POTENTIOMETER INSTALLATION.

ESPECIALLY FOR HIGH TEMPERATURE AND THERMOELECTRIC WORK.

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THE increasing interest shown in high temperature research by scientific workers in different fields has suggested the publication of various methods which have recommended themselves in this laboratory.¹ The present paper deals with the thermoelectric measurement of high temperatures, and more particularly with the apparatus auxiliary to the thermoelement, which consists for the most part of commercial potentiometers of familiar type, with the usual accessories. In the installation of this apparatus, several simple modifications have greatly increased the efficiency, not only for the more specialized work of the laboratory, but for general work as well. The present paper, therefore, may prove of interest to some not especially concerned with high temperature research.

The work for which this apparatus is specially arranged is the determination of melting points and similar thermal phenomena in silicates and other refractory substances. The determinations are carried out by the familiar method of Frankenheim. A charge of the substance under investigation is heated in an electric furnace, whose temperature is continually measured and controlled; the variations in the temperature difference between charge and furnace indicate the changes going on in the charge. This method will soon form the subject of another article, and need not be further

¹ Brief descriptions of some of the apparatus and methods have already been given in connection with the published work of the laboratory as follows: Of the furnace and thermoelements, Day and Allen, Carnegie Institution Publication No. 31, *PHYS. REV.*, 19, 17, 1904; of the general methods of measurement, Carnegie Institution Publication No. 31 (partly reprinted in *Zeit. f. Phys. Chem.*, 54, 1, 1905); also Allen, White and Wright, *Amer. Journ. Sci.*, 21, 89, 1906; Day and Shepherd, *Amer. Journ. Sci.*, 22, 265, 1906; Allen, Wright and Clement, *Amer. Journ. Sci.*, 22, 385, 1906; of the treatment of thermoelements, W. P. White, *PHYS. REV.*, 23, 449, 1906 (*Phys. Zeitschr.*, 8, 325, 1907).

considered here. The problem which it sets in electrical measurement may be stated as follows :

(a) Temperatures up to 1600° must be read to $.1^{\circ}$; with a platinum-platin-rhodium thermoelement, $.1^{\circ}$ corresponds to about one millionth of a volt.

(b) The materials of the furnaces, and also the air, become ionized and conduct electricity at the temperatures generally employed. The potential difference in the heating coils is about 100 volts, that is, one hundred million times the allowable error of the measurements, yet leakage from the coils must not be allowed to affect the measuring system.

(c) The measurements consist in following two or more continually changing temperatures. The only effective way to accomplish this is to read the various temperatures in rotation at definite intervals. Two or more readings per minute are usually needed. The experimenter must also have time to note carefully the progress of his experiment, to regulate the temperature of the furnace, and so forth, and must still be freed as far as possible from hurry or fatigue, since mistakes can seldom be corrected during the progress of the heating. Manipulation must therefore be simplified and the apparatus must respond as quickly as possible. Quickness and simplicity, then, without sacrifice of sensitiveness or accuracy under trying conditions, are the qualities required of the electric measuring apparatus in silicate work. Even if less imperatively needed, they are obviously desirable in other work as well.

Melting point determinations at high temperatures have hitherto been mainly made either with the platinum resistance thermometer or with the direct reading thermoelectric pyrometer. Neither of these instruments meets the demands of silicate work.

The direct reading pyrometer lacks sensitiveness, since intervals smaller than 5° cannot be read with certainty.¹ The resistance thermometer is well known to be poorly adapted for temperatures

¹ This is the unavoidable error of a carefully calibrated instrument in first-class condition. Ordinarily, very much larger errors are present. For instance, the scales in different instruments from the same maker sometimes differ 6° at 1000, and thermoelements of the best make may vary 12° . Calibration errors of 10° at 1000 have also been observed in new instruments, while a surprising amount of care is needed to avoid much greater errors from faulty contacts.

above 1000° , and is therefore out of the question for nearly all silicates. (The stretching of the wires when hot, failure of the insulation and the disintegration of the platinum at higher temperatures, all affect the readings of the resistance pyrometer much more than those of the thermoelement.) Another disadvantage of the resistance thermometer in melting point work at all temperatures seems less generally appreciated. This is the relative bulk of the working portion, which must be completely covered by the substance examined, and which therefore necessitates using large quantities of material. Some of our best melting point determinations at high temperatures are now obtained with about 1 cu. cm. of substance, in which the bare thermoelement is directly inserted. For work of this character, the resistance thermometer is obviously out of the question.

