RP506

A MULTIRANGE POTENTIOMETER AND ITS APPLICATION TO THE MEASUREMENT OF SMALL TEMPERATURE DIFFERENCES

By H. B. Brooks and A. W. Spinks

ABSTRACT

In determining, as a criterion of purity, the boiling range or the freezing range of a liquid which is being purified by fractionation, it is convenient to be able to determine accurately the small difference between the boiling points or the freezing points of the two end fractions. The occasional measurement of relatively large temperature differences between two fractions also requires that the total range of measurement be large in comparison with the smallest measurable temperature difference.

Thermocouples are very suitable for measurements of temperature difference. To increase the electromotive force per degree it was decided in a particular case to use a group of 10 copper-constantan thermocouples in series. Even with these 10 couples, the electromotive force corresponding to a difference of 0.001° C. would be only 0.4 μv, and its measurement to the nearest 0.0001° would require the measurement of the electromotive force to 0.04 μv. Measurements accurate to such a small quantity require not only that the potentiometer used shall be extraordinarily free from parasitic electromotive force, but also that provision should be made for readily detecting and eliminating any such intruding electromotive force in the galvanometer circuit.

The relatively little-used "second method" of Poggendorff, as first realized in practical form by Lindeck and Rothe, appeared to offer the most desirable basis for the design of a multirange potentiometer suitable for the above purposes. The potentiometer which will be described has 6 ranges, and when used with the group of 10 thermocouples provides 6 ranges of temperature difference; namely, from 0° to 0.1°, 0.2°, 0.5°, 1°, 2°, and 5°, respectively, corresponding in each case to a deflection of the pointer of 100 divisions, readable by estimation to 0.1 division. The potentiometer is readily adaptable to read directly in microvolts or in temperature difference, as may be preferred. For the particular application for which it was designed, it was desired to avoid entirely the use of the curves or tables which are necessary when the readings are in microvolts, and it was therefore arranged to read directly in temperature difference.

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I. INTRODUCTION

In the work of isolating particular hydrocarbons from petroleum by fractionation it became necessary to measure the difference between the boiling points or the freezing points of two nearly identical liquids with a precision which could be very moderate when the boiling points differed by several degrees, but which had to be much greater as the two boiling points approached equality. For example, if the difference in boiling points was only 0.001° C., it was desired to determine it within, say, 0.0001° C. If the boiling points differed by 0.1° C., a measurement of the difference to about 0.001° C. would suffice, and so on for still larger differences. The requirements were such that some form of electric thermometer was evidently needed, and the thermocouple was chosen as being well suited to the purpose. To obtain an adequate value of thermal emf with the very small temperature differences to be measured a group of 10 copper-constantan couples in series was used. It was decided to cover a range of temperature differences up to 5° C., and to be able to detect a change of 0.0001° C. when measuring temperature differences of 0.1° C. or lower. This required that the parasitic emf in the potentiometer to be used should be well below 0.04 μv, even under relatively severe thermal conditions. It was felt that no potentiometer was commercially available in which the extreme precautions necessary to secure this result had been taken; furthermore, it was desired that the potentiometer should be capable of ready adaptation to make it read directly in temperature difference rather than in a unit of electromotive force. For these reasons the design of a special potentiometer was undertaken.

II. PRINCIPLE OF OPERATION

In announcing his development of the "compensation" process which forms the basis of the art of potentiometry, Poggendorff [1] described what he called the "first method" and the "second method." The first method was taken up with great interest by other workers, and has resulted in a long line of potentiometers, embodying many ingenious ideas to extend the range and increase the precision of measurements. The underlying idea of the first method is the balancing of the unknown emf by an equal potential difference which is adjusted by changing the value of resistance between two tap-off points on a circuit in which a current is maintained constant at a preassigned standard value.

During all of this active development of the first method, Poggendorff's second method was almost forgotten. It was used in 1896 by Holman,[2] who merely assembled stock pieces of apparatus for the purpose. The first recorded development of Poggendorff's second method into a definite instrument for specific applications appears to have been made by Lindeck and Rothe [3] at the Reichsanstalt in 1899. The instrument was developed with the cooperation of Siemens and Halske,[4] who placed it on the market.

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[1] J. C. Poggendorff, Ann. der Physik und Chemie, vol. 54, p. 161, 1841.

[2] Holman, Lawrence, and Barr, Proc. Am. Acad. Arts and Sci. vol. 31, pp. 218–233, 1895–96.

[3] Lindeck and Rothe, Zeitschrift für Instrumentenkunde, vol. 20, pp. 293–299, 1900; foreshadowed in the annual report of the Reichsanstalt, ibid., vol. 19, p. 249, 1899. Hoffmann and Rothe, ibid., vol. 25, pp. 273–278, 1905, described a recording potentiometer developed from the Lindeck-Rothe potentiometer, using th deflection-potentiometer principle.

[4] Keinath, Elektrische Temperaturmessgeräte, 1923 edition, pp. 30–31.

In Poggendorff's second method the adjustment of the controllable potential difference was effected by changing the value of the current through a circuit while the resistance between the two tap-off points remained constant. This method requires the use of an instrument which will measure a direct current of any value between zero and a given maximum value; that is, ordinarily, an ammeter. Herein lies the chief limitation of the method, for an ordinary ammeter can be read to a precision of only about 0.001 of the full-scale value, and the total error resulting from inaccuracy of marking of the scale, imperfect elasticity of the springs, etc., in a good instrument may be assumed to be several times this value. At the start, therefore, one must reckon with this limitation, and apply the second method only where its limited absolute accuracy is sufficient. When this is the case the second method offers the following noteworthy advantages: (*a*) With a given ammeter, any number of ranges in any desired relation to each other may be readily obtained by providing a corresponding number of tap-off points; (*b*) sliding contacts being absent from the measurement circuit, parasitic emf can be excluded to almost any desired degree; and (*c*) since one has liberty of choice of both the I and the R which by their product give the desired potential difference the "internal resistance" of the potentiometer may in principle be made as low or as high as desired by choosing an ammeter of corresponding range.

Two possible misconceptions regarding potentiometers of the Lindeck-Rothe type should be avoided. The first is that they are "deflection potentiometers." This is not correct because in the deflection potentiometer, properly so called, an unbalanced part of the unknown emf occasions the observed deflection of the indicating instrument, which is directly in the measurement circuit. In the Lindeck-Rothe potentiometer the deflection is all occasioned by a current from an auxiliary source, and all of the unknown emf is balanced by the IR drop in the potentiometer, hence no current flows through the source of the unknown emf. The other possible erroneous idea is that the apparatus is not a potentiometer, because the entire result of the measurement depends on a deflection, and no standard cell is used. A potentiometer may be broadly defined as an instrument for measuring an unknown potential difference by balancing it, in whole or in part, against a known potential difference produced by the passage of known currents through a network of known electrical constants. Where the usual types of potentiometer produce this adjustable potential difference by means of an adjustable value of resistance and a current of fixed value which is frequently checked by reference to a standard cell, the Lindeck-Rothe potentiometer utilizes a fixed resistance and an adjustable current which is checked less exactly and much less frequently, namely, when the accuracy of the milliammeter is checked by reference to a resistance standard and a standard cell.

