EFFECTS OF CORONA IONIZATION ON ISOTHERMS ABOUT A HEATED WIRE IN AIR

By

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Introduction

Purpose: The object of this study is to investigate the effects of corona ionization on the isotherms about a heated wire in air.

In order to limit the investigation somewhat, the following problems were emphasized:

(a) To test the abruptness of the formation of the corona.

(b) To determine whether any appreciable effects preceded the formation of the visual corona.

(c) To use the Michelson interferometer in testing temperature and pressure changes in the air surrounding the corona.

(d) To compare positive and negative corona.

Some Previous Studies of the Corona: The properties of the air near conductors under high potentials have long been a problem to those interested in electrical engineering and physics.

(a) A number of studies have been made, from the viewpoint of the electrical engineer, on the corona, with emphasis on the voltage required to form the corona, and the attendant loss of energy, together with changes in this corona voltage caused by dimensions and materials of conductors and insulators and such local conditions as air pressures and temperatures, the presence of oil and dirt on the conductors and insulators and the presence of water vapor, snow, smoke, dust, etc. in the air. Among these engineering studies should be mentioned those of Steinmetz[1], Ryan[2], Watson[3], Whitehead[4], and Peek[5,6,7].

Steinmetz[1] found that the atmosphere surrounding solid dielectric specimens, and the electrodes applied there to, would break under the strain formed by the flux of electric force through it much more readily than the solid dielectric, giving rise to envelopes of conductive atmosphere located around the electrodes and over the surfaces of the powerful dielectrics. To this phenomenon, which has the appearance of the familiar brush discharges of electrostatic experiments, he gave the term, "corona".

Ryan[2] gave an analysis of factors responsible for atmospheric loss occuring on high voltage lines and developed equations for expressing the relation between voltage, conductor sizes and separation at which the sudden rise occurs in the curve of "loss between wires" at ordinary barometric pressures and temperatures. As a result of his work, Ryan suggests the use of the appearance of the visual corona between two parallel wires, or a conductor mounted at the center of a cylinder, as a method for guaging high voltages, being free from some of the difficulties present in the use of the spark gap for that purpose and having only the one disadvantage of inconvenience of making observations in the dark.

Watson[3] gave special attention in his studies to direct current. His conclusion was that the definite critical stress for which loss occurs in direct current is the same as the maximum alternating current one and therefore this critical stress is independent of frequency. He found no effect of the presence of water vapor on this critical stress for clean wires. He found values of this stress practically the same for positive and negative wires, when wires are clean, and that the critical stress is reduced by reduction of air pressure, but not proportionally. He attributes losses of energy when the critical stress is exceeded to ionization of the air immediately surrounding the conductor.

Whitehead[4] explains the abrupt breakdown of air near a conductor by the formation of ions by collision, breakdown being very abrupt and coming at a critical intensity approaching a value of 32 kilovolts per centimeter for conductors of large radius, or plane conductors. This is in close agreement with the 30,000 volts per centimeter[14] at which secondary ionization has been noticed to begin between plane electrodes at atmospheric pressure. It is also brought out in this paper that the electric intensity corresponding to the appearance of the corona is independent of the state of ionization of the air. Since secondary ionization depends only on the velocity of the ions, and thus on the electric intensity, it should be independent of the number of ions already existing in the gas, which again suggests that the formation of corona is due to secondary ionization. Another bit of evidence supporting this comclusion is the lowering of critical voltage by decrease of density of air, through lowering of pressure, or raising temperature, or both, since the mean free path of the ions is thereby increased and ionization by collision increased. This causes the corona to appear at a smaller value of the critical voltage. This is in accordance with his experimental results.

Whitehead and Pullen[8] in connection with a design of a corona voltmeter, show that the appearance of visual corona is simultaneous with indications of other effects as shown by the discharge of an electroscope, corona current observed by means of a galvanometer and the sound of the discharge as indicated by telephone transmitter and receivers.

Peek[5,6,7] has carried on a number of experiments on corona with both alternating and direct currents and has developed equations for the calculation of the power loss, the disruptive critical voltage and the visual critical voltage, the latter of which is somewhat the higher, since the corona does not yet begin when the dielectric strength of the air, that is the disruptive voltage gradient, has been reached at the conductor surface, but only after the disruptive gradient has extended a finite distance from the conductor, so that sufficient energy will be present for the luminosity and the power loss of the corona.

This work indicates that the direct current corona voltage is practically equal to the maximum alternating current voltage over a large range of conductor diameters. Therefore his formulas for alternating current corona[5] can be used in direct current corona. His formulas for direct current visual corona voltage, in kilovolts, are

$$e_v = g_v \log_e R/r, \quad \text{for wire in a cylinder,}$$

$$e_v = 2\, g_v \log_e R/r, \quad \text{for parallel wires,}$$

where R is the radius of the outer cylinder, or the center to center spacing of parallel wires, in centimeters,

r is the radius of the wire in centimeters,

$g_v = g_o\, \delta\, (1 + 0.3/\sqrt{\delta r})$ kilovolts per centimeter.

where $g_o = 31$, for concentric cylinders,

$g_o = 30$, for parallel wires.

$\delta = 3.92\, b/\,(273 + t)$

where b is the barometric pressure in centimeters,

t is the temperature in centigrade degrees.

In this paper[6], Peek suggests that with concentric cylinders, when the wire is positive the visual corona point is quite sharp and definite; when the wire is negative the slightest irregularity causes brush discharges at fairly low voltages. Even on apparently highly polished wires, when negative, the voltage for complete glow is generally several per cent. higher than for local brushes. The negative glow voltage will thus generally be read lower than the positive glow voltage.

(b) Anumber of studies in the field of experimental and theoretical physics are of interest in this work, for example, those of Fazel[9], Kuntz[10], Young[11], Parsons[12] and Smith[13].

Fazel[9] investigated the changes of pressure about corona discharges which took place from a fine wire inside a concentric tube. He used a manometric flame to study rapid changes of pressure under an alternating current corona and observed a periodic pressure change with twice the frequency of the impressed electromotive force. In both direct current and alternating current corona a number of effects seemed to be superimposed. When the wire was heated with either alternating or direct current the pressure curve reached a limiting value in about twenty seconds and showed no periodic variations. A corona discharge was started when a steady state was reached. Analysis by means of a quick acting recording pressure gauge showed either a decrease of pressure to a lower limiting value, or an increase to a maximum, followed by a decrease to a limiting value lower than before, or higher than before, depending on the voltage of the discharge. Fazel's conclusion is that characteristic pressures exist in the corona in addition to pressures due to the heating of the gas by current through the wire.

Kunz[10] has assumed that the characteristic pressure increase in the corona discharge is due to the fact that the ions impart their momentum to the gas. His values of mobilities of ions, calculated on this assumption, were of the same order of magnitude as those measured by Hess in the wind of ions from radioactive substances.

Young[11] used the Zeleny method for testing the mobilities of ions formed in a corona discharge on a wire in a tube, showing that nearly all the ions so generated have small mobilities , at atmospheric pressures. While he found no single mobility of ions which alone accounted for the corona pressure from which Kunz calculated his mobilities, he assumed that the pressure could be obtained by taking the sum of the impact energies of all ions generated by the corona.

Parsons[12] in his investigation on the effect of corona on the cooling of wires, found no cooling effect for a corona current of less than three microamperes per centimeter of wire, the effect increasing with current until a maximum is reached at about twelve microamperes per centimeter. Through his work with mobilities in estimated space charge, he states that much less than one ion per million molecules is sufficient to disturb the air enough to cause an appreciable change in its cooling power.

Smith[13] used the Michelson interferometer for indicating the flow of heat from a heated wire, assuming the interference fringes in the field to be isotherms. His fringe systems were very steady and were photographed with ease.

Description of Apparatus

Source of High Voltage: The source of the direct current high voltage was a Kenetron Rectifier, having connections as shown in the diagram, plate I. Two kenetrons, K_1 and K_2, together with twelve condensers, of 0.0017 M.F. capacity each, connected in three groups, C_1, C_2 and C_3, and two choke coils, CC, of 30 H. inductance each, gave direct current voltages that were fairly steady. T_1 and T_2 are step-down transformers for reducing the filament voltage, which was controlled by switch F and rheostat R_1. It was maintained at about 7.5 volts. The plate voltage was taken from the step-up transformer T_3 and was controlled by switch P and the rheostats R_2 and R_3, the latter being connected as a potentiometer. Direct current voltages as high as 9,000 were easily obtained with this rectifier.

Direct current voltages were measured with a Kelvin Electrostatic Voltmeter, whose range was sufficient and whose accuracy was probably satisfactory for this study, which is necessarily qualitative in nature.

Michelson Interferometer: The Michelson Interferometer has been used for a variety of purposes. Smith[14] used this instrument for indicating temperature gradients about a heated wire. This interferometer, illustrated in the diagram, plate II and photographs, plate III, consists of a plane parallel glass plate, P_1, which has been carefully

