

THE PHYSICAL REVIEW.

THE DISCHARGE OF ELECTRICITY FROM POINTED CONDUCTORS.

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1. In a previous paper ¹ are given the results of some experiments on the discharge of electricity from a set of points which consisted of cylindrical wires of different diameters whose ends were either hemispherical or plane. The points were placed opposite a brass disc and were enclosed in a cylindrical vessel containing dry air.

It was found that the discharge from points of this character gives consistent results which can be readily reproduced, and the way that the discharge depends upon the diameter of the point was given special consideration.

The apparatus, which is fully described in the paper mentioned, has been used for studying the discharge from steel needle points of various degrees of sharpness and from brass conical points of various sizes, and the results are here recorded together with those of some other experiments on point discharge.

The subject-matter is considered under the following subdivisions :

(a) Positive discharge from steel needle points.....	§§ 2, 3
(b) Relation between current, voltage, minimum potential, and diameter of points.....	§ 4
(c) Negative discharge from steel needle points.....	§ 5
(d) Formation of oxides on steel points.....	§ 6
(e) Positive discharge from 12° conical points.....	§§ 7, 8
(f) Negative discharge from 12° conical points.....	§ 9
(g) Discharge to different parts of a spherical surface.....	§§ 10, 11
(h) Discharge at different pressures.....	§§ 12, 13
(i) General remarks.....	§ 14
(j) Summary.....	§ 15

¹ J. Zeleny, PHYS. REV., 25, p. 305, 1907.

POSITIVE DISCHARGE FROM STEEL NEEDLE POINTS.

2. The steel needle points used were prepared from ordinary sewing needles, a variety of sizes of the points being obtained by altering the ends of some of the needles on an oil stone.

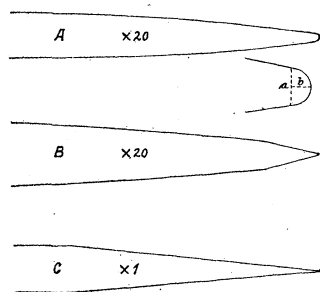


Fig. 1.

Two kinds of commercial needles were met with. In the one (see *A*, Fig. 1) the angle between the opposite walls of the needle increases gradually as the point is approached, reaching a value of from 10° to 12° at the point itself. In the other kind (see *B*, Fig. 1) there is a sudden increase in the taper near the end of the needle, the angle changing at a

distance of about one half a millimeter to a millimeter from the end, from about 10° to over 20° and to as much as 30° in one make. The sharpest points are found on needles of this type. Usually the finest needles were found to be of the first type and the coarser ones of the second type but in an assorted package from one maker the needles of all sizes were of the second type.

The sharpness or size of the needle point will be designated in each case by giving the diameter of the cross-section of the needle at a place where this diameter (a , Fig. 1) is twice the distance (b , Fig. 1) of this cross-section from the tip of the needle. The measurements were made with the stage micrometer of a microscope, the location of the cross-section specified being estimated by eye alone.

In order to describe more exactly the general nature of the needles used, not only is this diameter of the point stated for each needle but its length and maximum diameter are also given, together with the angle of the average taper for the first two or three point-diameters from the end. It has been found that one of the chief differences between different needles as regards point discharge lies in the value of the taper at the end. The angle of this taper usually increases as the points get sharper, because it is both difficult and inadvisable to make very sharp points with this angle small.

Preliminary experiments made in the open air with a promiscuous lot of needles gave results which varied quite regularly with the

diameter of the points, but among the finest points one would be found now and then with the taper exceptionally obtuse, which would give results considerably different from the rest. The largest difference observed was one of seven per cent., in the voltage required to produce a given current.

The experiments here described were carried out in exactly the same way as those described in the paper already referred to. The needles were supported above the plate by means of a brass rod, in the end of which a slot was provided for holding them axially.

3. The results obtained for the positive discharge in dry air with a number of selected needles placed at a distance of 1.5 cm. from the plate, are given in Table I. The temperature was practically 19° C. and the air pressure 74.7 cm. throughout the whole series of experiments.

TABLE I.

Positive Discharge from Steel Needle Points. Distance from Plate = 1.5 Cm.

Point Number.	1	2	3	4	5	6
Diameter of Point in Mm.	.0068	.012	.055	.096	.198	.364
Length of Needle in Mm.	34.7	x	39.7	36.3	49.0	45.5
Max. Diameter of Needle in Mm.	.51	x	.82	.57	1.17	1.03
Taper of Point.	26°	x	24°	12°	9° 2	7° 3
Starting Potential.	2,650	2,700	2,900	3,025	3,550	4,375
Potentials in volts with corresponding currents in 10 ⁻⁷ amperes.	3,000	3,000	3,500	3,500	4,000	4,500
	2.8	2.3	5.7	4.5	5.9	2.3
	4,000	3,500	4,000	4,000	5,000	5,000
	13.6	6.8	11.9	10.7	19.2	9.6
	5,000	4,000	5,000	5,000	6,000	6,000
	28.3	13.6	26.6	26.0	40.1	28.8
	6,000	5,000	6,000	6,000	7,000	7,000
	50.9	28.8	49.2	47.5	64.4	50.9
	7,000	6,000	7,000	7,000	8,000	8,000
	73.5	50.3	73.5	73.4	92.7 ¹	79.1
	8,000	7,000	8,000	8,000	9,000	9,000
	104.5 ¹	76.3	101.7	102.3	131.1 ¹	117.0
		8,000	8,350	9,000		9,500
		104.5	118.1	141.2		141.3
		8,500				
		125.4				

¹ Current more or less intermittent as indicated by telephone.

