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CURRENT DISTRIBUTION TO A PLANE SHIELDED
CATHODE IN THE ABNORMAL GLOW DISCHARGE

by

J. R. Mullaly

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IN NUCLEAR SCIENCE ABSTRACTS

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CONTENTS

	Page No.
Abstract.....	iv
Introduction.....	1
Summary and Conclusions.....	1
Experimental.....	2
Apparatus.....	2
Procedure.....	2
Results and Discussion.....	3
Effect of Discharge Parameters on Current Distribution.....	3
Discharge Voltage.....	3
Cathode Shield.....	3
Anode Parallel to the Cathode.....	4
Longitudinal Magnetic Field.....	4
Comparison of Cathode Metal Removal with Current Distribution.....	4
Illustrations.....	7
Appendix A.....	13
Appendix B.....	15
Magnetic Field.....	15
Total Discharge Current Increase with Magnetic Field.....	15

ABSTRACT

The distribution of current over the surface of a plane shielded cathode in the abnormal glow discharge was determined for different values of voltage, pressure, anode-cathode spacing, and magnetic field. All work was done with argon at pressures of 30 microns or lower in a 12-inch diameter Pyrex glass bell jar. Metal removal is compared with current distribution. Two appendices are given; one briefly reviews abnormal glow discharge and the other gives total discharge current increase as a function of magnetic field strength.

INTRODUCTION

The purpose of the experiments described in this report was to determine the effect of a cathode shield, anode-cathode spacing, voltage, pressure, and magnetic field on the radial distribution of current to a flat cathode in the abnormal glow discharge. The current measured was the total current, i.e., ion plus secondary electron current.

The geometry used (Figure 1) was one that has been used in this laboratory for cleaning metal coupons and by others⁽¹⁻²⁾ for metal deposition. The usefulness of this geometry is that the discharge to the cathode edge is completely suppressed by the shield. When thin films are to be sputtered from a metal placed on the cathode the undesirable metal from the cathode edge will be sputtered and eventually diffused to the substrate. Cathode heatup is also minimized since the discharge is established to only one side of the cathode.

This geometry can be quite different from the geometry of two flat electrodes in a glass cylinder on which the electric field and current distribution measurements have been reported. The difference of the geometry is in the electric field that exists at the cathode edge. In this experiment the ground potential shield is used and the full discharge is dropped across the cathode-shield spacing. This is several times larger than the field existing in front of central portions of the cathode where most of the discharge voltage is dropped across the length of the cathode dark space.⁽³⁾ (The length of the cathode dark space at 22.5 microns and 1800 volts has been observed in these experiments to be about 2 inches.) In the glass system the wall potential may vary from a few volts negative to several hundred volts negative (for argon). The wall potential is pressure dependent and is more negative at lower pressures. In addition, as the glass wall becomes coated with sputtered metal, the distribution of potential on the wall can change from that for an uncoated wall.

The influence of this strong edge field on current to the cathode is indirectly shown by the erosion of the cathode used by Altman.⁽¹⁾ He measured approximately twice as much metal removed just inside the cathode edge as from the middle of the cathode. This difference in metal removal was attributed to at least twice as much current striking the cathode edge as the center.

Further evidence of a complicated current distribution for this geometry is given by Blevis⁽²⁾ in a report on metal deposition on substrates at various distances from the cathode. Metal is evenly deposited only when the substrate is just outside the cathode dark space.

Measurements of current were made by a new technique described in the experimental part of this report. This technique, although not having the resolution of moving collector methods,⁽⁴⁻⁵⁾ is amenable to non-planar cathodes. No reference to this method has been found in the literature.

Two appendices are given with this report. The first appendix (Appendix A) is intended as a brief review for readers unfamiliar with the abnormal glow discharge. The second appendix (Appendix B) contains the details of the magnetic field used in this work and sets of curves on total discharge-current increase with the magnetic field. The curves are included to demonstrate what is vaguely stated in the literature, i.e., statements have been made to the effect that a longitudinal magnetic field increases total current by *several* times, but very little data are presented to substantiate these statements.

Throughout this report the word discharge will mean abnormal glow discharge.

