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POTENTIAL PHENOMENA IN VACUUM TUBES DURING
THE PRODUCTION AND INTERRUPTION
OF ELECTRICAL DISCHARGE.

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WHEN electrical energy is passing between the electrodes of a vacuum tube we know that the discharge may be either direct or alternating, continuous or disruptive; but not very much seems to be known, except in the case of the continuous discharge, concerning the variations in potential which occur in any of these cases. It was with the hope that something more might be learned regarding this question that, at the suggestion of Professor E. Wiedemann, I began the investigations described in this paper. The work was done in the Physical Laboratory of Erlangen University and I have to thank Professor Wiedemann for many valuable suggestions made during the continued progress of the work. Professor Schmidt and Dr. Wehnelt also have given valuable assistance.

Numerous experiments have been made in connection with the work, but this paper attempts to give only some of the preliminary results obtained. More complete results will be given later when other tests have been completed.

GENERAL OUTLINE OF THE WORK.

The first series of tests were made by calorimetric methods. Judging from previous results obtained by other investigators, it was thought that, if the anode were connected to earth, the average fall of potential at the cathode for either continuous or dis-

ruptive discharge could be determined from the total heating effect, using the well-known equation $H = 0.24 EI$. In the course of the experiments, however, it appeared that better results could be obtained by means of the Braun tube, and after making simultaneous determinations by the two methods the heat measurements were for the time being discontinued.

By means of the Braun tube we were not only able to determine the potential difference with considerable accuracy, but also to observe the variations of potential and the frequency of discharge. By means of it new and interesting facts were found out regarding the maximum and minimum potential of disruptive discharge; namely, that the potential rises to a certain maximum height and then suddenly falls off to a minimum value, but never to zero. Both the maximum and minimum values for any tube depend upon the particular conditions under which the tube is tested.

In connection with the work, a method was found by which the Braun tube can be conveniently used to measure high potentials, say of 1,000 or 1,200 volts, where the fluctuations are not too great. When the limits of variation are great, however, say 500 volts or more, the problem becomes more difficult; but a new method is given below which overcomes those difficulties quite satisfactorily.

The measurements show that the manner in which the potential develops and falls off is very largely affected by the capacity of the circuit.

Tests were also made to ascertain the effect upon the potential produced by reversing the direction of the current or by interchanging the electrodes, which show why certain results obtained by other investigators are in disagreement with one another.

I. APPARATUS.

The apparatus used in these tests included a storage battery of 1,120 cells, a twenty plate influence machine driven by a Schmidt water motor, a single plate influence machine driven by an electric motor, two Sprengle pumps, McLeod pressure gauge, a Wiedemann galvanometer, with rubber insulated coils, having a constant of 38×10^{-6} amperes per centimeter, two telescopes, a rotating mirror,

sensitive thermometers, two Kohlrausch condensers, an electric tuning fork, two static voltmeters reading to 10,000 volts, a Kelvin multicellular voltmeter, a telephone receiver, and vacuum tubes of various forms. In addition to these the parts which call for special description are as follows :

(a) *Cup Calorimeter*. — Fig. 1 shows a simple form of calorimeter discharge tube. *A* denotes a vacuum tube about 22 mm. long and about 13 mm. in diameter, surrounded by a glass calorimeter vessel *B* into which a liquid is placed. Both parts are made as small and light as possible so that the changes in temperature produced by the passage of the electrical discharge through *A* will be as great as possible. The water equivalent of the whole apparatus including the thermometer and 6 cubic cm. of terpineol, was found to be 8.03 by careful measurement.

Fig. 1.

Fig. 2.

(b) *Apparatus D* as shown in Fig. 2 is a form of the Bunsen calorimeter as modified to meet the requirements of these investigations. It is all made of glass and all the joints are fused, except *WW* where the aluminium electrodes *GG* are sealed in with wax. The vacuum tube *A* is enclosed by an outer vessel *BC* of which the upper part *BB* is filled with benzol and the lower part *CC* is filled with mercury all air being carefully removed. *M* and *N* are ground glass stopcocks and *E* is a tube which is convenient for introducing the liquids into the outer vessel. When *BC* has been filled with benzol and mercury, *N* is closed and *M* is opened. Then when the electric discharges are developed in *A*, the benzol becoming warmed expands and causes the mercury to rise in the capillary tube *DD*. The bore of *DD* being less than a millimeter in diameter, a very slight change in the temperature of the benzol produces a large variation in the length of the mercury column. A millimeter scale being placed directly behind the mercury column, the length of the col-

umn can be read to a tenth of a millimeter by means of a telescope placed some distance away.

Fig. 3.

(c) The Braun tube as used in these measurements is the form adopted by Dr. A. Wehnelt (*Verhandlungen der Deutschen Physikalischen Gesellschaft*, January, 1903) for potential comparisons, the potential plates being inside the glass tube. The form is represented in Fig. 3 where PQ is a glass tube 53 cm. long and 3 cm. in diameter fused to a larger cylinder QD 22 cm. and 8 cm. in diameter. S is a fluorescent screen fastened to the walls of the large tube by means of glass plugs. The cathode

k consists of an aluminium disc 1.5 cm. in diameter located at the extreme end of the small tube as far from S as possible. The anode G is situated in a short side tube which projects perpendicularly from PQ about 15 cm. from the end P .

The potential terminals a and b are flat plates of aluminium 8 cm. long and about 2 cm. wide. To the center of each of these is riveted a thick aluminium wire which, passing through the walls of the tube, is firmly attached to the glass. The plates are thus held rigidly in position 2 cm. apart and parallel to the axis of the tube. Electrical contact is made with them by means of platinum wires sealed in the glass. At each end of these plates is a mica diaphragm m and n fitted closely to the inner wall of the cylinder. The diaphragm m has an opening at its center only 1 mm. in diameter but the opening in the diaphragm n is some twenty millimeters in diameter. The purpose of these diaphragms is to intercept all unnecessary cathode rays. The bundle of rays which enters between the plates is only one millimeter in diameter, and that will be the size of the bright spot produced by it upon the fluorescent screen. Thus when a sufficiently high vacuum has been produced within the tube, and some 8,000 or 10,000 volts have been developed between the electrodes, a small greenish bright spot will be seen upon the screen S and its position thereon can be accurately read by a suitable scale. If, however, there is a difference of potential between

the plates *a* and *b* the cathode ray will be deflected; the displacement of the spot upon the screen will be proportional to the potential difference, and affords a method of potential measurement.

