THE EFFECT OF SURFACE CHARGES IN VACUUM DISCHARGE TUBES

By A. R. Olson and T. F. Young

Abstract

Current-voltage curves obtained with a four electrode tube with two rather widely separated gauzes, showed discontinuities at voltages which were evidently not critical potentials since they varied with the gas pressure. Since charges on the glass surface were thought to be responsible, *a simple case was studied.* Electrons were accelerated from a filament through two gauzes, 3.3 cm apart and held at the same potential, to a plate, the space between the gauzes being surrounded by a metal cylinder C insulated from both. This cylinder became negatively charged until the loss or leak just equaled the gain due to the faster electrons. As the accelerating voltage A_1 was increased, a value b was reached at which both the voltage of C and the current suddenly increased greatly, and these larger values were maintained until A_1 was decreased to a limit a, considerably lower than b. A study of the equipotential surfaces gives an explanation of these effects. The discontinuities may be eliminated by controlling the voltage of the cylinder C. In experiments in which electron velocities must be known, it is evidently necessary that insulated "floating" surfaces be avoided and that the potential of all parts of the wall be controlled.

IN numerous published researches on the critical potentials of gases, discontinuities in current-voltage curves have been obtained. Horton and Davies[1] obtained such discontinuous curves in their work on argon and Foote and Mohler[2] described similar results in their work on nitrogen. Working with oxygen, we have observed discontinuities in our curves, which are similar to those mentioned above. However, in our work, increased pressure caused the discontinuities to occur at lower voltages, whereas, in other work pressure had either no effect or the opposite effect. In Fig. 1 we have reproduced curves obtained in the preliminary work with oxygen. Each discontinuity, it appeared, could be explained by ascribing it to some combination of the published values of the critical potentials of this gas, yet such an explanation was not tenable when it was found that the positions of the breaks could be made to vary continuously by gradually changing the pressure. Moreover, it did not seem probable that the discontinuities could be explained, as may sometimes be done, by assuming the breaking down of a large space charge, for the currents used were about 10^{-7} ampere. There was, however, the

[1] Horton and Davies, Proc. Roy. Soc. **A97,** (1920)

[2] Mohler and Foote, Bur. Stds. Sci. Papers, No. 400, 1920

possibility that a surface charge, such as Elster and Geitel[3] found in their work on the photo-electric effect, might accumulate on the glass walls of the tube and exert an influence on the electron stream passing near it.

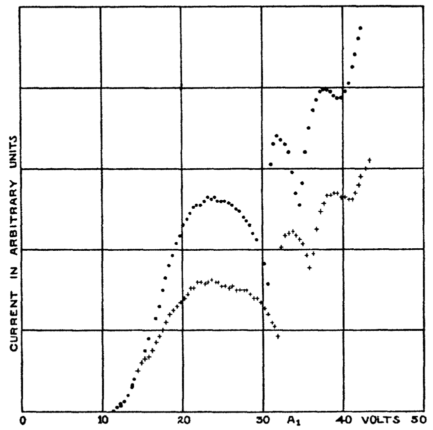

Fig. 1. Spurious discontinuities observed in oxygen.

APPARATUS

The ionization tube used in the investigation described below, which is similar to others frequently employed in work of this kind, is shown in diagram in Fig 2. To determine the existence or non-existence of a surface charge, a cylinder made of copper was substituted for the glass walls used in the work described above. At each end of the copper cylinder but insulated from it, were two platinum gauzes G_1 and G_2, forming an ionization chamber 3.3 cm long and 2.6 cm in diameter. The potential of the cylinder could be measured with respect to one of the leads of the

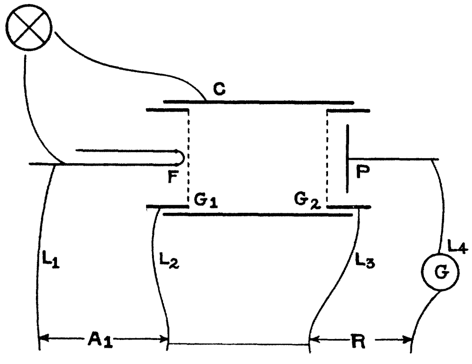

Fig. 2. Diagram of ionization tube and connections.

