RP217

APPARATUS FOR THE MEASUREMENT OF HIGH CONSTANT OR RIPPLED VOLTAGES [1]

By Lauriston S. Taylor

ABSTRACT

An improved form of high resistance to be used as a high-voltage voltmeter multiplier for use up to 150 kv. is described. The total resistance is 100 megohms, designed to be coronaless by placing one hundred 1-megohm resistors in 20 corona cases containing 5 resistors each, the corona cases being mounted in series on top of each other. The complete unit is readily portable. Methods of calibrating the resistance under full-load conditions are described. Errors are discussed and necessary corrections, to give a maximum error in high-voltage measurement of 0.01 per cent, are given. A new type of high-voltage string electrometer for use in connection with the resistance is also described.

CONTENTS

I. INTRODUCTION

With the increasing use of high rippled or constant voltages for precise physical and commercial purposes, it is becoming more necessary to make accurate measurements of the magnitudes dealt with. Of these, the most difficult is the measurement of potential, yet in the field of pure and applied X rays this is particularly important for various reasons.

Since the early work of Farnsworth and Fortescue,[2] Chubb,[3] and Peek,[4] a. c. voltages have been measured largely with the sphere-spark gap for which an empirical calibration was established. This calibration being independent of the frequency over wide ranges has justified its use to measure either rippled or constant voltages. However, to attain the highest accuracy by such a means the spheres must be so large (25 to 50 cm diameter) that it almost eliminates their

[1] Up to the present the term "constant potential" has been used indiscriminately in describing the potential supplied by kenotron or other valve tube rectification. Accordingly we will in the future use a new, more accurate designation of voltages which are actually not constant but fluctuate about a certain average value. We thus define a "Ripple Quantity" (potential or current) as a simple periodic quantity $y=V_0+V_1 \sin(\omega x+\alpha_1)+V_2 \sin(2\omega x+\alpha_2)+\ldots$ in which the constant term (V_o) is so large that all values of the quantity are positive (or negative). The amount of ripple ("Ripplage" or "Ripplance") in a ripple quantity is the ratio of the difference between the maximum and minimum values of the quantity to the average value.

The above definitions are being considered by the Committee on Electrical Definitions of the American Standards Association under the sponsorship of the A. I. E. E.

[2] S. W. Farnsworth and C. Fortescue, Trans. A. I. E. E., 32, pt. 1, p. 733; 1913.

[3] L. W. Chubb and C. Fortescue, Trans. A. I. E. E., 32, pt. 1, p. 739; 1913.

[4] F. W. Peek, G. E. Rev., 16, p. 286; 1913; and Trans. A. I. E. E., 32, pt. 1, p. 812; 1913.

use in the ordinary laboratory. In addition, the constructional details must conform to certain arbitrary specifications, and corrections must be made for atmospheric conditions. With the 125 mm spheres more commonly used, the errors increase until the precision necessary for many physical purposes is no longer obtainable.

Another important disadvantage of the sphere-gap method is that its use necessarily interrupts the high voltage which it is to measure. This is particularly troublesome in the case of the usual ripple voltage obtained from kenotron-condenser rectifier circuits.

Various types of electrostatic voltmeters have been devised for measuring these high voltages. They have been calibrated in most cases either with a 125 mm sphere gap or by means of the short wavelength limit of the X-ray continuous spectrum using the relation $V=1.234/\lambda_o$ where V is the maximum voltage expressed in kilovolts and λ_o is the spectrum limit expressed in angstroms. The sphere-gap method of calibration is limited by the inaccuracies of the sphere gap used; the second is possible only in a well-equipped X-ray laboratory having an accurate ionization X-ray spectrometer. A high precision absolute electrometer for a. c. potentials up to 250 kv. has been built by Brooks,[5,6] but unfortunately is not applicable to d. c. voltage measurements.

Thus far, the only accurate method of measuring high d. c. potentials has been by means of a high resistance used as a voltmeter multiplier. This method has been employed by Webster, Duane, and Terrell; and, while serving well the particular purpose, the resistances have been unwieldy and have drawn considerable power from the high-voltage source.[7]

As a part of the bureau's program of practical X-ray studies[8,9] it was considered necessary to make a careful study of high voltages under actual operating conditions. This has necessitated the construction and calibration of accurate electrostatic voltmeters and of small sphere gaps. For this there has been developed a compact and portable voltmeter multiplier which consumes but 1 milliampere per 100 kv. and hence can be maintained in continuous connection with the usual high-tension system without interfering with its operation.

II. CONSTRUCTION AND TEST OF MULTIPLIER RESISTORS

1. CONSTRUCTION OF INDIVIDUAL UNITS

It was desired to make the unit of standard materials, if possible; hence, a number of different types of commercial resistors were tried. Those finally selected were 1-megohm units of nickel chromium wire with a special insulation designed to withstand both high temperatures and high voltage. Nickel chromium was chosen in spite of its comparatively large temperature coefficient because manganin or constantan would have made the units too bulky. In these resistors the wire is wound on six-spool bobbins, 1 megohm to each, as shown in Figure 1.

