Field Measurements in Glow Discharges with a Refined Electron Beam Probe and Automatic Recording*

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By using a very sensitive and fully automatic magnetically compensated electron beam probe, the design of which is described elsewhere, studies were made of the fields in glow discharges some 40 cm long in a tube 10 cm in diameter with aluminum and copper cathodes at from 0.03 to 1.0 mm Hg pressure with currents ranging from 0.1 to 10 ma in flowing air, nitrogen, hydrogen, helium, and argon which were pure to 99.5 percent, but contaminated by vapors from various stopcock greases, waxes, and clean, but not outgassed, metals. Simultaneously, wall potentials and luminosities of the glows were measured and spectra of the cogent parts of the discharges were observed. Emphasis centered on the fields in the Crooke's dark space for discharge currents ranging upwards from the normal cathode fall region. Some stationary striations were also studied. The high resolving power obtained resulted in details of the dark space fields hitherto unrecognized which are amenable to theoretical interpretations to be given in a subsequent paper. Only the observed results are reported here.

INTRODUCTION AND DESCRIPTION OF THE GLOW DISCHARGES INVESTIGATED

THE development of an automatic field measuring device, described elsewhere,[1] enabled clear-cut and detailed determinations of the fields in glow discharges to be made in such small time intervals that discharge conditions did not change. The consistent and reproducible field strength *versus* position curves over ranges of current and pressure, show characteristic and uniform trends differing radically from the roughly linear variation with position previously reported by Aston,[2] Harris,[3] Geddes,[4] Stein,[5] and Little and von Engel.[6] The field curves for different gases differ mainly in the approximate values of the pressures at which evolutionary changes in the field curves occur. This uniformity enables a considerable consolidation of the data by certain reductions presenting curves amenable to theoretical analysis. It is the purpose of this paper to present the data for the gases studied, reserving theoretical interpretation, in so far as it has gone, for a later paper.

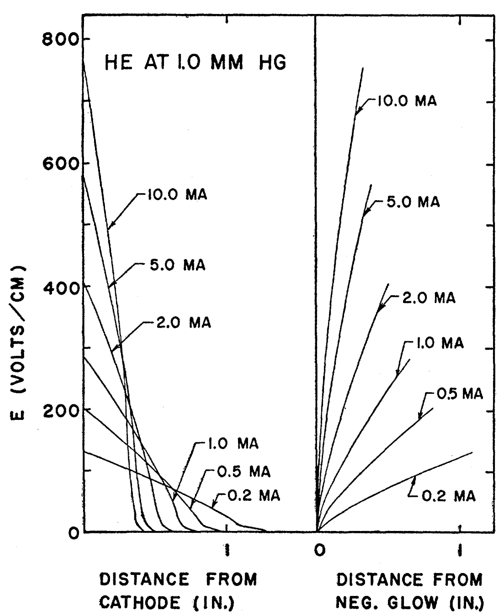

FIG. 1. Cathode fields in helium at a pressure of 1.0 mm Hg.

The discharge electrodes, normally of aluminum, were 40 cm apart, and had a diameter of 10 cm. The probing electron beam could measure fields ranging from 1000 or more volts per cm down to some 0.2 volt per cm. The beam could traverse the total length of the discharge in 40 minutes and the high-field cathode region in a small fraction of this time, the measured axial fields being automatically recorded on a chart together with the wall potentials determined at the same point.

All of the gases used, except air, namely, He, H_2, N_2, and A, were taken from metal cylinders. The indicated impurity content of these gases was less than one-half of one percent. The air was room air, dried and filtered. The gases were passed through a needle valve and then a liquid nitrogen trap before entering the discharge tube. A mercury diffusion pump continually exhausted the discharge tube through another liquid nitrogen trap, so that relatively clean dry gas was continually flowing through the tube. No attempt was made to use purer gases because of the unavoidable presence in the discharge tube of small amounts of vapor from rubber gaskets, sealing waxes, and greases. In the present tube

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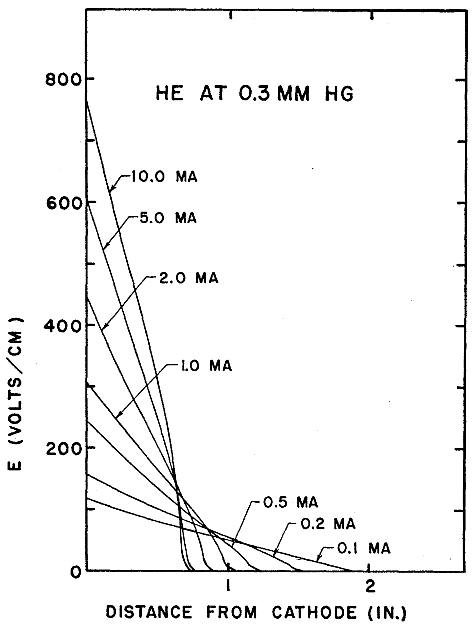

FIG. 2. Cathode fields in helium at a pressure of 0.3 mm Hg.

design, such sealing agents were essential to permit the movement of the electrodes. It is possible that, with great complexity and difficulty, a tube could be constructed using cleaner techniques involving sylphon bellows. Such an improvement, however, would come at a sacrifice of tube length and range of discharge variables effectively nullifying the objectives of this study.