III. BASIS FOR DESIGN

In practice the auxiliary current for a Lindeck-Rothe potentiometer will be supplied by some form of battery, and should therefore be kept down to moderate values. While storage cells are much used with potentiometers, they have some objectionable features which make the use of dry cells attractive. This suggests the use of currents not exceeding a few hundredths of an ampere, a suggestion which is fortified by the fact that the accuracy of direct-current milliammeters in which the entire current to be measured flows through the moving coil is almost independent of changes of the instrument temperature.[5]

In the present case the current to give full-scale deflection of the milliammeter could be conveniently given the value 10 milliamperes. To produce a potential difference of 2,000 μv,[6] this current must flow through a resistance of 0.2 ohm, a value which is negligible in comparison with the resistance of the group of thermocouples, namely, about 50 ohms. Considerations of speed of working required that the galvanometer to be used should be critically (or slightly under) damped with this latter resistance across its terminals.[7]

The galvanometer selected has a nominal coil resistance of 12 ohms, is critically damped with an external resistance of 40 ohms, has a sensitivity of 5 mm (at 1 m) per microvolt with this external resistance and a complete period of five seconds. It is constructed in such a way as to be relatively free from parasitic emf, but because of the very stringent requirements of the problem, the potentiometer was provided with means for readily detecting any parasitic emf in the galvanometer and for neutralizing its effect. Although the parasitic emf compensator can also be used to neutralize the effect of parasitic emf within the potentiometer, it was considered much better to simplify the manipulation by keeping such internal parasitic emf below the limit of detection, even at the expense of extraordinary precautions in design, materials, and construction.

IV. CONSTRUCTION

1. PLAN OF CIRCUITS

Figure 1 illustrates the principle of operation of the potentiometer and Figure 2 shows the plan of circuits used. In Figure 2, a resistor R_{13} of manganin strip [8] is provided with nine taps, of which the two outside ones are used as potential leads. A current from the dry cell B_2, controlled by the coarse rheostat R_5 and the fine rheostat R_4, flows through the slide rheostat R_{11}, the shunted milliammeter MA, the current-limiting resistor R_6, the reversing switch S_1, then through the manganin resistor R_{13}, entering at the common point C and leaving at one of the six taps connected to the studs of the range-changing switch S_2. The values of the 4-terminal resistance of R_{13} for the six positions of this switch are (from left to right) 0.004, 0.008, 0.02, 0.04, 0.08, and 0.2 ohm.

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[5] This independence of temperature changes depends on the facts (1) that no change in distribution of the measured current between the moving coil and a shunt circuit can occur as a result of temperature change; (2) that the small temperature coefficient of magnetic flux density in the air gap (about 0.01 to 0.03 per cent per degree C.) tends to offset a temperature coefficient of rigidity of the springs, which is about 0.04 per cent per degree C.

Although the requirements of the present case made it necessary to use a shunt around the moving coil, it was possible to give the shunt a value of temperature coefficient which reduced the temperature coefficient of the instrument (as a milliammeter) to zero.

[6] These nominal values of current and potential difference would correspond to the use of the actual group of thermocouples in baths at a mean temperature of about 22° C. As explained further on, the milliammeter was provided with a continuously adjustable Ayrton-Mather shunt which increased the total current for full-scale deflection to values between the limits 10.57 and 14.76 milliamperes, corresponding to the rate of change of thermal emf with temperature at mean bath temperatures of 50° and 300° C., respectively.

[7] This criterion is the one to be used in selecting a moving-coil galvanometer for a specific application, rather than the old rule, still quoted occasionally, that the galvanometer resistance and the resistance of the circuit to which it is connected should be as nearly equal as practicable.

[8] This strip was three-sixteenths inch wide, 25 mils thick, and was about 6 feet long.

The potential difference between the ends of the resistor R_{13} is opposed, through a galvanometer, to the emf of the thermocouples, the terminals of which are brought to the binding posts A and B. In the lead from the left-hand end of the resistor R_{13} to the binding post A are included three keys, two having the protective resistors R_1 and R_2. The lead from the right-hand end of the manganin resistor to one of the galvanometer binding posts includes the copper rheostat

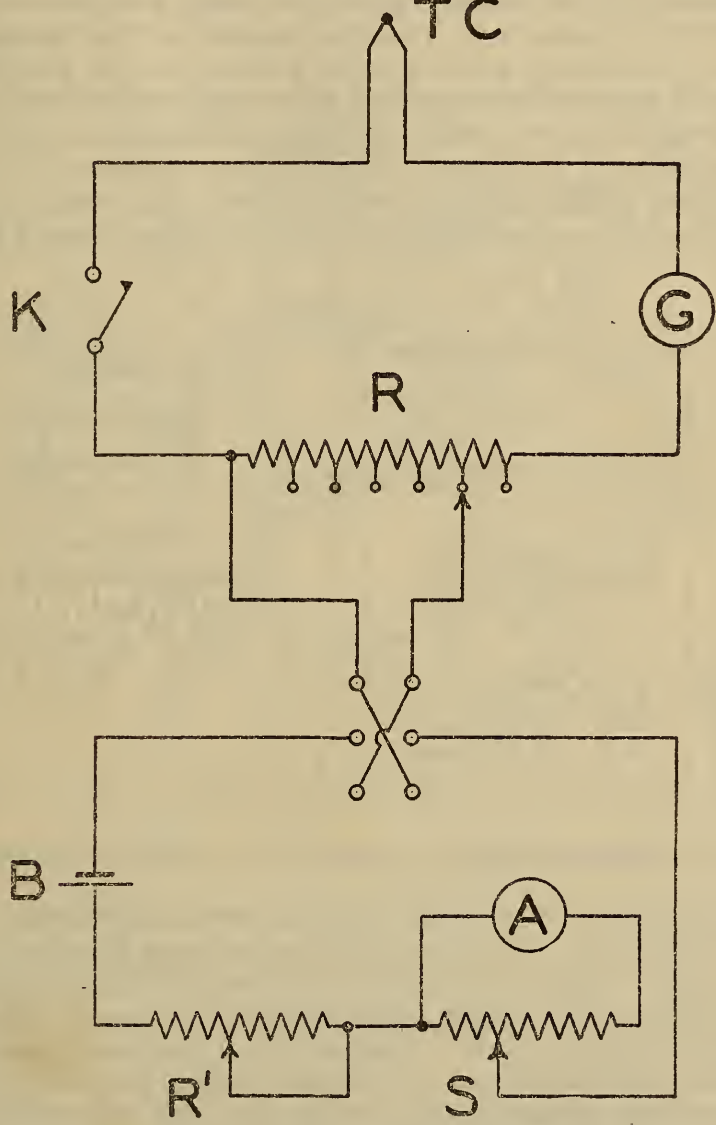

FIGURE 1.—*Diagram illustrating the principle of operation of the multirange potentiometer*

The emf developed in the thermocouple TC is balanced by the drop of potential produced in the resistor R by the current from a battery B. This current is adjusted by the rheostat R' and measured by the shunted milliammeter A.

