the onset potential is 12.65 kv with a value of $X/p = 200$ at the point surface. (The same values of $X/p$ are found along a vertical line above 0.3 mm in Fig. 3B for the respective point potentials of 6 and 12 kv.) This indicates the threshold of stability of the negative ions produced in freon. The negative ion formation and the relatively inelastic electron impacts in freon tend to decrease materially the first Townsend coefficient $\alpha$.

The hysteresis effect of increased onset potentials for the intermittent corona may be explained by the accumulation of decomposition products of freon which are particularly effective in electron capture. Since free atoms like Cl and F will recombine to form molecules, it is not surprising to find that the effect disappears with time. Such reactive gases can also be absorbed by electrode materials and similar substances. In an enclosed, air-filled chamber a transient lowering of the sparking potential was observed as a result of the formation of nitrous oxides after the passage of several sparks,[14] but in freon the reverse is true.

We wish to express our appreciation to Professor L. B. Loeb for the loan of the discharge chamber used in this work and for his assistance in the interpretation of the results in the light of recent data from his research group.

[14] W. R. Haseltine, Phys. Rev. 58, 188 (A) (1940).

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# Positive Corona in Freon-Air Mixtures

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In this investigation of positive corona, streamer pulses increased in frequency and strength to a maximum at one percent of freon in air. The visual characteristic of the corona changed markedly indicating also that the discharge sustained itself largely by the streamer mechanism. The dissociation of freon by the discharge created stable $Cl^-$ and $F^-$ ions which neutralized the positive space charges and therefore stimulated streamers. As the freon content was increased, streamers degenerated until they could not be distinguished from burst pulses. The onset potentials were shifted to higher values and the current *vs.* potential curves showed decreasing slopes with increasing amounts of freon.

## EXPERIMENTAL RESULTS

THE data on the positive point-to-plane corona in freon-air mixtures were obtained by using the techniques described previously.[1] In air the intermittent corona region (Geiger-counter regime) began with the onset of streamers[2] at a point potential of 5 kv, and it extended over a range of about 200 volts. Some burst pulses were also observed. At 5.2 kv onset of the continuous corona occurred, and streamers no longer were present. The current was 0.25 microampere, and the visual appearance of the discharge was steady. Further increase in potential resulted in monotonically increasing currents (Fig. 1). At between 20 and 25 kv occasional "breakdown" streamers were observed. Since these only occur close to the sparking potential, the runs were terminated. The visual character of the discharge was that of a uniform glow which extended over a larger surface area of the point as the potential was raised.

It has been pointed out before[3] that the addition of small amounts of impurities to the gas strongly influences streamer formation and thereby sparking potentials. Therefore, after several runs with the same dry air filling, streamers were observed in the continuous corona region. They did not occur in this region after the refilling of the chamber, and the results of

[1] G. L. Weissler and E. I. Mohr, preceding paper on negative corona.
[2] A. F. Kip, Phys. Rev. 55, 551 (1939).

[3] G. L. Weissler, Phys. Rev. 63, 96 (1943); R. W. Haseltine, Phys. Rev. 58, 188A (1940).

the first run were duplicated. The addition of from $10^{-4}$ to $10^{-1}$ percent of freon to pure air gave essentially the same results as those just described for *old* air: streamers were formed in the lower potential region of the continuous corona, and they disappeared at around 10 kv.

The characteristics in a one-percent freon-air mixture changed markedly. The onset potential of the intermittent corona region was again 5 kv, but the range was extended to about 9 kv. Visible, strong streamers were observed, and the currents fluctuated between zero and three microamperes. Streamers were still present after the onset of the continuous corona at 9.15 kv and were active throughout this entire region. The visual appearance of the continuous corona underwent a significant change from the uniform glow in air, which covered the point like a closely adhering sheath of about 0.05 to 0.1 mm in thickness, to a very localized discharge like a narrow and intense luminous channel or spindle (Fig. 2). The area of contact between the spindle and the corona point was very bright and about 0.05 mm in diameter. The maximum diameter of the spindle was never greater than two to three times the diameter at contact. As the potential was raised the spindle increased in brilliance, seemed to decrease in diameter, and grew in length up to six mm at 21 kv. Its tip swayed laterally and gave the impression of streamers feeding into it. The current *versus* potential curve was only very slightly below that of pure air.

