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RADIO AND ELECTRICAL ENGINEERING DIVISION

MEASUREMENT OF DIRECT VOLTAGE RATIOS WITH A CAPACITIVE DIVIDER - A FEASIBILITY STUDY

O. PETERSONS

OTTAWA

NOVEMBER 1963

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ABSTRACT

A voltage divider constructed from air-dielectric capacitors has been tested for the measurement of direct voltage ratios. In this preliminary series of experiments an accuracy of 100 parts per million has been achieved at potentials up to 400 volts. The equipment is described, and the major factors contributing to errors are discussed briefly. The need for future work towards extension of the voltage range and reduction of errors is outlined.

CONTENTS

Page

FIGURES

MEASUREMENT OF DIRECT VOLTAGE RATIOS WITH A CAPACITIVE DIVIDER — A FEASIBILITY STUDY

- O. Petersons -

INTRODUCTION

Capacitive voltage dividers are quite extensively used for measuring alternating voltage ratios to high accuracy; e.g., it is possible to measure the ratios of voltage transformers to an accuracy of 10 parts per million (ppm) at voltage levels of several hundred kilovolts. Standard capacitors, which are designed for high-voltage capacitance bridges, can be used in these measurements. The success of the capacitive divider in the aforementioned application raises the question whether such a divider could be used for measuring direct voltages.

For precision measurement of direct voltages above the range of potentiometers, resistive dividers are used almost exclusively. Up to 1000 volts the well-known volt-box is used for this purpose. For higher voltages special resistors, which do not vary in value with voltage, are needed. Such a resistor, rated up to 100 kv, has been described by Park [1]. Its resistance value (nominally 10^8 ohms) is claimed to be known with an accuracy of 10 ppm at voltages up to 50 kv, and 40 ppm up to 100 kv.

A resistive divider is thus capable of giving quite high measurement accuracy. The use of such a divider in some measurements is limited, however, by the burden which it imposes on the source. For Park's divider this is 100 watts at the rated voltage, and in many applications, such as experiments with particle accelerators, burdens of this magnitude cannot be tolerated. In these applications the capacitive divider appears particularly attractive. Other applications, more of an engineering nature, include calibration of other dividers and sphere gaps at full working voltage.

Capacitive dividers have been used previously for measuring direct voltages. Hess [2] describes one such technique which is capable of yielding an accuracy of 0.1%. Potentials up to 1100 volts can be measured with his apparatus. Another method is described by Larson and Myers [3]. Their circuit (Fig. 1) was used to measure the output voltage of a van de Graaff generator. A small plate having capacitance C_1 to the high-voltage electrode is installed in the pressure vessel of the generator and connected to the input of a vibrating-reed electrometer. The feedback loop of the electrometer contains a series capacitor, the capacitance value C_2 of which is several orders of magnitude larger than that of C_1. The electrometer functions so as to maintain zero charge at its input. If the gain of the system is high, the above condition is approximately achieved, and the output voltage of the generator can be obtained in terms of the voltage on the feedback capacitor

$$E_1 = \frac{C_2}{C_1} E_2 .$$

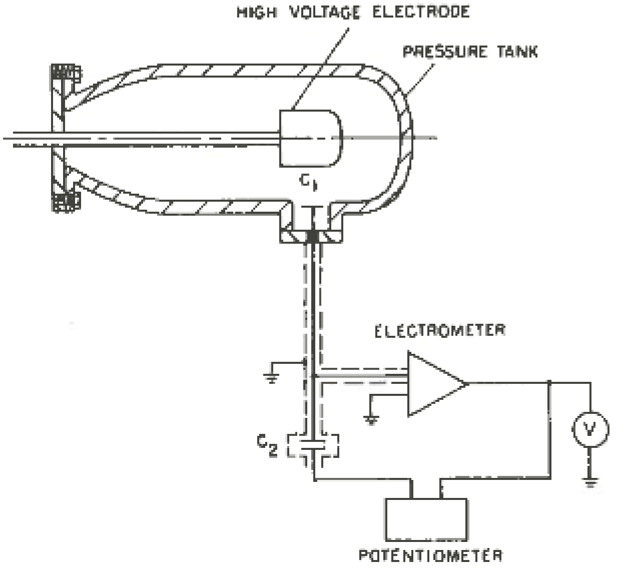


Fig. 1 Capacitive divider of Larson and Myers
for measuring voltage of a van de Graaff generator

To facilitate precise measurement of the output voltage, a potentiometer can be inserted in the feedback loop, as shown in Fig. 1. Before commencing the measurement the high-voltage electrode must be grounded and the input of the electrometer short-circuited to the output, in order to assure that no initial charge exists at the junction of the capacitors.