The thermoelement read with a potentiometer meets all requirements of the present work. Readings can be made with practically the same ease as on a direct reading instrument, so that whatever difficulty there is in this direction is chargeable to the nature of the measurements, not to the apparatus. When properly installed, the potentiometer will remain for months ready for instant use, with no other attention than an occasional oiling of the switches. The accuracy is, of course, that of the thermoelement, and has been sufficient for all work thus far undertaken. The elements are exposed to high temperatures for the shortest possible period and are used either in glazed porcelain tubes or in furnaces free from commercial platinum. Under such conditions, deterioration, though not entirely prevented, is slow.¹ By measuring to a millimeter the depth of insertion in the furnace, and by comparing occasionally with carefully kept standards, the relative error of the temperature measurements can be reduced to $\frac{1}{3}^{\circ}$, which is a little less than other errors inherent in the work.

Partial Direct Reading. — Simplicity of manipulation and quickness are promoted by making the maximum use of a direct reading instrument, the galvanometer. Since a galvanometer alone, in the form of a voltmeter, is sufficient for rough measurements with

¹ In twenty determinations near 1350° , occupying about 10 hours, an element inserted 17 cm. in the furnace fell a little over 1° .

thermoelements, a moderate increase in its efficiency is all that is needed for the most refined work. Yet when a potentiometer is added to secure greater efficiency, the whole burden is often thrown upon the potentiometer, and the galvanometer is used merely to indicate when a balance is obtained. This practice has some obvious advantages, but is not justified where rapidity is important. If the galvanometer is provided with a scale reading directly in micro-volts, and is used through a rather wide range, the potentiometer adjustments may be confined to the larger units and greatly reduced in number. The quickness and simplicity of exclusively direct reading are thus approached with no sacrifice of accuracy.

Fig. 1. To accompany formula 1.

A necessary requirement for this system is, of course, constant galvanometer sensibility, which is not found in ordinary potentiometer installations. I have elsewhere¹ shown how potentiometers can easily be constructed so as to give constant galvanometer sensibility. For ordinary instruments, and for the range needed in thermoelectric work, a sufficient approach to it can be obtained by inserting an extra variable resistance in the galvanometer circuit, as shown at R_A in Fig. 4. The operation of this resistance is as follows: Let Fig. 1 represent a simple potentiometer installation, where G indicates the resistance of the galvanometer, and T that of the thermoelement, whose electromotive force is balanced against the fall of potential along the resistance, M , in the main circuit. S is the storage cell of the main circuit, $M + N$ the total resistance in that circuit. The electromotive force of the thermoelement may be considered as equal to the sum of two others; one is equal and opposite to that given by the potentiometer setting, and has the effect of neutralizing the potentiometer electromotive force completely as far as any current through the galvanometer is concerned; the other, $\mathcal{A}e$, is the unbalanced electromotive force which is to be measured by the galvanometer, and which, by the well known principle that each electromotive force in a circuit produces its own

¹ Zeitschr. f. Instrumentenkunde, 27, 210, 1907.

current regardless of all others present, gives a current equal to

$$\frac{\Delta e}{T + G + \frac{MN}{M + N}} \quad (1)$$

Constant galvanometer sensibility is therefore secured by keeping the resistance $T + G + MN/M + N$ constant.

In measuring the comparatively small electromotive forces of platinum thermoelements, the resistance $MN/M + N$ differs but little from M ; hence sufficient compensation is obtained if resistance is subtracted from the ballast, R_A , equal to that added to M in setting the potentiometer. An ordinary switch rheostat of very moderate accuracy is sufficient. The labor of making the adjustments is usually slight. For instance, if the resistance of the galvanometer circuit is 500 ohms and an accuracy of 0.5 per cent. is desired in reading the galvanometer, the resistance must not vary more than 2.5 ohms. The auxiliary must therefore be changed whenever the potentiometer resistance, M , has altered 5 ohms. In a potentiometer of 20,000 ohms total resistance, 5 ohms correspond to 500 microvolts, or from 40 to 50° with a platinum-platinum-rhodium thermoelement, and the adjustment will not need attention oftener than once in 15 minutes in ordinary work. In a potentiometer of 2,000 ohms total resistance, on the other hand, 5 ohms will correspond to from 400 to 500°; the adjustment can be made before the observations begin, and will then need no further attention. A potentiometer resistance moderately — but only moderately — low compared to that of the rest of the circuit may therefore be of advantage where constant galvanometer sensibility is desired. (A rather high resistance of the whole circuit is also desirable to reduce the effect of accidental variations in resistance due to the changing temperature of the thermoelement, to defective contacts, etc.) In classes of work where widely differing electromotive forces are to be measured in succession, the difficulty of maintaining constant galvanometer sensibility obviously increases, and the need is greater for a potentiometer of low resistance, or, better still, of constant branch circuit resistance.¹

