R remains fixed, the changes in temperature of *T*, the thermometer coil, may be read directly in degrees on the slide wire if desired. The compensation by means of the leads *a*, *b*, *c* is effected as before. The arrangement used by Siemens and Halske is shown in Fig. 69. In Fig. 70 is shown a system of wiring for four thermometers of the Siemens type and used with a single indicator.

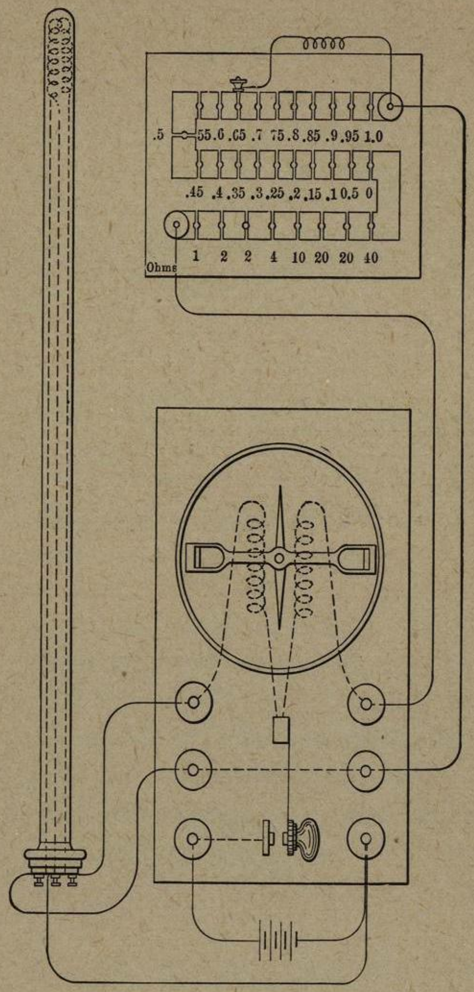

Fig. 69. Thermometer of Siemens and Halske.

For work of great precision, this method is of course capable

of elaboration and refinements, as in the calorimetric measurements of Jäger and Steinwehr, who, however, used a four-lead thermometer.

Four-lead Thermometer. — There are four ways in which the four-lead compensated thermometer of Callendar and Griffiths has been used, namely, the Wheatstone and Kelvin bridge, the potential terminal, and the differential galvanometer methods.

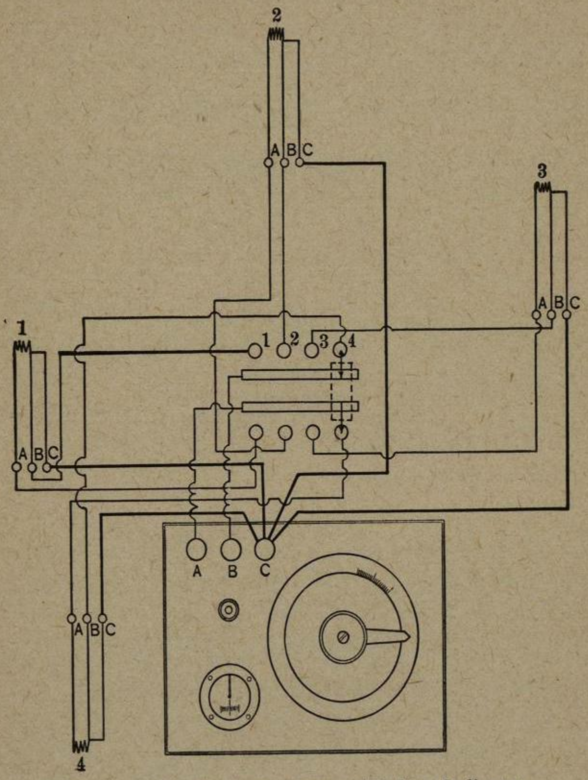

Fig. 70. Four Thermometers with One Indicator.