The pressures investigated ranged from 0.03 to 1.0 mm Hg, the exact range depending upon the gas. The discharge power supply was limited to a maximum potential of 2000 volts and/or a maximum current of 10 ma. When decreasing the current from a high value the potential fell, since the discharge was then in the abnormal glow discharge region. Eventually the current reached the threshold value for the normal discharge after which the potential remained constant while the current decreased through a decrease in the diameter of the glow on the cathode, the current density remaining constant. Since field measurements made when the diameter of the discharge is materially less than that of the electrodes, lose their significance, measurements with this technique were carried out only from well into the abnormal region down to the threshold of the normal region, or else at the very lowest, to currents of 0.1 ma. Below currents of 0.1 ma, various difficulties were encountered including among others the gradual accumulation of carbon deposits on the cathode from decomposition of traces of stopcock grease.

It was impossible to measure fields in discharges run at pressures greater than 1.0 mm Hg or so since the spreading of the electron beam became too great. Smaller tube diameters and higher beam energies would permit measurements at higher pressures, but were not of interest in this study. The lower pressure limit corresponded to that pressure for which the tube would barely breakdown under the highest potentials available. The upper and lower pressure limits always differed by a factor of approximately ten. In consequence, when fields near the cathode were measured in this work, each gas was studied at three different pressures. The high pressure value chosen was close to the upper limit; the low pressure value chosen was one tenth of the high pressure, and close to the lower limit, while the intermediate pressure was about half way between. At each pressure, measurements were taken for currents of 10, 5, 2, 1, 0.5, 0.2, and 0.1 ma to the extent allowed by the other conditions of the measurements. In the data presented, all of the curves of field values at different positions taken at a given pressure and various currents were plotted on the same graph.

Results of Field Measurements Near the Cathode

The results of the measurements near the cathode in helium are shown in Figs. 1, 2, and 3. Owing to the newly discovered and revealing sharp downward bend observed in the field curves at the edge of the negative glow, it was found desirable, both in comparing the various curves and in relating the curves to theories to be presented in a later paper, to replot the measured field curves as a function of the distance from the cathode edge of the negative glow instead of the distance from the cathode, as is usually done. The measured fields under the better operating conditions usually dropped fairly sharply to zero near the cathode edge of the negative glow, thus establishing a basic

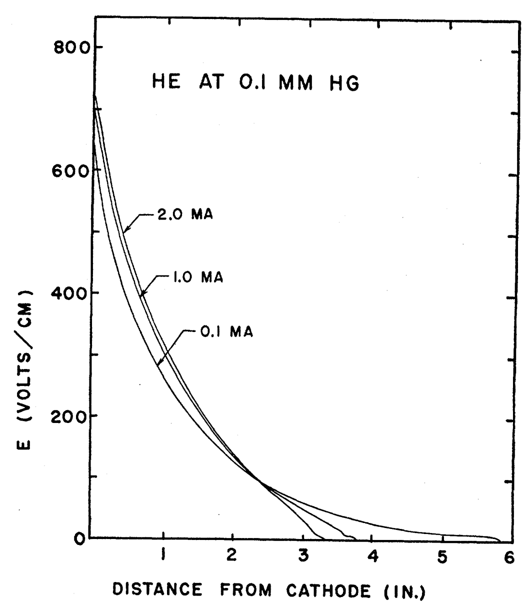

FIG. 3. Cathode fields in helium at a pressure of 0.1 mm Hg.

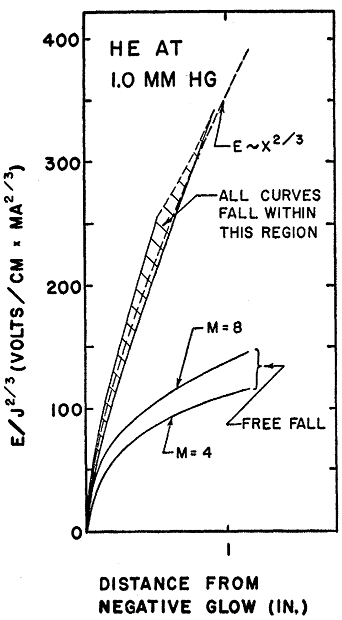

FIG. 4. Replotted cathode fields in helium at a pressure of 1.0 mm Hg.

trend. Since the edge of the glow was not always visually sharp and since the glow curved across the tube diameter, the fields observed did not always fall sharply all the way to zero. In these cases, the curves underwent an inflection near the axis, finally reaching zero more nearly asymptotically. It was assumed that the asymptotic approach of the fields to zero was caused