¹ H. B. Brooks has also, in his "deflection potentiometer" (Bull. Bureau of Standards, vol. 2, p. 225, 1906), made a systematic attempt to gain speed by increasing

The usefulness of the above method of relying largely upon the galvanometer will of course vary greatly under different circumstances. In melting point determinations, constant galvanometer sensibility is not only very easy to obtain, but is especially important, for the following reasons: (1) In the rapid reading of varying electromotive forces at definite time intervals, an exact balance of the potentiometer is out of the question. The galvanometer follows the varying electromotive force¹ and needs about as much time to reach its moving equilibrium as it requires to come to rest. Hence the nearest attainable approach to a balance is a potentiometer setting made a number of seconds before the time of reading. When that time arrives, the galvanometer nearly always shows a deflection which must be added to or subtracted from the potentiometer reading. Some use of the galvanometer as a deflection instrument is therefore unavoidable. The quantities read can, if desired, be kept within 20 microvolts, for which a sensibility constant to 5 per cent. is ample. (2) When once deflections of this magnitude have been provided for, however, an increase of the range to 100 or 200 microvolts causes very little further trouble. Moreover, in melting point determinations, such increase is especially advantageous. This is due to the fact that the temperature intervals concerned—those between the different elements as well as between successive readings of the same element—are usually more than ten and seldom over 200 microvolts. With the narrower galvanometer range, a separate setting of the potentiometer must be made twice each minute, involving a preliminary estimate, the setting of two or three switches, and afterward the addition of the readings obtained from both instruments. With the more carefully adjusted galvanometer, the potentiometer requires only to be advanced one unit every few minutes and the deflections are read and recorded directly from the scale. The saving in numerical work of various kinds is even more important than in switch manipulation, though

the use of the galvanometer. The small sensitiveness of this apparatus, and some of the other difficulties which Mr. Brooks ingeniously avoids, are due to the use of an insensitive pivot galvanometer, and, as his own discussion implies (p. 238) are not inherent in the method.

¹ Lagging behind it by a time interval which is approximately equal to T/π , if the galvanometer, of period T , is critically damped.

this latter may often be diminished ten times. For the more difficult kinds of work, where readings are numerous, or an especially careful regulation of the furnace is desired, this saving is indispensable.

The price paid for the advantage is merely a little attention to the galvanometer sensibility, which may change slightly with temperature, and becomes irregular if faulty contacts are permitted in the circuit. A verification of the sensibility, however, can be made at any time and requires nothing further than to change the potentiometer setting and note the resulting change in deflection.

The galvanometer sensibility should obviously have an integral as well as a constant value. This can readily be secured by varying the scale distance, which is also a convenient way to correct slight

Fig. 2.

Fig. 2. Arrangement of the scale. The numbering is direct, everywhere increasing with increasing E.M.F., yet the reading is zero at the middle of the scale, and readings less than zero are clearly indicated. The figures to the left are, following a common practice, in red, which often shows the direction of a deflection too rapid to permit of reading the numbers.

Fig. 3.

Fig. 3. To accompany formula 2.

variations in the sensibility. Fig. 2 shows the arrangement of the scale. The method of numbering has some obvious advantages.

Protection against Leakage. — The avoidance of leakage errors is made especially difficult in silicate work by the combination in the furnace of high voltage and poor insulation — the latter due to unavoidable electrolytic conduction at high temperatures.