[5] See L. S. Taylor, B. S. Jour. Research, 5 (RP211), p. 507, October, 1930.
[6] See C. Snow, B. S. Jour. Research, 1 (RP17), p. 513; 1928.
[7] H. M. Terrell, C. T. Ulrey, X-Ray Technology, pp. 112-116, Van Nostrand; 1930.
[8] L. S. Taylor, B. S. Jour. Research, 2 (RP56), p. 771; 1929.
[9] L. S. Taylor, B. S. Jour. Research, 3 (RP119), p. 807; 1929.

Two kinds of bobbin material, both of which proved satisfactory, were used: (*a*) Lavite, carefully baked after machining and then impregnated with paraffin; and (*b*) isolantite, which is supposedly less likely to absorb moisture. The spools are wound successively and the bobbins practically noninductively by reversing the direction of winding in adjacent spools, the wire passing from one spool to the next through the slot in the partition,[10] and its ends soldered to brass studs cemented into the ends of the insulating base. X-ray photographs were made of several to inspect the effectiveness of the cement and to reveal possible leakage paths through the insulation.

2. TEST OF INDIVIDUAL UNITS

The manufacturer's rating for each unit was given as 1 megohm ±1 per cent with an energy dissipation of 1 watt. With each unit subjected in air to an applied potential of 1,000 volts, d. c., for 8 hours no indication of breakdown appeared. With 1,415 volts, d. c. (2 watts), for 2 hours, the result indicated that a 100 per cent overload was safe; 2,000 volts (4 watts) for 2 hours caused breakdown in only 3 per cent of the units tried. These tests, repeated with the units immersed in ordinary high-tension transformer oil, showed no breakdowns.

A special high-voltage Wheatstone bridge was constructed so that the resistance of the bobbins could be measured under load conditions. In the two arms of the bridge on one side of the galvanometer were placed, respectively, the unknown resistor of about 1 megohm and a dial manganin resistance box, ranging from 0 to 1,111,111 ohms in 1-ohm steps. In the other two arms were placed manganin resistances of 5,000 ohms each. Voltages up to 2,000 volts, d. c., were applied directly to the bridge. With this operated at 1,000 volts it was possible to detect a change in resistance of the bobbins of 1 part in 100,000, although the absolute accuracy was limited to 0.01 per cent by the uncertainty in the calibration of the bridge arms.

With this bridge it was readily possible to examine any unit under operating conditions and detect any failure of the resistor, such as a breakdown between windings at high voltage. To determine the temperature coefficient of resistance, the resistor was immersed in a large beaker of transformer oil heated to 80° C., and resistance measurements made with the bridge every few minutes as the oil (well stirred) cooled down to room temperature. The results, plotted in Figure 2, gave a temperature coefficient of 0.0152 per cent per ° C. All resistance measurement at other room temperatures were corrected by this coefficient to 20° as standard.

For determining the resistance of each bobbin, two methods were used: (*a*) With low voltage (25 volts) applied to the bridge continuously, and (*b*) with high voltage (1,500 volts) applied for about one second, followed by a long interval of rest during which the bridge was adjusted in preparation for the next trial for balance. In neither case was appreciable heating of the coil produced. Results by the two methods agreed to better than 0.1 per cent, and thus justified the use of method (*a*) for routine measurements of room temperature resistance. Surface or body leakage of the lavite and

[10] Measurements made elsewhere have shown the inductance to be slightly negative but negligible for the purpose at hand.

isolantite was tested by connecting an unwound bobbin in series with a galvanometer of sensitivity 10^{-8} amps per millimeter and a source of potential of about 1,300 volts, d. c. No measurable current passed through, indicating the resistance to be greater than 10^{11} ohms and negligible as a source of leakage. A leakage test with the hard-rubber supports, similar to that for the bobbins, proved this insulation to be satisfactory also.