(*d*) For measuring the displacement of the fluorescent spot upon the screen the method used was as follows: A telescope was placed in convenient position some 2 meters away from the Braun tube and focused upon the screen *S*. At the left of the telescope and at a distance from it equal to that between the telescope and the screen, was placed a millimeter scale made of thick plate glass upon which the divisions and numbers had been cut by means of a diamond. One end of the scale was fitted tightly into an opening made into an opaque box. Inside of the box was placed a lighted glow lamp, and the only light transmitted from the box was made to pass through the opening into which the scale was fitted. The light which was thus emitted passed through the entire length of the glass plate and being totally reflected internally by the polished walls of the glass, nothing of the scale could be seen in a dark room,

Fig. 4.

except the division marks and numbers which stood out as so many bright lines. With proper adjustment this scale could be read very distinctly several meters away. By means of a mirror obliquely placed the image of this illuminated scale was reflected into the telescope in such a way that the spot on the screen *S* which could be seen at the same time through the telescope appeared to be located upon the illuminated scale. Thus the position of the fluorescent spot could be read at any time, and any change in its position or displacement of the spot could be thus read in millimeters.

(*e*) *Discharge Tubes.* — To test the effect produced by having the discharge take place under different conditions various discharge tubes were used, some of which are represented in Fig. 4. The tubes *E*, *F* and *H* were connected to the vacuum pump at the same

time so that the vacuum condition would be the same in all of them and the difference in the discharge phenomena obtained from them, if any, would be due simply to the different forms or dimensions of the tubes. The dimensions of these tubes are as follows :

Tube.	<i>E</i>	<i>F</i>	<i>H</i>
Diameter,	3 cm.	4 cm.	4.5 cm.
Length,	32	21	65
Distance between Electrodes,	1.5	14	Variable.

In tube *H* the electrodes are aluminium with the exception of the portion which connects *a* to *b* which is a fine copper wire wound in a spiral, while the portion *b* is iron and attached rigidly to *c*. If a strong electromagnet is applied to the outside of the tube the position of *bc* can be changed at pleasure and the distance between *c* and *d* can be made any desired magnitude.

II. METHOD OF DETERMINING THE MEAN POTENTIAL DIFFERENCE BY CALORIMETRIC METHODS.

If the total heat developed in the discharge tube can be measured then $H = 0.24EI$ and knowing the current *I* we can calculate the mean potential *E*. All heat measurements were made with the apparatus surrounded by a water jacket kept at constant temperature. In addition to this precaution, corrections were always made for radiation by observing the rate of gain or loss in temperature for the five minutes immediately before the current was turned on, and for the five minutes immediately after it was turned off. The current was always passed through the tube for ten minutes and a mean correction for the radiation was thus calculated.

The first heat measurements were made by the simple cup calorimeter of Fig. 1. In these the changes in temperature were measured directly by sensitive thermometers which were read accurately to tenths of a degree and estimated to hundredths of a degree by means of a telescope. The current which, passing through the tube, cause the rise in temperature, was measured by the Wiedemann galvanometer with rubber insulated coils, the constant of the instrument being 38×10^{-6} per centimeter deflection. The potential as derived from these measurements however, was

very much less than expected and led us to look for a more sensitive method. Accordingly, to meet this requirement the calorimeter which we have called apparatus *D* was constructed as in Fig. 2 which proved to be very sensitive and gave better results. To obtain the best results the readings were taken in a room of nearly constant temperature and the apparatus was surrounded by a constant temperature water jacket, corrections for radiation being made here as in the previous case.

To calibrate the apparatus a continuous current of measured intensity and potential was discharged for a known length of time through the tube. Thus a known quantity of heat was developed within the tube and the rise of the mercury column produced by it was carefully measured. After correcting for radiation, it was found that a rise of one millimeter of the mercury column corresponded to 0.2049 calories of heat developed in the tube, or in other words the constant of apparatus *D* was 0.2049 calories per millimeter. A number of calibrations of this kind gave results which differed only very slightly in the third significant figure. Some of these measurements are given in Table I. together with the potential measurements taken simultaneously by means of the Braun tube. As in this case the heat in the tube was developed

TABLE I.

Calibration of Apparatus D, by means of continuous discharge, together with simultaneous potential determinations made by means of the Braun Tube.

Potential Determinations by Means of the Braun Tube.							Heat Determinations. Calibration of Apparatus D.				
Test No.	Position of Fluorescent Spot.				Potential Derived.		Potential by Kelvin Volt Met.	Current by Wiemann Galvanometer.	Heat Devel. by Current in 10 Min.	Rise in Hg Col. Corr. for Radiation.	Calories per mm. of Hg Column.
	For Unknown Potentials.		For Known Std. Potentials.								
	Max. <i>x</i>	Min. <i>y</i>	<i>V</i> =480. <i>a</i>	<i>v</i> =240. <i>b</i>	Max. <i>X</i>	Min. <i>Y</i>	Volts	Amps.	Total Cal. <i>Q</i>	Total Rise. <i>h</i>	<i>Q</i> ₀
1	5.1	5.1	6.1	4.6	320	320	317	.000509	23.22	11.34	2.047
2	5.3	5.3	6.2	4.8	326	326	325	.000777	36.37	17.70	2.055
3	5.9	5.9	7.0	5.3	325	325	325	.000771	36.101	17.65	2.045
Average <i>Q</i> ₀ = 2.049											

by a continuous discharge in one direction, only one potential difference would exist between the electrodes and therefore only one potential value is given by the Braun tube.

