corded the primary streamer tips, but perhaps with their motion somewhat modified by the nonconducting photographic film in their paths. Whether Raether's[1] cloud track pictures show either a primary or a secondary is difficult to determine, since he was working with uniform field geometry and highly overvolted impulse breakdown. It is possible that he observed secondaries of high speed under these conditions.

ACKNOWLEDGMENTS

The authors wish to express their gratitude to the Office of Naval Research and the Research Corporation for their support of this project; to Dr. Harry J. White, Dr. Norman Seaton, Dr. R. G. Westberg, and Dr. Peter Wagner for many stimulating and helpful discussions; and to many others, too numerous to name, for their help.

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Streamer Mechanism in Filamentary Spark Breakdown in Argon by Fast Photomultiplier Techniques*

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Using techniques developed by Hudson on air and reported in the preceding paper, the phenomena were studied in Linde's spectroscopically pure grade Ar gas admitted to a system using Alpert vacuum techniques, and on that gas further purified by gas cataphoresis. Study was made in a point-to-plane gap with a 2.36-mm hemispherically capped cylinder opposite a 3-cm distant thin out-gassed Ni plane in the pressure range from 300 mm to 50 mm. For the spectroscopically pure grade Ar, transition from a positive point corona through a fine filamentary spark to an incipient arc breakdown on a time scale of 10^{-7} sec down to 100 mm pressure proceeds by movement of primary and secondary streamers progressing from anode to cathode at slower speeds and lower luminous intensities than air at 760 mm. Unlike the case for air, the main stroke in Ar appears to move from anode towards the cathode. At 50 mm a somewhat diffuse spark channel did not reveal any streamer-like progression but the time scale was still in the 10^{-7}-sec range. One percent air in Ar at 60 mm restored streamers. Purified Ar at 240 mm revealed a 2-mm wide diffuse channel breakdown occurring across the whole gap by a process unknown with a rise time of several microseconds and sustained luminosity for tens of μsec with no indication of streamers. This demonstrates the necessity of adequate photoionizable impurities in Ar for the development of the filamentary streamer spark transition.

INTRODUCTION

EVIDENCE has been presented by Hudson[1] for the transition from an antecedent positive point corona or glow discharge of low order to an incipient transient arc through the filamentary spark in consequence of a sequence of luminous streamers or dendrites starting from the anode and crossing to the cathode. These streamer-like luminosities taken from oscillograms of the light pulses crossing the slit at various distances from the anode may be depicted as luminous space waves moving from anode to cathode at various times by means of cross plots. This enables the velocities of the different portions of these waves to be evaluated. Quite complete data are thus obtained for the longer gaps with regions of low field where velocities are low. As one progresses to gaps with more uniform and higher fields and especially for the shorter gaps, velocities become so high and times so short in air that the complete analysis is no longer possible within the resolving time of the oscilloscopes. However, even then the presence of some of the pulses as they approach the cathode strongly suggests that the anode streamer mechanism persists, a matter consistent with the remarkably short time scales of breakdown which preclude any Townsend-like mechanism.

As the streamer mechanism was initially invoked by Raether[2] and Loeb and Meek,[2] it was believed that when an electron avalanche reached a magnitude to yield an adequate positive ion space-charge density at the anode, together with intense photoionization in close proximity to the space charge, a single positive streamer progressed across the gap from anode to cathode at high speed. From this point on, Raether working with overvolted gaps considered that the conducting channel was established and that the arc materialized by steady but fast increase in current. Loeb and Meek, in analogy to the lightning stroke and Allibone and Meek's[3] observations on long sparks, believed that the heavy

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[1] G. G. Hudson, doctoral dissertation, University of California, 1957 (unpublished); G. G. Hudson and L. B. Loeb, preceding paper [Phys. Rev. **123**, 29 (1961)].

[2] L. B. Loeb, in *Encyclopedia of Physics*, edited by S. Flügge (Springer-Verlag, Berlin, 1956), Vol. 22, p. 484 ff; H. Raether, Ergeb. exakt. Naturw. **22**, 736 (1949).

[3] T. E. Allibone and J. M. Meek, Proc. Roy. Soc. (London) **A166**, 97 (1938), **A169**, 246 (1938). F. F. Saxe, J. M. Meek, and T. E. Allibone, Nature **162**, 263 (1948).

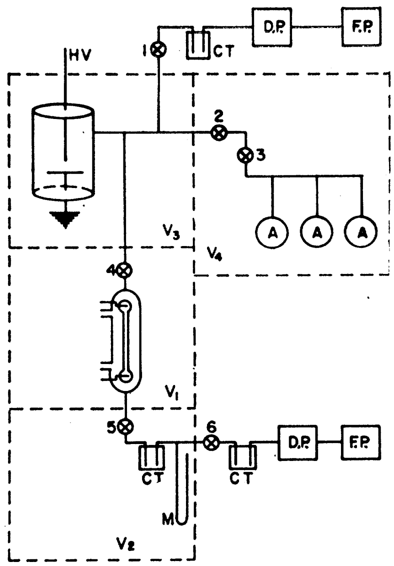

FIG. 1. Schematic diagram of Westberg's vacuum system for study of pure Ar by gas cataphoresis cleansing.

photoelectric emission at the cathode by streamer tip photons accelerated by the very high field of the approaching streamer tip sent a heavy and probably luminous *return stroke back to the anode*, at once rendering the channel highly conducting. It was recognized by all that in highly divergent fields and with heavily overvolted and long gaps, as in impulse breakdown, there was much branching of the anode streamers.