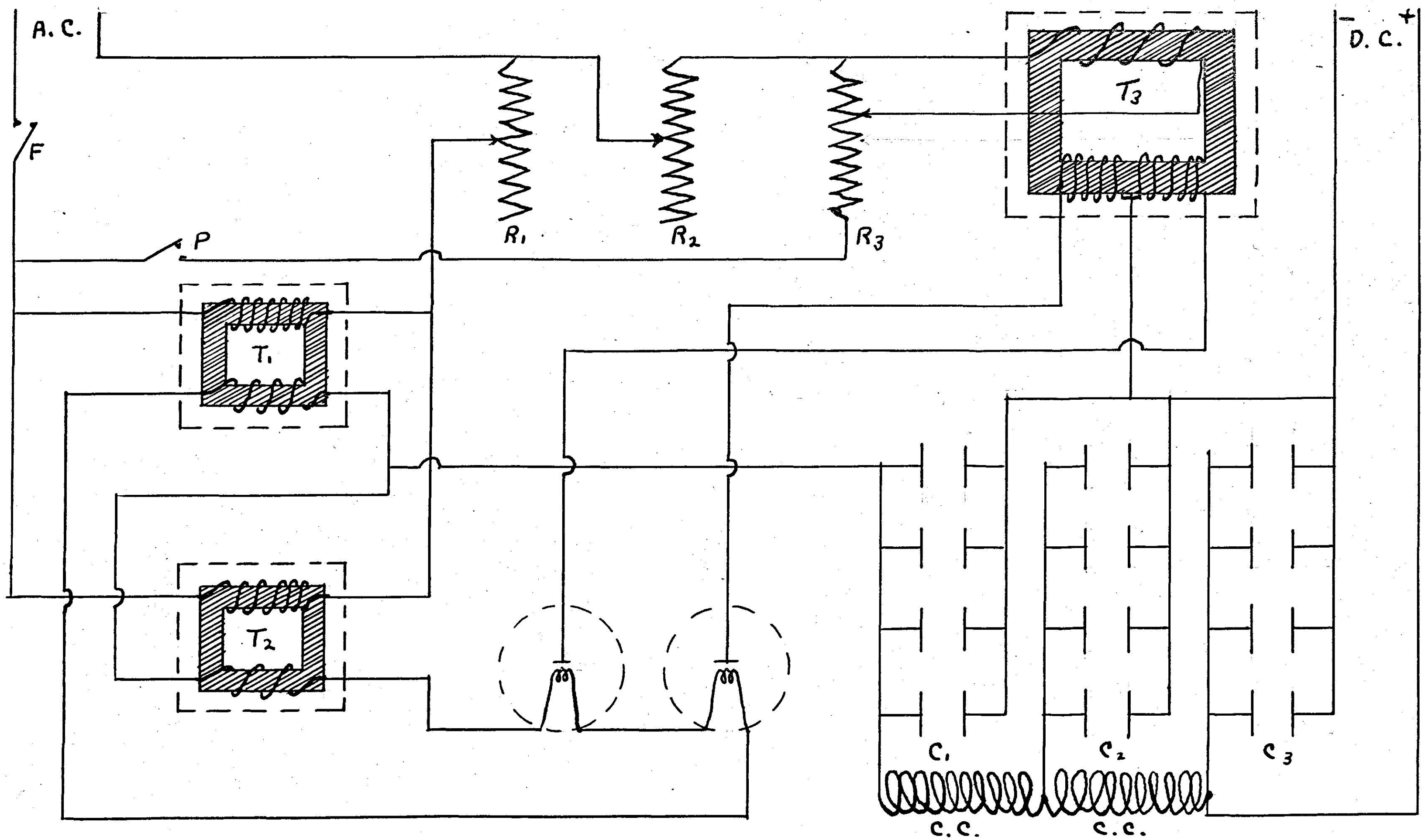


PLATE I KENETRON RECTIFIER

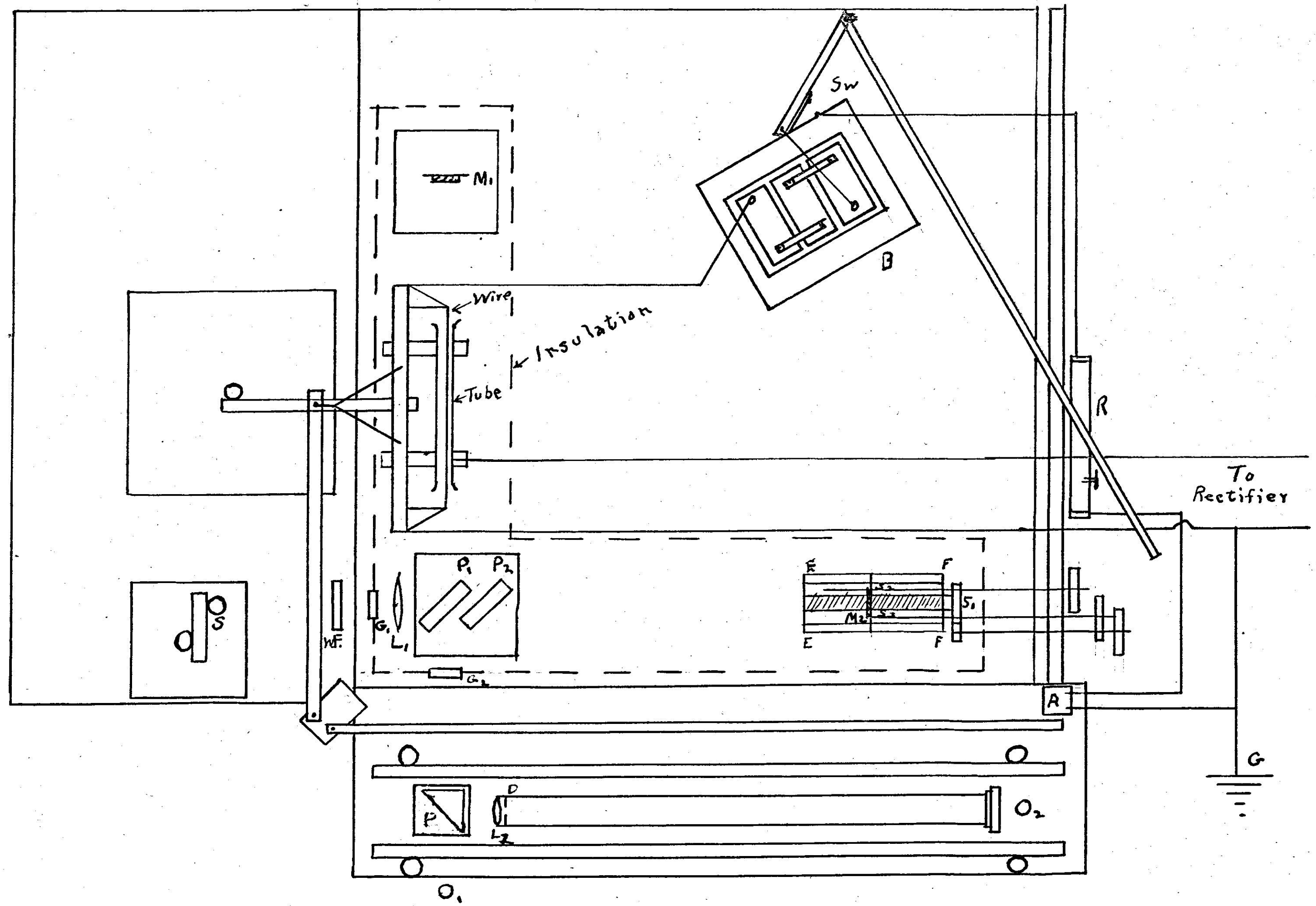
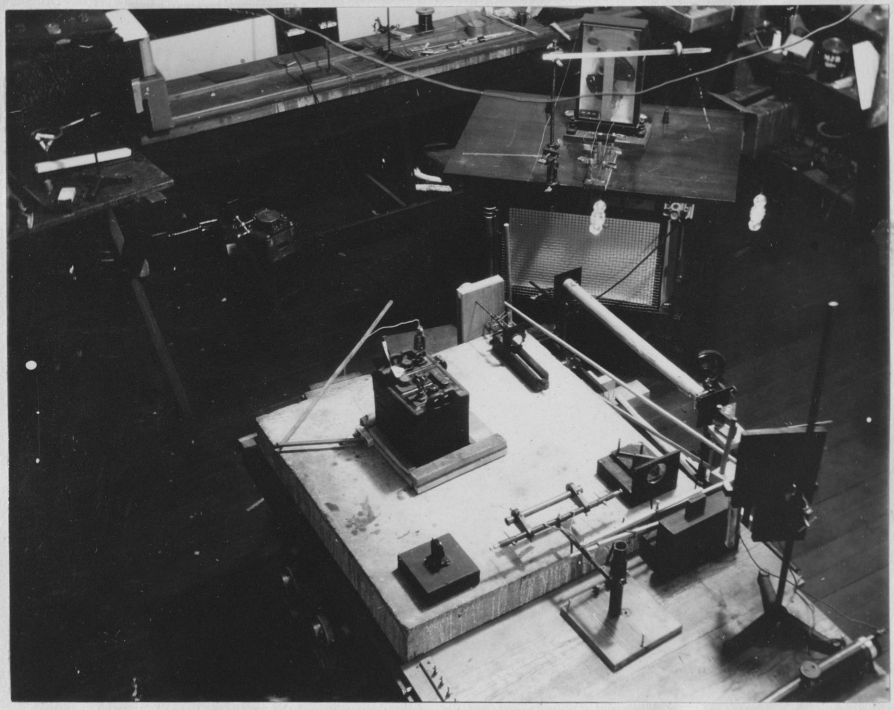
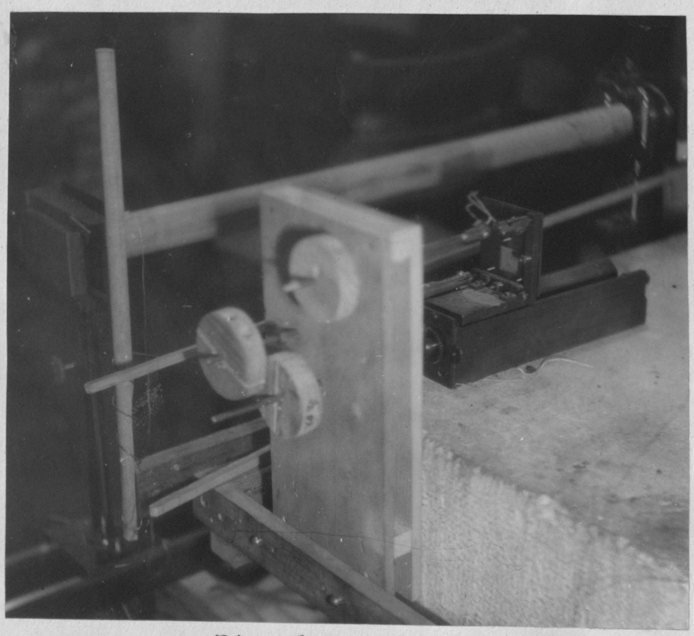


PLATE II MICHELSON INTERFEROMETER

PLATE III



Assembled Apparatus



Fine Adjustments

silvered on one side so that equal portions of incident light are reflected and transmitted. Light from a source at S, rendered nearly parallel by a lens L_1, is directed onto plate P_1 so that the reflected portion is perpendicular to the transmitted portion. These two halves of the incident beam are reflected back over nearly the same paths by plane mirrors M_1 and M_2, respectively. These beams are reunited on P_1 and can be observed at O_1. Since the light which is reflected by mirror M_1 passes through plate P_1 three times before reaching point O_1, while the light which is reflected by mirror M_2 is transmitted through plate P_1 only once, a compensating plate, P_2, which is as nearly plane parallel and the same thickness as P_1 as possible, is placed in the latter path, so that both beams will pass through the same thickness of glass. The two plates must be made from the same piece of glass.