The results have been reduced to a pressure of 74 cm. and a temperature of 22° C. to make them correspond to the conditions prevailing in the experiments described in the previous paper. The way in which this reduction is made is explained in §§ 20 and 21 of

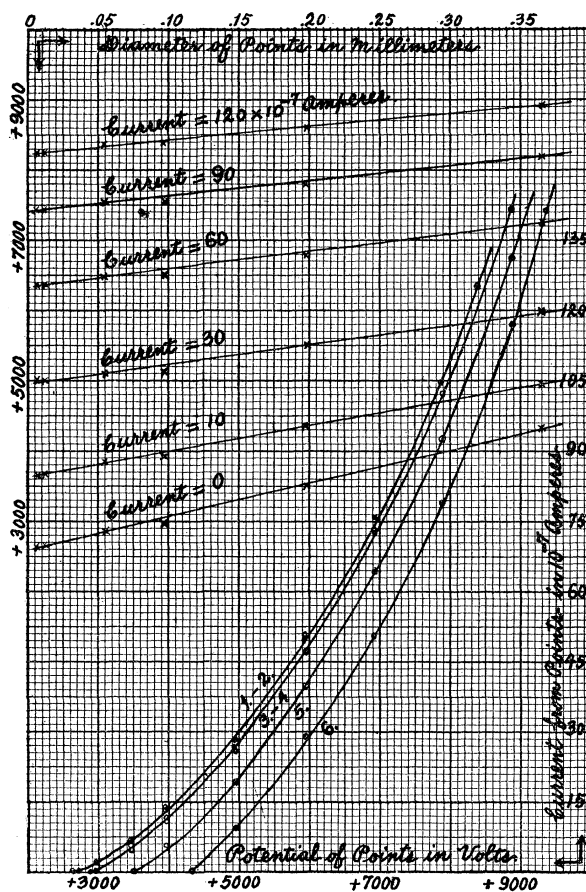


Fig. 2.

the paper mentioned, and in this case amounted to reducing the potentials by about 1.3 to 1.5 per cent. These reduced results are shown graphically in Fig. 2.

The lower right-hand curves give the relation between the voltage and the current for the different points. The values for the

points no. 1 and no. 2, and for the points no. 3 and no. 4 are so close together that but one curve is drawn for each of the two cases.

The curves in the upper part of the figure were drawn to show whether there is any relation between the size of the points and the voltage necessary to produce a given current. The potentials taken from the potential-current curves were plotted against the size of the points for each of the currents given. It is seen that there is good regularity in the results and that in each case the potential increases linearly with the size of the point. In view of this regularity, it is now possible to construct from these curves a potential-current curve for a needle point of any size, provided however that the angle of the taper at its point approximates to that on those needles here used which are of about the same point diameter.

The fact that the voltage required to produce any current increases linearly with the diameter of the point is incidental to the way that the angle of the taper increases as the points diminish in diameter. Had the taper of the finest points been as small as that of the larger ones their potentials for the same current would have been smaller than they are.

RELATION BETWEEN CURRENT, VOLTAGE, MINIMUM POTENTIAL, AND DIAMETER OF POINTS.

4. The relation between the current and voltage for any one point is fairly well represented by Warburg's formula, $C = aV(V - M)$, where V is the voltage of the point, M the minimum voltage required to start a current, and a a constant whose value depends upon the point used. This constant was found to increase linearly with the diameter of the point, so that it is possible to represent the results for all of the points by one formula, the current in amperes being given by,

$$C = 2.58 \times 10^{-13}(1 + .319d)V(V - M),$$

where d is the diameter of the point in millimeters.

In Table II., a comparison is made of the values of the current obtained for several potentials, by the use of this formula and the observed values as taken from potential-current curves similar to but larger than those in Fig. 2.

TABLE II.

Comparison of Observed Currents with those Calculated by the Formula, $C=2.58 \times 10^{-13}$
 $(1 + .319d) V (V - M)$.

Diameter of Point.		.0068	.012	.055	.096	.198	.364
M		2,615	2,665	2,860	2,985	3,505	4,320
Voltage.							
3,000	Current calc.	3.0	2.8				
	observ.	3.0	2.6				
4,000	Current calc.	14.3	13.8	12.0	10.8	5.4	
	observ.	14.3	14.0	12.1	11.3	5.7	
5,000	Current calc.	30.9	30.2	28.0	26.7	20.5	9.8
	observ.	30.2	30.2	28.0	27.3	20.2	10.3
6,000	Current calc.	52.6	51.9	49.4	48.0	41.1	27.3
	observ.	52.0	52.0	49.7	48.6	40.6	29.0
7,000	Current calc.	79.4	78.7	75.9	74.6	67.2	54.0
	observ.	79.3	79.3	76.6	75.3	66.7	53.2
8,000	Current calc.	111.6	110.9	107.8	106.6	98.6	84.8
	observ.	112.3	112.3	108.2	107.6	100.0	83.2
9,000	Current calc.			144.7	144.0	135.8	121.3
	observ.			143.4	143.4	136.5	122.4

It is seen that the two sets of values are in good agreement.

Since the minimum potential required to start a current increases linearly with the diameter of the point, as is shown by the potential-diameter curve for $C = 0$ in Fig. 2, its value in volts can be represented by the relation, $M = 2,590 + 4,750d$, where d is again the diameter of the point in millimeters.

NEGATIVE DISCHARGE FROM STEEL NEEDLE POINTS.

5. The results which were obtained for the negative discharge in dry air from the same set of needle points as used above, are given in Table III. The distance of the points from the plane was again 1.5 cm. The temperature throughout the readings was nearly constant at 19° C. and the air pressure was 74.7 cm. The starting potential was determined first in each case and then the currents were obtained for gradually increasing voltages. Where readings were repeated the average value is given.

