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Nature and Role of Ionizing Potential Space Waves in Glow-to-Arc Transitions*

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The transition from a glow discharge to a transient arc induced in Al cathode tubes 145 cm long by shorting of a series resistor has been studied for a variety of gases by observing currents at the electrodes, the potentials at various points in the tube using probes, and the movement of luminous pulses using photomultiplier tubes and fast oscilloscopes. By applying a dc power supply with up to 2600 volts and a large capacity parallel to the discharge tube, and with due regard to proper impedance matching, relatively pure gases N_2, A, H_2, O_2, and mixtures of N_2 and O_2, were studied from 50 microns Hg up to several hundred microns. In addition, shorter tubes with Cu, Ni, Pt, Hg, W cathodes and filled with He, or N_2, at intermediate pressures up to 7.2 mm Hg, were briefly studied. The decrease of the series resistance increased the very low current in the normal glow mode to higher values up to 50 ma usually in the abnormal mode. With slightly oxidized cathodes, there followed, after times varying from 10^{-3} second to many seconds, catastrophic breakdowns to a transient power arc of the order of 10–20 or more amperes. The transition was initiated by a burst of electrons from the cathode yielding a cathode current increase to several amperes in $\sim(2 \text{ to } 10)\times10^{-9}$ second. This burst sends a luminous pip or pulse to the anode at velocities varying from 5×10^8 to 8×10^9 cm/sec, depending on pressure, voltage, and gas. On arrival at the anode, a luminous return arc plasma front moves towards the cathode with speeds from 10^8 to 10^9 cm/sec or more. When it arrives at the cathode, the conductivity is sufficiently homogenized along the column so that the current and luminosity increase along the whole column until the drain on the capacity lowers the supply voltage. The luminous pip, and to a less clearly defined degree the return plasma front, are accompanied by potential space waves which can be established by cross-plots yielding luminosity and potential distributions across the tube at various times. The transition appears to be initiated by a sudden breakdown of the oxide layer on the cathode as it thins by ion bombardment, causing a small fraction of the oxide molecules to be ionized within millimicroseconds, thus yielding the initial current burst. These electrons, accelerated by nearly the full potential drop across the dark space, move as ionizing potential fronts, accompanied by luminosity, with velocities in most cases dictated by the cathode fall potential. In O_2, when pressures permit effective photoionization within the tube length, the velocities of the front are increased up to 8×10^9 cm/sec.

INTRODUCTION

THE transition of the glow discharge to an arc has previously been studied largely by considering the relationship of the cathode metal and its surface conditions to the problem of whether or not the transition occurs and not as to the detailed processes occurring in the transition. Such observations have been concerned with the effects of oxide layers, salts, powders, other impurities, vapor clouds, temperatures, and whether or not the metal was refractory.[1]

Hofert[2] studied transitions of glow discharges to arcs for short gaps of about 5 millimeters and at pressures in hydrogen, argon, nitrogen, and mercury between 200 microns and 2 millimeters Hg, for cathodes of copper, mercury, and tungsten at less than 1000°C. He found that all of the nonthermal transitions, if the elapsed time needed for the potential difference across the gap to decrease to that characteristic of the arc is used as a measure, took place in times shorter, in fact, than 50 millimicroseconds. This appears to be the only work performed where upper time limits to the transition period have been measured and here the electrode separation was very small.

Froome's[3] work on further growth of the arc current after it has already reached a minimum value of one ampere, seems to be the most complete as to current changes during the transitions. Apparently no studies have been made concerning potential or luminosity changes within the gaseous plasmas during the transitions.

Some pertinent work in areas allied to this study has

* This study has been supported by grants from the Office of Naval Research and from the Research Corporation.
[1] J. M. Meek and J. D. Craggs, *Electrical Breakdown of Gases* (Clarendon Press, Oxford, 1953), Chap. 12.
[2] H. J. Hofert, Ann. Physik 35, 547 (1939).
[3] K. D. Froome, Proc. Phys. Soc. (London) 60, 424 (1948).

been performed. Very early studies of Wheatstone[4] and of Thomson[4] concerned the luminous pulses produced by sudden impulse voltages placed across low-pressure tubes. Beginning in the late 1920's, Beams, Snoddy, and their collaborators[5] made studies not only of the luminosity changes, but of the potential changes within 15-meter long, low-pressure tubes when positive and negative impulse voltages up to 180 kilovolts were impressed upon one of the electrodes. For air and hydrogen at pressures between 34 microns and 20 millimeters Hg, it was discovered that a potential wave with a magnitude of the order of the impressed voltage and extending over a distance of about one to three meters traveled through the tube to the second electrode with a velocity between 0.9×10^9 and 5.0×10^9 cm/sec regardless of the sign of the impulse voltage impressed on the first electrode. If the second electrode was grounded, then there was a return potential wave traveling in the opposite direction at velocities between 0.9×10^{10} and 1.23×10^{10} cm/sec, but no such return wave existed if the second electrode was insulated from ground. Luminosity studies indicated that the luminous front traveled at approximately the same velocities as the corresponding potential waves.

Luminosity studies of lightning discharges by Schonland,[6] and studies of spark breakdown by Loeb, Raether, Flegler, Allibone and Meek, Holzer, Hudson[7] as well as many others, have indicated, by the large velocities of the luminosity fronts measured, that potential waves must be present during these phenomena.

The present study of the glow-to-arc transitions grew out of an attempt of the writer to study moving striation phenomena in glow discharges by suddenly increasing the voltage across the tube. Although this work proved unfruitful, inadvertently the apparatus and circuitry had been so constructed that transitions of the glow discharges to arcs became probable under the right conditions. Preliminary studies indicated that the long glow tubes, the recording photomultipliers, the oscilloscopes, and other measuring apparatus that were available for use with the striation problem, were also admirably suited for the study of the glow-to-arc transition.

It was determined that the nonthermal, glow-to-arc transition at low pressures begins with the extremely fast passage of a pulse of light from the cathode to the anode, with a second fast luminous front then returning back to the cathode. Behind the second front, the luminosity continues to build up in intensity, until, at some later time, a maximum of intensity is reached throughout the entire tube. The power supply and series impedance will determine whether the arc thus formed can be sustained. Coincident with the departure of the initial light pulse from the cathode is a rapid increase in the cathode emission current, while within the gas, a potential wave travels rapidly through the tube to the anode, in company with the initial light pulse. Further potential changes can be seen accompanying the return of the second front to the cathode and during the further buildup of the light intensity throughout the tube.

Studies of these high-velocity light pulses and of the accompanying potential changes as well as the increase in the current emission from the cathode were instituted in order to clarify the manner of the glow-to-arc transition as well as to attempt to perceive differences that might exist between individual gases and, to a lesser extent, cathode metals.

APPARATUS AND PROCEDURE

The glow discharge tube, its accompanying circuitry, and the photomultiplier measurement apparatus are shown schematically on Fig. 1. The several Pyrex discharge tubes used in most measurements were 40 mm in diameter and about 145 cm long, with the aluminum cathodes (to be discussed further) and tungsten anodes separated by about 135 to 145 cm.

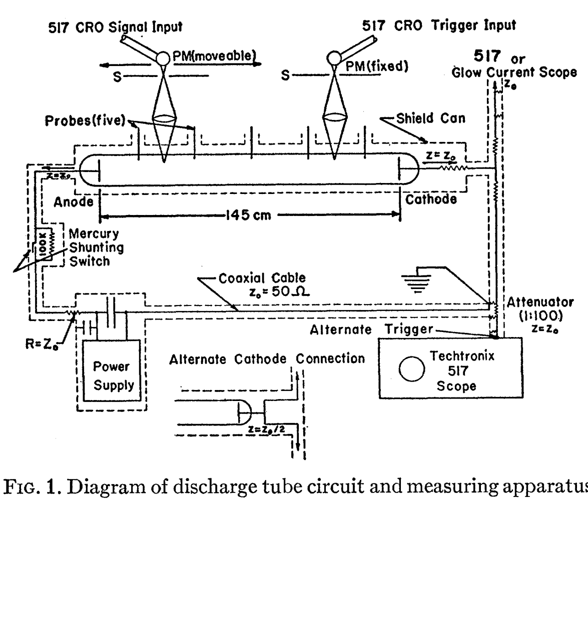

FIG. 1. Diagram of discharge tube circuit and measuring apparatus.

[4] J. J. Thompson, *Recent Researches in Electricity and Magnetism* (Clarendon Press, Oxford, 1893), p. 115.

[5] J. W. Beams, Phys. Rev. **36**, 997 (1930); Snoddy, Dieterich, and Beams, Phys. Rev. **50**, 739 (1937); F. H. Mitchell and L. B. Snoddy, Phys. Rev. **72**, 1202 (1947).

[6] B. F. J. Schonland and H. Collens, Proc. Roy. Soc. (London) **A143**, 654 (1934); Schonland, Malan, and Collens, Proc. Roy. Soc. (London) **A152**, 595 (1935); D. J. Malan and H. Collens, Proc. Roy. Soc. (London) **A162**, 455 (1938); B. F. J. Schonland, Proc. Roy. Soc. (London) **A164**, 132 (1938); Schonland, Hodges, and Collens, Proc. Roy. Soc. (London) **A166**, 56 (1938); D. J. Malan and B. F. J. Schonland, Proc. Roy. Soc. (London) **A191**, 485 (1947).

[7] W. Holzer, Z. Physik **77**, 677 (1932); E. Flegler and H. Raether, Z. tech. Phys. **16**, 435 (1935); **99**, 635 (1936); **103**, 315 (1936); H. Raether, Z. Physik **37**, 560 (1936); **94**, 507 (1935); **107**, 91 (1937); Z. tech. Phys. **18**, 564 (1937); Z. Physik **112**, 464 (1937); Arch. Electrotech. **34**, 99 (1940). T. E. Allibone and J. M. Meek, Proc. Roy. Soc. (London) **A166**, 97 (1938); G. Hudson, thesis, University of California, 1957 (to be published); A. M. Cravath and L. B. Loeb, Phys. Rev. **47**, 259 (1935); Physics **6**, 125 (1935). L. B. Loeb and W. Leigh, Phys. Rev. **51**, 149 (1936); J. M. Meek, Phys. Rev. **57**, 722 (1940); L. B. Loeb and A. Kip, J. Appl. Phys. **19**, 142 (1948); L. B. Loeb and R. A. Wijsman, J. Appl. Phys. **19**, 797 (1948); L. B. Loeb, Phys. Rev. **74**, 210 (1948).

Five tungsten probe wires were inserted into each discharge tube along its length to enable measurements of the plasma potentials. Use of coaxial cables and a shield can about the discharge tube served two purposes: (1) to make, as far as possible, the impedance in series with the discharge tube purely resistive, and (2) to shield further the photomultipliers and associated oscilloscopes against electrical pickup. The coaxial cables at the cathode and anode not only were terminated with their characteristic impedance but, in addition, were 20 to 35 meters long to minimize and delay any possible reflection effects.

The double cable connection at the cathode allowed the use of one cable to trigger a Tektronix 517 oscilloscope upon the sudden pulse of cathode current that appears with the initiation of the glow-to-arc transition, while the other cable could feed the cathode voltage signal either to the oscilloscope's amplifier input or directly onto the deflection plates of the cathode ray tube whose trace could be recorded with a Leica camera. Here the parallel cathode cable connection proved most satisfactory, passing signals with rise times as fast as 2×10^{-9} sec without distortion compared to the minimum distortionless rise time of 5×10^{-9} sec for the T cathode connection.

When both photomultipliers were used, one was operated as the alternate trigger source for the oscilloscope, starting the sweep, with the initial pulse of light appearing at the cathode, at the same relative instant for every glow-to-arc transition. The second photomultiplier fed its output to the vertical amplifier system of the oscilloscope. Since the second signal photomultiplier could be moved parallel to the length of the discharge tube, light intensities throughout the tube could be obtained as a function of the time and position after the initiation of the transition.

Voltage changes at the plasma probes inserted along the length of the tube were measured by using the cathode follower probe of the 517 Tektronix. The minimum rise time for the distributed amplifier system of the Tektonix 517, with or without the cathode follower probe, is 7×10^{-9} sec, although signals with rise times of 2×10^{-9} sec are accurately reproduced if they can be fed directly to the deflection plates of the cathode-ray tube.

