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Melvin J. Kofoid

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by

M. J. Kofoid
Plasma Physics Laboratory
Boeing Scientific Research Laboratories

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M. J. Kofoid

Boeing Scientific Research Laboratories
Seattle, Washington

ABSTRACT

When electrodes are immersed in a low-density gas plasma, breakdown in the ordinary practical sense cannot occur with an applied voltage less than the minimum of Paschen's curve. However, a leakage current can flow. The maximum circuit current will be numerically equal to the saturation positive ion current which flows from the plasma to the cathode. Attention is centered on the situation where one electrode has an area very much larger than the other. The difference in leakage current, as polarity is reversed, is then striking. The theory is discussed. The effects on the current vs voltage characteristics of changing the electrode area, electrode-area ratio, plasma ionization density, gas density, and gas were investigated experimentally. Practical expedients can greatly decrease the leakage current.

INTRODUCTION

This paper is concerned with the question of what can happen when a voltage is applied between electrodes immersed in a plasma in a gas of low density. Primary attention is given to the case of two highly unequal area electrodes with a d-c potential difference of up to 150 volts. The experimental work was planned and is discussed with emphasis on its relation to the situations which might exist with a hypersonic vehicle during re-entry into the earth's atmosphere.

An initial question is when can electric breakdown, in the ordinary sense of a large maintained increase in current limited principally by the metallic-circuit impedance, occur between electrodes inserted into a plasma. The theoretical answer[1] is that breakdown cannot occur with voltages smaller than the minimum value of the Paschen breakdown voltage curve for the particular gas and cathode material. Theory is supported by the results of different workers[2] during many years of studies of re-ignition voltages in circuit-interruption research. It is here assumed that the electrodes are at too low a temperature to thermally emit electrons. The minimum of Paschen's curve for nitrogen is 208 volts with a cathode of copper, and 215 volts with iron; for oxygen the values are similar. Therefore, it is believed that in practice breakdown in the ordinary sense will not take place in air between electrodes of commonly used metals with d-c or power-frequency voltages of up to 150 volts. It is worthy of emphasis that this conclusion applies to any electrode separation, any gas density, and in particular to any degree of ionization.

If breakdown cannot occur, will there be an appreciable leakage current through the plasma in which the electrodes are immersed? It is with this remaining question that this paper is concerned. On a theoretical basis it is concluded that the current can become appreciable only if the cathode area is large; it can then become large only if the anode conditions permit. The theoretical considerations will be discussed. Confirming experimental studies of the magnitude of the leakage current with the gas, gas density, plasma ionization density, electrode areas, and polarity as parameters will be described.

Throughout the paper it is assumed no negative ions existed; this is later justified. Implicitly the applied voltages are always less than Paschen's minimum value for breakdown.

THEORY

Small Identical Electrodes

Consider immersed and electrically floating in a plasma two small, and for this initial discussion, identical exposed terminals of a circuit which is to be energized with not more than a few tens of volts d-c. Let the electrodes be separated several cm.

Initially, with zero voltage applied between them, the terminals will each assume the same small negative potential with respect to the plasma. This potential will be the voltage drop across the sheath of positive ions which will form to surround the electrodes -- just as with the well-known Langmuir single probe. In volts it will be $V = \frac{T_e}{11,793}$, where T_e is the electron temperature of the gas in degrees Kelvin (K); it ordinarily will be of the order of some tenths of a volt to a few volts.

When the d-c circuit voltage is applied, the anode will shift its potential with respect to the plasma, becoming slightly less negative; the cathode will become more negative with respect to the plasma by the remainder, and major part, of the applied circuit voltage. The situation in the sheath region immediately surrounding each electrode has undergone a change. The voltage drop in the plasma proper is taken as negligible and unchanged. The circuit current will be very small, i.e. microamperes in ordinary low-temperature plasmas. The electrodes of equal area are acting in the identical manner of classical floating double probes used in plasma diagnosis, the theory for which has been discussed in detail by Johnson and Malter.

Double Probe Theory

The qualitative discussion of the classical double-probe phenomena, as described by Johnson and Malter[3], is reproduced here in abridged form since it is essential to an interpretation of the present results.

As an aid in understanding, they consider how the system reacts for several different values of differential voltage, or circuit voltage V_d. The associated circuit current is i_d . Refer to their circuit of Fig. 1. The positive sense of these quantities is shown by the direction arrows, where positive current is defined as the rate of flow of positive charge. The performance of the double-probe circuit is based on the Boltzman relation and the plasma-sheath properties of a gas discharge. Fundamental in the situation is an application of Kirchhoffs' current law which demands that the instantaneous net current of positive ions and electrons flowing to the system from the plasma must be zero.

Equal probe areas, no contact potentials, and no point-to-point differences in plasma potential are assumed. They further assumed that V_d has no effect on the ion current to the system.

Essential in the discussion are the potential diagram and voltage-current characteristic reproduced as Figs. 2 and 3. Three cases are discussed.

Case (a) $V_d = 0$ (Fig. 2a)

Each probe will assume the same floating potential and will collect zero net current. Since there is no net potential acting in the current loop, $i_d = 0$. The condition corresponds to point o on the curve of Fig. 3.

Case (b) V_d = small negative voltage (Fig. 2b)

The potentials of the probes with respect to the plasma must adjust so that the basic current relations are satisfied. As shown in Fig. 2b, probe No. 1 must shift closer to the plasma potential and collect more electrons, while probe No. 2 shifts away from the plasma potential and collects less electrons. The deficiency at probe No. 2 is made up by the passage through the circuit of extra electrons flowing to probe No. 1. This flow will be referred to as the deficiency current. All the conditions can be again satisfied and the system operates at some point b on the curve of Fig. 2.

Case (c) V_d = somewhat larger negative voltage (Fig. 2c)

Probe No. 1 shifts still closer to plasma potential and collects the entire electron current to the system, since probe No. 2 is now so highly negative with respect to the plasma that no electrons from the gas can reach it. Half of the electrons arriving at probe No. 1 now travel through the metal circuit to probe No. 2. Again all conditions are satisfied and the system operates at some point y on Fig. 3.

Making V_d still more negative cannot produce an increase in i_d since probe No. 1 is already collecting sufficient electron current to balance the total ion current to the system. Probe No. 1 therefore stays fixed in potential and probe No. 2 goes negative along with V_d. This probe can be considered saturated with respect to positive ions as the system moves along the flat portion yx of the characteristic of Fig. 3.

Because of symmetry, the system will reverse the results when V_d is positive, giving the upper half ozw. The total positive ion current to the system is sum of the positive ion current to probe No. 1 at y and to probe No. 2 at z, as symbolized by i_{p_2} and i_{p_1}. The electron current flowing from the plasma to probe No. 2 is equal to the sum of the absolute values of the positive ion current to this probe and of the deficiency current i_d. In Fig. 3 the value of i_{e_2} corresponding to a voltage V_d is illustrated.

The point of high interest for the present studies is that with a relatively very small applied circuit voltage the anode can attract all of the electrons reaching the two-electrode floating system from the plasma.

Theoretical Consequences of Large and Unequal Electrode Areas

If the cathode surface is small very little circuit current can flow even if the anode surface is made very large. The positive ion current to the cathode will be the governing quantity and will remain unchanged by an increase in anode area. The deficiency electron current flowing through the circuit will likewise remain unchanged, and hence very small. The anode electron current density will be decreased; hence the anode will become slightly less positive with respect to the plasma, remaining at close to its floating potential.

In extreme contrast, if the cathode area is made large while the anode is left small, much may occur.

The ion current from the plasma to the cathode will then be increased in proportion to the increase in cathode area.

The increased ion current will be collected with only the unchanged small potential difference between the cathode and the plasma. This potential difference is just sufficient to allow positive ions and electrons to reach the cathode in equal numbers when the applied voltage is zero; it is then just the ion sheath voltage and is the electron-volt equivalent of the electron temperature -- usually a few volts.

