

ON THE CONDUCTIVITY PRODUCED IN RAREFIED GASES BY AN INCANDESCENT KATHODE.¹

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THE increased electrical conductivity of rarefied gases produced by the employment of an incandescent kathode seems to have been noticed almost simultaneously by Hittorf² and by Edison. A result of this increased conducting power is strikingly shown in the case of the "Edison effect"³ where the relatively small fall of potential in a glow lamp is sufficient to produce a current of several milliamperes through the gas separating the two ends of the filament, or between the filament and a third terminal which is positive with reference to it. The destruction of the filament can often be traced to this leakage current through the gas. Elster and Geitel have found that insulated conductors acquire a charge when placed near an incandescent solid in a partial vacuum, and have made an extended study of this effect. The explanation offered by J. J. Thomson⁴ refers both of these phenomena to a common cause, namely the emission by the incandescent solid of negatively charged particles, which may either impart a static charge to a neighboring insulated body, or may act as the carriers of a current between the incandescent kathode and any suitable anode. Determinations of the ratio of charge to mass in the case of these particles indicate that they are similar to those which constitute ordinary kathode rays.⁵

There are many points of similarity between the behavior of an incandescent kathode and that of a kathode of suitable material, such as zinc, when illuminated by ultra-violet light. At sufficiently

¹ A preliminary account of the work here described was presented to the Physical Society, Feb. 22, 1902. (See *Science*, Vol. 15, p. 425.)

² Hittorf, *Wied. Ann.*, 21, p. 119, 1884.

³ Houston, *Trans. Am. Inst. E. E.*, Oct., 1884, Vol. I.; Fleming, *Phil. Mag.*, July, 1896; Preece, *Proc. Roy. Soc.*, 38, p. 219; Elster & Geitel, *Wied. Ann.*, 37, p. 315; Howell, *Trans. Am. Inst. E. E.*, 14, p. 27, 1897.

⁴ J. J. Thomson, *Conduction of Electricity through Gases*, Chap. VIII.

⁵ J. J. Thomson, *Phil. Mag.*, Vol. 48, p. 547, 1899.

high vacua true kathode rays appear to be developed in both cases. In one case these are due to the action of heat; in the other case to the action of short light waves. The experiments here described were suggested by this similarity between the two classes of phenomena.

In the case of the photo-electric discharge the current may be looked upon as consisting of two parts: (1) The current carried by the kathode rays produced by illumination; (2) the current carried by the ions that are developed by these rays in the surrounding air. That ionization is really produced by the slowly moving kathode rays of the photo-electric discharge has been shown by direct experiment.¹ We are not aware that there is any direct proof that the kathode rays from an incandescent solid possess the same ionizing power. But it seems highly probable that they do. If so, the current in the case of the Edison effect must also consist of two parts, one carried by the kathode rays themselves and the other by the ions produced by them. At high vacua we should therefore expect the phenomena to appear in their simplest form, since the conducting power of the slight remaining traces of gas would in all probability be inappreciable. For this reason our first experiments were made at high vacua, and experiments were afterwards made at pressures in the neighborhood of 1 mm., where the conducting power of the air proved to be an important factor. In the main the results obtained were such as would be anticipated from the above-mentioned analogy. But at high pressures a phenomenon was observed whose analogue in the case of the photo-electric discharge has not heretofore been detected.

APPARATUS.

The apparatus was arranged as shown in Fig. 1, which shows the lamp at half its actual size. The filament² was of low resistance, and in our experiments took a current of from 1.2 amp. to 1.7 amp. with a p. d. between its terminals ranging from 6 volts to 8 volts. The filament was surrounded by the brass cylinder *CC* which served as anode. A galvanometer served to measure the

¹ Merritt and Stewart, *PHYSICAL REVIEW*, Vol. XI., p. 230, 1900.

² A number of filaments specially mounted for this purpose were kindly furnished by the Edison lamp works.

current between CC and the filament. A battery D of adjustable e.m.f. in series with the galvanometer gave the desired potential difference between F and CC . The galvanometer current was in all cases so small that the resistance of the galvanometer and connections produced no appreciable fall of potential, so that the potential difference between CC and F was the same as the e.m.f. of the battery.