SUMMARY AND CONCLUSIONS

The radial current distribution over the surface of a plane shielded cathode was measured as a function of discharge voltage, pressure, and anode-cathode spacing. Data without the shield were also taken to determine its effect. A magnetic field was used to obtain information about the direction of secondary electrons leaving the cathode at its edge.

Results of the experimental work are summarized below. These results apply only to the geometry reported and should not be generalized. Possible causes for these results are discussed in the Results and Discussion section of this report.

- Discharge voltage was found to have no effect on the current distribution. It only intensified current uniformly across the cathode.
- The ground potential shield suppressed the current at the edge of the cathode face. The suppression was more severe at lower pressure.

(1) Altman, C., *Proc. American Vacuum Society*, 174-9 (1961).

(2) Blevis, E. H., *Glow Discharge Sputtering - Theory and Practice*, Distributed by R. D. Mathis Company, 1345 Gaylord Street, Long Beach, California 90813 (February 1964).

(3) von Engel, A., *Ionized Gases*, 2nd Ed., Oxford University Press, 1965.

(4) Blevis, E. H., *loc. cit.*, p 1.

(4) Chaudhri, R. M., and Baqui, M. A., *Proc. Phys. Soc. B65*, 324-8 (1952).

(5) Chiplonkar, V. T., and Joshi, S. N., *Physica* 30, 1746-56 (September 1964).

- A plane anode parallel to the cathode did not substantially change the current distribution from the no-anode case until the anode penetrated the cathode dark space. The current distribution then exhibits a maximum at the cathode edge.
- Data obtained with a magnetic field perpendicular to the cathode face tend to substantiate the thought that secondary electrons from the cathode edge are accelerated toward the cathode shield, but the data are not conclusive.
- Neglecting edge effects, a longitudinal magnetic field may be used to increase discharge current density by several times.

EXPERIMENTAL

APPARATUS

The discharge system used is shown in Figure 1. The shield was 1/16 inch higher than the cathode. Other dimensions are also given in Figure 1.

Vacuum was obtained with a Varian Associates 140 l/sec VacIon pump and a liquid nitrogen cooled VacSorb pump. Pressure during the discharge was measured by a thermocouple gauge calibrated for argon.

A precision voltage divider, Fluke Model 80B, was used to measure voltage directly between the cathode and ground. Both current and voltage were measured with ± 1 percent, or better, meters.

The discharge voltage was supplied by a single-phase; full-wave rectified, unregulated and unfiltered d-c power supply.

All work was done with Matheson research grade argon.

Coupons were weighed before and after sputtering on an Ainsworth Model BCT balance.

The magnetic field was produced by a solenoid, 13 inches inside diameter and 12 inches long, placed over the bell jar. The cathode face was in the mid-plane of the solenoid. Details on the field produced in this solenoid are given in Appendix B.

PROCEDURE

After each opening to the atmosphere (system vented with dry nitrogen) and before each day's work, the system was pumped to the 10^{-6} torr range. A freshly baked VacSorb pump was used to maintain the desired discharge pressure while argon was leaked into the system.

After pumpdown from atmosphere and before any current measurements were made, the discharge was run until the current reached a steady value at 22.5 microns at constant voltage. This value was always lower than the initial discharge current. This lower current may correspond to a lower secondary electron coefficient (electron/incident ion) for aluminum rather than for aluminum oxide and consequently be an indication of a reasonably clean cathode. Although values of the secondary electron coefficient for aluminum oxide are not given in the literature, Holland⁽⁶⁾ cites work on magnesium where the coefficient dropped from 1.88 to 0.37 as the oxide layer was removed, and states that a similar effect would occur with aluminum.

Current was measured at six points from the center to the edge of the cathode. Mechanics of the current measurement technique are shown in Figure 2. Each aluminum cylinder (plug) is the same size, is insulated from the cathode, and is at the cathode potential. Opening S1 (normally closed) and closing S2 (normally open) allowed the current to the desired plug to be measured with milliammeter M1.