Hudson's new studies in air, however, revealed that the mechanisms active were different in detail. It appeared likely in all gaps studied that the triggering avalanche initiated a primary streamer that crossed the gap at a constant high speed and increased in luminosity as it crossed the gap. In more divergent fields and longer gaps this primary streamer was highly branched, exhibiting the dendritic structure so named by Hudson and later confirmed more in detail by Nasser.[4] In all cases the primary streamers were followed by a *secondary streamer* of much greater luminosity, which was interpreted by Loeb[1] from these and other studies as related to a radial influx of ionizing electrons. It advances down some of the many primary dendritic channels. In the straight sections near the anode its speed is high but less than that of the primary. It decreases materially once it follows the branches. The arrival of this streamer at or in close proximity to the cathode appears to initiate the rapid increase in luminous intensity characteristic of the transient arc channel, across the whole gap designated by Hudson as the *main stroke*. In air the main stroke shows no marked advance from cathode to anode as had been expected by Loeb and Meek for their assumed *return stroke*. Likewise, there was no marked motion from anode to cathode. From the appearance of the filamentary spark in longer gaps, the spark generating secondary appears to be a more vigorous one following just one of the dendritic branches of the primary across to cathode. In shorter, more uniform field gaps, evidence seems to point to the absence of the branching and dendrites and primary and secondary streamers follow a single straight path.

The unexpected observations prompted Loeb[5] to propose the following picture of what he terms *catastrophic transitions or breakdowns* of this character. The picture arose from a recent study by Westberg[6] of the transition of a low-pressure glow discharge of some 20 ma to a transient power arc of some hundred amperes in a few tens of microseconds in long discharge tubes where temporal resolution of potential changes as well as luminous pulses was sufficient to reveal the events in detail. In that case the sudden breakdown of a thin film of oxides liberated an enormous number of electrons which accelerated in the cathode fall of some 1000 volts changed the glow current of 20 ma at the cathode to 12 amperes in 2 mμsec. This burst of current propagated a highly luminous *ionizing potential space wave* down the relatively slightly ionized glow discharge channel at speeds ranging from 2×10^8 to 4×10^9 cm/sec. These luminous fronts coincide with the sharp potential gradients of the rapidly advancing ionizing electron burst. It might be considered that the passage of such a burst would render the region behind it sufficiently conducting to yield the arc current. However, despite its high-field gradients, owing to its high speed, it does not spend enough time in any section of the column to ionize the gas sufficiently. Thus arrived at the anode, despite much decreased gradients, there is a return pulse of greater luminosity and equally high speed (because of

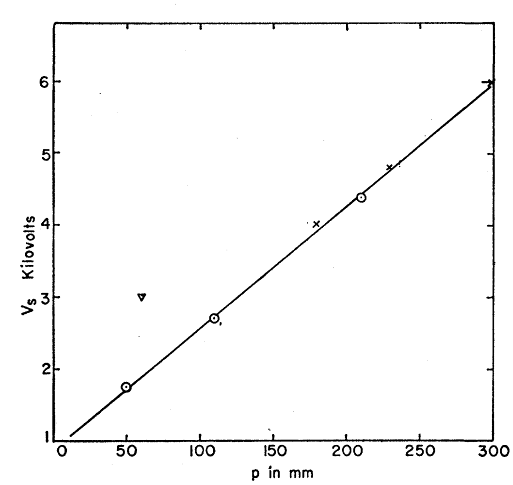

FIG. 2. Spark breakdown transition potentials as a function of pressure for Ar samples used.

[4] E. Nasser, Arch. Elektrotech. 44, 157, 455 (1959).

[5] L. B. Loeb, Proceedings of the Third International Conference on Ionization Phenomena in Gases, Venice, Italy, June 11–15, 1957; Italian Physical Society Report October, 1957 (unpublished), pp. 646–674.

[6] R. G. Westberg, Phys. Rev. **114**, 1 (1959).

the increased conductivity created by the initial burst) that sweeps back from anode to cathode. By this time multiplication of carriers is adequate to allow the arc channel to increase to the arc by the normal diffusive processes.

In Westberg's study, one of the striking indications of this breakdown were the highly luminous light pulses initiating the breakdown at the cathode. It is to be noted that one of the characteristics of the arrival of the primary streamers, which themselves are also ionizing potential space waves, at the cathode observed by Hudson and even earlier by Kip was precisely the flashes of luminosity at the cathode on arrival. Although Hudson's cross plots are perhaps not of sufficient reliability to permit firm conclusions, there is some evidence that when the primary streamer reaches the cathode a burst of ionization signaled by the cathode flash travels up the channel. In this case the high ion density in the primary streamer channel and the high air pressure will give space-wave speeds in excess of 10^9 cm/sec, which