In most cases the circuit containing the galvanometer and the battery was connected to the negative terminal of the filament. The positive pole of the battery was connected to the cylinder CC , thus making it the anode. When the e.m.f. of the battery was zero, the cylinder was at the same potential as the negative terminal of the filament. In this case there would be no galvanometer current, since the discharge takes place only from that part of the fila-

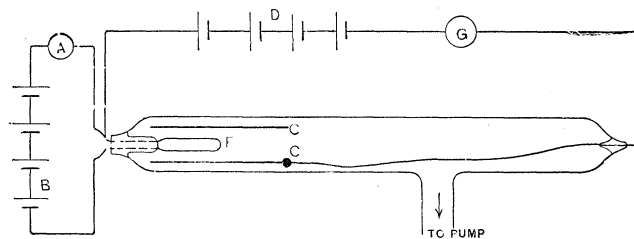


Fig. 1.

ment that is at a *lower* potential than the other conductor. But when the e.m.f. had any value greater than zero the galvanometer was deflected.

Upon reversing the battery D so as to make the filament the anode, the galvanometer showed no current unless the filament was heated to high incandescence; and even then the current was extremely small. This reversed current, already noticed by Fleming, has not been investigated in the work here described.

The magnitude of the current between CC and F , for a given e.m.f. and with all other conditions constant, was found to depend very greatly upon the degree of incandescence of the filament. This is well shown in Fig. 2. The upper curve is for an e.m.f. of 1.4 volts, or one Leclanche cell in the battery D , while the lower curve corresponds to an e.m.f. of 11 volts, or 8 cells. The vertical scale in the latter case is $\frac{1}{10}$ that of the former.

Since the galvanometer current was so greatly altered by changes in the lamp current, great care had to be taken to keep the latter constant. A storage battery was used as a source of e.m.f. But in determining the curves described below even the small fluctuations in the current from this battery were sufficient to introduce errors. An ammeter was therefore kept in the circuit and the current was adjusted, when this was necessary, before each reading.

A McLeod gauge was kept in connection with the pump through, out the work. Very little reliance can be placed on the indications of this gauge, so far as absolute values of pressure are concerned,

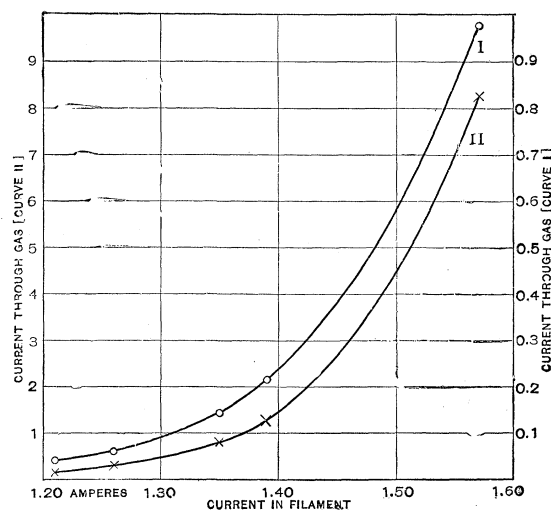


Fig. 2.

owing to the small bore of its graduated tube. The gauge seemed to be especially sensitive to the sources of error to which all gauges of this type are susceptible. But the readings give an indication of the relative values of the pressure in different experiments. The gauge was also useful in indicating the degree of constancy of the pressure during the progress of a series of measurements.

Experiments at High Vacua.

The character of the results obtained at high vacua is shown by the curves given in Fig. 3. In these curves the abscissas show the p. d. between filament and cylinder, while the ordinates give the cor-

responding values of the current. Each curve corresponds to a certain constant value of the current in the lamp, *i. e.*, to a constant temperature of the filament. During the determination of these curves the pressure as given by the gauge varied between .003 mm.

