NBS TECHNICAL NOTE

349

The Design and Operation of A High Voltage Calibration Facility

WINSTON W. SCOTT, JR.

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards

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Contents

Page

List of Figures

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The high-voltage calibration facility, in operation for seven years at the National Bureau of Standards Radio Standards Laboratory (RSL) but now at NBS Washington, is described with emphasis on several novel construction features and calibration techniques. The more usual calibration techniques are also outlined for the assistance of those personnel in standards laboratories assigned the task of calibrating with high accuracy, electrostatic voltmeters, resistive dividers, and potential transformers at high voltage. Precautions, based on experience in the calibration and use of high voltage standards, are given so that certain errors may be avoided by the users.

Key Words: alternating-current, calibration, direct-current, high-voltage, ratio, safety, standards enclosure, transformer, voltage-divider, voltmeter.

1. Introduction

Visitors have asked many technical questions of the Radio Standards Laboratory which, over a period of time, have indicated a need for a published record of the design, construction, and operation of a high-voltage calibration facility. On the conclusion of the transfer of most of the equipment to the Washington, D. C. high-voltage laboratory of the National Bureau of Standards, it seems especially appropriate to describe the calibration equipment and methods for the benefit of others who have an interest in high-voltage calibration.

The facility was used for the calibration of potential transformers, electrostatic voltmeters, and high-voltage resistive dividers. Potential transformers were calibrated with uncertainties within ±0.05 percent in ratio and ±2 minutes in phase-angle at 60 Hz. Electrostatic voltmeters were calibrated within ±0.5 percent of full scale reading at d-c or 60 Hz. Most high-voltage resistive dividers could be calibrated within ±0.03 percent using direct current.

2. Design

The facility has a safety enclosure with control circuitry, a telescopic reading-aid for electrostatic voltmeter calibration, and some standards including a high-voltage resistive divider, a potential transformer, and a potential-transformer test set.

2.1 Safety Enclosure

The safety enclosure was designed for the protection of both the operator and the standards. On several occasions previous to the construction, there was exposure (although fortunately not contact) to high voltage when observers were not aware of its presence. Furthermore, because of the need to wire control circuits prior to each calibration, there was danger of miswiring and applying sudden substantial voltage to a supply transformer. Undesired transient effects could occur which could harm both the supply and potential transformers. Therefore, two design objectives for construction of a safety enclosure were formulated:

1. Equipment which contains voltages above 120 volts would be placed within a grounded metal screen.
2. Control circuitry would have features preventing unexpected occurrences of high voltage.

The first objective was accomplished by designing the a-c and d-c power supplies so that only the low-voltage circuits are outside the enclosure. All high-voltage components, including transformers, rectifiers, filters, and standards (including those under calibration) are placed behind a grounded screen for protection of the operator and others in the vicinity. A screen built from 3/4-inch No. 13 expanded steel (on a 1-1/4-inch steel angle frame) proved satisfactory and is recommended for future constructions. Entry into the enclosure is controlled by means of a sliding door which has appropriate interlocks to help prevent harmful situations. Figure 1 shows the interlock circuits and the control selector unit, which provides power to either the alternating-voltage (a-v) or the direct-voltage (d-v) control box. (Alternating-voltage and direct-voltage are designated a-v and d-v in this paper.)

In order to accomplish the second objective, four possibly harmful situations were recognized and steps were taken for their prevention. The four situations are:

Situation 1. Supply-main voltage is applied to either the a-v or d-v high-voltage supply when the sliding door is open. This is especially dangerous when personnel are working on high-voltage equipment within the enclosure.

Situation 2. Supply-main voltage is suddenly applied to either high-voltage supply when the control settings are off zero.

Situation 3. Voltage is suddenly removed from a high-voltage supply when the control setting is off zero.

Situation 4. Supply-main voltage is suddenly removed from one high-voltage supply and applied to the other supply with controls of either or both supplies set off zero.

Each high-voltage supply uses a control box to control the high-voltage supply components within the enclosure. Figure 2 is a schematic of the a-v control box, a simple item which ordinarily is not commercially available. The isolation transformer eliminates the possibility of a ground duplication or cross ground through the supply main. The coarse and fine controls are variable autotransformers. The fine control is used with a step-down transformer to add an adjustable small voltage to the voltage provided by the coarse control. The microswitch is closed when the a-v coarse control is set at zero. The d-v control box is commercially available as part of a d-v high-voltage supply and therefore is not shown. However, a microswitch was added to the d-v coarse control, as in the a-v control box.

It was considered very important to avoid situation 1, and therefore, as shown in figure 1, an interlock was provided which inserts two contactor bars between the supply main and the control boxes. The contactor bars, one for each side of the supply line, are mounted on the sliding door. The electrical contacts, which the bars short when the door is closed, are mounted on a wall of the enclosure. In addition, a patch cable is fastened to the door so that when the door is open, the supply line must be electrically open. The interlock is primarily for the protection of high-voltage equipment, while the patch cable provides positive protection to personnel.

Situations 2, 3, and 4 endanger the reliability of the transformers and other standards. For example, a standard might not be dependable if excessive voltage were applied. In figure 1, a solenoid-operated latch prevents the sliding door from opening or closing the interlock until the solenoid is energized. Proper control of the solenoid helps prevent situations 2 and 3. Each coarse control has a rotatable voltage-pickup arm which can be made to operate microswitches. The microswitches, as previously described, close whenever the coarse controls are at zero setting. This arrangement insures that the solenoid-operated latch does not allow the door to be opened or closed unless high voltage within the enclosure is absent. The patch cable, which can be disconnected only after the interlocks are opened, serves to provide the same certain protection as pulling an electrical outlet plug.

Situation 4, which occurs when switching high-voltage supplies with high voltage present, is prevented with the help of the control selector unit shown schematically in figure 1. The control-selector unit contains an av-dv transfer relay, a control selector switch, a microswitch, and lamps that indicate which control box is energized. The a-v control box has power when the av-dv transfer relay is energized. But the relay will not energize unless the control selector switch is closed and the a-v coarse control indicates zero. The microswitch is mechanically arranged so that it is in the #1 position when the a-v coarse control indicates zero, and is in the #2 position when the control indicates other than zero. Ordinarily, once the relay is energized, a holding circuit keeps it energized for all non-zero settings. However, should a power failure occur on the supply main, and the potential transformer is energized, the relay will de-energize. When the failure is corrected, as most often happens within a few seconds, the relay will not energize until the a-v coarse control is turned to zero, thereby preventing possible further damage to the transformers. Unfortunately, no way has been found to prevent the initial sudden voltage change. This points out the advisability of keeping a reference standard available so that if a working standard is suspected of change, an intercomparison can be made.

