neutrons and to some extent to the question of whether part of the uranium and thorium metal was oxidized, so that the number of metal atoms present may be somewhat less than that calculated from the weight. By surrounding the ionization chamber with a shield of Cd $\frac{1}{2}$ mm thick, we made sure that no slow neutrons (below a few volts energy) were present. The cross section for thermal neutrons of the fission process in U has been determined in the Pupin Laboratory of Columbia to be between 2.5 and 3×10^{-24} cm^2, whereas the average cross section for the complicated spectrum of fast neutrons from a Rn-Be source was found to be about 1×10^{-25} cm^2.[11]

It is a pleasure to thank Professor Niels Bohr for his stimulating and continued interest. We wish also to thank Mr. W. Hane for valuable help in these experiments. The high voltage apparatus we owe to a grant from the Rockefeller Foundation.

[11] H. L. Anderson, E. T. Booth, J. R. Dunning, E. Fermi, G. N. Glasoe and F. G. Slack, Phys. Rev. **55**, 512 (1939); E. T. Booth, J. R. Dunning and F. G. Slack, Washington meeting Bulletin 1939, paper 68.

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The Effect of Pressure on the Positive Point-to-Plane Discharge in N_2, O_2, CO_2, SO_2, SF_6, CCl_2F_2, A, He, and H_2

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The voltages at which corona first appears in a 3-mm point-to-plane gap and the breakdown voltage of the gap have been determined with N_2, O_2, CO_2, SO_2, SF_6, CCl_2F_2, A, He, and H_2, and certain mixtures of these gases. This has been done with both positive and negative point polarity and over a pressure range of about 30 atmospheres. The types of corona which were observed are discussed and in particular the marked dependence of the positive point breakdown voltage on pressure in those gases which form negative ions.

INTRODUCTION

THE familiar increase in sparking potential of a gap with gas pressure does not continue indefinitely with every gas for all gap geometries. Investigations of the sparking potential *vs.* pressure characteristics of air in positive point-to-plane gaps have shown that distinct maxima in the curves exist near the pressure of 10 atmospheres. The maxima first become noticeable with gap widths above one mm and are more prominent as gap widths are increased. Goldman and Wul,[1] who have recently studied this effect in nitrogen with constant potential, alternating voltage and impulse voltages applied to the point, show that at high pressures a discharge often requires a much lower voltage to propagate itself across a gap of several centimeters width than it requires at slightly lower pressures. As considerable corona precedes sparking below this transition pressure, Goldman and Wul suggest that the shape of the sparking curve for a given gap depends largely on field distortion due to space charge around the point. We are reporting in this paper a similar study of N_2, O_2, CO_2, SF_6, CCl_2F_2, A, He, H_2, and of certain mixtures of these gases. We have also observed with an oscillograph the general character of any corona preceding breakdown. The types of corona which we discuss are very similar to those which Loeb,[2] Kip,[3] and Trichel[4] have studied in air at atmospheric pressure.

APPARATUS

The chamber in which the electrodes were placed (shown in Fig. 1) consisted of a glass tube

[1] I. Goldman and B. Wul, Tech. Phys. U. S. S. R. **1**, 497 (1935); **3**, 16 (1936). I. Goldman, Tech. Phys. U. S. S. R. **5**, 355 (1938).

[2] L. B. Loeb and A. F. Kip, J. App. Phys. **10**, 142 (1939).

[3] A. F. Kip, Phys. Rev. **54**, 139 (1938); **55**, 549 (1939).

[4] G. W. Trichel, Phys. Rev. **54**, 1078 (1938); **55**, 382 (1939).