The *Wheatstone bridge method* is illustrated in Fig. 71, from which it is seen that the compensating leads are inserted in one arm *R* of the bridge and the thermometer leads in the other. It is necessary that all four leads be as nearly as possible of the same length, diameter, and material. For work of great accuracy it is necessary to take all the precautions which obtain in exact resistance measurements, and in particular the elimination of thermoelectric effects and uncertainties in the exact value of the ratio coils.

Precision Bridges. — In Fig. 72 is shown diagrammatically the important features of a bridge designed and in use at the Bureau of Standards, constructed by Leeds and Northrup, and capable of measurements to 1 in 100,000, and connected, in the figure, for use with a four-lead thermometer. This bridge can also be used, however, with a three-lead thermometer. Some of its characteristics are possibility of reversal of all circuits, the interchangeability of the ratio coils, mercury contacts for the higher resistances to eliminate contact resistances, a device due to Waidner consisting in a split ohm shunted across three dials to give rapidity of setting for final adjustment, and the ability to test the bridge without other accessories. The bridge is oil-immersed and kept at constant temperature by thermostatic control, and all coils are of seasoned manganin, which for the very highest precision should be sealed air-tight separately to avoid effects of humidity even beneath the oil. As galvanometer, a very sensitive form of d'Arsonval, due to Weston, is used, and

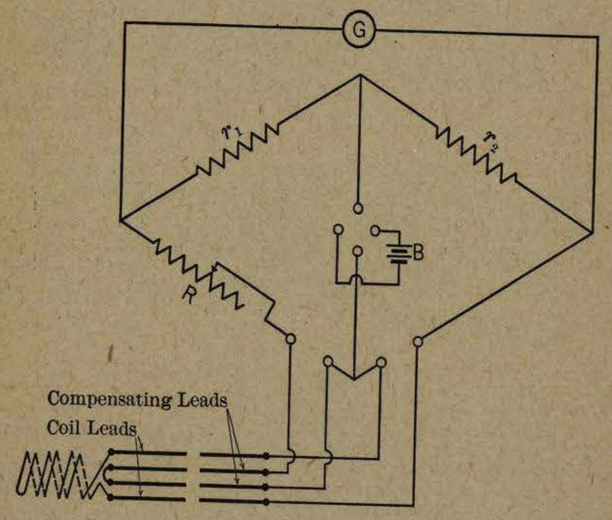

Fig. 71. Four-lead Compensated Thermometer.

as battery one to three dry cells. The thermoelectric key may be dispensed with and a single contact key put in the battery circuit, with a variable resistance to replace the usual galvanometer shunt for varying the sensibility.

Another form of the Callendar and Griffiths self-testing bridge, designed primarily for use with resistance thermometers of a fundamental interval of one ohm, is constructed by the Cambridge Scientific Instrument Company. To eliminate temperature variations in this bridge, not only the coils but the bridge wire and all contacts are oil-immersed; and it is capable of reading platinum temperatures, in the latest model, to better than 0.01° C. by direct reading on the scale of the bridge wire, when a galvanometer of suitable sensibility and resistance is used, such as a Broca instrument of 10 ohms.