In operation, a low-current glow discharge is initiated in the discharge tube by utilizing a 100-kilohm resistance in the anode cable circuit. At the appropriate moment, when all measuring apparatus is ready, this resistance is shorted out by using a coaxially shielded mercury relay tube[8] leaving only 75 or 100 ohms (depending on cathode cable connection) in the series circuit. The glow discharge current then increases to the value consistent with the regulated power supply voltage (up to 2600 v, with ripple less than 5 mv at 50 ma) and the small series resistance. This glow discharge will spontaneously break down to an arc should the conditions be right. The delay after the application of the shorting out of 100-kilohm resistance ranges from a few microseconds to several seconds, depending upon various factors which will be discussed later.

The condensers across the output of the power supply are sufficiently drained by the momentary arc current in a time of the order of several hundred microseconds, so that the arc extinguishes. Other circuitry within the power supply, triggered on the initiation of the arc, turns off the supply to prevent a subsequent recharging of the condensers and then another transition.

Before glow-to-arc measurements in each separate gas were made, the discharge tube was always baked out at at least 350°C for more than 12 hours under high-vacuum conditions. By manipulation of the inlet and outlet Alpert valves, the gas under study then was allowed to flow through the tube at a slow rate, maintaining the desired pressure. This constant flow method was believed to aid in removal of impurities freed from occlusion in the electrodes during the discharges as well as those possibly created in the gases (especially in the N_2 and O_2 mixtures). It should be noted that spectroscopic measurements did not detect any mercury within the discharge tubes which were subjected to this bakeout process.

While the baking out of the tube and the flushing through of the gases undoubtedly aided in maintaining the original purity of the gases used, it must be emphasized that the cathodes of the longer tubes, by design, were aluminum, and it was impossible and undesirable to outgas these beyond 350–400°C. Thus the cathode was and of necessity remained contaminated with an oxide coating during the bakeouts and was therefore a source of minor contamination. Gas-free metals could not be used since the glow-to-arc transitions appear to depend on the presence of this oxide layer and its transient breakdown. As each gas was examined, with the repeated and prolonged firing of the tube in the course of the measurements, the oxide coating tended to disappear by ion bombardment or chemical action. Hydrogen proved most active in this cleaning-up process while oxygen, of course, was an apparent exception.

Although most of the measurements were made with $1\frac{1}{2}$-meter long aluminum cathode tubes, for the purpose of studying the initial cathode current pulse for several different metals, shorter tubes, 30 cm long and 1 cm in diameter, were utilized. The auxiliary electrical circuitry remained unchanged.

The gases used were of standard Airco grade, 99.98% pure, except for oxygen which was manufactured from $KMnO_4$ and should have been of a comparable purity.[9] Actually, the mixtures studied showed that the phenomena were not critically dependent upon gas purity. Changes in characteristics required on the order of 1%

[8] R. L. Garwin, Rev. Sci. Instr. **21**, 903 (1950).

[9] N. E. Bradbury, Phys. Rev. **40**, 508 (1932).

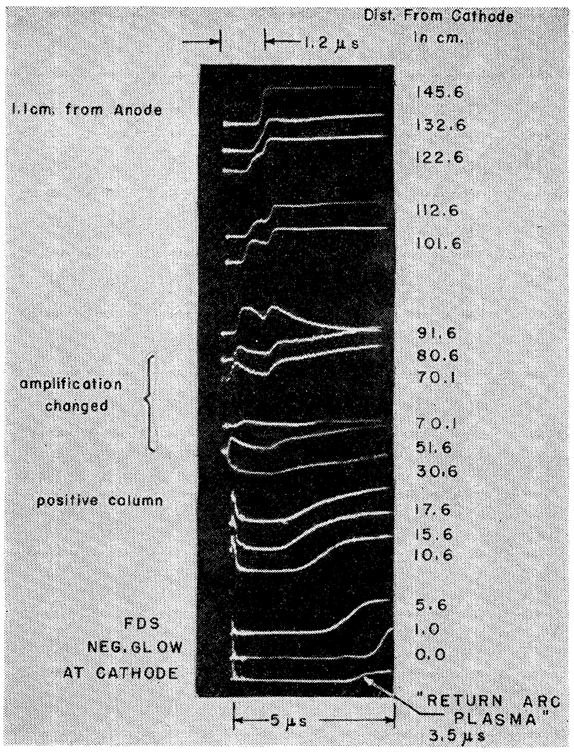

FIG. 2. Light intensities at various points within an Al-cathode discharge tube during glow-to-arc transition in N_2 at 190 microns and 1700 volts with 500 mμsec/cm sweep. Time moves from left to right in a tube 146.6 cm long. The bottom trace shows both the initial short pulse, the "pip," and the beginning of the light of the main arc, the "return arc plasma front." These two light fronts appear on each of the other traces, merging together only at the anode. Each trace is a separate arc transition with light traces from near the anode having been more highly amplified.

or more of impurities to be detected. Along this line it was observed that when mercury was allowed to contaminate the system, through removal of the liquid nitrogen on the cold trap of the vacuum system, there was no noticeable difference in the glow-to-arc transition characteristics.

RESULTS

The luminous aspects of the low-pressure, aluminum cathode, glow-to-arc transition proved similar for the several gases studied over the ranges of pressures and total voltages that were used. Oscilloscope traces showing light intensity changes, for nitrogen at 190 microns and with 1700 volts supplying the tube and its 75-ohm series resistance, will serve as guides to the general aspects of the low-pressure transitions. At this relatively low total voltage, the glow-to-arc transition in N_2 is a comparatively slow process and oscillograms are easy to interpret. Figure 2 shows a series of oscillograms of light intensities at various positions within the tube starting with the bottom trace showing the output from the region just in front of the cathode and progressing upwards so that the top trace depicts the light 1.1 centimeters in front of the anode. The oscilloscope sweep and thus time moved from left to right. In order to bring out the initial detail, the oscilloscope amplifiers were so adjusted that large signals overloaded them, as the several top traces with a higher amplification show most plainly.

An examination of the first (lowest) trace, showing the light intensity at the front surface of the cathode, discloses two features: (1) a short intense upward increase of light intensity, hereafter designated as the "pip," with an initial duration of about a tenth of a microsecond, but diminishing in intensity and spreading while moving from cathode to anode, and (2) a second pulse of light intensity, lasting several hundred microseconds, with a slower rate of increase. The second increase in intensity, which will be designated as the "return arc plasma" (RAP) front, is a wave of ionization and excitation that started at 1.2 μsec in the region of the anode on the arrival of the pip and traveled towards the cathode arriving there at 3 μsec, at which time the arc current began its increase.

It will be noted that the pip appears to travel along

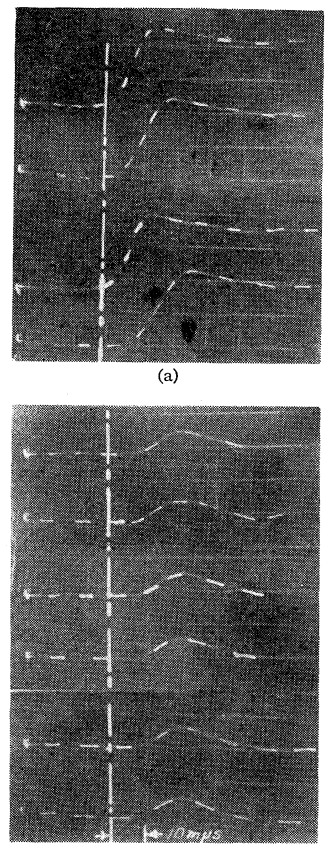

FIG. 3. Light intensities at Al cathode (a) and at front of the first stria (b) 18 cm from cathode during transition in argon at 128 microns and 1700 volts with 10 mμsec/cm sweep speed. Each trace represents a separate transition. Traces partially retouched because of photographic faintness. Light pip appears at the first stria an average of 8 mμsec after it appears at the cathode surface, indicating a velocity of 2.2×10^9 cm/sec.

the whole tube, diminishing in intensity through the Faraday dark space and increasing again in intensity when it reaches the positive column. For the first 30 cm or so, as shown on these traces with the medium fast sweep speed of 500 mμsec/cm here used, this light pip appears at all points almost simultaneously, indicating that it moves at an extremely high velocity. As the traces of light intensity further away from the cathode are examined, one notes that there is a delay in the beginning of the "pip," in addition to the diminishing of its intensity (increased amplification was required when the signal photomultiplier was placed 70.1 cm from the cathode), and the lengthening of its duration to microseconds. The average cathode-to-anode velocity of the pip front is 1.2×10^8 cm/sec in this particular case. The measurement of pip movement near the cathode at fast sweep is shown in Fig. 3, where the speed reaches 10^9 cm/sec.

The RAP front of Fig. 2, starting from the anode at 1.2 μsec after the pip appeared at the cathode, returns quickly through the region of the former positive column at about 2×10^8 cm/sec before it slows down to approximately 10^7 cm/sec in crossing the final 17.6 cm to the cathode. Neither the pip nor the RAP front are of a filamentary or constricted nature. Rather, as determined by observation with the photomultipliers of light at various positions away from the axis of the tube, they are diffuse and pass through the entire volume of the preceding glow-discharge plasma.

Figure 4 shows instantaneous spatial distributions of light intensity throughout the tube during a glow-to-arc transition. These distributions are constructed as cross-plots from the data taken under conditions nearly

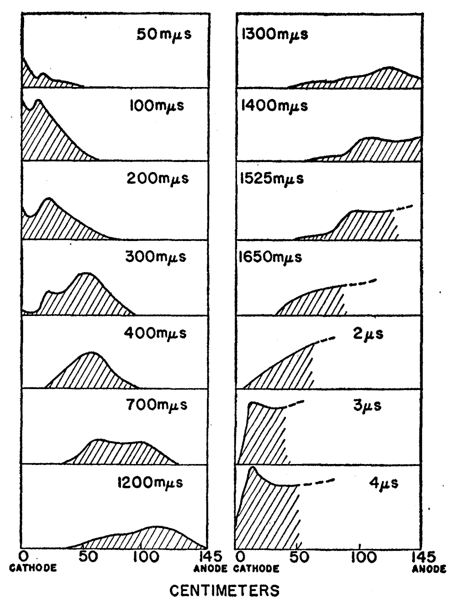

FIG. 4. Relative light intensities throughout the Al-cathode discharge tube from 50 mμsec to 4 μsec after the initiation of the transition in N_2 at 184 microns, 1740 volts.

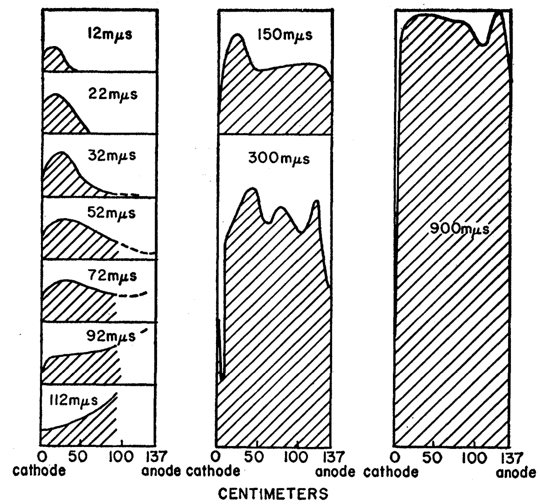

FIG. 5. Relative light intensities with an Al cathode during transition for various times from 12 to 900 mμsec after initiation. The H_2 pressure is 184 microns with 2600 volts across a tube 137 cm long.

identical to those of Fig. 2. Here, for nitrogen at 184 microns and 1740 volts, are plotted relative light intensities along the length of the tube at increasing times following the initial appearance of the light pip at the cathode. The light from the preceding glow discharge was relatively so faint that it does not appear on such a plot. The high velocity of the pip during the first 50 cm and the slower progress for the remaining 90 cm or so may be noted. The RAP front is plainly evident from 1400 mμsec on, with this front reaching the cathode between 3 and 4 μsec after the beginning of the transition.