The concentration of freon in dry air was gradually increased to 100 percent. The onset potentials of the intermittent corona region were raised to higher values, reaching 13 kv for 100 percent freon. The potential range became progressively larger with increasing amounts of freon, i.e., extending beyond 25 kv for 100 percent freon, and the current *vs.* potential curves decreased in slope (Fig. 1). The visual appearance of the discharge changed from a pinkish-purple color typical of air to bluish-white. It retained the general form of a spindle, at least at the higher potentials, but it decreased in length and increased in diameter as the freon content was increased. The discharge gradually lost its well-defined shape and became more diffuse (Fig. 2).

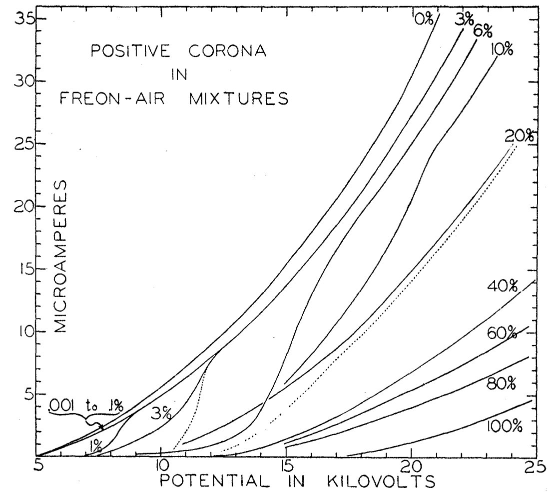


FIG. 1. Current *vs.* potential curves for positive corona in freon-air mixtures. The percentage number indicates the amount of freon by volume in dry, clean air. Total gas pressure: 745 mm of Hg. The dotted curves are representative of the values obtained in a second run, about 15 minutes after the first one was finished.

With large amounts of freon the general trend of streamer formation in both the intermittent and the continuous corona regions seemed to be one of degeneration. In mixtures containing three percent of freon streamers were immediately followed by burst pulses as indicated by decaying saw-tooth patterns in the oscillograph.[4] When the percentage of freon was increased further, streamers became weaker, formed less frequently, and assumed the characteristics of burst pulses which gradually decreased in amplitude.

The corona characteristics of each gas filling were checked by two or more runs. If the time interval between runs was of the order of a few minutes only, a hysteresis effect similar to that in negative corona[1] was observed. For mixtures of $10^{-2}$ to 100 percent of freon the onset potentials of the intermittent corona region were shifted several thousand volts higher than those of the first run. This effect seemed to depend only slightly on the concentration. In the lower part of the intermittent corona region the current *vs.* potential values of the second run were far below those of the first, and they gradually converged toward the point of onset of the continuous corona, i.e., the broken line curves in Fig. 1.

To summarize: (a) In from zero to 0.1 percent freon streamers and occasional burst pulses were

[4] A. F. Kip, Phys. Rev. **55**, 549 (1939), Fig. 6.

present in the Geiger regime, and the streamers persisted in the lower portion of the continuous corona; (b) one percent of freon resulted in predominant streamer activity with practically no burst pulses; and (c) increasingly higher percentages showed more burst pulses with a continual decrease in streamer frequency and strength until only burst pulses were discernible.

### DISCUSSION

A discussion of the mechanisms active in positive point-to-plane corona in air at atmospheric pressure has been given by Loeb.[5] The streamer represents the most significant space-charge phenomenon of the positive corona in air, and it occurs in a very narrow potential region termed the Geiger-counter regime.[6] Streamers disappear at the onset of the continuous corona and are replaced by the self-sustaining burst-pulse corona, which is composed of many rapid current fluctuations caused by a continuous succession of burst pulses.

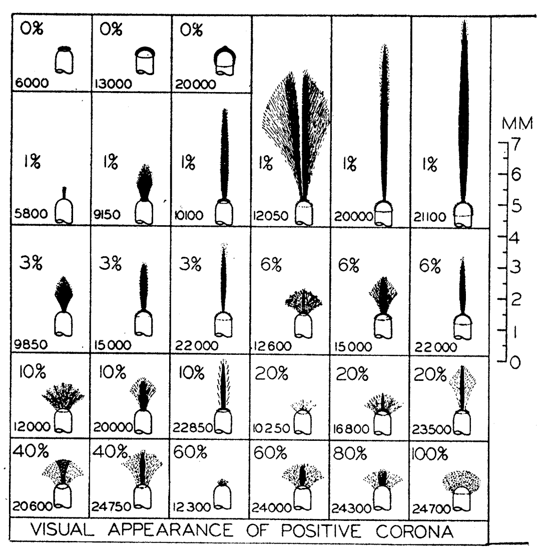


FIG. 2. Visual appearance of positive corona in freon-air mixtures. The percentage number indicates the amount of freon by volume in dry, clean air, the other number the point potential in volts. With a point diameter of ½ mm, it was attempted to make the drawings to scale.