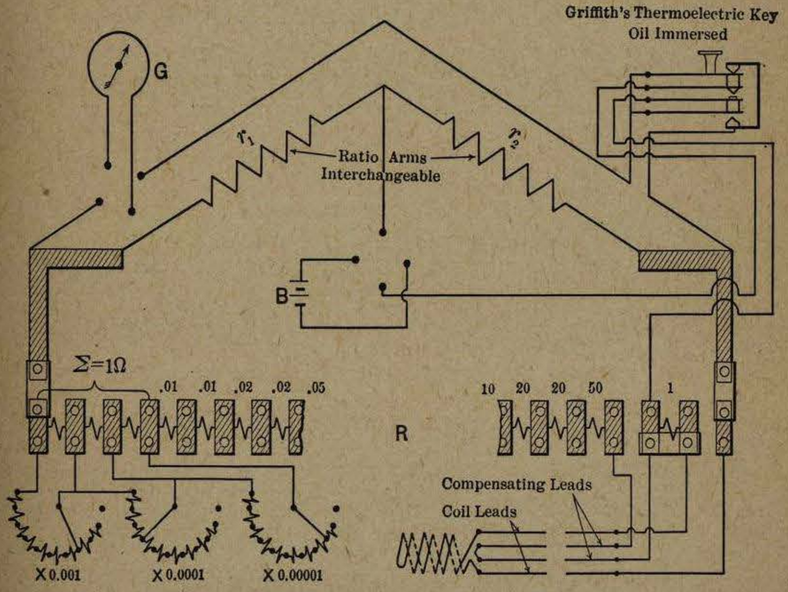

Fig. 72. Thermometer Bridge of the Bureau of Standards.

The principle of the construction and wiring of this bridge is shown in Fig. 73, in which R_1 and R_2 are ratio coils of 10 ω each, which should be interchangeable, *BC* the balance arm, adjustable by nine manganin coils *AR* and the slide wire *s*, while *DC* is the thermometer arm. P and C are the thermometer and compensating leads respectively.

The unit of the bridge is one degree on the platinum scale (page 201), and this corresponds to 0.01 ω for a F.I. of 1 ω in the thermometer. This bridge possesses many mechanical excellencies, such as a special form of combined plug and mercury contact, protection from mercury, and a convenient form of vernier and slide wire.

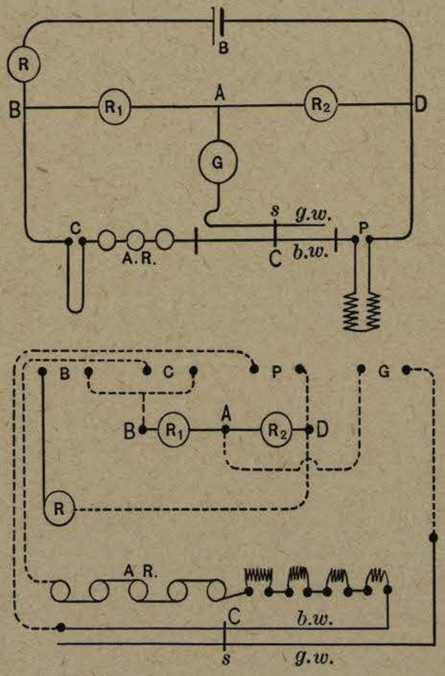

Fig. 73. Callendar and Griffiths Bridge.

The resistance of the *potential terminal thermometer* is determined by sending the same current from a storage battery through the thermometer and a known resistance in series, and measuring the potential drop by means of a potentiometer (page 138), first across the known resistance and then across the thermometer coil. This method of measurement for accurate work is illustrated in Fig. 74, which shows a rheostat and milli-

ammeter in the circuit for adjusting the measuring current. The mercury-contact resistance box may be adjusted to within 0.01 ohm of the thermometer, thus eliminating potentiometer errors. This box may of course be replaced by a single-standard resistance, in which case an accurate calibration of the potentiometer is required.

The current leads for this type of thermometer do not have to be adjusted to equality, and the potential leads may be of fine wire, as may also the current leads, but still keeping the thermometer sufficiently robust, so that errors due to heat conduction along the leads need not creep into the measurements.

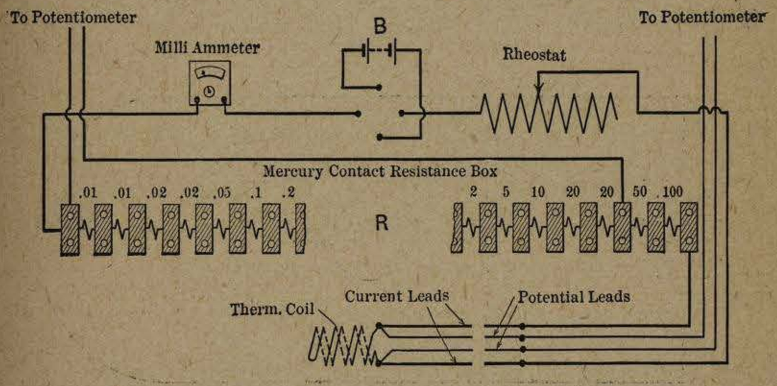

Fig. 74. Potential Terminal Thermometer of Precision.