Figure 5 shows instantaneous space cross-plots of light intensity for a hydrogen discharge at 184 microns and 2600 volts during the first 900 mμsec. The velocities of the fronts are much higher than for the transition depicted in Fig. 4, the pip reaching the anode in 50–70 mμsec. The RAP front has come back to the cathode by 112 mμsec after the initial appearance of the pip at the cathode surface. Thereafter the entire gaseous plasma increases in light intensity during the next 800 mμsec, reaching a maximum in light intensity for the particular set of conditions, some 900 mμsec after the transition was initiated. By that time, the discharging of the power supply capacity has significantly lowered its potential and light emission then begins to diminish. The arc extinguishes within a few hundred microseconds when the condensers supplying the current have been sufficiently exhausted.

The cross-plots of Figs. 4 and 5 are derived from traces of light intensity such as shown in Fig. 6. Here, from traces of light intensity at several positions along the positive column during the first half-microsecond of the transition, one can infer the motion both of the pip and of the RAP front. For a distance of 39.0 cm

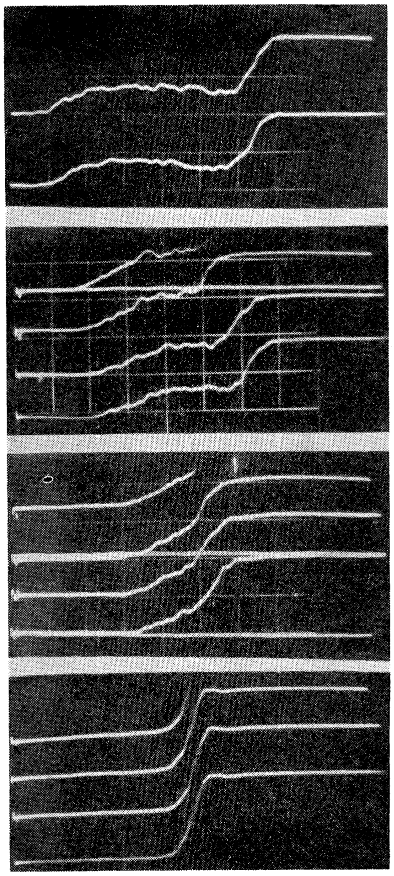

FIG. 6. Light intensities within positive column during transition with Al cathode in H_2 at 97 microns and 1850 volts, with sweep speed 50 mμsec/cm and tube 137 cm long. In the positive column the pip moves with a velocity of 6.2×10^8 cm/sec and the RAP at a velocity of 9.3×10^8 cm/sec.

from the cathode in the first stria of the positive column, there are shown two traces of two separate transitions, while at the remaining distances from the cathode, traces for four separate transitions are shown in each picture. At this voltage of 1850 volts across the tube, which is filled with hydrogen at 97 microns, the light pip travels through the 93 centimeters of the positive column in about 150 mμsec which corresponds to an average velocity of 6.2×10^8 cm/sec. The RAP front takes about 100 mμsec to go the same distance giving an average velocity of 9.3×10^8 cm/sec.

To the naked eye, the transition appears as a very bright, momentary flash, filling the entire tube, including the former Faraday dark space. Whenever the glow-to-arc transition occurs, there appears initially somewhere at the surface of the cathode a small, very brilliant cone of light, perhaps one or two millimeters in height and across its base. The point of the cone originates on the cathode. By examination with the photomultipliers, it was determined that the initial pip of light comes from this small region at the cathode surface, although what the observer sees is probably mainly light from the cathode spot of the momentary arc when it is fully established.

The 350°C, 12-hour bakeout in vacuum which preceded measurements in each of the various gases could not be expected to clean up the aluminum cathode surface, and observations tended to support the beliefs of other investigators[4,10] that either oxide layers, impurities, scratches, or other possible imperfections on the cathode surface are responsible for the initiation of the glow-to-arc transition. In all of the gases excepting oxygen, with continued repetition of measurements, clean-up of the cathode seemed to progress as measurements proceeded. Arcs were observed to *tend to start from the boundary areas between* the "soiled" and the "cleaned-up" sections. Continued work in hydrogen led to the "clean-up" of the entire cathode surface and no further glow-to-arc transitions would take place, at least under the limitation of a maximum of 2600 volts imposed by the power supply. Discharges in nitrogen and argon also cleaned up the cathode although there was a tendency for it to become soiled again if measurements and discharges ceased for any length of time. Probably either impurities or oxygen freed from occlusion during the discharges found their way, during the "off" time, back to the cathode surface. Relevant to this tendency of the transition to be initiated at edges between "soiled" and "cleaned" areas on the aluminum cathode surface is the problem of measurements of the minimum glow currents for the transitions in the various gases. In hydrogen, at pressures of 60–80 microns, transitions would occur at glow currents as low as 50 microamperes. At this pressure and current, the "enhanced" glow discharge covered only a central portion of the front face of the cathode, with the cathode spot of the arc forming at the edge of this area only after the "enhanced" glow discharge had been running several seconds. This was, of course, before the intensive series of measurements had "cleaned up" the surface as mentioned. There is probably no significance to the lower limit of 50 microamperes which was measured as the minimum transition glow current at this pressure and with 2600 volts. It would seem to have been merely the glow current under those conditions at which the glow discharge cathode glow touched

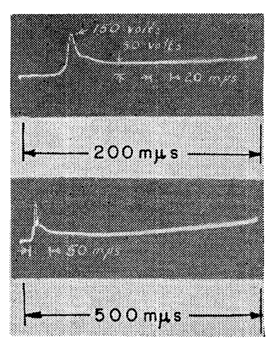

FIG. 7. Al cathode voltages at initiation of transition in N_2 at 130 microns and 2600 volts. Sweep speeds of 20 and 50 mμsec/cm are shown with traces partially retouched, with cathode resistance 25 ohms.

[10] Price, Ganbling, and Edels, Nature **176**, 28 (1955).

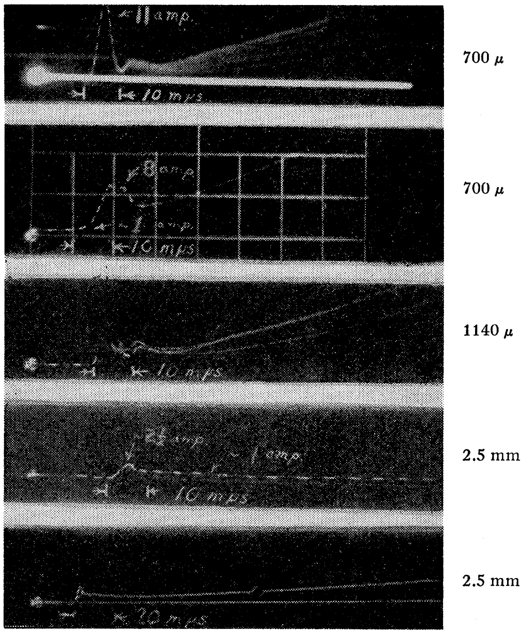

FIG. 8. W wire cathode voltage wave forms for transitions in N_2 at 2600 volts with pressures of 700 and 1140 microns and 2.5 mm in a discharge tube 24 cm long at sweep speeds 10 and 20 mμsec/cm. Traces are partially retouched.

the edge of the still "soiled" area of the cathode and it would appear that had an "all-soiled" cathode been used, transitions in hydrogen at even lower currents could have been possible. Minimum transition glow discharge currents for the aluminum cathode tubes are reported for the various gases in Table I. The observation in hydrogen as to the limited meaning of this measured transition glow current holds for the other gases also, even though the values for nitrogen tend to agree with those listed by Plesse.[11]

For the long aluminum-cathode tube at the low pressures of the order of a hundred to five hundred microns Hg, the glow-to-arc transitions began not only with a sudden "pip" of light which appeared at the cathode surface, but also with a sudden pulse of current emitted from the cathode. Figure 7 shows the cathode voltage in an aluminum-cathode tube filled with N_2 to 130 microns Hg pressure. The glow current of 20–30 milliamperes, which causes a drop of less than a volt across the 25-ohm cathode resistor, suddenly becomes six amperes and 150 volts in less than 10 mμsec. The duration of this sharp current pulse is about 20 mμsec, after which the current remains at a value of about two amperes for approximately 150 mμsec. Then a more gradual increase sets in. There is no corresponding change in the current to the anode as measured across a resistor until the pip arrives, at which time a gradual increase begins.

Measurements of nonthermal transitions in nitrogen for a tungsten cathode discharge at pressures up to 2.5 mm Hg also show the voltage and current pip as well as the light pip. Figure 8 showing the cathode voltage for pressures of nitrogen between 700 microns Hg and 2.5 mm Hg makes evident a decline in the amplitude of voltage pip at the higher pressure. The second smaller pulse upon the bottom trace is due to a burned out terminating resistance in the trigger cable circuit, showing that use of long cables in the cathode circuit of the glow tube can isolate and delay such reflections to prevent their interfering with the signal or distorting it. Light intensity patterns within the tungsten-cathode tubes indicate that the nonthermal tungsten transitions follow a luminosity pattern similar to that for the aluminum-cathode tubes, i.e., a light pip traveling to the anode and a RAP front returning back to the cathode. At a pressure of 2.7 mm Hg with 2600 volts in a 24-cm long tube filled with nitrogen, the light pip was measured as traveling to the anode at an average velocity of 1.7×10^9 cm/sec. The "return arc plasma" front was seen to travel back to the cathode in 25 millimicroseconds corresponding to a velocity of 9.6×10^8 cm/sec.

Figures 9 and 10 show cathode voltages for 20-cm long helium-filled tubes, with copper and nickel cathodes, respectively. The original negatives for these oscillograms had to be retouched for reproduction purposes, since, otherwise, the traces are too faint. The transitions in both cases occurred with 2600 volts across the tubes. In the copper-cathode tube, as has been also reported by previous investigators,[1] the cathode eventually "cleaned up" after a period of use and transitions to arcs could no longer be initiated. Nickel did not "clean up" during the measurements although there did appear to be such a tendency. These oscillograms show, with helium pressures of 3 mm Hg and 6.2 mm Hg in the copper-cathode tube and for 3.55 mm Hg in the nickel tube, that increases from glow currents of the order of one ampere to the arc currents of the order of

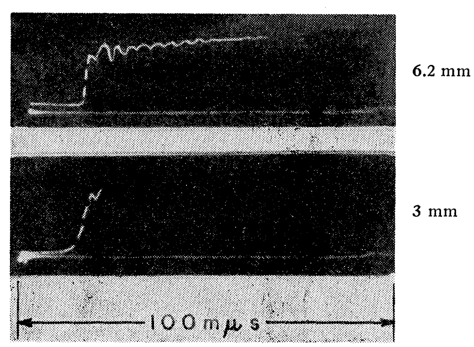

FIG. 9. Cu disk cathode voltage wave forms for transition in He at 3.0 and 6.2 mm Hg with 2600 volts in tube 20 cm long. Sweep speeds are 10 mμsec/cm. Traces partially retouched. At 6.2 mm Hg, the glow current of 1.5 amp increases to 9 amp in less than 3 mμsec. At 3 mm Hg the glow current of 800 ma increases to 10 amp in approximately 6 mμsec and continues to increase at such a rate that it disappears off the face of the oscilloscope. Note the absence of any current pip at these higher pressures.

[11] H. Plesse, Ann. Physik **22**, 473 (1935).