When a small potential difference is applied, the ion current to the cathode will not change. However, the electron deficiency current will increase with circuit voltage to a limiting, or saturation, value obtained when plasma electrons can no longer reach the cathode. It will numerically equal the ion current to the cathode. Since no positive ions will reach the anode after the applied voltage exceeds twice the sheath voltage, the anode electron current will then become simply the deficiency current.

The disturbing point is that electron current from the plasma to the small anode must increase to equal the total positive ion current to the now larger cathode surface. If the anode is relatively very small, the actions which will occur in the plasma at the anode are not simple and cannot be quantitatively predicted. It has been tacitly assumed so far that only the above primary phenomena existed. As will be discussed, secondary phenomena can act to considerably increase the ion saturation current, and hence the electron deficiency current.

The crux of the matter is that the small anode will attempt to collect sufficient electrons to compensate for the large positive charge excess arriving at the large cathode in the form of positive ion current. The anode drop will no longer be very small, but will be much increased. The anode-drop phenomena become controlling. Large electric fields will exist in the plasma near the anode because of the developing negative space charge as the anode attracts electrons and repels ions. If sufficient circuit voltage is available, starting with a critical voltage V_c , plasma electrons being drawn to a very small anode will produce an intense increase of the ionization of the gas close to the anode. This local ionization intensification can progress to the point where the plasma, exclusive of the cathode sheath, exhibits a negative resistance characteristic; then less voltage will be needed to maintain a large electron flow to the anode than the critical voltage V_c required to establish it. In effect, the intense local ionization can be thought of as increasing the size of the anode to such a degree that the necessary cathode deficiency electrons can be attracted from the plasma. Were it not for the local anode potential fall, the current would be limited only by the voltage drop through the body of plasma and by the cathode voltage drop. But both of these drops are usually small compared to an applied voltage of even only several tens of volts. Therefore, the circuit voltage is nearly all available for forcing current through the anode drop. This is true only as long as the electron deficiency current is less than the positive ion current to the cathode. Then the deficiency current flow of electrons through the circuit becomes equal to the positive ion flow to the cathode, essentially all of any further increase in circuit voltage will appear as an increase in cathode sheath voltage. The current of positive ions drawn through the sheath will then increase, but very slowly because of the heavy ion mass.

The anode situation is quite analogous to that which may exist in a mercury arc rectifier. The rectifier constitutes a low-pressure gas discharge with a practically unlimited supply of electrons at the negative end. The conditions at the anode must adjust themselves so that the current through the anode sheath, which depends on the plasma random current and sheath voltage, will equal the drift current through the plasma. If, with the anode at a particular potential with respect to the plasma, insufficient electrons are attracted to equal the current demanded by the circuit, the voltage drop in the plasma at the anode must increase. A quite strict analogy has existed in certain multi-anode mercury-arc rectifier tubes where the anode was located at the end of a restricted-diameter anode arm. The drop in the plasma in the arm, while trying to carry a current equal to the drift current, has been known to become so great as to choke off the discharge intermittently, resulting in current surging.

The sketch of Fig. 4 shows a deficiency electron current I_e vs applied voltage V characteristic, plotted with a linear abscissa and a logrithmic ordinate. It is typical of the curves obtained in the laboratory with a large cathode and a very small anode. If the anode had been sufficiently large so that the deficiency current could have been collected with such low fields that they caused negligible ionization and negligible increase in the ion diffusion, the plasma ion density adjacent to the cathode would have been the original plasma value n_+, the maximum deficiency current would have been some value indicated as the "original n_+ saturation level". However, when the situation demands an applied electric field so large as to cause appreciable ionization in the plasma near the anode, not only are extra electrons made available to flow to the anode but also extra positive ions are created which flow to the cathode. Furthermore, the applied field can make the general flow of ions a much larger value than existed with simply ambipolar diffusion; in the ensuing diffusion process, instead of having in the plasma just a radial, in the laboratory configuration field due to the positive charges restraining the flow of electrons, there is the applied field causing increased flow of the positive ions. In this paper this process will be termed "enhanced diffusion". The increase of the ion population and also the enhanced ion flow due to the applied field result in an augmentation of the ion density in the plasma at the cathode, and therefore of the plasma-to-cathode saturation ion current. If a deficiency current equal to the normal plasma ion saturation current cannot be collected with a low circuit voltage, the augmentation can be large. As in the situation of Fig. 4, the current may be increased to some value such as indicated as the "augmented n_+ saturation level".

Several important questions arise regarding the leakage-current problem when the anode area is very much smaller than that of the cathode. Quantitatively, how large a current will flow if the applied voltage is not great enough to cause an appreciable increase in the ionization intensity in the anode fall region or enhanced mobility? At what critical voltage V_c will the current start to increase rapidly due to the onset of discharge phenomena which will effect a negative resistance condition? Also, what must the circuit voltage be to obtain the maximum electron deficiency current, i.e. circuit current? Further, what will be the magnitude of this saturation current? To gain further insight to the answers to these questions an experimental study was made.

EXPERIMENTAL WORK

The investigation was conducted with the two test electrodes immersed in the central section of the positive column of a long d-c low-pressure arc. The ionization density of this background plasma was 5×10^8 to 100×10^8 electrons per cubic cm. Nitrogen, argon, or xenon gases were used at pressures of 10, 30, or 100 microns (mm x 10^{-3} Hg).

The study, in almost its entirety, was made with the smaller electrode as the anode, since with the reverse polarity an insignificant current flowed. Therefore, for convenience, the small electrode will be referred to as the anode and the large electrode as the cathode, except in the brief discussion of the results with reversed polarity or with a-c voltage. The ratio of the cathode area to the anode area was made large, i.e. as great as 80,000, to clearly display the unequal-area deficiency current phenomena.

A very limited investigation was made with 100 cps and 100,000 cps sinusoidal voltages to show the principal features of the a-c leakage current problem.

Apparatus

The general apparatus arrangement is indicated in Fig. 5. The arc which provided the background plasma existed between a heated coated cathode C' at one extremity of a long glass discharge tube and an anode plate A' at the other, with a separation of 90 cm. The test cathode C was a thin stainless steel cylinder of 9.5 cm diameter and 17 cm length. This cylinder fitted snugly with the inside of the glass discharge tube and only its interior surface was in contact with the plasma. The test anode A was an exposed section of an otherwise glass-covered small-diameter stainless-steel rod. To obtain the smallest anode area only the end area of a 0.09 cm diameter rod was exposed, giving a ratio of cathode to anode areas of 80,000; to decrease the ratio to 6,500, glass was removed to expose the necessary amount of side-wall area. The ratio was further reduced to 530 using an anode rod of 0.23 cm diameter with an exposed length of 1.30 cm. Each anode was located at the axis of the cathode cylinder, midway between its ends, and with the exposed anode area centered about the axis. The background plasma density and temperature were determined from measurements with a Langmuir probe P, 0.2 mm diameter and 6 mm long, located on the tube axis 1.0 cm from the anode A. The pressure in the chamber was measured with an ion gauge.

In order that the test circuit which was electrically floating with respect to the plasma was not disturbed by the measuring apparatus, batteries were used as the test voltage source and the potential was measured with a high-impedance vacuum-tube voltmeter or cathode-ray oscillograph -- both of which were battery operated.

Procedure

As a preliminary step, Langmuir probe measurements were made of the background plasma electron density and electron temperature. With discharge currents of 100 to 1,000 ma, sufficient data were taken to plot curves for nitrogen, argon, and xenon (N_2, A, and Xe) gases with n_e varying through the range of interest.

With a discharge current of a value predetermined to produce a desired electron density, the test circuit current flowing between test anode A and test cathode C was measured as a function of the voltage applied between them. The changes in the A-A' and C-A' voltages which occurred when the current was caused to flow in the test circuit were recorded in the d-c tests; these were identically the changes in the voltages between anode A and the plasma, and cathode C and the plasma.