Cathode metal removal was determined by weighing three copper coupons, 5/16-inch diameter by 1/16-inch thick, before and after sputtering. The coupons were placed on a radius at 7/8, 1-3/8, and 1-25/32 inches from the cathode center. All work was done at 22.5 microns and 1700 volts. No coupon was placed at the center of the cathode because the current measuring plug is there. The solenoid mid-plane was 3 inches above the cathode face for data obtained with the magnetic field. Most measurements were made with a cathode temperature of 90°C. No temperature effect could be found on the distribution from room temperature to 200°C. When the discharge was run without an anode parallel to the cathode (for brevity, called no-anode case) all parts in the vacuum system at ground potential served as the anode (see Figure 1).

Except where the voltage is specified, each curve referred to in the Results and Discussion section of this report has been drawn through points averaged from several voltages. In addition, all current distribution data (except for Figure 3) have been normalized by dividing each point by the magnitude of the current to the center plug. This gives all curves a starting point of 1.0 but does not change the shape of the curve. Data points have not been placed on the curves, but their position can be found by moving vertically from the arrows on the abscissa to the curve. Each curve has been drawn free-hand through data points and represents the author's judgement. The curves have not been mathematically made to "fit" the data.

(6) Holland, L., *Vacuum Deposition of Thin Films*, New York, John Wiley and Sons, Inc., 1961.

The magnitude of the current to each plug will not be given as it has no bearing on the objective of this work, i.e., to determine the current profile across the cathode. These values are not needed to reproduce this work and will vary with metal species, anode-cathode spacing, surface finish and surface contaminants. As an example of the magnitudes involved, at 22.5 microns, total discharge current was approximately 4 milliamperes (to the 4-inch cathode) and current to the center plug approximately 0.0030 milliampere. These currents, of course, increased with increasing pressure and voltage.

On the metal removal experiments, typical sputtering times were 6 hours without the magnetic field and 1-1/2 hours with the magnetic field. Total weight of copper removed from each coupon was approximately 0.0010 gram. Since only a comparison of the metal removed at the edge with the metal removed at the center of the cathode is desired, all weight data are not reported.

RESULTS AND DISCUSSION

EFFECT OF DISCHARGE PARAMETERS ON CURRENT DISTRIBUTION

Discharge Voltage

The discharge voltage (1600 to 2400 volts) was found to have no effect on the current distribution for any combination of pressure, electrode spacing, or magnetic field used. The only action of increasing the voltage was to uniformly intensify the current over the surface. Typical data are shown in Figure 3. This uniform intensification of current with increasing voltage has also been found by Chaudhri and Baqui⁽⁴⁾ for pressures of 22 to 50 microns (air) and 1250 to 1800 volts. The cathode that they used was a 3.98-cm diameter brass piece in a close-fitting glass tube.

A significant feature of the data given in Figure 3 is that an increase in the voltage will only slightly increase the current at the cathode edge. This has also been found by Chaudhri and Baqui.⁽⁴⁾ However, Chiplonkar and Joshi⁽⁵⁾ found a large voltage-effect on hydrogen ion current at the edge of the cathode. Their geometry was very similar to Chaudhri and Baqui and consisted of a 5.8-cm diameter aluminum disk in a close-fitting glass cylinder. At 33 microns they measured no hydrogen ion current beyond 0.8 cm from the cathode center. But at 1800 volts the hydrogen ion current could be measured at 1.6 cm from the center and the current at 0.8 cm had increased at least 100 times from the just measurable value at 920 volts.

They show that the shape of the ion current distribution curves is because of the ion loss to the walls of the discharge tube.

This large difference in the effect of voltage on current at the cathode edge cannot be explained as being due to measuring ion current versus total current. Both papers argue that the radial distribution of total current will be proportional to the radial distribution of ion current. The only apparent difference in the experiments was the use of H_2 versus air. And, since the drift velocity of H_2^+ in H_2 may be five or more times as great as the drift velocity of A^+ in A , N_2^+ in air, or O_2^+ in air,⁽⁷⁾ wall charges in each experiment may have been entirely different.

In view of the preceding information, it is not unreasonable to expect a voltage effect on the current distribution if light gases, i.e., He or H_2 , were used with the geometry under discussion.

Cathode Shield

As can be seen in Figures 4 and 5 the ground potential shield suppresses current at the cathode edge. The lower the pressure the greater the suppression. This suppression is visible as a region of no discharge.