R_3 forming part of the parasitic emf compensator. A very small current from a flashlight cell B_1 may be made to flow in either direction through any part of R_3 from zero up to one-half of R_3. Depression of the key marked "Shunt off" opens a shunt circuit across the galvanometer, namely, a copper resistor, R_{12} with taps at 30, 40, 60, and 80 ohms. As much of this coil is used as will make the motion of the galvanometer coil critically damped when the keys R_1, R_2, 0 are open.

The function of the reversing switch S_1 is to change the sign of the potential difference between the ends of the resistor R_{13} to take care of the fact that either of the two baths of liquid may on occasion be the hotter. The fixed resistance R_7 and the slide rheostat R_8 constitute the continuously adjustable Ayrton-Mather shunt to the milliammeter.

2. MAIN RESISTOR

The junctions of the copper potential leads with the ends of the manganin strip constitute a possible source of disturbing thermal emf.[9] It was necessary to take such precautions in the design and construction of this resistor as would insure that the two end junctions of manganin with copper would not differ in temperature by more than a few thousandths of a degree. This severe requirement was met by the combination of a number of expedients. As shown in Figure 3, the manganin strip was reflexed in circular fashion around two circles

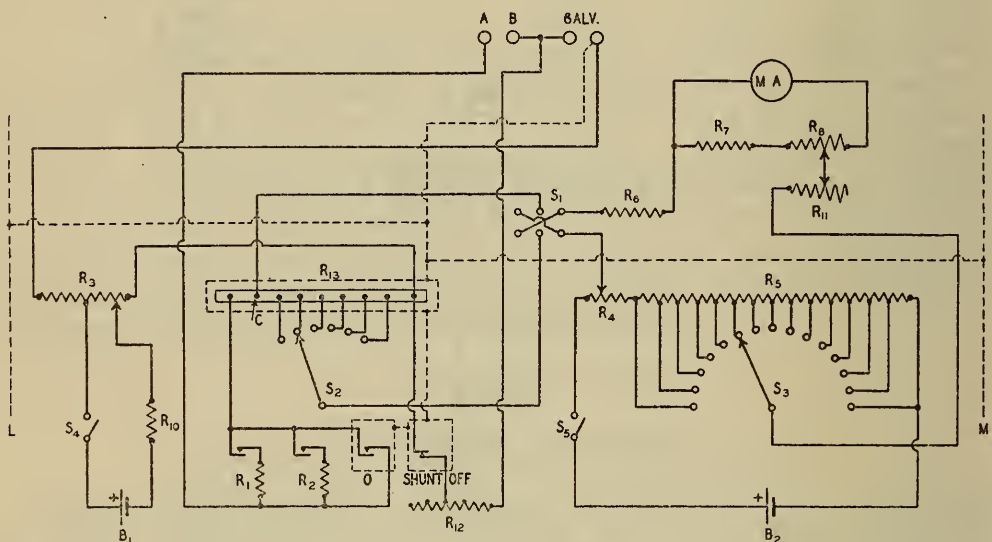

FIGURE 2.—*Diagrammatic plan of circuits of multirange potentiometer*

of bakelite pegs set in a bakelite plate; several thicknesses of $\frac{1}{16}$-inch felt separated the strip from the plate to increase the thermal insulation of the strip. The ends of the strip were brought in radially to the center of the circle, electrically insulated from each other by mica, but in good thermal contact. A layer of thin felt was placed over the strip, and the nine copper tap wires were wound several times around the outer circle of bakelite pegs,[10] then covered with two additional layers of felt and a second bakelite plate which was then secured by screws through the corners to the first plate. The space between the two bakelite plates was then filled in by winding a narrow strip of felt over the outer circle of bakelite pegs.

Before the main resistor was mounted in the structure just described, a similar resistor of constantan, made and mounted in this manner, was used as a check. Tests, such as placing a can of water

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[9] For a copper-manganin junction at ordinary room temperature, the thermal emf changes at the rate of about 1 to 2 μv per °C.

[10] The object of this procedure was to increase the length of path along which heat from other parts of the potentiometer must travel in order to reach the main resistor, and at the same time to permit heat exchange between these wires. The flow of heat uniformly to (or from) all parts of the main resistor would have no bad effect because it would not cause a difference of temperature between the end junctions.

at 40° C. on the upper bakelite plate, produced a thermal emf of the order of a microvolt. This showed that only a few hundredths of a microvolt would be developed with a manganin resistor similarly treated. To be on the safe side, however, the complete structure, with the manganin resistor in it, was mounted below the bakelite top of the potentiometer, midway between the bakelite and the bottom of the box, on four bakelite posts symmetrically placed, and was covered with a box of sheet aluminum 0.03 inch thick. In Figure 4 the bottom of this box has been removed to show the bakelite structure containing the main resistor.