EXPERIMENTAL CIRCUIT

The previous investigations in the capacitive divider methods of measuring direct voltages were rather limited. The work of Larson and Myers was restricted to a specific application, and their published article contains little about the measurement accuracy and the limitations of the method. The instrumentation which was used by Hess would be considered as obsolete in relation to the standard of electrometers now available.

The objective of this investigation was to gain further knowledge about the capacitive divider method and to establish its limitations in measuring direct voltage ratios. Experimental work was carried out using standard components in a circuit (Fig. 2) which is similar to that of Reference 2. The charge on the capacitor C_1

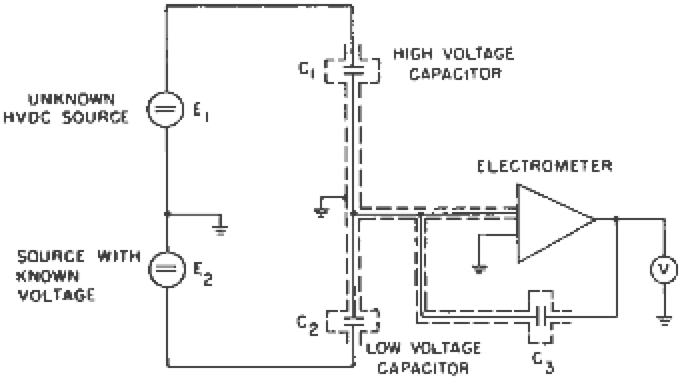


Fig. 2 Proposed circuit for ratio measurement of direct voltages

resulting from the voltage E_1 is balanced by that on C_2 due to E_2 . The electrometer, with its feedback capacitor C_3, now functions only as a null indicator. In the balanced condition of the divider there is no charge on C_3 , and therefore

$$E_1 = \frac{C_2}{C_1} E_2 .$$

By properly choosing the capacitance ratio, the value of E_2 can be kept sufficiently low to enable its measurement by a potentiometer and volt-box. The ratio C_2 / C_1 can be accurately measured by alternating voltage methods.

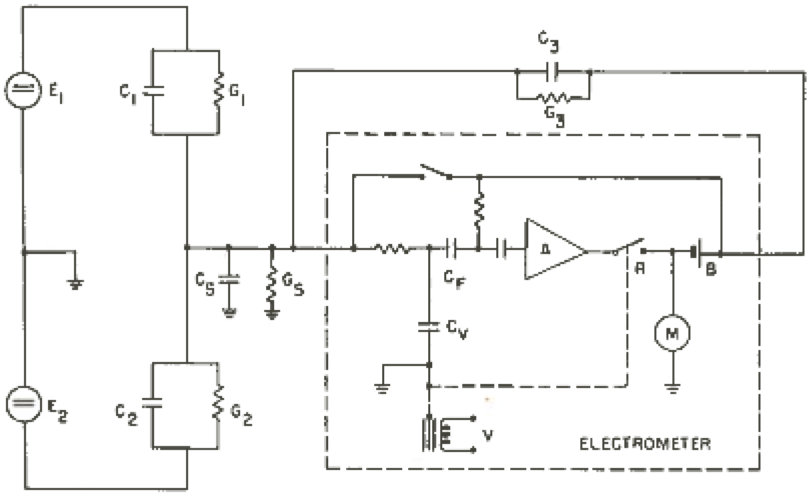
As in the circuit of Fig. 1, the balance equation is valid only if there is no charge on the capacitors prior to the application of the voltage. This condition is readily achieved by grounding the high-voltage electrodes of C_1 and C_2, and by short-circuiting the input of the electrometer to the output. The application of voltages E_1 and E_2 should be preferably simultaneous and gradual, to avoid transient voltages at the input of the electrometer. However, since feedback tends to counteract such voltages, perfect synchronism is not essential, and also small voltage steps can be tolerated. The leakage of charge in the capacitors and the related drifts in the electrometer must be kept sufficiently small so that significant error is not introduced during the time which is required for balancing the divider.