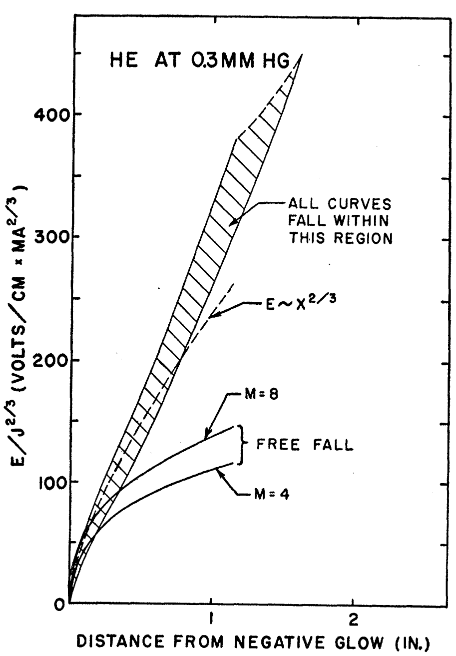

FIG. 5. Replotted cathode fields in helium at a pressure of 0.3 mm Hg.

by the averaging action of the measuring equipment and/or discharge effects of minor importance. In consequence, the field curves near the negative glow were extrapolated to zero following their initial sharp decline as would be expected in the absence of the minor disturbances noted. The modification was usually slight. Figure 1 shows a family of field curves for helium before and after replotting and modifying for the worst case, that at the high pressure.

Once the decline of the field at the edge of the negative glow was discovered, it was anticipated that the curves could be correlated with the form to be expected owing to the creation of an ion space charge by positive ions moving towards the cathode with a drift velocity. By applying modern data on drift

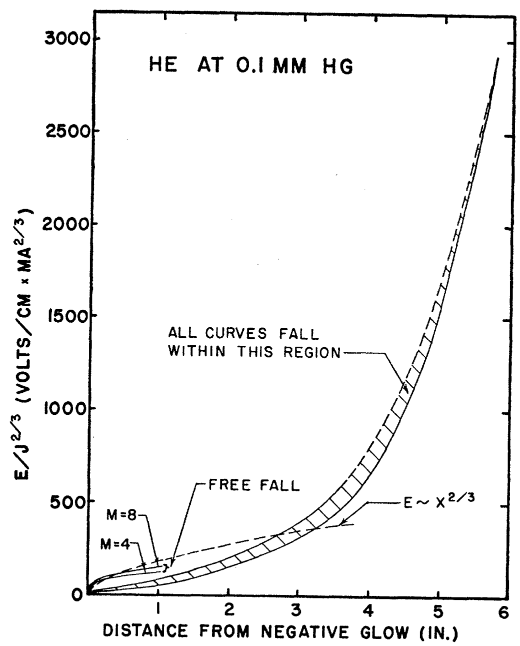

FIG. 6. Replotted cathode fields in helium at a pressure of 0.1 mm Hg.

velocities appropriate to the fields observed, a relationship between the field and ion current could be inferred. Thus, in addition to replotting as a function of the distance from the negative glow, each field curve was reduced in amplitude by the factor $J^{\frac{2}{3}}$, where J is the total discharge current in ma. Figures 4, 5, and 6, thus, contain curves of $E/J^{\frac{2}{3}}$ plotted against the distance from the negative glow and derived from the direct measurements obtained for helium, while Figs. 7 through 15 contain similar curves derived from the direct measurements obtained for all of the other gases except air. The field measurements in air are not given since in all cases the results are almost identical with those in nitrogen. The replotted and reduced field curves in a gas at a given pressure are often so similar that difficulty is found in reproducing them all clearly.

In these cases, a restricted region is outlined on the graphs within which every curve falls.

To reverse the aforementioned procedure and derive the original field measurements from the data of Figs. 4 through 15, each curve need be only multiplied by $J^{\frac{2}{3}}$ where J is the total tube current for which the field is desired. The lengths of the reconstructed field curves are unknown, but since the length is such a strong function of the cathode condition and since the cathode condition changed for different currents and pressures, the lengths originally measured had little significance, therefore no valuable information has been lost. Additional curves on Figs. 1 through 15 labeled "free fall" and "$E \sim X^{\frac{2}{3}}$" refer to theoretical treatments presented in a later paper.

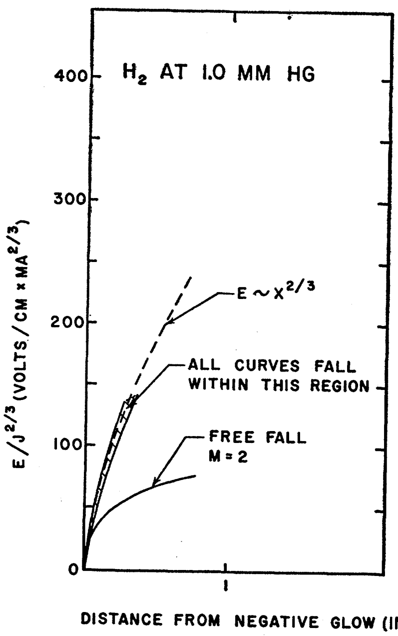

Fig. 7. Replotted cathode fields in hydrogen at a pressure of 1.0 mm Hg.