In the Geiger region the static field about the point is of sufficient magnitude so that a chance electron produces an avalanche of $\exp[\int \alpha dx]$ positive ions and electrons. Most of the positive ions form a concentrated space-charge boss near the point surface. Photons produced in the avalanche ionize the gas photoelectrically[7] and thereby create additional avalanches which feed into the space-charge boss as a result of its highly directive field. Thus the positive space charge extends into the gap well beyond the high field region about the point, and produces a streamer which dies out when the combined gradients become too weak. The production of a second streamer must await the clearance from the gap of residual positive space charges which decrease the field below the minimum value at which streamers may form. For this reason, at or above the onset of continuous corona, the field is only sufficient for the production of lateral avalanches which form a burst pulse. An extended glow spreads uniformly over the point surface in contrast to the extremely narrow channel of light characteristic of the streamer. In the intermittent corona region either streamers or burst pulses may occur, depending on the statistical distribution of the positive space charge at any instant. They are observed more frequently in mixed gases or in gases where metastable states are abundant,[3] since their mechanisms depend strongly on efficient photo-ionization in the gas.

In mixtures of low freon content the state of a mixed gas with intense photo-ionization was more fully realized than in air. This condition reached a maximum value for concentrations of about one percent, and streamers which were easily visible in the tele-microscope persisted over the entire potential range of our observations. The abundant formation of streamers in the continuous corona region may be explained by the presence of negative ions which neutralize the positive space charges in the streamer channels. The persistence of streamers and the radical change in the visual characteristics from an extended burst pulse corona in air to the narrow and brilliant channel in the one percent

[5] L. B. Loeb and A. F. Kip, J. App. Phys. **10**, 142 (1939); L. B. Loeb and J. M. Meek, *ibid.* **11**, 438 (1940); L. B. Loeb and J. M. Meek, *The Mechanism of the Electric Spark* (Stanford University Press, Stanford University, California, 1941), Chapter II.

[6] C. G. Montgomery and D. D. Montgomery, J. Frank. Inst. **231**, 447 (1941).

[7] E. Greiner, Zeits. f. Physik **81**, 543 (1933); A. M. Cravath, Phys. Rev. **47**, 254 (A) (1935); with L. B. Loeb, *ibid.* **47**, 259 (A) (1935); C. Dechene, J. de phys. et rad. **7**, 533 (1936).

freon mixture (Fig. 2) suggest that the discharge is propagated mainly by the streamer mechanism.

The spindle consisted of a highly conducting plasma of positive and negative ions and electrons, and it showed current densities varying from $1.7\times10^{-2}$ amp./cm$^2$ at a potential of 10 kv near onset of the continuous corona to one amp./cm$^2$ at 21 kv. The narrowness of this form of discharge can be explained by the following: When a strong streamer forms in a gas, lateral branching is reduced; also the existence of stable negative ions in the plasma of the streamer channel causes an increase in the lifetime of the channel, and therefore it will be re-used by succeeding streamers and appear as an intensely bright spindle. In pure $N_2$, in which negative ions do not form, a similar spindle-shaped corona has been observed at potentials close to breakdown. In $N_2$ the discharge channel is maintained because of the presence of atoms in the metastable state. In pure $H_2$, on the other hand, negative ions and metastable states are absent and, therefore, no such corona has been observed.[3]

Electron avalanches at higher freon concentrations do not develop to the size attained in air because of the greater stability and numbers of the negative ions. The positive ion space charges are consequently not strong enough to distort the field sufficiently for streamer formation and the discharge, therefore, develops into laterally spreading burst pulses.

At concentrations of 40 percent of freon or higher it became impossible to differentiate clearly between streamers and burst pulses. These results are similar to those found in air by Kip using sharp needle points,[8] which attenuate the high field region rapidly. Since $x_0$ and the number of ionizing free paths within $x_0$ are reduced, the $\int_0^{x_0}\alpha dx$ is smaller, and the positive space charges are insufficient to sustain streamer propagation. In the work on negative corona in freon[1] it has been shown that the negative ions formed are stable at values of $X/p\geqq200$, compared to an $X/p=90$ where the negative $O_2$ ions shed their electron. Therefore the high field region in which effective ionization by collision can take place with freon is confined much closer to the positive point and thus gives rise to similar phenomena to those observed with needle points in air.

We again wish to express our thanks to Professor L. B. Loeb for his assistance in the interpretation of our data.

[8] A. F. Kip, Phys. Rev. 55, 552 (1939), Fig. 8.