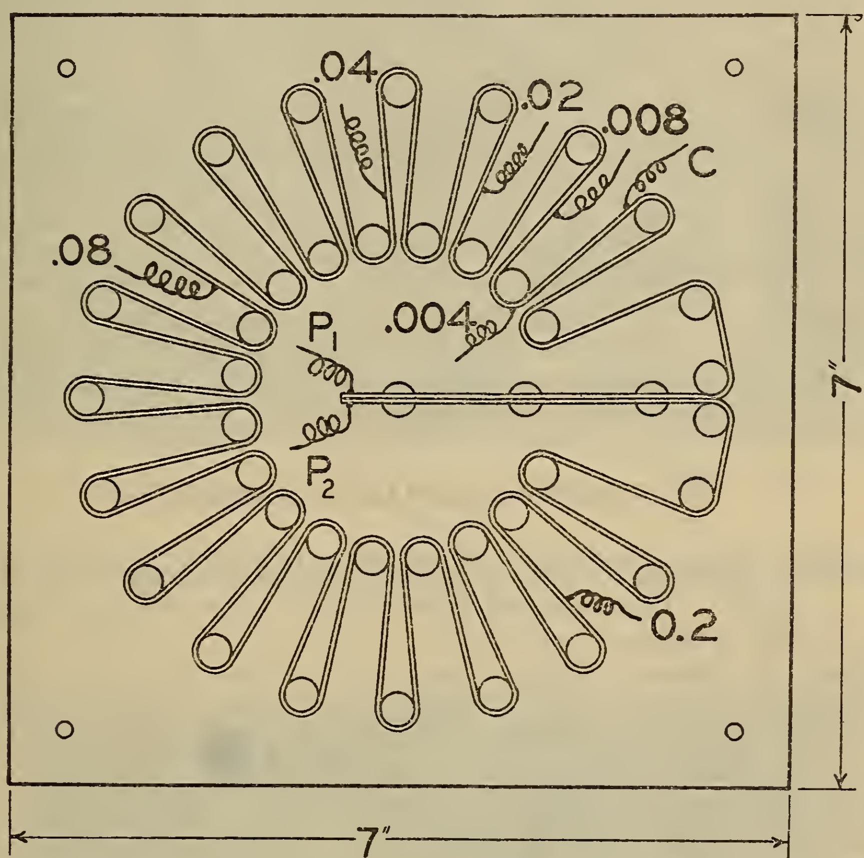

FIGURE 3.—*Plan view of main resistor with upper bakelite plate removed*

3. MILLIAMMETER

This instrument is a fan-shaped d. c. milliammeter of a type primarily intended for switchboard use, modified by the use of a knife-edge pointer, a parallax mirror, and a fine-line 100-division scale of the quality used in standard portable instruments. The resistance of the instrument was about 5 ohms and the current for full-scale deflection (before applying the shunt) was 10 milliamperes.

4. BATH-TEMPERATURE SCALE

In the ordinary procedure for measuring temperatures or temperature differences by means of thermocouples and a potentiometer, the latter is usually graduated to read in terms of a unit of emf (millivolt or microvolt) and its readings are subsequently translated into temperatures (or temperature differences) with the help of curves or tables for the particular couples used. In the present case, it was desired to be able to adapt the potentiometer to read directly in temperature difference for a given group of couples. To determine the electrical conditions which must be satisfied to obtain this result, one must start with the temperature-emf relation of the couples used. A sample couple made of the same wires as the 10 couples to be used was certified as having the following relation:

$$E = 38.062T + 0.04457T^2 - 0.0000288T^3$$

where E is the emf in microvolts and T is the temperature of one of the junctions in degrees C., the other junction being at 0° C. It was assumed that a similar equation, with numerical coefficients ten times greater, applied with sufficient accuracy to the group of couples to be used. If the curve of the above equation be plotted between $T=0°$ and $T=300°$, its slope, dE/dT, will be seen to increase with T throughout this range. In order that the potentiometer shall indicate small temperature differences directly for mean bath temperatures in the region 50° to 300° C., some means of adjustment must obviously be incorporated which, when set to a given mean bath temperature, will make the current through the manganin resistor for any given reading of the indicator proportional to dE/dT. Differentiating the expression for E gives the equation

$$\frac{dE}{dT} = 38.062 + 0.08914T - 0.0000864T^2$$

Using this formula, values of dE/dT were computed for $T=50°$, 60°, . . . 300°. They ranged from 42.303 microvolts per degree at 50° to 57.028 microvolts at 300°.

Taking the lowest range, 0 to 0.1°, for example, for which the 4-terminal resistance of the corresponding section of the main resistor R_{13} is 0.004 ohm; if the full-scale current of the unshunted milliammeter is passed through this section the potential difference at the potential terminals of R_{13} will be $0.004 \times 0.01 = 0.00004$ volt $= 40$ μv. This is equal to the thermal emf of the particular group of thermocouples when the temperature difference between the two sets of junctions is 0.1° C. and their mean temperature is 22.2° C., and consequently for these conditions the full-scale deflection of the milliammeter corresponds to 0.1° C. temperature difference. As the mean bath temperature increases from 22.2° to 300° C. the value of dE/dT increases continuously from 40 μv per degree to 57.028 μv per degree. Therefore, the current which must be passed through any section of the main resistor R_{13} to give a difference of potential equal to the thermal emf of the couples, for a given temperature difference, must be greater than 10 milliamperes by a factor which is equal to dE/dT for the given temperature divided by that for 22.2° C., namely 40 μv per degree. Thus for a mean bath temperature of 50° a shunt must be connected across the milliammeter to increase the full-scale current of the shunted instrument by the factor 42.303/40; that is, to 10.576 milliamperes; for a mean bath temperature of 300° the current for full-scale deflection must be 10 milliamperes multiplied by the factor 57.028/40; that is, 14.257 milliamperes; and similarly for intermediate values of mean bath temperature. This object was

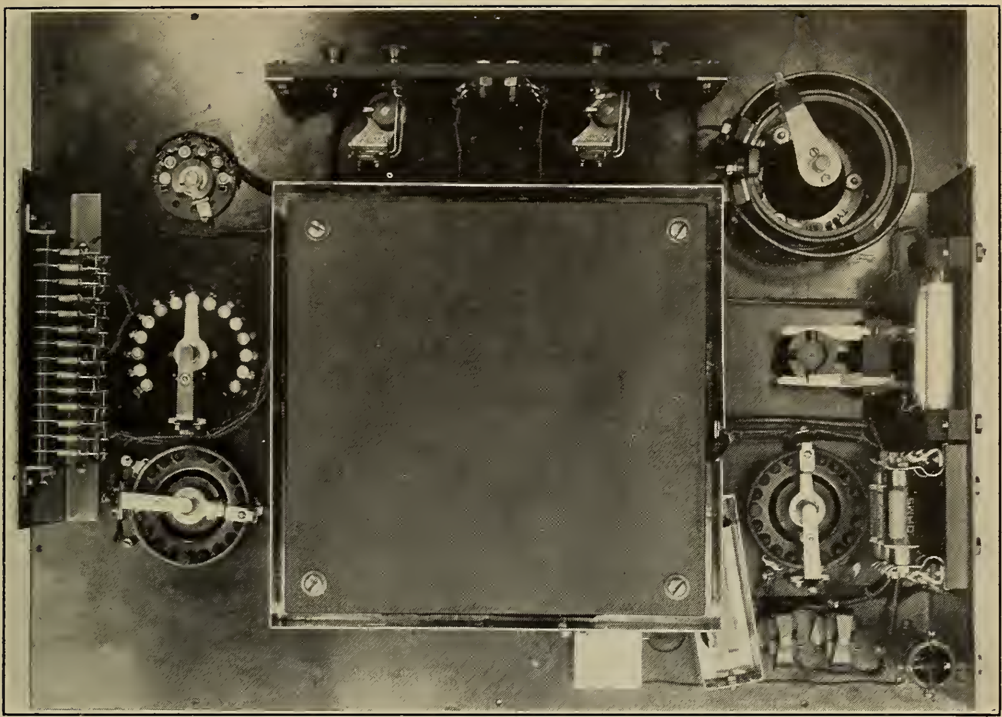

Figure 4.—*Structure of multirange potentiometer as seen from below the bakelite top*

Part of the aluminum thermal shield has been removed from the main resistor (center) and from the key marked 0 (near lower right-hand corner of main resistor).