In order to have leakage affect the galvanometer reading, there must be a failure of insulation in at least two points of the circuit. The law governing the magnitude of the effect may be found as follows :

In Fig. 3, let a and b be the (very high) resistances through which the leakage takes place ; let V be the external voltage causing the leak. Let G be the resistance of the galvanometer, and H the remaining resistance which lies with the galvanometer in the circuit

between a and b . Let K be the resistance of the other path from a to b . The total leakage current, L , will equal $V/(a + b)$ and will not be appreciably affected by the relatively small resistances in the circuit. The error caused by L will, however, depend on these resistances. The portion of the current passing through the galvanometer is

$$L \frac{K}{H + K + G}.$$

The resulting error, in microvolts, will be equal to this current divided by the current which is produced by one microvolt, that is :

$$\frac{LK}{H + K + G} \div \frac{1}{H + K + G} = LK = \frac{VK}{a + b} \quad (2)$$

Leakage errors may therefore be diminished in three ways : *first*, by increasing either a or b , that is, by improving the insulation ; *second*, by diminishing the resistance of the alternative path, K ;¹ *third*, by diminishing V . This last is the most effective way of removing leakage errors. It can be accomplished by an equipotential shield, a device whose essential features are shown in Fig. 4. The potentiometer, galvanometer, and all other apparatus belonging to the measuring system, are set on metal plates ; the leads are completely supported by wires ; the plates and the wires are connected so as to form a continuous conductor which is extended into the furnace, where it includes the crucible and also passes between the thermoelement and the furnace cover. This conductor thus interposes between the measuring system and every external electromotive force, while it needs itself but slight insulation in order to be an equipotential surface ; the most troublesome leakage, that from the high voltages in the furnaces and elsewhere, is therefore absolutely prevented.²

¹ This can often be accomplished by a mere transposition of apparatus, and does not necessarily demand a reduction of the total resistance. The leakage error may obviously be considerably influenced by the mere order in which the different pieces of apparatus stand in the circuit. Formula 2 explains why leakage is sometimes less with potentiometers of low resistance and also shows that this result may be accidental, according to whether the potentiometer resistance is included in the portion K of the circuit. It is always possible, by the method of page 343, to insert resistance so as not to increase the leakage error.

² The equipotential shield was suggested by C. T. R. Wilson's electroscope (Proc. Roy. Soc., 63, 152, 1901). H. P. Brooks has also applied the same principle in a different way to potentiometer work. (Lot. cit.)

The presence of external leakage may be tested by watching the throw of the galvanometer when *both* terminals of the heating circuit are suddenly disconnected. This test is applied from time to time in order to avoid the possibility of error due to accidental contact with or breaks in some part of the shield. If the shield is in

Fig. 4. Very diagrammatic representation, partly in plan, but with the furnace in vertical section, of the measuring apparatus, showing the relations and connections of the two leakage shields. The cold junctions and standard cell are omitted. G , galvanometer, R_A , auxiliary resistance (for adjusting sensibility); R_B , ballast-resistance; P , potentiometer; E , exchanging switch; H , short-circuiting link, for zero adjustment.

perfect condition, of course no external leakage error can possibly occur. As a rule, this test gives zero results during the winter, even in the absence of a shield. This is due to the fact that insulation then fails at but one point in the circuit, and of course does not indicate perfect insulation in the furnace itself.

The use of a complete shield is often inconvenient or impossible. In such cases, a partial shield can be employed, which is connected directly to the potentiometer circuit. Such an arrangement does not prevent the leakage, but guides it to some desired point, thereby reducing the resistance, K , of equation (2). Its effectiveness is more dependent upon good insulation than is that of the complete shield.

Partial shields have been used in three cases: (1) It is sometimes inconvenient to extend the shield into the furnace. By connecting the shield to the thermoelement as near the furnace as possible, K is diminished to the resistance of a few centimeters of the thermoelement wire, and satisfactory results are often obtained. The other cases arise where complete shielding is prevented because the source of leakage is in metallic connection with the circuit. One of these occurs where the voltage or current of a high potential circuit is being measured. The shield is then connected to the junction of the potentiometer circuit and the circuit in question. K is now zero, and the external protection is complete. Another case arises in the protection of the potentiometer system from leakage out of its own storage cell, which we have found by no means negligible in the humid summer months. The arrangement used is as follows:¹ The shield, lying under storage cell, potentiometer and ballast resistance, is connected, as shown in Fig. 4, to the *lower* terminal of the branch circuit, that is, the one nearest an end of the potentiometer wire. This terminal should be