Mirror M_1 is mounted on a small concrete slab, 15 centimeters square and 5 centimeters high, carefully placed on a stone pier, without facilities for fine adjustments. Mirror M_2 is mounted on a slide which can be moved by a screw, S_1, along the ways EF. These ways are carefully constructed so that the mirror can be moved yet remain parallel to its original position. Two adjusting screws, S_2 and S_3, on opposite corners of this mirror, permit adjustments until its image in P_1 is parallel to mirror M_1. These three screws are connected by toggle joints to larger wheels for convenient fine adjustments as needed, illustrated in photograph, plate III.

Both plane mirrors, M_1 and M_2, are circular stainless steal mirrors, 4 centimeters in diameter. Plates P_1 and P_2 are mounted together on a concrete slab, 15 centimeters square and 5 centimeters high. The lens L_1 is attached to the same slab and has a focal length of 25 centimeters and a diameter of 7 centimeters. Each of the two mirrors, M_1 and M_2, is about 62 centimeters from the plate P_1.

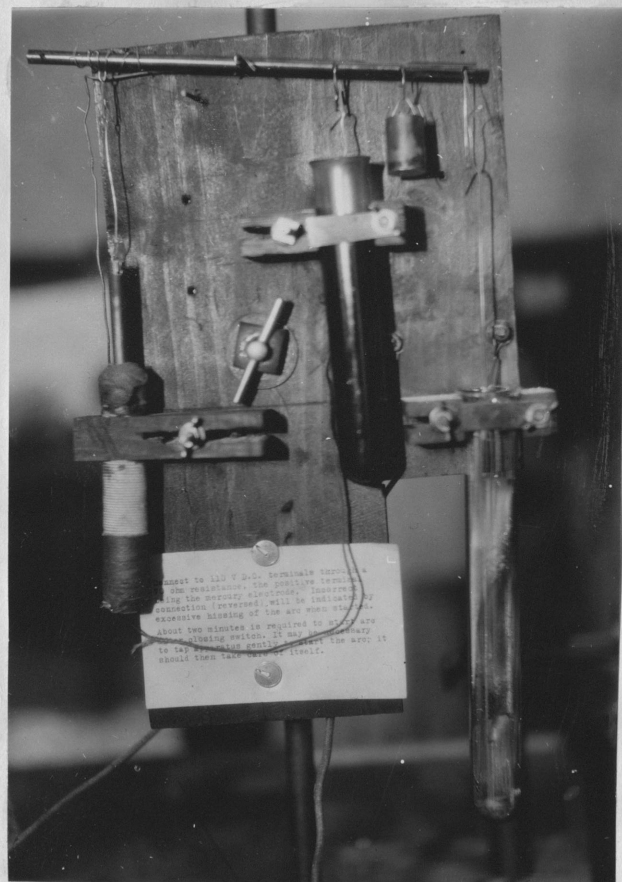
In order to facilitate adjustments of S_1, S_2 and S_3 during observation, a totally reflecting prism P was used so that observations could be made at O_2. A ground glass screen, a simple lens, a telescope eyepiece, or simply the eye of the observer, can be used at O_2. Photographs were taken by mounting a film pack holder at O_2. L_2 is an Eastman camera lens mounted with a diaphragm stop, D. An adjustable black paper tube is placed between lens L_2 and the pack holder at O_2 to prevent stray light from affecting the film. The lens, L_2, the diaphragm, the totally reflecting prism and the pack holder are mounted on a metal optical bench for ease of adjustments.

The test piece is mounted in the arm P_1M_1 with facilities for adjusting the wire in horizontal and vertical planes so as to place it well in the field. In many cases, the wire was heated by current from a storage battery, B, with rheostat, R, and ammeter, A. The wire was also grounded at G and connected to one side of the rectifier, the other electrode of the rectifier being connected to the other electrode of the test piece, in the first case a brass tube, later a parallel wire or plate. A reversing switch is used at the rectifier.

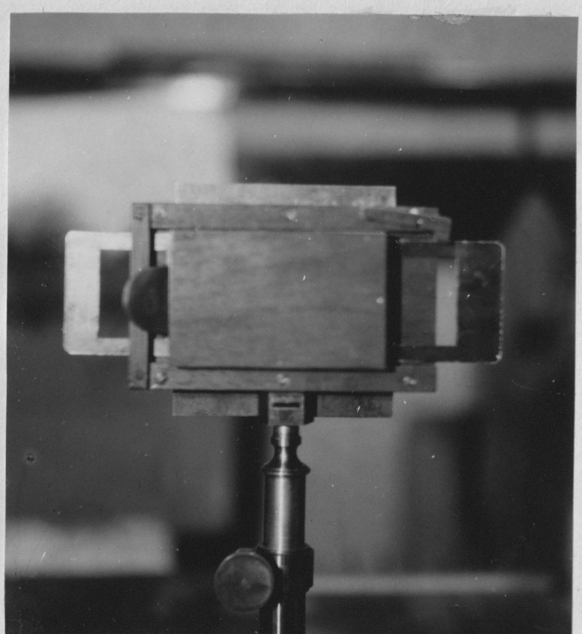
The entire interferometer is enclosed in a cardboard box, with glass windows at points G_1 and G_2, where light from the source enters, and where light emerges for observing or photoghaphing the fringe systems. High voltage wires from the rectifier were connected to the test pieces through pierced hard rubber insulating plates, which were sealed into the sides of the protecting paper box, at convenient positions. The paper box protected the test pieces from air currents, helping to keep the fringe systems steady, so that they could be photoghaphed.

Source of Light: The source of light was a simple mercury arc lamp, built on the design of Professor C. V. Kent. The lamp consists of a pyrex glass test tube, 8 by 1 inches, containing a small quantity of mercury. A pyrex glass tube is placed inside the test tube, and inside of it is a short tube of quartz. Connection is made to the mercury by a wire running down outside the pyrex tube for insulation, and dipping into the mercury. The arc is formed inside the quartz chimney between the carbon rod and the mercury. A Wratten filter, No. 77, is used to screen out all the light except the green line, λ=5461 Å. This lamp, with the filter, makes a bright monochromatic light that is very satisfactory for making visual observations of, and photographing, the

PLATE IV



Mercury Arc Lamp



Film Pack Holder

interference fringes. An electromagnet is connected in series with the arc to automatically maintain the carbon rod at the correct height and to lower the carbon to strike a new arc, should the arc be quenched, as sometimes happened. The small quartz chimney must be removed and cleaned to remove accumulated carbon, after a few hours operation of the lamp.

The Meaning of the Interference Fringes

In this investigation the interferometer was always so adjusted that its two path distances were the same before the special test pieces were used. Therefore any fringes observed were due to differences in density of the air in the two paths, and not to the adjustment of the interferometer. That is, the optical path of one branch of the interferometer was changed by changing the density of the air, and therefore its index of refraction, by changing its temperature, or its pressure, or both. Each fringe formed in this way must represent a locus of equal density points. Since the air about the heated element was not confined, and temperature changes were comparatively slow and small, pressures remained generally fairly constant and therefore the density of the air must be inversely proportional to its absolute temperature. This would indicate that each fringe is also an isotherm.

The following formula for calculating the temperature represented by each fringe was developed by Smith.[13]

$$T_1 = \frac{T_o(n_o-1)}{(n_o-1)-\lambda/2l}$$

where

T_1 = absolute temperature of the first fringe

T_o = absolute temperature of the room

n_o = index of refraction of air at temperature T_o

λ = wave length of light used, in centimeters

l = length of wire, in centimeters

or, in general, where N denotes the number of the fringe, counted from the outside of the system,

$$T_N = \frac{T_o(n_o-1)}{(n_o-1)-N\lambda/2l}$$

General Procedure

Adjusting the Interferometer: In using the interferometer, adjustments were made so that the optical distances of the two beams of light were equal. This was done with the aid of white light, as follows. In order to locate interference fringes, the mercury arc lamp was used, with the Wratten filter No.77, as a source of monochromatic light. The mirrors M_1 and M_2 were roughly adjusted so as to be nearly the same distance from the half-silvered plate P_1. A small object, a wire or pin, was placed between the light source and the plate P_1. The two images noted are brought together by adjustments of screws S_2 and S_3. At this point fringes appear with monochromatic light. These interference fringes were noted to be approximately circular.On moving M_2 back and forth, by means of screw S_1, the fringes seem to move and their curvature changes, at times being convex to the right, and at other positions of M_2 being convex to the left. When M_2 was adjusted as nearly as possible to the position at which the fringes seem to change from one form of circles to the other, a frosted electric light was substituted for the mercury arc and filter, and screw S_1 was turned back and forth very slowly until the fringes appeared. Adjustments were carefully made at S_1 until the middle black fringe was in the center of the field. If the plates P_1 and P_2 are correctly constructed, plane parallel, from the same piece of glass, of equal thickness, and adjusted to be parallel to each other, the central fringe will be black and on each side will be the colors of Newton's rings. At this point the path distances of the two arms of the interferometer, P_1M_1 and P_1M_2, are equal.

<u>Taking Photographs</u>: Photographs were taken by using a film pack holder, mounted at O_2, plate II. This pack holder was specially constructed, with facilities for sliding back and forth in order that two pictures could be taken on each film. Exposures were made by moving a protecting slide. In general the films were exposed for 30 seconds, with the diaphragm stopped down to f=32. Since only a small part of the lens was used, and with monochromatic light, an ordinary photograph lens was very satisfactory.

In general the following method was used in taking photographs. The mercury arc was started and sufficient time, about two minutes, allowed for it to heat up. The lamp was adjusted to the position for maximum illumination. The test piece was adjusted until it was well in the field of the interferometer. It was often difficult to adjust the interferometer, the lamp, the test piece, the photographic lens, the prism and the ground glass screen so that a clear image of the wire could be secured without multiple images of the wire and supports. Mirror M_2 was adjusted, by means of screws S_2 and S_3, until the field was as free from interference fringes as possible. After a sharp image of the wire was secured, heating current was turned on in the wire. The ground glass screen was moved back and forth to focus the fringes sharply. High voltage was turned on and adjusted for desired effects, as observed on the ground glass screen. After sufficient time was allowed to gain as stable conditions as possible, the film pack holder was substituted for the ground glass screen and the film was exposed for the proper time under the particular conditions. Best results were secured when the lens L_2 was 100 centimeters from the mirror M_1, and 72 centimeters fromthe film. Agfa film packs, 4.5 by 6 centimeters, were used.