In order to evaluate the magnitude of tolerable drifts, a divider with specific component values must be considered. Assume that $C_2 = 1000$ pf and $E_2 = 100$ volts. Thus the charge on the capacitor is $C_2 E_2 = 10^{-7}$ coulombs. In the time interval which is required to balance the divider, this charge should not change by more than the tolerable error in the measurement. If this error is 10 ppm, and if the time (t) required to perform the measurement is 5 minutes, then the drift current should not exceed $10^{-5} \times C_2 E_2 / t = 3.33 \times 10^{-15}$ amperes.

The drift aspect is the most serious limitation of the capacitive divider in this application. The investigation which is described in this report, therefore, concerns mainly the measurement and study of drifts in various components which comprise the entire measuring system.

DRIFT CURRENTS

For the discussion of the causes of drift it is useful to consider the circuit of the divider (Fig. 2) in a more detailed form as shown in Fig. 3. Here capacitors are not represented as ideal circuit elements. Conductances which could account for leakage currents are included in parallel with ideal capacitors.



C_1, C_2	Divider capacitances
G_1, G_2	Effective conductances in parallel with C_1, C_2
C_s	Capacitance from input to ground
G_s	Conductance from input to ground
C_3	External feedback capacitance
G_3	Effective conductance in parallel with C_3

	Electrometer
A	A-C amplifier
B	Bias battery
C_F	Internal feedback capacitance
C_V	Vibrating capacitor
M	Voltmeter
R	Synchronous rectifier
V	Vibrator

Fig. 3 Detailed diagram of capacitive divider and electrometer

The capacitors C_1, C_2, and C_3 will normally be of the three-terminal gas-dielectric type. Thus the effective conductances G_1, G_2, and G_3 in Fig. 3 represent the conduction through gas. As it will be seen later, an equivalent conductance, which justifies inclusion of G_1, G_2, and G_3 in the circuit, can be measured experimentally. Coaxial cables which connect the capacitors to the electrometer contain solid dielectric material, the conductance of which is represented by G_s. The insulator in the input head of the electrometer also contributes to G_s.

a) Inherent Drift of the Electrometer

For the vibrating reed electrometer (Cary 31 Vibrating Reed Electrometer, Applied Physics Corp.) which was used in this investigation the drift with the input open-circuited is specified by the manufacturer to be less than 10^{-16} amperes after a 20-minute warm-up period. This value was confirmed by the test on the available instrument (Serial No. 31-1021).

The cleanliness of the insulator in the electrometer input head appears to be very important. At the beginning of the investigation a drift of 1.3×10^{-15} amperes was observed. The reduction to the specified value was obtained by blowing off the dust from the insulator.

b) Drift When External Capacitors are Connected in the Circuit

The drift, as discussed above, was obtained by leaving the input terminal of the electrometer open-circuited and covered with the dust cap. This drift, measured by the charging rate of the internal 10-pf feedback capacitor, was relatively small. Unfortunately, when external capacitors were connected to the electrometer the drift increased by at least an order of magnitude.

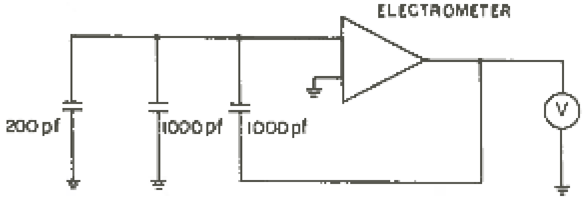


Fig. 4 Circuit for measuring ambient drifts

To investigate this effect, three air-dielectric capacitors were connected to the input of the electrometer, as shown in Fig. 4. Such a circuit, with capacitors connected to voltage sources, would be used for measuring a 5/1 voltage ratio. As the capacitors were not hermetically sealed, dry nitrogen was passed through them in order to keep the gas inside free of moisture. Under such conditions the drifts of several observations were between 5×10^{-16} and 3×10^{-14} amperes. Much larger drifts were measured when the dielectric was free air with high humidity. One measurement, taken when the relative humidity was 75%, gave a drift of 2.5×10^{-12} amperes.

It is significant that the abnormally large drift currents, which occur in high humidity conditions, are always positive, indicating that current is flowing into the input terminal of the electrometer. This behaviour would suggest that one cause of the drift is the contact potential across the vibrating capacitor. Because of this contact potential, the input terminal of this particular instrument is at -60 millivolts with respect to the grounded shields. A potential difference thus exists across the conductance G_g in Fig. 3.