¹ Those especially interested will readily find in the following equations an explanation for the arrangements here described. These equations are obtained by considering that an electromotive force in the leakage path equal and opposite to the normal electromotive force in the circuit between the two ends of that path would reduce the leakage to zero, and therefore, that the current produced by such an electromotive force is equal (but opposite) to the leakage current. The effect of such a current upon the galvanometer is easily calculated. If V is the storage cell voltage (in microvolts), L the leakage resistance, M the fractional portion of the circuit across which leakage occurs, T the resistance of the thermoelement, C the resistance between terminals of the branch (galvanometer) circuit, then the error in microvolts is, for leakage between two points, both in the main circuit, not including C ,

$$\frac{VM}{L} MC \quad (3)$$

or two such points, including C between them,

$$\frac{VM}{L} (1 - M) C \quad (4)$$

for leakage from the main circuit to a point between thermoelement and galvanometer, roughly,

$$\frac{VM}{L} T. \quad (5)$$

The efficiency of the above arrangement is dependent upon the small value of the voltage measured. A different disposition would probably be preferable where electromotive forces of the order of 1 volt are to be measured.

made as low as possible, that is, no ballast resistance should intervene between it and the battery. (Ballast resistances are found at this point in some potentiometers. They are, however, objectionable¹ for other reasons, and can easily be short circuited or removed.) The result of this arrangement is that leakage from the battery cannot reach any portion of the circuit outside the apparatus resting on the shield, while within the shield, such leakage as may occur will, in general, produce the minimum amount of error.²

Minor Details.—In all refined galvanometer work, provision must be made for eliminating the accidental electromotive forces of the circuit. In thermoelectric work, this requires that the large electromotive forces, those of the thermoelement and battery, be momentarily removed and the circuit then closed. This operation is accomplished by a switch of simple construction, which shifts the terminals of the potentiometer and galvanometer circuit from the thermoelement to a short-circuiting link, and at the same time opens the battery circuit at one point.³ A further motion of the handle makes connection with a second and a third thermoelement. Provision for the two essential operations, zero adjustment and exchange of thermoelements, is thus made by one simple piece of apparatus. The correction for the accidental electromotive forces is applied by simply adjusting the scale to read zero, and the trouble of making a numerical correction is thus avoided. A slow motion for this

¹ Principally because their presence may restrict the choice of a storage cell to one possessing exceptionally high voltage.

² Leakage into the balance resistance is further prevented by suspending this from its own metallic terminals. Such leakage, and also leakage along the potentiometer top from point to point in the circuit, will diminish with the resistance of the potentiometer, and may thus be made negligible. We have no evidence, however, that such leakage in a potentiometer of 10,000 ohms to the volt need be serious. Leakage to the direct junction upon the potentiometer top of thermoelement and galvanometer leads (*CD* in Fig. 4) will be serious only if the resistance of the thermoelement is high (with a constantan element, for instance), and can then be prevented by removing that junction from the potentiometer top altogether.

³ If this point is near the lower end of the potentiometer—that is, near *x* in Fig. 4—leakage at the switch will be prevented while the battery circuit is closed. Trouble from leakage may arise, however, during the zero adjustment, but this can be detected by occasionally disconnecting the other battery terminal. If the regular opening of the battery circuit is at the high end and the two leads are separated from each other and from the rest of the switch by an extension of the internal shield, as indicated in Fig. 4, there will be no danger from leakage at the switch whether the circuit is open or closed.

purpose, sufficiently delicate and entirely free from lost motion, has been found very easy to make. The scale is drawn along against the tension of a coiled spring by winding a cord upon a bent brass rod. Our regular telescopes have a slow motion supplied by the maker.

In this method of compensation it is not the accidental electromotive forces, but the deflection due to them, which is directly compensated, and the adjustment, therefore, is incorrect, if the removal of the thermoelement appreciably changes the resistance of the circuit. This difficulty is inappreciable with platinum thermoelements; with those of constantan, other methods are used.¹

None of these methods compensates the electromotive forces in the thermoelement leads, and in some portions of the switch itself. All such forces are therefore diminished by making these portions of the circuit entirely of copper. The only exception is the springs and bearing surfaces of the switch, which, for mechanical reasons, are made of manganin, a material at once hard and of small thermoelectric power compared with copper.