Accuracy and Significance of the Data

(1) Integration of the fields over the length of the discharge furnishes a very sensitive test of the accuracy of measurement since small errors in the extensive low-field regions could cause serious deviations from the applied potentials. Enough measurements were made to show that these errors were of the order of 2 percent. From this observation, from the fact that the magnetic field had little or not visible effect upon the cathode region of the discharge, and from a discussion given in the paper concerned with the measuring technique, it is concluded that the disturbing effect of the magnetic field upon the discharge was negligible. This is, of course, very important, for in spite of the great advantages of the compensating technique, it would be worthless if the compensating magnetic field

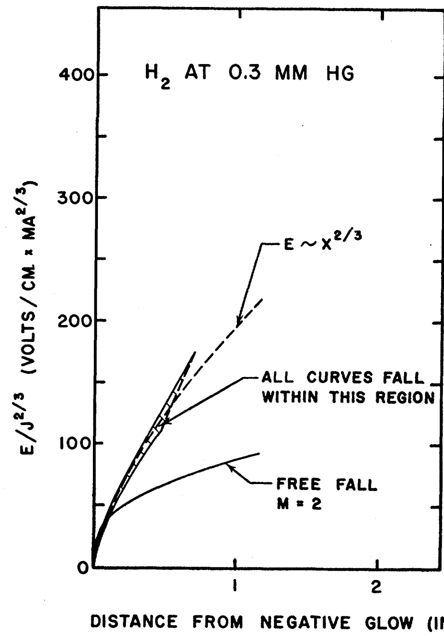

Fig. 8. Replotted cathode fields in hydrogen at a pressure of 0.3 mm Hg.

radically changed the electric field that it was being used to measure.

(2) It must always be remembered that the fields measured by the electron-beam probe are axial fields averaged across the diameter of the discharge tube. To investigate the variation of the axial field along a tube diameter, measurements were simultaneously made of

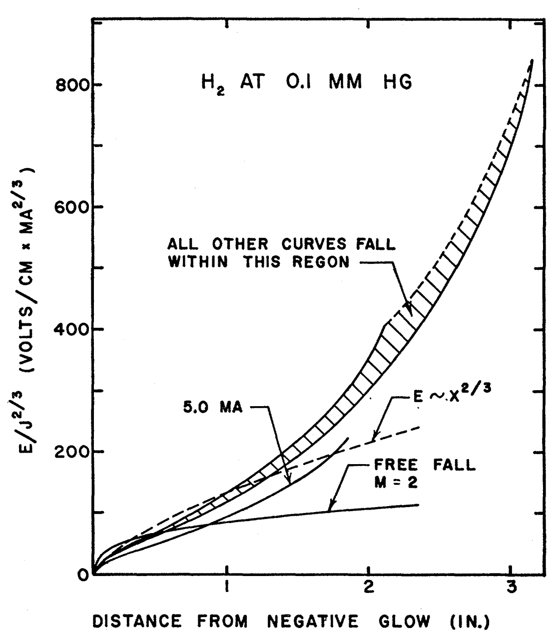

Fig. 9. Replotted cathode fields in hydrogen at a pressure of 0.1 mm Hg.

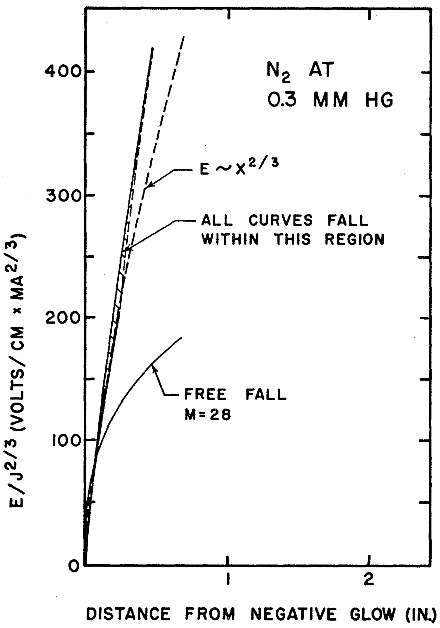

FIG. 10. Replotted cathode fields in nitrogen at a pressure of 0.3 mm Hg.

the potential of the walls of the discharge tube and the average electric field across a diameter. The field curve was then integrated, yielding an average potential curve. These curves are shown in Fig. 16. It can be seen that the wall field and wall potential are 20 percent or so less than the average field and average potential except near the cathode. Such is the case at most pressures and currents for all of the gases investigated. Because of this, the average field measured by the electron beam is not truly representative of the discharge alone, but also of the presence of the walls, unless the effect of the walls is confined to a small region of the discharge in the immediate vicinity of the walls. From observations of the variation of the light intensity in the tube across a diameter and through arguments involving the mechanics of the motion of the positive ions and electrons in the tube, it is believed that at high pressures, the wall field penetrates only a short distance into the discharge so that the measured average field is very nearly equal to the actual field at most points along a diameter of the tube. At low pressures, however, it appears that the wall field penetrates well into the tube so that near the negative glow, the field along the axis of the tube is about 10 percent higher than the average field, while near the cathode, it is about 10 percent lower. In most cases, therefore, the variation of the field along the path of the electron beam (due to the presence of the walls), is much greater than any errors introduced in measuring the field, and is, thus, more likely to affect the field measurements in such a way as to defeat attempts at interpretation.