---

[3] Elster and Geitel, Phys. Zeit. **14,** 741 (1913)

oxide-coated platinum filament *F*, by means of a potentiometer and quadrant electrometer. Electrons were accelerated from *F* to G_1 by a variable potential which we will call A_1. A low resistance galvanometer *G* is shown at its normal position L_4 but it could be shifted easily to L_1, L_2 or L_3, in order to measure the currents from the filament or from the gauzes.

EXPERIMENTAL RESULTS

In Fig. 3 we have plotted as a function of the potential A_1, the measured values of the current to the plate (Curve I) and of the potential of the copper cylinder (Curve II). In this experiment, hydrogen at a pressure of about 0.1 mm of Hg was used.

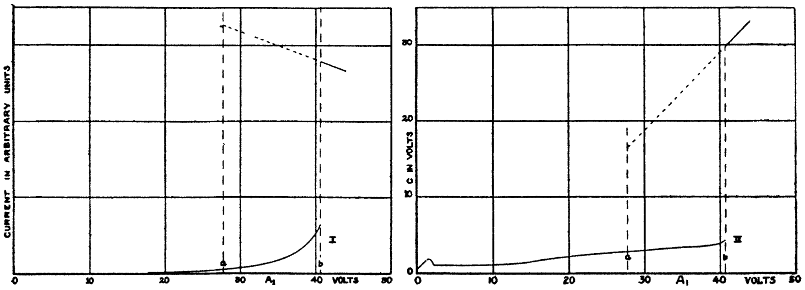

Fig. 3(I). Current to the plate *P* as a function of A_1.
Fig. 3(II). Potential of copper cylinder *c* as a function of A_1.

Every value of A_1 to the left of the line *a*, determined unique values of the cylinder potential and of the current to the plate, which were attained regardless of whether A_1 was increased or decreased to that point. At *b* both the current and the cylinder potential increased abruptly. Decreasing A_1 through *b* did not restore either the current or the cylinder potential to its former value, but they followed in the general direction of the dotted curves until the line *a* was reached when they changed suddenly to the solid curves. When A_1 was increased beyond *b*, the current to the plate and the cylinder potential were again single-valued functions of A_1.

With A_1 between *a* and *b*, the current to the plate and also the cylinder potential could be made to assume values on either the solid or the dotted curves, according to whether the cylinder potential was made to assume momentarily a value in the neighborhood of the one curve or the other. Either of these conditions could be maintained indefinitely, but in no case did we obtain any other condition if the cylinder potential was left free to vary.

DISCUSSION OF RESULTS

In order to understand clearly the conditions within the cylinder, it was desirable to know the potential at various points within this space. Since the two gauzes were kept at a known potential and since the potential of the cylinder was measured, such a calculation was easily made.[4] A cross section of certain calculated equipotential surfaces is mapped in Fig. 4. The difference between adjacent equipotential lines is one tenth of the potential difference between the cylinder and the gauzes. The potential on the .5 line, for example, is equal to the potential of the gauzes plus one-half the difference in potential between the gauzes and the cylinder.

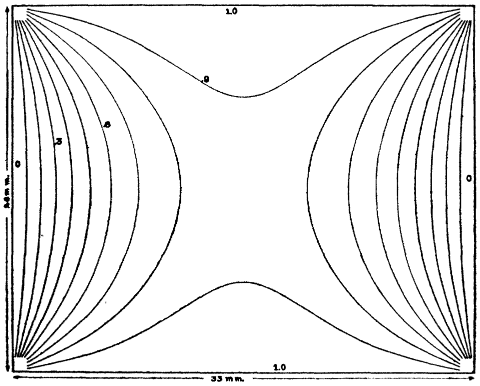

Fig. 4.

It will be seen from Fig. 4 that if an electron enters the space through the gauze G_1, it encounters a retarding field, due to the surface charge on the cylinder, until it reaches a point midway between the two gauzes. From there on it is accelerated, reaching G_2 with its original velocity if no impact has taken place. Those types of impacts such as ionization which can occur only when electrons have velocities exceeding a certain minimum value, must be confined to two regions near the gauzes. The extent of these regions depends upon the amount that A_1 exceeds the critical voltage and upon the potential of the cylinder. For example, if electrons pass through the gauze G_1 after having acquired a velocity equivalent to 30 volts, they can ionize hydrogen only as long as they have lost less than 14 volts velocity, for approximately 16 volts is necessary to ionize this gas. If the potential of the cylinder differs from that of the

---

[4] Byerly, Fourier's Series and Spherical Harmonics, p. 232, Ginn and Co., 1893. Anding, Sechsstellige Tafeln der Bessel'schen Funktionen Imaginaren Argumentes, Engelmann, Leipzig, 1911.

gauze by 23 volts, then ionization can occur only in the volumes bounded by the gauzes and the .6 lines, Fig. 4. In the following discussion we refer to the maximum width of these ionization (or resonance) regions (which can be estimated from Fig. 4) as T.

