The Propagation of Potential in Discharge Tubes

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(Received June 22, 1936)

The propagation of potential in a long discharge tube containing air was investigated as a function of pressure (0.017 to 0.24 mm Hg) and applied potential (74 to 171 kv). Impulsive potentials were applied to one end of the tube while the other end was grounded. By means of a high speed cathode-ray oscillograph, it was found that in the case of both positive and negative applied impulses a definite potential wave traversed the tube from the high voltage electrode to ground, immediately followed by a much faster return wave from ground back to the high voltage electrode. The wave velocity, voltage attenuation, wave form and energy carried in the wave front of the initial impulse were investigated and found, in general, to vary with both pressure and applied potential. The similarity of these results to the observations on the propagation of luminosity in long discharge tubes and in the lightning stroke are discussed. With the higher applied voltages the wave shows practically no observable distortion or attenuation so that the long discharge tube provides an excellent transmission line for many purposes.

THE propagation of luminosity produced by the application of an impulsive potential to long discharge tubes was first investigated by J. J. Thomson[1] and has since been studied with an improved method by one of us.[2] Thomson observed that the luminosity did not start simultaneously throughout the length of the tube but traversed it with a finite velocity. Beams found that the luminosity progressed from the high voltage electrode toward the electrode maintained at ground potential regardless of the polarity of the impressed surge. This luminous pulse travels through the tube with a high velocity (10^9 to 10^{10} cm/sec.) which for a given tube is determined chiefly by the pressure of the gas and the magnitude of the applied potential. In addition to this initial impulse found in all discharges he also occasionally observed a second pulse later than the first which started at the ground potential electrode and moved in the opposite direction. This type of propagation is similar to that observed by Schonland[3] and others in lightning discharges, and by Allibone and Schonland[4] for a million-volt spark between point and plane. In the lightning stroke the first luminous pulse or "leader" may travel continuously or in a stepped fashion from cloud to ground with a velocity as high as 5×10^9 cm/sec. This leader is followed by a return stroke of high luminosity starting from the ground and moving in the opposite sense with velocities as high as 1.4×10^{10} cm/sec.

In order to obtain a clearer insight into the mechanism responsible for this "traveling wave of luminosity" the present work was undertaken to determine the nature of the accompanying potential wave. Since a long discharge tube of this kind should constitute a transmission system for potential pulses, a knowledge of the wave velocity, voltage attenuation, wave form and energy carried in the wave front as a function of pressure and applied voltage is desirable.

APPARATUS AND METHOD

The apparatus is shown schematically in Fig. 1. The tube T was constructed of Pyrex of internal diameter 5 mm. The terminal electrodes E_1, E_4 were brass rods with hemispherical ends, and the electrodes E_2, E_3 short lengths of brass tubing waxed in place. The pump and drying system were attached at P and the pressure read on a type of Pirani gauge at G. During observations the pump was shut off to avoid any pressure gradient in the tube. The potential was applied to the tube through a spark gap from the three stage Marx circuit C. A high speed cathode-ray oscillograph of the Dufour type was used to determine the potential variations. The oscillograph circuit and the method used to synchronize the oscillograph and supply potential circuits are not shown as they followed the standard practice for such problems. The sweep was used at film speeds of approximately $0.3-1\times10^8$ mm/sec. The electrodes E_2, E_3 were connected to the deflection plates through symmetrical capacity dividers in

[1] J. J. Thomson, Recent Researches 115 (1893).
[2] J. W. Beams, Phys. Rev. **36**, 997 (1930).
[3] Schonland and Collens, Proc. Roy. Soc. **A143**, 654 (1934); Schonland, Malan and Collens, Proc. Roy. Soc. **A152**, 595 (1935).
[4] Allibone and Schonland, Nature **134**, 736 (1934).

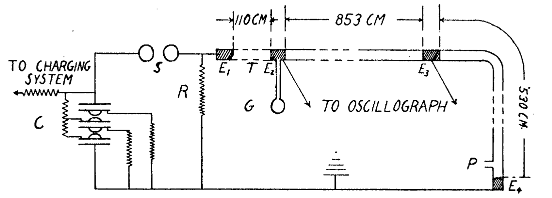

FIG. 1. Diagram of apparatus showing discharge tube and Marx circuit for supplying potential. The oscillograph and synchronizing circuits are not given.