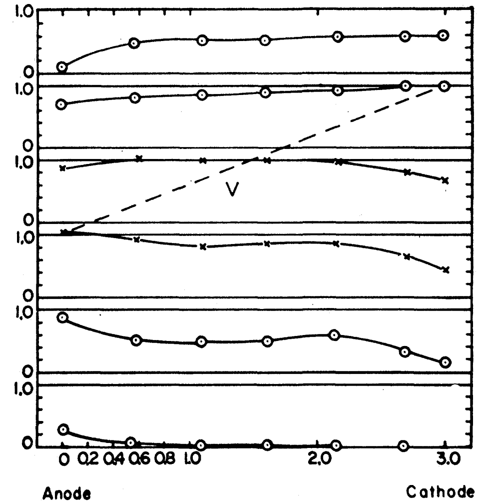

FIG. 4. Cross plot of Fig. 3 at 75, 100, 150, 200, 250, and 300 mμsec.

the oscilloscope cannot resolve. As in Westberg's observations, this enhances the primary conductivity and speeds up the secondary streamer advance. It will be only the more vigorous of the primary dendrites that achieve this increase accounting for the reduction in number of secondary dendrites observed. Whether the secondary streamer on arrival at the cathode launches a new space wave at high speed to leave the arc channel of the main stroke fairly complete is at present an open question. The sudden increases in luminous intensity in the cross plots on arrival of the primary and secondary streamers at the cathode noted by Hudson could be attributed to such action. In any event, it is clear, as recent papers of Raether[7] and his students, using ether and methane, indicate, that when an avalanche of appropriate magnitude reaches the anode in uniform field geometry a highly distorted field gradient aided by the ready photoionization of the gas or vapor launches the catastrophic streamer process. This process in Hudson's work and, as will be seen, in this study causes ionizing potential space waves either as streamers or cathode-to-anode pulses of higher velocity to sweep back and forth across the gap until the arc channel is completed in the form of Hudson's main stroke. As the filamentary spark breakdown in air and organic vapors exhibits this behavior, it is of importance to determine whether other gases also do so.

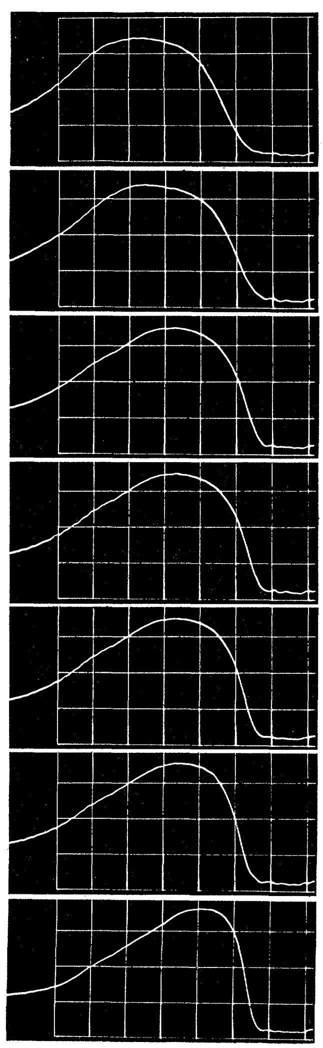

FIG. 3. Oscillograms for Ar at 300 mm, low gain, 50-mμsec/cm sweep speed, at various distances x from anode (below) to cathode (above). Time increases right to left.

Pure Ar gas should not be susceptible to photoelectric ionization by its own photons at sparking fields, unless through a prolonged Townsend predischarge a very high concentration of metastable states is created across the whole gap. Thus Ar should not reveal a catastrophic *filamentary spark breakdown transition* despite high fields.

Most studies of the breakdown of Ar gas, including

[7] H. Raether and J. Pfaue, Z. Physik **153**, 523 (1959). K. Richter, Z. Physik **158**, 312 (1960).

supposedly pure Ar, reveal filamentary spark transitions. It thus becomes of interest to study the breakdown of Ar using techniques that can detect the streamer at varying degrees of purity. It was for this reason that this study was undertaken. It was recognized that such a study would present difficulties owing to the relatively weak light emission and the use of low gas pressures, since most photomultiplier studies in air were undertaken at 760 mm with the high luminous intensities of molecular gases.

ARGON STUDIES

Westberg undertook a study of argon using a 2.36-mm diameter hemispherically capped Ni point and a thin Ni plate 7 cm in diameter, distant 3 cm, mounted inside of a glass vessel of 3 liters capacity. This was connected to the vacuum system depicted in Fig. 1 equipped with two Hg vapor diffusion pumps DP operating through cold traps CT and capable of being shut off from the system by Alpert valves 1 and 6. The Ar came from three liter flasks A A A of Linde's "spectroscopically pure" grade gas provided with devices for breaking the seals as needed. The whole system was mounted on a Marinite base and could be outgassed by baking at 360°C. Pressure was read by means of a mercury manometer, M,

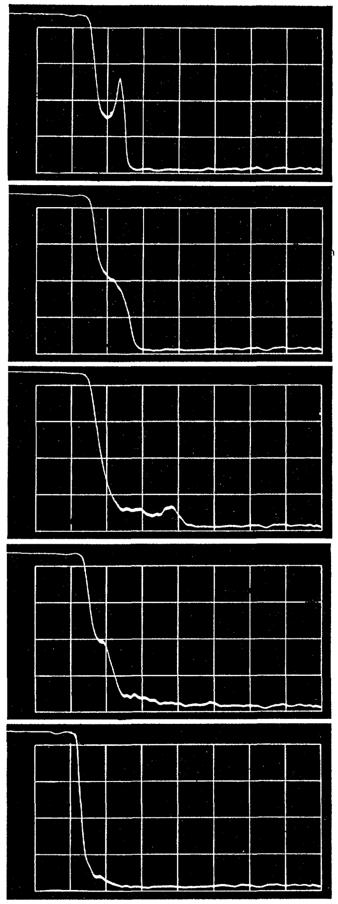

FIG. 6. Traces at 180 mm, 5 -mμsec/cm max imum gain.