The Kelvin Bridge. — The principle of this method of measuring resistances is shown in Fig. 75, in which S is an adjustable resistance, x the unknown, and the others are such that, by construction, $\frac{a}{b} = \frac{a_1}{b_1}$, when $x = \frac{a}{b} S$ for no current in the galvanometer. This method of bridge design, accompanied by a sufficiently sensitive galvanometer, permits the measurement of 0.01 ohm to be made with about the same precision as 100 ohms by the usual bridge methods, and is therefore particularly well adapted for resistance thermometers which are to be used at very high temperatures, because such instruments must be made of wire of large diameter, and therefore of low resistance, in order to avoid changes in their constants due to heating. The Kelvin bridge method permits cutting down the amount of platinum in the pyrometer, an advantage both in cost and in volume of the instrument.

Leeds and Northrup made a potential point indicator (Fig. 75 A), with slide wire for use with a heavy-coil low-resistance thermometer carrying a current of 0.3 ampere. The extension coils and slide wire may be graduated in degrees of temperature for any given thermometer. The high values (520 ω) of a and a' (Fig. 75), necessary to eliminate resistance changes in the potential leads, require that the galvanometer used shall have a greater sensibility than can easily be gotten in a portable pointer instrument. The type of galvanometer is the same as that required for high-precision Wheatstone bridge work with proper adjustment of critical external resistance.

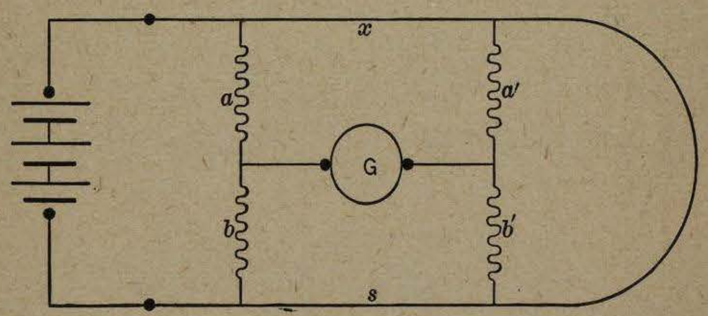

Fig. 75. Principle of Kelvin Bridge.

Sensibility. — The sensitiveness of the measurements in resistance thermometry is that of the very great precision attainable in resistance measurements, or it may be better than 1 in 100,000, or about 0.001° C. for a high-temperature thermometer whose resistance at 0° C. is from 3 to 25 ohms, if proper precautions are taken. The factors limiting the sensibility of resistance measurements in the Wheatstone bridge method, for example, and which are inherent in thermometric work, are the practical necessity of using a 1 : 1 ratio, required for the lead compensation; the need of keeping the current through the thermometer coil so low as not to raise its temperature unduly; and finally, the sensibility of the galvanometer. Due to the first and second of these conditions, the ordinary rules for the Wheatstone bridge do not apply without modification, and fortunately the limitations they impose may very largely be overcome by properly choosing the constants of the thermometer and galvanometer. It should be remarked that, with the d'Arsonval or