Light Intensity Measurements Near the Cathode

In order to supplement the field data, measurements have also been made of the light intensity at various positions in the discharges. Figure 17 is an example, where enough of the simultaneously-measured field curves is shown to indicate the relationship between

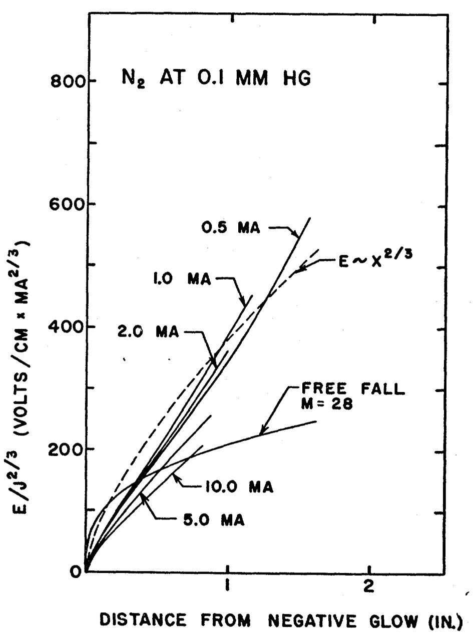

FIG. 11. Replotted cathode fields in nitrogen at a pressure of 0.1 mm Hg.

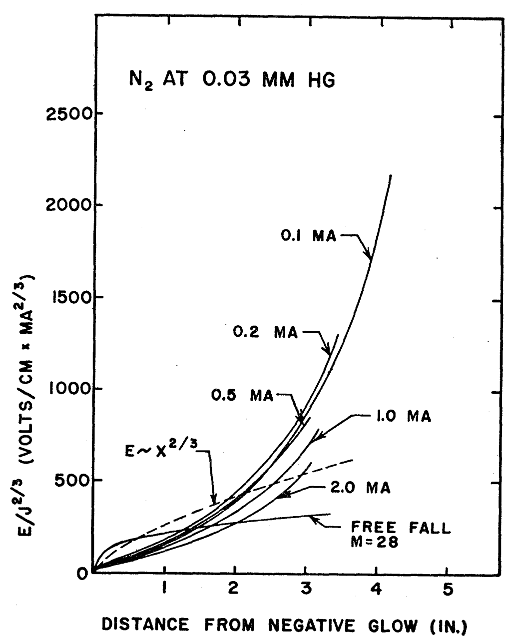

FIG. 12. Replotted cathode fields in nitrogen at a pressure of 0.03 mm Hg.

the position of the light maxima and the field minima. The exact shape of the intensity curves very near the cathode is determined by instrumental considerations. The numbers, 1 to 5, on the curves indicate discharge currents of 5 to 0.2 ma in that order. The light intensity peaks near the field minima are caused by excitation by electron impact, while the peaks near the cathode are probably to be ascribed to excitation by high-energy positive ions and neutral particles. This last conclusion is reached through a study of the light intensity curves, a study of spectra of the light emitted from the cathode region, and investigations of the light emitted from the canal rays using a pierced cathode. It should be noticed that the intensity peak at the cathode rises very rapidly as the tube current and, thus, the tube potential is increased.

It will be noticed that the segments of the field curves shown in Fig. 17 do not coincide with the field curves in nitrogen shown in Fig. 12. This results from the very marked changes in the characteristics of the cathode surface which occurred from time to time. For under operating conditions the cathodes inevitably had surfaces that were soiled to varying and changing degrees. Thus, undoubtedly, they were initially oxidized, but as time progressed they were somewhat cleaned by ion bombardment. In addition, especially at high discharge potentials, some of the hydrocarbon vapors, unavoidably present in the tube, were decomposed and visible deposits of carbon sometimes appeared on the cathode. During the short time for the measurement of a single field curve, however, the cathode characteristics were constant. However, as soon as the pressure or current was varied a considerable time had to elapse before the cathode characteristics settled down to new values so that more field measurements could be made.

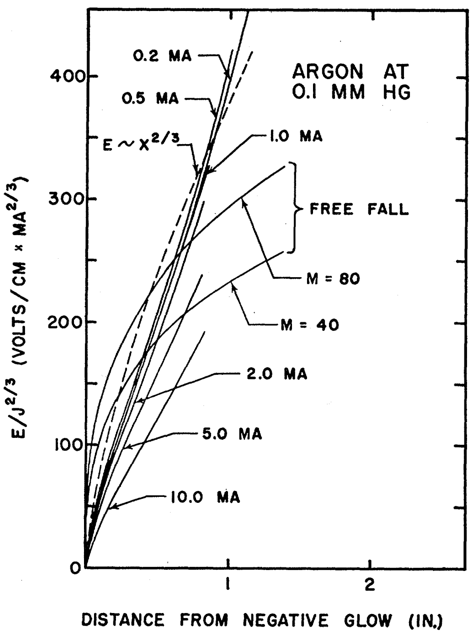

FIG. 14. Replotted cathode fields in argon at a pressure of 0.1 mm Hg.