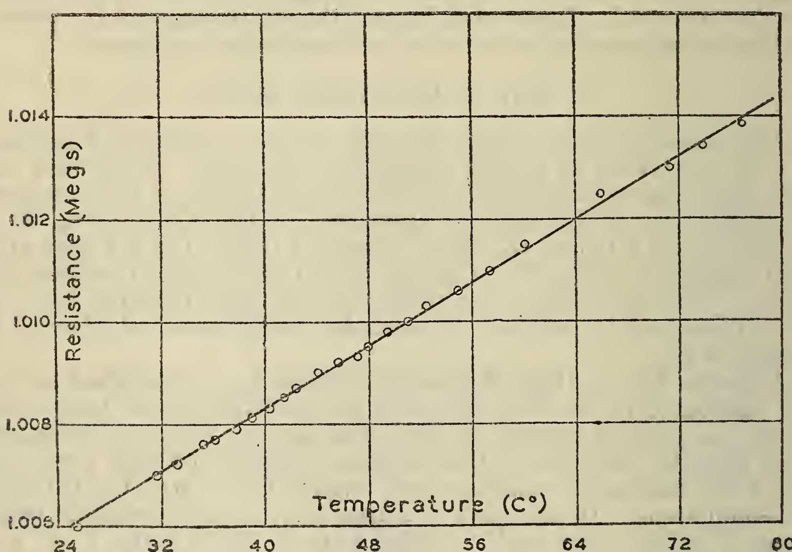

Figure 2.—*Curve for obtaining temperature coefficient of a single resistor*

III. CONSTRUCTION OF THE COMPLETE UNIT

For the purpose at hand a resistance suitable for the measurement of 150 kv. was needed. As a result of the above tests, 100 megohms were shown to carry 150 kv. safely, thereby giving a working current of 1.5 milliamperes and dissipating a maximum of but 225 watts. Connecting 100 resistors in series in open air would have resulted in excessive corona around those at the higher potentials and thus introduced three serious difficulties: (*a*) Corona bombardment which would eventually break down the insulation of the wire, (*b*) the precipitation of dust from the air which would eventually cause serious surface leakage, and (*c*) the possibility of a corona current of sufficient magnitude to introduce error. This might be avoided by immersing 20 bobbins in series in a 1½-inch pyrex tube filled with high-tension transformer oil. By so doing the maximum potential difference between the ends of the tube would be only 30 kv., thus eliminating excessive circulation of the oil. Five such units in series, properly suspended in air and kept free from dirt, would provide a fairly suitable multiplier for 150 kv. This method is open, however, to two main objections: (*a*) It is difficult to get at the individual resistors to measure their resistance, and (*b*) the oil may eventually break down sufficiently to cause appreciable leakage.

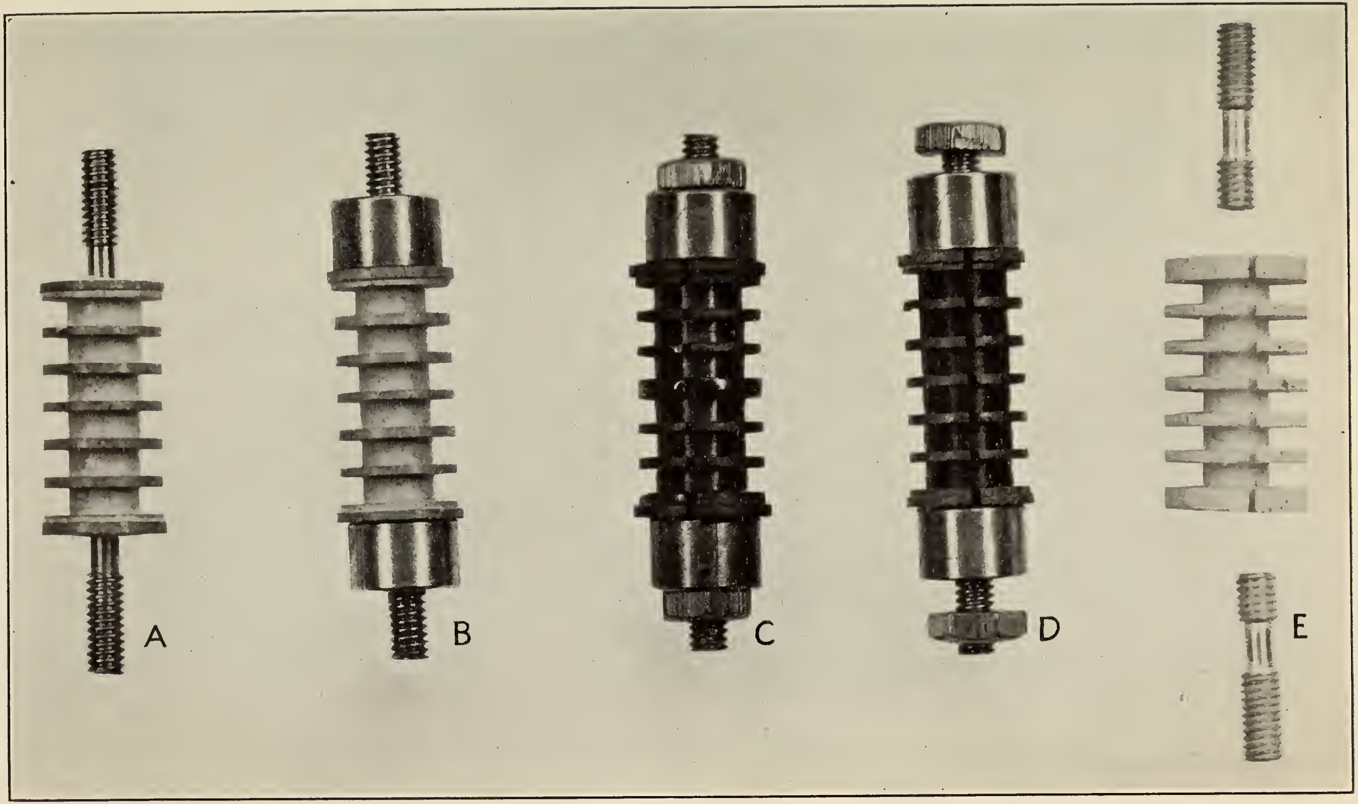

FIGURE 1.—*Wire resistors used in multiplier*

A, B, Lavite bobbins; *C, D,* complete resistor wound in 6 spools; *E,* Isolantite bobbin.