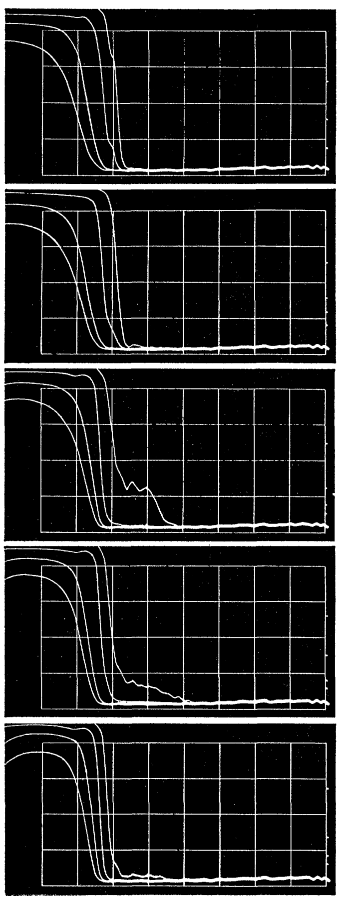

FIG. 5. Traces at pressure 300 mm, 50-mμsec/cm sweep speed at different gains, highest at right, anode below, time right to left.

kept separate by a cold trap and valve 5 except when read. Alpert gauges measured the low pressures. Electrodes and metal parts could be outgassed by induction heating to 950°C. Area V_1 contains an oil-cooled discharge tube connected to the discharge space for cataphoretic cleansing of the argon which on spectroscopic observation was found contaminated with Kr and N_2. The operation of the cataphoresis tube as used by Westberg will be discussed at a later point. Since the standard Linde gas exhibited filamentary spark breakdown, it was believed that streamers must be active so that after a quick survey indicating the presence of streamers, Westberg proceeded to the purification of argon which was achieved just before he left.

In order to complete the study, Huang investigated the spectroscopic argon. Some of the gas was cataphoretically treated using a modification of Westberg's oil-cooled system, without the cooling, that did not serve materially to improve the purity. A curve of the transition potentials from corona to filamentary spark leading to an incipient arc as a function of pressure of the gas using both untreated and treated Ar gas admitted to the system outgassed and exhausted to 4×10^{-10} mm Hg is shown in Fig. 2. The circled points are for the Linde argon while the treated argon corre-

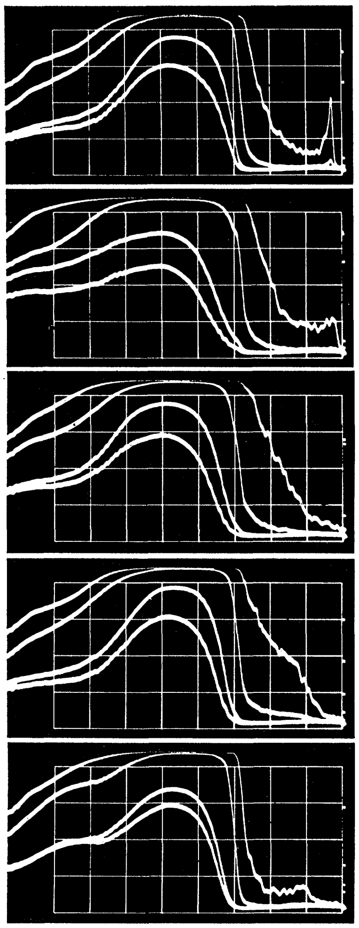

FIG. 7. Traces at 110 mm: Linde Ar at 100 mμsec/cm showing fast primary and slower secondaries.