Figure 5.—*Plan view of multirange potentiometer*

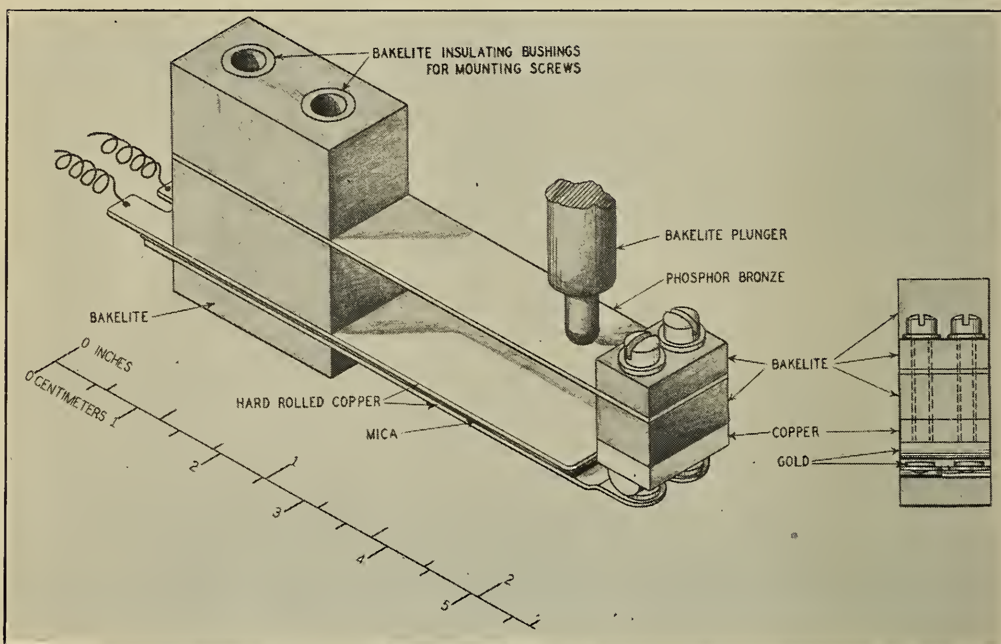

FIGURE 6.—*Galvanometer key embodying refinements to minimize thermal emf*

readily attained by a continuously adjustable shunt of the Ayrton-Mather type[11] connected to the terminals of the milliammeter. This shunt is shown diagrammatically in Figure 2 as consisting of a fixed resistor R_7 in series with the winding of a circular slide rheostat R_8, the two being connected to the terminals of the milliammeter. The current enters by the slider of R_8 and divides between the two parallel paths. As the slider is moved toward the left, the total current for full-scale deflection of the milliammeter increases. A pointer attached to the slider may therefore indicate on a fixed scale either the corresponding value of dE/dT in microvolts per degree or the mean bath temperature. The former would be preferable in general because it would facilitate the use of the potentiometer with any thermocouple for which the value of dE/dT under the conditions of use fell within the range of the scale. In the present instrument, however, it was desired to avoid entirely the use of tables and curves, and the scale was accordingly marked in terms of mean bath temperature for the particular set of copper-constantan thermocouples which had already been made. Attention is called to the fact that the scale divisions were engraved on a disk which is an integral part of the knob of the circular slide rheostat which performs the function of R_8 in Figure 2, and only a fiducial mark was engraved in the bakelite top. (See figure 5.) If for any reason the original set of couples is to be replaced by another, a new scale may be engraved on the disk, which may be readily removed for the purpose. If desired, the scale of bath temperature could be replaced by another scale reading values of dE/dT in microvolts per degree.

If the circular slide rheostat R_8 were of the ordinary type in which the rate of change of resistance with respect to rotation is approximately constant, the bath-temperature scale would be open at one end and crowded at the other because of the quadratic form of the relation between dE/dT and T. It was possible to obtain a nearly linear scale by using a circular slide rheostat in which the resistance wire is wound on a tapered strip of sheet insulating material, giving a quadratic relation between the resistance and the angle of rotation. The close approach to a linear bath-temperature scale which was obtained may be seen from Figure 5, in which the dial at the upper left-hand corner of the potentiometer is the one to be set to the mean bath temperature. The scale was laid out by adjusting the current through the shunted milliammeter successively to the computed values of current for full-scale deflection for bath temperatures of 50°, 60°, . . . 300°, and turning the knob of the bath-temperature rheostat until the pointer of the milliammeter came to the full-scale mark. For each such adjustment a mark was drawn, opposite the fiducial mark, on the scale disk which moves with this knob. The 10° lines were then engraved, with 5° lines spaced midway between them. The results of a test to check the correctness of the resulting scale are given in a later section of this paper.

The current-regulating rheostats R_4 and R_5 operate properly only if the resistance of the circuit beyond them (that is, connected between the slider of R_4 and that of R_5) is substantially constant. The effect of moving the slider of R_8 to the left is to increase the resultant resistance of the milliammeter and its shunt, and the tapered slide

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[11] Ayrton and Mather, J. Inst. Elecl. Engrs. (London), vol. 23, p. 314, 1894.

rheostat R_{11}, connected as shown, compensates for this change and maintains a substantially constant resistance in the circuit beyond the sliders of R_4 and R_5.

5. GALVANOMETER KEYS

In the effort to reduce parasitic emf in the "measurement circuit" to a value below the limit of detection, particular attention was given to some of the keys which had to be used. These keys must be operated frequently; they must contain contact points of metals or alloys nobler than copper because the latter is subject to corrosion; heat from the observer's hand will flow to the contact points through the key spindle; and heat is developed at the contact points by their mutual friction. In many ways the problem of avoiding parasitic emf in the keys is much more difficult than in the main resistor, which has no moving parts and can be thermally shielded to any desired degree.

Referring to Figure 2, it will be seen that there are four keys in the galvanometer circuit. Of these, the ones marked R_1 and R_2 may be of ordinary construction because they are used only in obtaining an approximate balance between the emf to be measured and the adjustable potential difference developed within the potentiometer. The "working microvolt sensitivity"[12] with either R_1 or R_2 in circuit is too low to permit the effect of parasitic emf to be detected. The keys marked "0" and "Shunt off," on the contrary, are in circuit with the galvanometer when measurements are being made; the total resistance in the galvanometer circuit is then low and the working sensitivity correspondingly high; consequently any appreciable parasitic emf in these keys will cause an error in the measurement. The conditions in these two keys are somewhat different. The key marked "0," normally open, is closed just before a reading is taken; that marked "Shunt off" is closed until just after the key marked "0" is closed. Any parasitic emf in the "Shunt-off" key would cause an error in the zero reading of the galvanometer while any such emf in the "0" key would cause an error in the deflection. It was obviously necessary to make these keys so nearly "thermofree"[13] that no perceptible error could be introduced by them. Their design, materials, and construction are based upon the results of a series of experiments which will not be detailed here. If a galvanometer key be constructed of random materials, with consideration given only to its mechanical functioning, it is liable to be the source of objectionable thermal emf under many conditions encountered in practice. The production of a good thermofree key[14] requires that attention be given to three important matters, each of which acts in its own way to minimize the thermal emf. These three matters are:

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[12] This term, ordinarily to be abbreviated to "working sensitivity," has been proposed by one of the authors (B. S. Jour. Research, vol. 4, p. 299, 1930) to denote a constant of importance to the galvanometer user, defined as follows: "The working sensitivity applies only to the user's particular problem at the moment, and may be defined as the response of the galvanometer for unit electromotive force in a circuit which includes the galvanometer and a particular external circuit."