The important contacts on the potentiometer are kept in good condition by oiling every few weeks with typewriter oil, in accordance with a suggestion from the Reichsanstalt. A reasonable amount of attention to other contacts in the circuit is also necessary in order to maintain constant galvanometer sensibility.

The cold junctions, protected by glass tubes, are in a bath which is usually maintained at 0° by means of ice. To insure the junctions being at the temperature of the ice, fine copper leading-in wires are used, while oil or paraffin inside the tubes and water outside improve the thermal contact between the ice and the junctions.

¹ A. D. Palmer (PHYS. REV., 21, 72, 1905) compensates the electromotive forces directly by an auxiliary potentiometer. This method, in the one case where its complication is needed, that is, where the resistance of thermoelement is high, evidently fails unless the galvanometer is at zero on open circuit. Practically, therefore, in employing it, two separate adjustments must be made, of which that on open circuit, with the galvanometer undamped, is somewhat tedious and altogether inadmissible in rapid work. In our laboratory, therefore, another method is employed, and the circuit is closed for zero adjustment through a resistance equal to that of the thermoelement which is then removed from the circuit. The value of this resistance evidently need be only approximate, but it must be so wound as to be free from thermoelectric force — a condition easily realized.

The constancy of the storage cells is increased by shielding them from temperature changes with a wrapping of cotton wool.

Insulation of the standard cells is promoted by suspending them from their own leads.

Since the zero adjustments, as well as the readings, are made on a closed circuit whose resistance is kept constant, the galvanometer is adjusted so as to be damped entirely by the reaction of the circuit, and maximum sensibility is thus obtained. To insure proper damping while the circuit resistance is increased during the comparison of storage and standard cell, a coil is connected between appropriate terminals of the standard cell and galvanometer. This coil has no effect except when the cell is connected to the potentiometer. It then acts as a shunt to the galvanometer, giving critical damping together with a decrease (here unobjectionable) in sensibility.

The galvanometers are placed upon Julius suspensions, which are enclosed against air currents. We have found that the position of the center of gravity with reference to the galvanometer head does not appreciably influence the steadiness, that is, the oscillations which the supports perform about their centers of gravity are not of a character to affect our moving coil galvanometers.

Galvanometer Requirements.—A satisfactory adjustment of the potentiometer system, according to the methods above described, requires a galvanometer which, while not necessarily of extraordinary quality, is well adapted to its work. Leading instrument makers, in this country at any rate, will, as far as possible, furnish instruments to meet specified requirements.¹ The necessary or desirable galvanometer constants are as follows:

(a) *Sensibility.*—The most convenient method of defining the sensibility of a galvanometer is to give the deflection in millimeters produced by unit current or voltage with the scale distant 1 meter from the mirror. For sensitive instruments, the unit voltage is 1 microvolt. An instrument, then, which gives a millimeter per microvolt at 1 meter's distance has a sensibility equal to 1.

With reasonably good optical arrangements and fair steadiness, a sensibility of .3 is quite sufficient for silicate work. Half a scale

¹ For a more detailed discussion of the problems of galvanometer adjustment, see "Every Day Problems of the Moving Coil Galvanometer," *PHYS. REV.*, 23, 382, 1906.

division will then correspond to a microvolt, and the scale distance will usually be more than 1 meter. A sensibility of .5, with 1 scale division per microvolt, is a little more desirable, and may be necessary for reading to tenths of microvolts, or with poor optical arrangements.

(b) *Period*. — A period of 10'' is sufficient only for the simpler portions of our work, and scarcely satisfactory in those. 5'' is short enough for almost anything, though a still shorter period is often convenient.

(c) *Resistance*. — The necessary total resistance of the galvanometer circuit depends largely upon the type of potentiometer. The resistance of platinum thermoelements at different temperatures varies an ohm or more. Hence for sensibility constant to .5 per cent. a total branch circuit resistance of 200 ohms is desirable. For a potentiometer of high resistance whose branch circuit is (as usual) not constant, the total resistance should be 500 ohms or more (see page 338). This requirement is less important if the range of interpolation is small (see page 339).