The extent of the suppression is shown in Figure 6 and it can be seen that the width of the no-discharge zone at the cathode edge decreases rapidly and non-linearly with pressure. Data for Figure 6 were obtained from another series of experiments with slightly different geometry. The cathode was 1/8 inch away from the shield and 1/8 inch higher (instead of being 1/4 inch away and 1/16 inch lower) than the shield. The point labeled 1 was taken from the series of experiments under discussion. Point 2 was taken from Altman's paper⁽¹⁾ and has been arbitrarily placed since he specified no pressure for his 1/8-inch suppression. However, he worked in the 21-45 micron range. The top of his shield was in the same plane as a tantalum cathode and was 1/8 inch away from the cathode.

After several hours of sputtering at constant pressure (and at a lower pressure than the previous experiment), the no-discharge zone always appeared darker in color than the rest of the cathode. The zone also had a very definite edge. A copper coupon was placed on the cathode (at 22.5 microns) so that one-half of the coupon was in the discharge and one-half in the no-discharge zone. The one-half of the coupon in the suppressed

(4) Chaudhri, R. M., *loc. cit.*, p 1.

(5) Chiplonkar, V. T., *loc. cit.*, p 1.

(7) Loeb, L. B., *Basic Processes of Gaseous Electronics*, 2nd Ed., Berkeley and Los Angeles, University of California Press, 1961.

(1) Altman, G., *loc. cit.*, p 1.

zone was coated with aluminum. Deposition of sputtered metal was also found by Stein⁽⁸⁾ who used a 5.8-cm diameter Dural cathode surrounded by a 6-cm diameter glass cylinder. He found a grey deposit of sputtered material 6 mm wide at the cathode edge.

Anode Parallel to the Cathode

Figures 7, 8, and 9 show the variation of current distribution for anode-cathode spacings of 5 inches, 2-1/2 inches, and 1-1/4 inches respectively. No distribution could be measured for the 2-1/2 inch separation at 10 microns or for the 1-1/4 inch separation at 16 and 10 microns due to the very small currents involved.

These data show that the anode does not appreciably change the current distribution from the no-anode case at the 5-inch separation. At 16 microns and 2-1/2 inch separation the distribution shows the current starting to peak, and at 1-1/4 inch separation and 22.5 microns the distribution shows a large maximum.

At 1-1/4 inches from the cathode, the anode is well within the visual cathode dark space and the discharge is probably being maintained by ions coming in from the region outside the space which is between the anode and the cathode.

The current distribution at the 1-1/4 inch separation should be compared with Figure 9 of Blevis' paper⁽²⁾ on sputter deposition of films. He shows that the deposit on a substrate that is placed a short distance into the cathode dark space is "annular in nature with a maximum thickness on a circle slightly smaller than the target (cathode)."

Longitudinal Magnetic Field

The effect of a longitudinal (field perpendicular to cathode face) magnetic field on the discharge has been described by Kay.⁽⁹⁾ In general, electrons and ions in the cathode dark space will be only slightly affected by a longitudinal magnetic field because in this region they are moving parallel to the magnetic field. But in the negative glow region the radially scattered electrons and ions will be spiraled around magnetic field lines. This should produce a small increase in current and keep the charged particles from desorbing impurities from vacuum system walls.

Data on the above effects have been given by Chiplonkar and Joshi⁽⁵⁾ at 250 microns where a longitudinal

magnetic field was used to reduce ion loss to the glass cylinder surrounding the cathode.

However, with the strong electric field that exists between the shield and cathode edge in the geometry under discussion, it is very likely that, at the edge, secondary electrons are accelerated toward the shield at an angle to the cathode normal. If this is so, a longitudinal magnetic field should cause these electrons to spiral around magnetic field lines. This would increase the electron path length and consequently increase ionization which would give an increase in current to the cathode edge.

The increase in current across the cathode, which is caused by the magnetic field, is shown in Figures 10 through 13. Although the curves on Figures 10 through 12 show a larger current increase at the cathode edge than at the center, the situation is obviously more complicated than the simple discussion presented in the preceding paragraph. The maximum in the current at 10 microns on both figures has no ready explanation. If additional data points could have been taken between the last point on each curve and the cathode edge, this maximum might have been observed on each curve. Figure 13 shows the increase (at 22 microns, 1-1/4 inch separation) when the anode is in the cathode dark space. Again, no ready explanation can be given.