[13] This term is offered as an arbitrary short equivalent of complete but unwieldy expressions, such as "free from thermoelectric forces," "thermal emf free," "thermoelectrically neutral," etc. While it was suggested by the well-known German adjective "thermokraftfrei," it was felt unnecessary to include the English equivalent of the syllable "kraft."

[14] Some makers of potentiometers have been using keys intended primarily for telephone purposes. Some telephone keys contain pairs of springs of very dissimilar alloys (evidently phosphor bronze and nickel silver) and in consequence should not be used in the construction of potentiometers. There should be no difficulty in having telephone keys assembled for the purpose with none but bronze springs.

1. The choice of materials for the key springs and the contact points which are very close to copper in their thermoelectric properties.

2. The design of the key to be "thermoelectrically astatic" with respect to heat flow; that is, so that all junctions of dissimilar metals occur in adjacent pairs so arranged that a flow of heat in any direction will set up nearly equal thermal emf's of opposite sign in the circuit containing the key.

3. The inclosure of the key within a shield which tends to maintain uniformity of temperature of all parts of the key in spite of heat radiation and conduction to or from the shield.

Such a shield may be a jacket of heat-insulating material, or a metal shield of high thermal conductivity, or a multi-layer thermal shield embodying both these features repeated as often as necessary. It is clearly useless to incur expense in reducing the parasitic emf much below a value which will produce a barely perceptible deflection (for example, 0.1 mm) of the galvanometer to be used.

The plunger for operating the key provides a path along which heat may travel into the key structure. The plunger should therefore be preferably of material of low thermal conductivity and be rounded or pointed where it bears on the part of the key to be depressed; furthermore, special care should be taken to make this part of the key "astatic." If the use of metal for the plunger is considered essential, it may be noted that either manganin or constantan is preferable to brass because of their very much lower heat conductivity.

Keys meeting the exacting needs of the present case have been made by caring for the three principal matters as follows: (*a*) The use of hard-rolled copper for the key springs and United States coin gold [15] for the contact points, (*b*) using an astatic arrangement which will be described below, and (*c*) inclosing the key in a box of sheet aluminum 0.03 inch thick.

These two keys, one with part of the aluminum shield removed to show the interior, are shown in Figure 4 near the lower edge of the bakelite top, to the right of the center. To the right of them are the two ordinary keys, R_1 and R_2.

Figure 6 shows the construction of the key marked 0. Two springs of hard-rolled copper, separated by a sheet of mica, are clamped at one end between bakelite blocks and carry gold contact disks at their free ends. Above these contacts is a transverse half-cylindrical gold contact piece soldered to the lower surface of a block of copper which is secured to a flat phosphor-bronze spring by blocks of bakelite used for thermal rather than electrical insulation. The plunger through which the bronze spring is depressed is of bakelite to retard the flow of heat from the observer's hand. However, even if an appreciable amount of heat did flow through the plunger, the construction of the key is thermally astatic to such a high degree that the development of an appreciable thermal emf would be almost impossible. Heat entering the bronze spring by way of the plunger will flow in part to the left, where a thick block of bakelite impedes its flow to the upper copper strap. Although the temperature of this strap will be slightly raised above that of the lower strap, the adjacent junctions to connecting wires are of hard-rolled copper to soft copper,

[15] This alloy is composed of gold 90 parts, copper 10 parts, and has a thermal emf against copper, at room temperature, of 2.2 μv per ° C.

for which combination the thermal emf is very small, namely, about 0.25 μv per °C.

Heat flowing to the right through the bronze spring is retarded by the block of bakelite between the spring and the massive copper block. Because of the symmetrical construction there will be no tendency for unequal heating of the copper block; and even if heat did enter the upper surface of the copper block in a nonuniform manner, the high thermal conductivity of the copper and the small rate of heat transfer would maintain a very high degree of temperature uniformity in the copper and therefore in the transverse gold contact piece soldered to it. Heat will flow from this contact piece to the gold contact disks in the free ends of the hard-rolled copper springs. However, this part of the key is astatic to heat flow in the vertical direction because a current in the circuit which is closed by the key flows up to the transverse gold contact piece on one side and down on the other. Any thermal emf in one of the copper-gold junctions will thus be balanced by an equal and opposing emf in the other junction.

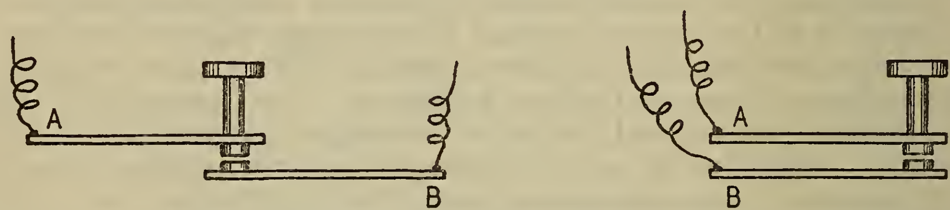

Figure 7.—*Keys illustrating poor design (left) and mediocre design (right) as regards the liability to thermal emf*

In contrast to this key, Figure 7 shows diagrammatically two constructions which are not thermally astatic. The key at the left has the junctions A and B as far apart as possible, and is consequently not astatic as to lateral heat flow. The key at the right is free from this objection, but neither key is astatic as to vertical heat flow.

6. PARASITIC EMF COMPENSATOR

The parasitic emf compensator, shown diagrammatically as R_3 in Figure 2, is shown in Figure 4 just above the two ordinary keys. It is merely a circular slide rheostat as used in radio apparatus but with the resistance-alloy winding replaced by one of copper wire. The material [16] of which the sliding contact lever is made is of no consequence thermoelectrically.