Results and Discussion

For a typical case, the shifts in potentials of the electrodes with respect to the plasma are plotted as a function of leakage current in Fig. 6. The phenomena can be conveniently considered as developing in three stages. In stage A, as the applied voltage was increased the current increased monotonously until a critical voltage V_c was reached. During this phase, as predicted in the discussion, the cathode potential did not shift a detectable amount; the rise in the anode potential with respect to the plasma was equal to the total applied voltage. Stage B was entered with the attainment of voltage V_c ; the electric field had then increased to the point where in the plasma, in the immediate vicinity of the small anode electrode, there was the onset of anode discharge phenomena characterized by effectively negative resistance properties. In stage B, with applied voltages greater than V_c , there occurred a very rapid increase in current due to the increased ionization density about the anode and to enhanced diffusion; this was accompanied by a small decrease in anode potential. The cathode still remained at essentially its original floating potential. The current ceased its high rate of increase at the start of stage C; here the condition had been attained where the flow of electrons to the cathode had become practically zero. Essentially all of any further increase in circuit voltage appeared as an increase in the departure of the potential of the cathode from that of the plasma. Two reasons can be given for the break in the curve not being extremely sharp when the cathode starts to shift in potential. The electrons have a thermal velocity distribution and, also, the ion flow to the cathode was ever-increasing with increase in applied voltage. The accompanying minor increase found in the anode voltage, when the cathode shifted rapidly, is not understood; it may be attributable to the finite volume of plasma and the manner in which it was created.

The curves of the remaining figures show the current as a function of the applied circuit voltage with a variety of parameters. The curves of Figs. 7, 8, and 9, (and Fig. 6 also) are for the smallest anode area; Figs. 10 and 12 show results for the smallest area, and also for other areas.

The effects of changing pressure in nitrogen are shown in Fig. 7. At a lower pressure, the mean free path of an ionizing electron is greater, or stated differently, the macroscopic collision cross-section for ionization is less. Therefore, at a lower pressure a larger electric field, hence larger V_c , is required to cause an anode discharge. With only 10 microns pressure (i.e. $p = 10\mu$) the discharge condition was not attained. The starting points of stage B and of stage C are indicated on the 30 microns pressure curve.

The effect of gas pressure, and also of change in the degree of ionization of the background plasma, are portrayed for argon in Fig. 8. At a particular pressure, the greater the plasma electron density n_e , the lower is the value of the critical voltage of V_c . Anode discharges are attained with lower fields with higher n_e since more electrons are initially available to participate in the ionization buildup processes.

Since V_c is the applied voltage with which a critical local ionization density is obtained, at a given pressure V_c should be less in a more easily ionized gas. This is demonstrated by the curves of Fig. 9 for the several gases used. Xenon is the easiest of these gases to ionize, as its ionization potential is low and in it an electron produces the largest number of ion pairs per cm of travel. Nitrogen is the most difficult to ionize.

The effects of increasing the anode area are shown by the curves of Fig. 10. The minimum anode area of Case I was increased by a factor of 12.2 in Case II, and 150 in Case III.

The critical voltage and the voltage at which current saturation is reached are both less for a larger anode area. Also, the deficiency current electrons are drawn from the plasma with a lower electric field.

Referring to the curves for Case I (minimum anode area), the onset of the anode discharge occurred at a lower voltage in the higher-density gas, as should be expected. That the saturation current was greater at the lower pressure is attributed to increased diffusion.

The application of an electric field between the centrally-located anode and the cylindrical cathode always increased the diffusion to some degree over that which existed before, the increase tending to be proportional to the strength of field applied.

However, the electron collection process at a very small anode constitutes a substantial impediment to the current flow. As mentioned earlier, when the electrode area becomes so small that the drift current (thermal random motion current) coming to it is less than the current demanded by the circuit, sufficient voltage must be applied to supply the necessary positive anode drop. For this reason with the smaller anodes of Case I and Case II the electron current augmentation was not due primarily to enhanced diffusion, although the applied voltages were greater than with the largest anode.

In the Case III curves (maximum anode area) there is no evidence of a critical voltage; the deficiency current was collected without much ionization intensification at the anode. Thus, in this case the augmentation of the deficiency current, which proved to be considerable, must have been due primarily to enhanced diffusion.

The calculated current and the measured current should be in reasonable agreement if the causes of increased positive ion flow to the cathode are not active. With a pressure of 100 microns, an ionization density $n_e = 18 \times 10^8$, and the 530 square cm area cathode of the experiment, the saturation leakage current calculated for the nitrogen will later be shown to be about 3.3 ma; it would calculate to be about 2.8 ma for argon, but only about 1.5 ma for the much heavier xenon.

The calculated current for nitrogen is less by a factor of 5 than the measured value shown in the curve of Fig. 7. The high critical voltage V_c apparently led to considerable ionization intensification and to a large diffusion current.

As seen in Fig. 8, with argon at the somewhat higher $n_e = 25 \times 10^8$, the 100 microns pressure current started to saturate at a value again well above the value of 3.9 ma calculated for these conditions, using the smallest anode. However, when in argon with the same conditions except that instead of using the smallest anode, a special much larger 50 square cm area anode (a cylinder 2 cm long and of 4 cm diameter) was used, the current saturated at only about 6.5 ma -- with 6 volts applied. The low collection voltage, made possible by the use of the extra-large anode, precluded appreciable current increase due to ionization and allowed the diffusion current to remain very small. Then, with the conditions those assumed for calculation, the experimental and calculated current values agreed within a factor of less than 2.

Referring to Fig. 9, it is seen that the saturation current with xenon (at 10, not 100 microns) was only a little greater than 1.0 ma with the smallest anode. Any current augmentation should have been very minor since the normal plasma density saturation current was relatively small, and probably more important, any necessary anode discharge could be obtained with such a low voltage in this easy to ionize gas and the diffusion of the heavy ions with only a low field was small. The experimental value compared very well with the calculated value of 1.5 ma.

In the test situations discussed (except with the special large 50 square cm anode), when the small electrode was made the cathode, the circuit current flow was never greater than about 15 microamperes; this is a negligible flow compared to the reversed polarity current.

With applied sinusoidal a-c voltages of low frequency, i.e. 100 cps, the current flow during alternate half-cycles should be analogous to the d-c case with the small electrode first the anode and then alternately the cathode. When the frequency is so high that an appreciable amount of the additional ionization, produced in the plasma when the small electrode is the anode, persists for a half-period, or longer, the current flow pattern must change. Data were obtained at 100 kc, where the persistence of ionization effects were pronounced, for comparison with 100 cps data.

The nature of the currents at 100 cps and 100 kc is illustrated by the oscillograms of Fig. 11. Electron current flow is recorded as a downward displacement. The gas, pressure, and background plasma density were the same in all cases. The basic differences caused by increased frequency are evident in a comparison of oscillograms (A) at 100 cps, and (B) at 100 kc, both taken with a maximum area small electrode (Case III); the effects of residual ionization, including a small ion current flow, are clearly evident in (B). That with 100 cps with the minimum area small electrode (Case I), the current flow was relatively minute until the critical voltage for local intense ionization was reached is shown by a comparison of oscillograms (C) and (D); in (D) voltage V_c has been just exceeded. At 100 kc with the (Case I) small electrode, oscillogram (E) shows a measurable ion current when the small electrode was cathode and only 30 volts was applied; with the identical situation, except with the applied potential increased to 88 volts, the ion current flow was several times larger as shown by oscillogram (F). In contrast, when the small electrode was positive not only did the current increase generally when 88 volts was applied, but with critical voltage exceeded a high peak of electron current was obtained.

The effect of frequency is further illustrated by the curves of values of peak current vs crest voltage of Fig. 12. The electron current and V_c , when the area of the smaller electrode was the minimum employed, are little different with 100 cps than with d-c voltage (compare the 100 cps, Case I curve with the 100 microns pressure curve of Fig. 7). The electron current is much greater at 100 kc than at 100 cps at all voltages up to the 100 cps critical value, apparently due to more intense ionization being produced by the higher-frequency voltage. As with d-c, the saturation currents were obtained with lower voltage in Case III where a maximum area of the smaller electrode was employed. Also, in this case, the effect of increasing the frequency was less. Summing up, only with one electrode extremely small compared to the other will the leakage current obtained with a voltage less than the d-c critical value be much greater with 100 kc than with 100 cps or d-c voltage.