The only reason that the families of curves in Figs. 1 to 15 appear as regular as they do, is that all of the curves in a family were taken on the same day in a

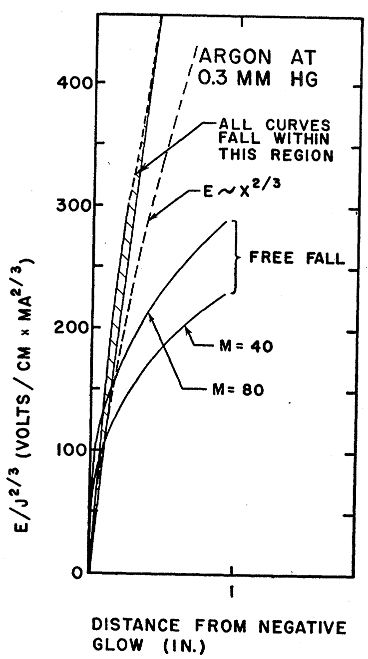

FIG. 13. Replotted cathode fields in argon at a pressure of 0.3 mm Hg.

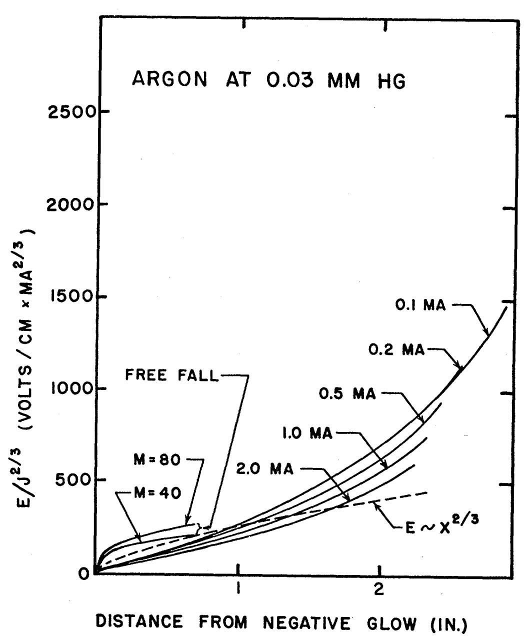

FIG. 15. Replotted cathode fields in argon at a pressure of 0.03 mm Hg.

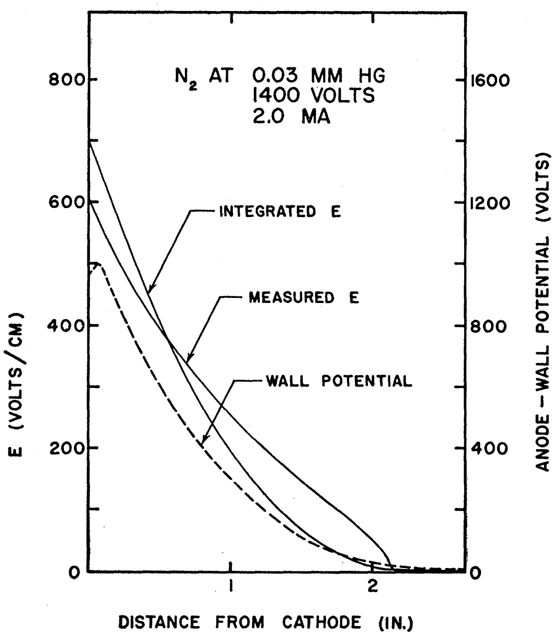

FIG. 16. The wall potential and average field in nitrogen.

systematic order (in order of decreasing current), so that the characteristics of the cathode surface also varied in some systematic way. If, after the last field measurement (lowest current) in a certain family of curves was taken, the first one (highest current) was repeated, a fair approximation to the original parameters could be achieved. However, if the discharges were then returned directly to the lowest current, it was impossible to repeat the same parameters. Apparently the high current discharges partly cleaned the cathode surface while the low current discharges did not, so that the past history of the cathode surface was very important in determining its characteristics for low currents, but not so much for high currents.

A further investigation of the effect of the cathode surface upon field measurements was made by operating discharges in a given gas at fixed pressures and current densities, but with different cathode materials and, necessarily, different discharge potentials and cathode-negative glow separations. It was found that if the measured fields were plotted against the distance from the negative glow, and not the distance from the cathode, all field curves taken with different cathode surfaces but identical pressures and currents were superimposed, even though some curves would extend further from the negative glow than others. Thus, the shape of the curves of the field *versus* the distance from the negative glow appears to be independent of the cathode characteristics. On the other hand, the length of this curve is determined, in part at least, by the cathode condition as is well known from other studies. This interesting observation will be discussed and interpreted in the following paper.

Field Measurements in Striations

Figure 18 is a reproduction of an actual field measurement of striations in nitrogen at a pressure of 0.3 mm Hg, a potential of 525 volts, and a current of 5.0 ma. The graph looks complicated because it actually consists of four separate curves. The recorder was at this time connected to measure alternately the average field and the wall potential. The vertical lines on the graph represent the recorder's transition from measuring one variable as a function of position to measuring the other.

