# ELECTRICAL CONDUCTION ACROSS MINUTE AIR-GAPS.

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## SYNOPSIS.

*Electrical Conduction across Minute Air-gaps.*—As some results obtained by R. W. Wood are at variance with those of other observers, further experiments seemed desirable in which the separation of the metallic electrodes was determined optically. Therefore, two optical surfaces of nearly the same curvature were made conducting by depositing gold upon them by cathode discharge and were supported so as to be nearly in contact. Then, as the upper one was semi-transparent, the distance apart was determined by the interference rings produced by light of wave-length 0.546 $\mu$. Using voltages of from 1.5 to 60, the minimum distance at which no conduction took place and the maximum distance at which conduction occurred were observed. Both these distances varied from less than a wave-length to several wave-lengths. In some cases the resistance of the gap during conduction was measured; it was found to obey Ohm's law and to be unaffected by radiation from 3 mg. of radium. The results suggest that the conduction was due to small projections from the electrodes or to dust particles. No disruptive discharge took place even when the potential gradient rose to 640,000 volts/cm., probably because the potential was less than the minimum which previous researches had indicated is necessary.

*Existence of electron atmospheres at metallic surfaces,* which was suggested by R. W. Wood to explain his experiments, seems very doubtful in view of the above results. At any rate, the atmosphere cannot extend more than one fourth wave-length or 0.14 $\mu$ beyond the molecular surfaces of the gold electrodes.

SOME time ago R. W. Wood [1] performed experiments which provided strong evidence of the existence of a medium, presumably an atmosphere of free electrons, capable of carrying electric currents between differences of potential of the order of one volt and extending beyond the molecular surface of a metal through a distance as great as thirty wave-lengths of sodium light. Not only were these results at variance with those of previous experimenters with small gaps (Carr,[2] Shaw,[3] Almy,[4] Williams,[5] etc. . . .) who found evidence that as a gap in an electric circuit is made very small there exists a minimum potential of the order of 350 volts which can cause a current to flow without actual contact, but Brown,[6] Englund,[7] and Householder[8] have since

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[1] Phil. Mag. (6), 24, p. 316, 1912; R. W. Wood.

[2] Proc. Roy. Soc., LXXI., p. 374, 1903; W. R. Carr.

[3] Proc. Roy. Soc., LXXIII., p. 337, 1904; P. E. Shaw.

[4] Phil. Mag. (6), 16, p. 456, 1908; J. E. Almy.

[5] PHYS. REV., 31, p. 216, 1910; E. H. Williams.

[6] PHYS. REV. (2), 2, p. 314, 1913; F. C. Brown.

[7] Phil. Mag. (6), 27, p. 457, 1914; C. R. Englund.

[8] PHYS. REV. (2), 4, p. 47, 1914; F. F. Householder.

performed experiments dealing directly with the question and have secured negative results. It is important to observe, however, that in practically every instance the point of actual molecular contact (if one may say that) was established by electrical means, thus eliminating the true field of experimentation, for by this means it could only be determined that a continuous circuit, perhaps partially composed of an atmosphere of free electrons, had been established. This objection can not be offered against the work of Brown and Householder, but in the one case perfect insulation could not be obtained across a gap of less than nine wave-lengths, and in the other the actual areas of the opposed electrodes were exceedingly small, and no statement was made concerning the precautions taken to insure conductivity at all parts of the circuit other than the one under investigation.

Because of these considerations, it was suggested by Dr. W. F. G. Swann that the problem be investigated by a method which should reproduce as nearly as possible the conditions under which Wood found the effect most noticeable and which should at the same time eliminate difficulties involved in other methods used. The writer was able to do this in the following manner:

Care was taken to select a double-convex and a double-concave lens such that a very regular series of Newton's rings could be secured at whatever place the lenses were brought into contact. After a heavier ring had been deposited about its edge, one surface of each lens was then completely covered with a deposit of gold thrown down in a vacuum. A concave surface, of about 206 cm. radius of curvature and 3 cm. diameter, was covered with a film rather heavier than that known as semi-transparent, while a convex surface of about 127.5 cm. radius of curvature and 5 cm. diameter was covered with a film which was quite transparent.