When a stream of electrons passes through the gauze G_1 after falling through the field A_1, their directions are changed due to mutual repulsions and to collisions or interactions with gas molecules. Some of the electrons reach the cylinder and build up a charge upon it which is negative with respect to the gauze. This charging would continue until the potential built up would be sufficient to repel the fastest electrons if there were no opposing factors. However, due to leakage across the insulators, to photo-electric emission from the cylinder, to positive ions reaching the cylinder, and to "splashing"[5] of electrons from it, the potential that the cylinder acquires is less than that corresponding to the fastest electrons. The potential reached is that at which a dynamic equilibrium exists between the electrons reaching the cylinder and those leaving it.

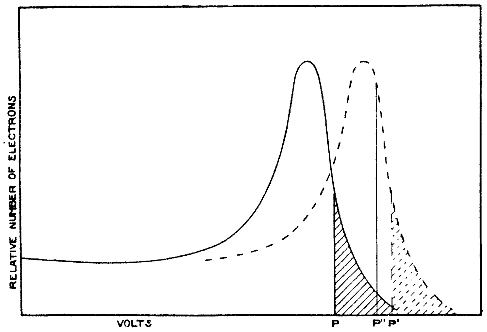

Fig. 5. Distribution of electron velocities.[6]

Let Fig. 5 represent the distribution of velocities of the electrons[6] for some single value of A_1. If P is the potential of the cylinder with respect to the gauze, then electrons with velocities greater than P can reach the cylinder. The number of electrons with velocities sufficiently high is represented by the shaded area under the curve to the right of P, and these, minus those whose energy is diminished by collisions must just neutralize the "leak." If A_1 is increased to A_1' so that the dotted curve represents the distribution of electron velocities, the "leak" from the cylinder is increased and more electrons are required to reach it. Hence

---

[5] Barber, Phys. Rev. (2) **17**, 322 (1921)

[6] Goucher, Phys. Rev. (2) **8**, 566 (1916);
Pawlow, Proc. Roy. Soc. **90**, 398 (1914);
Congdon, Phil. Mag. **47**, 458 (1924).

P does not move to a new position P' so that the shaded area to its right is equal to the former value, but moves only to P''. The difference between P' and P'' is equal to the change in cylinder potential C measured with respect to the filament. This difference between the potential of the cylinder and the filament is controlled by electrons leaving the cylinder and those reaching it. Since some may be prevented from reaching it because of ionizing collisions and since ionization increases the "leak" from the cylinder, the potential difference C is a function of the volume in which ionization can take place. In other terms it is a function of the maximum width T of the ionization regions,[7] which can be estimated from the measured value of the cylinder potential with the aid of the plot in Fig. 4. The dependence of C upon T is exhibited by the solid curve I, Fig. 6.

We can use this curve to determine the rate at which C would increase with T, but to determine the way in which T depends upon the value of C is another problem. By the aid of the map, Fig. 4, we can calculate T for any series of values of C when A_1 is constant. The dotted curves in Fig. 6 illustrate the dependence of T upon C for several values of A_1, as parameter.

When A_1 is increased by a small amount, an increase in the volume of ionization results. Since C is a function of the volume of the ionization region T as expressed by the solid curve Fig. 6, C increases also. T is simultaneously determined by C according to curve II, Fig. 6 (drawn for the new value of the parameter A_1). Hence the values which C and T assume are those at the intersection b of the two curves.

