provide the maximum distance to the cathode from the breakdown spot. The PIG arc appears to develop a mechanism for the concentrated discharge of electrons across the magnetic field.

5. The discharge conduction characteristics are likely influenced by proximity to electrode failures.

6. Breakdown tests of electrodes and shields over a range of uniform pressures within a system are feasible, and it is possible to have the initial discharge take place between the desired electrodes.

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