The results, reduced to a pressure of 74 cm. and a temperature of 22° C., are represented graphically by the lower right-hand curves in Fig. 3. The points agree quite well with their respective

curves. Nevertheless, the smaller negative currents often show considerable irregularity. This is especially the case after a point has been used with the higher currents, as some resistance to the flow of small currents seems to be introduced

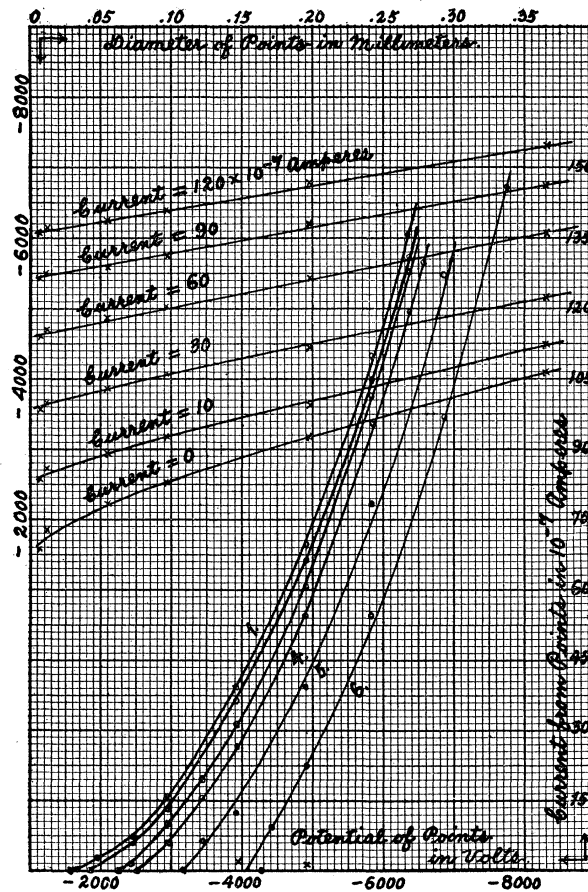


Fig. 3.

thereby on the surface of the point, so that the values now obtained with a given voltage are much below the normal values obtained at first. The two points marked by crosses below the curves for the two largest points in Fig. 3, represent experimental results and show how large this deviation may be and to what sized

TABLE III.

Negative Discharge from Steel Needle Points. Distance from Plate = 1.5 Cm.

Point Number.			1	2	3	4	5	6
Diameter of Point in Mm.			.0068	.012	.055	.096	.198	.364
Starting Potential.			1,600	1,900	2,250	2,550	3,225	4,350
Potential of points.	2,000	Current from points in 10^{-7} amperes.	2.8					
	2,500			7.3	3.0			
	3,000		16.0	14.3	10.1	5.9		
	3,500				19.6	15.7	6.2	
	4,000		39.2	36.4	31.4	26.9	12.3 ¹	
	4,500							9.5 ¹
	5,000		69.4	66.1	60.5	54.3	39.2 ¹	22.4
	6,000		109.8	104.7	101.4	95.2	78.4	54.9 ¹
	6,500		135.5	130.6	127.7	119.3		
	6,700					129.9		
	7,000						127.2	96.9
	7,925							145.6

currents it may apply. As the voltage is increased when these abnormal conditions obtain, the resistance mentioned disappears more or less suddenly and the current rises to its normal value.

The curves in the upper part of Fig. 3 show the relation between the size of the points and the voltage required to produce the current given in each case. These curves can be used as before for the construction of a potential-current curve for a point of any intermediate diameter, when this has a taper corresponding to that of the points here used. The results for one of the points nos. 1 and 2 do not agree well with the rest, and there is reason to believe that the discharge from no. 2 was retarded for some reason.

The relation between the current, voltage and the diameter of the points is not as regular in this case as it was for the positive discharge but is given approximately by the formula,

$$C = 4.18 \times 10^{-13} (1 + .63d) V(V - M),$$

where the letters have the same significance as before.

FORMATION OF OXIDES ON STEEL POINTS.

6. After a discharge has passed for some time from a steel point in air, it is found that some substance has accumulated at the end

¹ Currents marked by a figure (1) were somewhat intermittent.

of the point. This is especially true if the point has been discharging positive electricity. The difference between the positive and the negative discharges in this respect is very marked.

As an example of this action *A*, in Fig. 4, shows the appearance under the microscope, of the end of a steel needle point after a positive current of about 10^{-5} amperes had been flowing from it for five minutes. The substance on the end of the point is of a reddish

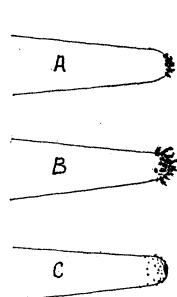


Fig. 4.

brown color, and is doubtless an oxide of iron since it does not form on a platinum point. *B*,

Fig. 4, shows the same point after the same current had been flowing from it for 44 minutes. It is noticed that the material is attached to the point in irregular pieces which extend outward some little distance. The substance is readily removed with a cloth leaving the surface of the point apparently as bright as ever. It is natural

that the presence of this material should have

some effect upon the discharge current, and points which have been used for some time must be cleaned to have them regain their normal condition.

When the same point was used with a negative current of the same value for five minutes, it showed no change in appearance. Gradually, however, a readily removable tarnish appeared on the point for a distance of a little over its diameter, dulling somewhat the bright luster of that portion of the needle. The appearance seemed to indicate an accumulation of a lot of fine dark particles. After the negative current had been flowing for over an hour, the point had the appearance shown by *C* in Fig. 4. The little patch at the very end of the point was of the same reddish-brown color as the accumulation in the case of the positive discharge, but it was in the form of a thin coating. The rest of the deposit was black and some of the larger particles showed a black luster as if they were coal dust.

The reason why the oxide forms so much more readily during the positive discharge than it does during the negative, may be that in this case negative ions of oxygen are carried from the surrounding air to the metal surface, and forming as they do the negative parts

of the iron oxide molecules they unite more readily with the iron than do the positive ions which are carried to the metal surface during the negative discharge.

The deposit can hardly be due to the ozone which is formed by the discharge, attacking the iron, as the ozone is formed in not very unequal quantities during both the positive and negative discharges.

POSITIVE DISCHARGE FROM 12° CONICAL POINTS.

7. Since the taper at the ends of steel needles varies so much for the different needles and of necessity changes along the length of the needle, it was thought worth while to study the discharge from a number of points where this angle is the same for all and remains unchanged for some distance back from the point. Six brass conical points were therefore made, the angle of whose cones was 12° for all alike. These cones were 6.35 mm. in diameter at the base (see *C*, Fig. 1), and tapered uniformly to the points which were rounded off so as to be of different diameters. The diameters were measured in the same way as was done with the steel needles.