2.2 Remote Reading System

In order to enclose fully all high-voltage equipment, including electrostatic voltmeters, (objective 1), a system had to be devised to read the electrostatic voltmeters from outside the enclosure. The electrostatic voltmeters referred to are portable high-voltage standards in the 1 percent and 1/2 percent accuracy classes and have scales marked on a cylindrical surface which covers an arc of about 80 degrees. The major problem in accurately reading this type of scale is to reduce satisfactorily the effect of parallax error. The following system was devised for remote reading. The electrostatic voltmeter is placed on a turntable which can be rotated at about one-half rpm in either a clockwise or counterclockwise sense. Two tapping keys control the sense and amount of rotation. A telescope with a magnification of about 20 is used to read the scale from outside the screen. If the screen is within about one-half meter of the telescope objective, the view of the scale is not blocked, although the scale must be artificially illuminated for good visibility. Most electrostatic voltmeters built today have mirrored scales for the reduction of parallax error. To obtain an accurate reading, it is necessary to focus the telescopic image of the scale and to rotate the turntable so as to place the pointer over the pointer reflection. The system is most convenient to use when the telescope is aimed at the axis of rotation of the turntable and the moving-system axis of the electrostatic voltmeter is approximately both collinear with the turntable axis and vertical.

3. Calibration Techniques

3.1 A-V Measurements

The high-voltage calibration facility permits two types of a-v measurements: alternating-voltage and alternating-voltage ratio. Figure 3 is the schematic used for a-v calibration of an electrostatic voltmeter. The standard transformer is a supply transformer and an instrument potential transformer in one container and therefore has two sets of windings. One set of windings transforms low voltage (obtained through the a-v control box from the power main) to high voltage for supply purposes while the other set accurately transforms the high voltage to a low level suitable for reading with a low-range standard voltmeter. The high voltage is accurately determined from the exact potential-transformer winding ratio (corresponding to the burden imposed by the standard voltmeter) and the standard voltmeter correction. This voltage is then compared with the indication of the electrostatic voltmeter to obtain the correction. Correction (kv) = Actual Voltage - Voltmeter Indication. When the electrostatic voltmeter is used for measurement, the actual voltage is the sum of the voltmeter indication and the correction.

Alternating-voltage ratio measurements are used in the calibration of instrument potential transformers. Figure 4 shows the interconnection between a potential transformer under calibration and the standard transformer, burden box, and a potential transformer test set. The potential transformer test set [Harris, 1952] is used to determine differences in ratio and phase angle (at a given frequency and burden) between the transformer under calibration and the standard transformer. The burden box may be adjusted for resistive (or resistive and inductive burdens) up to the volt-ampere rating of the transformer under calibration. In using the two transformers, one side of both high-voltage and low-voltage windings is connected to ground potential so that, if insulation breakdown between the high voltage and low voltage circuits should occur, the observer is protected. Furthermore, certain undesirable electrostatic effects are avoided. The ratios and phase angles of potential transformers are generally very stable with time and if the standard is treated with normal care, a typical recalibration interval might be about five years. However, as suggested earlier, it is always wise for the user to intercompare standards in his own laboratory more often, to check his measurement technique occasionally and to discover whether his standards are changing with time.

3.2 D-V Measurements

Both direct-voltage measurements and direct-voltage ratio measurements are of interest in high-voltage calibration laboratories. Figure 5 is the schematic of the circuit used in the direct-voltage calibration of electrostatic voltmeters. The high-voltage resistive divider (or Park divider) is of special construction [Park, 1962] to control leakage and temperature errors to within about ±50 ppm under laboratory conditions. The design incorporates 100 shielded one-megohm wire-wound resistors connected in series and arranged in the form of a vertical helix between a ground plane and a toroidally shaped corona cap. Connections are provided to allow application of convenient voltages up to 100 kv, with rated or near rated current in selected resistor-pairs on the helix. Each resistor-pair effectively has zero temperature-coefficient because of matching one resistor of positive coefficient with another of negative coefficient [Park, 1962]. The four-terminal resistor is of sufficient value (often 100 ohms) to develop convenient voltage (100 millivolts) for the d-c potentiometer.

Two observers are used to calibrate an electrostatic voltmeter. One observer adjusts the d-v control box until the pointer is deflected to the desired scale division at which time the second observer adjusts the d-c potentiometer and obtains the voltage reading. The current through the four-terminal resistor is the voltage drop, accurately determined by the d-c potentiometer, divided by the actual four-terminal resistance. If, as determined by current "in"-"out" tests [Park, 1962], the current is sufficiently uniform throughout the H-V resistor, then the product of the current and the resistance gives the voltage. This is the voltage applied to the electrostatic voltmeter.

Direct-voltage-ratio measurements are used in calibrating high-voltage resistive dividers. The divider under calibration is compared with another divider which serves as a standard. The standard divider consists of the H-V resistor, described earlier, and a conveniently selected four-terminal resistance standard connected in series. The NBS standard divider has been carefully studied for sources of systematic and random errors [Park, 1962]. For example, a Direct Reading Ratio Set [Brooks, 1962] was used in conjunction with two one-megohm resistance standards to help determine the value for each resistor-pair of the H-V resistor. These measurements were periodically performed using low voltage (approximately 90 volts). The four-terminal resistance standard was calibrated at the same time. A check for current uniformity and related current leakage was made. Finally, temperature coefficients were investigated for the H-V resistor. The study showed that the standard divider, after low-voltage resistance corrections had been applied, was suitable for measurements within ±0.01 percent uncertainty without applying further corrections. If the divider under calibration is carefully constructed, then the low-voltage resistance determinations will remain valid for high voltage use. However, some dividers are constructed with large-valued resistors which have large temperature coefficients. In those cases, because of significant resistance changes resulting from joule heating, several measurements of the divider are necessary to determine the ratio as a function of time after "turn-on".

To compare high-voltage resistive dividers at rated or near rated voltage, one of two simple methods was used. For both methods, the ratio of the NBS standard was conveniently adjusted to approximate the ratio of the divider under calibration by selecting the proper number of resistor-pairs and choosing a convenient nominal value for the four-terminal resistor. The first method (later abandoned) consisted of connecting each divider input across the high-voltage supply and determining the divider output voltages separately with a d-c precision potentiometer. Disadvantages were that a highly precise potentiometer was required to obtain enough significant places, and a well-regulated high-voltage source was required to obtain a stable galvanometer null.

The second method makes use of a very simple and inexpensive Lindeck potentiometer [Oliver, 1955] and does not require a highly regulated high-voltage source for precise measurements. As shown in figure 6, a Lindeck potentiometer generates a voltage which, at galvanometer balance, equals the voltage at the terminals of the selector switch. For two dividers which have the same nominal ratio, the voltage will be small (usually millivolts). The voltage polarity necessary for galvanometer balance is controlled by the reversing switch. The Lindeck balance voltage is the product of the four-terminal resistance R_p and the milliammeter indication I. For the two positions of the selector switch, the corresponding Lindeck voltages are designated e_1 and e_2. If the voltage drops across the leads from resistors D and B to ground are equal then $e_2 = 0$. The voltages e_1 and e_2 can be obtained very precisely, even in the presence of short-time power supply variations. If the voltages V_1 and V_2 (fig. 6) are increasing or decreasing in the same manner, their difference tends to remain constant. The more nearly equal the two voltages are, the better the stability of their difference. The stability is directly observable on the galvanometer. If the galvanometer indication drifts, the ratio of the voltage divider under calibration is changing, provided the standard voltage divider is stable. From appendix 1, the exact ratio X for the voltage divider under calibration is:

$$X = X_n\left(1 + s + \frac{e_1 - e_2}{V/S_n}\right)$$

where X is the voltage ratio V_i/V_o of the voltage divider under calibration.