Large drift currents can also be caused by dielectric absorption in the connecting cables. Electric stresses, including those caused by switching surges, should be avoided. It is equally important to avoid mechanical stresses in solid dielectric materials. To prevent mechanical deformations of coaxial conductors, all connections to the capacitors were made by rigid coaxial lines. These were constructed from standard BNC fittings.

Rather large drifts also appear to be caused by temperature changes. These drifts are too large to be accounted for by the change in capacitances with temperature. A possible explanation, which could be advanced for their presence, is the change in contact potential in external capacitors.

c) Drifts in the Divider When Voltage is Applied to the Capacitors

It was observed that significant leakage currents can exist across the electrodes of a guarded three-terminal capacitor. To measure these, the input of the electrometer was short-circuited to the output and voltage was applied to one of the capacitors. After this, the short circuit was removed and the current measured by the electrometer. Assuming that the applied voltage does not change, any current in addition to the ambient drift can be attributed to leakage across the electrodes.

The leakage currents were particularly large in the air-dielectric capacitors whose electrodes had not been cleaned for some time. Furthermore, under such circumstances they were nearly proportional to the applied voltage, indicating a constant equivalent conductance in parallel with the direct capacitance, as represented by G_1 and G_2 in Fig. 3. A leakage current of 2.2×10^{-14} amperes was observed in one 1000-pf capacitor with 150 volts applied across its electrodes. This current was doubled when the potential difference was raised to 300 volts. When the above capacitor was cleaned, the leakage current was reduced by approximately a factor of ten. It was then comparable in magnitude with the ambient drift currents.

The direct voltage level up to which the capacitors operate satisfactorily is considerably lower than the corresponding alternating voltage level. The 1000-pf capacitors which are used in a-c dividers up to 1000 volts rms, were satisfactory in d-c operation only up to 500 volts. At higher voltages there were discontinuities in the leakage current, indicating sudden discharges within the capacitor.

It is fortunate that, when the capacitors are used in a voltage divider, the leakage currents in the two arms tend to cancel each other. Of course, perfect balance of these currents would be difficult to maintain. However, the over-all leakage current will not be larger than the largest current in any one arm.

d) Drift in High-voltage Capacitors

For the sake of simplicity, the preliminary investigations were carried out mostly with low-voltage capacitors in the range from 50 to 1000 pf constructed in our laboratory. A limited number of tests were made on our 50-pf 10-kv and 5-pf 30-kv capacitors. In these capacitors the measured ambient drifts and leakage currents were considerably larger, approximately by an order of magnitude, than those which were obtained in the low-voltage capacitors. This inferior performance may have been caused by dirty electrodes. No conclusive statements can be made on the performance of compressed-gas capacitors, as only one isolated test was made on the available 250-kv unit.

CALIBRATION OF THE DIVIDER

The tests on the capacitive divider described above indicated that accuracies between 100 and 10 parts per million could be achieved in direct voltage ratio measurements. An attempt was made, therefore, to test the performance of the divider in an actual measurement. For this purpose an accurate 5/1 voltage ratio was established by means of a battery and a resistive divider which was referred to two arms of a precision Wheatstone bridge. Two General Radio resistance decade boxes served as the divider. A capacitive divider with the same nominal ratio was made up of two parallel-plate capacitors rated at 1400 volts, peak. This divider was calibrated at 60 c/s against a ratio transformer. Both dividers then were compared by using the circuit shown in Fig. 5. The maximum voltage which was applied to the dividers was limited at 500 volts by the current rating of the resistive divider. The results of the comparison indicated that an agreement of one part in 10^4 can be readily achieved. Under the most favourable conditions one part in 10^5 can be approached.

The agreement between the two dividers was better when the applied voltage was below 400 volts. At higher voltages, immediately after the application of the voltage, there was an exponential change in the output of the electrometer. The causes of this change are not known although the behaviour is similar to dielectric absorption. It is conceivable that, because of the rather large voltage step and the possibility of unequal time constants in the arms of the divider, a voltage surge can exist at the junction of the capacitors causing dielectric absorption in the connecting cables. It is planned to repeat this test by applying the voltage gradually.