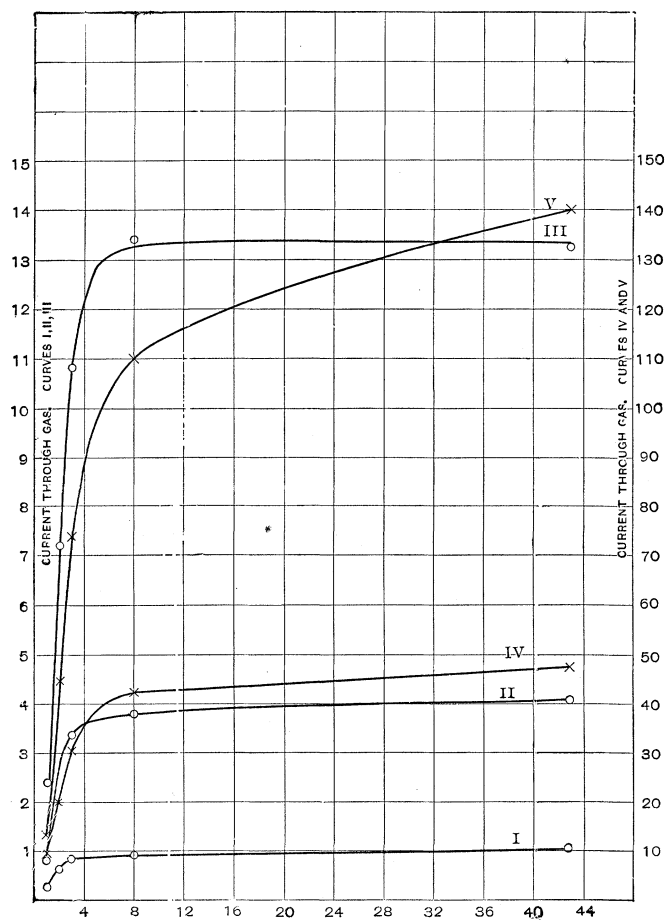


Fig. 3.

The unit in the case of the abscissas of these curves is the e. m. f. of one Leclanché cell — approximately 1.4 volts.

The curves were taken with the following values of the current in the filament.

Curve I. 1.2 amp.	Curve IV. 1.52 amp.
Curve II. 1.3 amp.	Curve V. 1.6 amp.
Curve III. 1.4 amp.	

Pressure, 0.003–0.007 mm.

and .007 mm. This variation was without appreciable influence on the results.

It will be noticed that the curves plotted in Fig. 3 show the characteristics that we should naturally expect in the case of gaseous conduction. The current at first increases approximately in proportion to the potential difference. A limit is soon reached, however, beyond which a further increase in the p. d. causes only a slight increase in the current; "saturation" has been reached. Saturation is more complete in the curves corresponding to low lamp currents, *i. e.*, to a relatively low temperature of the filament.

To some extent these curves are misleading. Under the conditions of the experiment very similar curves would be expected even if the galvanometer current did not depend at all upon the magnitude of the p. d. between filament and cylinder, but only upon its sign.

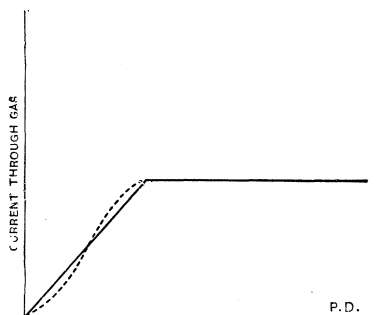


Fig. 4.

It will be remembered that the galvanometer circuit was connected to the negative terminal of the filament, and that the current in the filament was sufficient to maintain a p. d. of from 5 to 8 volts between its terminals. At the beginning of each experiment, therefore, with no e. m. f. in the galvanometer circuit, all portions of the filament are posi-

tive with reference to the cylinder. Since it is only when the incandescent filament is a kathode that the Edison effect is observed, no current will flow. If a small e.m.f. is placed in the galvanometer circuit so as to make the cylinder positive, a portion of the filament near its negative end will now be at lower potential than the surrounding cylinder, and current can flow. As the potential of the cylinder is raised, a greater proportion of the filament becomes negative with reference to it, and can therefore take part in the transmission of current. When the potential of the cylinder is equal to, or greater than, the potential of the positive end of the filament, the whole incandescent surface has become kathode. If we assume that the current is in proportion to the kathode surface,

and that the fall of potential through the filament is uniform, we should expect the form of curve shown by the full line in Fig. 4, regardless of any direct dependence of current on p. d. Since the ends of the filament are cooled a little by conduction, the curve to be expected would be rounded somewhat as shown in the dotted line. This is exactly the form of curve obtained experimentally.