X_n is the nominal ratio of the voltage divider under calibration.

s is the correction to the standard voltage divider in ppm.

e_1, e_2 are the difference voltages as determined by the Lindeck potentiometer.

V is the voltage applied by the high-voltage power supply.

S_n is the nominal ratio of the standard voltage divider.

4. Discussion

Various experiences in the use and calibration of high-voltage standards are discussed here so that the user may properly account for certain sources of measurement error. Especially considered are some of those sources not usually accounted for in the calibration process.

In the calibration of electrostatic voltmeters, the practice is to zero the instrument and then take two measurements at each of five cardinal scale divisions spaced conveniently across one range. One set of measurements is taken while increasing the voltage and then the other set is taken while decreasing the voltage. The results are then averaged. For a calibration using direct-voltages, the first and second determinations occasionally differ by an amount which seems related to the time interval between determinations. Further study usually reveals that this drift in voltage indication is caused within the electrostatic voltmeter. Figure 7 illustrates the change of power supply voltage with time necessary to keep a constant indication for a particular electrostatic voltmeter. One exceptionally faulty electrostatic voltmeter drifted about 1 percent in 17 minutes. This defect, when observed, can occur with either polarity of d-v and generally is in a downscale direction with constant voltage. The defect creates no problem if the voltmeter is used on a-v. Such drift can be eliminated by replacing a feedthrough insulator, which insulates from case ground a conductor bringing high voltage to the stator within the electrostatic voltmeter. Some insulators apparently become charged thereby distorting the electrostatic field within the voltmeter. The user can check his own electrostatic voltmeter by connecting in parallel another voltmeter or, for more precise results, a high voltage resistive divider. Any drift in the second voltmeter or in the divider may be effectively eliminated beforehand by applying the test voltage for 30 to 60 minutes. Then any drift which occurs after connection can be attributed entirely to the electrostatic voltmeter being tested. This procedure is of particular interest to those who desire to use an electrostatic voltmeter to help hold a particular direct-voltage constant for an interval.

It is good operating practice, during calibration, to gently tap those instruments having jewel and pivot bearings in order to avoid possible error from pivot friction. Because the voltmeter under calibration is placed inside the safety enclosure, a special method was devised to tap the instrument. This was accomplished by placing a tennis ball at one end of an insulated rod and inserting this combination through the mesh of the enclosure. The mesh served as a fulcrum. In one instance, excessive pivot friction caused a change of nearly 2 percent of full scale deflection when the voltmeter was tapped. Instruments with a large amount of pivot friction should, of course, be repaired.

A less noticeable source of measurement error in an instrument is an unbalanced deflection system. The voltmeter reading should not depend on the degree of instrument leveling. Sometimes this occurs, however, because a balance weight has shifted position. On one occasion, a faulty electrostatic voltmeter was first calibrated at full scale while level. Then one side was elevated 5 mm, and it was recalibrated, with the zero reset in each case. The two calibrations differed by 1.2 percent. The instrument calibration made under one condition of leveling, is not valid under other conditions. Repeated measurements in the same position would not reveal this source of systematic error.

Other sources of systematic error may exist, such as the rotational position or exact in-out position of the slide used to change ranges in the instrument. However, in the author's experience, these effects are less significant than the d-v drift problem. It is emphasized that many electrostatic voltmeters do not have these problems. However, unless each instrument is checked for sources of systematic error and the large sources are accounted for, the user may be seriously misled in regard to the measurement accuracy achieved.

One problem in calibrating high-voltage resistive dividers is that of resistance change due to self-heating. In particular, the resistance change between "cold" and "warm" conditions depends on the temperature-coefficient of the resistance material used. Most older high-voltage resistive dividers were built of material which had a sizable temperature-coefficient, and therefore these dividers were difficult to calibrate. Some of these dividers changed as much as 0.2 percent in ratio in 30 to 45 minutes before reaching temperature equilibrium. In these cases, it is necessary to relate the resistance of the divider to both the applied voltage level and the time from initial turn-on. It is obvious that a calibration at low-voltage, such as that obtained using a direct-reading ratio set, would not be valid at rated high voltage. The high-valued resistors in one divider had been immersed in oil, apparently in an effort to reduce temperature effects. However, in thirty minutes the ratio changed by about 0.03 percent, and temperature equilibrium was not obtained even after two hours of operation.

Other high-voltage dividers of more successful design have been seen recently. One divider, built by a company laboratory following the Park design, had heating effects of less than 0.005 percent in thirty minutes of operation. Another divider, using unshielded construction, showed a similar lack of ratio dependence on heating but was rated for use at only 10 kv.

Figure 8 is a photograph of the high-voltage calibration facility. The laboratory personnel are calibrating an electrostatic voltmeter using direct-voltage. The standard transformer and Park divider are within the enclosure. The d-v and a-v control boxes are on the bench. The potentiometer, standard voltmeter, and potential transformer test set are inset just below the bench.

5. Conclusion

A high-voltage calibration laboratory should provide for the safety of its personnel and standards. Methods and aids can be developed for accurate comparisons of high-voltage standards. The National Bureau of Standards provides calibration services for suitable standards and enables the calibrator to tie his comparative measurements to the NBS standards. However, even an NBS calibrated standard must be used correctly by observant personnel who are alert to conditions which could unknowingly alter the calibration.

6. Acknowledgements

The author gratefully acknowledges the work of David S. Bailey and Kenneth V. Ballard. Mr. Bailey designed and placed into operation the remote reading system. Mr. Ballard wired the control circuitry and contributed to its design.

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8. Appendix

Derivation of Equation used in Calibration of High-Voltage Resistive Dividers

This derivation is presented to help the reader more fully understand the method described in the text for calibrating a high-voltage resistive divider by comparison with a standard resistive divider.

Figure 9 illustrates certain sources of error inherent in the bridge circuit components of figure 6. Resistors A and C are one megohm or larger, depending on rated voltage and ohms-per-volt criteria, while resistors B and D are in the order of 100 ohms. The distributed leakage resistance to ground from resistor C is represented by r_1. This leakage effect, as well as corona effects, makes the current through the high resistance nonuniform. Current uniformity can be determined at high voltage by the current "in" vs. "out" method described by Park [1962]. In standards using modern insulating materials and electrode designs, this current leakage usually is negligible. Leakage current between the turns of resistor C also occurs and is represented in figure 9 by r_2. The effect of r_2 on the adjustment of resistor C is accounted for in the calibration of the divider. For a stable divider resistance r_2 must be stable. The resistances r represent lead resistances which can be treated as part of the internal resistance of the power supply and are of no practical concern. The lead resistances r_3 are small (usually much less than an ohm) compared with the megohms of resistor C and if neglected will cause an error in measurement of less than one part per million (ppm). The primed quantities can be treated in a similar manner. However, lead resistances r_4 and r_4', if they differ by 0.01 ohm or more, are significant compared to resistances D and B. In fact they could cause a measurement error of 0.01 percent (100 ppm) or larger unless accounted for. The described calibration method eliminates this source of error and does not restrain r_4 and r_4'.