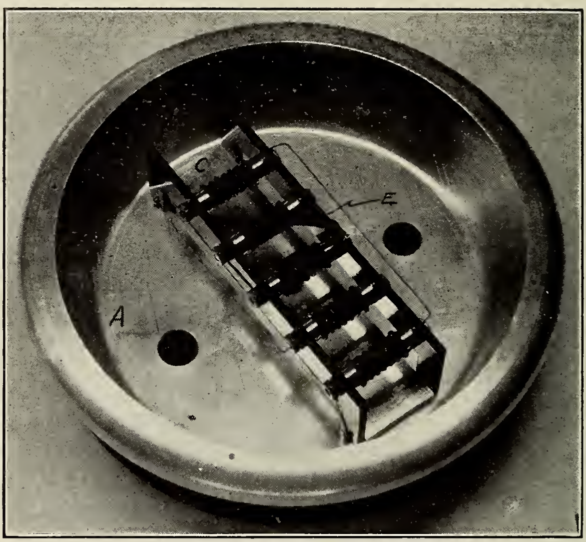

FIGURE 3.—*Assembled unit of five resistors in spun aluminum corona shield with cover removed*

FIGURE 4.—*Complete unit with cover attached*

To eliminate the difficulties above, the 100 units were finally assembled into 20 sets of 5, each 5 being mounted in a spun aluminum corona shield, *A* (fig. 3), on a frame of polished hard rubber, *B*, carried by an aluminum base plate, *C*, which is bolted to the shield with a 3-inch disk of one-eighth-inch aluminum, *D*, serving as a nut. The resistors are connected in series in such a way that only 40 per cent of the potential applied to a shield exists between each bobbin and its nearest neighbor and thus effects a minimum potential difference along the hard rubber support.

One end of this group resistance is permanently fastened to the shield, and the other end to a flat phosphor bronze spring, *E*, mounted on the hard rubber frame. Covering the open face of the corona shield is a one-fourth-inch hard rubber disk. (Fig. 4.) In both shield and cover are two 1-inch holes to provide ventilation. A stud, *F*, protruding from the aluminum disk, *D*, is screwed into the hard rubber cover of the next corona case so as to make electrical contact with the spring *E*.

For convenience, 2 stacks of 10 shields each were supported (fig. 5), top and bottom on electrose insulators mounted in a dried oak frame which had been painted with several coats of shellac. These frames can be used separately as in Figure 5 or placed one on top of the other and connected in series as in Figure 6.

The assembled multiplier has the following advantages: (*a*) The maximum potential difference between any resistor and its surroundings is only 7.5 kv.; hence, there will be no corona inside the shield and a minimum of dust precipitation; (*b*) all corona shields are maintained at a fixed potential difference of 7.5 kv., maximum, with respect to adjacent shields, so the total stack is coronaless; (*c*) the electrostatic shielding effect of the corona case protects the hard rubber cover of the next above from corona bombardment; (*d*) the small gap between corona case minimizes the possibility of sunlight affecting the insulating qualities of the hard rubber; (*e*) dull black lacquer on the inside and outside of the corona cases permits a maximum of heat radiation;[11] (*f*) the separation into 5 megohm units permits easy tests for possibly defective resistors, and likewise a ready calibration of the resistance of each.

It might be pointed out that for continuous use, the hard rubber deforms appreciably. This has been avoided by making the covers of one-fourth-inch pyrex glass plates, pyrex being used in preference to other glass because its surface leakage is small. The stack is, however, rendered more fragile. For measurements of short duration, hard rubber has proved to be satisfactory, and, moreover, furnishes a readily portable apparatus.

IV. PERFORMANCE TESTS

It was found that the assembled stacks, when subjected for several hours to high d. c. potentials up to 75 kv. (per stack), carried the load without damage. The resistance of each case was measured before and after application of the voltage, as described above, with approximately one-fifth of the maximum working voltage applied

[11] The size of the corona case is such that 10 resistors might have been placed in each instead of 5. However, this is undesirable, since it would double the amount of heat to be dissipated per unit and cause additional heating of the coils.

across the case. The few units which showed any change in resistance were then discarded.

It was impossible in actual operation to make any measurement of the temperature attained after temperature equilibrium had been reached, since this is affected by the proximity of other heated coils and the restricted air space of the corona case. However, a temperature correction for single resistors may be determined as a function of the current passing through the coil. This is obtained by applying a given potential to the single resistor and measuring the resistance after equilibrium has been reached. A curve may then be plotted giving directly the change in resistance as a function of either the voltage drop or the current in the coil. A number of resistors were so tested in open air and the characteristics of all were found to be exactly the same.

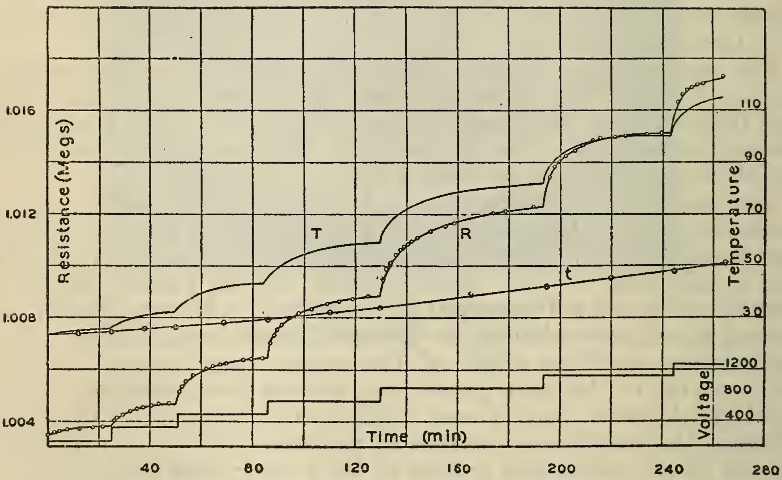

Figure 7.—*Resistance curves to show effect of heating of the resistors under operating conditions*

Voltage increased by steps.