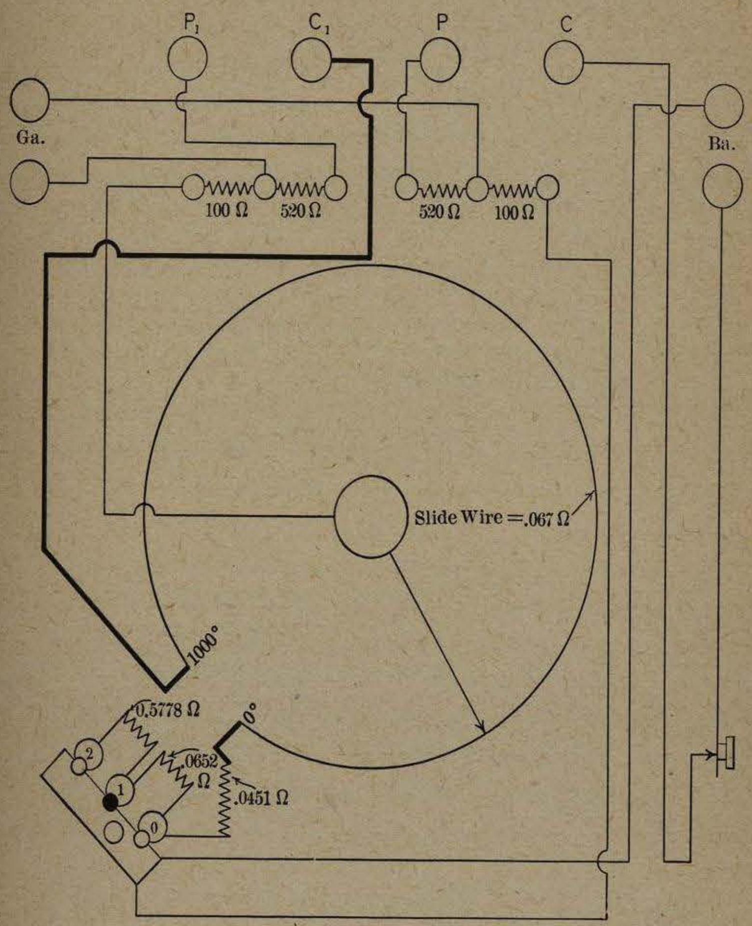

Fig. 75 A. Potential Point Indicator.

moving-coil galvanometers of very great sensibility and of practically constant zero which are available to-day, the question of the realization of sufficient sensibility is of distinctly secondary importance in accurate work. In the case of recording instruments, when in general a less sensitive instrument must be used, some attention has to be paid to the matter, and particular care has to be taken here to so arrange as not to overheat the thermometer with the larger currents required by such galvanometers. For the maximum current through the galvanometer and the minimum through the thermometer coil, with a battery of negligible resistance, the bridge should be arranged as follows, as shown by Callendar: " Connect the battery so as to make the resistance in series with the thermometer greater than the resistance in parallel."

Direct-reading Thermometers. — There have been in recent years a considerable number of direct-reading resistance pyrometers devised by several manufacturers. We shall be able to call attention to only a few typical instruments, which are, of course, of interest mainly in technical practice. A principle commonly made use of in some of its modifications is that of the *ohmmeter*, in which a variable resistance, that of the thermometer, is balanced against a fixed resistance by means of the deflection of a galvanometer coil carrying currents from circuits shunted around the two resistances in question. Such deflection instruments are constructed by Paul, Hartmann and Braun, Carpentier, Leeds and Northrup, and others.

The Harris Direct-reading Resistance-thermometer Indicator, manufactured by Mr. Robert W. Paul of London, indicates temperatures directly by the movement of a pointer over a scale; moreover its accuracy is independent of the battery or supply voltage used.

In principle it is a two-coil ohmmeter, or coil-controlled galvanometer; the requisite sensitivity to the small changes in resistance, which are utilized in platinum thermometry, is attained by making the action of the deflecting coil differential.

The differential windings of the deflecting coil are respectively connected in shunt with the platinum thermometer and a resistance equivalent to that of the thermometer at any desired temperature, dependent upon the part of the temperature scale at which it is desired to work. The control coil of the ohmmeter system is connected in shunt with a resistance suitably chosen to give the required sensitivity. These combinations are connected in series. Hence, on the passage of an electric current, the forces due to the windings are proportional to the resistances they respectively shunt.