III. METHOD OF DETERMINING THE LIMITS OF POTENTIAL DIFFERENCE BY MEANS OF THE BRAUN TUBE.

At the same time that the heat method was being perfected, tests were also being made by means of the Braun tube which proved to be the better method for present purposes. The method was as follows :

Potential leads connected the electrodes AB , Fig. 3, of the discharge tubes to the potential plates Ab of the Braun tube, then whenever there was a difference of the potential between A and B the same potential difference existed at ab , and caused a displacement of the fluorescent spot upon the screen S . Moreover the displacement was proportional to the potential difference and when read off on the illuminated scale which has been described, it afforded a means of measuring the potential. The potential of a constant discharge between A and B is constant, and the round fluorescent spot accordingly remains steady upon the screen at whatever point the constant potential difference places it. The varying potentials of a disruptive discharge cause rapid oscillations of the spot, which produces a thin, bright, fluorescent line upon the screen varying in length according to the potential variations at AB . A constant potential of two or three hundred volts or more at AB may cause the spot to disappear. The reason for this is that the applied potential bends the cathode rays so much that they no longer fall upon the screen. The spot or line can be brought back again, however, in a very simple manner by means of the electromagnets placed opposite the plates. The magnets should be so located that their magnetic lines of force are perpendicular to the axis of the Braun tube and parallel to the plates. Increasing the strength of the magnetic field decreases the whole deflection of the cathode ray proportionally and thus brings the spot upon the screen. If the field thus produced is uniform and constant, the displacement of the spot will still be proportional to the potential difference between the plates, though the displacement will be less than before. The deflections produced by the potential differences, as thus affected by the magnetic field, can now be calibrated by direct comparison with known potentials in the following way. The

connections given in Fig. 3 show the method of calibration used in these measurements. An upward throw of the transfer switch T_1 places the plates ab of the Braun tube in connection with the electrodes AB of the discharge tube. A downward throw places ab in connection with the terminals of storage battery S_2 . While this is down, changing the position of the transfer switch T_2 places upon the plates ab either of any two standard voltages of battery S_2 which may be chosen for purposes of calibration. The best results were obtained when, for this purpose, standard voltages were selected which coincided as nearly as possible with the unknown limits to be measured. Moreover, the deflection should be calibrated for each observation at the instant that the observation is made, for the length and position of the fluorescent line varies instantly with any slight change in the vacuum conditions of the Braun tube. By means of the telescope, the limits of the fluorescent line or the position of the spot, was read upon the luminous scale, first with the Braun tube connected to the terminals AB , then to a known high voltage and immediately afterward to a known low voltage of battery S_2 , these adjustments being rapidly made by the transfer switches T_1 and T_2 . Having thus obtained the readings for the two known voltages we can calculate the unknown voltages corresponding to the other points read upon the screen at that time. The maximum and minimum voltages for any oscillation of the spot of course will be the points represented by the upper and lower ends of the fluorescent line. Thus if x and y are the readings upon the scale corresponding to the upper and lower ends of the fluorescent line, as produced by the various potentials to be measured, and if a and b denote the two points upon the scale corresponding to the two known calibration voltages, V and v , then the unknown voltages X and Y corresponding to the two readings x and y will be

$$X = (x - a) \left(\frac{V - v}{a - b} \right) + V$$

and

$$Y = (y - b) \left(\frac{V - v}{a - b} \right) + v.$$

This magnetic method of diminishing the fluorescent displace-

ment does not apply for the measurements of potential variations which exceed the limits of the fluorescent screen. Thus for example, by means of this method I could measure the potential difference between 750 and 900 volts, but could not measure the difference between 300 and 900. For if the magnetic field were made strong enough to bring the deflection corresponding to 900 volts down upon the screen, then that corresponding to 300 volts would fall below it.

For the measurements of wide variations of potential of this kind

Fig. 5.

the following method of diminishing the fluorescent displacement was employed successfully. Two equal condensers CD and GH having movable plates were placed in series with the potential plates ab of the Braun tube, as indicated in Fig. 5. Only a fraction of the total potential then fell upon the plates ab and by adjusting the distances between the plates of the condensers the fluorescent displacement could be made as small as desired. Since a constant potential applied to the condenser plates C and H only produced an instantaneous effect

upon the fluorescent spot, and since alternating current could not be used, the only direct method of calibration was that of rapidly interchanged applications of different positive potentials. Fig. 5 shows the connections as applied for this purpose. F represents an electro-tuning fork, making 100 vibrations a second and $mnop$ represent mercury contacts to which the terminals of the storage battery S_2 were connected. When the transfer switch T_1 was thrown downward, the condenser plates C and H were connected to the storage battery S_2 through the mercury contacts of the tuning fork. When the tines of the fork approached each other, the circuit was opened at op and closed at mn and there was a difference of potential of say 800 volts between the plates C and H , but when the tines of the fork separated the circuit was broken at mn and closed at op , and there was a difference of potential of say 400 volts between C and H . Thus

two known positive potentials were interchanged between the plates *C* and *H* 200 times each second and a known variation of potential was maintained between the condenser plates by means of the storage battery and tuning fork with which to compare the unknown differences of potential produced by the glow tube. Hence the interchanging known potentials as thus employed for calibration purposes were applied to the plates very much as they occurred in actual practice when coming from the discharge tube, and they produced a very definite line on the screen *S*, the maximum and minimum of which could be read very distinctly on the scale. The calibration curve given in Fig. 6 shows the variations of potential as they actually existed when the connections to the battery were made to the tuning fork in this manner, the potential development thus obtained

Fig. 6.

being very different in character from those obtained from the discharge tube. By means of the tuning fork the condenser method can be applied to the Braun tube for all interrupted discharges of one direction. It can be applied without the tuning fork to all discharges of alternating directions.

IV. METHOD OF OBSERVING THE DISCHARGE FREQUENCY AND THE SUCCESSIVE STAGES THROUGH WHICH THE POTENTIAL PASSES IN THE PROGRESS OF EACH DISCHARGE.

The measurements taken by means of the Braun tube and telescope as previously described determine simply the limits of potential differences. If, however, the fluorescent images on the screen *F* be observed by means of a rotating mirror, the lines will appear as curves, or waves, as seen in the charts. In most cases the complete wave is not visible, for only the rising portion and crest can be seen, while the falling portion is invisible. Each crest denotes a single charge and the number of these seen per second determines the frequency of discharge.

Moreover the form of the rising portion that is visible shows the various stages through which the potential passes from the beginning of each charge formation until the accumulated charge is discharged between the electrodes. For the elevation of the spot upon the screen at any instant measures the potential, and the hori-

zontal projection of the line, taken in connection with the speed of the mirror, measures the duration of time required for each charge to accumulate.