To determine the correction for an assembled stack, one resistor in the center was detached from the main circuit and leads taken out to the Wheatstone bridge by which the resistance was measured at room temperature and corrected to 20° C. Next the resistance was measured for a series of potentials up to the maximum while in each case a potential from an independent source of 49 times the bridge potential was applied to the remaining 49 units in series. By this means the resistance of a single unit under actual operating conditions of voltage and heat radiation was obtained, the measurements being made at a given potential every two or three minutes until equilibrium was reached.

The results of this are plotted in Figure 7 for potentials up to 1,300 volts per resistor. Examination of the curves shows that equilibrium, within about 0.02 to 0.03 per cent, is reached in about 20 minutes. Having the no-voltage resistance at 20° C., the percentage correction for each voltage (or corresponding current) was calculated from these curves.

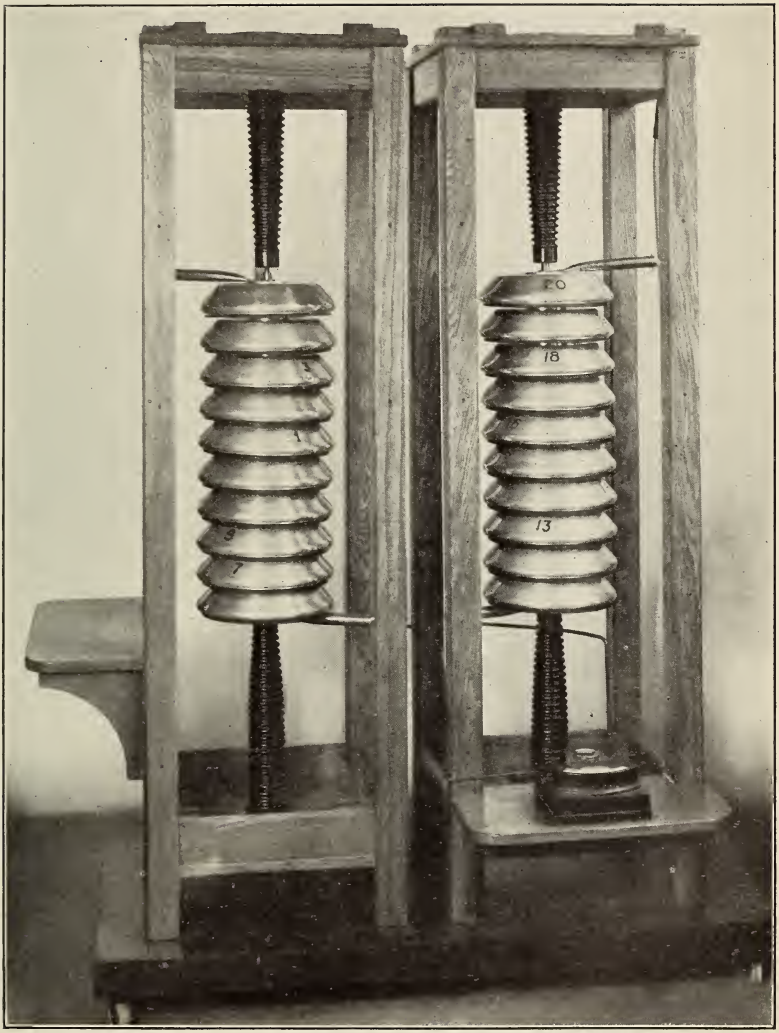

FIGURE 5.—*Assembled resistor of 50 megohms per stack*

In the particular case shown a microammeter is in a grounded circuit dividing the stacks.