Conditions of current choking were sought and encountered, using the smallest area anode. At voltages roughly several times V_c the current was found to surge at widely divergent frequencies of the order of some tens to a few hundred kilocycles, the frequency depending on the gas, pressure, and excess of voltage.

Prediction of Leakage Currents

The laboratory results can be useful, in varying degrees, in estimating or interpreting leakage currents or in developing electrode designs to minimize them in electrically or thermally ionized plasmas.

On an orbiting vehicle live electrical terminals may be exposed to the plasma surrounding the vehicle during high-speed re-entry into the earth's atmosphere. Interest in such a thermally ionized gas problem gave rise to this study. This plasma produced by shock-wave thermal ionization is different in important aspects from the electrically-ionized plasma of the experiments. The principal differences will be mentioned in the following quantitative considerations for a typical re-entry problem.

The atmosphere at an altitude of interest of 60 km (200,000 feet) has nearly the composition of air at normal temperature and pressure. The charged particle concentration[4] is about 3.5×10^{15} per cubic cm which corresponds to a pressure of 100 microns at room temperature (any increase in concentration due to a shock wave is ignored). The plasma gas temperature near the vehicle surface can be about 4,400 K. The thermal ionization density is calculated by Saha's equation[5] to be $n_e = 2 \times 10^{11}$ per cubic cm for air. Experimental difficulties prevent laboratory studies in air at the above combination of particle and ionization densities, even at room temperature. However, the experimental studies in N_2 provided reasonably related results. The corresponding ionization density which would exist in N_2 would be the considerably smaller value of $n_e = 35 \times 10^8$, since n_e is very strongly inversely dependent on the ionization potential, which is higher for N_2 than for O_2. The degree of ionization is an even faster, and extremely rapidly varying function of temperature. Thus, a small change in assumed temperature would alter the results as much as a change from air to N_2 gas. The effects of changing temperature or ionization potential can be rapidly evaluated with the help of curves shown by A. v. Engel[6].

With n_e equal to 35×10^8, only 10^{-4} percent of the molecules are ionized. This ionization density is within the range which can be conveniently produced in N_2 in the laboratory equipment.

In the thermally ionized plasma the electron temperature T_e and the ion temperature T_+ are equal, i.e. $T_e = T_+ = 4{,}400$ K, while in the laboratory plasma $T_e = 2.5 \times 10^{-4}$ K and T_+ is reasonably estimated to be about only 1,000 K. In the laboratory plasma the thermal velocity of the positive ions would be

$$v_+ = \sqrt{\frac{8\,k\,T_+}{\pi M_+}}\,, \text{ where}$$

k is Boltzman's constant, and

M_+ is the positive ion mass.

For nitrogen (N_2) gas

$$v_+ = 9 \times 10^4 \text{ cm per second.}$$

The positive ion current density is

$$j_+ = 1/4\; n_+\, e\, v_+\,, \quad \text{where}$$

n_+ is the positive ion density,

e is the electronic charge, and

v_+ is the positive ion directed velocity.

With $n_+ = 35 \times 10^8$ and $T_+ = 1{,}000$ K,

$$j_+ = 12 \times 10^{-6} \text{ amperes per square cm.}$$

With the cathode of the laboratory experiment having a 530 square cm area, the N_2 positive ion saturation current would be 6.4 ma with $n_+ = 35 \times 10^8$ (or 3.3 ma with $n_+ = 18 \times 10^8$).

The positive ion current density to the surface of the vehicle immersed in the plasma with $T_+ = 4{,}400$ K would be higher than in a room temperature plasma in proportion to the square-root of the positive ion temperature. For the N_2 component,

$$j_+ = \sqrt{\frac{4{,}400}{1{,}000}} \times 12 \times 10^{-6} = 25 \times 10^{-6} \text{ ampere per square cm.}$$

The corresponding value for the O_2 component is

$$j_+ = 1300 \times 10^{-6} \text{ ampere per square cm.}$$

For practical purposes, this may also be taken as the value for air, since the ion flow due to the O_2 is so very large compared to that due to N_2. Under the assumed conditions a positive ion current with a density of at least this order flows from the plasma through the positive ion sheath to every exterior area of the vehicle, (assuming identical plasma everywhere), regardless of potential differences between different surface areas due to internally applied voltages.

If the exposed area of negative electrode is only 1.0 square cm, the maximum leakage current is 1.3×10^{-3} ampere, regardless of the anode area -- which might be most of the remainder of the exterior vehicle surface of, say, 4.5×10^{5} square cm (500 square feet). (Augmentation of ion density by increased ionization as a result of applied voltage is momentarily disregarded.) However, if the polarity is reversed, for the same areas the saturation leakage current could be 620 amperes before a cathode ion current limitation would be reached. To what extent this saturation leakage current would be approached would depend primarily on the ability of the small anode to collect the deficiency current electrons from the plasma and on the limitations of the power supply. To what extent it could be exceeded if the required voltage were so large that the ion current were augmented cannot be calculated, but some guidance in making an estimate might be obtained from the laboratory data. A scale-model test, made in keeping with the law of similitude, may be of aid in obtaining practical answers.

The leakage current with more than one anode should be about the same as with a single electrode having an area equal to the sum of the areas of the multiplicity of anodes, if all surfaces are exposed to identical plasma.

It has been tacitly assumed that all the negative particles were electrons. This was essentially correct both in the laboratory tests and in 4,400 K thermally ionized air. If negative ions had been present they conceivably might have exerted a pronounced effect. However, the formation of negative ions by attachment to a neutral atom is negligible in Xe, A, and N_2, even at low temperatures[7]. Although in a gas such as O_2 negative ions can be readily formed by attachment at the lower temperatures, it is unlikely that negative ions are formed[8] in a plasma with a temperature of 4,400 K (which is of the same order as found in arcs in air at atmospheric pressure). The strong electrical field in the region close to the anode lessens the chance of attachment[8,9]. Low gas density also further precludes attachment. Therefore, it is concluded that negative ions cannot play any significant roll in the leakage current phenomena during re-entry into atmosphere while the gas temperature is several thousand degrees, or more.

Minimization of Leakage Currents

By taking advantage of simple design considerations the d-c leakage current often can be kept small, i.e. to a few milliamperes, or less.

The collection of electrons from the plasma by the anode should be made as difficult as possible in order to increase V_c. However, care must be taken that the advantage gained with a small anode is not lost due to an increase in the density of the positive ions produced by the anode discharge phenomena and enhanced diffusion.

As a practical expedient, the critical voltage V_c can be increased to above the circuit voltage by placing the anode in a recessed location where the ion temperature and in particular the ionization density will be very much reduced. The effectiveness of this simple expedient was demonstrated by a laboratory test. Except for the recessing of the electrode, the test was the same as that of the 100 microns pressure curve of Fig. 7. The 0.066 cm diameter rod electrode, instead of having its end flush with the end of the covering glass sleeve, was withdrawn into the glass sleeve just a distance equal to one rod diameter. The leakage current was thereby reduced from more than 20 ma to less than 100 microamperes with 150 volts applied.

If it is not possible to make the smaller electrode negative, as in some cases such as that of the skin of an aircraft, much of the otherwise exposed cathode area might be fairly effectively eliminated by coating it with a refractory insulation; the conduction current through such a coating would have to be given proper consideration.

CONCLUSIONS

The d-c leakage current is a flow of electrons collected from the plasma by the anode, and carried through the circuit to make up for the deficiency of the electrons collected by the cathode.

This flow of electron deficiency current is necessary to maintain electrical neutrality of the electrode system immersed in the plasma.

The circuit current, i.e. leakage current, attains a maximum when, as the end result of applying circuit voltage, the cathode-sheath voltage becomes so great that no electrons from the plasma can travel through the sheath to the cathode.

The maximum, or saturation, deficiency current is equal in magnitude to the total positive ion current arriving at the cathode from the plasma.

The leakage current is directly proportional to the cathode area (if there is no ion density augmentation), the ionization density of the plasma in which the circuit electrodes are immersed, and the square-root of the ion temperature.