The important influence on the results of the difference of potential between different parts of the filament is well brought out in Fig. 5. The curves were taken under identical circumstances

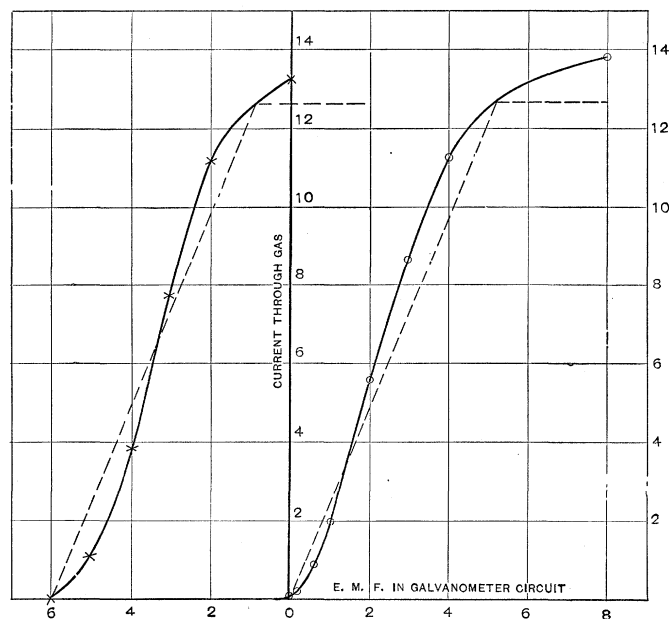


Fig. 5.

except that in one case the galvanometer circuit was connected to the negative terminal of the lamp filament, as usual, while in the other case it was connected to the positive terminal and the e.m.f. reversed. The character of both curves is readily explained then by the variation in the amount of the filament that was the kathode with respect to the cylinder.

In Fig. 5 the curves to be expected from the known p.d. between the lamp terminals upon the assumption of a uniform drop through the filament are shown as dotted lines.

These curves, and others like them, show that the increase in current is a little more rapid, and continues longer, than could be accounted for by increase in cathode surface only. The current does depend somewhat upon the p.d. between filament and cylinder. But this dependence is slight. The number of negative ions developed at the incandescent surface is therefore increased very little by increasing the potential gradient. Lenard found that the behavior in the case of the photo-electric discharge at low pressures is similar to this, for the discharge current for a given illumination was changed very little by changes in e.m.f. It appears that the development of these negative ions, either in the case of an illuminated surface or an incandescent one, is more largely dependent upon some phenomena occurring at the surface itself than upon any electrical influences from outside.

It will be observed that there is nothing in the results obtained at high vacua to suggest that the phenomena are influenced by the small trace of gas left in the tube.

EXPERIMENTS AT LOW VACUA.

A series of curves taken under the same conditions as before except that the pressure in the tube was much higher had the same general form at low voltages as the curves shown in Fig. 3. In each case practically complete saturation was apparently reached at 10 or 11 volts. But when a larger potential was employed the current was found to be much larger than the saturation value. In Fig. 6 are shown three such curves. The vertical scale is different for each curve. The pressure in these cases was about 0.5 mm. Similar curves were obtained at a pressure of 0.16 mm., except that for a very low temperature of the filament (current in filament = 1.19 amperes) no abnormal increase in current was observed, even with an e.m.f. of 60 volts.

It was in these observations that what we have called the "creep" was first noticed. For low e.m.f.s the galvanometer promptly took a steady deflection; but when an e.m.f. greater than about 10 volts was employed the galvanometer current did not reach a steady value at once, but slowly increased for some minutes.