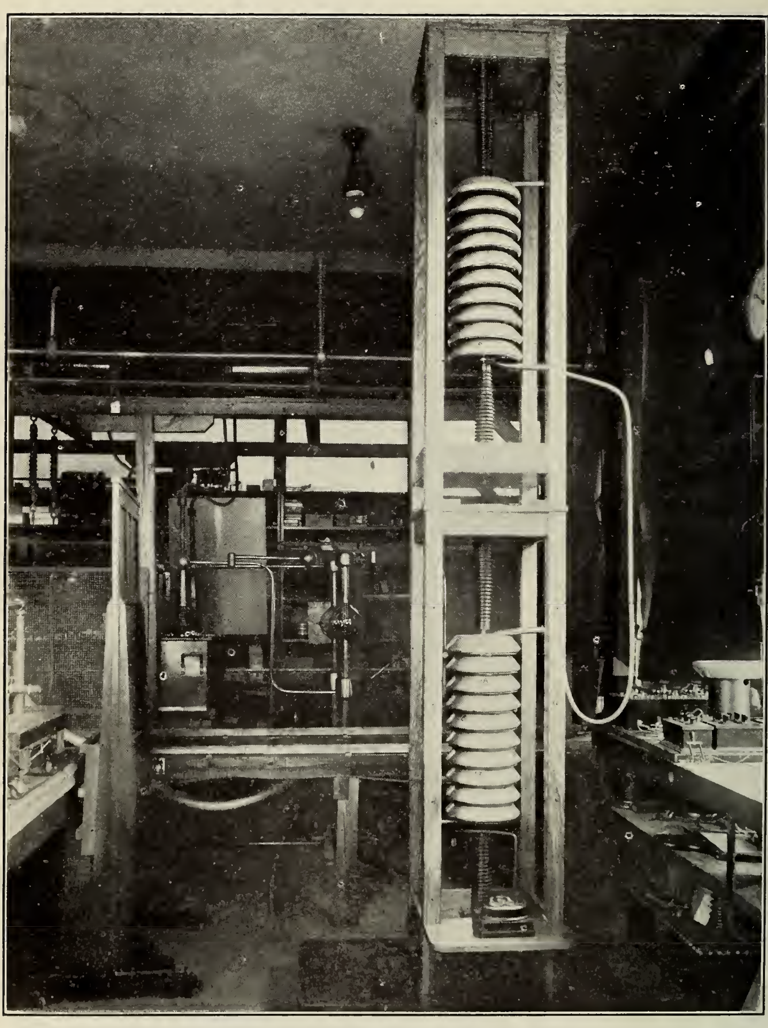

Figure 6.—*Two 50-megohm stacks, connected in series and mounted one above the other*

At right can be seen the high-voltage bridge and in the background a part of the high-voltage generator.

Curve *a* Figure 8 shows the correction to be applied to the resistance when the reading is taken 20 minutes after the potential is applied. Thus, when using the stack for voltage measurements, this curve gives for every current the necessary correction for the resistance to within 0.02 per cent. Curve *d* shows a similar result for 40 minutes readings. Curves *b* and *c* give corrections for readings taken, respectively, 10 and 5 minutes after application of voltage. The fact that *b* and *c* are smooth curves indicates that such readings are just as reliable as those taken nearer equilibrium. The difference between any two of these correction curves is only about 0.04 per cent so that great care does not need to be taken in timing the duration of the current. When neglecting corrections, the error is only of the order of 1 per cent.

Curve *T* in Figure 7 shows temperature of the coils as calculated from their temperature coefficient, while curve *t* gives the air temperature within the corona case, indicated by a mercury thermometer inserted through one of the holes.

The same correction was found when voltages were brought up to the desired value instantly instead of in steps.

It should be mentioned that a correction must be made, of course, for any room temperature differing from that at which the resistance was calibrated under no-load conditions. In the present case the no-load resistance must be increased by 0.015 per cent for each degree rise in temperature of the room above 20° C.

V. APPLICATION TO HIGH D. C. VOLTAGE MEASUREMENTS

The application of such a resistance to high-voltage d. c. measurements is well known and straightforward, and consequently need not be dealt with in detail.[12] Two methods are common: (*a*) To measure the potential drop v across a small known resistance r in series with the high resistance R, calibrating the galvanometer with a standard cell for each reading; and (*b*) to make a direct measurement, by means of a suitable galvanometer or microammeter, of the current i flowing through the resistance. By method (*a*) the high voltage V_o is given by $V_o=v(R+r)/r$ where R is the total resistance. By method (*b*) the voltage is given by Ohm's law, $V_o=iR$.

For some purposes; for example, our X-ray studies, it may be desired to make not only an accurate measurement of the high potentials, but to determine also the magnitude of any small irregular fluctuations in the ripple voltage. To do this a new type of high-voltage electrometer was developed suitable for measuring voltages up to 1,000 volts to within ± 0.1 per cent. (Figs. 9 and 10.) A drawn platinum wire, *A*, of 0.01 mm diameter (shown in a heavy line) is suspended about 2 mm from a 2.5 cm brass tube, *B*. This wire is under the tension of a loop of coarse quartz filament *C* at the lower end and its adjustable suspension above. This system is surrounded by a cylindrical copper case about 5 inches in diameter, supported at the base by a good insulator. With the case grounded and a potential applied to the inner insulated system, consisting of tube and wire, we have an idiostatic electrometer the sensitivity of which may be altered at will by changing the tension on the wire.

[12] See footnote 7, p. 610.