The exact ratio X of the voltage divider under calibration can be expressed in terms of the nominal ratio X_n, the voltages e_1 and e_2 shown in figure 10, the correction s to the standard voltage divider, the nominal ratio of the standard S_n, and the applied voltage V. If D and B are high quality four-terminal resistors, such as the Thomas type, and if voltages e_1 and e_2 are determined using a Lindeck potentiometer, then voltages e_1, e_2, and V can be expressed in terms of bridge elements as follows (see note 1):

$$e_1 = Di_1 + r_4 i_1 - r_4' i_2 - Bi_2$$

$$e_2 = r_4 i_1 - r_4' i_2$$

or

$$e_1 - e_2 = Di_1 - Bi_2$$

But $i_1 = \frac{V}{C + D}$ and $i_2 = \frac{V}{A + B}$. Thus

$$\frac{e_1 - e_2}{V} = \frac{D}{C + D} - \frac{B}{A + B} = \frac{1}{S} - \frac{1}{X}$$

where S and X are the exact ratios of the standard and "unknown" dividers. Solving for X,

$$X = \frac{S}{1 - \frac{e_1 - e_2}{V/S}} \doteq S\left(1 + \frac{e_1 - e_2}{V/S}\right) \qquad (1)$$

As mentioned in the text, the nominal ratios of the two dividers must be equal ($X_n = S_n$) and therefore $e_1 - e_2$ is very small compared with V/S (see note 2).

Since $S = S_n(1 + s)$, substituting into (1) and simplifying (see note 3) gives

$$X = X_n\left(1 + s + \frac{e_1 - e_2}{V/S_n}\right) \tag{2}$$

Equation (2) is useful for dividers of ratio 10,000:1 or larger because resistances r_3 can be neglected.

Note 1

In figure 10, e_1 and e_2 are considered positive when the high-voltage supply is connected as shown and the terminals connected to the standard are more positive than similar terminals connected to the divider under calibration.

Note 2

From the algebra of small numbers, if

$$\left|\frac{e_1 - e_2}{V/S}\right| = |u| \leqq 0.001,$$

then

$$\frac{1}{1 - u} = \left(\frac{1}{1 - u}\right)\left(\frac{1 + u}{1 + u}\right) = \frac{1 + u}{1 - u^2} = 1 + u$$

because u^2 contributes a very small error (1 ppm or less) to the result if it is neglected.

Note 3

If $|u| \leqq 0.001$ and $|s| \leqq 0.001$, then $(1 + s)(1 + u) = 1 + u + s + us = 1 + u + s$ because us contributes a very small error (1 ppm or less) to the result if it is neglected.