Each complete period then may be considered as consisting of two distinct intervals, viz. that of charge accumulation, in which there seems to be no transmission of electricity between the electrodes, but in which the potential rises from minimum to maximum and the tube becomes charged; and that of charge transmission, in which the potential falls suddenly from maximum to minimum and the accumulated charge passes between the electrodes. This latter we may call the *true discharge*, and the mean rate at which the transmission takes place during this latter interval we have called the *true current intensity*. The true discharge takes place so rapidly that in most cases it leaves no line of light upon the mirror owing to the insufficiency of light, and the duration of the interval is denoted by a break in the visible line. The line, if seen during the true discharge, would differ but slightly from a vertical line. In a few cases such a line was actually visible faintly connecting the maximum to the minimum potential.

By means of this method, therefore, it is not usually possible to trace the potential variations which occur during the true discharge, but they can be plainly seen during the charge accumulation. It is also possible to determine with considerable accuracy both the frequency of discharge and the time required for the charge transmission, as well as to calculate the true current intensity.

Various conditions which affect the charge and discharge phenomena were examined at this time.

V. DESCRIPTION OF TESTS MADE AND RESULTS OBTAINED.

(a) *Simultaneous Measurements of Potential by Means of Calorimeter and Braun Tube.*

Table II. gives the results of potential measurements of disruptive discharge made simultaneously by means of the calorimeter (apparatus *D*) and the Braun tube. The object of this series was to ascertain whether the results obtained by one method would agree with those obtained by the other, when applied to disruptive discharges. The potential measured was that produced by

the discharge between the electrodes of apparatus *D*, the vacuum being varied as indicated in the table. Column 3 of the table gives the mean voltage as determined by heat measurements, column 4 gives the corresponding potential as measured directly by means of the Kelvin multicellular voltmeter, and columns 5 and 6 give respectively the maximum and minimum voltage as obtained by the Braun tube measurements, while column 7 is the numerical mean of 5 and 6.

It will be seen from this that the potentials obtained by the calorimeter method are very nearly the same as those obtained by the Kelvin voltmeter. The differences may be accounted for perhaps,

TABLE II.
Potential of Disruptive-Discharge, as Determined Simultaneously by Means of Calorimeter and Braun Tube.

Test No.	Air Pressure in mms. 1	Galv. Deflection $k=38 \times 10^{-6}$. 2	Potential Determined by Means of				
			Calorimeter App. D. 3	Kelvin Voltmeter. 4	Braun Tube.		
					Max. 5	Min. 6	Mean. 7
1	4.9	1.05	391	381	416	224	320
2	1.8	2.15	418	425	544	240	392
3	1.7	2.22	401	417	480	223	352
4	1.7	2.23	406	413	480	240	360
5	1.7	1.75	400	413	480	225	352

by errors in measurement. They also lie between the maximum and minimum values obtained by the Braun tube, as would naturally be expected, but they are much larger than the numerical mean given in column 7. So great a difference as this cannot be attributed to errors of measurement, especially since the difference is always in the same direction. It may be remarked, however, that according to the potential curves, given later, the numerical mean of the maximum and minimum would probably be less than the actual mean. But the most important point to be noticed in these results is the fact that the potential never even approaches zero, but falls to a minimum only, which remains constant for the particular condition under which the test is made. The conditions of test seem to affect both the minimum and maximum potentials. This is referred to again later. The Braun tube method made it

possible to examine the phenomena in tubes of many forms and under many conditions which would not have been possible by means of the calorimetric method. Having reason for believing that the character of discharge was not the same for all tubes nor the same for any one tube under all different conditions, we made tests on various kinds of tubes, some of which are represented in Fig. 4, and varied the conditions for each different tube.

(b) *To Test the Effect Produced by Changes in Resistance and Air Pressure.*

Chart I. gives the results of a characteristic series of tests made upon discharge tube *E* for the purpose. The connections are represented in Fig. 3. The discharge was produced by a current from storage battery S_1 of 1,040 volts. A liquid rheostat *R* of very high resistance was placed in series with a tube *AB*; experiments proved that by varying the amount of this resistance the character of the discharge could be entirely changed. With a small resistance the discharge was always continuous and the image upon the fluorescent screen was a small round spot fixed in its position. For such conditions the curve in the mirror was seen to be a horizontal straight line at some definite constant potential, as represented in Chart I., tests number 1, 7, 8, 14 and 19. With a large resistance, however, the discharge became disruptive and the fluorescent image upon the screen was a thin vertical line varying in length according to the difference between the maximum and minimum potentials in the glow tube. Tests 3 to 6 are good examples of this. Accordingly tests were made with various resistances while the pressure was kept constant as shown in tests 1 to 8 inclusive. Then with a different air pressure the tests were repeated with the same series of resistances as nearly as possible, (see tests 7 to 13 inclusive). This was repeated for a number of different air pressures. In every case the potential measurements were first made and immediately afterward the curves were observed in the rotating mirror. In this way the potential limits were determined and the character of the discharge was plainly seen as to whether it was continuous or disruptive, and if disruptive, how great was the frequency and what stages of development the potential passed through at every

CHART I.
Changes in Resistance and Air Pressure.

Test No.	Air Pressure.	Resistance in Circuit.	Galv. Defl. $K = 21 \times 10^{-6}$	Max. and Min. Volts of Curves.	Potential Curves for Each Test, Representing Form, Amplitude and Approx. Relative Frequency.	Remarks.
1	2	3	4	5	6	7
1	3	1	21.3	284		Apparently a continuous discharge. Is stable and no breaks are visible in the line.
2	3	2	15.5	458		Unstable discharge. Fluctuates between continuous and disruptive, without change in external resistance. The glim is longest when the discharge is disruptive.
3	3	3	8.9	488		Stable disruptive discharge. Discharge lines are distinct in mirror, but too numerous to count. Have form as here given.
4	3	4	5.8	535		Frequency not so great as in Test 3, but greater than in Test 5. Character of curves in Test 5 seems to be the same as in former tests. Seven lines visible in the mirror.
5	3	5	3.4	556		Only two lines can be seen in the mirror at a time in Test 6, though in Test 3 they were too numerous to count.
6	3	6	3.3	561		The external conditions in Test 7 are the same as in Test 1, but the air pressure is less here. Discharge stable and continuous. Glim is very short.
7	1.07	1	12.6	320		Discharge is unstable in Test 8. Fluctuates between continuous at 328 volts and disruptive discharge with min. at 245 and max. at 435 volts. Tests 8 and 9 are practically the same test, the discharge fluctuating spontaneously from one form to the other.
8	1.07	2	8.5	328		The glim in 8 is short, but in 9 it nearly covers the cathode. Tests 8 and 9 seem to correspond to Test 2, but with less air pressure.
9	1.07	2	7.5	435

CHART I.—Continued.
Changes in Resistance and Air Pressure.