A partial cross-sectional diagram of the apparatus made to hold the electrodes and to adjust the extent of their separation is shown in Fig. 1. The base of the instrument consisted of two brass rings about 4 mm. thick and with external diameters of 10 cm., held rigidly separated at a distance of 2.5 cm. by stout brass rods. The upper surface of the second ring was made with a raised collar about its inner circumference, the top of this being cut down until the remaining ledge supported the concave lens with its gilded surface well above any portion of the ring. At one place an incision was made in the collar to enable a small clamp, fastened to the lower side of the second ring and extending up along the cylindrical side of the lens, to hold a small piece of tin foil tightly against that side without exposing any metal at an altitude as great as that of the upper surface of the lens.

The convex lens was held similarly in a third ring with its gilded surface down, the diameter of the lens being sufficiently large that its supporting clamps were further separated from the second ring than was the upper film from the lower. The third ring was supported above and insulated from the rest of the instrument by brass rods which turned freely in the base and passed through threaded bone plates fastened to the ring. Adjustments were made either by heating the rods last mentioned or by turning them. While backlash was largely eliminated by insulated spiral springs, there was still sufficient freedom to enable the films to be brought into contact at any point desired.

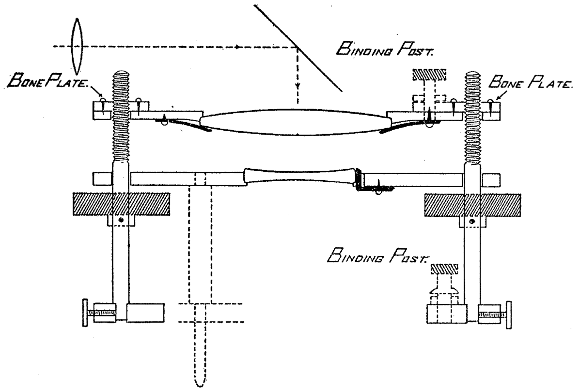

Fig. 1.

By means of a small plate of glass placed in a frame at an angle of 45 degrees to the planes of the rings, the green light from a mercury arc lamp was reflected against the lenses so that a system of Newton's rings was formed by reflection from the two gold films. In effect, then, two sections of very smooth thin spherical gold shells could be made to approach each other in a uniform manner. The center of the system of rings formed was observed through a traveling microscope between parallel hairs. Metallic contact was taken as occurring when the center of the system remained light and spread out over the field when greater pressure was exerted upon the lenses. As the thumbscrews were turned in a direction which would separate the films, each change in the center of the system from light to dark or from dark to light indicated an increase of one fourth wave-length between the points on the films nearest contact. The monochromatic filtered line used was .546 $\mu$. Future reference to "wave-length" will be taken as indicating this distance.

The apparatus holding the films was first connected as the unknown resistance in a Wheatstone net with a very sensitive galvanometer, and the resistance of the gap was measured as its magnitude was varied. Observations made when true metallic contact had been made certain in the manner described showed the resistance to be quite constant under such conditions, varying only as points of contact between the films varied in their distance from the conducting clamps. Observations of the resistance of the gap were then made, usually at every quarter wave-length increase in the shortest distance between the films. Readings secured in this manner are given in Tables VII., VIII., IX., and X. The potential applied was 1.4 volts, supplied by one dry cell. Infinite resistance in these tables is taken to mean that the resistance was greater than 9,000,000 ohms.

## Tables.

In the following tables a row labelled (*A*) contains the values of the magnitudes in wave-lengths of the gaps at which conduction ceased, while one labelled (*B*) indicates the corresponding values for the resumption of conduction.

### Table I.

(*A*) 2½, 1, 10, 2½, 2¾, 13½, 3¾, 1½, 3½, 1½, 2½, 1½, 3, 2½, 3½, 3¾.

### Table II.

| | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (*A*) | 1½ | 3½ | 1½ | 2½ | 1½ | 3 | 2½ | 3½ | 2 | 7 | 3¾ | 9½ | 6 | 3½ | 8 | 2 | 6½ | 1½ | 1½ | 1½ | 2½ | 4¼ | 2 | 2 |
| (*B*) | | | | | | | | | 1½ | 4 | | 7½ | | 3½ | 2 | 1½ | 1½ | 1½ | 1¼ | 1 | 1¾ | 2 | 1½ | 1¾ |

### Table III.

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| (*A*) | 1½ | 2¾ | ¾ | ¾ | 1 | 1 | 1½ | 3½ | 5¼ | 3½ | 2½ |
| (*B*) | | | ⅝ | ½ | | 1 | 1¼ | 2¾ | 4¾ | 3⅛ | |