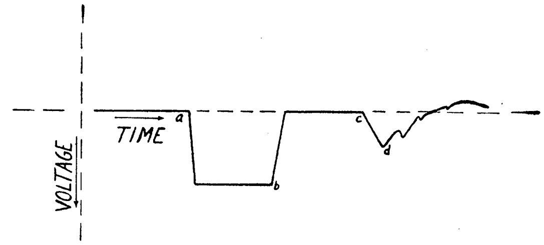

FIG. 2. Diagram giving the main features of the potential variations observed on the oscillograph for both positive and negative impulses.

such a manner that equal potentials at E_2, E_3 would produce no displacement of the electron beam. With this arrangement a potential wave passing down the tube produces a deflection of the beam when it arrives at E_2. This deflection is decreased when the wave arrives at E_3, the amount of decrease depending upon the voltage attenuation between E_2 and E_3. In like manner a return wave from E_4 can be followed from E_3 to E_2. By observing the deflection at each electrode separately a fairly complete picture of the voltage variations can be obtained.

It has been observed[2] that the luminous pulse originating at E_1 started relatively slowly at first and did not reach its final constant speed until it was some 40 cm down the tube. This is probably due to the time lag inherent in the starting of a gaseous discharge and depends for any given potential impulse upon the size of tube, shape of electrodes and initial degree of ionization of the gas. The electrode E_2 was placed at a distance from E_1 such that the rate of potential increase observed was a maximum and did not vary appreciably from one discharge to the next. This minimizes any effect due to a variation in the initial rate of breakdown. Dry air was used for all the observations. The tube was outgassed by continual pumping and repeated discharging with a high applied potential.

RESULTS

A typical diagram of the voltage variations for both positive and negative pulses is shown in Fig. 2, and typical oscillograms in Fig. 3. The arrival of the wave at E_2 is shown at (*a*), and at (*b*) the wave has reached E_3. The time *b–c* represents the time of transit of the initial wave from E_3 to E_4 plus the time taken by the discharge wave to reach E_3 from the grounded end of the line. Since the gas is made highly conducting by the initial pulse, this discharge wave is similar to that obtained by grounding one end of a charged transmission line and travels with a velocity nearly equal to that of light. The time *c–d* is approximately that required for the discharge wave to travel the distance E_3–C and return to E_3 as a reflected wave. A number of successive reflections can be seen on the oscillograms superimposed upon the potential variation due to the slow damped oscillation of the circuit as a unit.

At relatively high pressures and high potentials the time *b–c* is variable. This is caused by the practical difficulty of maintaining E_4 at constant potential when the gap S discharges. The potential appearing at E_4 ionizes the gas in that end of the tube and produces variations in the wave velocity near that end. E_3 was placed at such a distance from E_4 that the time of transit over E_3 to E_4 and back to E_3 was always greater than the time length of the initial wave front. When this precaution was observed the time between *a–b* remained constant for a given pressure and voltage to within five percent. When the electrode E_4 is disconnected from the ground and insulated the initial wave appears the same but the part from (*c*) on is lacking, showing that the last part is due to the discharge wave.

A number of values of wave velocities, applied voltages and pressures are given in Table I. In general an increase of either pressure or voltage produces an increase in the speed of propagation over the range studied. There seems to be for any given pressure a critical potential necessary for the production of a wave which will travel with a definite velocity without appreciable attenuation. At the higher potentials (127–171 kv) there was no noticeable voltage attenuation or wave distortion in traveling the distance E_2–E_3 (853 cm). However, at 74 kv and the higher pressure (0.24 mm) the voltage variations were analogous to

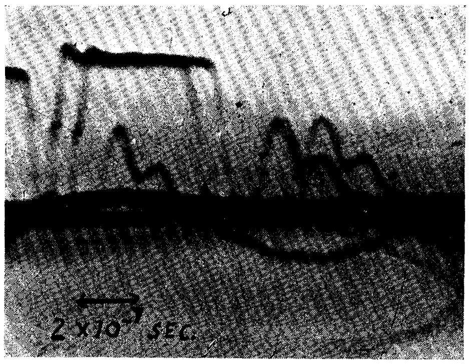

FIG. 3. Oscillogram of negative impulse. Applied potential of 123 kv. Pressure 0.032 mm.

those obtained in charging a cable with a high resistance per unit length. The return wave was not observable in this case.