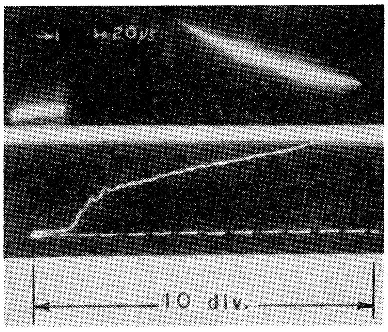

FIG. 10. Ni disk voltage wave forms for transitions in He at 3.55 mm and 2600 volts in tube 20 cm long with sweep speeds 10 mμsec/cm and 20 μsec/cm. Fast traces partially retouched. On slow sweep of 20 μsec per cm, the increase of the glow current to 1.2 amp in some 20–30 μsec is followed by the 300 or more μsec arc, with a maximum current of well over 15 amp. The initial detail may be seen on the fast 10 mμsec/div per cm sweep. Here an arc initiation begins at a glow current of 800 ma, the current increasing to 6 amp in less than 8 mμsec/div followed by a further slower rate of increase. Note the absence of any initial current pip at this higher pressure.

ten amperes take place in less than 10 mμsec. At the 6.2 mm Hg pressure, the current transition takes place in less than 3 mμsec. It is to be noted that no voltage or current pip appears at these higher pressures. At 7.0 mm Hg in the nickel-cathode tube, the current increase, from a glow discharge level which varied between one and eight amperes to arc currents only known to be greater than 15 amperes, was so rapid that the trace could not be photographed, indicating that the increase took place in less than 3 mμsec.

Studies were made of glow-to-arc transitions in mercury-cathode and mercury vapor-gas-filled tubes, with the electrodes separated by some 10 cm, and at pressures of 112 and 275 microns Hg as determined by temperatures of a water bath. With a supply voltage of 2000 volts placed across the discharge tube circuit, small initiating current pips of the order of one ampere were observed. These occurred as the glow discharge, which was limited to only a few milliamperes by a 100-kilohm series anode resistance, broke down to 200-mμsec duration transient arcs. These arcs were made possible by the 60-meter length of cable separating the anode of the discharge tube from the 100-kilohm anode resistance. This cable length was such that the anode resistance appeared to be only 50 ohms for twice the delay time of the cable whenever transient currents appeared in the discharge tube. Some 10 mμsec after the appearance of the pip, the main increase in the arc current began indicating that the sequence of light pip to anode and RAP front to cathode which occurred in the aluminum-cathode and nonthermal tungsten-cathode transitions is also observed. No special effort was made to clean the mercury beyond the initial distillation so that the surface of the liquid cathode could easily have had small arc-initiating contaminants floating upon its surface.

Oscillograms of the changes in potential distribution taking place within the gases during transitions in the $1\frac{1}{2}$-meter long aluminum-cathode tubes are shown in Fig. 11. Here, for a hydrogen-filled tube at 184 microns Hg pressure and 2600 volts, are shown the various voltage wave forms on a microsecond full-scale sweep. The voltage at each electrode and at each of the plasma probes within the tube are shown and the gradual change of voltage at the anode should be noted. This is emphasized in Fig. 12 showing the same changes at a faster sweep of 200 mμsec full scale. The time delay in the appearance of the voltage pip the further the probe is from the cathode is noticeable (the probes are somewhat unevenly spaced along the length of the tube as seen in Fig. 15).

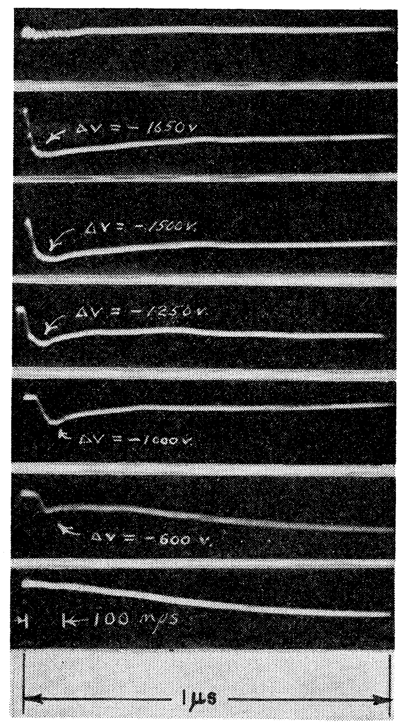

FIG. 11. Voltage wave forms of cathode, anode, and plasma probes during first microsecond of transition with Al cathode in H_2 at 184 microns and 2600 volts/cm in tube 137 cm long.

Using oscillograms such as those of Figs. 11, 12 and correlating them with data pertaining to the initial glow discharge potentials makes it possible to cross-plot the instantaneous potential distributions within the long tubes during the transitions. The potential distribution during the first 160 mμsec of a transition for argon at 97 microns Hg pressure, with 1700 volts and 75 ohms in series with the 146-cm long tube, is shown in Fig. 13. Figure 14 shows the instantaneous distributions of the values of field E and the ratio of E to pressure p, E/p, during the first 80 mμsec throughout the length of the tube. It is obvious that the motion of the light pip from the cathode to anode coincides with the motion of the high-field region. Less obvious from the instantaneous potential distributions of Fig. 13 is the relationship of the progress of the RAP front to the increasing linearity of the potential distribution. Figure 15, showing cross-plots for nitrogen at 280 microns Hg and 2600 volts in a 137-cm long tube, shows both the movement of the pip potential wave to the anode and the subsequent straightening of the potential distribution. This later action results in a nearly linear fall of potential from the cathode fall region to the anode fall region of the arc 1.8 μsec after the transition began. The correlation of the initial straightening of the potential distribution, following the arrival of the pip at the anode, with the RAP front, is again not too evident. It is suggested by the

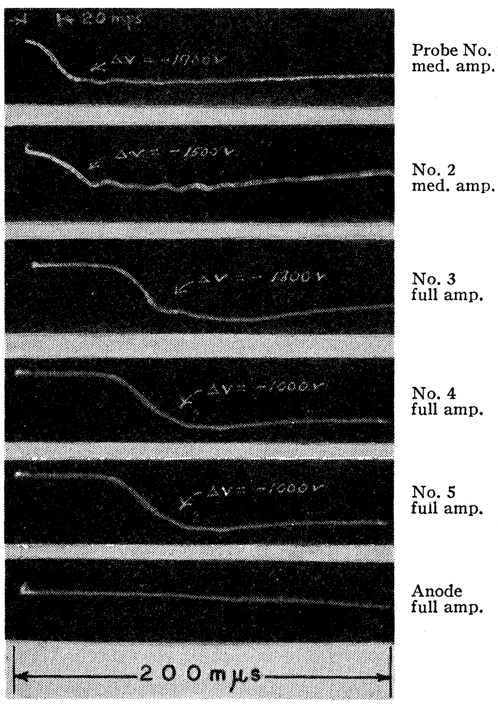

FIG. 12. Voltage wave forms at anode and plasma probes during first 200 mμsec of transition with Al cathode in H_2 at 184 microns and 2600 volts in tubes 137 cm long.

continuous rearrangement of the distribution curves. Figure 16 shows fields and values of E/p for the potential distributions of Fig. 15 during the first 200 mμsec of the transition.

Oxygen, at a pressure below an apparently critical value lying between 128 microns Hg and 184 microns Hg, is similar to argon, hydrogen, and nitrogen—the velocities of the pip are measured at or below approximately (2 to 3)$\times 10^9$ cm/sec. Above that critical value, to at least 470 microns Hg pressure, extremely high light-pip velocities have been measured beginning with a velocity of 4.6×10^9 cm/sec at 184 microns Hg pressure and increasing with pressure to 8.1×10^9 cm/sec at 460 microns Hg.

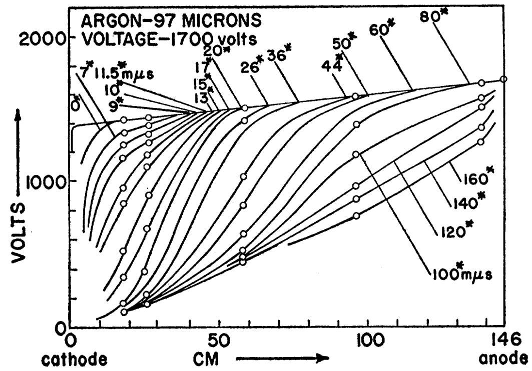

FIG. 13. Potential distribution plots for A at 97 microns and 1700 volts during first 160 mμsec of transition with Al cathode in tube 146 cm long. Asterisks indicate zero time which is the instant the potential begins to change at the first plasma probe.

This increase in velocity of the light pip is accompanied by an increase in the velocity of the voltage pip. Figure 17 shows, at 460 microns and 2600 volts, how the potential distribution across the oxygen filled tube is rapidly altered in the first 25 mμsec after the transition is initiated. Under these conditions, the light pip was observed to have reached the anode within 16 mμsec.

Tables I and II present a summary in tabular form of data concerning glow-to-arc transitions taking place in the long tubes for the various gases. In general, the time interval and average velocity data for measurements over the entire tube length, in contrast to those dealing with the initial pip velocity, are considered accurate to within 10%. This 10% spread is due to real variations connected with differences in the initial glow discharge currents and in the related effects of ionization density and cathode fall potential difference. Fields and field-to-pressure ratios are believed accurate to within 20%. Values of the initial pip velocities are of varying accuracy: 10% at 1×10^9 cm/sec, 20% at

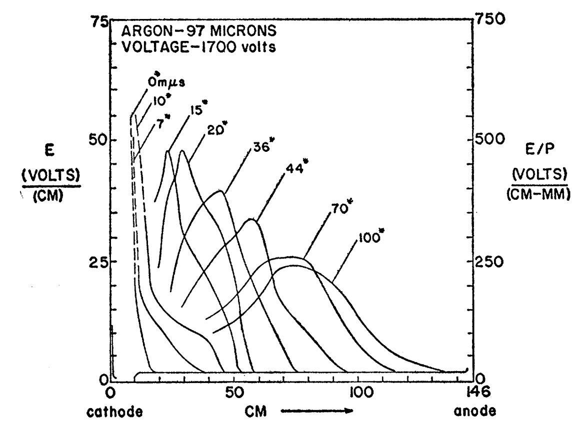

FIG. 14. Electrical field and field-to-pressure ratio distributions during the first 100 mμsec after initiation of transition in argon at 917 microns and 1700 volts with Al cathode for tube 146 cm long. These curves are derived from plots of Fig. 13.

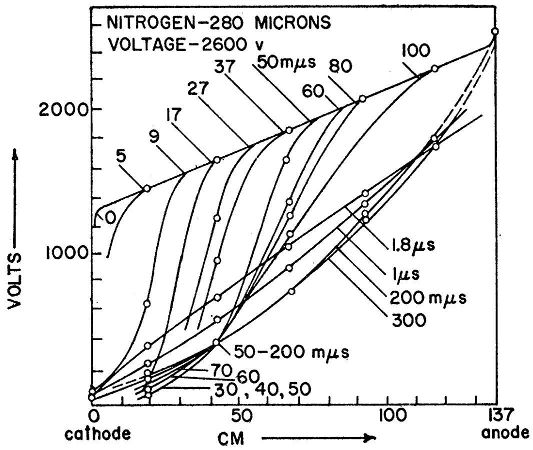

FIG. 15. Potential distribution plots for N_2 at 280 microns and 2600 volts during first 1.8 μsec of transition with Al cathode and tube 137 cm long.

2×10^9 cm/sec, and $33\frac{1}{3}\%$ at 3×10^9 cm/sec. This variation, which is partially due to the reciprocal nature of time in velocity calculations, also is additionally caused by jitter of the sweep starting time of the oscilloscope and difficulty in finding the exact toe of the pip on the oscillogram traces.

Tables I and II contain information on oxygen-nitrogen mixtures, not mentioned previously. All of these mixtures and the nitrogen at pressures of 97, 128, and 184 microns Hg were possibly mercury-contaminated, in contrast to the situation in the other measurements. There was no indication that such a mercury contamination made any difference.

The following information can be garnered from Tables I and II:

(1) In all gases, velocities increase with higher voltages across the tube.

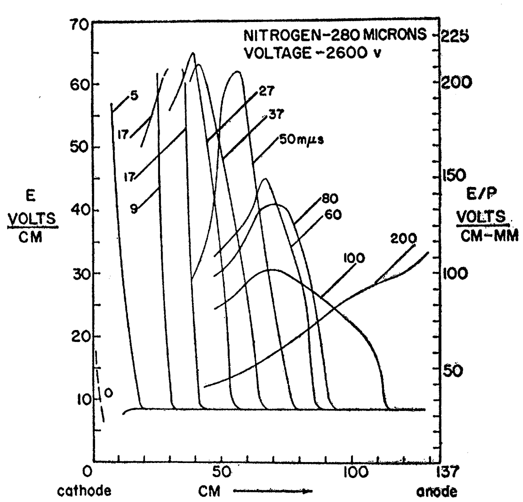

FIG. 16. Electrical field and field-to-pressure ratio distribution for N_2 at 280 microns and 2600 volts during the first 200 mμsec of the transition, with Al cathode in tube 137 cm long. These curves are derived from plots of Fig. 15.