Test No.	Air Pressure.	Resistance in Circuit.	Galv. Defl. $K = 21 \times 10^{-6}$	Max. and Min. Volts of Curves.	Potential Curves for Each Test.	Remarks.
1	2	3	4	5	6	7
10	1.07	3	6.3	534		Stable disruptive discharge. The frequency here is less than in Test 9, and the amplitude is greater.
11	1.07	4	3.8	604		The glim light does not cover the cathode in Tests 7 to 13 inclusive. In Test 13 the curves have a decided curl upward at the lower limit, but no connecting line is visible between the upper end of one curve and the lower end of the next.
12	1.07	5	2.4	560		In Test 14, a hazy continuous horizontal band is seen in the mirror, with constant potential of 376 volts.
13	1.07	6	2.0	592		Stable disruptive discharge in Test 15. Frequency too great to count the lines in the mirror. Glim does not cover the cathode in Tests 14 to 18 inclusive.
14	0.52	1	10.8	376		The numerals in column 3, "Resistance in Circuit," indicate the amount of resistance that is placed in series with Battery S and the glow tube. No. 1 signifies the smallest resistance that can be obtained by the Liquid Rheostat, while No. 8 denotes the largest amount.
15	0.52	2	8.3	436		The intervening numbers denote relatively proportional amounts. This applies throughout all the tests.
16	0.52	4	3.8	458
17	0.52	5	1.6	495
18	0.52	8	0.4	500

CHART I.—*Concluded.*
Changes in Resistance and Air Pressure.

CHART II.
Changes in Capacity and Air Pressure. Tests all made at the Critical Point.

Test No.	Air Pressure.	Resistance in Circuit.	Galv. Defl. $K = 21 \times 10^{-6}$	Max. and Min. Volts of Curves	Potential Curves of Each Test.	Remarks.	Test No.	Air Pressure.	Resistance in Circuit.	Condenser.	Galv. Defl. $K = 42 \times 10^{-6}$	Max. and Min. Volts of Curves.	Potential Curves for each Test, Representing Form, Amplitude and Approximate Relative Frequency.	Relative Freq. cy.	Remarks
1	2	3	4	5	6	7	1	2	3	4	5	6	7	8	9
19'	0.25	6	1.4	426		The glim light is short Stable continuous discharge.	22'	0.53	3	Out	4.7	304			Continuous discharge which changes spontaneously to disruptive or vice versa. This condition we have called the "Critical Point" When the condenser is "out" (not connected) the discharge is as seen in Test 22' or 22'', but when the condenser is "in" (is connected) the discharge becomes that of 22'''. The ratio of frequency in 22'' to that in 22''' is 10 to 1.
19''	"	6+	"			As the resistance in the liquid rheostat is gradually increased from Resistance 6 in Test 19' to Resistance 7 in Test 20', the curves undergo the following changes as seen in Test 19', 19'', 19''' and finally Test 20' where the potential was again measured.	22''	"	"	Out	4.0	416		30	
19'''	"	6++	"				22'''	"	"	In	4.4	496		3	
20'	"	7	1.4	448 408		As the resistance is gradually increased from Resistance 7 to Resistance 8 the interruptions become more frequent and the max. potential rises slightly. See 20'' and 20'''.	23'	0.30	4	Out	7.0	320			When the air pressure is reduced to 0.30 mm the discharge at Critical Point becomes that of Test 23', 23'' and 23'''.
20''	"	7+					23''	"	"	Out	6.5	464 256		20	
20'''	"	7++				With this low air pressure (0.25) the character of discharge as seen in Tests 19' to 21 is quite different from that of greater air pressure as seen in Tests 1 to 18 inclusive.	23'''	"	"	In	6.3	496 256		8	The ratio of frequency in 23'' to that of 23''' is 10 to 4. The glim light in 22''' and 23''' covers the cathode, but, not so in the other cases. Notice the decided curl upward at the lower limit of the curves in Test 22''' and 23'''.
21	"	8	0.3	476 408		Resistance 8 = two high-resistance liquid rheostats, are in series. A fine discharge-line is seen in all of these tests (19' to 21) connecting the max. to the min. potential. In all other parts the band is broad. The glim covers the cathode in Tests 20' to 21 inclusive, but not so in the previous tests.									

discharge. The mirror was rotated as nearly as possible with uniform speed so that the relative frequency in the various tests was approximately seen. In the charts each horizontal space (except the one at the top) which we have called a horizontal "row" is devoted to a single test, and the test to which it is devoted is indicated by the numeral at the left. The vertical spaces we have called "columns" and each column is devoted to some particular phase of each respective test. The horizontal row at the top of the page tells what particular phase of the test each column is devoted to. Thus in Chart I., column number 1 tells the number of the test to which each row is devoted, and column number 5 gives the maximum and minimum potential obtained in each test, while column number 6 represents the potential curves for that test. Thus column number 5 shows that the curves of column number 6, test number 3, begin at a minimum of 270 volts and rise to a maximum of 488 volts, and the form of the curves in column number 6 shows the stages through which the potential passes. The curves are drawn on a scale which is common to all tests, the ordinates denoting potential and the abscissas denoting time. For want of space the potential from zero to 200 volts has been omitted from the charts, since in the tests the minimum potential was never found to fall below 200 volts. The bottom ordinate in each test-chart, therefore, denoted 200 volts, while the top one represents 700 volts. As nearly as possible the curves in each row represent the discharge lines as actually seen in the mirror both in form and relative frequency. The numbers in column number 5 then denote the upper and lower potential limits as measured by the curves in the same horizontal row in column number 6 and the number of lines drawn in the row in column number 6 denotes the relative frequency of discharge for that test, the mirror being kept as nearly constant as possible throughout.

Among the things learned from the experiments represented in Chart I. in which the resistance in the external circuit was varied, while other conditions remained unchanged, was the fact that a change in external resistance will change the character of discharge from continuous to disruptive or *vice versa* and also that there is one point where the resistance can be such that the discharge will

fluctuate spontaneously from continuous to disruptive or *vice versa* without any external change in resistance; this may be called the critical point and is apparently the only condition that can be reproduced from time to time with approximate certainty.

