DETERMINATION OF THE LAWS RELATING IONIZATION PRESSURE TO THE CURRENT IN THE CORONA OF CONSTANT POTENTIALS.

By Earle H. Warner.

Introduction.

THE " corona " is the glow which surrounds conductors when there exist high potential differences between them and neighboring bodies. A careful study of the corona phenomena is necessary (1) to determine the factors which regulate the loss of power due to the corona, which on long transmission lines may be an important item, and (2) to obtain data from which a theory can be developed which will, with mathematical rigor, explain the corona effects. The first of these objects has been quite successfully carried out by Peek, Whitehead, Ryan and others. The only advances toward a theoretical explanation of the corona have been made by Bergen Davis[1] and Townsend.[2] In these two theories the authors have assumed that the corona is an ionization phenomenon. That is, they assume that the high potential difference causes the few ions which are always present in a gas to move with a velocity sufficiently great to break the molecules with which they collide into two parts, one bearing a positive charge and one a negative charge. All these charged particles then move, because of the influence of the field, toward one or the other of the terminals. The presence of these ions thus explains the conductivity of the gas and the acceleration of the ions explains the light effect. If the corona is an ionization phenomenon one would expect, if the corona apparatus was inclosed, at the instant the corona appeared, *i. e.*, at the instant the molecules were broken up into ions, that the pressure in the apparatus would increase; because according to kinetic theory the greater the number of particles in a given volume the greater the pressure. This pressure increase was first discovered by Dr. S. P. Farwell,[3] working in this laboratory. The above mentioned theories assume ionization but do not account for such a pressure increase. Under certain circumstances this pressure increase can amount to as

[1] "Theory of the Corona," Proc. A. I. E. E., January, 1911.

[2] "The Discharge of Electricity from Cylinders and Points," Phil. Mag., May, 1914.

[3] "The Corona Produced by Continuous Potentials," Proc. A. I. E. E., November, 1914.

much as three cm. of mercury. This pressure increase can not be due to the heating effect of the current, because it occurs very quickly and if the current is broken in a few seconds, the pressure at once returns to its initial value. The heating effect of the current becomes noticeable only after several seconds and then when the current is broken the pressure does not at once return to its initial value but it requires some time for the heated gas to cool off. Since the conception of ionization is so intimately associated with the idea of increase in pressure, it seemed important to determine the laws relating this ionization pressure to the corona current.

THEORY.

Dr. J. Kunz has developed a theory which predicts how this pressure increase should vary with the current. One can best understand his development by thinking of the corona as occurring around a wire which is coaxial with a cylinder. See Fig. 1, which represents a cross section

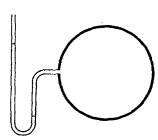

Fig. 1.

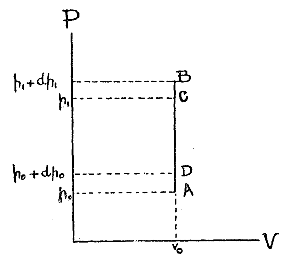

Fig. 2.

of such a corona tube. Suppose the ends of the tube to be closed, so as to inclose a constant volume v_0. When the wire is connected to a very high positive potential and the case grounded the corona glow appears around the wire and the pressure instantly increases from atmospheric to some higher value. Let the condition of the gas at the beginning of the experiment be represented by the point A, on the $p-v$ plane. (See Fig. 2.) The volume is then v_0 and the pressure p_0.

Step I.—Apply a potential difference e between the wire and the case. Some current i will flow and the pressure will immediately jump from p_0 to a higher value, say p_1. The state of the gas will now be represented by the point C. The work done by the current per second, ei, will then be equal to the increase of internal energy of the gas ΔU, plus the work done by the gas W_1, due to the pressure increase. This energy equation gives us

$$ei = \Delta U + W_1. \qquad (1)$$

Step II.—Let us force into the tube a small amount of gas. This will require work dW_2 and the pressure will increase from p_1 to $p_1 + dp_1$ and can be represented by the state point B. Then

$$dW_2 = - v_0 dp_1. \tag{2}$$

The total work to change the gas from state A to state B has then been

$$ei + dW_2 = \Delta U + W_1 - v_0 dp_1. \tag{3}$$

Now let us start again with the same initial conditions and by two different steps arrive at the same final condition.