(2) In hydrogen, velocities increase with higher pressures between 97 and 184 microns Hg.

(3) In argon, velocities decrease with higher pressures between 97 and 128 microns.

(4) In nitrogen, velocities decrease with higher pressure between 97 and 280 microns. There are large increases in pip velocity at any total pressure when the nitrogen is diluted with oxygen.

(5) In oxygen, there is a sharp increase in the velocity of the pip as the pressure increases between 128 and 184 microns Hg. The velocity is exceptionally high at the higher pressure.

(6) Within the tube, the maximum E/p values, except for regions very near the cathode, lie between 100 and 500 volts/cm mm Hg during the transition for all gases but oxygen at 184 microns Hg and above. Oxygen at 470 microns Hg has E/p values at most not much above 50 volts/cm mm Hg so that the oxygen pip velocity increases even with the decrease of E/p.

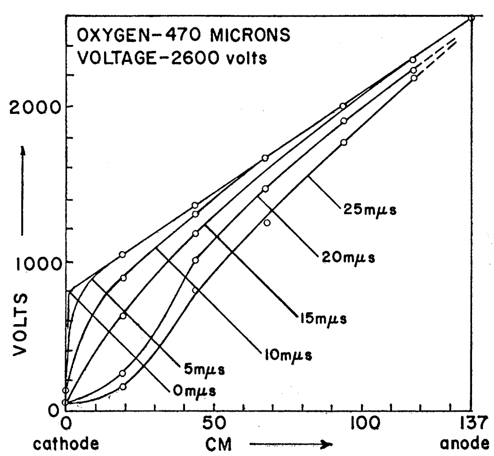

FIG. 17. Potential distribution plots for O_2 at 470 microns and 2600 volts during the first 25 mμsec after the initiation of the transition with Al cathode and tube 137 cm long.

(7) Except for oxygen at pressures of 184 microns Hg and above, there is fair agreement between the initial cathode fall voltage and the electron volt energies equivalent to the initial pip velocities. (Differences in the two measured values can be accounted for most of the time by the experimental errors connected with each measurement.)

Rates of current increase in tubes with several different cathode materials are shown in Table III. Here are summarized the maximum rates of current increase of the initial pip, or for the sudden current increase if no pip occurs, as, for instance, can be seen to be the case with the copper cathode in Fig. 9. Maximum values of the pip current, or, if "pipless," of the initial current rise, as well as the elapsed time, are also listed. In addition, there are tabulated the maximum rates of increase of the arc currents at times well removed from the appearance of the initial pip or of

TABLE I. Glow discharge currents at glow-to-arc transition, elapsed time, and average velocities of light "pip" and "RAP," initial velocities of the light "pip" along with the equivalent electron-volt energy, and the measured glow-discharge cathode fall voltage, for various gases at different pressures and voltages. In all cases the series resistance was 75 ohms.

Gas	Pressure (microns)	Total volts	Average trans. glow current (milliamperes)	Light "pip" time, cathode to anode (10^{-9} sec)	"RAP" time anode to cathode (10^{-9} sec)	Average vel. "pip," cathode to anode (10^9 cm/sec)	Average vel. "RAP" pos. col. (10^9 cm/sec)	Initial vel. "pip" (10^9 cm/sec)	Initial "pip" vel. (equiv. elec. volts)	Initial cathode fall (volts)
H_2 (137-cm tube)	97	1850	<1	182	100	0.75	1.1	1.5	640	...
		2175	<1	141	60	0.97	2.1	1.7	820	...
		2600	<1	105	35[a]	1.3	1.1[a]	1.8	920	...
	128	1850	<1	162	60	0.84	1.3	1.5	640	...
		2175	<1	139	40	0.99	2.0	1.7	820	...
		2600	<1	89	40	1.5	2.0	2.8	2200	...
	184	1900	5–6	145	65	0.94	1.2	2.0	1170	1200
		2175	6	120	30	1.1	2.7	2.0	1170	...
		2600	10	90	30	1.5	2.7	2.2	1370	1900
A (146-cm tube)	97	1700	8–10	116	160	1.25	0.8	2.1	1250	1400
	128	1700	8–10	161	120	0.87	0.96	1.8	920	...
	184	1300	8–10	237	540	0.60	0.2	2.0	1170	...
O_2 (137-cm tube)	49	2600	...	112	...	1.3	...	...	...	...
	65	2600	...	99	...	1.4	...	...	...	...
	76	2600	...	92	...	1.5	...	...	...	...
	97	2600	20–30	87	40	1.6	10	2.3	1480	1700
	128	2600	20–35	95	45	1.5	2.2	...	...	...
	184	2600	...[b]	35	55	4.0	2.4	6–8	$(10–20)\times 10^3$	1650
	200	2600	...[b]	23	82	6.1	1.7	...	...	...
	260	2600	...[b]	20.5	...	6.7	...	...	...	...
	380	2600	...[b]	19	...	7.2	...	...	...	...
	470	2600	...[b]	16	...	8.5	...	8–10	$(20–30)\times 10^3$	800
N_2 (137-cm tube)	174	2175	...[c]		600		0.2	...	...	...
		2400	...[c]		340		0.4	...	...	...
		2600	...[c]	60–80	180	1.7–2.3	0.8	2.0	1170	1700
	200	2600	...[c]		180		0.8	...	...	...
	240	2600	...[c]		200–400		0.3–0.6	...	...	...
	280	2600	...[c]		340		0.4	1.8	920	1350
N_2[d] (146-cm tube)	97	1700	20–25	300	250	0.4	0.8	2.0	1170	...
	128	1700	20–25	450	350	0.3	0.6	0.8	180	...
	184	1700	20–25	700	2.5 μsec	0.2	0.16	0.5	70	...
$N_2+1\%\ O_2$[d] (146-cm tube)	97	1700	8–10[e]	260	550	0.6	0.8	...	...	...
		1700	20–25[e]	200	600	0.70	0.6	3	2500	...
	128	1700	20–25	230	900	0.59	0.54	1	300	...
	184	1700	20–25	220	3.5 μsec	0.65	0.24	0.9	230	...
$N_2+20\%\ O_2$[d] (146-cm tube)	97	1700	8–10	240	...	0.6	...	5	7000	...
		1700	20–25	170	600	0.84	0.8	...	...	...
	128	1700	20–25	180	1 μsec	0.78	0.7	...	...	...
	184	1700	20–25	220	5 μsec	0.65	0.2	2.0	1170	900

[a] RAP appeared at cathode before appearing at head of positive column, giving smaller RAP velocity in positive column.
[b] Transition too fast; glow current could not be measured.
[c] No measurements made.
[d] Possible mercury contamination.
[e] Two glow current modes possible.

the initial pipless increase. Times listed show the time interval following the initiation of the transition before this maximum rate of arc current increase is reached.

The studies with a tungsten wire cathode showed transitions that all took place in times of the order of 10^{-8} sec and therefore cannot be considered to be thermal transitions. Platinum cathodes and mercury cathodes were also briefly studied with results shown in the table. The mercury cathode was even frozen without any discernible difference.

Information that might be garnered from Table III is as follows:

(1) The changes of emission of the cathode currents at the beginning of the arcs, from milliamperes (or sometimes amperes) to several amperes, take place in less than 10^{-8} second. Under some conditions this increase takes place in 3 or 4 mμsec. Rates of increase of the pip current up to $(3 \text{ or } 4)\times 10^9$ amperes per second are possible. The rate of increase and the maximum current in the pip are probably determined by several factors including the initial cathode fall potential difference, how effectively it is neutralized, the pressure, and the mechanism of emission. There is no particular rule observable in the rates of emission of the maximum pip current.

(2) The rates of current increase of the main arc current become less with the higher pressures. As both the tungsten-nitrogen and the mercury-helium transi-

TABLE II. Maximum electrical fields and field-to-pressure ratios during passage of the voltage "pip" from cathode to anode during the glow-to-arc transition in various gases at different pressures and voltages. In all cases the series resistance was 75 ohms.

Gas	Pressure (microns)	Total volts	Average trans. glow current (milli-amperes)	Max field 30 cm from cathode (volts/cm)	Max field 60 cm from cathode (volts/cm)	Max field 90 cm from cathode (volts/cm)	Max field 120 cm from cathode (volts/cm)	Max E/p 30 cm from cathode (volts/cm—mm Hg)	Max E/p 60 cm from cathode (volts/cm—mm Hg)	Max E/p 90 cm from cathode (volts/cm—mm Hg)	Max E/p 120 cm from cathode (volts/cm—mm Hg)
H_2 (137-cm tube)	184	1900	5–6	60	55	45	40	375	300	245	220
		2600	10	80–90	70–80	60	45	435–500	380–400	325	245
A (146-cm tube)	97	1700	8–10	47	35	25	20[a]	470	350	250	200
O_2 (137-cm tube)	97	2600	20–30	50	45	35	25	500	450	350	250
	184	2600	...[b]	40	...[a]	...[a]	...[a]	220	...[a]	...[a]	...[a]
	470	2600	...[b]	27	...[a]	...[a]	...[a]	57	...[a]	...[a]	...[a]
N_2 (137-cm tube)	174	2600	...[c]	100	50–55	30	...[a]	575	290–315	170	...[a]
	280	2600	...[c]	70	55–60	30	...[a]	250	195–215	110	...[a]
$N_2+20\%\ O_2$[d] (146-cm tube)	128	1700	20–25	35	23	16	12	275	180	125	94

[a] "Pip" field is still increasing when the "RAP" reaches same position.
[b] Transition too fast, glow current could not be measured.
[c] No measurements made.
[d] Possible mercury contamination.

tions show, this rate can be nearly 10^9 amperes/sec at pressures in the hundreds of microns, but it decreases to 10^8 amperes/sec and lower as pressures exceed one or two mm Hg. The rates of main arc current increase are also, as would be expected, higher for the short tubes than for the long tubes, the total voltages being the same in both cases.

DISCUSSION

The study of the glow-to-arc transition can be divided into two main sections: (1) cathode processes, and (2) processes within the gases. It is proper to discuss the cathode processes first, since the conditions at the cathode concern the initiation of the transition and define whether or not it will take place as well as how it will take place.

Cathode Processes

The glow-to-arc transition here described can owe its manifestation to only one circumstance. This is the sudden creation of an exceedingly high emissivity at the cathode in the form of a burst of electrons of such magnitude and on such a time scale that it launches an ionizing potential space wave instead of increasing conductivity by the normal diffusive ionization processes. This fact is borne out by direct observation of the brilliant flash of light at the cathode surface, which estimate places as 1 mm diameter though it could be too large by a factor of 10, the current increase of from $(1\text{ to }50)\times10^{-3}$ amp to 1 to 10 amp in 5×10^{-9} sec, and the importance of the oxide film at the cathode in triggering this phenomenon. The influence of the nature of the gas filling, the nature of the oxide film, as well as the predilection for the breakdown occurring near the clearing edge of the layer together with the changes of current and the elapsed time in producing the phenomena permit some conclusions to be drawn. The creation of a current pip of 1 to 10 amperes in 5×10^{-9} sec corresponds to the liberation of $(2.5\text{ to }25)\times10^{-9}$ coulomb of electrons in that time interval. This corresponds to roughly $(1.6\text{ to }16)\times10^{10}$ electrons from a layer of area of 0.01 cm^2 or less of surface in 5×10^{-9} sec. Had these electrons been created by some cumulative ionizing process in the gas by electrons equivalent to the initial existing current of 1 to 50 ma with a density over the assumed 1 mm^2 of 10^6 electrons in 10^{-8} sec per mm^2, this would have taken some 10 to 12 successive ionizing generation of events. At the electron free paths and collision frequencies possible in the cathode fall, the time consumption, even assuming an ionizing probability of unity, would have been many times that observed and the volume involved, owing to the high energies and diffusion, would probably have corresponded to the whole volume of the dark space and a large section of the negative glow. This does not agree with observations.