sponds to the crosses. The one point with a triangle is that for the Ar with 1% air. The transition potential for Westberg's pure Ar at 240-mm pressure was 4800 volts which does not differ sensibly from Huang's curve. Thus removal of traces of Kr and N_2 did not alter transition potentials. The observing system was the same as that of Hudson's except for greater difficulty in screening out the electrical noise of the spark with the glass-enclosed bakable system. Since the transition potentials at the pressures from 300 mm down to 50 mm were about one-third or less of those applicable to air in a similar gap, the electrical energy available in the breakdown was much reduced. In addition, the Ar giving largely a line spectrum yields light of much lower intensity than air with its mixture of lines and bands in the visible. This rendered photomultiplier observations difficult especially for the weak primary and secondary streamer processes. In Fig. 3 are presented a set of traces taken on treated Ar at 300-mm pressure at low gain with a sweep speed of 50 mμsec/cm. Time goes from right to left in all Huang's traces and the graticule marks represent 1 cm each. Seen are the rise and peak of the main stroke. The anode trace is at the bottom and the traces reading up apply to 0. 5.3, 10.8, 16.1, 21.4, 26.7 mm from the anode to 30 mm which is at the cathode. The movement is seen distinctly to be from anode to cathode, the temporal displacement of the peak being 3 times as great as that of the rising toe indicating that the peak of luminous intensity also crosses the gap but at a speed about one-third of that for the unresolved primary and/or secondary streamers concealed in the rising toe. A cross plot of this sequence is shown in Fig. 4. The cross plot reveals what is probably a secondary followed by the main moving from anode to cathode beginning at the bottom trace and reading up in time. The speed of the peak is seen to be roughly 3.7×10^7 cm/sec while that of a point 0.17 of peak value on the rising toe is 1×10^8 cm/sec. Figure 55 shows a sequence of traces for treated Ar at 300-mm pressure and 50 mμsec/cm sweep speed. Here the anode trace is at the bottom with traces at 5.3, 16.1, 26.7, and 30 mm from the anode reading up. There are four traces for each distance with increasing gain. All of these quite clear on the negative and on primary prints had to be reinforced. The furthest trace to the left is lowest gain and represents the undistorted main stroke. With increasing gain, the main stroke flattens by overloading; however, even at the anode it is seen that there is fine structure about 2 cm to the right of

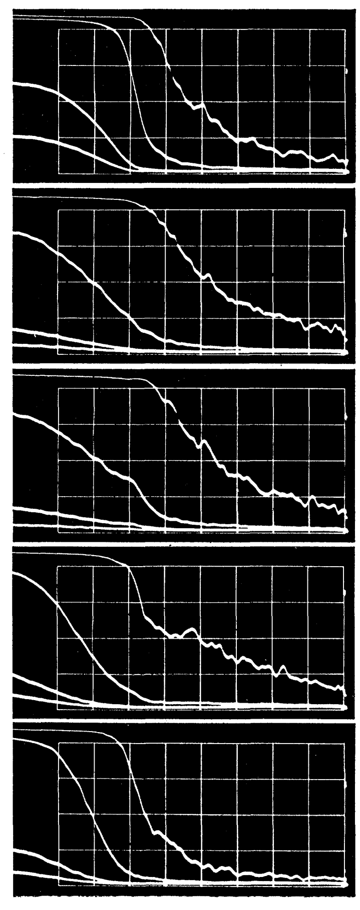

FIG. 8. Traces at 50 mm, 100-mμsec/cm sweep. There is no streamer motion apparent.

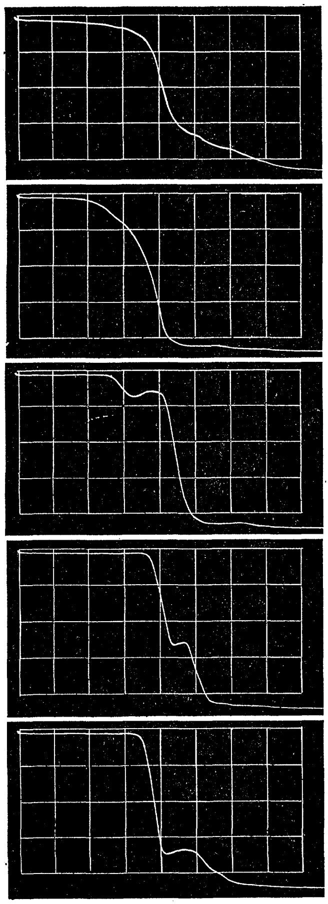

FIG. 9. Ar with 1% air at 60 mm at 20 mμsec/cm and highest gain. Note reappearance of streamers.

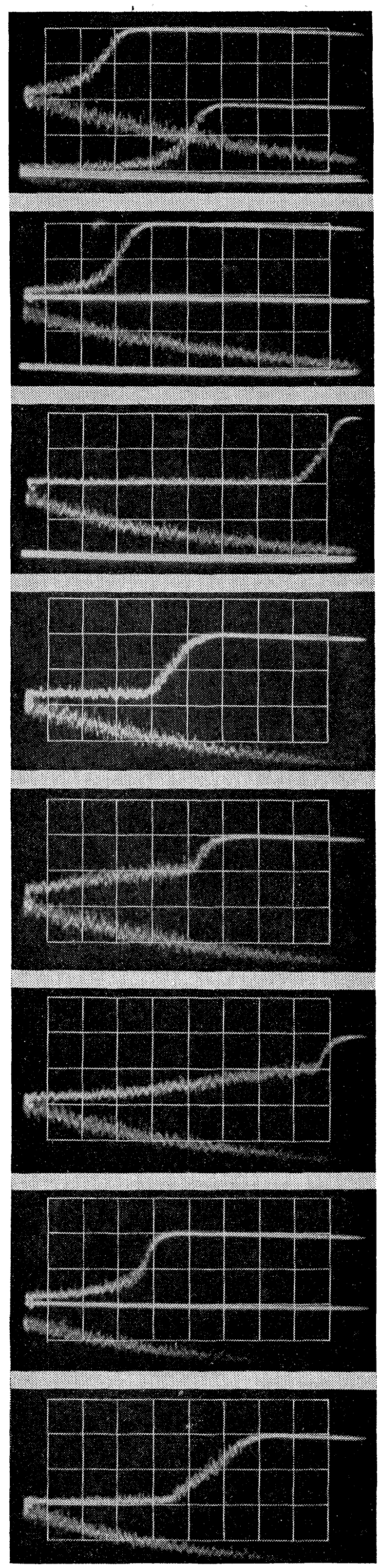

FIG. 10. Westberg's traces for breakdown in pure Ar. Sweep speed 1 μsec/cm. Cathode is at bottom, anode on top. Time progresses left to right.