If the positive ion density is not augmented due to the applied voltage, the value of the positive ion current is subject to rough calculation. Also, under this condition -- but only then, the saturation leakage current is independent of the anode area.

The saturation leakage current may be greatly augmented if, with a sufficiently small anode, the applied voltage is large enough to cause an anode discharge or to cause enhanced diffusion, or both.

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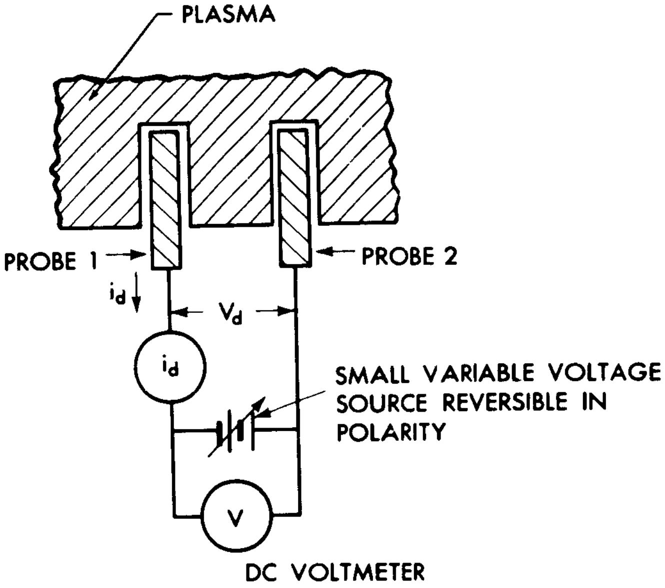

Fig. 1. Basic double-probe circuit.

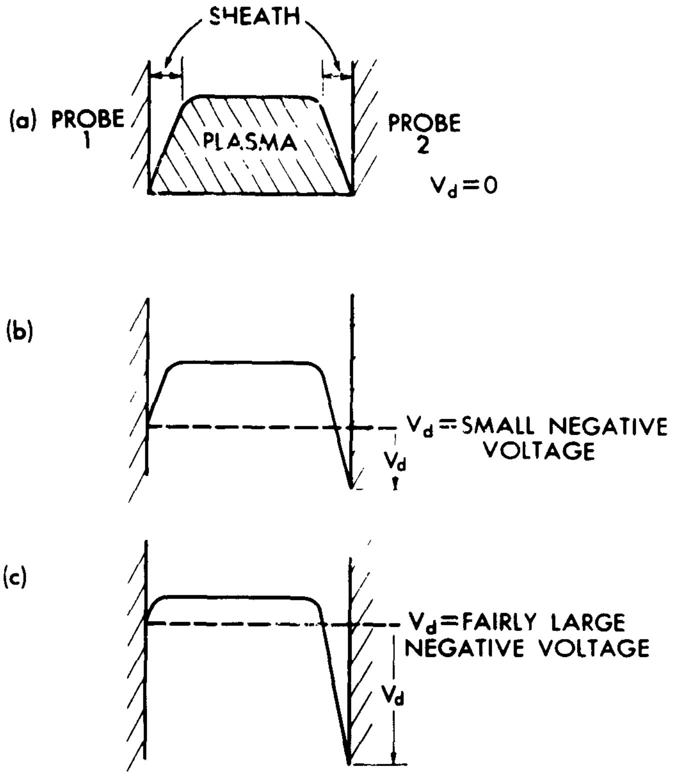

Fig. 2. Shifts in electrode potentials caused by applied voltage.

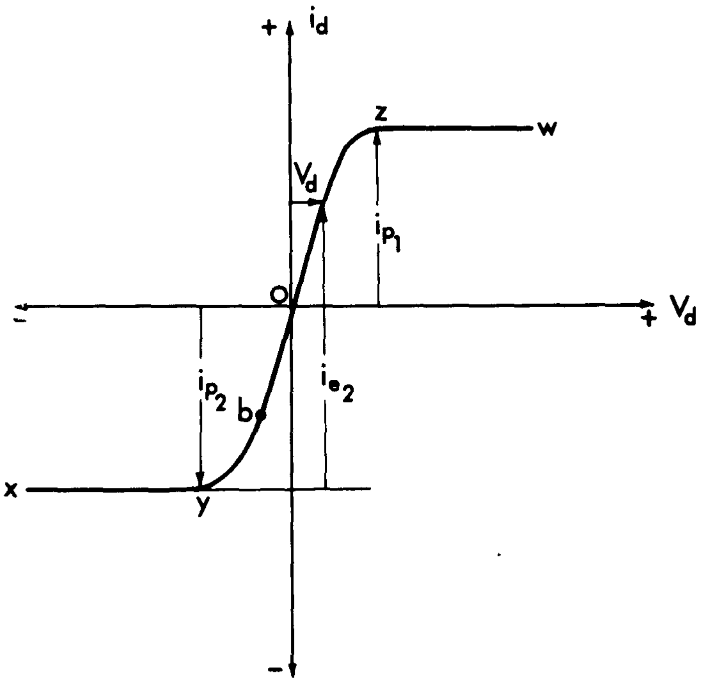

Fig. 3. Voltage-current characteristic of a double-probe measurement.

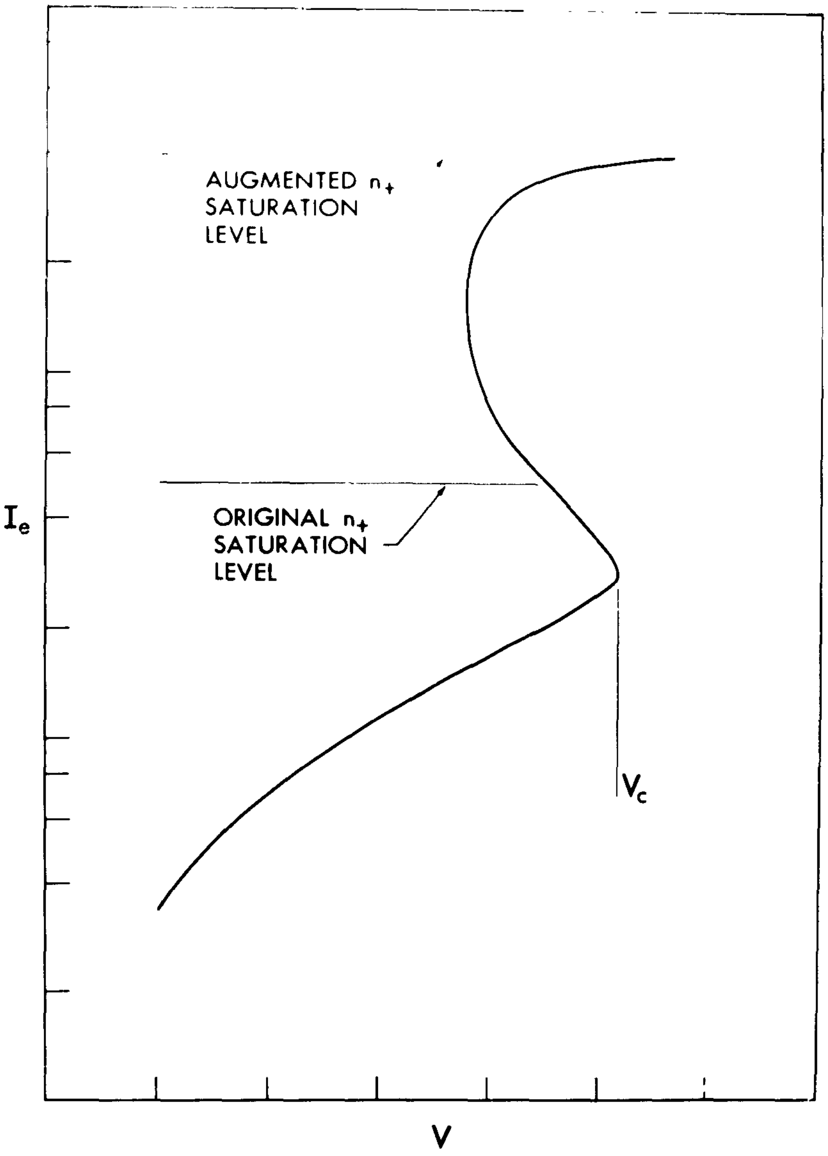

Fig. 4. Increase in leakage current due to augmented ionization.