Step III.—When the state of the gas is A let us force in a small amount of gas. This will require work dW_3 and the pressure will increase from p_0 to $p_0 + dp_0$, which may be represented by the state point D. Then

$$dW_3 = - v_0 dp_0. \tag{4}$$

In the existing conditions the size of the current depends not only on the potential difference but also upon the initial and final pressures. The increase in current causes an increase in pressure which tends to stop the current. The steady condition of the current represents a condition of equilibrium between the attempt of the current to increase the pressure and the attempt of the increased pressure to stop the current.

Step IV. Now apply the same potential difference e. Let that current i' flow so that it will cause the pressure to increase from p_0+dp_0 to $p_1 + dp_1$, that is, so that the state of the gas can be represented by B. Then as in Step I.

$$ei' = \Delta U' + W_4. \tag{5}$$

In the last two steps the total work required to change the state of the gas from A to B is

$$ei' + dW_3 = \Delta U' + W_4 - v_0 dp_0. \tag{6}$$

Then by the law of the conservation of energy, the work required to change a system from one state to another is independent of the path, we have

$$\Delta U + W_1 - v_0 dp_1 = \Delta U' + W_4 - v_0 dp_0 \tag{7}$$

or

$$\Delta U - \Delta U' + W_1 - W_4 = v_0(dp_1 - dp_0). \tag{8}$$

Subtracting (5) from (1) we have

$$\Delta U - \Delta U' + W_1 - W_4 = e(i - i'). \tag{9}$$

Therefore

$$e(i - i') = v_0(dp_1 - dp_0). \tag{10}$$

But

$$i = i' + di.$$

Then

$$edi = v_0 d(p_1 - p_0) \tag{11}$$

and integrating

$$i = \frac{v_0}{e}(p_1 - p_0) + \text{a constant}. \tag{12}$$

Since $(p_1 - p_0)$ represents the increase in pressure, that is, the ionization pressure, this equation shows that the ionization pressure should be exactly proportional to the corona current.

It was the object of the experiments which have been performed to test this relationship with pure gases in the tube.

Apparatus.

The constant potentials were obtained from a battery of continuous current shunt-wound 500-volt generators connected in series.

The corona tube was of the wire and coaxial cylinder type. (See Fig.

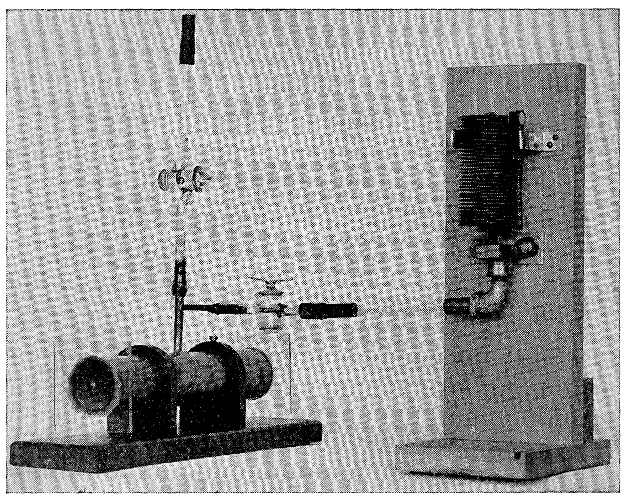

Fig. 3.

3.) Glass plates with holes for the wire to pass through were sealed to the ends of the tube so that the holes were on the axis of the cylinder. The wire, No. 32, copper, passed through the holes and was thus coincident with the axis of the cylinder. The wire was sealed into these holes and held taut by red sealing wax. To the cylinder was soldered a small " T " tube, one side of which was joined to the vacuum pump and the other side was connected to a Bristol aneroid pressure gauge.