It should be noted that, as indicated on the figures, the above curves were not all obtained at the same magnetic field. (The magnetic field is given in amperes and the conversion to gauss for this solenoid is given in Appendix B.) They were obtained at the magnetic field that gave the maximum increase in total current. For the cases where total current did not reach a maximum with increase in field, the increase at 6 amperes was chosen. The relationship between the total current increase with the magnetic field is shown in Appendix B.

COMPARISON OF CATHODE METAL REMOVAL WITH CURRENT DISTRIBUTION

Results of metal removal determinations are shown on Figures 14 and 15. Data have been normalized to make possible a direct comparison between distribution of current and the metal removal. Data scaled from Figure 2 of Altman's paper⁽¹⁾ and normalized have been included on Figure 14 to show the generality of this edge effect with this type geometry. Exact agreement with Altman's data cannot be expected since he used a slightly different geometry and operated over a range of pressures.

(8) Stein, R. P., *Physical Review* 89, 134-42 (January 1953).

(2) Blevis, E. H., *loc. cit.*, p 1.

(9) Kay, E., *J. Appl. Phys.* 34, 760-8 (April 1963).

(5) Chiplonkar, V. T., *loc. cit.*, p 1.

(1) Altman, C., *loc. cit.*, p 1.

Although metal removal does not correspond exactly to the current distribution, the agreement is close enough for practical purposes. That is, current measurements should allow prediction of metal removal. The agreement of the magnetic field data does not appear to be as satisfactory as the agreement for the no-field case.

Additional data are needed before more information can be presented on this relationship. However, comparison of Figures 14 and 15 shows that a magnetic field can be used to control the metal removal near the cathode edge.

The reason for making a comparison between metal removal and current distribution is a practical one. That is, when cleaning metal in the discharge area it is desirable to have fairly even metal removal from the surface. Determining discharge parameters for this even removal can be a lengthy process. The technique of placing coupons at intervals on a surface and weighing the coupons before and after sputtering requires long sputter times at constant discharge conditions.

Current measurements, though, can be made rapidly and easily and, as seen in Figure 14, do relate to metal removal. This is one case only and should not be generalized to other geometries for reasons given in the following discussion.

The use of current as a test for metal removal is based on ions comprising the same fraction of the current at all parts of the surface. For example, if twice as much current is measured at the cathode edge as at the center, then it is reasonable to expect twice as many ions at the edge as at the center and consequently twice as much metal removed at the edge. However, if ion energy, ion angle of incidence, and metal return (see Appendix A) are not the same at all points on the surface, then metal removal might not be based on the current. For example, an ion striking the surface at 45° may remove twice as much metal as an ion incident at 90° , but still contribute only one charge to the measured current.

illustrations

- A Anode, 4-inch diameter aluminum, ground potential
- B Shield, stainless steel, 4.5 ID, 1/8-inch thick, ground potential
- C Cathode, 4-inch diameter aluminum
- D Current measuring plugs
- E Ceramic support
- F Support plate, ground potential
- G Plate supports, ceramic standoff
- H Pyrex bell jar, 12 inches ID by 18 inches high
- J VacSorb pump port
- K Vacuum system base, ground potential
- L To VacIon pump
- M Thermocouple vacuum gauge
- N Solenoid

Figure 1. SCHEMATIC OF DISCHARGE CHAMBER (not to scale)

Figure 2. CATHODE CROSS SECTION (not to scale). Plug location and electrical hookup

Figure 3. CURRENT DISTRIBUTION AS A FUNCTION OF VOLTAGE (22.5μ , 2.5-inch anode-cathode separation)

Figure 4. CURRENT DISTRIBUTION AS A FUNCTION OF PRESSURE (with shield, no anode)

Figure 5. CURRENT DISTRIBUTION AS A FUNCTION OF PRESSURE (no shield, no anode)

Figure 6. VARIATION OF WIDTH OF NO-DISCHARGE ZONE WITH PRESSURE

Figure 7. CURRENT DISTRIBUTION AS A FUNCTION OF PRESSURE (5-inch anode-cathode separation, with shield)