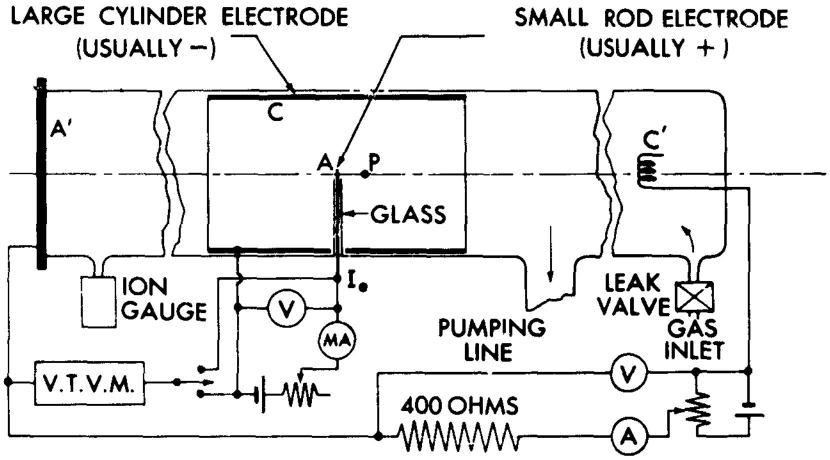

Fig. 5. Test apparatus arrangement.

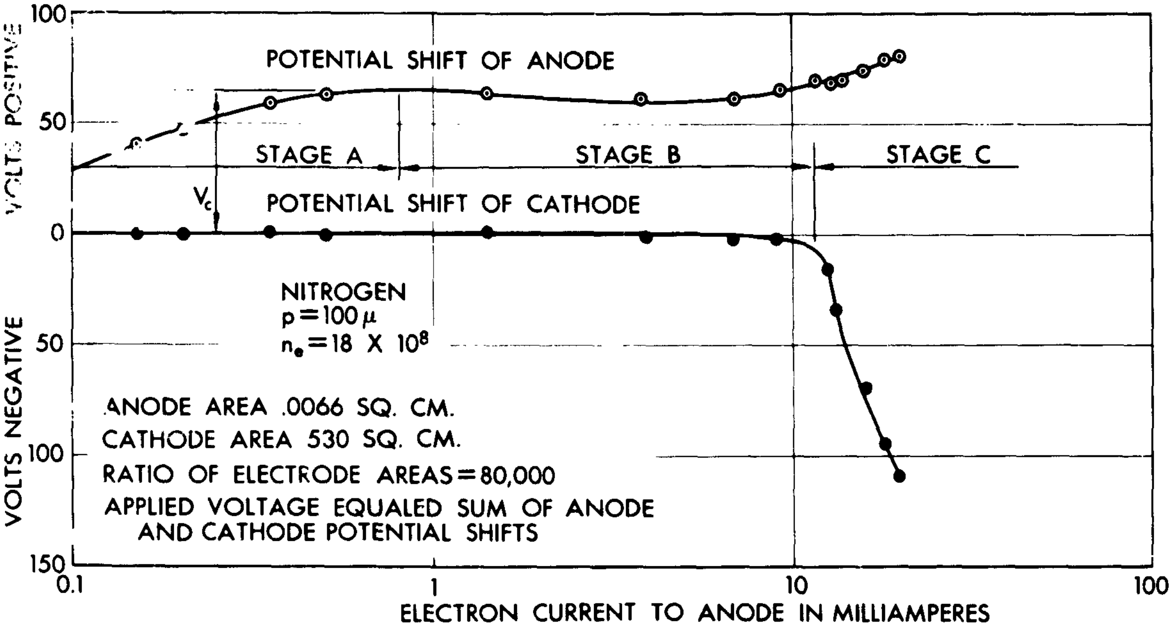

Fig. 6. Changes in electrode potentials from their floating potential caused by applied voltage.

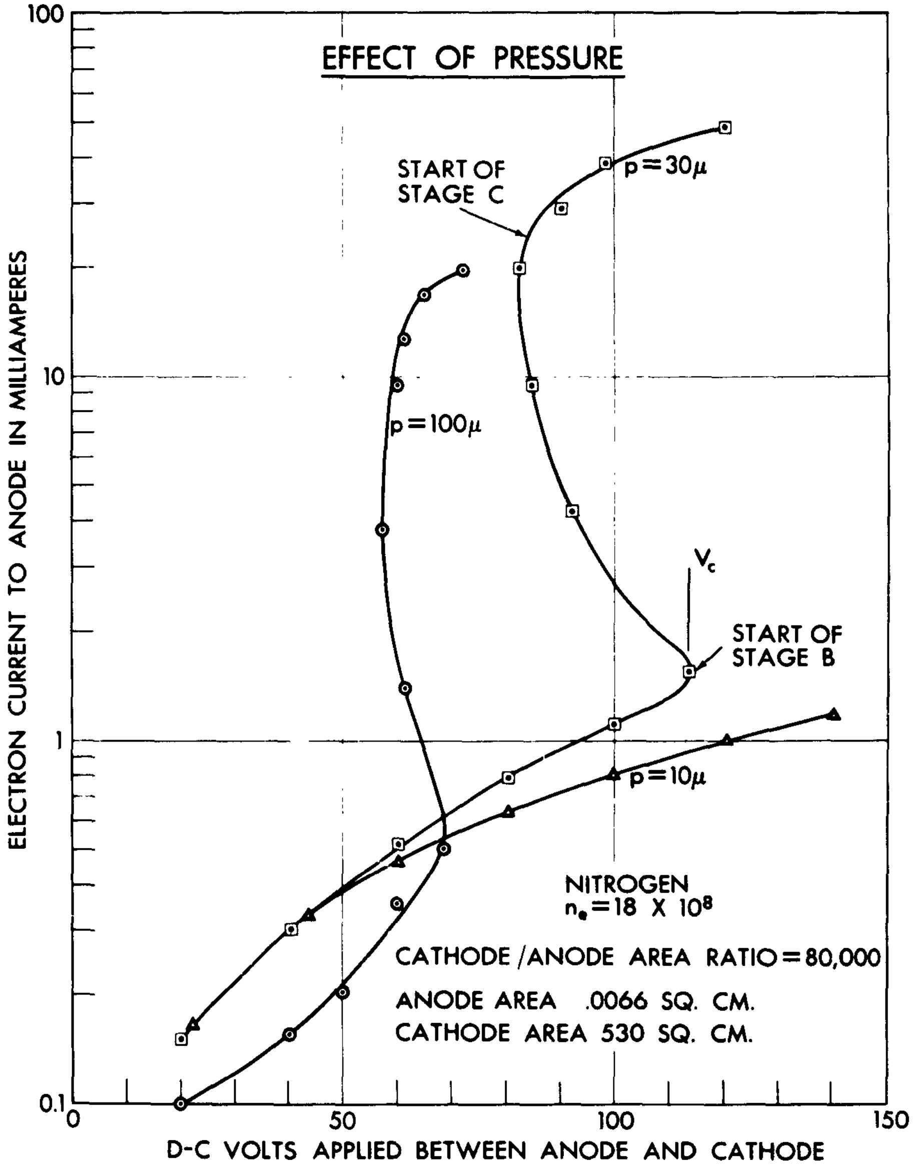

Fig. 7. Leakage current as a function of gas pressure.