Specific Experiments

Concentric Cylinders: (1) Heating of wire and tube under corona discharge. A clean nickle wire, size, B. & S. guage No. 28, 0.032 centimeters in diameter, was mounted in a brass tube whose diameter was 1.74 centimeters. This assembly is illustrated in diagram, plate V. Both wire and tube were supported on a hard rubber rod, which was carried by a support with rack and pinion for adjusting its height. Facilities were arranged for adjusting the wire and tube together on horizontal and vertical planes so that the wire could be conveniently oriented in the interferiometer field. The tube was adjusted coaxial with the wire by means of three screws in each of the fiber supports of the tube. The wire was 27.6 centimeters long and the tube was 22.9 centimeters long. The tube was belled at the ends to eliminate premature corona at these places. A mercury

PLATE V

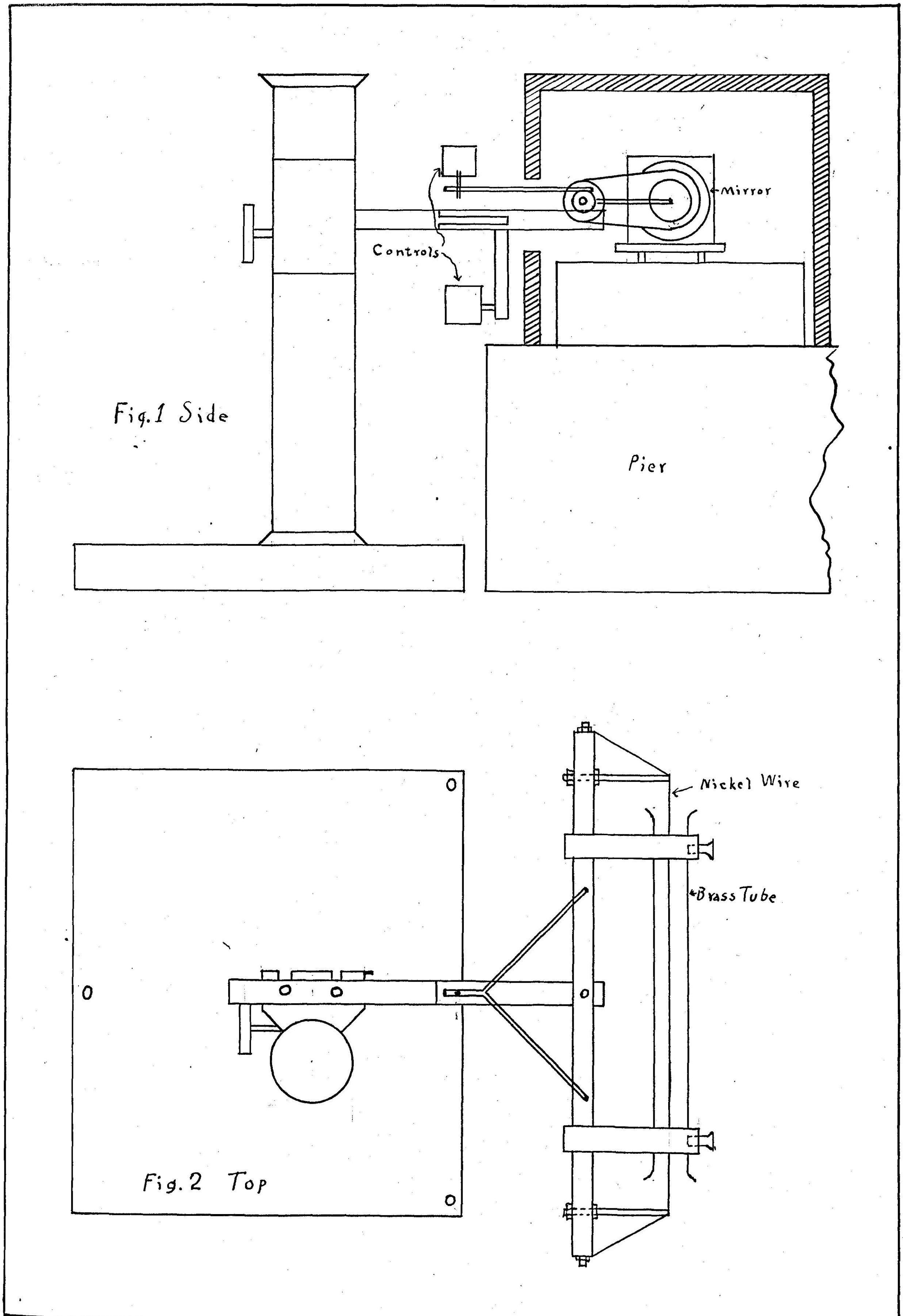


Fig. 1 Side

Fig. 2 Top

thermometer was mounted in the protecting box in order to observe the temperature of the air. Another mercury thermometer was mounted with its bulb against the brass tube and protected from the air by cotton, so that the temperature of the tube could be estimated. The temperature of the wire was very roughly estimated by noting the changes in its resistance by testing with a Leeds & Northrup Type S Testing Set, No. 26736, Physics No. 985.0. The wire temperature was then estimated by the following formula,

$$R_t = R_{t_1} \frac{1+\beta_t t}{1+\beta_{t_1} t}$$

where R_t = resistance of wire, in ohms, at temperature t,

R_{t_1} = resistance of wire, in ohms, at room temperature, t_1

β_t = temperature coefficient of resistance at $t^\circ C$.

β_{t_1} = temperature coefficient of resistance at t_1° C.

Since t and t_1 do not differ by more than five degrees and both are near 20° C., the value of 0.003 from Smithsonian tables is used for both β_t and β_{t_1}.

Corona current was measured by connecting a Weston Galvanometer, Model 375, No. 3816, Physics No. 901.2, in series with the high voltage circuit. This instrument was calibrated as explained later. Corona voltage was measured with the Kelvin Electrostatic Voltmeter.

The wire was connected to the positive terminal of the rectifier and the tube to the negative terminal. Voltage was slowly increased until the galvanometer indicated a corona current. No further adjustments were made during this experiment. The same procedure was used with the negative corona, the reversing switch being used to connect the wire to the negative terminal of the rectifier, and the tube to the positive terminal. The data of tables I and II were secured in this way. In these tables, R is the resistance of the wire in ohms; t_w is the temperature of the wire, in centigrade degrees, roughly estimated from resistance, as explained above; t_t is the temperature of the tube, in centigrade degrees; E is the corona voltage in kilovolts; I is the corona current in amperes times 10^{-5}. Readings of E and I were not taken simultaneously with readings of R and t_t because of inconvenience, since the instruments for measuring E and I were at a considerable distance from those for reading R and t_t, and no assistant was available.

It is noted that the corona voltages and currents remained fairly constant, during the experiment, while the temperatures of the tube and of the wire seemed to approach maximum values. In the case of the positive corona the wire seemed to have the higher maximum temperature, while with the negative corona, the tube seemed to be slightly warmer than the wire. The methods of estimating temperatures make these results uncertain. However the data of tables II and I leave no doubt that both the wire and the tube become heated under the influence of the corona.

Table I

Positive Corona on Wire

Time of Reading	R	t_w	t_t	E	I
1:58:30	.495	27	27	6	7.5
2:01:00	.500	28.95	27.5		
2:02:30				5.94	7
2:03:30	.501	29.3	28		
2:04:40				5.96	7.5
2:06:00	.502	29.7	28.5		
2:09:00	.503	30.1	29		
2:12:00	.503	30.1	29.4		
2:12:30				5.9	7
2:15:00	.504	31	29.8		
2:15:45				5.9	7.5
2:18:00	.504	31	30		
2:18:40				5.9	7
2:21:00	.504	31	30		
2:21:20				5.9	7
2:24:00	.504	31	30.1		
2:25:30				5.9	7
2:27:00	.504	31	30.1		
2:30:00	.504	31	30.2		
2:31:30				5.92	7
2:33:00	.504	31	30.3		
			Mean	5.92	7.14

Table II

Negative Corona on Wire

Time of Reading	R	t_w	t_t	E	I
4:04:00	.495	28	28		
4:05:00				5.8	12.5
4:06:00	.498	29.1	28.6		
4:06:45				5.76	11.8
4:09:00	.499	29.6	29.4		
4:10:00				5.78	12.5
4:13:00	.500	29.9	30		
4:14:00				5.8	11
4:15:00	.501	30.7	30.2		
4:16:00				5.8	11.5
4:18:00	.501	30.7	30.5		
4:19:00				5.74	11.5
4:21:00	.501	30.7	30.6		
4:22:40				5.8	12.5
4:24:00	.501	30.7	30.8		
4:25:00				5.8	12.5
4:28:00	.501	30.7	31		
4:30:00				5.74	12.5
4:31:00	.501	30.7	31		
4:32:00				5.7	12.5
4:34:00	.501	30.7	31		
4:35:00				5.74	13.25
4:37:00	.501	30.7	31		
			Mean	5.77	12.19

The Weston Galvanometer, Model 375, was calibrated for use in measuring corona current by connecting it to a cell of known E. M. F. and a known resistance, consisting of standard resistance boxes. The current was calculated for a number of readings along the scale. The resistance of the galvanometer was carefully measured and found to be 23.73 ohms. Current was reversed through the galvanometer to check readings both to the left and to the right of the zero point, and found to be nearly enough the same for the purposes of this experiment. The E.M.F. of the cell used was 1.54 volts. This was checked a number of times to insure constancy. In the table, which follows, D is the deflection on the galvanometer scale, either right or left of the zero, R is the resistance added to secure that deflection, R_T includes the galvanometer resistance and I is the current, calculated by using Ohm's Law. The calibration curve is on plate VI.