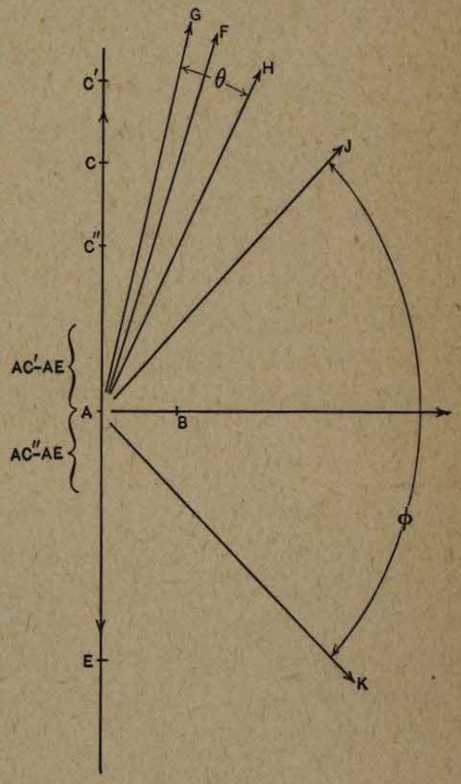

Fig. 76. Vector Diagram for Ohmmeter.

In the accompanying vector diagram, the platinum thermometer is assumed to have a Fundamental Interval of one ohm and to be brought up to a resistance of three ohms at 0° C., by means of a resistance which has no temperature coefficient, suitably introduced into the circuit. This enables the thermometers to be made electrically interchangeable with each other.

Considering first the case of an ohmmeter system without the differential winding of the deflecting coil, let AB represent the controlling force of the ohmmeter system (proportional to the control-coil shunt referred to above, and in this instance taken as one ohm); and let AC represent the deflecting force with a platinum thermometer of one ohm Fundamental Interval at 0° C. The pointer of the instrument will then take up the position AF.

Suppose the temperature of the thermometer is raised to 100° C.; the deflecting force now increases by the amount of CC' (proportional to one ohm) and becomes equal to AC', causing the pointer to set along AG. Similarly, if the thermometer drops to $-100°$ C., the position taken up by the pointer is along AH, giving an angle θ for 200° C. variation.

If, however, the deflecting coil be wound differentially, and a current equal to that producing the deflecting force AC be passed through the other winding in such a direction that its effort is in opposition to AC, introducing the vector AE, the initial position of the pointer will be along AB, and a variation CC' in the vector AC gives a resultant AC'' and causes the pointer to set along the line AJ. Similarly, should AC decrease by an amount equal to CC', the resultant deflection is on the opposite side of the initial position, and the pointer takes up the position AK, giving the large angle ϕ for the change in the thermometer resistance equal to that which only gave the angle θ with a nondifferential arrangement. It will be noted that AE may be given a value equal to AC at any required temperature of the platinum thermometer, the position of the pointer at such temperature lying along AB and covering the same angles as before for the same ohmic variation in the thermometer resistance. By simultaneously varying the vector AB the angle ϕ may be kept true to gas-scale temperature. It is thus possible to construct a multiple-range instrument.

The accompanying diagram, Fig. 77, shows the scheme of connections for such an instrument. One of the differential windings (X in the figure) is shunted with a platinum thermometer, the other winding S being shunted with a resistance s, which is made variable so as to equal the resistance of the thermometer at certain fixed temperatures. The control coil of the ohmmeter system is also shunted with the resistance d, the value of which is determined by the degree of sensitiveness required, and may be made variable with s. These shunted windings are connected in series, and the circuit is completed through a battery and switch.

In this arrangement, since the currents in the ohmmeter system windings depend upon the resistance of the platinum thermometer, s and d respectively, the value of s may be taken as the vector AE, increasing by steps equal to the rises in resistance of the platinum thermometer for each range of temperature. The platinum thermometer represents the vector AC, AC', etc., while d represents AB. This is made variable with s in order that the instrument shall read in gas-scale degrees on all ranges, and its values are calculated in accordance with Callendar's formula for the platinum thermometer.