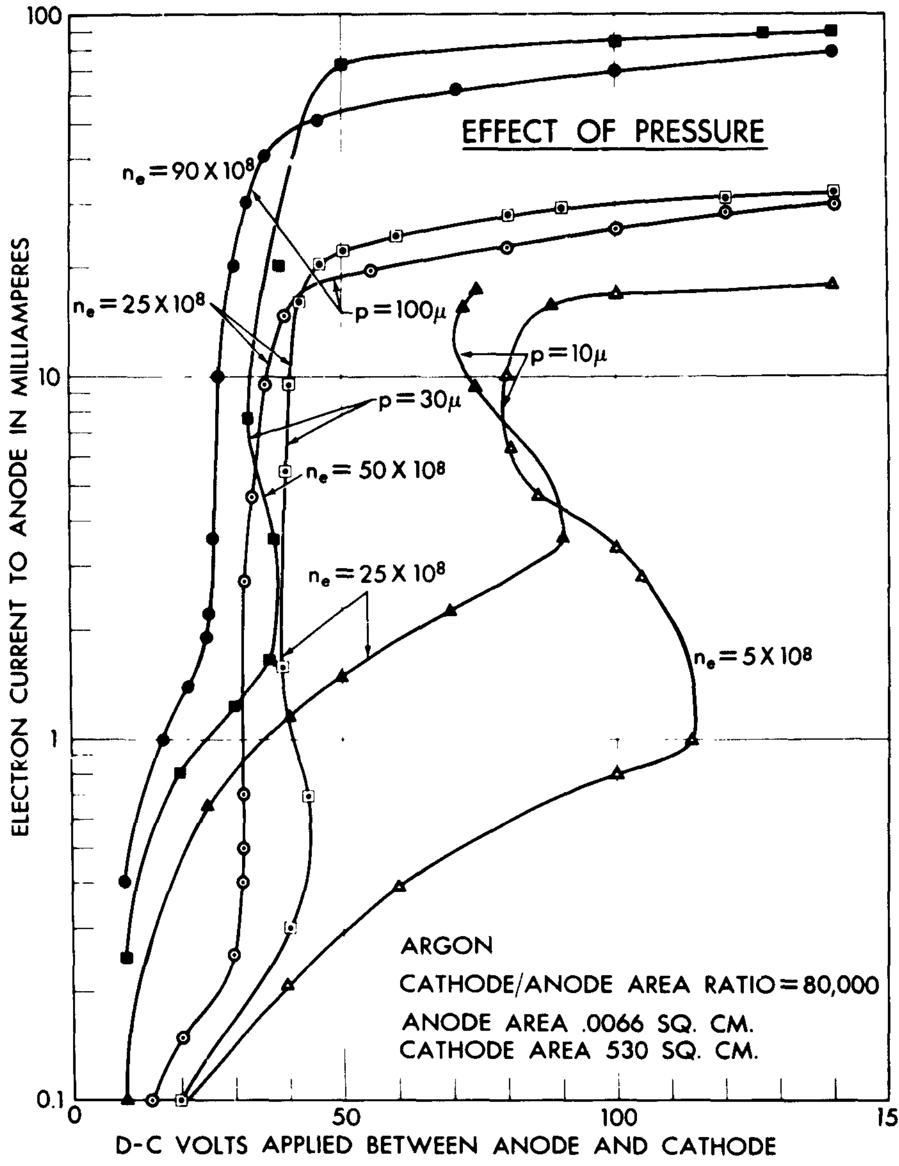

Fig. 8. Effect of changes in gas pressure and in background ionization density.

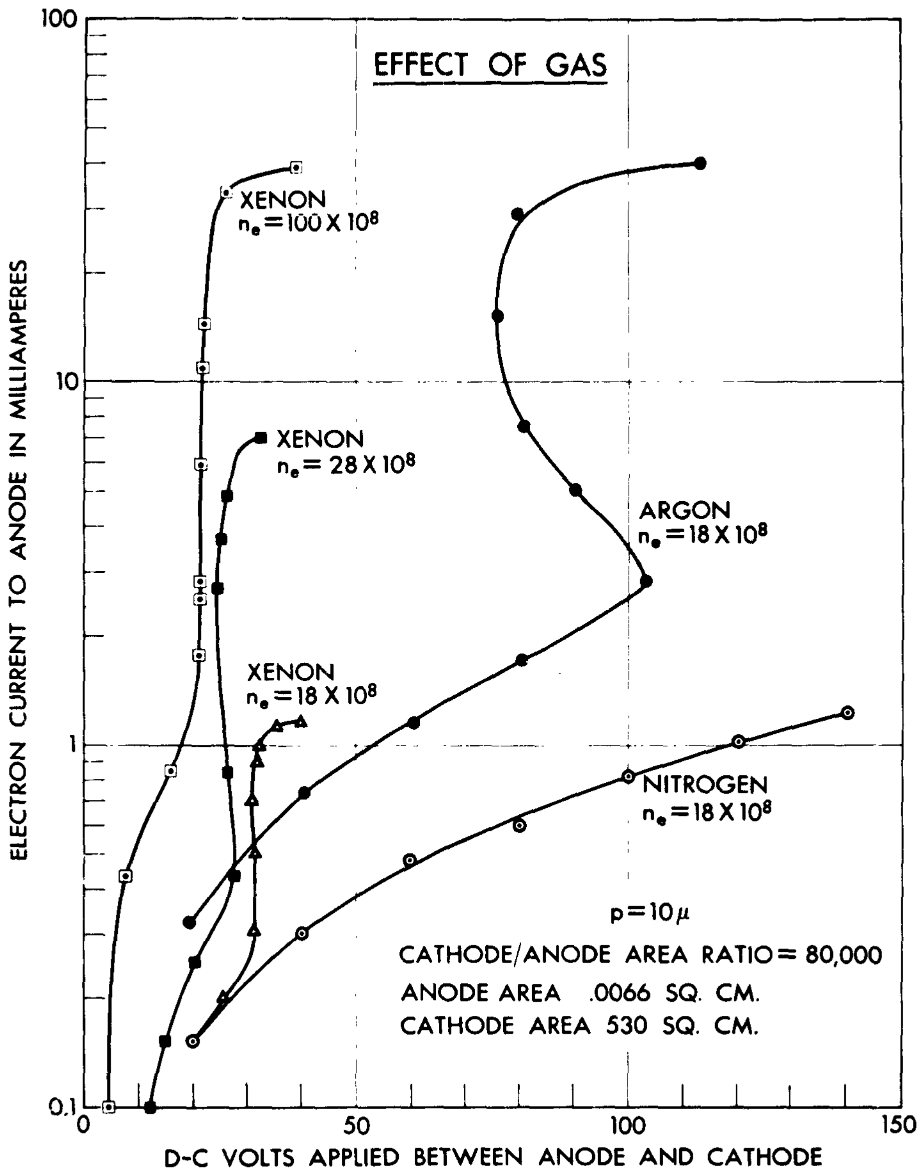

Fig. 9. Results with gases differing in their ease of ionization.