(A), $3\frac{1}{2}''$ in diameter, sealed at each end to Fernico sleeves (C), which were in turn soldered into grooves in brass end plates (B). The glass cylinder was held in a large Herkolite cylinder (G), which forms at the same time a pressure tank and a high voltage bushing. Although the glass cell alone will only stand a pressure of 100 lb./sq. in., the Herkolite cylinder makes it possible to work with pressures of 600 lb./sq. in. The electrodes, held by rods from the end plates, were in these experiments a $1''$ hollow nickel sphere (D) and a tungsten wire (E) which had been ground to a point whose hemispherical end had a radius of curvature, as measured with a microscope, of 0.25 mm. The point electrode was insulated from ground by a glass seal (F). During later experiments the supporting rod was replaced by a small pressure-tight caliper head which permitted adjustment of the electrode spacing while the cell was filled with gas.

Voltage was supplied from a 100-kv transformer with a full-wave rectifier and filter circuit. A 5-megohm liquid resistor was placed in series with the gap to limit the sparking current and so avoid melting the point. To measure the voltage a 400-megohm resistor with a microammeter in series was connected from the high voltage electrode to ground. The current was measured both with an ultra-sensitive microammeter and, alternatively, with a cathode-ray oscillograph. With the latter the character of the current could be observed when the amplifier was used. These instruments were protected from impulse surges by an argon-filled tube placed in parallel. The oscillograph was provided with a single sweep circuit to permit photographs to be made of a single transit of the beam.

An x-ray tube, placed above the Herkolite cylinder, made it possible to irradiate the gap. Those curves labeled "x-ray measurements" were taken when the tube was operating at 80 kv with a current of 5 milliamperes.

The gases were of ordinary commercial purity, except the nitrogen,[5] which contained less than five parts per million of impurities other than rare gases. This special nitrogen was used, since small quantities of impurities, such as oxygen, capable of forming negative ions, affect considerably the spark characteristics of a positive point in a gas whose molecules do not readily form negative ions. For a study beyond the survey which we have intended, it would be essential to purify each gas, particularly nitrogen, helium, hydrogen, and argon, and to avoid possible contamination by the test equipment. Gas pressures were measured with several new three-inch gauges of standard Bourdon type.

[5] Provided by the Incandescent Lamp Department, General Electric Company, Cleveland, Ohio.

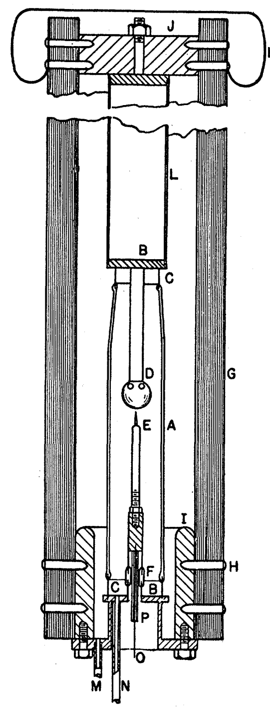

FIG. 1. Test cell installed in pressure jacket.

PROCEDURE

Before each experiment the test cell was evacuated and flushed with gas several times. Then with the cell filled to the desired pressure, and the air pressure in the Herkolite cylinder adjusted to the same value, voltage was applied from the Kenotron set to the high voltage end of the bushing. The voltage was raised slowly until both the initiation of corona and breakdown were recorded. This procedure was repeated several times to obtain each point shown on the curves. If there was as much as ten percent scatter in the voltage values, usually six or more repetitions were made. Similar data were then