Figure 8. CURRENT DISTRIBUTION AS A FUNCTION OF PRESSURE (2.5-inch anode-cathode separation, with shield)

Figure 9. CURRENT DISTRIBUTION AT 22.5μ
(1.25-inch separation, with shield)

Figure 10. INCREASE IN CURRENT WITH MAGNETIC
FIELD (with shield, no anode)

Figure 11. INCREASE IN CURRENT WITH MAGNETIC
FIELD (with shield, 5-inch anode-cathode
separation)

Figure 12. INCREASE IN CURRENT WITH MAGNETIC
FIELD (with shield, 2.5-inch anode-cathode
separation)

Figure 13. INCREASE IN CURRENT WITH MAGNETIC FIELD AT 22.5μ , 1 AMP (with shield, 1.25-inch anode-cathode separation)

Figure 14. COMPARISON OF CURRENT AND METAL-REMOVAL DISTRIBUTION (with shield, 5-inch anode-cathode separation, 1700 volts, 22.5μ)

Figure 15. COMPARISON OF CURRENT AND METAL-REMOVAL DISTRIBUTION WITH MAGNETIC FIELD (with shield, 5-inch anode-cathode separation, 1700 volts, 22.5μ)

APPENDIX A

The abnormal glow discharge is a discharge in which a current increase is accompanied by an increase in voltage. This is in contrast to the normal glow discharge where voltage remains constant as current is increased. In large bell jar discharge systems, the normal glow discharge can be observed at several hundred microns pressure, but the normal glow discharge cannot be observed easily at the low pressures used for the experiment described in this report.

The visible regions of the low pressure abnormal glow discharge are shown in Figure A1. The regions shown are the ones that are easily visible. The physical phenomena causing these zones are complex and are explained, in general, in the literature reviews for the glow discharge.^(3,10-11)

A practical problem is the determination of the origin of ions in the glow discharge. Such information is useful when determining substrate holder positions. Relative contributions of the cathode dark space and negative glow regions to the ion current have not been precisely determined for the low pressure abnormal

glow discharge. In general, as an anode is moved closer to the cathode (at constant voltage and pressure) the current diminishes. When the anode reaches the edge of the cathode dark space, the current falls to a low value. This indicates that a large share of the discharge current originates in the negative glow region.

The first theoretical work on the problem of where ions originate in the abnormal glow discharge was apparently done by Druyvesteyn and Penning.⁽¹¹⁾ They calculated that almost all the ions reaching the cathode must have originated in the negative glow. Warren⁽¹²⁾ found that a theory based on most of the ionization taking place in the cathode edge of the negative glow agreed well with his electric field measurements down to about 100 microns. Below this pressure an increased ionization in the cathode dark space could be expected from electrons freed when high energy ions ionize neutral gas atoms. The validity of this last sentence has been demonstrated by Kay⁽⁹⁾ with a movable quadrupole magnetic field. His data show that, while most ionizing collisions by electrons take place well-outside the cathode dark space, a significant current increase occurs in the cathode dark space. He used a 4-1/2 inch diameter shielded aluminum cathode with argon at 32 microns.

(3) von Engel, A., *loc. cit.*, p 1.

(10) Francis, G., *Encyclopedia of Physics* 22, Berlin, Springer-Verlag, 1956, pp 53-208.

(11) Druyvesteyn, M. J., and Penning, F. M., *Rev. Mod. Phys.* 12, 87-174 (April 1940).

(11) Druyvesteyn, M. J., *loc. cit.*, p 7.

(12) Warren, R., *Physical Review* 98, 1658-64 (June 1955).

(9) Kay, E., *loc. cit.*, p 4.

Figure A1. VISIBLE REGIONS OF LOW PRESSURE ABNORMAL GLOW DISCHARGE

A different thought on the importance of the negative glow has been advanced by von Engel.⁽³⁾ He suggested that the negative glow acts as an intense source of ultraviolet light which would increase (by photoemission) the number of secondary electrons leaving the cathode and subsequently increase the ionization.