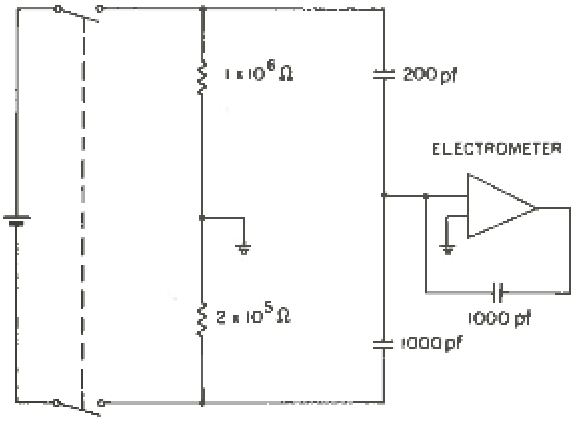


Fig. 5 Circuit for comparing resistive and capacitive dividers

FUTURE INVESTIGATIONS

The results so far have indicated that further investigation of the causes of the drifts in the divider is needed. It would be desirable to test the performance of different types of gas-dielectric capacitors. Hermetic sealing of capacitors also appears to be essential. Capacitors with inert electrode surfaces (gold-plated) may offer some advantage over those with aluminum electrodes.

The capacitors which have been used in the divider circuit so far are very crude by the standards of those which are used in the input circuit of the electrometer. Construction of such capacitors is described in Reference 4; it involves four coats of gold plate followed by the final coat which is produced by simultaneous evaporation of gold on both electrodes. Such surfaces have been found to give stable contact potentials. In particular, future tests should be concentrated on the use of high-voltage capacitors in the divider circuit. It may become necessary to construct a special capacitor for the direct-voltage work.

The investigation thus far has dealt with voltage sources which are free of ripple. In actual practice, the source may be a rectifier, and thus considerable ripple may be present. The operation of the divider under such conditions should be examined.

CONCLUSIONS

At present the results of the investigation indicate that a capacitive divider may be suitable for measuring direct-voltage ratios. In measurements at relatively low voltages (up to 400 volts) an accuracy somewhat better than 1×10^{-4} has been achieved. With presently available test data, it is difficult to estimate the accuracies which could be approached in measurements at voltages of 100 kv and higher, for which the capacitive divider, of course, would be particularly useful. In the available high-voltage capacitors the drifts are too large to permit accurate ratio measurements. However, there is no fundamental reason why drifts could not be reduced to the same level as those in the low-voltage capacitors.

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APPENDIX

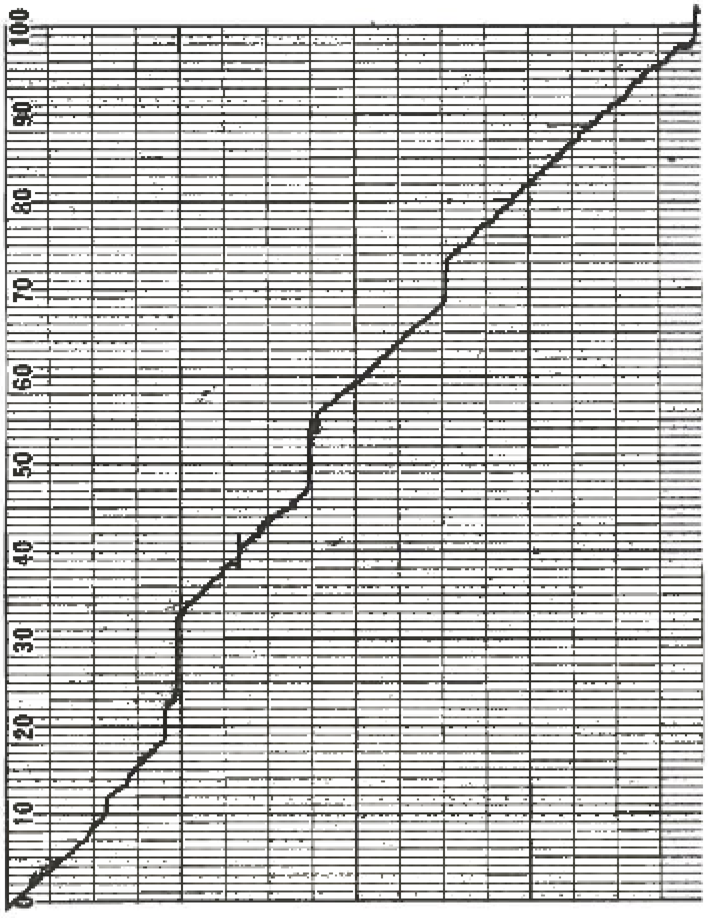
MEASURED VALUES OF DRIFT CURRENTS

The drifts in the capacitive divider and the electrometer are given in the chart records of Figs. 6 to 8. These records show the voltage on the feedback capacitor. The drift current can be obtained from the capacitance value of the feedback capacitor and from the rate of change of the voltage.