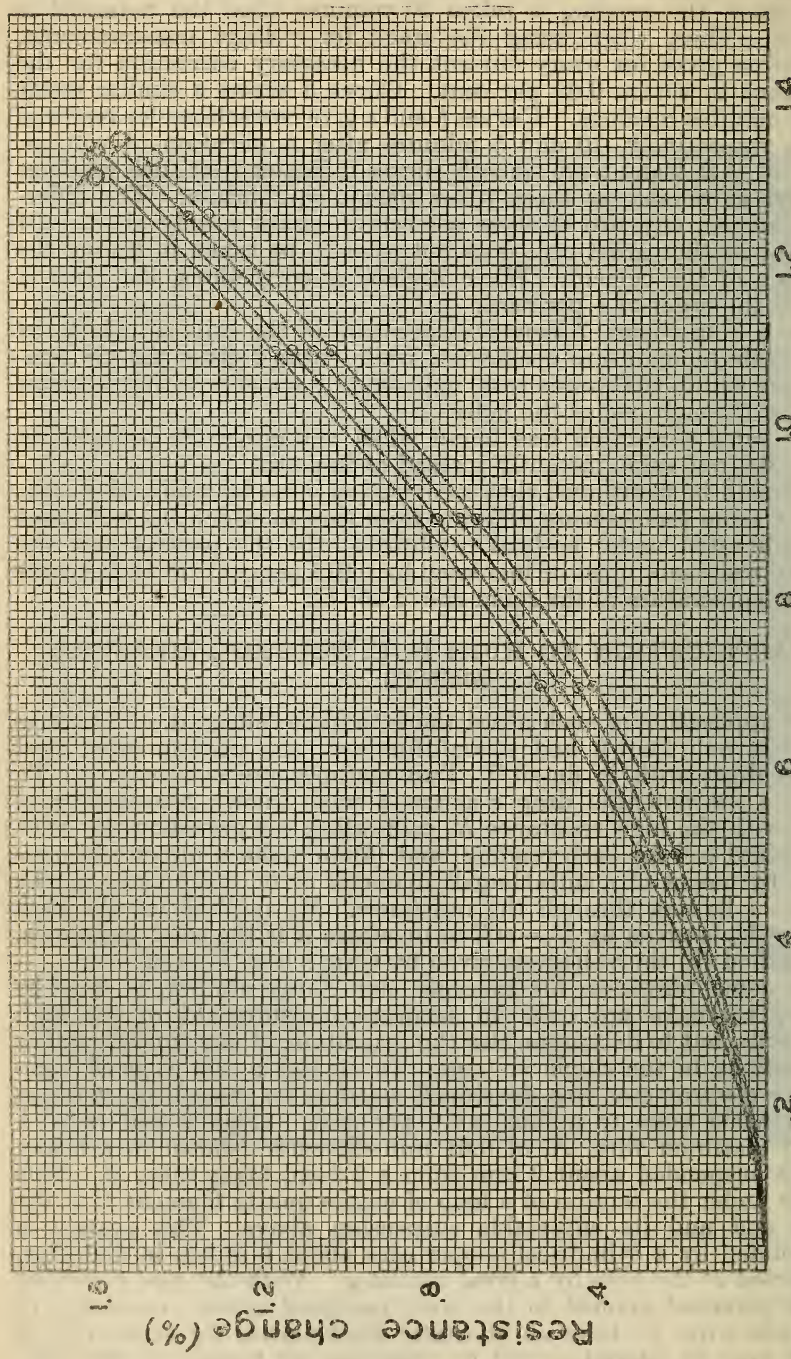

FIGURE 3.—*Curves showing the percentage correction to be added to the total resistance to correct for heating*

Voltage increased by steps.

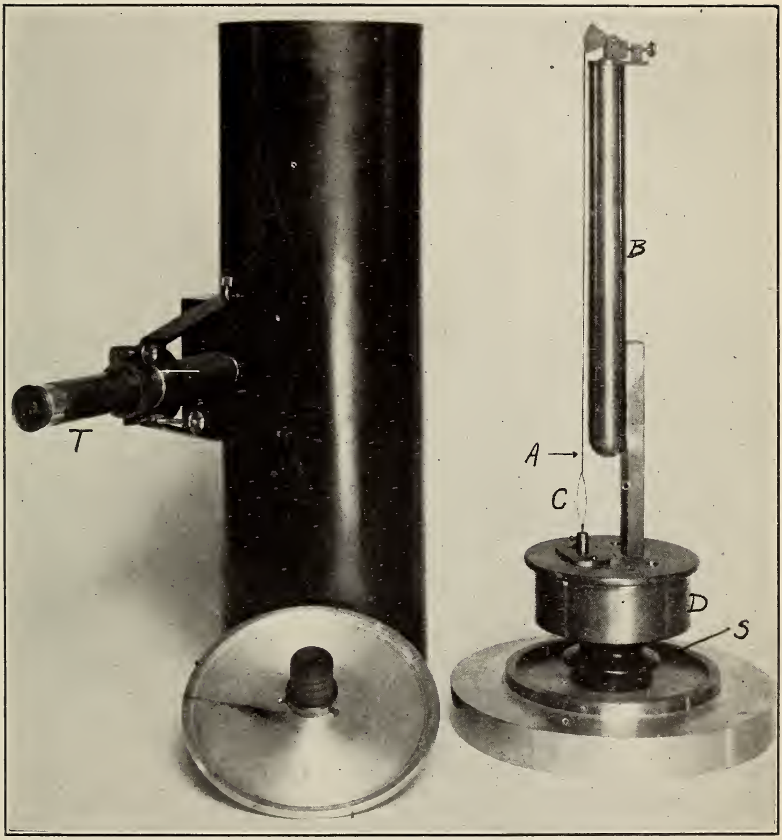

FIGURE 9.—*Details of electrometer*

Fiber and quartz loop have been drawn in so as to be visible.

The period of the wire is so short that it follows rapid fluctuations in voltage.