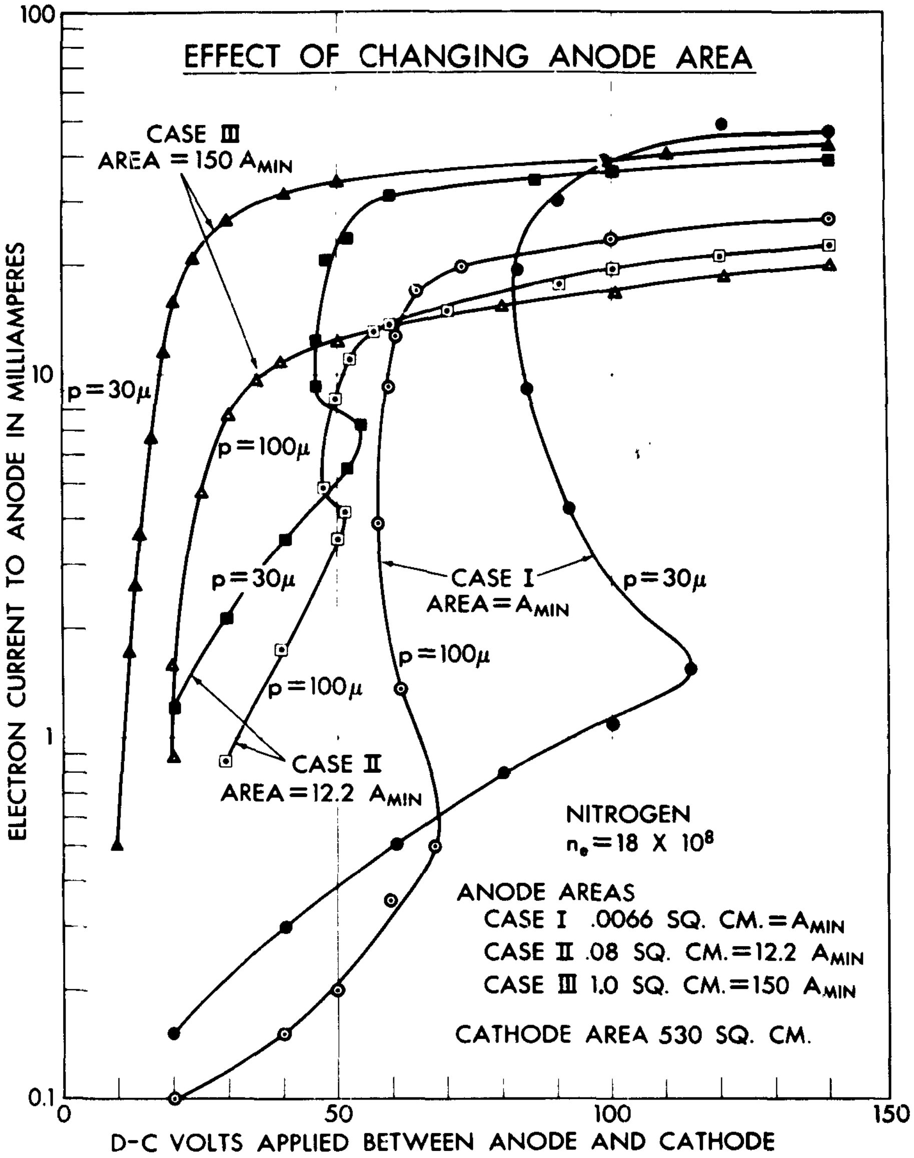

Fig. 10. Effect of changing anode area with constant cathode area.

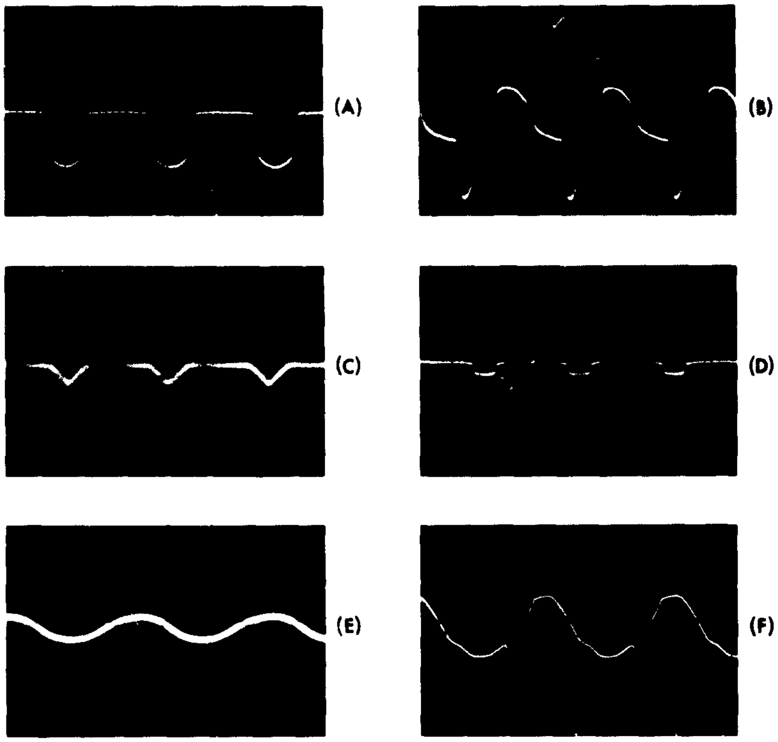

Fig. 11. Sinusoidal-voltage leakage currents vs time. N_2 at 100μ pressure. $n_e = 18x10^8$ per cm^3. (A) and (B) at 70 v crest with Case III electrodes; (A) 100 cps , (B) 100 kc. (C) and (D) at 100 cps with Case I electrodes; (C) for 70 v crest, (D) for 88 v crest, (E) and (F) at 100 kc with Case I electrodes; (E) for 30 v crest, (D) for 88 v crest. Current sensitivity 1.0 ma per division in (C), 10 ma per division in remainder.

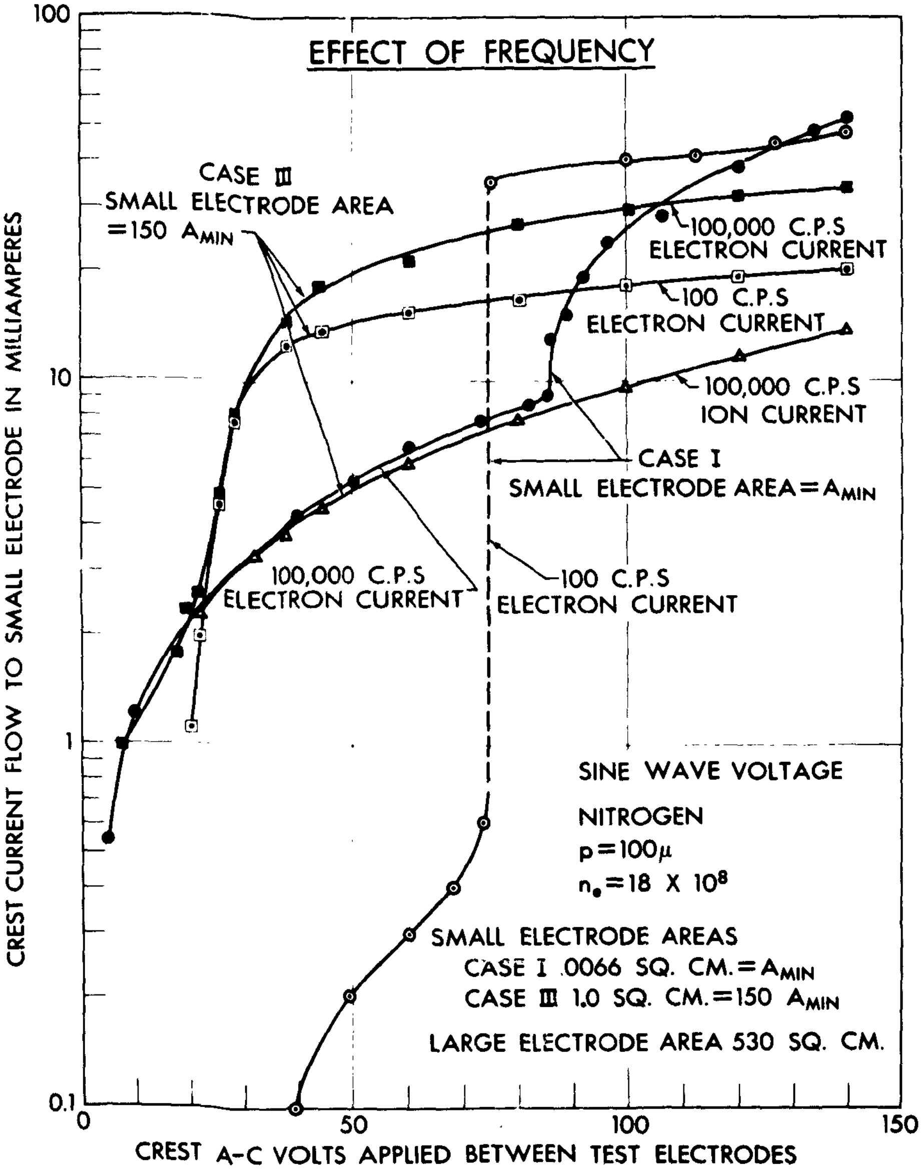

Fig. 12. Leakage currents with sinusoidal voltages.