Thus, starting on the left side of the tracing, fields and wall potentials were alternately measured near the aluminum anode with the measuring beam steadily moving closer to the aluminum cathode. At the center

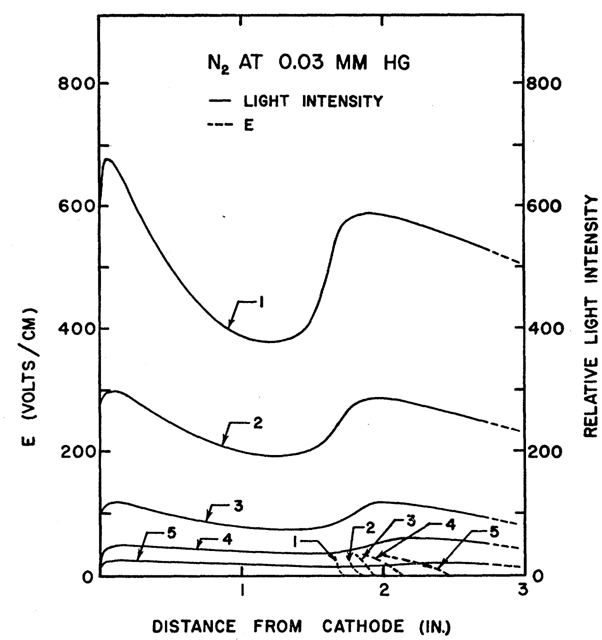

FIG. 17. The light intensities and average fields in nitrogen. The numbers, 1 to 5, on the curves indicate discharge currents of 5, 2, 1, 0.5, and 0.2 ma in that order.

of the tracing the potentials of the electrodes were reversed so that the old anode became the new cathode, but the electrodes still moved in the same direction. Because the electrodes were identical, it was possible to reverse their polarities in such a fashion and still retain the same discharge parameters. Thus, from the center of the graph on to the right, the fields that were measured were negative, and the wall potentials were returning to low values with respect to the anode.

Measurements were made in this fashion to permit a determination of the zero field condition, for an integration of the fields under both the direct and reversed field curves yields both a correct zero field and a correct potential drop per striation. In the case shown, the potential drop per striation was found by integration to be 33.6 volts, while the potential drop per striation determined from the wall potential curves was 33.5 volts. This excellent agreement is fortuitous. However, within the precision of these measurements, the potential drop per striation appeared constant for each gas over the range of currents and pressures for which stable striations could be obtained. Generally also it seems that in inert gases the potential difference between striations was about the ionization potential while in molecular gases it was twice the ionization potential. Measurements were made of field curves under other conditions. In general, it was found that in the negative glow, the fields were from $\frac{1}{4}$ to $\frac{1}{2}$ volt per cm, and in the Faraday dark space, of about the same magnitude, occasionally dropping well below $\frac{1}{4}$ volt per cm. In unstriated positive columns, the fields were from 1 to 2 volts per cm. Since the field curves at the anode could take so many forms, no special study was made of them. These approximate values of the fields may depend greatly upon the gases, pressures, voltages, and, especially, the tube diameter used (since ambipolar diffusion to the walls largely determines the discharge economy there).

Again it must be mentioned that all field measurements are averages taken across a tube diameter. This is especially important in measuring striations, for the wall charges cause them to curve seriously. For example, striations six cm apart in the discharge tube, which is ten cm in diameter, are so curved that the striations at the axis of the tube are 1 to 3 cm closer to the cathode than they are at the walls. This causes no error in the determination of the potential drop per striation, but does give measured maxima and minima fields which are not as extreme as the actual ones. Thomson[7] has reported negative fields in striations and other observers have measured negative fields in the negative glow. None were observed in these measurements, either in the fields of the striations or in fields elsewhere in the discharge.

Field measurements were not taken in the positive column when light, voltage, or current oscillations or moving striations were observed. These phenomena were occasionally present when field measurements were taken in the cathode region of the tube. Visual observation of the fluorescent screen, however, showed no broadening of the spot which would have been expected if oscillating electric fields of any magnitude had penetrated into the cathode region of the discharge.

Spectrographic Observations

Spectrographic investigations of various regions of the discharges in all of the gases have been made. These lead to three general conclusions.

(a) Much of the light emitted from the negative glow and striations in the various gases is emitted from nitrogen impurity molecules. This is especially true for helium where all of the light emitted from the striations comes from the nitrogen impurity. One might have expected this, since the ionization and excitation potentials of nitrogen are so much less than those of helium, and since the positive column in any mixture of gases is characterized by electrons which have energies only high enough to occasionally ionize the constituent with the lowest ionization potential (unless some more involved ionization process occurs). Because of these observations, the characteristic potential per striation observed for each gas is probably not truly characteristic of the gas alone, but of the impurity content also.

(b) Relatively little of the light observed from the cathode glow is emitted by impurity molecules. This is probably because the excitation and ionization here are caused by high-energy positive ions and neutral particles, for high speed particles are likely to ionize and excite mixed gases more nearly in proportion to the concentration of the various constituents.