D	R	R_T	I
3	30000	30024	.0000513
5	17800	17824	.0000864
10	8800	8824	.0001745
15	5800	5824	.0002644
20	4380	4404	.0003497
25	3430	3454	.0004459
30	2840	2864	.0005377

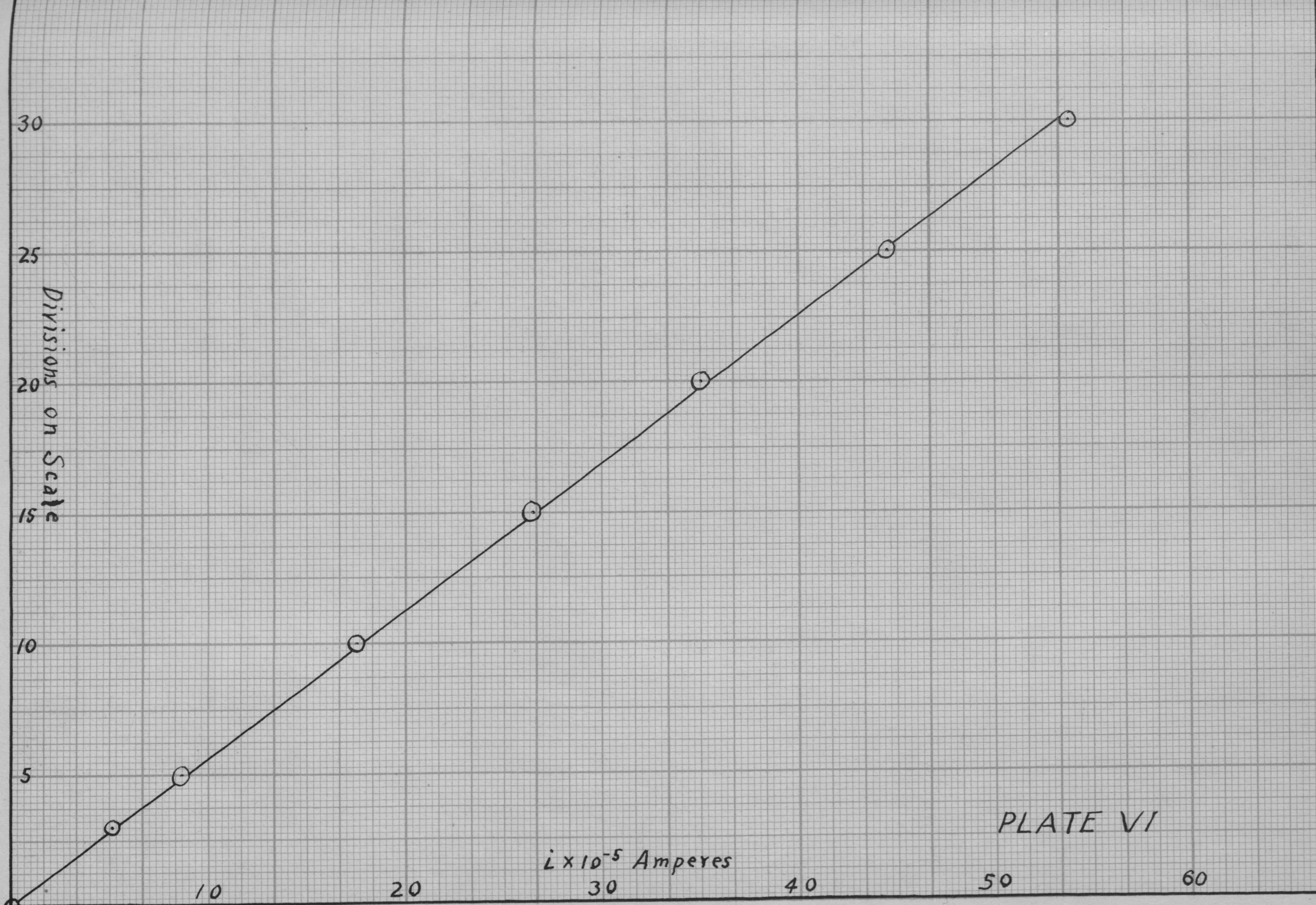

Divisions on Scale
30
25
20
15
10
5
i x 10^{-5} Amperes
10
20
30
40
50
60

PLATE VI

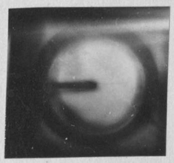
27.

The concentric cylinder assembly was placed in one arm of the interferometer, as indicated in plate II, and carefully adjusted so as to be parallel to the light beam, photograph No. 1. The wire was heated with a current of 0.8 amperes from a storage battery. A fringe system, consisting of four circular fringes, was observed, photograph No. 21. When the heating current was turned off these fringed slowly collapsed to the wire until the field was again clear as in photograph No. 1. This shows that the wire has cooled to the temperature of its surroundings.

In this paper the term, "positive corona" , is used to indicage a corona discharge from a wire when the wire indicated is carrying a positive electric charge, that is it is connected to the positive terminal of the rectifier, and must be attracting negative ions and repelling positive ions. In the same sense, the term "negative corona" is used to indicate that the wire in question is connected to the negative terminal and therefore carries a negative charge, attracting positive ions and repelling negative ions.

With no current through the wire, a positive corona was placed on it by connecting it to the positive terminal of the rectifier, the negative terminal being connected to the tube. The voltage was slowly increased until the first effects were noticed, when a fringe begins to form at the wire, photograph No. 2. At this stage the voltage, as read

PLATE VII



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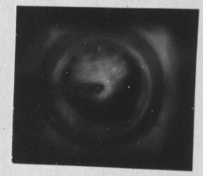

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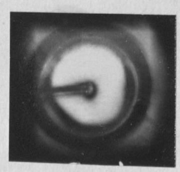

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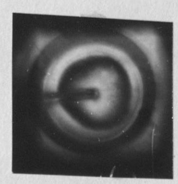

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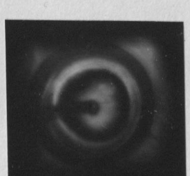

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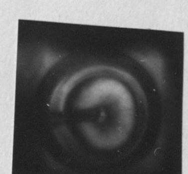


6

by the electrostatic voltmeter, was 5.8 K.V. When the corona voltage was suddenly cut off, the fringe slowly collapsed, showing that the wire had been heated by the corona.

The corona voltage was again connected and raised until the first fringe seemed to disappear at the tube and another form about the wire, photograph No. 3. These fringes moved about considerably in the field and were very difficult to photograph, the exposure being about thirty seconds. The corona voltage at this stage was 5.9 K.V. When the voltage was suddenly cut off, the two fringes slowly collapsed to the wire, until its appearance was again as in photograph No. 1.

The corona voltage was again connected and raised until two fringes seemed to go into the tube and a third remained in the field, as shown in photograph No. 4. In this case the voltage was 6.2 K.V. On suddenly cutting off the voltage, one fringe collapsed suddenly, while two collapsed slowly as before, until the field was clear.

When corona voltage was connected and raised to 6.3 K.V. three fringes seemed to disappear at the tube while one remained in the field and a fifth seemed to be appearing at the wire, photograph No. 5. On suddenly breaking the high voltage circuit, a number of fringes passed across the field toward the wire, too quickly to be counted. Three fringes slowly collapsed to the wire.

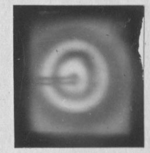
The results of this experiment seem to indicate that at a ceftain voltage, 5.8 K.V., positive corona begins to heat the wire, while at a higher voltage, 6.2 K.V., and above, two effects are noticed, one resulting in slow collapse of fringes, whem corona voltage is turned off, interpreted as slow cooling of the wire, while the other effect results in a sudden collapse and is possibly due to a pressure effect that ceases abruptly with the corona voltage. This seems to be in agreement with the results of Fazel[9], who noted pressure changes rapid enough to follow the voltage changes of an alternating current potential, mentioned on page 6.

Concentric Cylinders: (2) Cooling of wire under corona discharge.

The concentric cylinder assembly was carefully adjusted in the interferometer so as to give a clear field, photograph No. 7. The wire was heated with a current of 0.4 amperes to form one circular fringe, photograph No. 8. Voltage was connected so as to form a negative corona on the wire and slowly raised until the first effects were noted. These first effects proved to be a slight collapse of the fringe toward the wire, photograph No. 9. This effect came at a voltage of 5.44 K.V. When the voltage was raised to 5.66 K.V. the fringe began to grow larger, photograph No. 10, while at 5.9 K.V. this first fringe seemed to disappear at the tube and another formed at the

PLATE VIII

7



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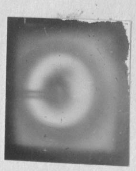

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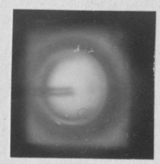

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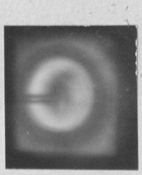

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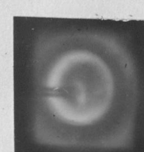


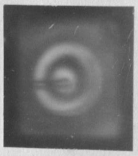
12

wire. As the voltage is increased fringes seemed to disappear at the tube and others appeared at the wire, making very little difference in appearance of successive photographs as shown, No. 11 being taken at 5.9 K.V. and No. 12 at 6.16 K.V.

No point could be found with the positive corona where the fringes collapsed to the wire, at the heating current of 0.4 amperes. Photograph No. 13 shows the concentric cylinders with 0.4 amperes through the wire and no corona; No. 14 shows the fringe at first noticable corona effect, when the voltage was 5.7 K.V. The fringe has expanded somewhat, showing a heating effect. Photographs No. 15 and 16 show conditions under increased voltages. In the former it was 5.88 K.V., with the second fringe in the field. In the latter it was 6.24 K.V., with the third fringe in the field, the first two having apparently disappeared at the tube.

The current in the wire was increased to 0.6 amperes, photograph No. 17. The positive terminal was connected to the wire and the negative one to the tube. Voltage was slowly increased until the first effects were observed. In this case the first effects were noticed to be a slight collapse of the fringes, as shown in photograph No. 18, at 5.64 K.V., which is somewhat less than the voltage of the corona which shows first effects when wire was heated to a lower temperature, as shown in photograph No. 14.

PLATE IX



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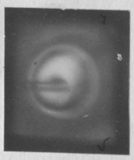

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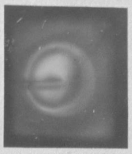

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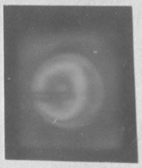

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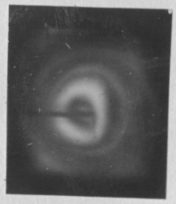
PLATE X

17



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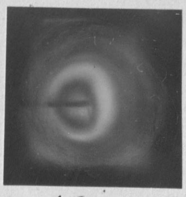

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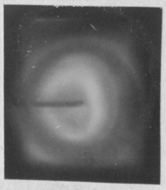

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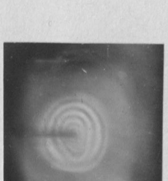

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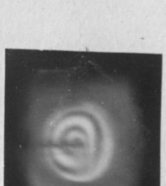


22

When the voltage was raised to 5.9 K.V. the fringes went out to the tube, as shown in photograph No. 19, and continued to go out, new ones being formed at the wire, when the voltage was raised to 6.26 K.V., shown in photograph No. 20.