### Table IV.

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| (*A*) | 3 | 2 | 2 | 3 | 2 | 3 | 2 | 2 | 1½ | 2– |
| (*B*) | 2 | 1 | 1¼ | 2½ | 1¼ | 1½ | 1 | 1½ | 1 | 1¼ |

### Table V.

| Volts. | Amperes. | Ohms. |
|---|---|---|
| .06 | .00066 | 91 |
| .07 | .00070 | 100 |
| .10 | .00060 | 166 |
| .155 | .00086 | 174 |
| .20 | .00120 | 166 |
| .175 | .00105 | 157 |
| .22 | .00130 | 170 |
| .23 | .00135 | 170 |
| .24 | .00140 | 170 |
| .25 | .00170 | 150 |
| 1.238 | .00820 | 150 |
| 1.345 | .00840 | 160 |

## TABLE VI.

In row (*C*) of this table are given the magnitudes in wave-lengths of the gaps across which the higher voltage discharges occurred.

(For Preliminary Potential Differences.)

| | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (Volts) | 3 | 3 | 4 | 4 | 3 | 4¾ | 3¾ | 3½ | 2¾ | 3¼ | 3 | 3 | 3¼ | 3½ | 3 | 3 | 3 | 4 |
| (*A*) | 1½ | 4½ | 2½ | 3 | 1½ | 2 | 2 | 1¼ | 2 | 2½ | 1½ | 4 | 2½ | 1½ | 2 | 2 | 2 | 3½ |
| (*B*) | | 2 | ½ | 1½ | 1¼ | 1½ | 1 | ½ | 1½ | 1¼ | 1 | 2½ | 1½ | 1 | 1 | 1½ | 1½ | 1½ |

(For Higher Potential Differences.)

| | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (Volts) | 40 | 23 | 30 | 40 | 31 | 40 | 38 | 60 | 64 | 27 | 70 | 60 | 53 | 36 | 36 | 25 | 15 | 67 |
| (*C*) | | 2½ | 2 | 3½ | 1¾ | 2 | 1¼ | 4½ | 2 | 1½ | 2¾ | 3 | 2½ | 1¼ | 1 | 1½ | 1½ | 5½ |

In Tables VII., VIII., IX., and X., row (*D*) gives the magnitude of the gap in wave-lengths, while row (*E*) gives the respective resistances in ohms.

## TABLE VII.

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| (*D*) | 0 | ¼ | ½ | ¾ | 1 | 1¼ | 1½ | 1¾ | 2 | 2¼ | 2½ |
| (*E*) | 8– | 8 | 9 | 9⅓ | 9½ | 10 | 11 | 13 | 15 | 50 | inf. |

## TABLE VIII.

| | | | | | |
|---|---|---|---|---|---|
| (*D*) | 0 | ¼ | ½ | ¾ | 1½ |
| (*E*) | 13.4 | 23.6 | 29.4 | 31.8 | inf. |

## TABLE IX.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| (*D*) | 0 | ¼ | ½ | ¾ | 1 | 1¼ | 1½ |
| (*E*) | 19 | 45.7 | 65.5 | 200 | 40,000 | 3,000,000 | inf. |

## TABLE X.

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (*D*) | 0 | ¼ | ½ | ¾ | 1 | 1¼ | 1½ | 1¾ | 2 | 2¼ | 2½ | 3½ | 4 |
| (*E*) | 16.4 | 19.6 | 21 | 23.1 | 25.2 | 28.8 | 31.7 | 34.7 | 37 | 37.5 | 45.8 | 4,600 | 9,999 |

* * * * * * * *

(Continued.)

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (*D*) | 4½ | 5 | 5½ | 6 | 6½ | 7 | 8¼ | 8½ | 9½ |
| (*E*) | 14,100 | 20,000 | 33,000 | 160,000 | 250,000 | 450,000 | 1,200,000 | 3,200,000 | inf. |

With certain films, conduction continued in some cases until the films had been separated more than 50 wave-lengths. The magnitude of the distance of separation of the electrodes for cessation of conduction varied greatly with the points on the electrodes nearest contact, but it was impossible to bring some films within three wave-lengths of each other without conduction. It was only after repeated trials with the making of the deposits and with particular care to keep the films at all times protected from dust particles that films were secured which could be brought very nearly together without conduction.