In consequence, it is clear that the triggering event requires that the electrons be emitted from the solid and in this instance, by the thinning oxide layer. With this in mind, two possibilities exist: The first is that when a layer of insulating oxide of the right thickness becomes heavily charged by positive ions and/or by secondary electron emission accompanying positive-ion bombardment, so that the field across the oxide reaches very high values, the metal cathode surface liberates an equivalent field emission current density of the order of at least 100 amperes/cm^2. The second is that in consequence of the high fields across the oxide layer, an actual breakdown of the thin oxide layer takes place. Since a layer of Al_2O_2 10^{-5} cm thick and 10^{-2} cm^2 in area contains of the order of 2.4×10^{16} molecules, ionization of such a layer by collision could readily furnish the $(1.6\text{ to }16)\times10^{10}$ electrons with only one in $(1.6\text{ to }16)\times10^5$ of the oxide molecules ionized.

The exact process by which this ionization occurs is

TABLE III. Peak cathode currents and maximum rates of cathode current increase during the initial processes in the first several millimicroseconds of the glow-to-arc transitions for various cathode metals, gas pressures, and tube lengths. Parentheses about listed currents and times, usually for gases at higher pressures, indicate transitions where the initial cathode current increase was *not* followed by a subsequent, though temporary, decrease. The final column lists maximum rates of arc current increase at indicated times well removed from the initial cathode current increase. This rate of increase is associated with the plasma ionization density increase in contrast to the initial increase due to the arc initiation process and influenced in part by the large glow discharge cathode fall. In all cases the series resistance was 75 ohms.

Cath.	Gas	Pressure in microns	Peak "pip" current in amperes (or init. rise if no "pip")	Time to "pip" max in milli-microseconds (or to end of init. rise)	Max rate of "pip" current increase (amp/sec)	If no "pip," init. max rate of current increase (amp/sec)	Apparent max rate of arc current increase (amp/sec) (Time of measurement)
Short tubes[a]							
W (24-cm tube)	N_2	280	4[b]	4	1.3×10^9	...	8×10^8 (40 mμsec)
			7	5	2.5×10^9	...	
		620	15	4	4.0×10^9	...	4×10^8 (40 mμsec)
		640[c]	4[b]	4.5	2×10^9	...	3×10^8 (40 mμsec)
			10	10	2.5×10^9		
		700	16	4	4.5×10^9	...	2.5×10^8 (40 mμsec)
		780	14	4	3.5×10^9	...	1×10^8 (40 mμsec)
		1140	...	3–4	...	...	2.7×10^8 (40 mμsec)
		2.5 mm	2.5	4	1×10^9	...	8.5×10^6 (120 mμsec)
Cu (20-cm tubes)	He	3.0 mm	(12)	(7)	...	3.2×10^9	...
		6.2 mm	(11)	(3.5)	...	4.5×10^9	1×10^8 (40 mμsec)
Ni (30-cm tube)	He	3.55 mm	(5)	(6)	...	1.2×10^9	1.2×10^8 (40 mμsec)
		7.0 mm	...	...	...	2×10^9	...
Pt (20-cm tube)	He	3.3 mm	2	4	1×10^9	...	...
		6.2 mm	2	10	...	...	...
Hg (10-cm tube)	He	1.5 mm	(2)	($2\frac{1}{2}$)	...	8×10^8	8×10^8 (20 mμsec)
		1.8 mm	(2)	($2\frac{1}{2}$)	...	1.2×10^9	6×10^8 (20 mμsec)
Hg (frozen) (10-cm tube)	He	1.8 mm	(2)	(2)	...	1.2×10^9	8×10^8 (20 mμsec)
		3.4 mm	(2)	(2)	...	1.2×10^9	6×10^8 (20 mμsec)
		3.6 mm	...	...	...	...	4×10^8 (20 mμsec)
Hg (10-cm tube)	Hg	112	2	2	10^9	...	1×10^9 (20 mμsec)
		275	2	2	10^9	...	1×10^9 (20 mμsec)
Long tubes[a]							
Al (137-cm tube)	N_2	130	6	8	3×10^9	...	...
		228	3	8	7.5×10^8	...	...
		300	4	5	1×10^9	...	...
Al (137-cm tube)	O_2	97	3	15	2×10^8	...	30×10^6 (200 mμsec)
		184	4	10	5×10^8	...	$15–20\times10^6$ (100 mμsec)
		470	6	10	8×10^8	...	$3–5\times10^6$ (50 mμsec–1 μsec)

[a] All work done with 2600 volts across the tubes except the Hg cathode-Hg vapor work where the voltage was about 2000 volts.
[b] There were two humps to the "pip," so rates of rise of each hump are calculated here.
[c] The tungsten "high-temperature transition." Cathode became red hot but transitions still nonthermal.

at present not known. Malter[12] and Koller and Johnson[13] have observed that when layers of Al_2O_3 (in the former case coated with Cs) were bombarded with energetic electrons, the surfaces charged sufficiently positively by secondary emission to yield a discharge from the surface characterized by minute brilliant local flashes of light, i.e., scintillations. The potential differences across the oxide layer in Koller and Johnson's work equalled 50 volts across 10^{-4} cm or less. The electrons were emitted at various points and had energies up to the full voltage of 50 volts across the layer. The appearance of the flashes in Malter's work coincided with a clean-up of the surface. Haworth[14] suggests that Koller and Johnson's scintillations may have represented minute arcs as the surface was pitted after the scintillation took place. Studies of Dobischeck, Jacobs, Freely, and Brand[15] indicated secondary emission of a high order from thin films of MgO laid down on metal surfaces. They used bombardment by energetic electrons to create the positive charge on the outer MgO surface and the secondary emission currents from the oxide layer and metal backing exceeded by many times the bombarding electron current. Their rather complete study ruled out field emission from the metal as the primary source of the currents. This is certainly true also in the observations of the glow-to-arc transitions, as the fields required to give bursts of the order of 100 amp/cm^2 or more are not to be achieved. However, field emission, according to Jacobs *et al.*, may play a role in starting the processes they envisage. They assume that relatively weak field-emitted electron currents from the metal create much excitation and ionization of the oxide in the pores or channels. These excited states produce high-energy photons that liberate further electrons from the metal which escape through the pores in the layer and give a heavy low-energy electron current, electron energies being less than the potential drop across the oxide. That the pores in the

[12] L. Malter, Phys. Rev. **49**, 879 (1936); **50**, 48 (1936).
[13] L. R. Koller and R. P. Johnson, Phys. Rev. **52**, 519 (1937).
[14] F. E. Haworth, Phys. Rev. **80**, 223 (1950).
[15] Dobischek, Jacobs, and Freely, Phys. Rev. **91**, 804 (1953); Jacobs, Freely, and Brand, Phys. Rev. **88**, 492 (1952).

oxide layer are of influence was evident from the fact that nonporous MgO layers were not efficient. This type of action is in keeping with the observation in glow-to-arc transitions that it is the portion of the oxide layer that is being cleaned up that appears to cause the effect. Since in the transition high-energy positive ions of up to 1000 volts charge the outer layer, the high fields produced may cause the field-emitted electrons and such photoelectrons to cumulatively ionize the oxide and thus cause a complete breakdown of the layer and perhaps a localized power arc. In Jacobs' studies with lower surface charges on the oxide, cumulative ionization appears not to have occurred. The mechanisms of the transition and of Jacobs are not related to the arcing process occurring on closing metallic contacts at higher gas pressures of from 50 mm up, the theory of which has been developed by Kisliuk[16] and Boyle and Haworth,[17] for the pressures in the transition are too low as is also the case in the vacuum studies of Jacobs and Malter, cited.

Enough has been said to indicate that a thinning insulating oxide layer charged on the outside by positive ions from the dark space having the order of 10^3 volts energy, the layer being of the order of 10^{-5} cm thick and thus having fields across it which could reach 10^8 volts/cm, will suffer through field-emission currents from the metal a partial or complete breakdown of the oxide layer with $7\times(10^{-3}$ to $10^{-4})\%$ ionization of the atoms within the layer in times as short as (2 to 10) $\times 10^{-9}$ sec. Thus flash breakdown, yielding of the order of (1.6 to 16)$\times 10^{10}$ electrons over an area of the order of 10^{-2} cm^2 or less in a high-field region of low pressure, will project the electrons as a beam in the cathode fall region. This beam, by further ionization amplifying and expanding the localized surface discharge, then leads to the relatively brilliant and rapidly moving luminous displays characterizing the transition. By chance it happened that in setting up the techniques presented for another purpose, conditions proved suitable for precipitating the glow-to-arc transition under conditions such that the sequence of phenomena could appropriately be studied to establish their relation to the ionizing potential space waves to be considered and of which they are the cause.

Processes within the Gases

The sudden transition of the cathode mechanism from a secondary emission process, needing a large cathode fall voltage, to a transient intense cathode arc emission process, results in the large and short-range cathode fall of the glow discharge suddenly becoming the connection between a relatively large-current and high-ionization-density arc plasma at the cathode and the low-current, low-ionization-density glow discharge plasma of the column.

In consequence of this catastrophic field distortion, the observations indicate that there are created rapidly moving transient high fields called ionizing potential space waves, with correspondingly high E/p values moving through the gas. These fields are observed to extend over distances up to several tens of centimeters and are far higher than those encountered in striations of glow discharges such as those measured by Warren,[18] Watanabe and Oleson,[19] and others.

An important clue as to the origins of the high velocities of the potential waves observed comes from the reasonably good agreement (except in the case of higher pressures of oxygen) between the measured initial pip velocity and the equivalent velocity that an electron would have in free fall through a voltage equal to the cathode fall of the glow discharge. That electrons can and do gain such energies in the cathode fall has been shown in the studies of Brewer and Westhaver.[20]

In view of these conclusions and the experimental data, the following mechanism of the low-pressure nonthermal glow-to-arc transition is suggested:

A. Motion of the Pip to the Anode

(1) There is a sudden, greatly increased emission of electrons from the cathode, from milliamperes to amperes of current in millimicroseconds. This emission initially can become very large since the large cathode field of the glow discharge does not instantaneously disappear and the current is not space-charge limited.

(2) The first electrons of this initial burst gain nearly the full energy of the cathode fall and then begin to dissipate that energy in ionizing collisions in the low-field region.

(3) Some of these first additional electrons which are stopped by the collisions will begin to neutralize the excess positive-ion space charge of the dark space and the cathode fall voltage will begin to decrease. At the same time, the field in the negative glow will increase rapidly owing to advance of the cathode-emitted electron cloud marking the propagation of the cathode fall potential difference. Most of the initial electrons will pass into the negative glow and dissipate their energies along its length. As the cathode fall potential is propagated, electrons emitted slightly later will pass the first electrons, since the later electrons have been in a high-field region over a longer distance, without a significant difference of energy loss in that high-field region.

(4) The approach to more complete neutralization of the positive-ion space charge of the dark space, which takes place in a time $\Delta t \cong 10^{-8}$ sec, with the production of an overwhelming number of new positive ions and electrons, reduces the field and the cathode arc current to a low value as it becomes space-charge

[16] W. S. Boyle and P. Kisliuk, Phys. Rev. **97**, 255 (1955); Boyle, Kisliuk, and Germer, J. Appl. Phys. **26**, 720 (1955).
[17] W. S. Boyle and F. E. Haworth, Phys. Rev. **101**, 935 (1956).
[18] R. W. Warren, Phys. Rev. **98**, 1650 (1955); **98**, 1658 (1955).
[19] S. Watanabe and N. L. Oleson, Phys. Rev. **99**, 1701 (1955).
[20] A. K. Brewer and J. W. Westhaver, J. Appl. Phys. **8**, 779 (1937).

limited. The very short time interval of 10^{-8} sec, owing to the rapid movement of the potential wave, limits the amount of ionization that the initial burst of electrons can produce in any cross-sectional volume, so that the ionization density created, while large compared to the glow discharge density, is just enough to support a low-current arc.