Curve I. in Fig. 7 shows the manner in which this change took place. The ordinates are proportional to the galvanometer deflec-

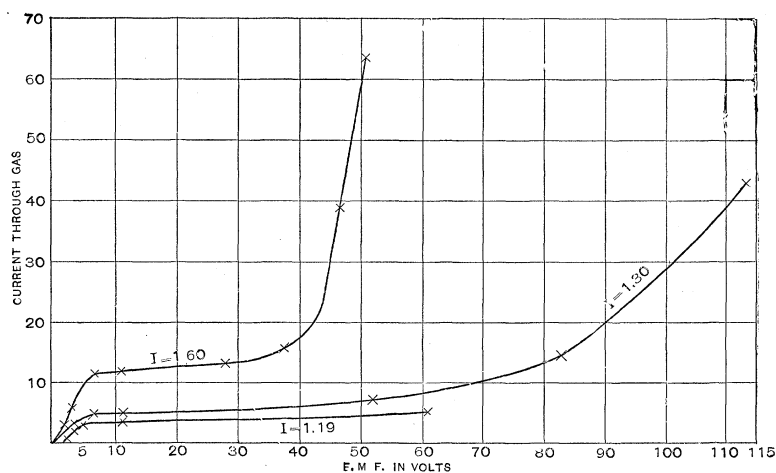


Fig. 6.

tions and the abscissas to time. In this case the current through the lamp filament was 1.50 amperes and the e.m.f. in the galva-

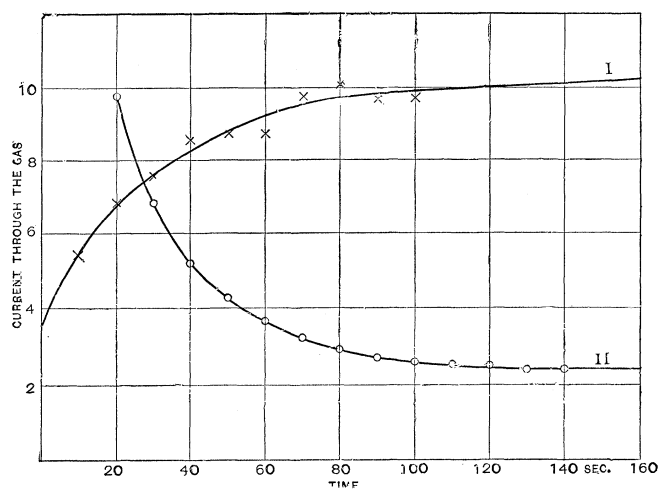


Fig. 7.

nometer circuit was 60 volts. As shown in the curve, readings were taken every ten seconds. Even at the end of 100 seconds the cur-

rent had not attained a steady value. Cases were noted where it required a much longer time than this for the current to reach its maximum value; in one instance an increase was observed for fifteen minutes after closing the galvanometer circuit. But for lamp currents greater than 1.74 amperes the galvanometer current, for all values of the difference of potential, reached its maximum apparently at once; certainly in a time too short to be observed with the galvanometer.

The data used in the curves of Fig. 6 were the values obtained after the deflections had become steady. The first deflection for a p. d. greater than 10 volts was in general approximately the same as that given by 10 volts; but the current increased slowly up to the value shown in the curves of Fig. 6.

If a rather high difference of potential between the filament and the cylinder was maintained for some time and then suddenly decreased, the reverse effect was obtained. For example, if the galvanometer circuit had been closed for some time with 60 volts, and if the e.m.f. was then suddenly decreased to 10 volts, the galvanometer current would at first be much larger than that corresponding to an e.m.f. of 10 volts as shown on the curve. It would, however, slowly decrease until it reached the value that would have been obtained had the higher e.m.f. not been used. Curve II. in Fig. 7 is a curve plotted from the observed values of the current at different times after the e.m.f. had been suddenly decreased from 60 volts to 11 volts. In this case the lamp current was 1.75 amp.—a value so great that the time *increase* could not be detected on applying the higher e.m.f.s. This slow decrease in the current was always noticed on suddenly changing to any lower p. d. from a p. d. greater than the one corresponding to the point of inflection of a curve like one of those in Fig. 6. Although the “creep down” was observed for the higher lamp currents, the duration of it was less than in the cases where the values of the lamp current were those corresponding to cases that gave the “creep up.”