Satisfactory values, then, are, a sensibility of .3, a period as short as 5'', and a total or critical resistance of 200 ohms, which should be increased to 500 ohms or more with an ordinary high resistance potentiometer. Greater sensibility, greater quickness and higher resistance are more or less in the nature of luxuries. As far as the galvanometer is concerned, these three constants are antagonistic. For a given type of instrument, an increase in one involves a sacrifice of the others. A high resistance potentiometer (10,000 ohms to the volt) may in thermoelectric pyrometry contribute as much as 170 ohms to the galvanometer circuit; with 500 ohms total resistance, then, over 300 may be in the galvanometer alone, a condition which greatly facilitates the attainment of short periods in galvanometers with weak magnets.¹

We have found no great difficulty in securing the above performance with several different types of galvanometer, although the majority of the instruments now on the market do not seem to permit of anything very much better. With a low resistance potentiometer the reduction of the total resistance to 200 ohms easily

¹ Every Day Problems, etc., pp. 384, 387.

allows, with the same type of instrument, a sensibility of .5 or a period as short as four seconds. A much better galvanometer performance is certainly possible,¹ although it seems worth while to emphasize the fact that such increase, while desirable, is not necessary for most thermoelectric work and would be dearly bought at the cost of even a slight sacrifice of constancy or steadiness, such as is apt to result from too great delicacy of construction. A considerably better performance, however, than the one above described should be attainable along with ample steadiness and constancy.

Either an especially good galvanometer or a low resistance potentiometer, therefore, allows a short period and excellent sensibility. With an ordinary galvanometer and a high resistance potentiometer a satisfactory arrangement can still be obtained, though it requires fair steadiness and good optical arrangements.

The Potentiometers. — Three reasons have been given for desiring potentiometers of low resistance: The internal leakage is less; better results can be obtained with an inferior galvanometer; and especially, the adjustment for constant sensibility is more easily made. This latter advantage is, of course, far more completely secured in a potentiometer with automatically constant branch circuit resistance. In point of fact, a switch potentiometer constructed to have either low resistance or a constant branch circuit may just as well have the other also.²

Of far greater importance, however, are ability to set the potentiometer quickly, and freedom from uncertain contacts, which may affect the resistance of the galvanometer branch. In both these respects the slide wire potentiometer is deficient, so much so as to be very unsatisfactory for melting point work. That it takes more time and attention to set a pointer exactly on a mark than to put a switch somewhere upon its appropriate button is perhaps a minor disadvantage, but the time required to wind the drum of a slide wire instrument from one position to another absolutely precludes simultaneous work with two elements differing much in temperature, while the resistance of the sliding contact is, in ordinary instruments, so uncertain as to make constant sensibility impossible. Devices designed to over-

¹ Every Day Problems, p. 388.

² Instrumentenkunde, loc. cit.

come this difficulty are at best open to the objection of introducing an additional complication. It may not be superfluous to call attention to the fact that apparatus which under most circumstances would be quite satisfactory, may fail in melting point work, where the demand for certainty of operation is so much greater. A single faulty observation may destroy the value of a thermal curve several hours long, and the frequent readings leave no time to correct even slight or temporary defects in the apparatus.¹

Hitherto, all-switch instruments have necessarily been made with high resistance on account of the internal contacts at some of the switches. Since the disadvantages of high resistance are small compared to those presented by the slide wire, the older instruments in this laboratory are Wolff potentiometers of 10,000 ohms to the volt.

Fig. 5. Simple low resistance potentiometer, of sufficient range, and very convenient for high temperature thermoelectric work. The branch circuit is kept of constant resistance by the coils, CCC, and the galvanometer sensibility is therefore constant. MMN, main circuit potentiometer coils. PS, standard cell connection. A key and a switch are here omitted for simplicity.

There should now be no difficulty in getting all-switch potentiometers possessing not only the low resistance of the slide wire instrument, but a constant branch circuit as well.² The slide wire

¹ Much of the difficulty in regard to galvanometer sensibility and contact resistance disappears if the familiar method is adopted of noting the varying times at which regular and integral values of the electromotive forces are reached; but this method is considerably more laborious where one thermoelement is being read, and often inadmissible with two or more.