A higher temperature was tried with the positive corona, as shown in photograph No. 21, where 0.8 amperes were used. When voltage was applied and raised to 5.52 K.V. the fringes collapsed somewhat, photograph No. 22. This voltage was somewhat lower than that required to collapse the fringes when the heating current was 0.6 amperes.

These experiments seem to indicate that, when the wire has been heated to a certain temperature, the first effect of a corona is a collapse of fringes. This may be the cooling effect noticed by Parsons,[12] mentioned on page 7. In order to test this cooling effect, the voltage was suddenly turned off. The fringes slowly assumed their original positions, as photographed, with heating current alone. Since the return was slow and not sudden, the cooling effect of the corona is a reasonable conclusion. The collapse is followed by an enlargement of the fringes, as the voltage is increased, which is surely a result of heating of the wire by the corona. It was also noted that, in general these effects occur at a lower voltage with the negative corona than with the positive.

<u>Concentric Cylinders</u>: (3) A comparison of positive and negative corona.

To compare the effects of positive and negative corona of the same voltage, the fringe system was noted when the wire was heated with a current of 1.2 amperes, and under a corona voltage of 5.4 K.V. This voltage was reversed by means of the reversing switch and the effects observed, since the fringes were too unsteady to be photographed. It was noted that the fringes moved a little closer to the wire when it was negative, and moved out toward the tube slightly when the wire was positive.

This seems to indicate that there is an easily recognizable difference between positive and negative corona, probably due to a difference in mobility of the two kinds of ions, the positive ions, in general, being the slower of the two.

<u>Concentric Cylinders</u>: (4) Comparison of appearance of visual corona with appearance of other effects.

The concentric cylinder assembly was placed in a light tight box, with a glass window protected with a black cloth hood, for observation. Conditions were made the same as in other tests by heating the wire with an equal current. The corona voltage was slowly increased until the first visual corona appeared. This was done several times in order to test for consistancy of results. The corona tube was then placed in the interferometer, the wire heated with the same current and voltage noted when the first effects on the fringes were observed. These results are arranged in table III, together with other voltages as explained below. In this table, E_1 indicates the voltages when visual corona first appear; E_2, the voltages when first effects on fringes are noted, in this case a collapse; E_3, the voltages at which the fringes cease to collapse and become stationary; E_4, the voltages at which the fringes begin to go out toward the tube; E_v, the direct current visual corona voltage, computed from Peek's equations, mentioned on page 5.

Comparison of results indicated that there are no appreciable effects before the visual corona is formed, and that these effects are quite abrupt and consistant. The visual corona voltage, as computed from Peek's equations, is somewhat larger than the observed results, for a number of probable reasons. Peek, in his formulas, made no provision for differences in voltages of positive and negative corona. In this experiment no special care was used in cleaning and polishing the wire and the tube, and in removing all irregularities from the wire. The readings by means of the Kelvin electrostatic voltmeter are probably not very accurate. The formula was not corrected for the temperature of the air in the region immediately surrounding the wire, which was raised when the wire was heated with the electric current.

Table III

Trial	E_1	E_2	E_3	E_4	E_V
		Positive Corona			
1	5.5	5.5	5.56	5.96	
2	5.6	5.52	5.62	5.96	
3	5.3	5.5	5.6	5.88	
4	5.5	5.54	5.56	5.84	
5	5.4	5.52	5.56	6.00	
Mean	5.46	5.52	5.58	5.93	6.537
		Negative Corona			
1	4.9	4.86	5.34	6.04	
2	4.9	5.0	5.5	6.0	
3	5.1	4.86	5.5	6.0	
4	4.9	4.9	5.52	5.96	
5	4.5	4.8	5.4	5.96	
Mean	4.86	4.9	5.45	5.99	6.537

All voltages are recorded in kilovolts.

Parallel Wires: (1) In horizontal plane.

Two nickel wires were mounted on circular insulators turned out from transparent bakelite and mounted on a wooden frame, so that the wires were parallel to each other. This assembly is illustrated in diagram in figure 3, plate XI and in photograph , plate XII. The frame was placed on the same upright support that was used for the concentric cylinders, with the same facilities for adjustments in the interferometer. The wires were 0.032 centimeters in diameter and were separated 0.832 centimeters from center to center.

These parallel wires were carefully placed, in a horizontal plane, in one arm of the interferometer and adjusted parallel to the beam of light. After the interferometer was adjusted for a clear field, the left hand wire, as viewed from the camera, was heated with a current of 0.75 amperes. A fringe system, consisting of continuous fringes about the wire, displaced upward, elliptical in appearance, was observed, photograph No. 23. These fringes indicate slow moving convection currents in connection with heat loss by conduction, as explained by Smith.[13]

Connection was made with the rectifier so that a positive corona could be placed on the heated wire. The voltage was slowly raised until the first effects of the corona were noticed. Very little change was noted at

PLATE XI

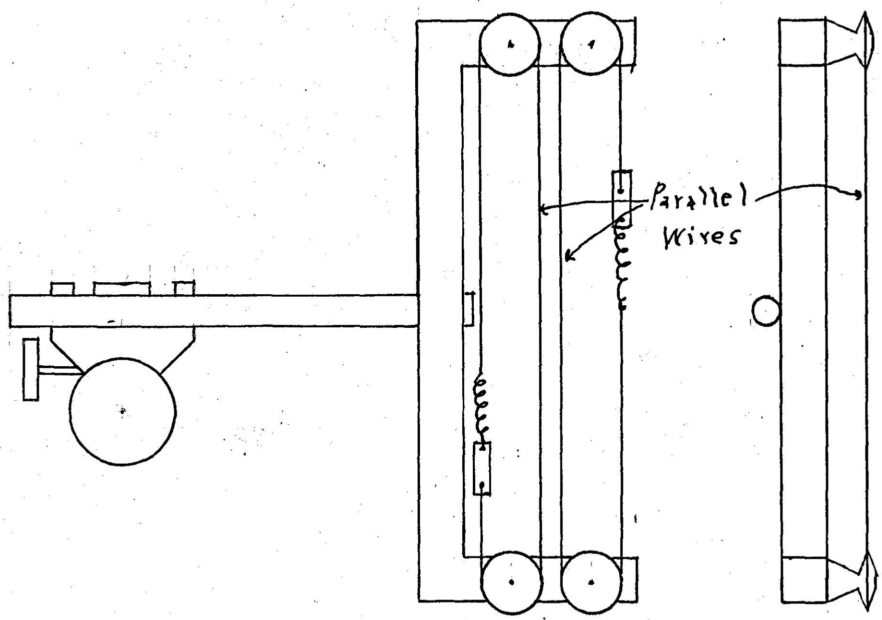


Fig 3

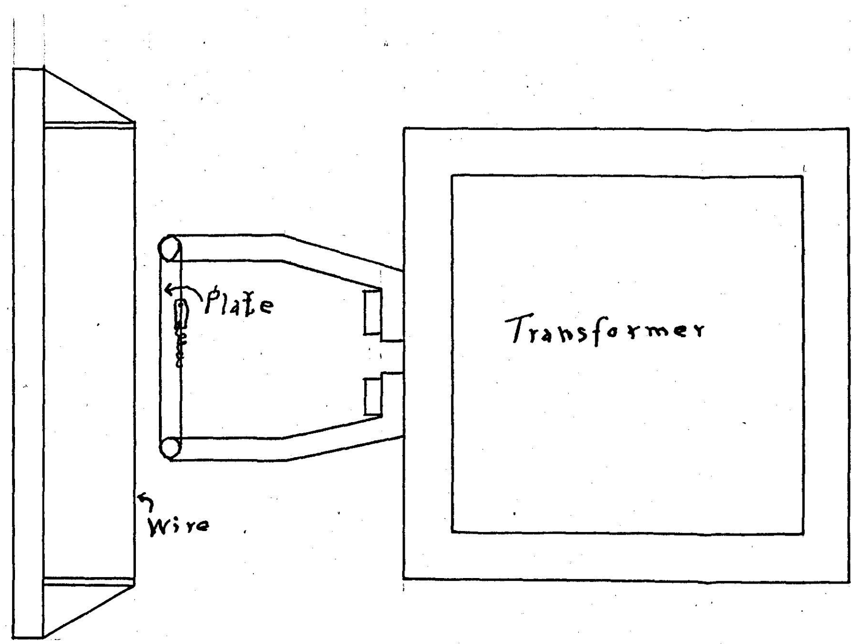
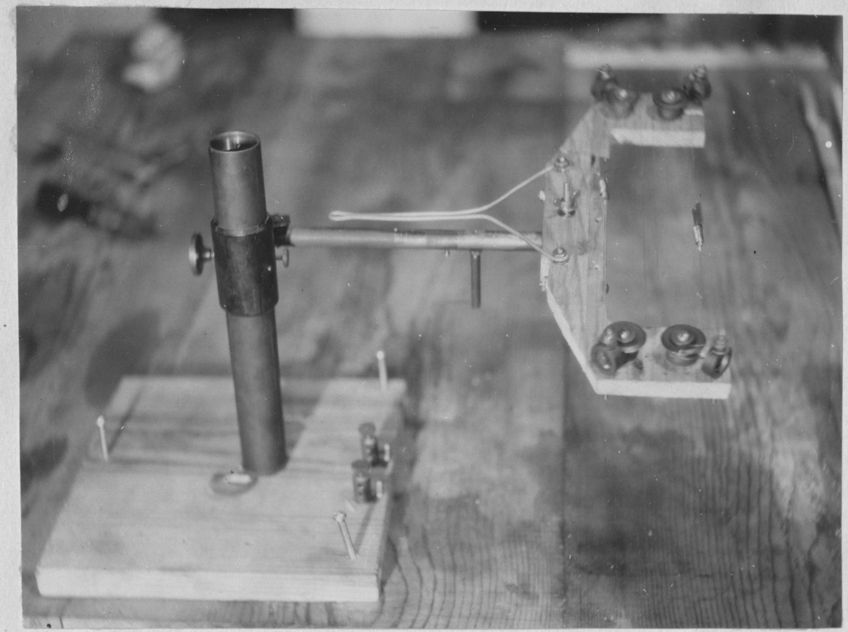
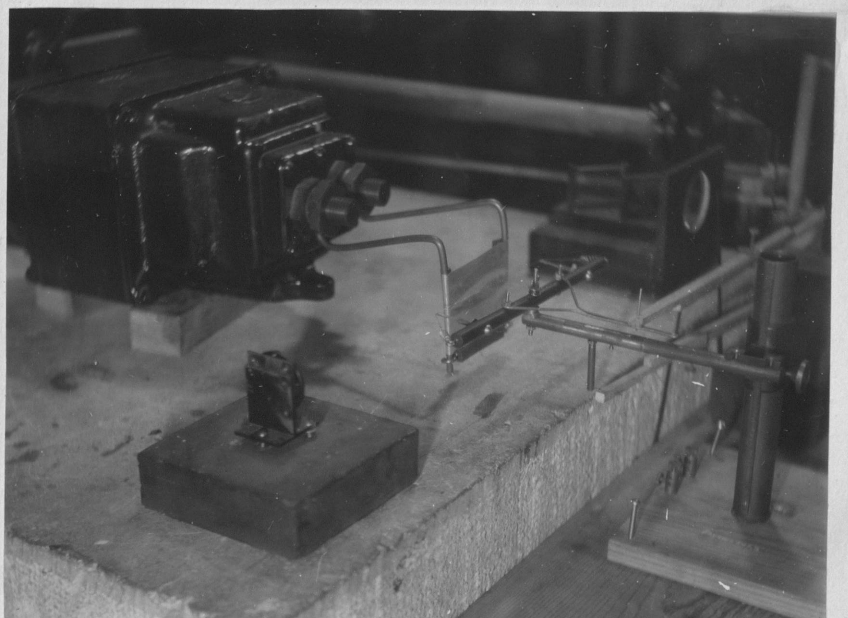