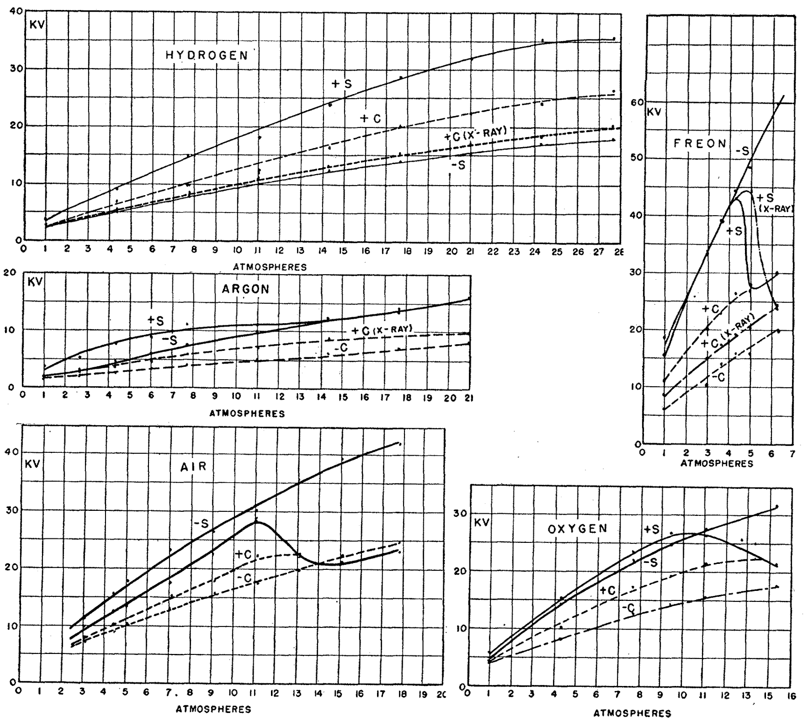

FIG. 2.

FIGS. 2 and 3. Variation with absolute pressure of the d.c. voltages at which corona (C) and spark breakdown (S) appear in various gases in a 3-mm point-to-plane gap. The polarity indicated is that of the point electrode.

taken with the polarity reversed, before gas was added to the cell for measurements at the next pressure. This procedure was varied in a number of ways, and the sparking values were found to be substantially the same as long as a minute or more elapsed between successive measurements. To check the reality of the maxima, additional data were taken in their vicinity. With some gases a complete refilling of the cell after a spark would raise the first subsequent measurement of the corona initiation voltage. The corona initiation voltage was usually lowered by x-ray irradiation. It appears that corona onset curves are sensitive to the presence of ionization in the cell.

When sparking occurs at high pressure, the protective gap sparks vigorously. In some gases at low pressures, corona does not change to a definite spark discharge as the voltage is increased, and so the breakdown voltage must be considered that at which the voltage-current characteristic of the gap becomes negative.

The point and sphere were cleaned and examined occasionally. No perceptible alterations in point diameter and shape were observed throughout the set of experiments.

DISCUSSION

The experimental results with a gap width of 3 mm for a number of gases and mixtures are plotted in Figs. 2 and 3.

The $+C$ and $-C$ curves indicate the voltages at which, with the point respectively positive and negative, evidence of corona first appears on the oscillograph. At this onset voltage the beam is deflected by sudden pulses, isolated from one another, and random in time (Fig. 5A). The $+S$ and $-S$ curves indicate the spark or glow discharge voltages. For those gases in which for a particular polarity no corona, or only one or two pulses, preceded the spark, the C curve has been omitted. At sufficiently high pressures, with the point positive, corona does not precede sparking in most gases, so the $+C$ curves merge with the $+S$ curves.

At lower pressures and with positive point, there is a fairly wide corona region in all gases which readily form negative ions. One observes with the oscillograph, as the voltage is raised slightly above the onset voltage, that the isolated pulses are replaced by another pattern, which has