² Instrumentenkunde, loc. cit.

instruments might still have an advantage in the matter of cost, but in this respect also they can be excelled, provided the range of the switch potentiometer is limited to the requirements of thermoelement work. Such an instrument was designed and ordered for this laboratory in April, 1906, and is now in use (Fig. 5). It has only two main switches and measures from 100 to 18,900 microvolts. The coils, *cc*, are so adjusted as to keep the resistance between *P* and *P'* always constant. Since the simplest kind of switch will suffice for an instrument of this character, the total cost should hardly exceed that of the coils. Another decade would be desirable,¹ but the advantages of the instrument here figured are believed to be, for melting point work, on the whole superior to those of the usual types. One of these is the possibility of using the instrument as a double potentiometer,² a great advantage in work requiring the simultaneous measurement of very different temperatures.³

The general usefulness of the resistance thermometer is increased by the fact that ready-made outfits varying in accuracy and elaborateness can be bought for different purposes. For the thermoelement there is at present in commercial instruments practically nothing between the crude, direct-reading voltmeter and the expensive and yet relatively inconvenient five-decade potentiometer with a range of a million microvolts, 98 per cent. of which would never be used. For thermoelectric work, potentiometers of appropriate range may, in spite of their simplicity, be better adapted

¹ And can easily be introduced by the use of a shunted element (*Instrumentenkunde*, loc. cit.), since with the low range of 18,000 microvolts a single shunted element with a simple switch suffices, and will give an accuracy of .05 microvolt if the switch contact resistance does not exceed .01 ohm.

² *Instrumentenkunde*, loc. cit.

³ By changing the internal connections of a Wolff 20,000 ohm potentiometer, an instrument of constant galvanometer circuit resistance can be made for thermoelectric ranges; the changes involve a rearrangement of the different *groups* of coils without dividing the group, much less touching the individual coils. There is therefore no danger of injury and the instrument can in a very short time be restored to its original condition if that is desired. In making the readjustment the two higher switches are entirely cut out. The compensating coils of the next two decades are changed from the potentiometer circuit proper to the galvanometer circuit; the result is a three-switch instrument of 5,000 instead of 10,000 ohms to the volt, reading up to 19,980 microvolts by steps of 20 instead of 10 microvolts. In dispensing with the two higher switches one terminal of the standard cell must be permanently connected to the potentiometer circuit, but this connection is in itself a decided advantage.

for measurements of the greatest difficulty and refinement than the existing types, while in instruments where less accuracy is required the simplicity can be correspondingly increased.

SUMMARY.

I. For the most accurate pyrometry, with temperatures up to 1600° , the direct reading pyrometer is not sufficiently sensitive, the resistance thermometer has not sufficient range and is, moreover, too bulky for the best melting-point work. A thermoelement with a potentiometer is the most satisfactory measuring apparatus.

II. The most characteristic requirement in melting-point and calorimetric work at high temperatures is rapidity. This is secured : (a) by proper selection and arrangement of the galvanometer. Periods of five seconds are almost necessary and are readily obtained ; (b) by the use of switches to exchange thermoelements, adjust zero, etc., (c) by relying upon the galvanometer for as much of the reading as possible, so as to minimize potentiometer manipulation. For this, constant galvanometer sensibility, and therefore constant resistance in the branch circuit of the potentiometer, is needed. An adjusting rheostat in the circuit secures this result fairly well for ordinary potentiometers, whose branch circuit resistance is variable.

III. External leakage can be absolutely prevented and internal leakage greatly diminished by equipotential shields, which interpose a continuous metallic surface between the circuit and the source of disturbance. Internal leakage also decreases with the resistance of the potentiometer.

IV. The constancy of the potentiometer storage cell is increased by a wrapping which protects it from temperature changes. For some other minor devices, those interested are referred to the body of the article.

V. With galvanometers of familiar commercial types, a sufficiently short period, five seconds, with satisfactory critical resistance and sensibility, can be obtained with a high resistance potentiometer. Either an especially good galvanometer or potentiometer of low resistance makes possible a somewhat better adjustment.

VI. A slide wire potentiometer is very undesirable in rapid work, and especially in melting-point and calorimetric determinations.

VII. By confining the range of the potentiometer to that actually needed in thermoelectric work, an instrument of almost ideal convenience and usefulness can be obtained at relatively low cost. It has constant galvanometer sensibility, low resistance, and ease of manipulation, and can be used on two circuits alternately without resetting.

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