(c) *To Test the Effect Produced by Changes in the Capacity of the Circuit at Various Air Pressures.*

Having reasons to believe that the character of discharge was altered by changes in capacity, experiments were made to test the supposition. For this purpose tube *F*, Fig. 4, was used in the same manner as *E* was used in the preceding experiments, except that the plates of a Kohlrausch condenser were connected to the electrodes of the tube by means of a switch in such a way that they could be connected or disconnected, quickly, at pleasure, without changing the speed of the rotating mirror. The tests were made at the critical point. That is while the charge was continuous and the condenser was disconnected (out), the external resistance was gradually increased until the critical point was reached and the measurements made, then the measurements were repeated with the condenser connected (in), the speed of the mirror being kept constant. The change in potential was easily determined and the character of the curves observed. Characteristic results are given in Chart II.

(d) *Changes in Capacity and Distance Between the Electrodes.*

To test the effect of variations in capacity and distance between the electrodes, measurements were made upon tube *H*, Fig. 4. This tube was so constructed that by applying a magnet externally to the iron portion *b* of the electrode *ac* the distance *cd* between the electrodes could be made any desired length. Results of a characteristic series of measurements are given in Chart III. All tests were made at the critical point, and with the exception that the resistance in the circuit had to be increased a little to produce the critical point, when the electrodes were further apart, the conditions were alike in all corresponding tests. The air pressure was one millimeter throughout the series.

CHART III.
Changes in Capacity and Distance Between the Electrodes.
All Tests Made at Critical Point on Tube H.

Test No.	Distance Between Electrodes in Cms.	Condenser.	Galv. Defl. $K = 42 \times 10^{-6}$	Resistance.	Max. and Min. Volts of Curves.	Potential Curves for Each Test, Representing Form, Amplitude and Approx. Relative Frequency.	Frequency.	Remarks.
1	2	3	4	5	6	7	8	9
24'	2	Out	18.1	3—	320		—	Glim light covers about $\frac{1}{10}$ of cathode. Discharge fluctuates at critical point as seen in 24' and 24''. Glim covers about $\frac{1}{2}$ cathode in 24''.
24''	2	Out	17.5	3—	432 272		—	Lines too numerous to count in 24''. Glim covers entire cathode and only 5 lines visible in 24'''.
24'''	2	In	16.9	3—	476 290		5	Discharge changes from 24'' to 24''' spontaneously, simply by connecting "in" the condenser.
25'	5	Out	15.3	3	334		—	Glim covers about $\frac{1}{10}$ of cathode in Test 25. Test 24 differs from Test 25 respectively only in cms. distance between electrodes.
25''	5	Out	14.2	3	456 278		—	Glim covers $\frac{1}{2}$ of cathode. Lines too numerous to count.
25'''	5	In	14.2	3	490 292		4	Discharge changes from 25'' to 25''' spontaneously, and from 25'' to 25''' by connecting "in" the condenser. Glim covers entire cathode and only 4 lines visible in 25'''.

CHART III.—Concluded.
Changes in Capacity and Distance Between the Electrodes.
All Tests Made at Critical Point on Tube H.

Test No.	Distance Between Electrodes in Cms.	Resistance.	Condenser.	Galv. Defl. $K = 42 \times 10^{-6}$	Max. and Min. Volts of Curves.	Potential Curves for Each Test, Representing Form, Amplitude, and Approx. Relative Frequency.	Frequency.	Remarks.
1	2	3	4	5	6	7	8	9
26'	10	3+	Out	13.8	336		—	Glim light covers $\frac{1}{10}$ of the cathode in 26'.
26''	10	3+	Out	13.1	512 272		40	Glim covers about $\frac{1}{2}$ of the cathode in 26'' and 40 lines are visible in the mirror.
26'''	10	3+	In	12.4	530 290		3	Glim covers the entire cathode in 26''' and 3 lines are visible in the mirror.
27'	20	3++	Out	7.1	352		—	Glim covers about $\frac{1}{2}$ of the cathode in 27'.
27''	20	3++	Out	5.7	560 272		8	Glim covers about $\frac{7}{10}$ of the cathode in 27'' and 8 lines are visible in the mirror.
27'''	20	3++	In	5.0	672 288		1	Glim covers entire cathode in 27''' and one line is visible in the mirror. A decided upward turn is seen at lower limit of curve.

(e) *Comparison of the Phenomena of Positive and Negative Discharge with Reference to Frequency and Capacity.*

Professor G. Wiedemann found (*Elektricität* von G. Wiedemann, 4, p. 459), that with the current from an influence machine, and therefore of uniform intensity, the frequency was greater when the negative electrode was free and the positive connected to earth, than when the positive was free and the negative was connected to earth. That is to say, with uniform current a negative discharge gave a greater frequency than the positive. From this he assumed that the voltage varies inversely as the frequency, on the assumption that

$$n = \frac{I}{CV}.$$

In other words that, if the frequency is decreased one half, the voltage should be doubled. This assumption must be true, of course, if the capacity remains constant. Professor E. Wiedemann and others have, at various times, obtained results some of which verify this law of frequency and some contradict it, and no satisfactory reason has been given for the discrepancy. Professor E. Wiedemann has suggested that perhaps the capacity does not remain constant. To ascertain whether this can be the case or not, two series of tests were made. Results of the first series are given in Chart IV. while those of the second are given in Chart V.

In both series the current was kept constant in all cases and no changes were made, except that of reversing the current through the tube and interchanging the earth connection. The connections for the first series are as shown in Fig. 3 with the exception that the earth could be instantly connected to the electrode *A* or *B* of the glow tube at pleasure by means of an independent switch. In this series four combinations were possible as shown by I., II., III. and IV. in column 8 of Chart IV., where *R* in column 8 denotes the liquid rheostat as indicated by *R* of Fig. 3, in series with the battery *S*₁ and discharge tube *AB*. In I. and II. the direction of the current was unchanged while the earth was connected first to *A* and then to *B*. In III. and IV. the current was reversed in direction while the earth was again connected first to *A* and then to *B*. With these combinations it was found that the frequency obtained

CHART IV.

To Test the Effect of Interchanging the Earth Connection, i. e., to Compare the Phenomena Produced by a Negative Discharge, with that Produced by a Positive, the Tests Being on Tube F, with 2.8 mm. Air Pressure.