The rate of decrease of the galvanometer current on changing from a higher to a lower e.m.f. was to a large extent independent of other changes in the connections. For example the decrease for

a given time after the higher e.m.f. was cut out was practically the same whether (1) the lower e.m.f. had been connected all the intervening time or (2) the circuit had remained open, up to this time, or (3) the cylinder had been connected directly to the filament.

DISCUSSION.

It is clear from the experiments here described that the phenomena are much simpler at high vacua. The incandescent filament still discharged negative electricity, even in the highest vacuum that our pump could give. It seems probable, therefore, that the electrons by which the charge was carried come from the incandescent body, rather than from gases in contact with it.

The resemblance between the behavior of an incandescent kathode and an illuminated kathode, already referred to at the beginning of this article, is too striking to be overlooked. In each case the phenomena are primarily due to the emission of negative electrons by the surface in question. In one case it is light — more especially ultra-violet light — that acts as the agent to bringing about the emission of such electrons. In the other case the high temperature of the surface produces the same result. The number of negative particles sent off in unit time depends in one case upon the intensity of the illumination; in the other case upon the temperature of the surface. In neither case is it largely influenced by the electric field, provided only that the direction of the field is such as to make the electrode a kathode.

At high vacua the kathode ray particles are the sole carriers of the current, and since their number depends chiefly on the degree of incandescence the curves show saturation at low values of the e.m.f. As the pressure is increased the air surrounding the kathode becomes an important factor. As the p. d. is increased the kathode rays will move at an increasing speed, and will finally move fast enough so that upon colliding with the molecules of gas these will be ionized. The ions thus formed will participate in the conduction between the filament and the cylinder, so that the current will again increase with the e.m.f. An explanation is thus offered of the form of the curves shown in Fig. 6. Similar curves have been observed for the photo-electric discharge by several observers.

¹ Kreusler, Beibl., 22, p. 698; v. Schweidler, Wien. Sitzungsber., 107, p. 881 and 108, p. 273, 1898; also Beibl., 23, pp. 513 and 585.

Townsend has also observed a somewhat analogous phenomenon in the case of the conduction through gases that have been ionized by the action of Röntgen rays.¹ The effects observed by him were satisfactorily explained upon the assumption that the negative ions produced were able to ionize other portions of the gas, just as cathode rays do, provided that the conditions were such as to enable them to acquire a certain minimum speed between collisions. Curves similar to those shown in Fig. 6 were also obtained by McClelland² in the case of the current passing between a hot platinum cathode and a cold anode.

Although the hypothesis of ionization by collision at first appears to afford an entirely satisfactory explanation of the results obtained at low vacua, yet the various peculiarities of the "creep," and especially its long duration, offer serious objections to this explanation. Many attempts were made to throw further light on this phenomenon. If it were merely a case of a slow change in the ionization in the gas, the conductivity might be expected to last a short time after the circuit through the filament was broken. But the galvanometer current dropped at once to zero when the lamp circuit was broken. Yet if the lamp circuit was at once closed again it was found that the increased conductivity was still present. Suddenly reversing the direction of the e.m.f. in the galvanometer circuit also brought the needle promptly to a vibration about its zero.

An e.m.f. of 60 or 80 volts was applied long enough to obtain a steady current, and the galvanometer circuit was then broken for a definite time, from 10 to 30 seconds. On closing the circuit the galvanometer current was found to be somewhat less than its steady or maximum value, but still much greater than if the circuit had not previously been closed. The current would creep up to the value it had before the circuit was broken; but the fact that it was initially larger indicated that the increased conductivity of the tube had in part remained during the time the circuit was broken.

Reversing the e.m.f. in the galvanometer circuit for 20 seconds had no appreciably different effect from that of merely breaking the

¹ *Phil. Mag.*, Series 6, Vol. I, p. 198. 1901.