(5) With the disappearance of the large glow-discharge cathode fall, the tube now consists of an arc plasma, extending one or two centimeters from the cathode, and a glow-discharge plasma beginning approximately $v_0\Delta t$ centimeters from the cathode, v_0 being given by $5.94\times10^7(V)^{\frac{1}{2}}$ cm/sec. In the zone between these plasmas is a very-high-field region containing many very fast electrons, mainly at the front tip of the high field, as well as many slow electrons, mostly created by ionizing collisions.

(6) Owing to their high velocity and the low pressure, significant loss of energy for any electron takes place over distances of the order of centimeters.[20,21]

(7) The velocity of the potential wave can be explained if one takes into consideration the velocities of a group of electrons at the front tip of the moving field region. This group originally consisted of the first electrons of the additional emission burst. If individual electrons in the group move faster than the potential wave, they will lose their energy in the low field ahead of it. At the same time, the ionizing collisions made by all of these additional electrons will increase the conductivity in the plasma and advance the region of the high potential gradient into the gas. This increased conductivity has a velocity equal to the velocity of the very fast electrons which are creating it. Within the high-field region, new electrons will be accelerated to the front of the potential wave to replace some of those lost, and some of the electrons which slow down in the region ahead of the potential wave will regain their energy in the high field when it catches up, and move ahead again. However, as the front advances, it is continually losing energy to ionization and gradients are reduced by diffusion so that the ionizing zone widens, declines in luminous density, and gradually decreases in velocity.

(8) Losses of electrons from the fast group to the walls and in ionizing and exciting collisions may be partially compensated by the addition of others created and accelerated in the high-field region, but since close analysis of data shows that pip velocities decrease as the pips move from cathode to anode, it appears that the compensation is never complete. How much influence the walls exert in the processes described is not known. Owing to the very short time intervals involved, the usual diffusive influence does not have time to develop. The observations of Snoddy,[5] however, indicate that in similar waves the influence of wall diameter is minor.

[21] A. von Engel, *Ionized Gases* (Clarendon Press, Oxford, 1935).

(9) At and behind the high-energy group at the head of the moving field are many lower-energy electrons which continue the ionization process in the still-high-field region, so that eventually the ionization density will be as great as in the low-current arc plasma which extends from the cathode and the potential at the point in question will have changed from the glow discharge level to the low-current arc plasma level which "anchors" the cathode end of the pip potential wave.

The possibility of photoionization within the gas during the transition, as most certainly occurs in oxygen, can lead to propagation of the potential waves through the tube with extremely high velocities. When the pressure is too low, the photoionization will occur too far and too weakly in advance of the potential field and its high gradient to be efficiently exploited. If the pressure is too high, then the short-range photons will be active in increasing local ionization, thus speeding the buildup of the plasma column from the cathode but otherwise not advancing the front. However, between these extremes, at just the right pressures, velocities of propagation may be materially increased.

The rate of ionization at time t at a distance r from a source at x, y, z, neglecting loss factors, of strength N photons per second per unit volume is given by

$$\left(\frac{dI}{dt}\right)_t = N\left(x, y, z, t-\frac{r}{c}\right)dV\left(\frac{1}{4\pi r^2}\right)\mu_1 p e^{-\mu_1 p r},$$

where μ_1 is the absorption coefficient at 1 mm Hg pressure, and p is the pressure in mm. Hg. To get the total rate of change of ionization density, $(dI/dt)_t$ would have to be integrated over the entire tube and since the strength of each volume source element $N(x, y, z, t-r/c)dV$ is itself the result of time and volume integrations, to say nothing of the loss factors neglected, a solution is of extreme difficulty.

An intuitive assumption, that can be sustained only weakly by loose arguments, would be that the condition $e^{-\mu_1 p r}=e^{-1}$ defines the minimum limiting value of pL at which photoionization is an important process during the transition, L here being of the order of the dimensions of the tube. If we substitute $L=137$ cm, the length of the long tube, and $p=150$ microns, the medium between 128 microns Hg and 184 microns Hg where the extreme change in pip velocity in oxygen became apparent, we get $\mu_{760\text{ mm}}=36$ cm^{-1} or $Q=1.4\times10^{-18}$ cm^2. If instead we use $L=4$ cm, the diameter of the discharge tube, we get $\mu_{760\text{ mm}}=1250$ cm^{-1} or $Q=49\times10^{-18}$ cm^2.

Photoionization absorption data for oxygen have been measured by Wainfan, Walker, and Weissler,[22] and Lee.[23] Other studies are summarized in an article by Weissler,[24] Wainfan, Walker, and Weissler found

[22] Wainfan, Walker, and Weissler, Phys. Rev. **99**, 542 (1955).
[23] Po Lee, J. Opt. Soc. Am. **45**, 703 (1955).
[24] G. L. Weissler, in *Handbuch der Physik* (Springer-Verlag, Berlin, 1956), Vol. 21, p. 304.

ionizing cross sections for O_2 between 473 A and 1100 A of between 5 and 30×10^{-18} cm^2. Lee made an extensive study of the absorption coefficients of oxygen between 1300 A and 200 A, finding three weak dissociation continua above 1040 A, and between 1040 A and 740 A diffuse absorption bands with a maximum coefficient of 100 cm^{-1}. The main ionization continuum begins at 683 A, reaching a maximum $\mu_{760\text{ mm}}=590$ cm^{-1} at 510 A. Very recent findings of Przybylski and Raether,[25] using radiation in O_2 from the high-field region of a coaxial cylindrical corona discharge, find ionization for a wavelength less than 1022 A (the ionization potential of O_2) with $\mu=38$ cm^{-1} at 760 mm Hg in fortuitously good agreement with the calculation above. Further ionization takes place for a more highly absorbed radiation. This probably corresponds to the over-all photoionization absorption coefficient critical in streamer and burst-pulse corona due to the shorter wavelength part of the band beginning at 1040 A, which is of the order of 100 cm^{-1} as determined by Loeb[7] from corona studies and indicated by Weissler in a private communication to Loeb.

The two values calculated above straddle the estimates of Przybylski and Raether and Weissler, the second larger value utilizing the diameter of the tube as a critical dimension probably being not too important since the work of Snoddy, Dietrich, Beams, and Mitchell[5] has shown that potential waves are little affected by the tube diameters.

B. Motion of the "Return Arc Plasma" (*RAP*) *Wave Front to the Cathode*

(1) The "return arc plasma" wave front moves from the anode to the cathode with velocities comparable to and often even greater than those of the oppositely moving pip. Nevertheless, measurements of the potentials show an adjustment in the potential space-wave pattern of such a gradual character compared to those associated with the pip that further consideration is needed.

(2) With the final movement of the pip potential wave to the anode, the potential distribution profile is a simple curve with gradient increasing in value towards the anode. The increased rate of ionization in the high fields near the anode very quickly results in higher ionization density and rate of ionization in that region. The higher ionization densities tend to decrease the gradient and thus "lift" and "straighten" the potential profile in the region where they occur. As long as the anode end of the profile is "anchored" to a fixed potential by a high capacity and small series resistance, the "lifting" and "straightening" of the profile will tend to increase the field closer and closer to the cathode. The "return arc plasma" light front is just this region of intensified field moving toward the cathode.

[25] A. Przyblski and H. Raether, Z. Naturforsch. **13a**, 234 (1958).

(3) While the fields and field-to-pressure ratios in the RAP wave are far lower than during the pip motion to the anode, the light output of the "return arc plasma" front is soon comparable to that of the pip. By the time that the RAP field has begun to increase at any point, the ionization density at that point is far higher than it was in the preceding glow column and corresponds to that of a low-current arc. Thus even with far lower fields, the total *rate of excitation and ionization* is soon comparable with that of the pip potential wave since the rate is proportional to and then greater than the pre-existing ionization densities as well as field strengths. This increased rate of ionization despite the lower E/p ratio also results in a more rapid advance of the RAP point which is sometimes observed. Here, however, the nature of the gas is paramount and may involve secondary photoionization processes in the highly excited plasmas of some gases.

(4) Once the "return arc plasma" front has reached the cathode, the ionization density throughout the tube is relatively uniform as is evidenced by the near linearity of the potential profiles. The field within the positive column of the arc is still so large that the ionization density multiplication continues, and the current will continue to increase quite rapidly. The rates of increase of arc current at pressures of 2 to 7 mm Hg, as recorded in Table III, are in general of the same order of magnitude as those measured by Froome[3] with comparable fields and E/p ratios in the same pressure range.

(5) It is obvious that the second potential wave, moving from the anode to the cathode, represents the beginning of the light emission of the main arc at any point within the tube. It increases the ionization left by the pip and neutralizes the excess negative charge left in the gas so that when it reaches the cathode, the arc current can begin to build up by conventional processes since the gradients existing along the plasma are still high. Thus on moving back to the cathode it creates the arc plasma conditions necessary for higher arc current. It is for this reason that it has been designated the "return arc plasma" front. Once the RAP front has reached the cathode, the discharge currents begin rising to the order of tens of amperes, continually increasing as the arc column homogenizes and becomes more conducting. This increased current and higher conductivity, in connection with the IR drop in the external series resistance and the draining of the condenser, progressively lowers the still high gradient acting across the arc column. The increase in the potential drop through the small resistors at cathode and anode can be seen clearly in Figs. 13 and 15.

C. Intermediate-Pressure Glow-to-Arc Transition with Cathodes other than Al (1–7.22 mm Hg)

In the nonaluminum-cathode tubes, as gas pressures increase above 1 mm up to 7.2 mm, the pip and RAP fronts are still observed to travel with velocities comparable to those at the lower pressures. The only significant change is in the initial phase of the cathode current. Whereas at low pressures the breakdown of Al_2O_3 film results in an increase of current from $\sim$1–50 ma up to 1–10 amperes in $\sim(5\text{–}10)\times 10^{-9}$ sec, followed by a decline to some 1 to 2 amperes in another (5–10) $\times 10^{-9}$ sec, the cathode current at higher pressures increases to a steady value of the order of several amperes in $(2\text{–}3)\times 10^{-9}$ sec and remains there until the RAP front reaches the cathode. No potential studies were made under these conditions, which involved short tubes designed for the study of cathodes other than aluminum.

Under these conditions, the cathode fall was less $\sim$150–350 volts, but otherwise total potentials were the same even for the shorter tubes so that E/p values in the glow discharge columns were comparable to those in the longer tubes. Obviously the same type of breakdown of an oxide layer that takes place with low pressure and Al cathodes and comparable burst of electrons occurred here. However, with higher pressures, shorter ionizing free paths, and lower cathode falls, the initially emitted electrons achieved their intense ionization within shorter distances from the cathode (mm instead of cm) and very rapidly (10^{-9} sec instead of 10^{-8} sec). The dark space was rapidly neutralized by the intensely concentrated ionization. The current rise by electron emission was rapidly accommodated by the decreasing cathode fall caused by the increased localized rate of ionization incident to higher collision rate at increased pressure. While a potential front was propagated, it left sufficiently high conductivity behind it as it progressed along the tube to make possible higher subsequent current flow than is present at lower pressures. This continuity of conductivity is indicated by the maintenance of the initial current burst at a steady value.

Here one sees the approach to conditions where emission fluctuations of the cathode can be compensated nearly as rapidly as formed. That, with a cathode fall of only 300 volts or so and with increased molecular and initial ionic densities in the plasma, the pip and RAP nevertheless move with sensibly the same velocities as at the lower pressures, presents a strong argument for the interpretation of the brilliance and speed of the RAP front at the lower pressures. For here at the intermediate pressures E and E/p values are lower but ion densities and rate of increase in ionization are still as high. It is not impossible that with these conditions, the existence of excited states and dissociation, etc., may be such that photoelectric processes may also play a role.

Unfortunately, time and lack of high-potential, high-capacitance power sources did not permit the extension of these studies to longer tubes or higher pressures. However, it is quite clear from these observations that as cathode falls decrease and gas densities increase, the bursts of discharge leading to the arc transition, if they occur at much increased pressures, may produce the necessary carrier multiplication propagation of the pip alone. As pressures further increase, it is possible that breakdown of the oxide layer may not produce sufficient disturbance to propagate the space waves so that increased currents resulting will build up on time scales and in such manner more nearly comparable with the commonly observed striationary process.