At 171 kv and 0.17 mm pressure the time length of the wave front is 7.8×10^{-8} sec. and the space length 209 cm. Since the rate of charging observed on the oscillograph for this case is approximately linear, the field in the wave front is about 810 volts/cm. With this value of field and pressure it is probable that the propagation can be explained by the rapid building up of space charge in the front of the wave. It seems possible that the necessary electron supply immediately ahead of the wave is furnished by photoelectric absorption in this region of the gas.

The wave front at E_3 in this case (171 kv, 0.17 mm) is slightly less steep in the initial portion than that at E_2 but reaches its maximum value in about the same time. This indicates that the charging current to the oscillograph deflection plate system does not produce very much wave distortion. Assuming the capacity of this system to be 8 $\mu\mu$fd and the rate of charging linear, the charging current is 17 amp. The current in the initial pulse must consequently be many times this amount. With 74 kv at both 0.017 and 0.24 mm pressure there is pronounced wave distortion increasing greatly with increase of pressure. The ratio between the charging currents to the oscillograph for 171 kv at 0.17 mm and 74 kv at 0.017 mm pressure is 7.4. This gives a current of 2.4 amp. in the 74 kv case. This leads one to expect that a rather high value of current is necessary in the initial wave before the space charge propagation can be maintained without appreciable change throughout the tube.

TABLE I. *Wave velocities for different applied voltages and pressures.*

Applied Voltage (kv)	Pressure (mm Hg)	Speed of Potential Impulse Between E_2–E_3
+127	0.08	9×10^8 cm/sec.
+127	0.18	24
+127	0.24	43
−123	0.032	15
+171	0.17	27
+ 74	0.017	5.4
+ 74	0.24	14

To obtain the maximum currents flowing during the initial wave an electrolytic resistance of 41 ohms was placed in the circuit between S and E_1. E_4 was disconnected from the ground and insulated. The maximum voltage across this resistance was measured by a spark gap irradiated by ultraviolet light. For 170 kv and 74 kv at 0.025 mm pressure the maximum currents were respectively 429 amp. and 146 amp. With E_4 grounded the maximum discharge currents for the same potentials at 0.053 mm pressure were 940 amp. and 480 amp. respectively. With high current values in the initial impulse it is evident that the slope of the wave front at the electrode E_2 is governed to a considerable extent by the impedance of the input circuit and could be made considerably steeper by decreasing this impedance.

This investigation is being continued with the hope that measurements over a wider range of voltages and pressures with tubes of different diameters and with different gases will lead to a quantitative explanation of the mechanism responsible for this propagation of potential. In addition to their close connection with the propagation of luminosity in discharge tubes and in lightning strokes the results already obtained show that for relatively short distances a discharge tube of this kind serves as a transmission line in which the speed of propagation is easily controllable at a value much less than that of light. This is of importance in many problems[5] where it is necessary to obtain time separations between the application of potential at different points.

We wish to acknowledge a grant from the American Philosophical Society which has made it possible for one of us (L. B. S.) to work on this problem.

[5] Beams and Snoddy, Phys. Rev. **44**, 784 (1933).

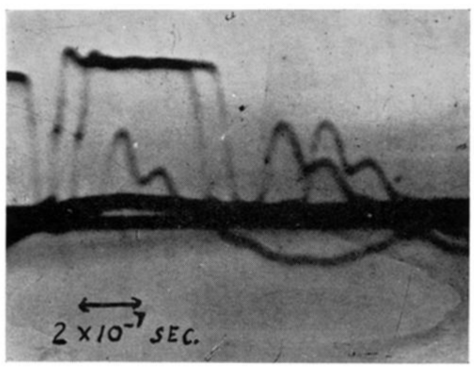

Fig. 3. Oscillogram of negative impulse. Applied potential of 123 kv. Pressure 0.032 mm.