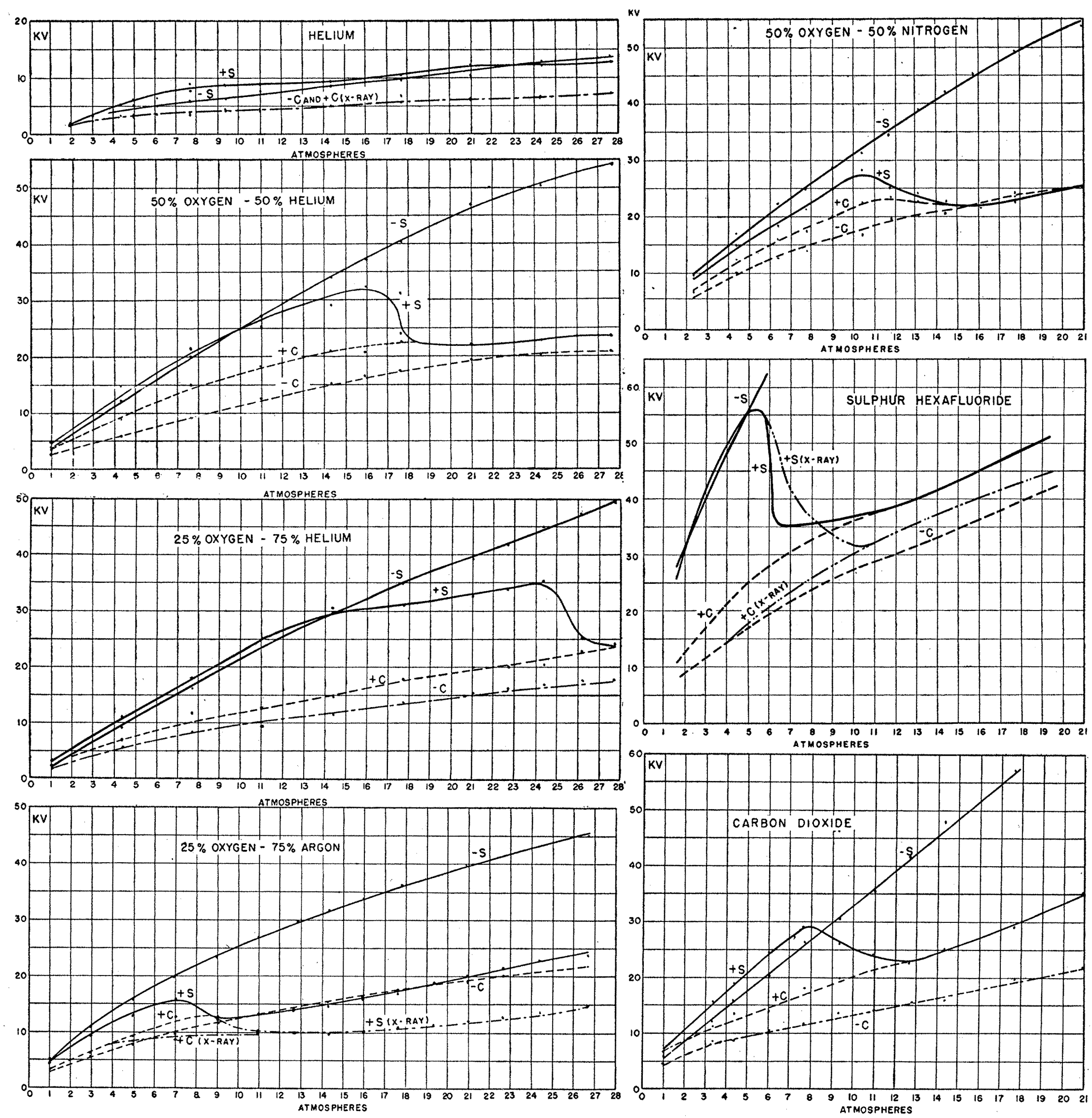

FIG. 3.

been termed by Loeb "burst corona." (See Fig. 5*B*.) There is now a d.c. component, and the fluctuating component represents only about five percent of the total current. Usually the burst pattern begins after one of the kicks which is produced by the intermittent corona first observed. As the voltage is raised, the burst corona increases rapidly in magnitude. Just before the spark, isolated kicks, which are superimposed on the burst pattern and are much higher, may reappear.