ACKNOWLEDGMENTS

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Gratitude must also be expressed to the Office of Naval Research and the Research Corporation for their grants, which were of the utmost help in making this work possible.

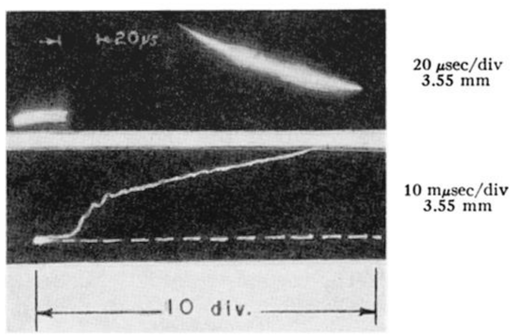


FIG. 10. Ni disk voltage wave forms for transitions in He at 3.55 mm and 2600 volts in tube 20 cm long with sweep speeds 10 mμsec/cm and 20 μsec/cm. Fast traces partially retouched. On slow sweep of 20 μsec per cm, the increase of the glow current to 1.2 amp in some 20–30 μsec is followed by the 300 or more μsec arc, with a maximum current of well over 15 amp. The initial detail may be seen on the fast 10 mμsec/div per cm sweep. Here an arc initiation begins at a glow current of 800 ma, the current increasing to 6 amp in less than 8 mμsec/div followed by a further slower rate of increase. Note the absence of any initial current pip at this higher pressure.

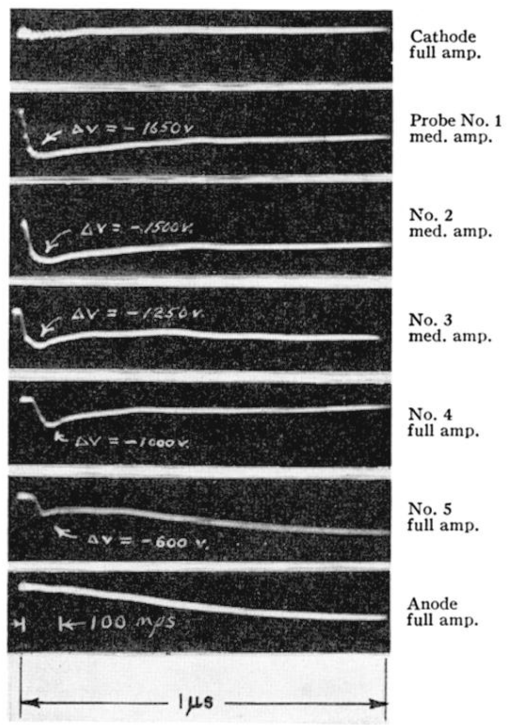


FIG. 11. Voltage wave forms of cathode, anode, and plasma probes during first microsecond of transition with Al cathode in H_2 at 184 microns and 2600 volts/cm in tube 137 cm long.

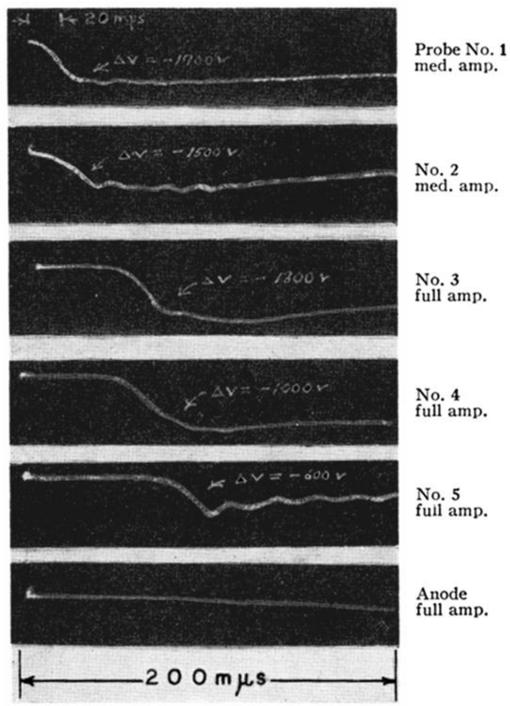


FIG. 12. Voltage wave forms at anode and plasma probes during first 200 mμsec of transition with Al cathode in H_2 at 184 microns and 2600 volts in tubes 137 cm long.

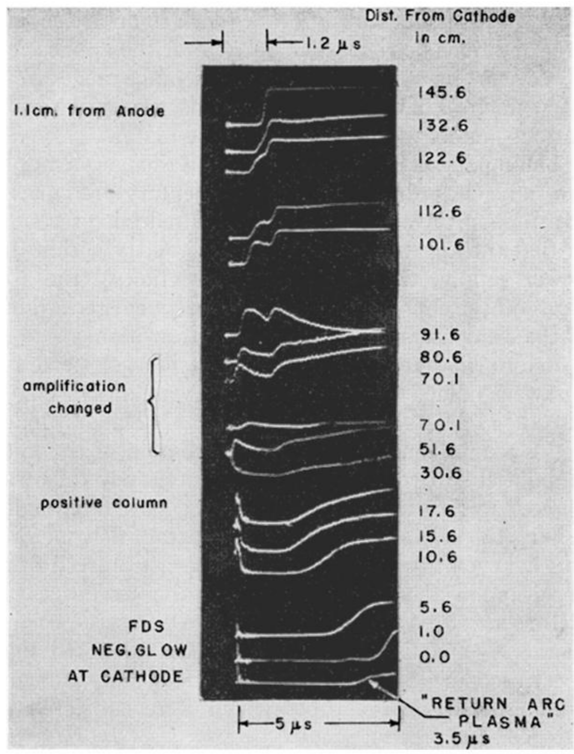
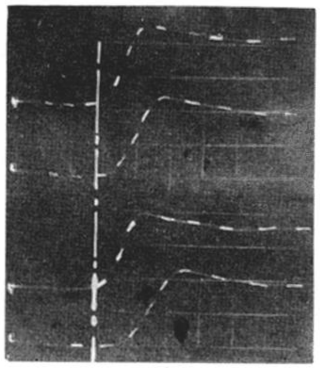
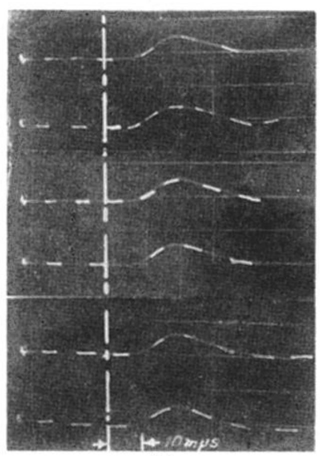


FIG. 2. Light intensities at various points within an Al-cathode discharge tube during glow-to-arc transition in N_2 at 190 microns and 1700 volts with 500 mμsec/cm sweep. Time moves from left to right in a tube 146.6 cm long. The bottom trace shows both the initial short pulse, the "pip," and the beginning of the light of the main arc, the "return arc plasma front." These two light fronts appear on each of the other traces, merging together only at the anode. Each trace is a separate arc transition with light traces from near the anode having been more highly amplified.



(a)



(b)

FIG. 3. Light intensities at Al cathode (a) and at front of the first stria (b) 18 cm from cathode during transition in argon at 128 microns and 1700 volts with 10 mμsec/cm sweep speed. Each trace represents a separate transition. Traces partially retouched because of photographic faintness. Light pip appears at the first stria an average of 8 mμsec after it appears at the cathode surface, indicating a velocity of 2.2×10^9 cm/sec.

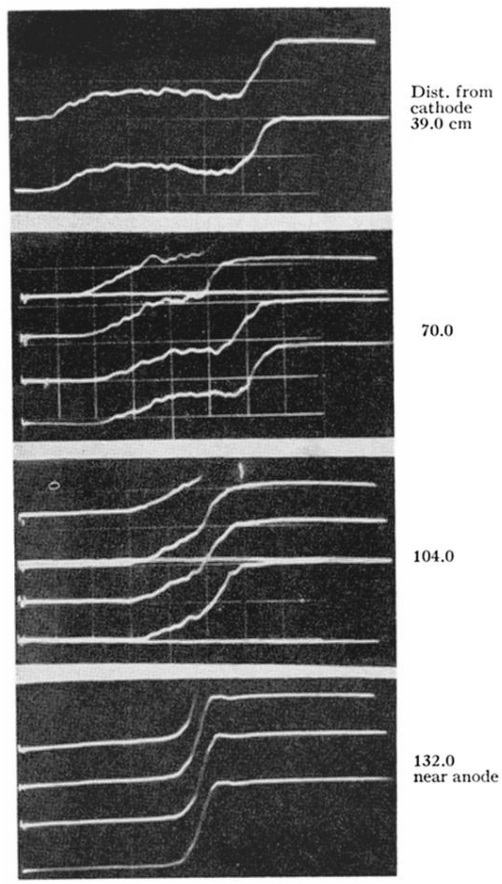


FIG. 6. Light intensities within positive column during transition with Al cathode in H_2 at 97 microns and 1850 volts, with sweep speed 50 mμsec/cm and tube 137 cm long. In the positive column the pip moves with a velocity of 6.2×10^8 cm/sec and the RAP at a velocity of 9.3×10^8 cm/sec.

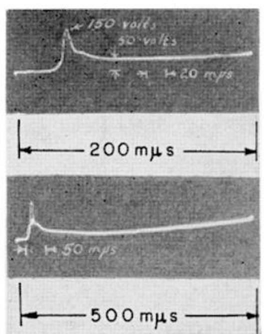
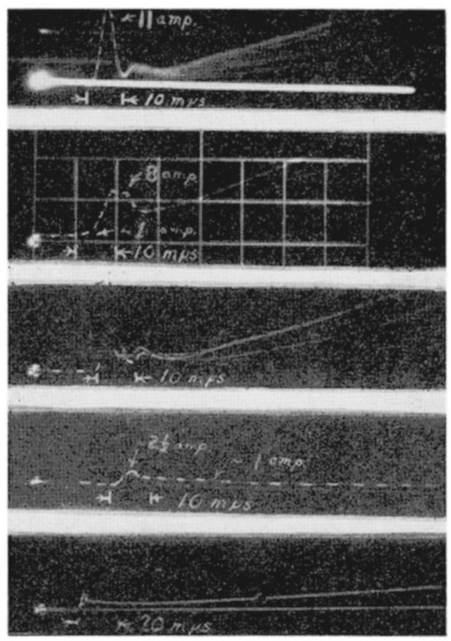


FIG. 7. Al cathode voltages at initiation of transition in N_2 at 130 microns and 2600 volts. Sweep speeds of 20 and 50 mμsec/cm are shown with traces partially retouched, with cathode resistance 25 ohms.



700 μ

700 μ

1140 μ

2.5 mm

2.5 mm

FIG. 8. W wire cathode voltage wave forms for transitions in N_2 at 2600 volts with pressures of 700 and 1140 microns and 2.5 mm in a discharge tube 24 cm long at sweep speeds 10 and 20 mμsec/cm. Traces are partially retouched.

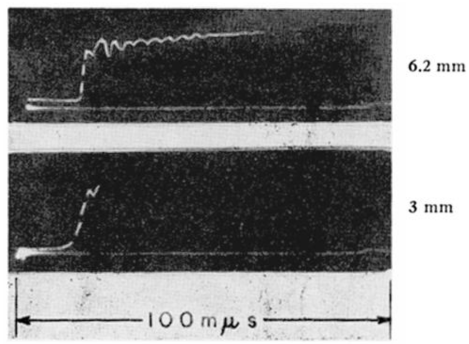


FIG. 9. Cu disk cathode voltage wave forms for transition in He at 3.0 and 6.2 mm Hg with 2600 volts in tube 20 cm long. Sweep speeds are 10 mμsec/cm. Traces partially retouched. At 6.2 mm Hg, the glow current of 1.5 amp increases to 9 amp in less than 3 mμsec. At 3 mm Hg the glow current of 800 ma increases to 10 amp in approximately 6 mμsec and continues to increase at such a rate that it disappears off the face of the oscilloscope. Note the absence of any current pip at these higher pressures.