The manner of using the parasitic emf compensator may be understood by reference to Figure 2, which shows that when none of the four keys is depressed the tapped copper coil R_{12} is across the terminals of the galvanometer. Assuming that the slider of R_{12} is at the central point of its winding (or that the switch in series with the cell B_1 is open), any parasitic emf in the galvanometer will maintain a deflection. When the "Shunt off" key is depressed, the galvanometer coil will come to its true zero position, revealing by its motion the fact that an unwanted emf exists in the galvanometer circuit. With the switch S_4 closed, the slider of R_3 may be moved until a position is

[16] An interesting experience illustrates the necessity for great caution in the construction of highly thermo-free apparatus. The complete potentiometer, exposed to heat radiation from a slide rheostat 10 inches away, dissipating 300 watts, showed a parasitic emf of 0.2 μv. Careful search revealed that a strip of metal, forming a lug to which one end of the copper winding of the compensator had been soldered, was of bronze instead of copper as had been assumed. After this strip had been replaced with one of copper, the parasitic emf with the radiation test above described dropped to about one-tenth of its previous value.

found for which the galvanometer coil does not move when the "Shunt off" key is opened or closed. In this condition the parasitic emf in the galvanometer is just annulled by an equal and opposite potential difference in the copper winding of the compensator.

The resistor R_{10} in series with the cell B_1 has a resistance of 50,000 ohms. It is of the "wire-wound" type developed in recent years for radio purposes, and may be easily removed from holding clips if a change in the value of this resistance is desired. The greater the parasitic emf found in the galvanometer by actual use, the lower this resistance must be, but it is desirable not to make it much lower than necessary. The current taken from the flashlight cell is so small as to have no appreciable effect on the life of the cell, and the only reason for providing the switch S_4 for opening the circuit of this cell is to provide a ready means of annulling the small compensating emf set up by the parasitic emf compensator, without altering the position of the slider.

7. MISCELLANEOUS DETAILS

When the temperature difference between the baths A and B changes sign the direction of the thermal emf to be measured reverses. One way to meet this situation would be to provide a reversing switch between the leads from the couples and the potential taps from the ends of the manganin resistor R_{13}. (See fig. 2.) This would require that the reversing switch be highly thermofree. A better method was used, which is shown in Figure 2, namely, the reversing switch S_1 is placed in the wires which carry the adjusted current from R_4 and R_6 to the main resistor. Parasitic emf in the switch can do no harm whatever with this arrangement. Above the bakelite top the two positions of this switch are marked "A higher" and "B higher," respectively, A and B being the designations of the two baths of liquids.

The dry cells B_1 and B_2 are contained in metal receptacles within the potentiometer. There is a door in the back of the potentiometer box which does not appear in Figure 5 and which gives access to the cells and to four copper binding posts. These posts are supported on a small bakelite panel attached to the bakelite top, as shown near the top of Figure 4. As a precaution against possible differences of temperature among the four wires which come from the couples and the galvanometer to these binding posts, the two insulated wires from the couples, twisted together, enter the rear wall of the box and pass through a copper tube which extends to a point near two of the binding posts; and the pair of wires from the galvanometer pass through a similar tube. Any difference of temperature between the two wires of either pair will be equalized by their thermal contact with each other and with the tube.

Near the middle of the small bakelite panel are mounted two pairs of jacks for disconnecting the dry-cell leads when the bakelite top is to be removed from the box. Below the binding-post panel (fig. 4) are the two single-pole switches S_4 and S_5 of Figure 2, for opening the circuits of the two dry cells.

When the potentiometer was under test for freedom from thermal emf during the winter some difficulty was experienced because of electrostatic effects. For example, the galvanometer was found to deflect when the observer rubbed his shoes on the dry floor while his hands were on the galvanometer keys. These difficulties were overcome by shielding as indicated in Figure 2, in which the dotted lines L and M denote two brass angle plates for supporting some of the resistors at the sides of the potentiometer (see fig. 4) and the dotted outlines around R_{13} and the keys marked 0 and "Shunt off" denote the aluminum thermal shields. These five metal structures were connected together and to the right-hand galvanometer binding post as shown by the dotted lines. It was also necessary to shield the leads from the potentiometer to the galvanometer by inclosing them in a metal tube which was electrically connected to the same binding post.

V. TESTS

1. PARASITIC EMF IN COMPONENT PARTS

In testing experimental keys and other parts to determine their thermoelectric behavior under thermal exposure, a sensitive reflecting galvanometer was used in series with a parasitic emf compensator [17] and a device (a small Lindeck-Rothe potentiometer) by means of which a measured emf from 0 to 10 μv could be injected into the galvanometer circuit. To prepare for the measurement of parasitic emf in a key, for example, the galvanometer circuit as above described was first closed by directly joining two copper wires. No current flowed in the compensator circuit and no emf was injected into the galvanometer circuit by the Lindeck-Rothe potentiometer. The resulting deflection, if any, was caused by parasitic emf in the galvanometer, and was then reduced to zero by using the compensator. Then a small emf, say 1 μv, was injected, and the resulting deflection noted as the basis for reducing to microvolts the subsequent observations with the key in ciruit and the injected emf removed.

While ordinary keys, not designed to be specially thermofree, showed appreciable values of parasitic emf, the combination of good materials and thermally astatic design reduced the thermal emf to values so small as to be almost inappreciable. Two expedients assisted in the measurements of emf of only a few hundredths of a microvolt. The first was to replace a part made of good material (for example, the hard-rolled copper spring of a key, or the manganin main resistor) by a similar part made of a very unsuitable material. Constantan was used for the latter. Since its thermal emf per degree with respect to copper is about 20 times the thermal emf per degree for the combination manganin-copper, the values of parasitic emf observed with constantan, divided by 20, gave the values of thermal emf which would have been obtained for the same structure made of good materials; that is, with copper for the key springs and manganin for the main resistor.

The other expedient, used in final tests of parts (and later of the complete potentiometer) which had been made of very suitable materials, was to increase very greatly the sensitivity of reading the galvanometer deflection. A special optical arrangement was devised, usable only for very small (but nevertheless adequate) angular deflections of the galvanometer coil, which gave a sensitivity equal to that which would have been obtained if the galvanometer had been

[17] This compensator was similar to the one in the potentiometer. It was a small, self-contained device, complete with dry cell, and has been very convenient for purposes other than the present development.

used in the ordinary way, but with the scale 13 m from the galvanometer mirror.

2. MAIN RESISTOR

The 4-terminal resistances of the six sections of the main resistor were determined after final adjustment and found to have the desired values within 0.06 per cent. The manganin strip composing this resistor had been formed on an iron plate with two circles of iron pegs, which was a replica of the bakelite housing in which the strip was finally mounted. The manganin was annealed while on the iron plate at about 550° C. to relieve internal stresses. It is believed that this treatment insures the permanency of the resistance values to a degree much higher than the needs of the case require.

3. BATH-TEMPERATURE SCALE

The second of the two factors which jointly determine the accuracy of measurements with the potentiometer is the accuracy with which the current for full-scale deflection of the milliammeter approaches the ideal values, calculated from the emf-temperature relation of the couples, as the bath-temperature dial is turned to various readings over its range of 50° to 300° C. This matter was checked by measuring the full-scale current, using a resistance standard and Wolff potentiometer, at each of the 10° divisions over the entire range. The relative differences between these measured currents and the currents calculated from the emf-temperature relation for the thermocouples averaged 3 parts, maximum 8 parts, in 10,000. The errors in temperature-difference measurements from this cause will therefore be below the usual limit of reading of the scale.