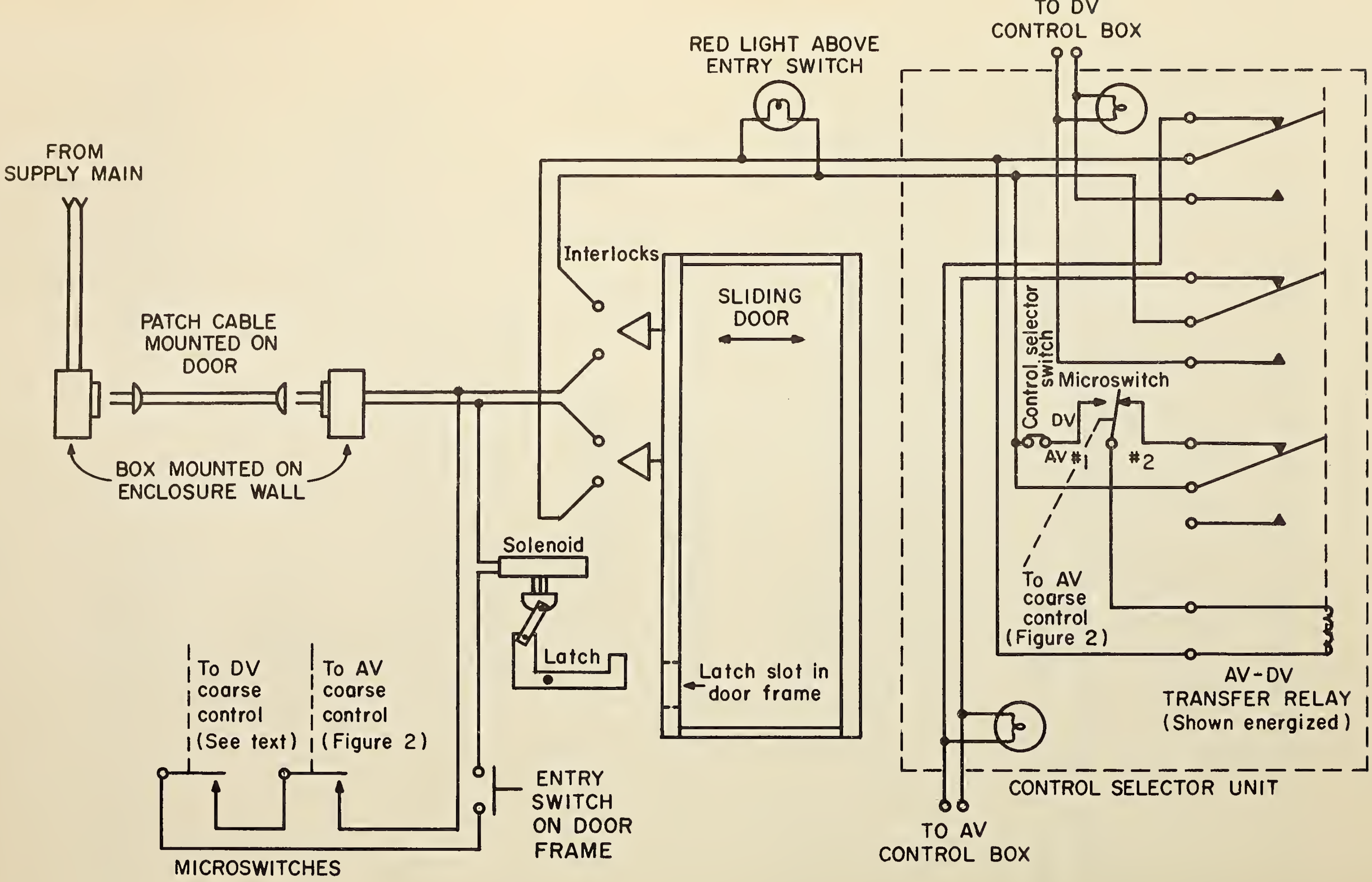

FIG. I CONTROL SELECTOR UNIT AND INTERLOCK CIRCUITS

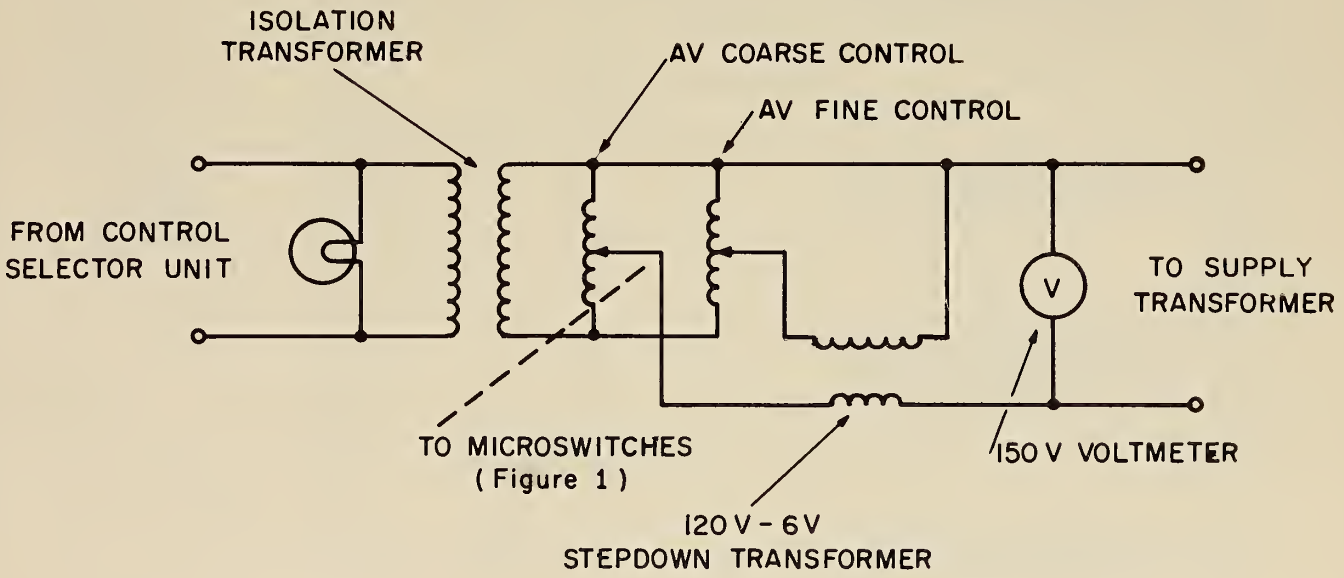

FIG. 2 AV CONTROL BOX

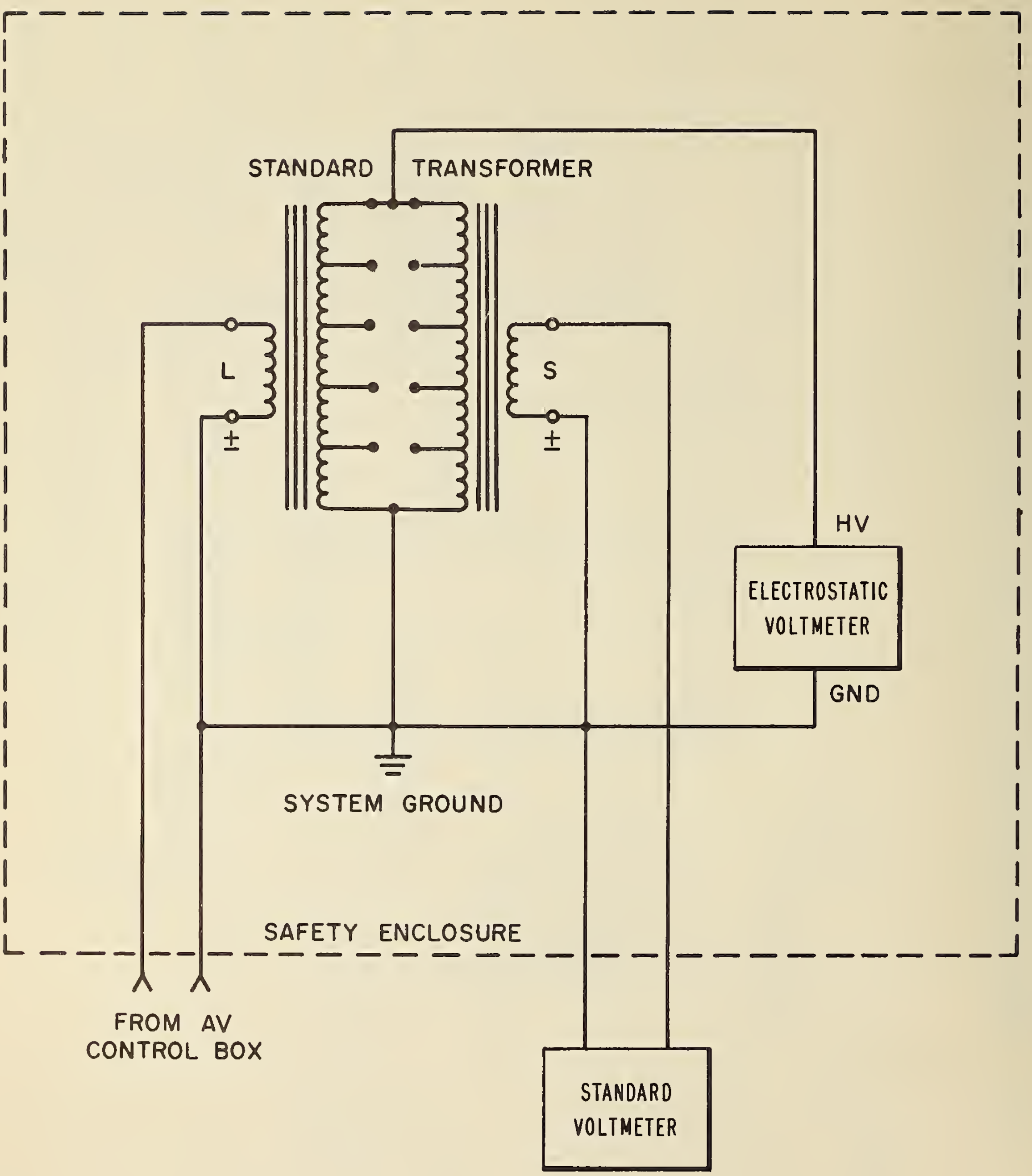

FIG. 3 AV CALIBRATION OF ELECTROSTATIC VOLTMETERS