The displacement of the fiber is observed by means of the telescope, T, provided with an ocular scale of 100 divisions. By suitably adjusting the fiber tension the electrometer will deflect 100

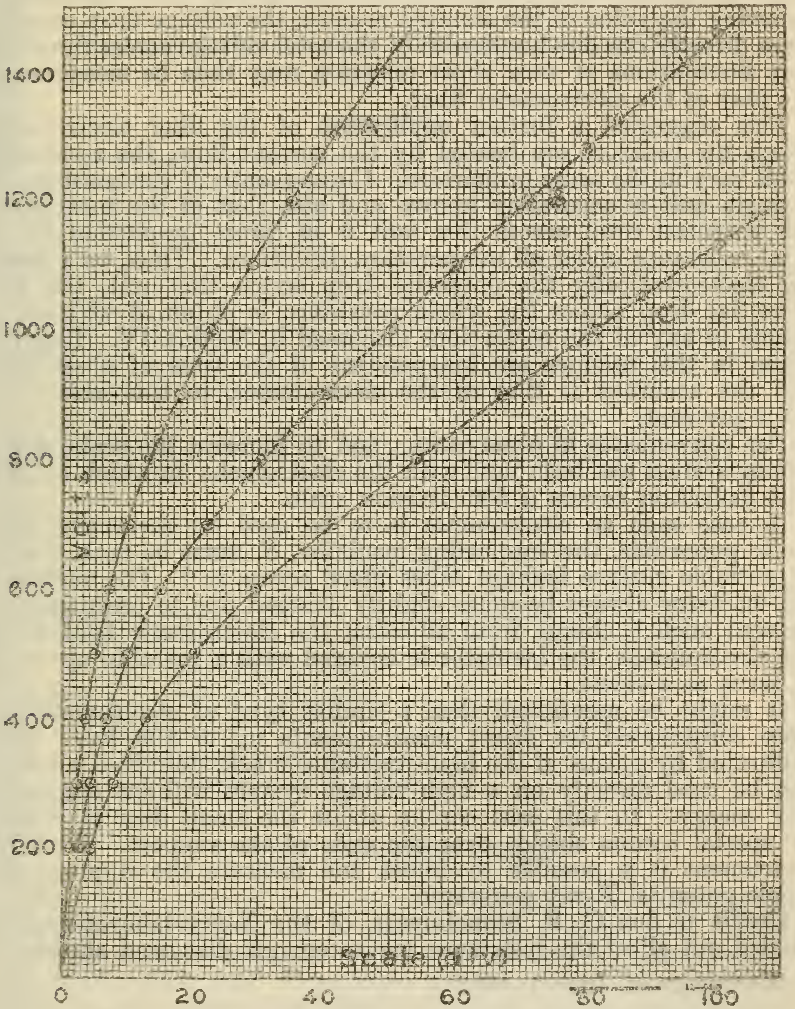

FIGURE 10.—*Calibration curves for high-voltage idiostatic electrometer*

Fiber tension for curve B less than for curve A, etc.

divisions per 1,000 volts, and readings can be readily made to within one-tenth division, which is equivalent to about 0.2 volt at the extreme end of the scale. Calibration of the electrometer is effected by means of a 1,500-volt d. c. generator. As an alternative, the zero may be set off scale and the fiber tension adjusted to bring the desired voltage range on the scale.

Figure 10 shows three calibration curves for the electrometer when the tension, t, of the fiber is changed ($t_A > t_B > t_C$). Thus, in measuring a potential of the order of 1,000 volts, the conditions represented by curve C are most suitable. In using this instrument, as suggested above, it is shunted around the last 1 megohm resistor (at the grounded end of the stack) and the electrometer case grounded. Knowing the value of the shunted resistor, the voltage drop across it gives directly one one-hundredth of the total voltage across the stack. Any fluctuations of very short duration may then be measured by the play of the electrometer fiber.

This suggested a further application of the fiber electrometer. When the resistors are heated by the current flow, the resistances of all vary in the same proportion. Consequently if the resistance of a single unit is accurately known and also that of the total stack, the potential drop across this unit is in direct proportion to the total resistance under all temperature conditions. Thus, by measuring electrostatically the potential drop across this unit, the total potential drop across the whole resistance is obtained without recourse to any of the corrections discussed in Section IV. Readings taken in this manner are independent of the time of observation and the accuracy is that of the electrometer, in this case about ± 0.1 per cent.

For convenience in observation, and to increase the scale, a projecting system has been used with the electrometer in which a 1,000-volt deflection covers a 500 division scale.

In case such an electrometer is to be used for measuring high-static potentials, the supporting insulator, S, must be such that no appreciable surface leakage takes place across it.[13] The surface of the insulator always becomes slightly charged due to creepage. To prevent such a charge from affecting the electrostatic field within the electrometer, the insulator is covered with a metallic apron, D, to serve as a shield.

It might be mentioned that a similar type of electrometer has been constructed for direct measurements up to 100 kv. When calibrated by means of the high-resistance stack, described above, it can be used directly on a high-voltage system without consuming any energy. In this case corona about the small fiber is avoided by special corona shields over the ends of the support. With this instrument it is possible to detect and measure the ripplage of a ripple potential X-ray generator.

Credit is due C. F. Stoneburner, of the X-ray laboratory, who carried out all of the resistance measurements discussed above.

WASHINGTON, June 4, 1930.

---

[13] Bakelite is unsuitable for such insulation.