The ambient drift of the electrometer is shown in Fig. 6. It was obtained by leaving the input terminal open-circuited and covered with the dust cap. The sharp discontinuities in this record indicate the emission of alpha particles.

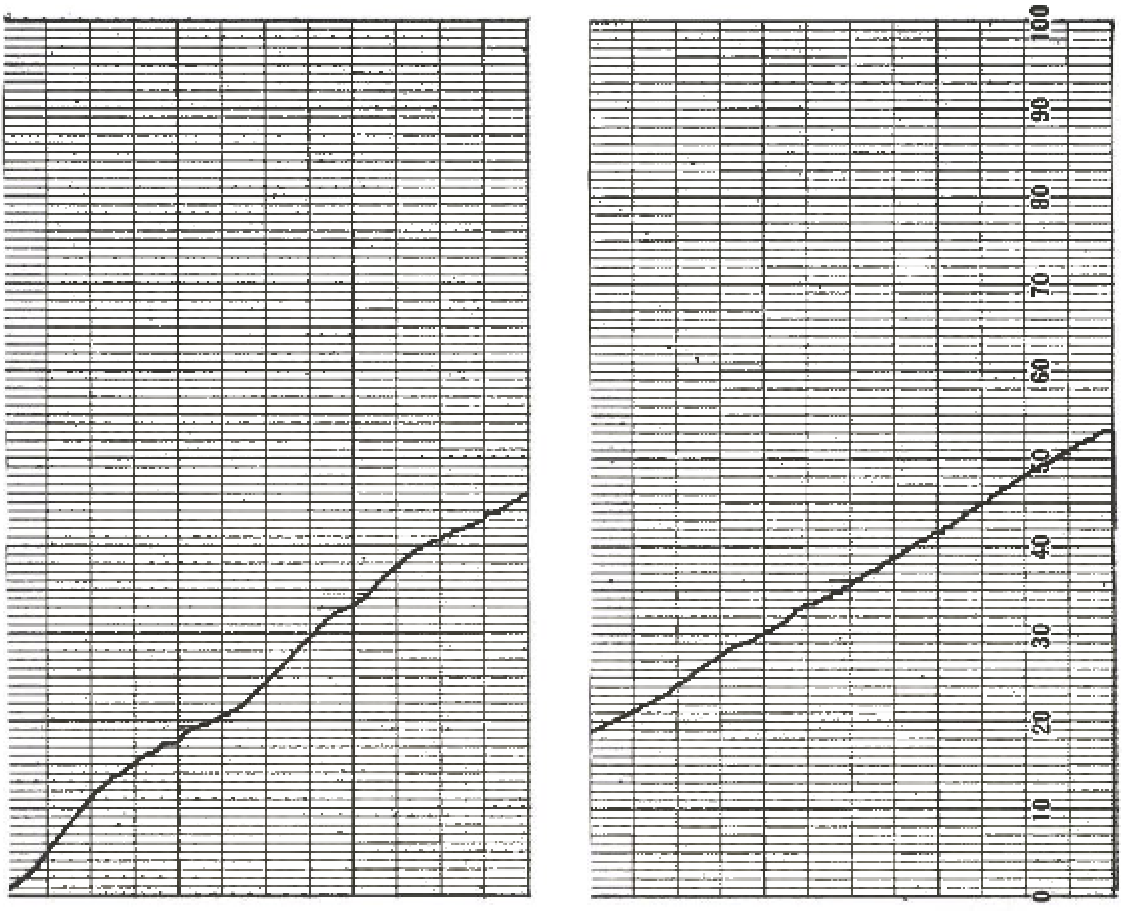
Fig. 7(a) gives the drifts when a homemade cable adaptor is connected to the input. This adaptor consists of a G.R. connector mounted in a suitable cap. Fig. 7(b) is the drift when a six-inch piece of rigid coaxial line is connected to the input. This line is supplied by the manufacturer of the electrometer.

Fig. 8 gives the drifts when three capacitors are connected to the electrometer as in Fig. 4. The external circuit includes, aside from the three capacitors, a number of BNC fittings which are used for making coaxial connections.