TABLE IV.

Positive Discharge from 12° Conical Points.

Point Number.			1	2	3	4	5	6
Diameter of Point in Mm.			.c60	.107	.336	.464	.64	1.09
Starting Potential.			2,825	3,125	4,500	5,000	5,850	7,525
Potential of points in volts.	3,000	Current from points in 10 ⁻⁷ amperes.	1.7					
	3,500		6.2	3.9				
	4,000		12.3	9.0				
	4,500		19.2	15.1				
	5,000		27.4	23.5	6.2			
	5,500		38.1	33.4	14.6	7.8		
	6,000		48.1	43.1	22.9	15.7	3.3	
	6,500		59.9	54.8	32.8	25.2	11.8	
	7,000		72.2	66.6	43.7	35.3	21.3	
	7,500		83.9	78.4	54.8	45.4	30.2	
	8,000		98.5	94.0	67.7	59.3	42.5	10.6
	8,500		117.7	112.5 ¹	85.0	75.0	58.1	24.1
	9,000		136.6 ¹	132.0 ¹	103.0	92.9	75.0	39.2
	9,500				124.1 ¹	114.0 ¹	95.1	57.1
	9,725				132.5 ¹			
	9,825					128.8 ¹		
	10,000						115.2	76.1

¹ Currents marked with a figure (¹) were somewhat intermittent.

The results obtained for the positive discharge in dry air from these points when placed at a distance of 1.5 cm. from the plate in the same apparatus as used before, are given in Table IV.

The temperature during the experiments was practically constant

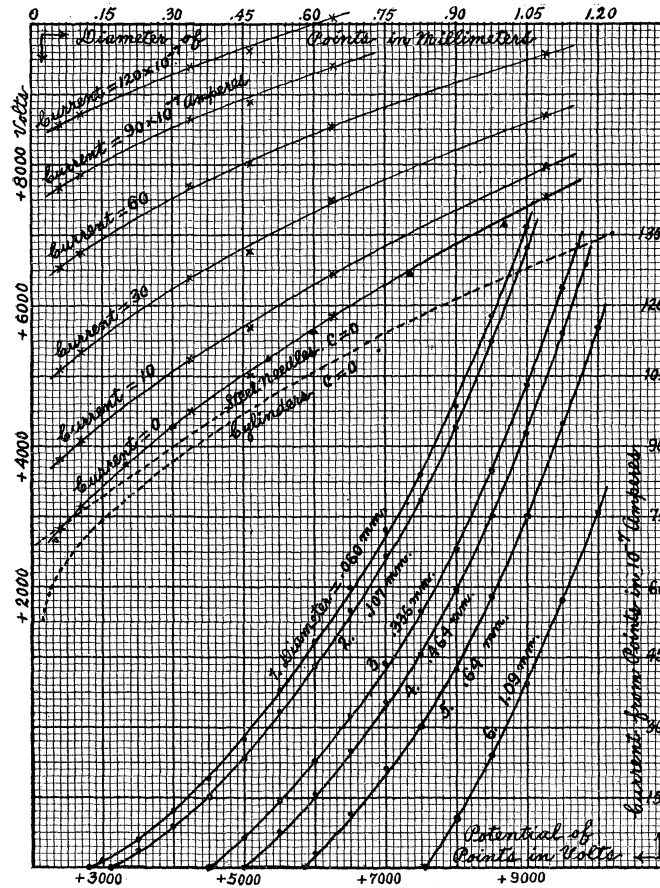


Fig. 5.

at 21° C., and the pressure was 73.7 cm. To reduce the results to a temperature of 22° C. and a pressure of 74 cm. as has been done in the other cases would only require a correction of the order of one tenth of one per cent.

The results are represented graphically by the curves in the lower right hand portion of Fig. 5.

The individual readings are seen to be in good agreement with their respective curves. In the upper part of the figure are shown the potential-diameter curves for the various currents given, the points for each current being taken from the potential-current curves in the lower part of the figure. The good agreement of these points with their respective curves shows the regularity in the results, the values from any point being dependent upon the size of the point only, and not upon any peculiarities of its surface.

8. The relation between the current and potential may be represented again fairly well for each point by the formula, $C = aV(V - M)$, although at the highest voltages used the observed values tend to be larger than what this formula demands. The values of a obtained for the smallest points are nearly alike, but they increase rapidly for the larger points, so that the current in amperes from any point may be approximately represented by the formula,

$$C = 2.49 \times 10^{-13}(1 + .176d^3)V(V - M),$$

where d is the diameter of the point in millimeters. In the cases previously considered d appeared in the first power.

TABLE V.

Comparison of Observed Currents with those Calculated by the Formula,
 $C = 2.49 \times 10^{-13}(1 + .176d^3)V(V - M).$

Diameter of Point in Mm.		.060	.107	.336	.464	.64	1.09
M		2,825	3,125	4,500	5,000	5,850	7,525
Voltage.							
4,000	Current calc.	11.7	8.7				
	observ.	12.2	8.9				
5,000	Current calc.	26.8	23.4	6.3			
	observ.	27.9	23.7	6.2			
6,000	Current calc.	47.4	43.0	22.6	15.2	2.4	
	observ.	48.0	43.0	22.7	15.3	2.8	
7,000	Current calc.	72.6	67.4	43.8	36.0	21.0	
	observ.	71.0	66.0	42.4	34.5	20.0	
8,000	Current calc.	101.5	97.1	70.1	60.8	44.7	11.6
	observ.	100.3	94.1	68.5	59.6	43.0	10.6
9,000	Current calc.	138.2	130.7	101.6	91.2	73.9	40.6
	observ.	136.6	132.0	103.0	93.0	75.0	40.0
10,000	Current calc.					108.1	75.6
	observ.					115.0	76.0

The degree of agreement between the values obtained from this formula and the experimental values taken from the potential-current curves in Fig. 5, is shown for several potentials by the comparison given in Table V.

The potential required to start a current increases with the diameter of the point, in a more complex manner than it did in the cases given before, but its value may be obtained quite accurately for any point by means of the formula,

$$M = 1,980 + 5,200d^{\frac{3}{2}},$$

where d is again the diameter of the point in millimeters.