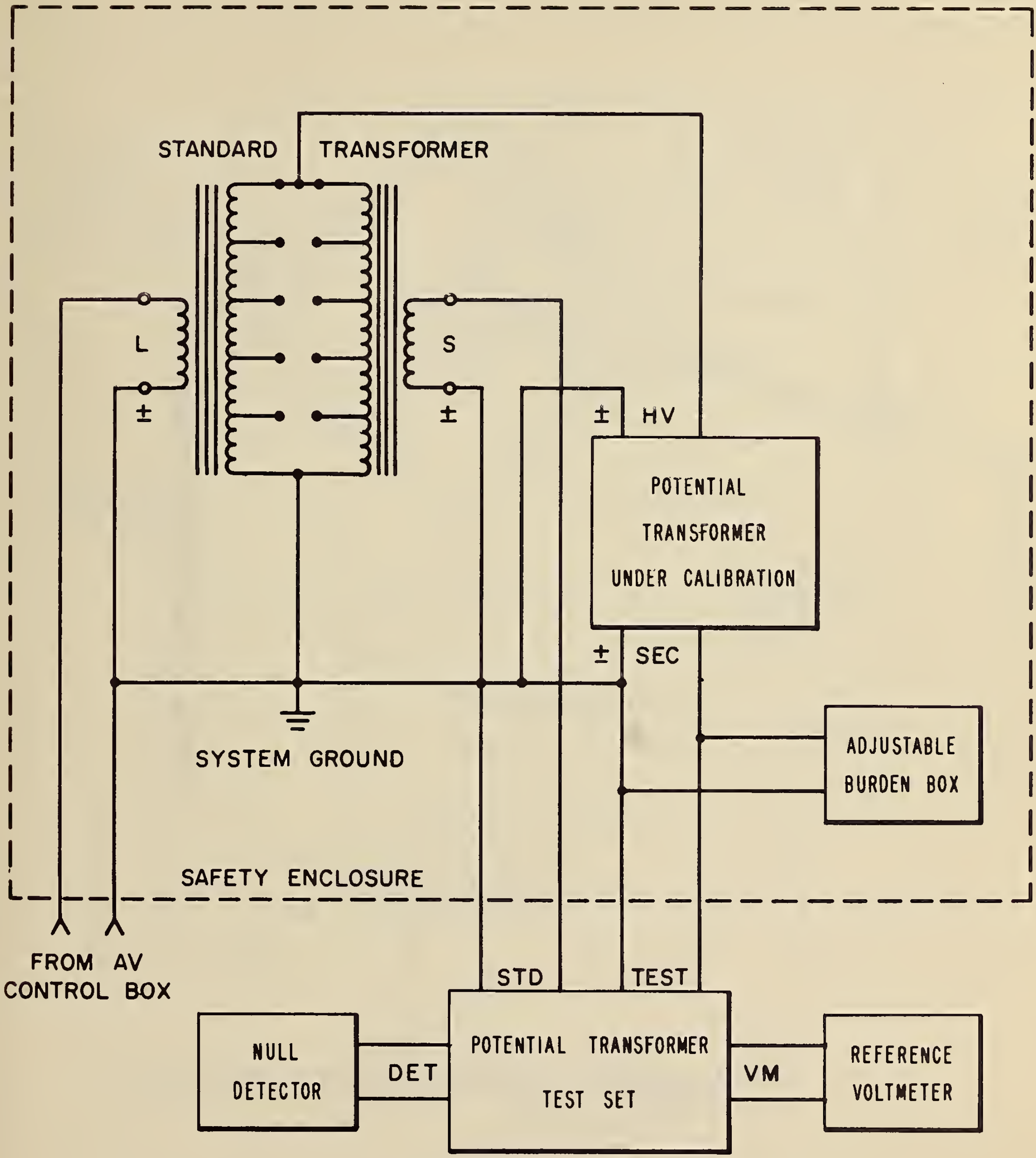

FIG. 4 CALIBRATION OF POTENTIAL TRANSFORMERS

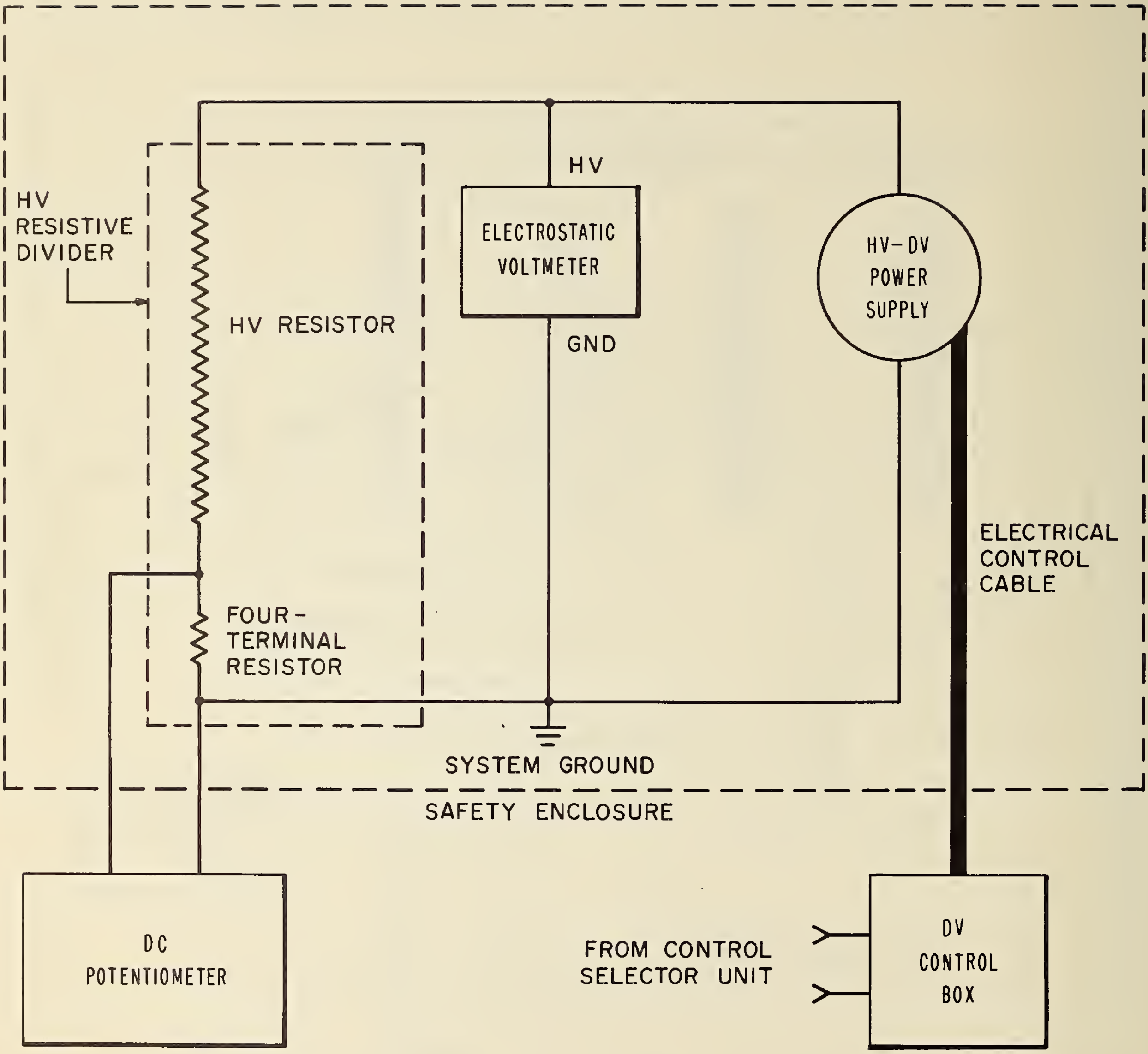

FIG. 5 DV CALIBRATION OF ELECTROSTATIC VOLTMETERS

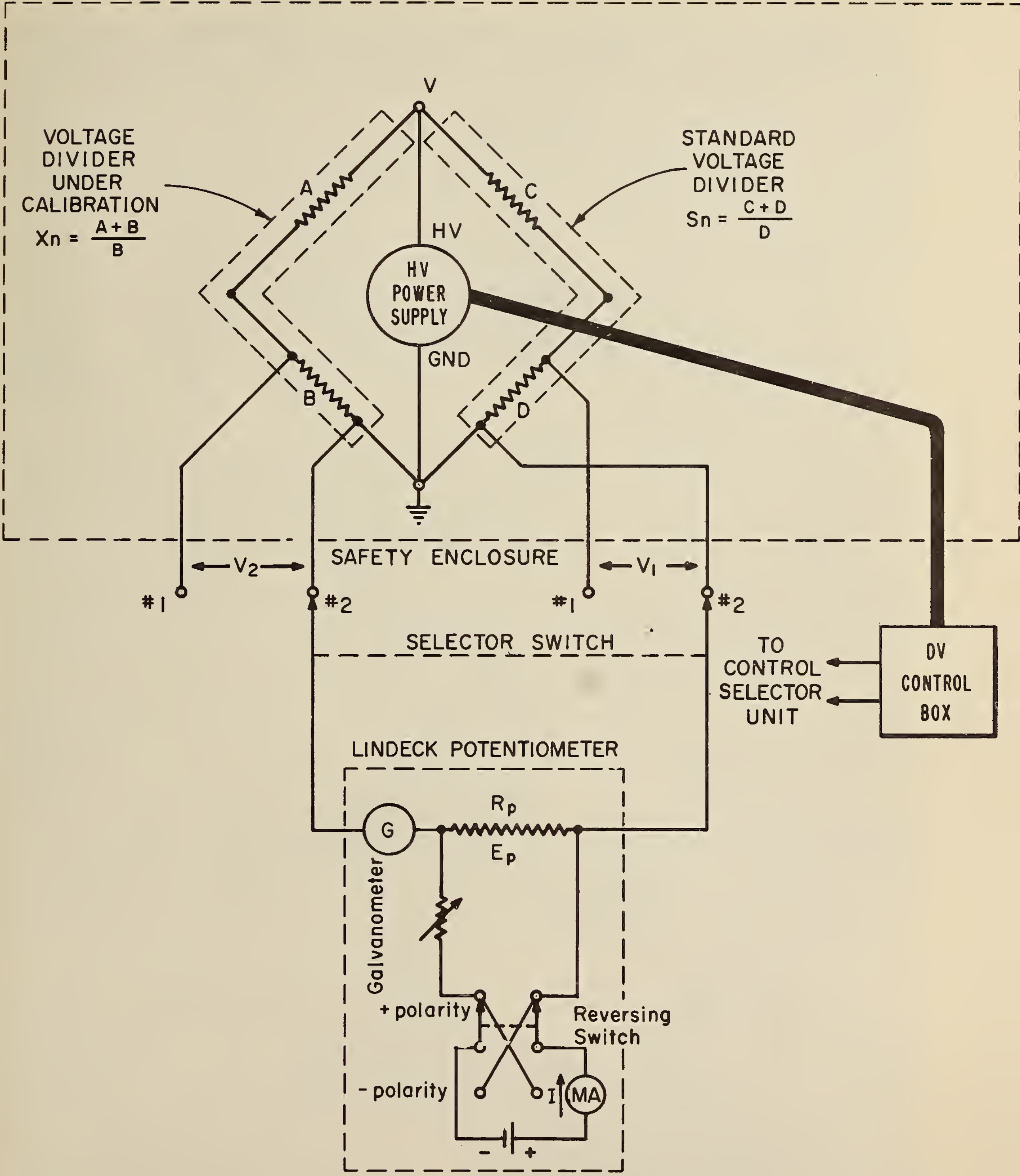