the toe of the main suggesting streamers. As these progress across the gap they reveal themselves at 16.1 mm to be two close streamer peaks that grow in intensity as they cross the gap moving from right to left with speeds of about 6.6×10^7 cm/sec. It is difficult to identify these but later observations at lower pressures where reduced speeds give better resolution suggest that these may represent the secondary streamer, the crossing of which leads to the main stroke. If so, the light of the primary at the higher speed is too weak to be observed. Clearer resolution is seen in Fig. 6 for treated Ar at 180 mm, at 50 mμsec/cm and maximum gain. Figure 7 is for Linde Ar at 110-mm pressure and sweep speed of 100 mμsec/cm instead of the one at 50 mμsec/cm which is reproduced here because of clarity. The data were taken from the one at a sweep speed of 50 mμsec/cm. The traces show sweeps at four different gains. On highest gain the secondary begins to rise at coordinate 0.5 to the left of zero time. At 26.7 mm it has pretty well merged into the rise of the main with a speed of 1.4×10^7 cm/sec. The primary peak starts near the origin at 16.1 mm showing a peak at the cathode at coordinate 0.3 cm. It has a speed of the order of 5×10^7 cm/sec. Figure 8 is for treated Ar at 50-mm pressure using a sweep of 100 mμsec/cm and it is again shown

in place of the higher resolution at 50 mμsec/cm because of reproducibility, despite its lack of resolution for which the high speed sweep will be used in discussion. Here the *clearly defined* primary and secondary pips are no longer discerned. In fact, there is no apparent motion across the whole gap. Luminosity is greater at the cathode, even the main stroke appearing three times as intense there. If there is motion, it would be from cathode and anode to midgap. The spark channel was more diffuse having an apparent diameter of 1 mm with pronounced higher visual luminosity at the cathode. The formative time lag, however, showed no sign of increasing as was the case when streamer breakdown ceased in Westberg's work. It is nonetheless clear that some change in spark mechanism was beginning in this gas at 50 mm. Using 1% air in Ar at 60-mm pressure, the traces shown in Fig. 9 were obtained. Here sweep was 20 mμsec/cm and the traces are so faint that for reproduction reinforcement must be resorted to. At 5.3 mm from the anode the start of an anode streamer may be perceived which is clearly developed at 16.1 mm, reaching considerable prominence at 26.7 mm. The speed is of the order of 1×10^8 cm/sec. This shows clearly

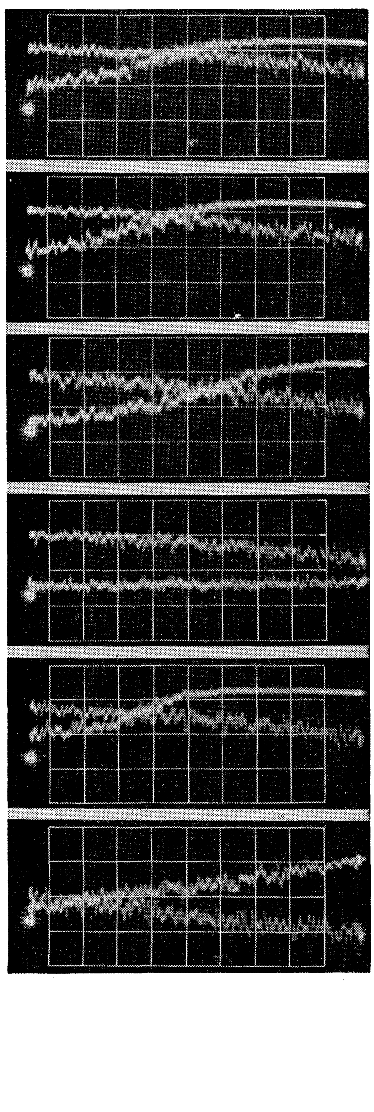

FIG. 11. Pure Ar. Sweep speed 200 μsec/cm at maximum gain. Conditions, otherwise, same as in Fig. 10.

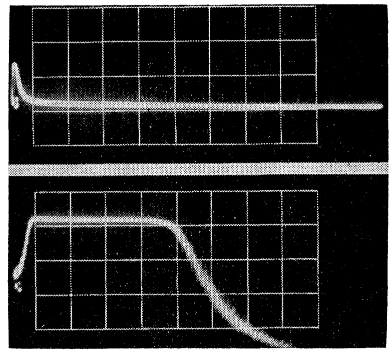

FIG. 12. Two traces at 5 μsec/cm at tip of anode, upper trace, low gain; lower trace, high gain. Shows long duration of low-current arc pulses.

the importance of even small quantities of a readily photoionizable gas that restores streamers at pressures at which they are disappearing in purer Ar enhancing their speed as well as their luminosity.