In the region of intermittent corona the positive point acts somewhat like a Geiger counter. This can be interpreted in the following manner: Single electrons or ions, approaching the point, produce an electron avalanche by collision ionization in the high field region. The electrons produced flow to the point, and the positive ions remain to distort the field and virtually to prolong the positive point. Moreover, radiation emitted in the course of the avalanche process will have ionized photoelectrically some molecules outside the avalanche region. These electrons are available to produce new avalanches

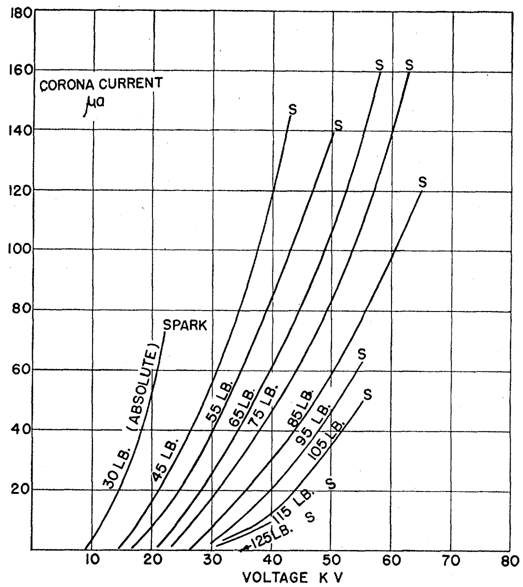

FIG. 4. Corona current *vs.* applied d.c. voltage for sulphur hexafluoride in a 3-mm point-to-plane gap, point positive.

and so to extend the space charge further into the gap. The incipient streamer advances until it is extinguished in the low field region away from the point. Negative ion formation in the body of the streamer as it builds outward may tend to choke off the streamer by interfering with electron flow to the positive point. The number of streamers formed can be increased greatly by introducing an external source of ionization, and, with the x-ray irradiation which we used, the onset voltage is lowered, as has been indicated by the "*C* with x-ray" curves on some of the figures. Kip discusses this effect when radioactive material is used to increase the ionization in a gap.

As the voltage is raised slightly, burst corona sets in, indicating that some of the electrons which are photoelectrically produced as the streamer travels away from the point are effective in producing other avalanches into the point, and a succession of such avalanches, constituting a burst, may produce enough ionization so that the whole region about the sharp point shows a slight glow. Near the onset potential bursts may be intermittent, but when the point potential is raised slightly, one observes a stabilized burst corona which is continuous because of an adequate supply of photoelectrons and negative ions in the gap. As the voltage increases, the current increases very rapidly. Typical current-voltage curves at various pressures are shown in Fig. 4 for sulphur hexafluoride. The sharp kicks which reappear just before breakdown probably indicate the formation of streamers from the edge of the burst region as it extends outward across the gap. The streamers can no longer be extinguished by space charge; they extend toward the cathode and, eventually, crossing the gap, result in breakdown.

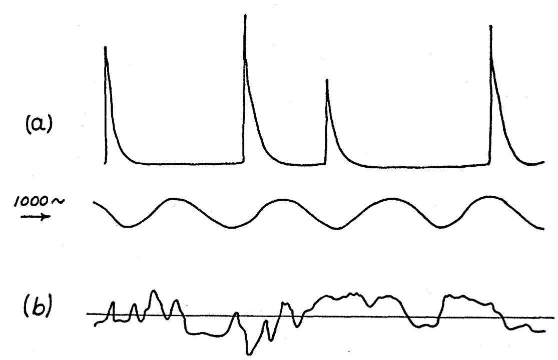

FIG. 5. Typical oscillograms of positive point streamer (*A*) and burst corona (*B*). In (*B*) the large d.c. component does not appear.