Some values obtained from this formula have been plotted as triangles on the curve for $C = 0$ in Fig. 5, and the good agreement of these points with the observed values is to be noted.

One of the main physical differences between steel needles and these conical points is that at some distance back from the point the needles approximate to cylinders while in the cones, of course, no such change takes place. The difference in the formulæ necessary to represent the results in the two cases is probably due to this difference.

NEGATIVE DISCHARGE FROM 12° CONICAL POINTS.

9. The results obtained for the negative discharge in dry air from the same conical points as used above when placed at a distance of 1.5 cm. from the plate, are given in Table VI. The temperature throughout was approximately $18^\circ.2$ C. and the pressure 72.2 cm.

The results, for the larger points especially, are quite irregular. With the point .64 mm. in diameter the current fluctuated so much that it was not possible to take any readings at all. A star is placed opposite the values of those currents which are given where the telephone indicated an intermittence. The values for the smallest currents were erratic and fluctuated somewhat. Some irregular resistance to the discharge seemed to be present on the surface of the point which only disappeared after the current had reached a certain value.

The results are shown graphically in the lower part of Fig. 6. In drawing the curves some of the erratic values for the smaller

currents were disregarded altogether. The results are not regular enough, as a whole, to permit of being used to test any formula, but Warburg's formula appears to hold well for the smallest points, the value of the constant for point no. 1 being 4.3, in the same units as have been used throughout.

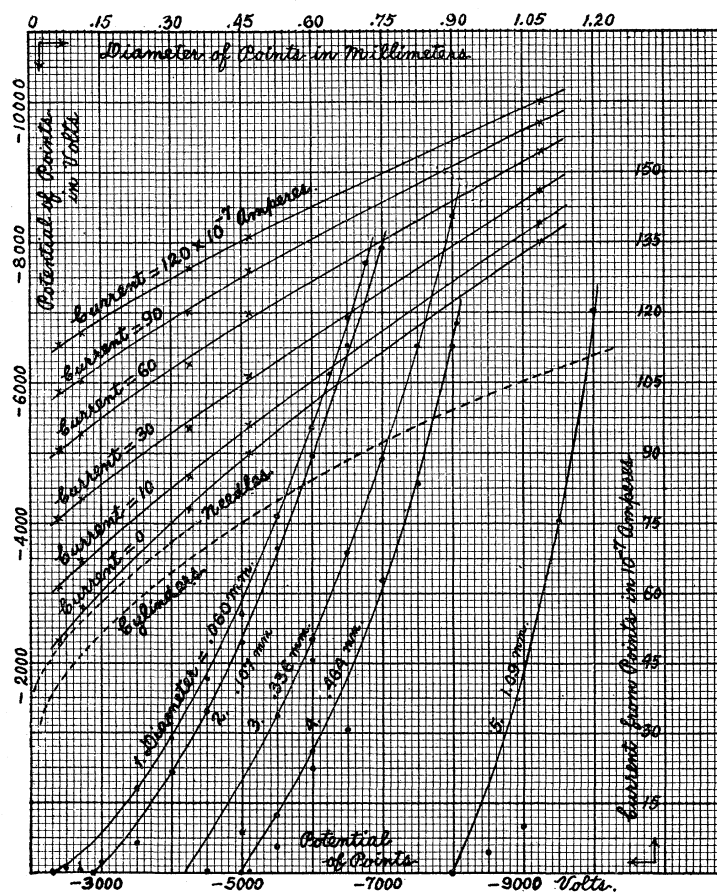


Fig. 6.

The curves in the upper part of Fig. 6 again give the relation between the size of the points and the voltage necessary to produce the currents stated in each case. The agreement of the individual points with these curves seems to justify the drawing of the potential-

current curves without regard to the low erratic values of the current which so often appeared.

DISCHARGE TO DIFFERENT PARTS OF A SPHERICAL SURFACE.

TABLE VI.

Negative Discharge from 12° Conical Points.

Point Number.			1	2	3	4	5
Diameter of Point in Mm.			.060	.107	.336	.464	1.09
Starting Potential.			2,300	2,875	4,500?	5,100	8,000
Potential of points in volts.	2,500	Current from points in 10^{-7} amperes.	1.2				
	3,000		3.9	2.0			
	3,500		18.0	6.2			
	4,000		28.7	21.7			
	4,500		41.4	34.7			
	5,000		55.4	49.5	8.9*		
	5,500		76.5	69.2	33.8	12.5*	
	6,000		95.6	89.5	50.0	26.0*	
	6,500		118.8	113.0	68.7	30.4*	
	6,750		130.5				
	7,000			133.9	89.0	63.0	
	7,500				112.6	83.3*	
	8,000				140.8	112.6	
	8,500						4.5*
	9,000						10.1*
	9,500						75.5*
	10,000						120.5*

10. Warburg¹ has found the law according to which the current flowing from a point to a plane distributes itself over the area of the

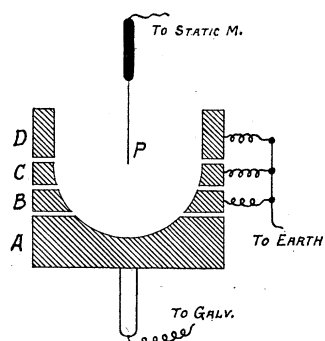


Fig. 7.

plane. It seemed of some interest to see how the current would distribute itself to the various parts of a spherical surface from a discharging point situated at its center of curvature, inasmuch as the electrostatic field is much simpler in this case and approximates at least roughly to that between two concentric spheres.

The apparatus used is shown in section in Fig. 7.

¹ E. Warburg, Wied. Annal., 67, p. 69, 1899.