Fig 4

PLATE XII



Parallel Wire Assembly

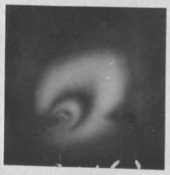


Wire and Plate Assembly

PLATE XIII

23

24



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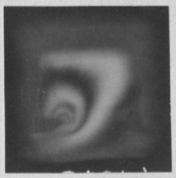

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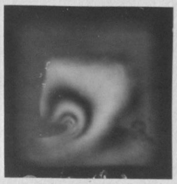


28

first, except a bending over of the entire fringe system toward the other wire, as in photograph No. 24. This first effect was apparent at a corona voltage of 6.7 K.V. As the voltage was increased the fringes seemed to shrink toward the wire, still being bent toward the other wire. Photographs No. 25 and No. 26 show effects of increasing voltage, the former at 7.8 K.V. and the latter at 8.2 K.V.

When a negative corona was placed on the heated wire, somewhat different effects were noted, as shown in photographs No. 27 and No. 28. The former shows the first effects as the voltage was raised and the latter at a higher voltage, 6.46 and 7.8 K.V. respectively. Here it will be noted that the fringes, under the influence og the negative corona, become very nearly circular in form and shrink toward the wire as the corona voltage is increased.

This series of photographs with parallel wires leaves little doubt of the difference in mobilities of positive and negative ions, since with the positive corona the positive ions do not seem to have sufficient speed to overcome the influence of convection currents, while the negative ions seem to travel out from the wire with a negative corona, at a sufficiently high speed as not to be disturbed by convection currents, and therefore the fringes become circular in form.

Calculation of the direct current visual corona voltage for parallel wires of the diameter used and with the separation of 0.832 centimeters, resulted in a value of 12.778 kilovolts. Peek's formulas, mentioned on page 5, were used. This calculated value is very nearly twice the average values secured with the Kelvin electrostatic voltmeter. Since no attempt was made to clean and polish the wires, and to correct for changes of temperature and pressure, this comparison is not very satisfactory.

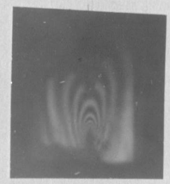
<u>Parallel Wires</u>: (2) In vertical plane.

The two parallel wires were mounted in a vertical plane and adjusted in the interferometer to be parallel to the beam of light, as illustrated in photograph No. 29. When a current of one ampere was used to heat the lower wire, the ordinary system of fringes was produced, showing slow convection currents. The region immediately below the wire is somewhat disturbed by the heating of the lower portion of the wire that is bent around the insulators for support. This system of fringes is shown in photograph No. 30.

The positive terminal of the rectifier was connected to the lower wire and the negative terminal to the upper one. The voltage was slowly raised until the first effects were observed, as shown in photograph No. 31. Careful comparison of the latter two photographs shows that the fringes have been pulled down slightly by the corona. The voltage, when these first effects were noticed, was 4.16 K.V. As the voltage was raised, the fringes were drawn closed to the lower wire and disturbed mostly toward the left, as viewed from the camera. The fringes moved about

PLATE XIV

29



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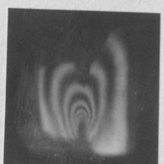

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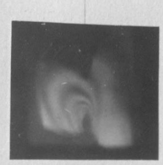

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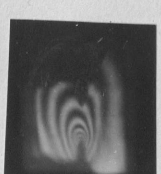


33

34

considerably and were difficult to photograph. The fringes are shown in photograph No. 32 under a corona voltage of 5.64 K.V.

The effects of the negative corona, on the heated wire, were photographed in the same way and are shown in photographs No. 33 and No. 34. The former shows first effects, at 5.24 K.V., while the latter was taken at the higher voltage of 7.16 K.v. It was noted that very little difference can be distinguished between the positive and the negative corona, except the voltages at which the effects begin, the positive corona starting at 4.16 K.V., which is considerably lower than than that at which the negative corona started, namely 5.24 K.V.

When the upper wire was heated, no appreciable effect on the fringe systems was noticed when either the positive or the negative corona was placed on the heated wire. This was probably due to the limited field of view above the upper wire. The lower portion of the fringes seemed to remain approximately circular in form before and after the corona voltage was applied.

<u>Parallel</u> <u>Wires</u>: With high frequency potential.

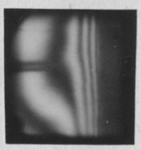
The parallel wires, in vertical plane, were connected together at one end and the lower wire was heated with a current of 0.75 amperes. When the fringe system became stable, in the usual form, the heated wire was connected to the terminal of a Cenco Midget Tesla Coil.

No effects on the fringe system were observed, the fringes remaining steady and undisturbed. Apparently at the high frequency produced by this equipment, ions have not sufficient time in which to develope the energy necessary to form fresh ions by collision, before their direction of travel is reversed. Therefore corona effects are absent.

Heated Plate with Parallel Wire: A plate, 10 by 7.5 centimeters, made by stretching aluminum foil between two brass rods which are connected to, and supported by, the terminals of G. E. Transformer No. 3955978, Physics No. 452.1, was placed, with its plane vertical, in the field of the interferometer, and carefully adjusted parallel to the beam of light. A nickel wire, supported on a hard rubber tube, was mounted on the same support used for the concentric cylinders, and placed in the same arm of the interferometer, in a horizontal position, one centimeter from, and parallel to, the aluminum plate. Adjustments of wire, plate and interferometer were made to get the field as free from fringes as possible, photograph No. 35. This assembly is illustrated in diagram, figure 4, plate XI, and in photograph, plate XII. The voltage at the primary of the transformer was controlled by G. E. Induction Voltage Regulator, No. 3955978, Physics No. 452.2. When the smallest current possible was used to heat the plate the fringe system consisted of four fringes, three of which were

PLATE XV

35



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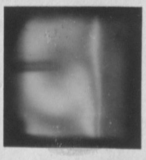

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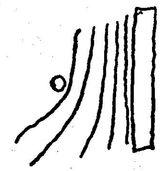
nearly parallel to the plate, and the one the greatest distance from the plate was displaced in a direction away from the plate, in the upper region. This fringe system is shown in photograph No. 36.

When a positive corona was placed on the wire, the plate being connected to the negative terminal of the rectifier, the fringe system was changed to that shown in photograph No. 37, where the corona voltage was 7.4 K.V. It was noticed that some of the fringes, under the influence of the corona, were displaced toward the plate, others were moved away from it. When a higher voltage was used , 7.8 K.V., photograph No. 38, the remaining fringe that was parallel to, and near, the plate, seemed to be pushed into the plate, and is not in view. One or more fringes moved about in the field, sometimes looping about the wire, and were too unsteady to be photographed with much success.

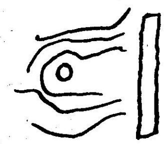
A negative corona was placed on the wire, disturbing the fringes in much the same way that was noticed with the positive corona. Photographs No. 39 and No. 40 show results with 7.5 K.V. and 8 K.V. negative corona respectively.

When the plate was heated to a higher temperature, by increasing the voltage at the primary of the transformer, more fringes appeared in the field, parallel to the plate. A slight difference in effects of positive and negative corona was observed, but photographs were unsuccessful because of unstable conditions, the fringes moving about in the field continuously.

In the case of the positive corona, at 7.06 K.V., the fringes more distant from the plate appeared to be moved farther from the plate below the wire and pushed slightly toward the plate above the wire.

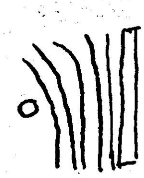


At the higher voltage of 8.4 K.V. those fringes near the plate seemed to disappear at the plate, others appeared to be moved down and away from the plate , moving continuously about in the field, sometimes momentarily forming one or more loops about the wire.



When the corona voltage was turned off, a number of fringes appeared to emerge quickly from the plate, parallel to each other and to the plate, while what seemed to be an equal number came up more slowly from the left of the field and became parallel and close to those that had emerged from the plate.

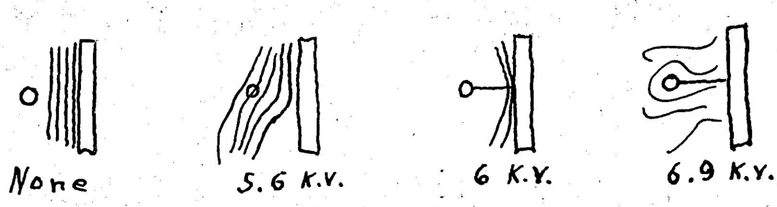
When a negative corona of 6.3 K.V. was placed on the wire, the fringes seemed to be displaced away from the plate in the field above the wire, and disturbed very little below the wire.