If A_1 is further increased, T and consequently C continue to assume larger values. A given change produced in one has a larger and larger effect upon the other, as is evident from the changing slopes of the curves. Eventually a point is reached such that any increase in T produces a change in C so large that the reciprocal effect upon T is larger than the original variation. This condition arises when the solid and dotted

---

[7] What is here said applies most simply to electrons having the single velocity A_1. It applies similarly to those with higher and lower velocities but for them the volume of the ionization regions are larger or smaller respectively than the regions indicated by T. However, these regions increase as T increases (due to variation in A_1 etc.) and T may be considered a function of the average volume in which all the electrons may ionize the gas. An application of the Kinetic Theory of gases, together with the curve for the distribution of electron velocities might determine completely the manner in which T determines C. Such a study would have to take account also of the possibility of two collisions by one electron and relations might have to be determined for various values of A_1 as a parameter. We will assume the simple relation expressed by the solid curve of Fig. 6 for the purpose of this qualitative discussion.

curves become tangent and is, of course, unstable. Consequently a large change suddenly occurs in T, resulting in a value so large that ionization may fill the whole tube. Since the extent of the influence of C and T upon each other continues to increase during these changes, the value of C after the sudden large increase is considerably larger than is necessary to maintain ionization throughout the whole volume of the tube. Hence if A_1 is decreased, T may not do so until A_1 has reached a considerably lower value. Eventually T may begin to decrease and by means of phenomena similar to those described above, a second discontinuity may result as the cylinder potential leaves the dotted curve (Fig. 3) and assumes values on the solid curve. It might be predicted that between the points a and b, the cylinder potential could be made to assume stable values on either curve. The experimental confirmation of this we have already mentioned.

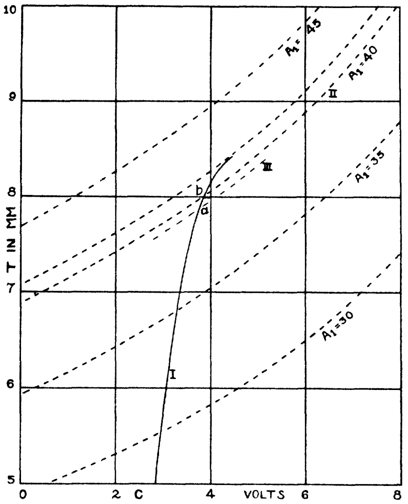

Fig. 6.

The relation of the cylinder potential to the current through the tube can now be considered. A high negative charge on the cylinder drives back many electrons having velocities too low to overcome its retarding influence. Hence when the cylinder potential drops from a large negative value with respect to G_1 to a much smaller value, many slow speed electrons previously turned back toward G_1 are now able to reach the second gauze G_2 and the plate.

A large retarding field (for electrons) between the gauze G_2 and the plate enabled the positive ions reaching the plate to be studied separately. The number reaching the plate was found to be considerably decreased when the cylinder potential suddenly assumed a less negative value. This was probably due to the fact that at high pressures of the gas the electrons were removed so thoroughly in the part of the tube near the first gauze that few were left to produce ions at the second gauze. The effect was more pronounced with increase in pressure, and at high pressures the positive ion current dropped almost to zero.

The larger number of collisions at higher pressures results in a greater rate of change of C with increase in the volume of ionization. This means that the curves of Fig. 6 change slope more rapidly and become tangent at lower values of A_1. Consequently the discontinuity in the cylinder potential and the resulting changes in the number of electrons and ions reaching the plate occur at lower values of the accelerating potential A_1 when the pressure is increased.

It is very significant that no discontinuity in the current passing through the tube was found when the cylinder was held at a constant potential and A_1 was increased to very large values. The change in cylinder potential is evidently, then, the primary cause of the discontinuous phenomena within the tube. Were an ordinary space charge or increased emission from the filament responsible, a sudden change in the current should result even if the cylinder is held at constant potential, providing at least that such a potential is near its natural value just before the break. This reasoning is substantiated by the fact that the algebraic sum of the changes in current to the two gauzes and to the plate was found to be zero. It is further to be noted that there is some quantative support for our postulate in the fact that the discontinuities appeared very close to the values which one would predict from inspection of the curves in Fig. 6.

The close similarity of these breaks to those obtained before the glass cylinder was replaced by one of copper is strong evidence that glass also can hold a surface charge under these conditions. It is important, therefore, to shield all of the glass surfaces in an electron tube in which conditions must be accurately known, or to so construct the tube that corrections can be determined for the surface charges residing on the glass or other insulated surfaces. We have shown how this can be done in one instance.

This research was begun while the first author was a National Research Fellow in chemistry. We take this opportunity for expressing our appreciation to the National Research Council.

UNIVERSITY OF CALIFORNIA,
June 4, 1923.