Streamers from a positive point occur in hydrogen, helium, argon, and nitrogen, but we have failed to observe a continuous burst corona pattern similar to that in gases which readily form negative ions. In hydrogen the oscillograph shows a rapid and regular succession of small streamer-like pulses. While some stabilizing influence prevents spark breakdown, it is evident from the oscillograph that the process differs from that in negative-ion-forming gases. In the other gases the individual streamers are able to propagate entirely across a short gap before a sufficient number of streamers form simultaneously to give burst corona; i.e., the region of intermittent corona extends to the breakdown voltage. Thus the formation of negative ions in some gases is able to stabilize a continuous burst corona as well as to choke off extensive individual streamers. Also, negative ion formation is largely responsible for the observed high dielectric strength of these same gases.[6]

[6] E. E. Charlton and F. S. Cooper, Gen. Elec. Rev. **40**, 438 (1937).

Effect of Pressure on Spark Curves

It might be supposed that the stabilizing influence on positive-point corona due to the negative ions formed in some gases might be effective at all pressures. Experimentally this is not the case, and one must explain why negative ions do not effectively stabilize corona above a certain critical pressure. The transition seems to be due to so rapid an increase in the rate of positive ion formation in a streamer that it can no longer be offset by the formation of negative ions. This follows logically from the behavior of Townsend's ionization coefficient, α, with pressure, p. Since α/p varies approximately as E/p, where E is the gradient, α then increases about as rapidly as the pressure throughout the low pressure range where the breakdown voltage *vs.* pressure curve is linear. This linear increase in α results in an exponential increase in the number of positive ions. The number of negative ions formed is to a first approximation a fraction of the number of positive ions. However, the net charge density depends on the difference between the number of positives and negatives, and so tends to increase very rapidly with pressure. The accompanying rapid increase in gradient at the tip of a streamer will therefore result in the certain propagation of any initial streamer to complete breakdown. The rate at which positive ion formation increases with pressure should result in a sudden transition from a region of stabilized corona to a region where breakdown is initiated by the first streamer. This transition, as indicated by the curves for SF_6, CCl_2F_2, etc., is observed to be quite abrupt.

A justification of the above argument by numerical calculations would be complicated, since the number of positive ions produced in a moving streamer depends on factors such as the velocity of streamer propagation, streamer diameter, electron production by photons absorbed ahead of the streamer, and electron capture to form negative ions. Also, the relative number of negative ions will vary with pressure and as the volume of that region of field in which they can exist varies. Finally, the life of an individual negative ion will become considerably shorter when the current through unit cross section of streamer increases with pressure.

Effect of X-Rays and Diffusion

The increase of strength which x-ray irradiation produces in some gases beyond the maximum probably arises because the ionization from this source makes more uniform the outer edge of the burst corona region and stabilizes the avalanches which compose this corona. Streamers are less able to escape from the edge of the burst corona discharge toward the cathode. At higher pressure the x-ray irradiation lowers the gap strength, for then it is a question only of releasing the first streamer on its path across the gap. The higher values when there is no irradiation reflect the effect of spark lag.

Diffusion has a role similar to negative ion formation in that it decreases the field at the tip of a streamer and in other regions where space charge gradients tend to be high. Howell[7] has recently shown how diffusion may increase spark voltages and the pressure at which the maxima appear. In Fig. 3 the $+S$ curves for the two oxygen-helium mixtures show this effect. A comparison of the curve for the oxygen-argon mixture with that for the corresponding oxygen-helium mixture shows how much greater is the shift of the pure oxygen maximum with the lighter gas. The position of the maximum for oxygen-nitrogen mixtures seems not to be dependent on the composition. But with mixtures of low oxygen content, burst corona yields place to intermittent corona. In hydrogen the $+S$ curve is higher than the $-S$ curve.

All of these curves were obtained with a 3-mm gap. Some preliminary experiments being made with greater spacings indicate that the principal effect of increasing the spacing is to shift the curves along the y axis. This appears to be true both for the pure gases and for mixtures.

In conclusion we should like to thank Dr. A. W. Hull and Dr. E. E. Charlton for their suggestions and interest in this investigation.

[7] A. H. Howell, Elec. Engineering, **58**, 193 (1939).