The increase in pressure was measured by this Bristol gauge. Any increase in pressure caused it to bend slightly and so rotate the mirror. By observing the deflection of a beam of light over a scale, which had previously been calibrated by reading simultaneously the deflected beam and a water manometer connected directly to the gauge, the increase in pressure in cm. of water could be determined. The advantage of such a pressure measuring instrument in this experiment is that it is very quick in its action. The instant the pressure increases the gauge jumps right up to its new position and a reading can be taken in a very few seconds. It was necessary to read this pressure increase quickly because if much time was required, the heating effect of the current would increase the pressure also.

The current was measured by a Type *H* D'Arsonval galvanometer. The apparatus was connected as is shown in Fig. 4.

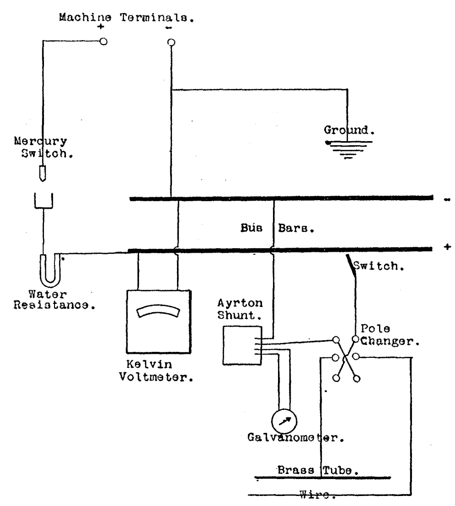

Fig. 4.

Discussion.

Experiments were made when the wire was positive and the case grounded with dry air, hydrogen, nitrogen, carbon dioxide, oxygen and ammonia as the gases in the tube. Considerable care was taken to see that these gases were absolutely pure. They were all dried carefully before they were used. The following curves (Figs. 5, 6, 7, 8, 9) show graphically the results. Fig. 10 shows all the curves plotted to the same scale. With this scale the hydrogen curve should be continued until its ordinate is equal to that of the carbon dioxide curve.

The fact that the points all lie so accurately on a straight line shows conclusively that experiment verifies the prediction made by Dr. Kunz's theory. The law can then be stated that, in the gases studied with the

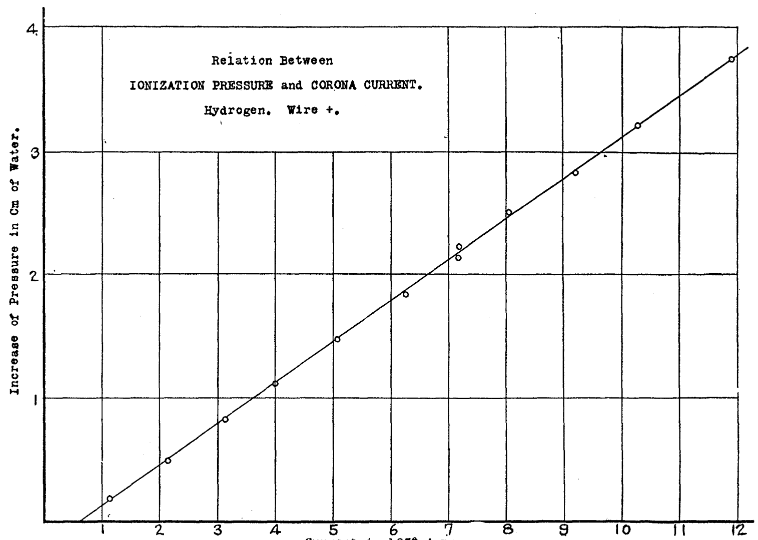

Fig. 5.

wire positive *the ionization pressure is exactly proportional to the corona current.*

In the case of oxygen a considerable amount of ozone was formed due to the corona discharge. Evidently the curve as shown is a resultant of two effects: (1) A chemical change due to the formation of ozone. This would tend to cause a decrease in pressure. (2) The increase in