² *Cambridge Philosophical Proceedings*, Vol. 11, p. 296, 1902.

galvanometer circuit for the same time. The conductivity decreased apparently less if the lamp circuit alone was broken than if the galvanometer circuit alone was broken, *i. e.*, after keeping the lamp circuit open for 20 seconds the galvanometer current was larger than if only the galvanometer circuit had been broken for the same length of time. Breaking both circuits simultaneously for 30 seconds apparently produced even less diminution of the increased conductivity than breaking the lamp circuit alone.

These observations show that the gas in the tube does not remain a conductor for any considerable length of time. Even if a current too small to deflect the galvanometer should flow, the gas would rapidly lose its ions and its conductivity. Yet, as shown, the increased conductivity is affected little, if any, by breaking the lamp circuit.

It therefore appears that the creep cannot be explained simply by the ionization of the residual gas. We are led to suggest that the effect is due rather to some gradual change in the incandescent surface, this change being of such a character as to increase the rate at which cathode rays are produced; when the filament is no longer negatively charged, or when it is allowed to become cold, the surface gradually returns to its original condition. In forming any opinion regarding the nature of this assumed change in the incandescent surface we must bear in mind the fact that it occurs only at low vacua; at high vacua nothing abnormal was observed. It is therefore clear that the presence of an appreciable amount of residual gas is essential. The temporary nature of the change in question shows that it cannot be due to oxidation of the carbon surface, or to any similar chemical action. But the results may be satisfactorily explained if we assume that something is deposited on the surface without uniting with it chemically. The material deposited must have a positive charge, for it is only when the filament is negative that the effect is observed.

When considered from this point of view the phenomena of the creep effect have many points of similarity with cases of excited radio-activity. One is tempted to believe that an active gas is liberated by the hot carbon and that the negatively charged filament acquires temporary radio-activity in the same way that it would do if surrounded

by the emanations of radium or thorium. There is, however, one peculiarity in the effect which shows this explanation to be untenable. The change in the filament which caused the creep persisted for several minutes, even if the current in the filament was broken; but no current could be detected in the galvanometer while the filament was cold. It seems, therefore, that the material deposited on the filament does not possess in itself any marked power of ionizing the gas; it merely intensifies the effect of incandescence. The phenomena are more satisfactorily explained if we assume that the deposit on the filament produces a condition analogous to polarization in a voltaic cell. If the positive ions attracted to the surface experience a certain difficulty in giving up their charges, a double layer will be formed at the surface, positive just outside and negative within. This will greatly strengthen the electric field at the surface, so that the tendency for negative electrons to escape from the carbon will be increased. It seems surprising that such a double layer is not at once destroyed when the e.m.f. is reversed. But the porous character of the carbon probably permits the positive ions to penetrate to a considerable depth, so that they cannot be quickly removed even by a reversed field. For the same reason the polarized condition requires an appreciable time for its complete development.

It is hardly to be expected that the negatively charged filament itself can be the source of the positive ions which cause this polarization; these come rather from the residual gas. It is evident therefore that the effect can only occur at relatively high pressures. The formation of the assumed layer, and the consequent "creep" effect, can only take place when positive ions are present in the gas. But there is nothing to produce ionization except the cathode rays from the hot carbon; hence we cannot expect the polarized layer to form until the velocity of the cathode rays is sufficient to produce ionization in the surrounding gas. In other words the creep effect will only be observed when the e.m.f. in the galvanometer circuit exceeds a certain critical value. For e.m.f.'s less than this we have the ordinary phenomena of conduction in a gas with ionization at the negative terminal only; the gas itself has no influence upon the conduction, except so far as it alters the speed of

the negative ions. No positive ions are present. For higher electromotive forces the phenomena are modified in two ways: (1) The kathode rays produce ionization in the air, which now participates in the conduction; (2) positive ions now being present, some of these collect on the carbon filament and form there a positively charged layer. This increases the ease with which negative electrons escape from the hot carbon, so that kathode rays are produced in greater intensity. When the critical value of the electromotive force is exceeded there are therefore two reasons for an increase in current, and the sudden bend in the curves of Fig. 6 is a natural result.