Vertical scale : 10 millivolts/full scale
Horizontal scale : 2 minutes/small division
Feedback capacitor : 10 pf
Current in absence of alpha emission = 3.7×10^{-17} amp
Temperature : 86°F Relative humidity : 60%

Fig. 6 Drifts in electrometer

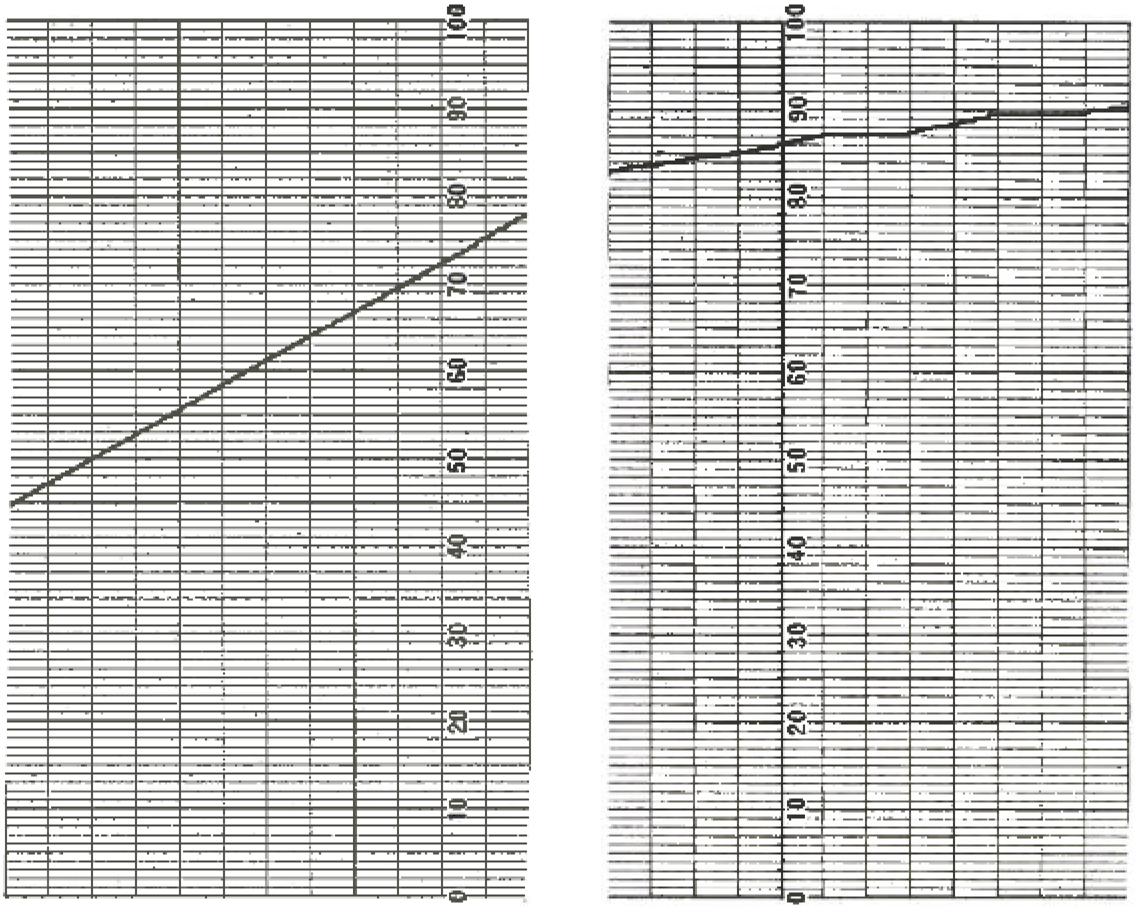


a) Coaxial cable adaptor:
Average current = 3.1×10^{-16} amp

b) Rigid coaxial line:
Average current = 2.4×10^{-16} amp

Vertical scale: 100 millivolts/full scale
Horizontal scale: 2 minutes/small division
Temperature: 86°F Relative humidity: 60%

Fig. 7 Drifts when adaptors are connected to the input



a) High Humidity Conditions
Temperature: 85°F Relative humidity: 75%
Current = 2.4×10^{-12} amp

b) Capacitors in Dry Nitrogen
Temperature: 85°F
Current = 4.9×10^{-16} amp

Vertical scale: (a) 10 volts/full scale, (b) 10 millivolts/full scale
Horizontal scale: 2 minutes/small division

Fig. 8 Drifts with external capacitors connected to electrometer