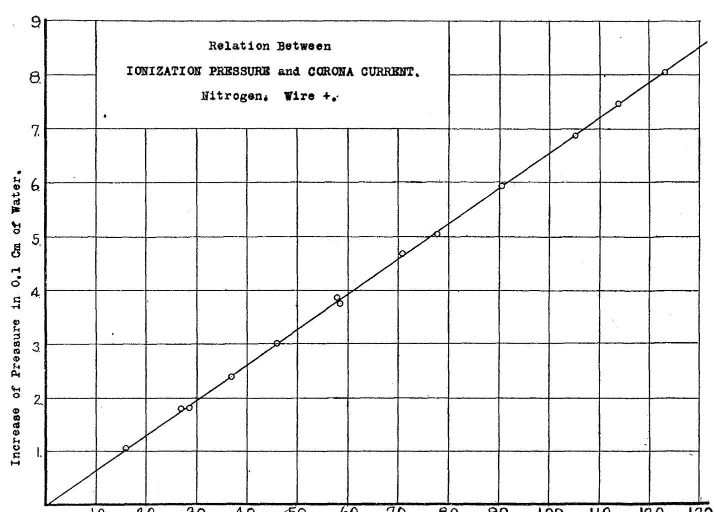

Fig. 6.

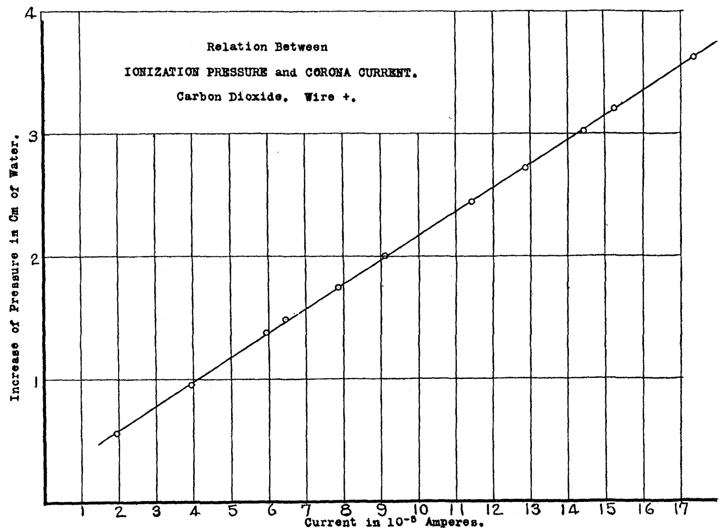

Fig. 7.

pressure due to the ionization of the oxygen. Since the ionization curve is a straight line, as is shown by the gases in which probably there is no chemical action, and since this resultant curve of oxygen is a straight line, the following law can be stated:

Whenever chemical change takes place due to the corona the chemical change is exactly proportional to the current.

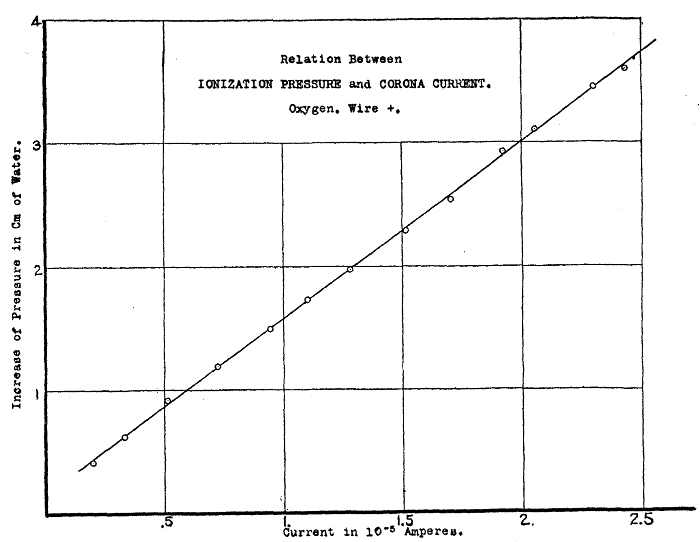

Fig. 8.