FIG. 6 DV CALIBRATION OF HV RESISTIVE DIVIDERS

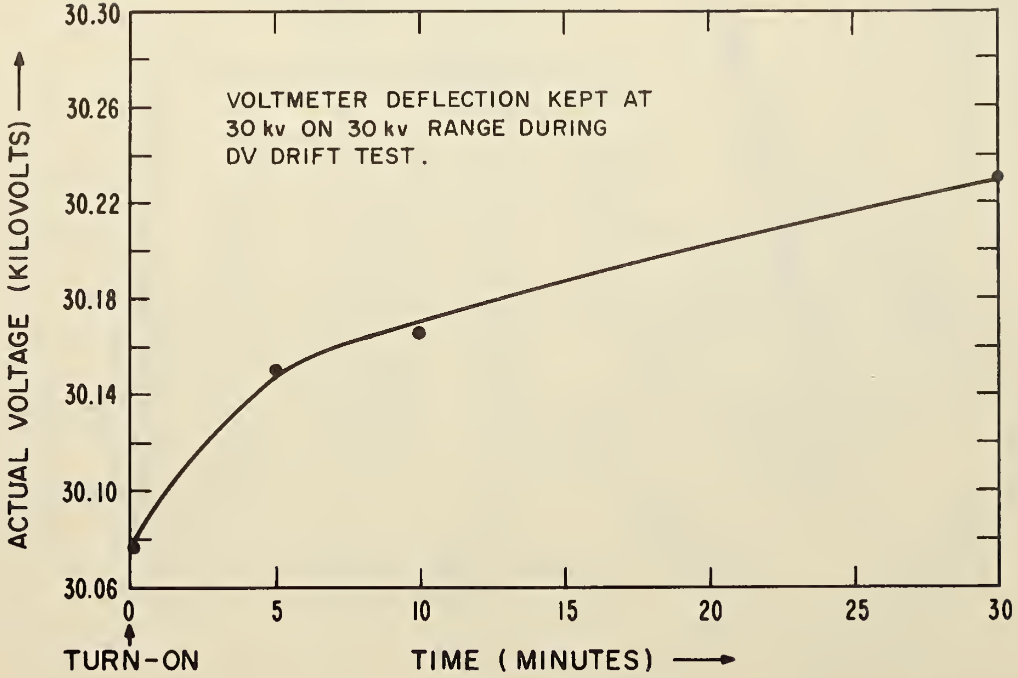

FIG. 7 ELECTROSTATIC VOLTMETER DRIFT

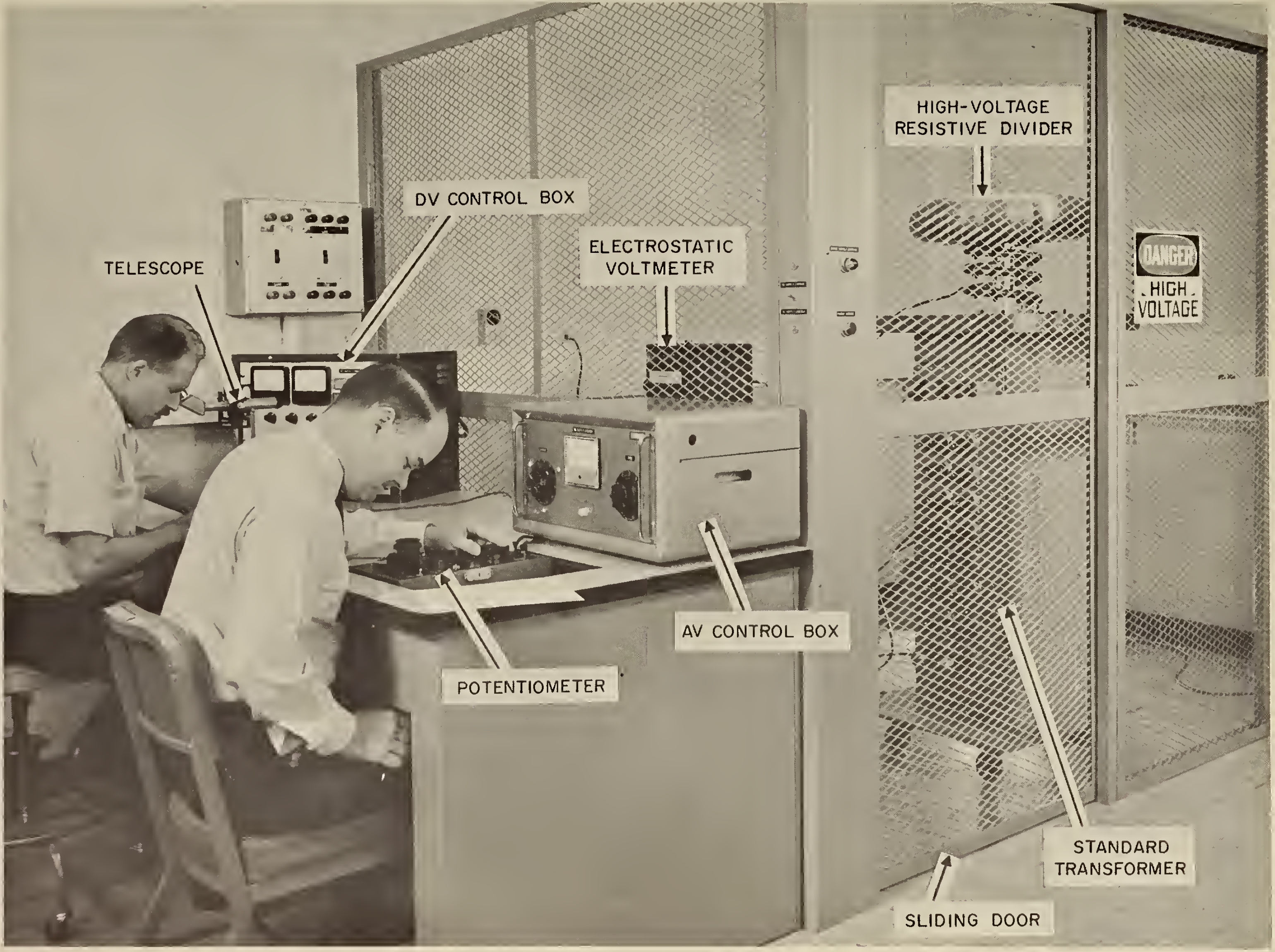

FIG. 8 HIGH VOLTAGE CALIBRATION FACILITY

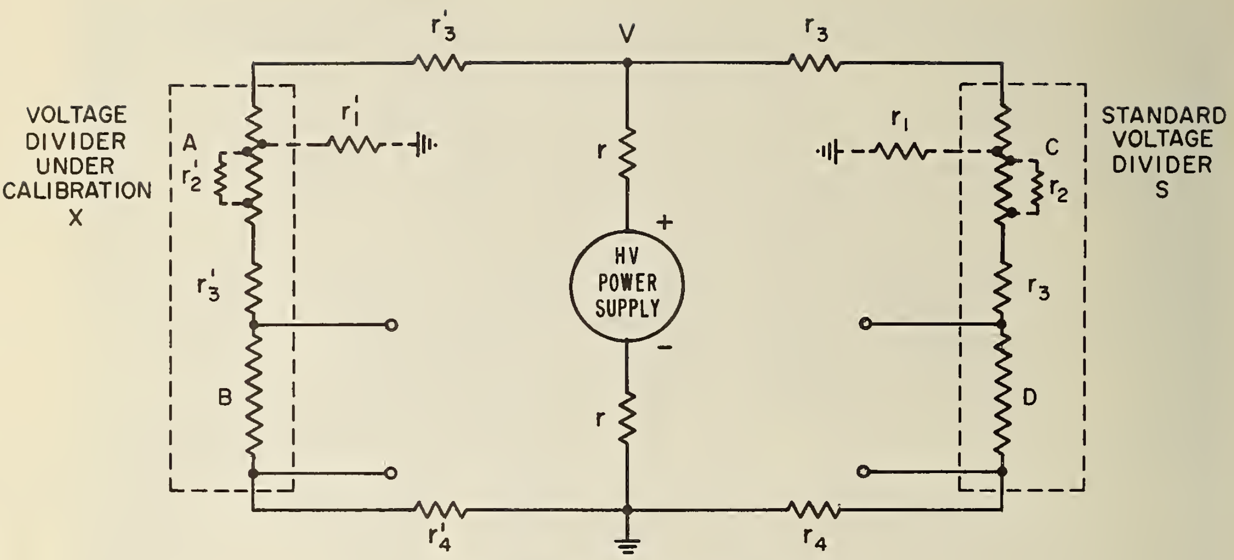