It is now of interest to present data on the purification of the argon by cataphoresis. This technique was developed by Diesz and Dieke[8] for the purification of gases at some 20–30 mm pressure at which pressure currents in the glow discharge needed were only 20–30 ma. For studies at 300-mm pressure it was estimated that at least 300 ma of current would be required. In Diesz and Dieke's work the chamber with the gas to be purified was in direct contact with the discharge tube. The discharge was run for some time at the rated current and concentration of the more ionizable impurities could be noted at the cathode. Then the chamber was cut off from the discharge tube and some of the gas at the cathode was withdrawn by the pump. The pump was then cut off and the gas chamber was again placed in contact with the discharge tube. In this case diffusion of the impurities to the discharge tube with no doubt some gas circulation induced by the discharge current served rapidly to cleanse the gas. The same principle was followed by Westberg using a system, which is shown in Fig. 2, subject to Alpert vacuum techniques, bakeout being at 360° for 24 hours and the induction heating of electrodes at 950°C for 6 hours. The gas volume of the cataphoresis tube with its 6-mm inner diameter and 20-cm length was 5% of the total volume. V_3 had a volume of $3l$. The argon flasks A were in parallel. Since these and the associated tubing could not be outgassed, the space between valves 2 and 3 was a bleeder space to flush out the gas in the section which had not been baked when the seals were broken. Alpert ion gauges (not shown) were located near valves 3 and 1. Gas pressure was measured after gas was admitted to the system by opening valves 4 and 5. Valve 5 was then closed and with only valve 4 open the discharge was run for 3 to 4 hours. The discharge quickly changed color from bluish to pink at the anode, the

[8] R. D. Diesz and G. H. Dieke, J. Appl. Phys. 25, 196 (1954).

gas at the cathode assuming a green color. Spectroscopic study revealed Kr and N_2 at the cathode with mainly Ar at the anode. Valve 4 was then closed and 5 and 6 were opened, removing all gas in the discharge tube. Valves 5 and 6 were then closed and valve 4 opened and current run for another 3 to 4 hours. This process was repeated five times. After the first run the new gas admitted did not show the grayish cast but was pink in color for the whole length of the column. However, as time went on green again collected at the cathode. It appeared as if towards the last runs the green became less intense. By this time the pressure in the system had dropped to 240 mm. Using extrapolated data from Diesz and Dieke, Westberg estimated that the impurity could have been reduced by a factor of 0.33 for each run. This was undoubtedly optimistic, impurity probably being reduced by a factor of 0.1 instead of 0.041. Attempts to monitor the purification by using photomultipliers on the light of the green Kr line was unsuccessful owing to its low intensity. The gas finally used, however, showed breakdown properties entirely different from that previously studied. The spark channel had a diameter of 2 mm at 240 mm and light intensity was feeble with highest intensity at the cathode, less at the anode, and least in midgap. Transition occurred at 4800 volts for 240-mm pressure possibly meaning that removal of traces of Kr, which lower breakdown threshold, at the same time removed traces of N_2 and O_2 which raised it. The oscillograms were radically altered. First is shown a series of traces starting with anode at the top and going to the cathode at 0, 0.35, 0.70, 1.21, 1.89, 2.11, 2.93 to at the cathode in Fig. 10. The sweep speed was 1 μsec/cm. Time goes from *left to right*. Here difficulty lies with the triggering. The 517 scope triggers best on a light pip at the anode with rise time of the order of 10^{-8} sec or less. Gradual rise times with indefinite beginnings and shapes that do not repeat lead to poor trigger pulses. In the first trace at the anode there are two sweeps and the faulty triggering is clearly demonstrated by difference in breakdown time. The declining traces noted below are unavoidable retriggering of the scope during later phases of the sparks. Ignoring the differences in starting times, it is clear that the breakdown is distinctly different from the phenomena occurring on time scales of 10^{-7} sec with less pure argon. Here there is a gradual rise to an overloaded peak in all cases consuming more than 10^{-6} sec for the steep part and of the order of a gradual rise from zero of several microseconds. The rise of luminosity was faster at cathode and anode than in midgap. Here there was a very slow rise to half intensity in some 4 to 6 μsec and a final sharp rise to peak in a half a microsecond. The long duration of the luminosity in the channel extending beyond 6 μsec in some cases indicates that the discharge current was of an entirely different order, taking a long time to discharge the capacity. Figure 11 shows a sequence taken at 200 mμsec/cm sweep. While the noise was not eliminated as well in these traces as in those of Huang and Hudson, still at a sweep of one-fourth to one-tenth that used by Huang there is seen to be no fine structure even at maximum gain. Rise to overloading at this high gain occurs on a scale of 1 μsec or so relative to one-twentieth of this on Huang's traces. Figure 12 shows two traces taken with sweeps of 5 μsec/cm. The light observed was just at the anode tip. The first trace at *low gain* shows the full pulse shape indicating that the duration of most of the light output is in the first 2 or 3 μsec. Increasing the photomultiplier gain comparable to that of high gain in Figs. 7 and 8 in the second trace showed that there was light output for some 35 μsec at the level of the secondary pulses.