In order to obtain an indication of the nature of the medium providing conduction across the gaps, a test of Ohm's law was made for a constant gap of about 2¾ wave-lengths at which there was a considerable resistance. The electrodes were connected in series with a milliammeter, and various voltages applied, the potentials being determined by a voltmeter constantly shunted across the gap. The results are given in Table V.

For the same reason, the electrodes were left separated by a constant gap whose resistance was about 25.5 ohms, and 3 milligrams of radium contained in a lead case with a small slit were brought from a distant room to a position very near the electrodes. No change could be observed in the resistance of the gap.

It should be noted that the question of chief significance is not across how large an apparent gap conduction could be observed, but how nearly the electrodes could be made to approach without conduction. Since the films were observed to be continuous over the whole opposed surfaces of the lenses, and since considerable areas were separated by practically the same minimum distances, if any one spot could be found at which the electrodes could be brought within two wave-lengths of each other without conduction, and if it were certain that the remainder of the circuit were complete at the same time, this one observation would be sufficient to show that there could not be a general and uniform atmosphere of free electrons extending more than one wave-length above each metal surface, and conduction across apparently greater gaps at other places could be explained by a probable roughness of the surfaces.

Because of this consideration, observations were made of the magnitude of the gaps necessary for no conduction, without finding the values of the resistance during the intermediate steps. The films were first brought into contact and conduction assured. Then they were gradually separated and the point noted at which conduction ceased. Causing the electrodes to approach in such a manner that the point nearest contact should remain as nearly as possible the same throughout the observation, the films were next made slowly to approach each other, and the magnitude of the gap at which conduction was resumed was noted. Such observations were made at various places over the areas of the films. Readings secured in this manner are given in Tables I., II., and III. In each the potential difference applied was 1.4 volts, with the exception of the last ten readings in Table II., which were taken with 2.8 volts.

As a check, similar observations were made in a different manner. The electrodes, one dry cell, and the sensitive galvanometer were connected in series, and the positions for no conduction were taken as those positions at which no deflection of the galvanometer could be observed when the circuit was closed. It should be noted that before or after each reading conduction was secured by bringing the films into contact, thus making sure that the lack of conduction was not due to a break in any other portion of the circuit. Readings secured in this way are given in Table IV.

It was next decided to find just how large potential differences must be applied in order to break down the resistance of the very short gaps which proved insulators for small voltages. A rheostat of considerable resistance was connected directly in a D.C. circuit. Between one end of this and the sliding contact were shunted the electrodes, a resistance of 62,000 ohms, and the galvanometer, all in series. A voltmeter was left permanently shunted across the same two points. The films were first brought together and conduction established with very low voltages. They were then slowly separated and the positions at which conduction ceased were noted, after which they were brought together with the same voltage and the positions at which conduction was resumed were determined. When a spot had been found in this way where the electrodes could be made to approach very closely without conduction with low voltages, they were separated to a distance just greater than that at which conduction with low voltages was known to occur, and the magnitude of the gap kept constant. The applied voltage was then very slowly increased. It was found that as the potential was increased the electrostatic attraction between the electrodes became so great that they were drawn together, but by observing the rings the distance of separation at any instant could be discerned. By waxing a weight to the lower surface of the lower lens, and by slowly turning the thumbscrews in a direction tending to separate the electrodes as the potentials were increased, the magnitude of the gap could be kept quite constant. Since this magnitude could be continuously observed, the electrodes were sometimes separated by a distance greater than that at which it was desired to test the discharge potential, and then allowed to drift down to that distance, the extent of the gap across which conduction first occurred being noted in each case. Although conduction was understood to have taken place whenever the galvanometer began to be deflected, tiny clicking sounds could sometimes be distinguished when the gap was considerably greater than that across which general conduction occurred.

From the readings given in Tables I., II., III., IV., and VI., it is seen that with applied potentials of the order of a volt, it was possible to bring the electrodes so close together that their nearest points were separated by a gap of one half wave-length before conduction took place. This shows that at these points, and necessarily over a considerable area surrounding them, no medium conducting at such potential differences could have extended farther than one fourth wave-length beyond the metallic surface of each electrode.