Test No.	Distance Between Electrodes in cms.	The Negative Charge is on	The Negative Electrode is	Max. and Min. Volts of Curves.	Potential Curves for Tests, Representing Form, Amplitude and Approx. Rel. Frequencies.	Ratio of Frequencies.	Plan of Tube Connections.	Remarks.
1	2	3	4	5	6	7	8	9
28'	10	B	Free	603 309		1		No condenser was used in these tests. A medium resistance was used in series and left constant throughout. The only changes made were the interchanging of the earth connection and the reversing of the current.
28''	"	B	Earthed	597 276		2		
29'	"	A	Free	603 298		1		
29''	"	A	Earthed	593 256		5		
30'	40	B	Free	688 288		1		
30''	"	B	Earthed	672 270		2		
31'	"	A	Free	670 305		1		
31''	"	A	Earthed	704 288		2		

from the positive electrode, as in II. and IV., was always very much greater than from the negative electrode as in I. and III. These results are therefore directly opposite to those obtained by G. Wiedemann and are not in accordance with his law of frequency, for although the frequency is doubled in some cases the potential varies very little, if at all. It will be noticed, however, that in I. and III. the earth connection is made between the tube and the rheostat, while in II. and IV. it is not. It is possible therefore that the position of the rheostat may produce the change in frequency by changing the capacity of the circuit.

In the next series of tests the combinations were modified to avoid this difficulty. Fig. 7 shows the plan of connection for the second series and the four possible combinations are indicated in V., VI., VII. and VIII., column 10 of Chart V. The tests in this series were made as follows :

Fig. 7.

First two measurements were made with unchanged connections as in V. and VI., but with the direction of the current reversed in one of them, so that in V. there was a negative discharge from *A* while in VI. there was a positive discharge from the same terminal, all other conditions being unchanged. Then all of the circuit connections, except those connecting to the Braun tube, were removed from *A* and *B* and interchanged in position. That is, the connecting wire *p* was removed from *A* and connected to *B* while the wires *m* and *n* were removed from *B* and connected to *A*. With these interchanged connections two more measurements were made as before with the current first in the direct and then in the reverse direction through the tube. In other words in VII. there was a positive discharge from *B* while in VIII. there was a negative discharge from the same electrode, all other conditions being the same. Hence, VII. and VIII. are exactly the same as V. and VI., respectively, except that the discharge proceeds from the opposite electrodes. If then, there is any difference between the frequencies obtained in these four cases, or if the potential in any case is greater than in another it must be due, either to some difference in the electrodes, or to some intrinsic difference in the character of the positive and negative discharge. Apparently the difference does not lie in the electrode, for interchanging the terminals does not seem to produce any different effect. An examination of Chart V. will show, however, that in all cases, whenever the discharge is negative the frequency is decidedly greater than when the discharge is positive. This is in agreement with G. Wiedemann's results, but the law of frequency does not seem to be verified in this series, for if

$$n = \frac{I}{CV}$$

CHART V.

To Test the Effect of Changing the Earth Connection, i. e., to Compare the Phenomena Produced by a Negative Discharge with that Produced by a Positive; 1st, With Changes in Air Pressure; 2d, With Changes in Resistance, and 3d, With Changes in Capacity. All Tests made on Tube F.

Test No	Resistance in Circuit.	Condenser.	Air Pressure.	The Negative charge is on	The Negative Electrode is	Max. and Min. Volts of Curves.	Potential Curves for Tests, Representing Form, Amplitude and Approximate Relative Frequencies.	Frequencies	Plan of Tube Connections.	Ratio of Max. Voltages.	Remarks.
1	2	3	4	5	6	7	8	9	10	11	12
32'	3	Out	3.8	A	Free	560 274		3		560 = 1.06 274	
32''	3	Out	3.8	B	Earthed	526 274		2		560 = 1.06 526	
33'	3	Out	3.8	B	Free	547 266		3		547 = 0.94 573	
33''	3	Out	3.8	A	Earthed	573 266		2		547 = 0.94 573	
34'	3	Out	1.21	A	Free	449 245		3		449 = 1.01 443	
34''	3	Out	1.21	B	Earthed	443 245		2		449 = 1.01 443	
35'	3	Out	1.21	B	Free	449 251		3		449 = 1.03 437	
35''	3	Out	1.21	A	Earthed	437 251		2		449 = 1.03 437	
36'	2	Out	1.8	B	Earthed	449 267		ABOUT 150			
36''	7	Out	1.8	B	Earthed	481 256		ABOUT 100			
36'''	"	In	1.8	B	Earthed	688 309		ONE			

The frequency in 36' is too great to count and can only be estimated, but is plainly greater than it is in 36'' which is estimated at 100. Only one line in the curve is visible in the mirror in test 36'''.

is true, when the current is uniform, then if C is constant, n should vary inversely as V , which does not seem to be the case in these results. If the potential changes at all, it seems to increase with the

frequency rather than otherwise. At any rate, even after making full allowance for errors in measurement, the potential does not vary inversely as the frequency. This, then seems to indicate that the capacity of the tube does not remain constant.

VI. OBSERVATIONS AND CONCLUSIONS DERIVED FROM THE RESULTS.

Facts which may be noticed by examining the charts, combined with the phenomena noticed in the progress of these investigations may be condensed into the following observations :

From Chart I. it may be noticed :

1. With sufficiently low resistance in the circuit the discharge is continuous, but when the resistance is increased sufficiently the discharge suddenly becomes disruptive ; the frequency of discharge continues to decrease, and the maximum potential to increase, from that point on as the external resistance is increased.

2. If the low resistance, at which the discharge is continuous, is increased very slowly, a critical point may always be found where the discharge fluctuates between the continuous and disruptive form without any change in the external circuit. Simply touching with the finger a point here or there in the external circuit is sufficient to cause the discharge to change back or forth from one form to the other, or the change may occur without any point being touched, or without any external variation whatever being made. This apparent spontaneous fluctuation is probably due to slight changes in the capacity of the external circuit, which is very easily affected. The tests which follow seem to indicate this.

3. The glim light is always longer when the discharge is disruptive than when it is continuous. This is true even at the critical point. But the true current intensity is greater for disruptive discharge than for continuous and, as already known, the glim is always longer the stronger the current. These observations have been noticed in course of the experiment although the facts have not been so stated before.