Phenomena at the cathode surface are as unresolved as those mentioned for the origin of the ions. An ion striking the cathode surface removes (sputters) metal atoms and causes electrons to be released. The number of atoms released for each incident ion (yield) depends on the energy of the ion and the angle at which the ion strikes the surface. The number of electrons released depends on the angle of incidence of the ion, and in a complicated way, on ion energy. The electron release mechanism (potential versus kinetic) is energy dependent. These data have been determined by using ion beams at low pressures. They are assumed, in principle, to apply for the higher pressures used in discharge work.

(3) von Engel, A., *loc. cit.*, p 1.

In general, neither ion energy or ion angle of incidence is known for the low pressure abnormal glow discharge. Ion energies probably have a Maxwellian distribution with a shift toward higher energies as discharge pressure is lowered. Ion angles of incidence probably have a similar distribution with a shift to normal incidence (perpendicular to the cathode surface) with decreased pressures.

An additional feature, which is also pressure dependent, is the return of sputtered metal to the cathode. This feature has been shown⁽¹³⁾ to make calculation of yield a virtual impossibility.

Problems of gas penetration of the cathode surface, removal rates of different surface contaminants (oxides, etc.), and surface damage in the abnormal glow discharge, are largely unresolved and have not been subjected to systematic study under carefully controlled conditions.

(13) Ecker, G., and Emeleus, K. G., *Proc. Phys. Soc. B67*, 546-52 (1954).

APPENDIX B

MAGNETIC FIELD

The magnetic field, from 0 to 6 inches above the cathode, may be calculated using data given in Figures B1 and B2. The magnetic field is the resultant of vectorially adding the longitudinal and traverse components for a corresponding point. Since the data in the figures are given for 1 ampere through the solenoid, the field at any other current is simply a multiple of the field at 1 ampere, e.g., if the resultant field at a particular point is 50 gauss, the field at the same point with 3 amperes through the coil is 150 gauss.

TOTAL DISCHARGE CURRENT INCREASE WITH MAGNETIC FIELD

Increase in total discharge current with magnetic field is given in Figures B3 through B8. Magnetic field is given in terms of current through the solenoid and may be converted to gauss as described in the previous paragraph. The discharge conditions are stated on the figures. Since the increase had at most a very slight dependence on discharge voltage, the curves are the average of data obtained at several voltages.

No explanation of these increases will be attempted beyond that already given in the Discussion part of this report. The difficulty of giving an explanation in terms of particle trajectories is obvious from examining the equations of motion for this geometry. The force on a charged particle in a magnetic and electric field is a function of the electric field, the velocity of the particle, and the magnetic field (gauss). The electric field in the discharge is unknown and is quite different from the static field that can be measured in an electrolytic tank. The only assumption that can be made is that the electric field has no angular component (cylindrical coordinates). Also, the velocities of electrons and ions are unknown.

Unless marked otherwise on the figures, the mid-plane of the solenoid was at the cathode face.

Data points have not been placed on the curves. Each curve has been drawn free-hand through data points. Data were taken at intervals of 0.1 ampere from 0 to 1 ampere; 0.2 ampere from 1 to 2 amperes; at each interval of 0.5 ampere from 2 to 3 amperes; and at each interval of 1 ampere from 3 to 10 amperes.

Figure B1. LONGITUDINAL COMPONENT OF MAGNETIC FIELD (1 ampere)

Figure B2. TRAVERSE COMPONENT OF MAGNETIC FIELD (1 ampere)

Figure B3. INCREASE IN CURRENT WITH MAGNETIC FIELD (no anode)

Figure B4. INCREASE IN CURRENT WITH MAGNETIC FIELD (5-inch anode-cathode separation)

Figure B5. INCREASE IN CURRENT WITH MAGNETIC FIELD (5-inch anode-cathode separation, mid-plane of solenoid 3 inches above cathode face)

Figure B6. INCREASE IN CURRENT WITH MAGNETIC FIELD (5-inch anode-cathode separation, mid-plane of solenoid 6 inches above cathode face)

Figure B7. INCREASE IN CURRENT WITH MAGNETIC FIELD (2.5-inch anode-cathode separation)

Figure B8. INCREASE IN CURRENT WITH MAGNETIC FIELD (1.25-inch anode-cathode separation)