Since the MS. of the preceding article was sent to the printer, a preliminary paper has been published by J. Stark, which deals in part with experiments upon the same subject.¹ The arrangement of apparatus in these experiments was somewhat different from that adopted by us; and to this fact is doubtless to be ascribed a part of the difference in the results obtained. But we are unable to account for all of the differences in this way.

The filament employed in Dr. Stark's experiments required a potential difference of 6 volts at its terminals to bring it to the proper incandescence. This is approximately the same p. d. that was used in our own work. Instead of a cylindrical anode, however, a wire was used, this being placed in a side tube at a distance of 6 mm. from the filament. At pressures ranging from 0.029 mm. to 4.2 mm. the curves connecting the e.m.f. and the current through the gas show a general resemblance to those plotted in Fig. 6 on p. 247, but differ from them in three ways, viz.: (1) the rapid increase in conductivity, which indicates the beginning of ionization by collision, begins at about 11 volts, instead of at about 30 volts; (2) a second more rapid rise in the conductivity of the gas occurs at about 27 volts; (3) at about 40 volts the current reaches a new saturation value, far greater however, than the value corresponding to e.m.f.s below 10 volts.

The sudden increase in conductivity observed by us seems to correspond to the *second* break in the curve obtained by Stark. That this point corresponds to the beginning of ionization by collision in

¹ Physikalische Zeitschrift, Vol. 5, p. 51, Jan. 15, 1904.

the nitrogen remaining in the tube, as suggested by Stark, seems to us quite probable. In fact this is practically the explanation reached by us. The third stage mentioned by Dr. Stark, corresponding to potentials higher than 40 volts, was not observed in our experiments; there was nothing to suggest renewed saturation, even at potentials as high as 115 volts. This may perhaps be due to differences in the form and dimensions of the apparatus. We are at a loss, however, to account for the absence in our curves of the first stage mentioned by Dr. Stark. No sudden increase in conducting power in the neighborhood of 11 volts was observed in our experiments. Dr. Stark explains the break in his curves at about 11 volts as due to the ionization of mercury vapor, and therefore sets the ionizing potential for mercury vapor at 11 volts. Since the tube used in our experiments remained in connection with the pump for days at a time there is every reason to believe that mercury vapor was present. Yet there is no indication that it participated in the conduction in any way. This is true not only in the case of the observations at the relatively high pressure of 0.5 mm. (Fig. 6) but also in the case of the observations at low pressures (.003 mm.) shown in Fig. 3. The latter observations seem especially well adapted to show the influence of the mercury vapor if such influence exists, for the disturbing effect of other gases is reduced to a minimum. Unfortunately the observations of Dr. Stark do not extend to pressures below 0.029 so that no direct comparison of our results is possible.

In this connection the great difficulty that is always experienced in completely freeing a carbon filament from occluded gases should not be forgotten. In order to accomplish this so far as possible we were in the habit of running the filament during the process of exhaustion at a higher temperature than that used when making measurements. Such a procedure was indeed absolutely necessary in the work at low pressures, since the liberation of gas by the filament made it otherwise impossible to maintain a high vacuum. When it is remembered that some liberation of gas will still occur even when this precaution is taken, and that it will occur with greater rapidity when the temperature of the filament is high, certain peculiarities in the curves shown in Fig. 3 become significant. Curves I., II. and

III. in this figure show practically complete saturation, with no indication of ionization by collision. There are the curves corresponding to small lamp currents and therefore low temperatures. In Curves IV. and V., for which the temperature of the filament was higher, the saturation is not so complete. May it not be that we have to deal here with ionization of the gas liberated from the filament? And may it not be that the effects ascribed by Dr. Stark to mercury vapor were in reality due to some readily ionized gas given off by the filament?

Dr. Stark does not appear to have observed the phenomenon referred to by us as the "creep." It seems probable that the filament was kept at so high a temperature in his experiments that steady deflections were reached almost instantly.