It should be noted that when conduction was first established by bringing the electrodes into contact, after which they were slowly separated, conduction persisted in most cases across a much larger gap than that at which conduction was resumed, although great care was taken that the point nearest contact during the approach should be the same as that during the separation. Such a lag might be explained by the presence of long dust particles which would adhere to the two surfaces as they were being separated but which, after the circuit had been broken, would fall down so that the upper lens must descend much lower before reëstablishing contact. Or we might suppose that the particles were distended due to the electrostatic forces acting upon them. It would be difficult to conceive of such a pronounced effect with a uniformly distributed medium.

When the magnitude of a gap was left constant and the current measured for various potential differences, the ratio of the potential difference to the current was, as shown in Table V., as nearly constant as might be expected in the case of a metallic conductor, if one considers the possibility of vibrations of the electrodes and the accuracy with which the ammeter and voltmeter could be read.

Tables VII., VIII., IX., and X. were included as representative of the manner in which the low voltage conductance varied with the magnitude of the gap. If the relative variation be represented by curves, it will be seen (from those representing the data in VII. and VIII.) that the conductivity may vary in a random manner with the extent of the gap. Those for IX. and X., however, have a considerable regularity and the curve (Fig. 2) drawn from the data in X., in which the logarithm of the resistance is plotted against the magnitude of the gap, shows that there were three distinct phases in the variation of the conductivity in this particular case. If the conduction here is to be explained in terms of electron atmospheres, it would seem that we must grant them the privilege of existing in three distinct layers.

It would be much more natural to conclude that the conduction was due to dust particles of different dimensions.

It may be noted that in the case of reading no. (15), Table VI., the potential gradient for discharge if we consider the gap to be the distance between the reflecting surfaces of the films, was about 640,000 volts/cm., while if we consider the gap to be merely the increase over the largest which provided conduction at low potentials, the gradient was practically infinite. When compared with the 30,000 volts/cm. required for discharge across large air-gaps, this seems significant in its relation to the minimum discharge potential theory.

Because of the fact that the two electrodes could be brought within a distance of from one to one half wave-length from each other without conduction with applied potential differences as high as 36 volts, it seems that a uniform atmosphere of free electrons conducting for low voltages can not extend more than half that distance beyond the true metallic surface of a gold electrode.

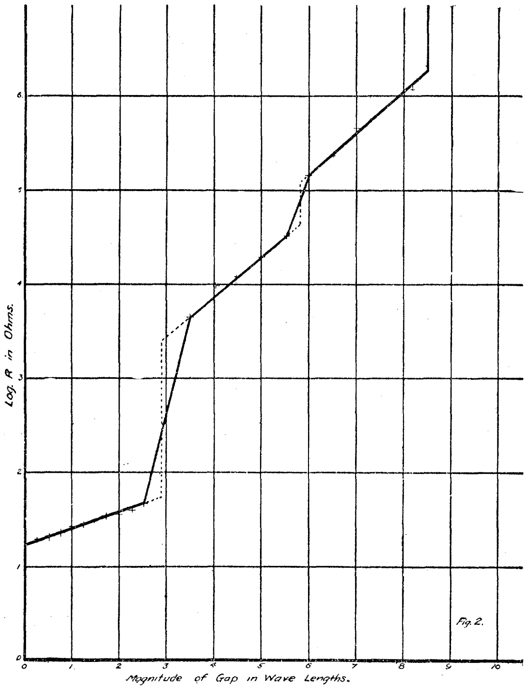

Fig. 2.

Because of the fact that Ohm's law held for a considerable gap, because the proximity of radium produced no effect upon the conductance of the gap, because conduction persisted over a longer gap upon separation than that across which it was resumed when the electrodes were brought together, because electrodes could be brought nearer contact without conduction when particular care was taken to keep them entirely free from dust, because of the tiny clicks heard during the operations made in securing the data for Table VI. before general conduction was observed, and because of the peculiar forms of the curves showing the relations between the magnitudes of the gaps and their resistances, the writer feels confident that the conduction across the gaps as observed was due to small metal projections or to dust particles, rather than to a uniformly distributed medium.

The data showing the value of the voltages necessary for electrical discharges serving as insulators for small differences of potential, indicates that a minimum potential may be required to force an electrical discharge across small air gaps, or at least that the potential gradient required is much greater than that required across larger gaps.

The writer wishes to thank Professor W. F. G. Swann for the very kind advice and encouragement which he extended throughout the course of this work.

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June 12, 1922.