4. The potential never falls to zero nor even near it but varies between a maximum and minimum at each interruption. Plotting the potential curves with the potential, as ordinates and the time as abscissas, it is seen that from the minimum point the potential at

first rises very abruptly, but as it approaches the maximum, especially in discharges of low frequency, the increase occurs but slowly and the curve becomes nearly a horizontal line near the upper potential limit. When the potential has fully reached the maximum it falls off so quickly that the path of the fluorescent spot upon the screen usually becomes invisible in the mirror. This sudden drop in potential evidently denotes the instant at which the real discharge between the electrodes takes place. The potential develops as it does when a condenser is charged until the discharge potential is reached. Apparently the discharge takes place only after the walls of the tube have been fully charged. That is, there is a silent discharge from the free electrode to the walls of the tube which gradually raises the potential. Then when the maximum potential is fully reached there is a sudden discharge from the walls and from the free electrode to the electrode which is connected to the earth. Such a manifestation was formerly observed in the like phenomena examined by E. Wiedemann and Lehmann. In this manifestation may be found the reason for the results of G. Wiedemann concerning the difference between positive and negative discharges, in which the existing velocity of the negative electrons plays an important part. That the potential drops suddenly the instant the discharge sets in, is in agreement with the results which Hittorf has previously found, namely, that it requires a higher potential to begin a discharge than to maintain it.

5. With the discharge proceeding always from the same positive or negative terminal, it is seen that as the frequency of discharge decreases the limits of potential differ more widely, the maximum potential increasing greatly while the minimum limit seems to drop slightly. Or conversely, the greater the current intensity, that is, the greater the number of discharges per second, the smaller the amplitude of potential variation becomes. The reason for this is that the shorter the time interval existing between discharges the greater is the number of free electrons then in the tube, and accordingly the greater the conductivity of the gas. From this it follows that there can be no definite fixed discharge potential or normal potential for disruptive discharges, but the value will vary with every varying condition that may exist.

6. In some cases, especially in Chart II., an upward turn is distinctly seen at the lower limit of the curve. That is to say, as the fall in potential approaches the lower limit the fluorescent line gradually becomes visible and when the minimum is reached, the bend from a downward to an upward direction is clearly seen. This plainly indicates the direction of the curve in the invisible portion, and shows that the potential does not fall at any time below the so called minimum. In other words, the potential drops most rapidly near the maximum and then more slowly until it reaches the lower limit, when it begins to rise again. The change in the curve from a downward to an upward direction, so clearly seen at the minimum point, plainly indicates the lowest limit of potential. This is also verified by the fact that the mean potential obtained by heat measurements and by direct voltmeter measurements as seen in Table II. lie between the maximum and minimum potential limits.

7. The minimum potential of disruptive discharge is seen to be lower than the constant potential of continuous discharge. This indicates that there are more free electrons in the gas during the instant of actual transmission in disruptive discharge than at any time during the continuous. This makes the conductivity greater and consequently the minimum potential lower in the former case than in the latter. In other words it indicates that the true current intensity during the short periods of active transmission in disruptive discharges is greater than the current intensity of a continuous discharge. In like manner it is seen from Charts I. to III., inclusive, that within limits, as the air pressure within the tube is decreased the potential of continuous discharge is increased.

8. The results given in Charts II. to III. show also that as the capacity of the tube is increased the maximum potential of disruptive discharge is raised and the minimum is lowered; also, the frequency is diminished.

9. As the air pressure is decreased the capacity of the tube is increased. This seems to be true, for in tests which were alike in all respects, except in air pressure, the results indicate that the tube had a greater capacity with a high vacuum than it had with a low one. An example of this is seen in tests 22'' and 23'', Chart II.

in which the air pressure was 0.5 mm. in the former and 0.3 mm. in the latter. Now, if C , I , N and V denote respectively capacity, current intensity, frequency and potential, then

$$\frac{C_1}{C_2} = \frac{I_1 N_2 V_2}{I_2 N_1 V_1}.$$

Supplying the corresponding values obtained in 22" and 23" we have

$$\frac{C_1}{C_2} = \frac{4 \times 20 \times 464}{6.5 \times 30 \times 416} = \frac{1}{2.2} \text{ nearly.}$$

That is, the tube has a greater capacity when the air pressure is small than when it is larger.

10. Results given in Chart III. show that the potential of continuous discharge rises slightly as the distance between the electrodes increases, as would be expected.

11. As the distance between the electrodes is increased the frequency of discharge decreases and the maximum potential increases. In other words, increasing the distance between the electrodes seems to have the effect of increasing the capacity of the tubes.

12. It is seen from these measurements that the minimum potential is not affected either by changes in capacity or distance between the electrodes.

13. Results given in Chart V. show that, other things remaining the same, the negative discharge has a higher frequency than the positive, though Chart IV. shows that the external circuit may easily be modified so that the positive discharge will have a higher frequency than the negative. In other words, the character of discharge within the tube is so intimately related to every external condition of the circuit, that any apparently slight modification without may entirely change the phenomena within. This being true the discrepancies between the results of G. and E. Wiedemann may easily be accounted for on this basis.

14. The results given in Chart V. do not verify the law

$$n = \frac{I}{CV},$$

since the potential does not in any case vary inversely as the fre-

quency. On the other hand, they show that the capacity is not a constant quantity, but is different when the discharge is negative from what it is when the discharge is positive. Perhaps the explanation of this may be found in the difference that exists between the velocities of the positive and negative electrons.

15. In sending a disruptive current through a vacuum tube each period seems to consist of two very short intervals, the interval of charge accumulation and that of charge transmission. During the first interval the electrodes and walls of the tube become charged while the voltage rises from the minimum to the maximum potential. The various stages through which the potential passes during this first instant is denoted by the curved line as seen in the mirror, the first portion of which gradually curves away from the vertical and the latter portion is nearly horizontal. During the second interval, or instant, the true transmission of electricity takes place and is denoted by the break in the line indicating the drop in potential, as the voltage falls from maximum to minimum. The second interval is very short compared with the first. In other words, the time required for the true transmission of electricity between the electrodes is only a very small fraction of the total period. Apparently it is possible here to measure the duration of each interval, that is, not only to determine the frequency and time required for the charge to accumulate and the voltage to rise, but also to determine the duration of time required for the actual passage of electricity between the electrodes and the mean actual current intensity during that instant. Further tests are in progress for deriving these values.

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