A brass cylinder was divided into the four parts *A*, *B*, *C* and *D*, which were separated by spaces of one millimeter and held in place by means of sealing wax. The cavity in the parts *A*, *B* and *C* formed a hemisphere with a radius of 1.5 cm. The portions of the hemisphere on the three sections were of equal area. The effective areas of these sections for receiving the current, however, include parts of the air spaces between them, and as section *B* has air spaces on both sides, its effective area is about ten per cent. larger than that of section *A*. Section *D* was one centimeter in height and its interior surface was a cylinder three centimeters in diameter, thus forming a continuation of the spherical surface in the other sections.

The point *P* was a brass cylindrical wire .18 mm. in diameter. It had a rounded end which was placed at the center of the spherical surface in *A*, *B* and *C*. The auxiliary apparatus was the same as that used in the other experiments.

In taking readings each of the sections *A*, *B*, *C* and *D* was connected in turn to the galvanometer while the rest were joined to earth. The readings were taken with the apparatus in the open air, in the winter when the humidity was low, so that the results are but little different from what would have been obtained had dry air been used.

One set of readings taken for both the positive and the negative discharges is given in Table VII. The temperature was 21° C. and the air pressure was 74.8 cm.

TABLE VII.

Discharge to Different Parts of a Spherical Surface.

Positive Discharge.					Negative Discharge.				
Voltage of Point.	Current in 10^{-7} Amperes Flowing to				Voltage of Point.	Current in 10^{-7} Amperes Flowing to			
	<i>A</i>	<i>B</i>	<i>C</i>	<i>D</i>		<i>A</i>	<i>B</i>	<i>C</i>	<i>D</i>
3,500	4.2	4.2	2.2	—	2,750	1.8	1.6	1.6	—
4,000	7.2	7.7	6.0	.06	3,000	4.4	3.9	3.5	—
5,000	15.4	16.5	14.9	3.3	3,500	—	—	10.2	3.0
6,000	26.4	28.6	26.4	10.7	4,000	15.4	17.1	16.5	8.3
6,500	33.0	—	—	—	5,000	32.1	36.3	34.7	26.4
7,000	39.8	42.9	40.7	20.9	5,500	45.1	50.6	48.4	39.6
Min. voltage	2,800	2,850	3,075	—	Min. voltage	2,550	2,625	2,625	3,075

11. When due allowance is made for the inequality of the effective areas of the different sections as explained above, it is seen that the current is quite uniformly distributed over the whole surface of the hemisphere, for all but its smallest values. The effective area of *B* is about ten per cent. larger than that of *A*, and the currents going to it are larger by about the same amount. The effective area of *C* is also very likely somewhat larger than that of *A*, but as the upper air space is outside of the hemisphere it is more difficult to estimate its effect.

The values obtained by computing the current per square centimeter from the current flowing to the whole hemisphere, can be represented quite well for the positive discharge by the formula,

$$C = .60 \times 10^{-13} V(V - 2,800) \text{ amperes,}$$

where *V* is the voltage of the point and 2,800 is the voltage at which the current started to flow to the central section.

Similarly the negative current in amperes per square centimeter can be represented by

$$C = 1.23 \times 10^{-13} V(V - 2,550).$$

The values of the potential required to start a current in this case are nearly 200 volts smaller than is required to start a current from a point of the same size when placed at a distance of 1.5 cm. from a plane.¹

The positive current flowing to the whole hemisphere at any voltage is not quite twice as large as would flow to a plane at the same distance, while the negative current flowing to the hemisphere is a little more than twice as large as the corresponding current flowing to a plane.²

Most of the current which flows to the section *D* at the higher voltages is due to a discharge from the side of the wire point, since owing to their high velocity it is not likely that many of the ions are forced out from the hemispherical volume by mutual repulsion.

When the section *D* was removed, the current received by section *C* was considerably smaller than that flowing to either *A* or *B*.

¹ J. Zeleny, loc. cit., see Figs. 2 and 5.

² Ibid.

A small hole was bored in the center of a middle section of an apparatus similar to the above, and the pressure in the air was measured at that point during a discharge, by means of a sensitive manometer. The value obtained was about one third of that calculated¹ on the supposition that there are no convection currents. In the middle of the next section the pressure was still smaller.

DISCHARGE AT DIFFERENT PRESSURES.

12. The results of some experiments which were carried out some time ago on the discharge from a point in dry air under pressures varying from that of the atmosphere to the very lowest at which a discharge could be made to pass, will now be described briefly.

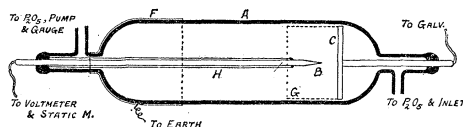


Fig. 8.

The apparatus that was used is shown in Fig. 8, the auxiliary parts being practically the same as were used above.

The glass tube *A*, 4.6 cm. in diameter, contained the point *B* and the plate *C*. The point *B* consisted of a brass rod, 3.2 mm. in diameter, whose end was turned to a 15° cone, the diameter of whose point was .068 mm.

The rod was covered with the glass tube *H*, up to a distance of 1.6 cm. from the point. The brass plate *C* which received the current had a wire-gauze cylinder *G* attached to its rim. This protected the space between the point and the plate from the effects of any electrification that might collect on the walls of the glass tube. The distance between the point and the plate was one centimeter.

The part *F* of the glass tube was covered with earthed tinfoil to prevent the spreading over the outer surface of static charges from the high potential wire. A static machine was used for producing potentials above 1,000 volts, and a battery of storage cells was used for potentials below 1,000 volts.