4. OVER-ALL ACCURACY

The final test of the potentiometer was a direct check of the accuracy of the potential difference which it develops at the terminals marked A and B (fig. 2) for full-scale deflection of the milliammeter and various settings of the bath-temperature scale. This potential difference was measured with a Wolff potentiometer, with the bath-temperature dial set in succession at each 10° point over its whole range. The check was made with the range-changing switch S_2 set at the extreme position on the right, corresponding to a difference of 5° C. between the temperatures of the two baths for full-scale deflection of the milliammeter. The average relative difference between observed and computed values of potential difference in microvolts was 0.1 per cent, the differences ranging from 0 to 0.2 per cent at various points on the bath-temperature scale.

5. PARASITIC EMF IN COMPLETE POTENTIOMETER

In addition to the heat-radiation tests of separate portions of the potentiometer, main resistor, keys, etc., as constructed, to determine how much parasitic emf would be set up in them, a similar test was made on the complete potentiometer. The source of heat was a small tubular slide rheostat dissipating 300 watts. It was placed on the table 10 inches from the front of the potentiometer; that is, in about the usual position of the observer when measurements are in progress. With the heat source in this position, the heat passing through the wooden box would be communicated to the keys and the main resistor. (See fig. 4.) That these parts were properly designed and well protected by their aluminum shields was shown by the fact that even after prolonged exposure the thermal emf in the potentiometer was so minute that it would have produced an error corresponding to about 0.1 division on the indicator scale with the lowest range (0 to 0.1° C.); that is, corresponding to an error of 0.0001° C. in the result. Although, it would doubtless be possible to reduce parasitic emf in potentiometers to a lower amount, by more refined methods of shielding the "thermoelectrically vulnerable" parts, the refinement would not usually be worth the extra cost because even high-grade moving-coil galvanometers would not be capable of showing the difference in performance.

VI. PROCEDURE IN USE

The complete procedure to be followed in measuring the temperature difference of the two baths is as follows:

1. With both battery switches open, depression of the "Shunt off" key will show whether any appreciable deflection of the galvanometer has been existing because of parasitic emf. If the spot of light moves when this key is depressed, the left-hand battery switch is to be closed and the knob of the parasitic emf compensator is to be turned by trial to a position such that the spot of light does not move when the "Shunt off" key is depressed.

2. The bath-temperature dial is to be set to the mean temperature of the two baths, as determined by independent means. This temperature does not need to be known very accurately because an error of 5° to 10° C. in T will produce an error of only 1 per cent in the value of dE/dT.

3. The right-hand battery switch is to be closed, the range-selecting switch set to a value of full-scale temperature difference which includes the estimated or expected value, and the reversing switch set to "A higher" or "B higher" as may be thought necessary; then by means of the coarse rheostat and the fine rheostat at the right of the "indicator" (milliammeter) the pointer is brought to a reading corresponding to the estimated temperature difference. Key R_1 is now closed, the direction of the galvanometer deflection noted, and the reading of the indicator changed by using the coarse rheostat until the direction of the galvanometer deflection becomes reversed. With the aid of the fine rheostat the deflection is to be reduced to zero; the key R_2 is then closed, increasing the working sensitivity; the resulting deflection is again reduced to zero; and similarly with both the keys 0 and "Shunt off" depressed. The difference between the temperatures of the baths is then indicated by the pointer, the reading in divisions being interpreted in degrees C. by noting the setting of the range-selecting switch. If the actual temperature difference is greater than the anticipated value, it may be impossible to reduce the galvanometer deflection to zero until the range-selecting switch has been advanced to a higher setting. If the temperature of bath B is actually higher than that of bath A, and the knob has been set to "A higher," the fact will be shown by the impossibility of reducing the galvanometer deflection to zero, this deflection increasing con-

tinually as the reading of the indicator increases and as the range-selecting switch is advanced to higher settings.

The check for parasitic emf in the galvanometer, made as the first step in the procedure, should be repeated occasionally, the intervals depending on the degree of freedom of the galvanometer from such emf, its environment as regards temperature uniformity, air currents, etc., and the magnitude of the temperature difference under measurement. The smaller this difference the more carefully must parasitic emf be detected and compensated.

By setting the bath-temperature scale at 158°, at which temperature dE/dT is 50 μv per degree, the potentiometer may be made to indicate the potential difference between the terminals A and B (fig. 2) in microvolts, the full-scale deflection of 100 divisions then corresponding to 50, 100, 250, 500, 1,000, and 2,500 μv when the range switch is set at 0.1°, 0.2°, 0.5°, 1°, 2°, and 5°, respectively. This procedure adapts the potentiometer to the measurement of very small values of emf for any purpose where the limitations on the relative accuracy of Poggendorff's second method do not interfere. A good illustration is the determination of the emf of a standard cell in terms of the emf of another cell taken as a reference cell, the two emfs being opposed and their difference being measured by the potentiometer. Even if the two cells differed in emf by as much as 1,000 μv and the relative error of measuring this quantity were 0.5 per cent, the value of the unknown cell in terms of the reference cell would be obtained with an error of only 5 parts in 1,000,000. Reading directly in microvolts, the potentiometer may be used with thermocouples of characteristics different from those for which it was designed, and might also be used, with the couples for which it was designed, for temperatures lower than 50° or higher than 300°. However, since this procedure would involve inconvenient calculations or reference to curves to obtain values of temperature difference, a more convenient method would be as follows:

For any given mean bath temperature, set the bath-temperature dial to a corresponding value, taken from a curve or table, such that all observed values of temperature difference need only multiplication by a convenient factor to give actual temperature difference. For example, in the present case, the range +50° C. down to −40° C. can be covered by setting the bath-temperature dial at 208° for actual bath temperature of 50°; at 57° for actual bath temperature of −40°, and multiplying observed temperature differences by 1.25. The use of the factor 1.5 makes it possible to cover the range −40° to −100° C., and the factor 2 continues this down to −160°. These factors, increasing as the bath temperature decreases, represent the fact that dE/dT decreases with the temperature.

It would be possible to design the rheostat R_8 (see fig. 2) to provide a scale of dE/dT (or of mean bath temperature) covering a very much wider range of bath temperature, but this might make the scale more crowded than is desirable. It is probably preferable, as a rule, to provide an open scale covering the temperature range for which the greater part of the work is to be done, and to use expedients, such as those of the preceding paragraph, for the very occasional work outside this range.

Although particular attention has been given in this paper to the specific application which occasioned the design and construction of this potentiometer, it is obvious that it, or others of similar design, may readily be adapted to many other purposes involving the rapid measurement of small electromotive forces, particularly in the lower ranges where it is necessary to avoid errors arising from parasitic electromotive forces in the measurement circuit.

WASHINGTON, August 16, 1932.