At the higher voltage of 8.6 K.V. the fringes were very similar to those with the positive corona at the same voltage, as described above.

The wire was moved to a distance of 0.5 centimeters from the plate. When the negative terminal of the rectifier was connected to the wire, with the positive terminal connected to the plate, there were no noticable effects on the fringes before sparkover. This probably means that the wire was too close to the plate for the negative corona to form at all, spark over being the first effect.

A positive corona, at this separation, showed effects, very similar to those mentioned above when the separation was one centimeter. Three rather distinct effects were noticed as the voltage was slowly raised. these are illustrated in the following diagrams, since photographs were not successful.



At the higher voltages, 6 K.V. and 6.9 K.V. respectively, one fairly constant fringe appears, extending from the wire, perpendicular to the plate. This is probably due to a pressure caused by an ionic wind.

These drawings are not very certain and much dependence cannot be placed on them.

Discussion of Results

Abruptness of Corona effects: Attention has been called to the abruptness with which corona effects start. This seems to be in accord with Whitehead's explanations[4] from theories of ionization by collision. Any sample of air contains a small number of ions, probably from radioactive material, effects of flames, ultraviolet light and other sources. When the sample of air is placed in an electric field, say between two plates, these ions are drawn toward the electrode having the opposite charge, forming a current. However there would ordinarily be far too few ions present to cause an appreciable current, from that source alone, even at very high potentials. As the field strength is increased, the ions are caused to move at higher velocities. Since the space contains many molecules of gas, as well as the few ions, collisions result between ions and molecules, the ions traveling until stopped by a collision, then starting again and traveling until another collision, etc. The mean free path between collisions has been calculated, for different conditions, such as temperature and pressure, from the kinetic theory of gases. Ionization by collision is accomplished when the ions have sufficient kinetic energy to separate negative charges from molecules on impact. This amount of kinetic energy depends on their velocity, which depends on the field strength and their mean free path. As the mean free path depends on the number of molecules present in a unit volume, at constant temperature and pressure, the field strength must be raised to a certain definite value, under the given conditions, before the energy of the moving ion is sufficient to cause fresh ions by colliding with neutral molecules in its path. If the corona is a result of ionization by collision, it too should start at a very definite voltage, depending on the nature of the electrodes, their size, shape, distance apart, and the temperature and the pressure of the air between them. This abruptness was very noticable in all cases.

Since raising the temperature of a gas reduces the number of molecules per unit volume, the mean free path of ions should be increased, and the field strength required for ionization by collision decreased. Therefore the voltage required for forming a corona discharge should be decreased when temperature is raised. On page 33 it was noted that when the wire was heated with a current of 0.6 amperes, corona effects started at 5.64 K.V. On page 36 attention was called to the results when the temperature of the wire, and therefore of the air near it, was raised by increasing the current to 0.8 amperes. This would, of course decrease the density of the air. In this latter case the first corona effects were noticed at 5.52 K.V., which is appreciably smaller than that at the lower temperature. Other cases were noticed in confirmation of this theory of ionization by collision.

Investigation of changes of corona voltage under different pressures was not attempted.

Differences Between Positive and Negative Corona: For comparison, data from various specific experiments are collected in table IV. With two exceptions, the negative corona showed its first effects at lower voltages than the positive corona.

In the case of the two parallel wires in a vertical plane, the negative corona voltage is appreciably higher than the positive. These voltages were read several times to confirm the results. Both positive and negative corona voltages, in this position, were much lower than when the wires were in a horizontal plane. Without doubt the air immediately above a heated wire would have a higher temperature than the air near the wire in a horizontal direction. Therefore it seems reasonable that the mean free path of the ions should be greater, and the corona voltage less, when the wires are in a vertical plane, than when in a horizontal plane, all other things being equal. The reason why the negative corona, in this case, should require a higher voltage than the positive corona, is not clearly understood. It may be that the velocity of the positive ions, supposed to be larger, at least in mass, is affected more by convection currents than the negative ions. These convection currents must aid the migration of the ions when they are attracted in the same direction, as in this case.

Table IV

First Effects of Corona

	Voltages in K.V. Positive	Negative	Ratio of Positive to Negative
Wire and Tube			
Wire not heated, mean	5.92	5.77	1.026
Wire heated, 0.4 amp.	5.7	5.44	1.048
Wire heated, 1 amp.			
Visual corona, mean	5.46	4.86	1.123
Effects on fringes, mean	5.52	4.9	1.127
Parallel Wires, Corona on lower			
Horizontal plane			
Lower Wire heated, 0.75 amp.	6.7	6.46	1.037
Vertical plane			
Lower wire heated, 1 amp.	4.16	5.24	0.794
Plate and Wire, 1 cm. apart			
Plate heated, Corona on wire			
Lower temperature	7.4	7.5	0.987
Higher temperature	7.06	6.3	1.121

The other exception, that of the heated plate, with a parallel wire carrying a corona, one centimeter from the plate, shows such a slight difference that it is well within experimental error, and therefore uncertain.

In all the remaining cases the positive corona starts at the higher voltages. It is interesting to compare the ratios of the positive corona voltage to the negative corona voltage with Zeleny's ratios of velocity of negative ion to velocity of positive ion (Thomson, Conduction of Electricity Through Gases, 2nd Edition, pages 52 and 58) which is given as 1.24 for air. In some later experiments, Zeleny secured the value of 1.10 for this ratio, for moist air. It can be seen that these ratios are at least in the same order, and suggest that the negative ion has somewhat the higher mobility. It should be remembered that the voltage necessary for corona discharge is lower for higher mobilities of ions, which would make it reasonable to suppose that the ratio of the velocity of the negative ion to the velocity of the positive ion would be equal to the ratio of the positive corona voltage to the negative corona voltage.

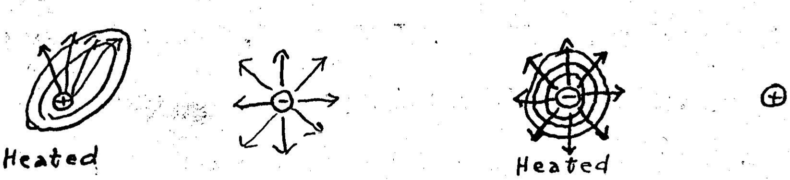
Attention should be called to the results mentioned in tables I and II. Here we noticed that the positive corona current was 7.14×10^{-5}, while the current under the negative corona was considerably higher, namely 12.19×10^{-5}, these being mean currents, with concentric cylinders. A complete explanation of this would be quite complicated. The current is directly proportional to the potential difference between wire and tube, the density of space charge and the mobility of the ions. This relationship is developed by Parsons,[12] who gives the following equation:

$$i = \frac{2\pi\rho kV}{\log_e R/r}$$

where i is corona current per centimeter length of wire; ρ is density of space charge; k is mobility of the ions; V is potential difference between wire and tube; R is radius of the tube; r is radius of the wire.

Since we are fairly sure that the ratio of mobilities of negative and positive ions is in the region of 1.1, and the ratio of negative corona voltage to positive corona voltage must be near the reciprocal of that ratio, the increased current in the negative corona must be due to a much greater space charge density, the ratio between negative and positive currents being 1.717. Currents were estimated rather roughly, and in only one case, as shown in tables I and II, which leaves considerable doubt as to their reliability.

Attention has already been directed to the differences between positive and negative corona, as shown by photographs No. 24 and No. 27.



When the wire that is heated carried the positive corona, the fringes are merely bent over toward the other wire, at the lowest corona voltage. When the heated wire carried the negative corona, its first effect was to change the fringes to a circular form. This probably can be explained by the difference of mobilities of the positive and negative ions. In the first place the positive ions, being slower in motion, are no doubt swept upward somewhat by convection currents, as well as toward the other wire by the electric field. In the second place the negative ions are probably shot out, from the region immediately surrounding the wire, at higher speeds, so as to go off nearly uniformly in all directions, thus tending to make the temperature gradient uniform, as shown by the circular fringes.

The same phenomena are suggested by the experiments with a horizontal wire parallel to a vertical plane that was heated by an electric current. Some differences were observed when the wire carried a positive corona and when it carried a negative corona, but since the fringes were too unsteady to photograph, these differences were uncertain and explanations are not attempted in the present paper. It is to be hoped that future studies will clarify these phenomena.

Summary of Results

Results are summarized as follows:

(1) In general, positive corona require higher voltages than negative corona.

(2) In general, negative corona currents are higher than positive corona currents.

(3) Corona voltages are reduced by raising the temperature of the air.

(4) At a certain temperature, with concentric cylinders, the first effect of corona is that of cooling the wire, followed, as the voltage is increased, by a heating of both wire and tube, and ,at higher voltages, a pressure effect that ceases abruptky with the woltage.

(5) Corona on parallel wires show cooling effects when one or both wires are heated.

(6) The optical interferometer is very useful for investigating corona phenomena.

(7) The start of visual corona is very closely related to other effects, as observed with the interferometer.

Suggestions for Future Investigations

A number of variations of this study suggest themselves for future work.

(1) The corona tube should be closed by sealing the ends with glass plates, so that pressure effects could be studied with the interferometer. Of course this would require considerable expense and care in selecting pieces of glass of the right type for sealing the ends of the tube, and samples exactly like them to place in the other optical path for compensation.

(2) It would be of value to place the entire interferometer in a gas tight box, so that different gases could be tested under different pressures.

(3) More complete and accurate studies should be made of corona voltages and currents, as well as temperature effects, from a quantitive point of view.

(4) It was noted that when parallel wires are in a horizontal plane, the negative corona voltage is lower than the positive, while when the wires are in a vertical plane, the negative corona voltage is the higher of the two. It would be of interest to rotate the wires to find a position at which both corona will form at the same voltage.

The writer considers this study as a bit of pioneering in the field, and hopes to see other studies, and to make other and more complete investigations himself.

In conclusion the writer wishes to express his thanks to Professor C. V. Kent, who suggested the problem and whose patience, enthusiasm and helpful suggestions have been a constant inspiration for this work; to Henry and Robin Hood for helping to construct the apparatus; and to Professor F. E. Kester for the use of the laboratory facilities.

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