Potential-current curves were obtained for both the positive and

¹ A. P. Chattock, *Phil. Mag.*, 48. p. 401, 1899.

the negative discharges, for a large number of decreasing pressures until the discharge ceased to pass with the potential of the point at over 10,000 volts. The nature of the results obtained is shown by the curves in Fig. 9, which indicate how the potential required to

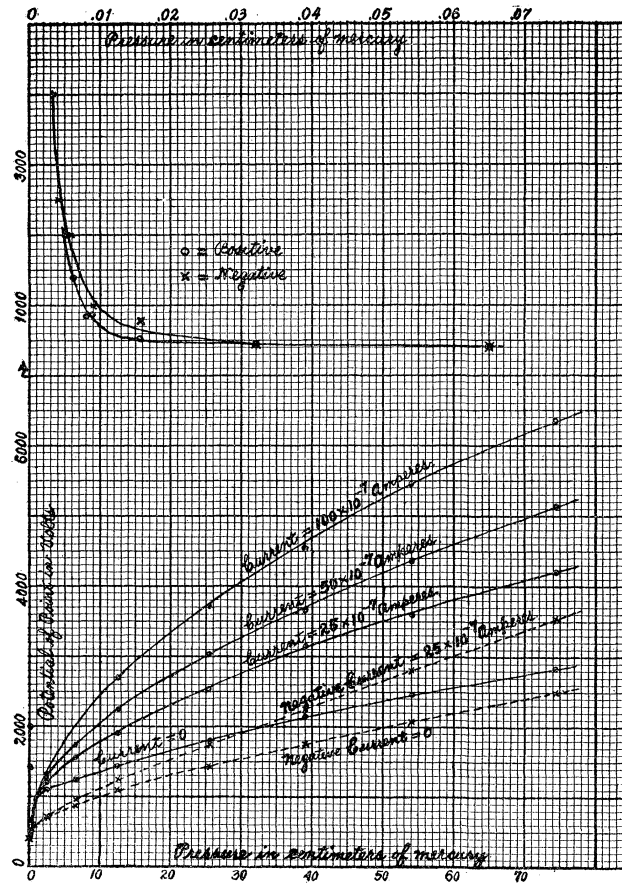


Fig. 9.

produce a given current changes with the pressure of the gas. The curves given were obtained from the potential-current curves for the different pressures, by plotting the potentials required at these pressures to produce the current stated in each case.

The full line curves are for the positive discharge and the two

broken line curves are for the negative discharge. The only values used in plotting the positive potential-current curves were those where the current was steady as indicated by the telephone receiver which was placed in the galvanometer circuit.

In considering the results it must be borne in mind that not only does the nature and the appearance of the discharge change as we reach the lower pressures, but in addition the area of the electrodes to and from which the discharge passes, increases until at the lowest pressures the current passed between the whole exposed surface of the point and the whole surface of the plate and the gauze cylinder attached to it.

At many of the low pressures the current would only begin with a high value, and as the voltage was diminished the current would drop as suddenly to zero.

It is seen from the curves in the figure that at the lowest pressures the current increases rapidly with change of voltage, since the potential-pressure curves for the different currents converge very rapidly for pressures below five centimeters, and below one centimeter the different curves are not distinguishable on the scale used.

For the positive discharge the voltage required to produce a current changes rapidly from about 1,000 volts for a pressure of one centimeter to a minimum of about 400 volts. With the negative discharge, for the same range of pressure, the voltage only changes from about 600 to 400 volts, the minimum voltage being the same as for the positive.

The curves in the upper part of Fig. 9 show how, at the lowest pressures used, the voltage required to produce a current changes with the pressure. It is seen that for a considerable range of pressure the voltage remains about constant and the same for both kinds of discharge, but that as the pressure is diminished below .01 cm. the potentials rise rapidly for both discharges.

With the positive discharge no current could be obtained with over 12,000 volts when the pressure was reduced to .0042 cm., while for the negative discharge, when the pressure was as low as .0023 cm., a little flash of light appeared in the tube now and then with the potential somewhat over 12,000 volts.

It is worthy of notice that the lowest potential at which either the

positive or the negative discharge would take place at any pressure, is about 400 volts, which value approximates to the cathode fall of potential in air which is observed in vacuum tubes where larger sized electrodes are used.

13. The general luminous aspect of the steady positive discharge at the different pressures will now be described.

(a) The light was confined to the immediate neighborhood of the point, appearing as a violet tinted speck of light, for all pressures down to 6.5 cm., at which pressure a violet glow extended back over the point for a distance of about two millimeters, the light at the point itself being more intense than that farther back.

(b) At a pressure of 2.5 cm. this glow had already spread back over the whole exposed surface of the point (1.6 cm.).

The discharge at this pressure would usually start with an instantaneous flash of light, consisting of a bright speck of light on the point itself, with a brush of light extending nearly to the plate, where a dark space separated it from a luminous coating on the plate itself. After this one flash, the appearance of the discharge changed to the violet glow over the point, described at first. When the static machine was stopped, the current gradually diminished and just as the discharge ceased a flash similar to that at the beginning would pass through the tube.

Sometimes the current continued intermittent, having to the eye the general appearance described for the flash discharge. At other times, again, a combination of the steady and intermittent discharges was noticed. These may not have been simultaneous, the discharge possibly alternating rapidly between the two kinds.

(c) At a pressure of .9 cm. the appearance of the steady discharge was the same as at 2.5 cm. pressure. Once at this pressure the current alternated back and forth between the steady and intermittent kinds described under (b), being intermittent for 20 seconds and then steady for 45 seconds, for a period of over 20 minutes, when the current was discontinued.

This indicates that during one of the discharges some surface condition necessary for its existence is altered by the discharge, so that the discharge changes to the other kind during which the original surface condition is recovered, enabling the discharge to change back again to the first kind.

(*d*) At a pressure of .39 cm. the glow over the whole point had become somewhat wider than it was in the last case, being now about one millimeter wide and fading off into the gas.

(*e*) At a pressure of .19 cm. the glow over the point was still less sharply defined and extended for about three millimeters into the gas.

(*f*) With the pressures at .065 cm. and .032 cm., the glow extended out over half way to the plate and gauze, its exterior surface taking somewhat the outline of these two. There was now a reddish glow on the surface of the plate.

(*g*) At a pressure of .015 cm. there was a glow throughout the whole tube, except for a curved dark space near the middle of the volume.

(*h*) At a pressure of .0088 cm. and up to the limit when the discharge would no longer pass, the tube was filled with light of a bluish tinge, with a whitish glow on the point; and the discharge was intermittent.

The negative discharge at the low pressures was for the most part intermittent, and a few peculiarities only will be noted.