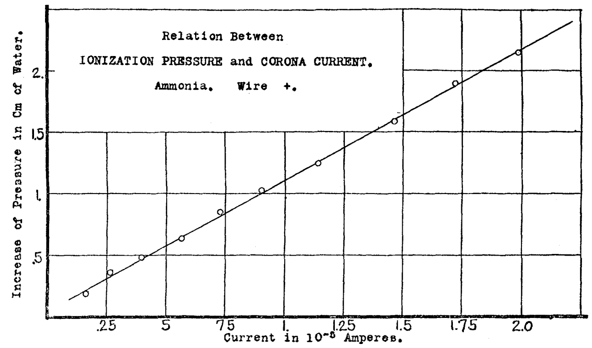

Fig. 9.

With the wire negative beads always appear on the wire, and since the pressure increase varies with the arrangement of the beads which are not stable, it is impossible to accurately verify the above relationship. When, instead of the quick acting gauge, an ordinary open manometer which is slow in its action was used, it was discovered that the same relationship as above stated is very nearly true for the wire negative as well as positive.

The increase in pressure in the case of nitrogen, showing ionization, is one of the exceptional cases where nitrogen is largely ionized at low temperatures and thus probably chemically active.

How nitrogen, carbon dioxide and ammonia are ionized, are questions which require further study.

The arrangement of the apparatus could be used as a high potential voltmeter by simply calibrating the increase in pressure against volts, as determined by a disc electrometer.

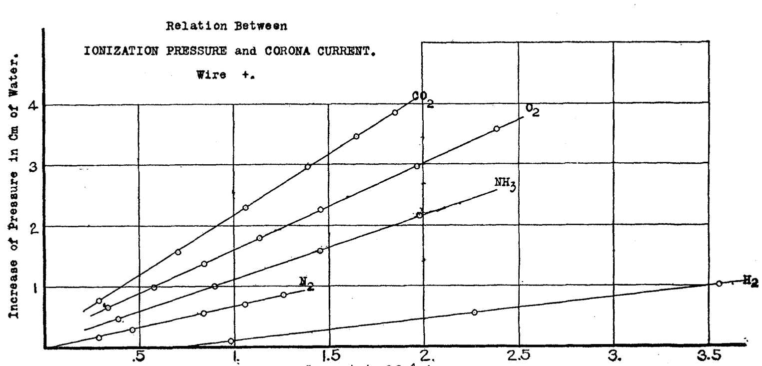

Fig. 10.

Summary.

The ionization pressure in the positive corona is exactly proportional to the corona current in dry air, hydrogen, nitrogen, carbon dioxide, oxygen and ammonia.

Any chemical action that takes place due to the corona is exactly proportional to the corona current.

The writer wishes to acknowledge his indebtedness to Professor A. P. Carman and to Dr. Jakob Kunz, associate professor of physics, for their deep interest and helpful suggestions concerning the conduct of this work.

Laboratory of Physics,
University of Illinois,
May, 1916.

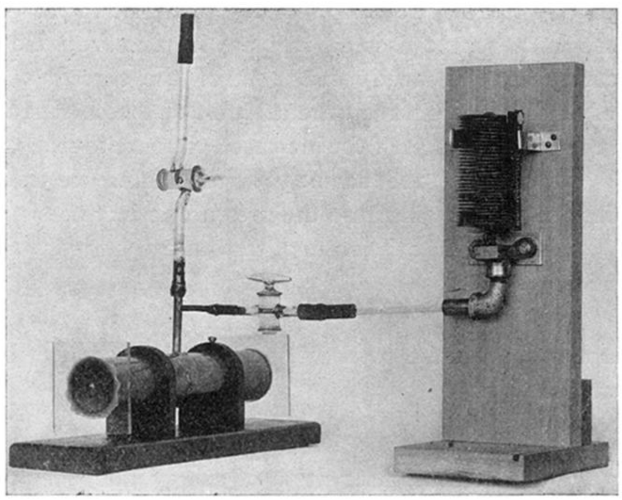

Fig. 3.