(c) It is believed that the majority of the ionization by electrons occurring in the negative glow is by fairly high energy electrons that also ionize and excite all gases with approximately equal probabilities. Field measurements taken both with impure helium (99.5 percent pure) and with a much purer helium sample were identical, while spectrographic investigations showed much weaker nitrogen bands and lines for the purer sample. Therefore, it is concluded that the current between the negative glow and the cathode, carried by positive ions formed mainly in the negative glow, is carried largely by ions of the main constituent

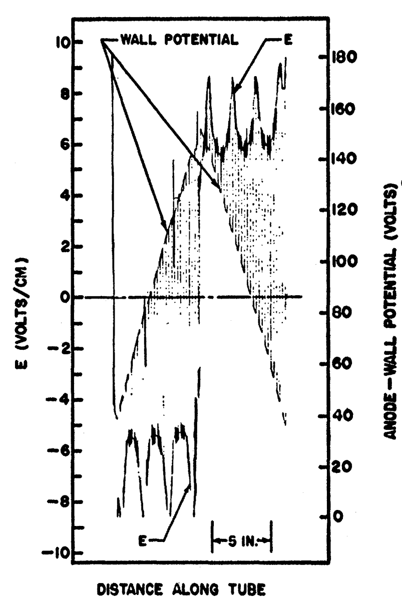

FIG. 18. Typical fields in striations in nitrogen. N_2 at 0.3 mm Hg, 525 volts, and 5.0 ma; 34 volts/striation.

[7] J. J. Thomson, Proc. Cambridge Phil. Soc. **15**, 70 (1909).

gas and not by impurity ions. A great deal more work, however, would be necessary to establish this point definitely.

ACKNOWLEDGMENTS

The writer wishes to express his thanks to Professor Leonard B. Loeb, under whose direction this problem was undertaken, for his encouragement and valuable suggestions throughout its prosecution, and especially for his assistance in the presentation of the results. Thanks are also due to C. D. Maunsell and R. G. Westberg for assistance in taking the spectral and light intensity measurements.

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Interpretation of Field Measurements in the Cathode Region of Glow Discharges*

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A theory for the cathode region of glow discharges is developed in which the major assumptions are: (a) electron emission from the cathode due to positive ion impact is the dominant secondary mechanism; (b) the probability of ionization by electrons occurring in the high-field cathode region is small, so that electrons carry a negligible portion of the total tube current there; and (c) in this region the positive ions drift towards the cathode with a velocity governed by a mobility law. This theory is found to agree well with measurements in abnormal discharges in various gases at pressures above about 0.1 mm Hg. For lower pressures, measurements indicate that a great number of electrons are present in the cathode-negative glow space, probably due to ionization by high-energy positive ions and molecules; and, that at high enough values of E/p, the application of a mobility theory becomes completely invalid.

GENERAL THEORY

General Mechanism of a Glow Discharge

It is usually assumed that the dominant mechanisms operating in a glow discharge are the primary one of ionization of gas molecules by high-speed electrons and a secondary one of electron emission from the cathode due to the impact of positive ions. γ_i, the ratio of the electron current emitted from the cathode to the positive ion current striking it, ranges between 0.01 and 0.1. Other secondary mechanisms additional to γ_i but akin to it in action are known to occur in gaseous discharges. Some of these are: (a) photoemission from the cathode due to light coming mainly from the negative glow (Little and von Engel[1] have recently proposed a theory based upon this as the dominant cathode mechanism), (b) emission from the cathode due to the impact of metastable atoms or molecules (especially important in the rare gases), (c) ionization of the gas molecules by photons, excited molecules, and/or positive ions. However, because of the relatively high cathode fields and low pressures which favor large values of γ_i compared to other processes, the γ_i mechanism appears to dominate other secondary actions in glow discharges.

The Economy Condition

It will be assumed that all secondary mechanisms other than γ_i can be ignored. Since a glow discharge is self-sustaining and constant in all of its characteristics assuming that no oscillations exist, a certain economy relationship must hold. Namely, each electron emitted from the cathode must on the average cause just enough ionization so that those positive ions formed which return to the cathode cause just one new electron to be emitted. The economy condition may be written $\gamma_i GF=1$, where F is the total number of new electrons and positive ions formed per original electron and G is that fraction of the positive ions formed which arrive at the cathode. G includes losses of electrons and ions to wall and volume recombination. It may have a wide range of possible values.

The Current Continuity Condition

The sum of the electron and positive ion currents at any point in the tube must be a constant equal to the total tube current. Now, $1/(1+\gamma_i)$ of the tube current *at the cathode* must be carried by positive ions. Since positive ions move much more slowly than electrons of the same energy, the space charge of these positive current carriers will be much greater than that of the electrons and thus the net positive charge will be quite large near the cathode. The electric field necessary to achieve high electron velocities, however, is quite low. Therefore, the field in the discharge tube will fall almost to zero as soon as each emitted electron has formed more than $1/\gamma_i$ new ones by ionization. For when this relationship is satisfied, the electron density is high enough so that the tube current of electrons alone will be too high to satisfy the current continuity condition if some minimum field is exceeded. Therefore, the field

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† Now at Westinghouse Research Laboratories, East Pittsburgh, Pennsylvania.
[1] P. F. Little and A. von Engel, Proc. Roy. Soc. (London) **A224**, 209 (1954).