FIG. 9 SOME SOURCES OF ERROR IN CALIBRATION OF HV RESISTIVE DIVIDERS

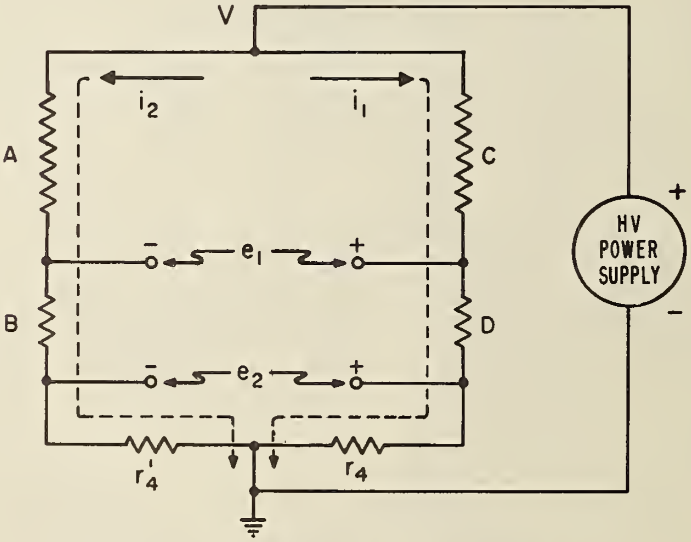

FIG. 10 POTENTIAL DIFFERENCE AND CURRENT LOOP DIAGRAM

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