At a pressure of 2.5 cm. there was a considerable time interval between the application of the voltage (storage cells being used) to the point and the beginning of the discharge, being at times as much as eight minutes. When a glass tube containing one gram of one per cent. radium bromide was placed near the tube, however, the discharge always commenced immediately on applying the voltage.

At a pressure of .9 cm. a reddish spot of light, five to eight millimeters in diameter, appeared on the extreme edge of the wire gauze, with a corresponding spot on the point opposite. These spots of light rotated irregularly about the axis of the tube keeping more or less together. They seemed to be part of an arc discharge. At lower pressures down to .19 cm. these spots became more and more extended and diffused, finally appearing to envelop the whole point and gauze cylinder.

At the lowest pressures at which the negative discharge would pass its appearance was that of a diffused light throughout the whole space, being somewhat more intense at the surface of the point electrode.

GENERAL REMARKS.

14. It is of some interest to compare the potentials required to start a discharge from the three classes of points which have been studied. Such a comparison is made in Figs. 5 and 6, where, under the potential-diameter curves for $C = 0$, are drawn in broken lines the corresponding curves for needle points (taken from Figs. 2 and 3), and for cylindrical wires (taken from Figs. 2 and 5 of the previous paper — loc. cit.).

The comparison shows how much easier it is to start a current from the cylindrical wires than from the other points of like diameter. And while much finer needle points can be obtained than the diameters of the smallest wires, still the discharge from the fine wires takes place at considerably lower voltages than it does from the finest needles. The wires are preferable, too, because the fine needle points become blunter with use, while the wires of necessity do not. The formation of oxides on steel points, especially during the positive discharge, is also a disadvantage.

For the sake of comparison, the formulæ which have been found to represent best the experimental results for the positive currents from all of the points tried in each of the different cases, are here brought together. The distance between the point and the plane was 1.5 cm. in each case.

$C = 2.58 \times 10^{-13} (1 + .110d) V(V - M)$ for cylindrical wires with hemispherical ends.

$C = 2.60 \times 10^{-13} (1 + .30d) V(V - M)$ for cylindrical wires with plane ends.

$C = 2.58 \times 10^{-13} (1 + .319d) V(V - M)$ for steel needle points.

$C = 2.49 \times 10^{-13} (1 + .176d^3) V(V - M)$ for 12° conical points.

The values of the minimum potentials (M) in the four cases are given in turn by, $755 + 5.465d$; $705 + 5.670d$; $2,590 + 4.750d$; and $1,980 + 5,200d^{\frac{2}{3}}$.

The initial constants in the current formulæ are quite alike, but there is much variation in the way that the current and the minimum potential depend upon the diameter of the point. The range of diameters used was different for the different cases and so the limits over which the formulæ have been tested are not alike.

The beginning of a discharge from a point and the smaller currents from it, are often subject to considerable irregularity, especially if the discharge is negative. Some irregular resistance is present in these cases on the surface of the point, due perhaps to a condensed layer of gas on the metal surface hindering the free passage of the ions to and from the surface. The exposure of the point to radiations, like those from radium, removes the irregularity completely in some cases and partly so in other cases. It may be that the ions formed by the radiations in the condensed layer, moving under the action of the strong electrostatic field, are able to break up this surface layer more or less completely.

There is much less trouble with the larger currents from the point, possibly because the heat generated by the discharge dissipates the gas layer. Nevertheless when a large negative current from a point is reduced to a small value the irregularities become more pronounced than before and often a higher voltage is now required to start the current than was necessary in the first place.

This applies to the brass and steel points used in these experiments, and it is possible that some new effect is added due to an oxidation of the point or some other condition produced by the heating effect of the discharge. Users of platinum points have found, on the contrary, that often the potential at which a current stops is smaller than that at which it began, and hence in this case the gas layer may have been removed by the discharge and no new resistance introduced.

The reason why the positive discharge is on the whole so much more regular than the negative, may be due to the greater facility with which the smaller negative ions, produced by collision outside of the gas layer, penetrate the condensed layer and get to the metal surface.

The value of the minimum potential has been taken throughout as the lowest potential at which a current could be detected flowing from the point. The points have in all cases been exposed to the radiation from radium, and the potential at which a positive current was first observed to begin, as the voltage was gradually increased, was the same as that at which the current ceased, as the voltage was diminished. The smallest difference of potential that could be observed with the voltmeter used was about 25 volts.

When the results for the negative discharge were not completely consistent, it was deemed advisable to use for the purpose of calculation those which showed the current to flow most easily, as they were the most free from the disturbing resistances which have been discussed. As already stated these results were those that were first taken with the point, before it had been used with large currents.

A formula, such as has been used to represent the potential-current curves, assuming as it does a gradual increase in the current from the beginning, as the voltage is raised, is better adapted to represent results for the simplest conditions obtaining at a point, than does one where a discontinuous rise of current at the start is assumed.

SUMMARY.

15. (a) Results are obtained from which it is possible to find the current that would flow in dry air to a plane 1.5 cm. distant, from points of any diameter, at any potential, when these points are either steel sewing needles of the usual taper, or 12° cones.

(b) The potential required to start a discharge from a point of any diameter and the current flowing from any point at any potential, can each be represented by a formula, for the positive discharge from either of the two kinds of points mentioned.

(c) The potential required to produce a current from the finest needles or cones, is considerably greater than is necessary when fine cylindrical wires are used.

(d) Masses of iron oxide form at the tips of steel needles during the positive discharge from them, and to a much less extent during the negative discharge.

(e) The negative discharge from the points shows considerable irregularity, especially for the smaller currents.

(f) The current flowing to a spherical surface from a point placed at its center of curvature distributes itself quite uniformly over the whole surface of the hemisphere opposite.

(g) With diminution of pressure the discharge between a point and a plane (distance = 1 cm.) takes place at gradually lower and lower potentials, and the current increases more and more rapidly with change of voltage. Below a pressure of one centimeter the

potential required for the discharge drops rapidly to about 400 volts as the pressure is reduced to a few hundredths of a centimeter, and then at about a hundredth of a centimeter it begins to increase again rapidly.

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UNIVERSITY OF MINNESOTA,
November 8, 1907.