It is clear that when the argon is *purified* in the absence of adequate photoionization the *streamer mechanism does not occur*. Breakdown starts as some sort of a constriction of the Townsend glow discharge process which funnels to a fairly broad confined column and builds up to heavy localized glow in some 3 μsec of time. The current is possibly of the order of one-tenth as heavy as with the streamer spark so that the luminous discharge lasts of the order of ten times as long as with streamer sparks since the quantity of charge dissipated is constant.

From these data it is possible to conclude that where the sharp filamentary spark is observed it is caused by an anode streamer mechanism and that the gas in which it occurs is sufficiently mixed or impure so as to yield adequate photoionization in the gas by avalanche-produced photons. In slightly soiled Ar gas streamers persist to about 50-mm pressure. If 1% O_2 is added even at this low pressure, the streamer transition occurs. In relatively pure Ar even at 240-mm breakdown is diffuse and requires a formative time at least 10 or more times that for streamers.

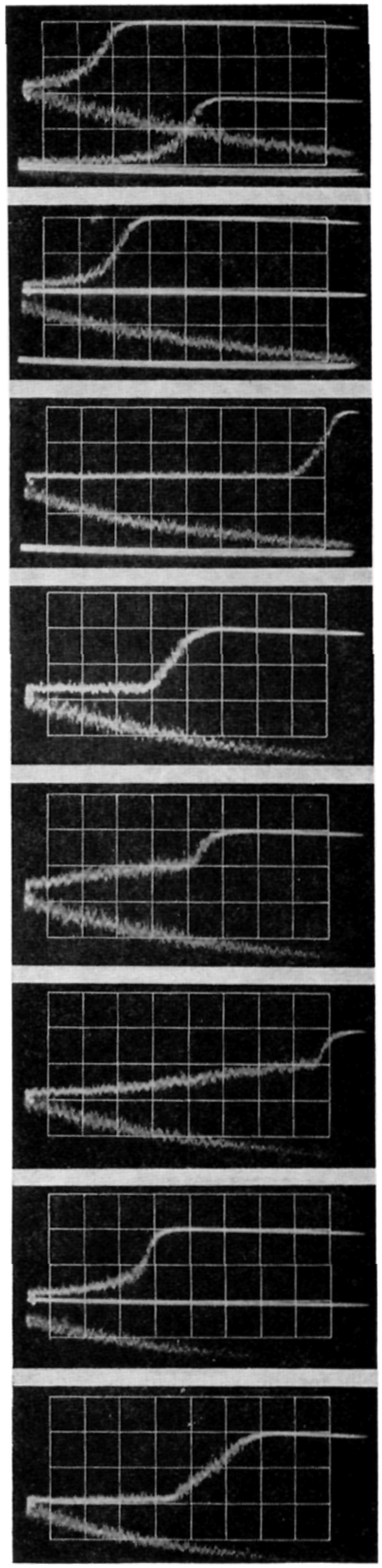

FIG. 10. Westberg's traces for breakdown in pure Ar. Sweep speed 1 μsec/cm. Cathode is at bottom, anode on top. Time progresses left to right.

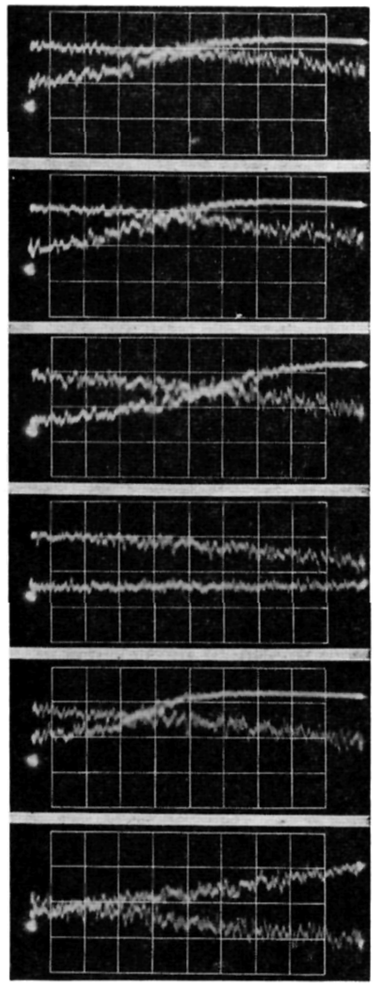

FIG. 11. Pure Ar. Sweep speed 200 μsec/cm at maximum gain. Conditions, otherwise, same as in Fig. 10.

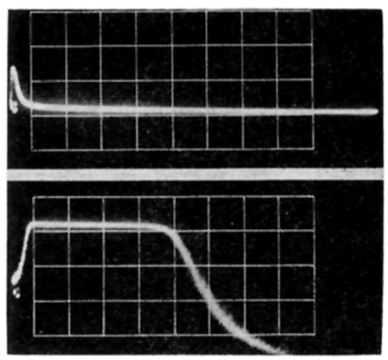

FIG. 12. Two traces at 5 μsec/cm at tip of anode, upper trace, low gain; lower trace, high gain. Shows long duration of low-current arc pulses.