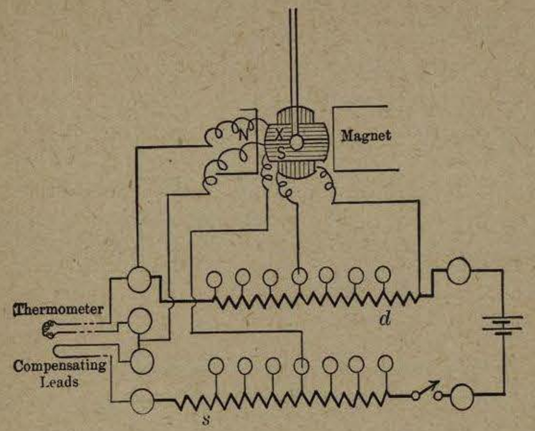

Fig. 77. Harris-Paul Indicator.

The Logometer and Ratiometer. — Messrs. Carpentier and Joly have also proposed the construction of a deflectional-resistance pyrometer based on the use of the logometer, an apparatus designed for the measurement of the ratio of two currents. This is shown in plan in Fig. 78, where two oppositely wound coils, similar to those of a d'Arsonval galvanometer, are mounted by double pivot in the unsymmetrical field of a permanent magnet NS. If the two coils

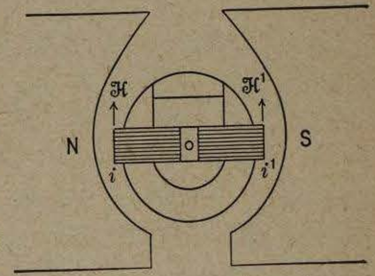

Fig. 78. Logometer Coil.

have the same number of turns, we have $iH = i'H'$, and since the electromagnetic force of each coil is directed toward a weaker field, the final position of the coils will be stable and will depend only on the ratio of the two currents i and i' in the coils.

For the measurement of resistance, the circuit, in one of its simplest forms, is arranged as shown in Fig. 79, the logometer coils being shunted, one about a manganin resistance r and the other about the platinum thermometer of resistance p; when if s and s' are the coil resistances, their currents are $\frac{ir}{s}$ and $\frac{ip}{s'}$, where i = current in principal circuit, and their ratio is $\frac{p}{r} \cdot \frac{s}{s'}$, a quantity whose variations depend only on p, the resistance of the platinum thermometer, neglecting any variations in the resistance of leads to the logometer coils. The logometer dial, over which moves a pointer attached to the moving coils, may therefore be graduated directly in degrees of temperature. The readings of the instrument are independent of the value or of variations in the current i. Measurements may be taken with alternating currents, and when the manganin and platinum coils are noninductively wound, the readings will be independent of changes in voltage and frequency. This instrument may be arranged to develop relatively powerful directing couples and is therefore readily rendered recording.

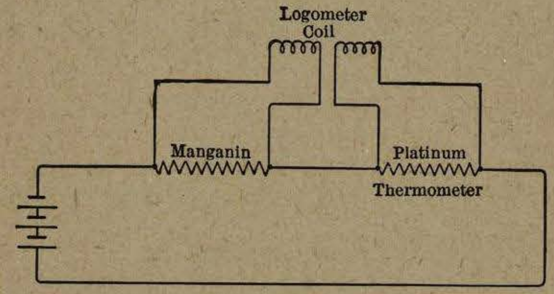

Fig. 79. Simple Logometer Circuit.

Northrup's ratiometer, similar to the preceding, is also an adaptation of the deflection-ohmmeter principle to temperature measurements. Northrup makes use of the three-lead thermometer with connections as shown in Fig. 80, in which C_1 and C_2 are two flat coils mounted on a damped movable system between the two crescent-shaped pole pieces of a permanent magnet. This instrument, which is made in a compact form and read by an attached microscope, can be made sensitive to about 0.1° C. and constant to better than 2° C.

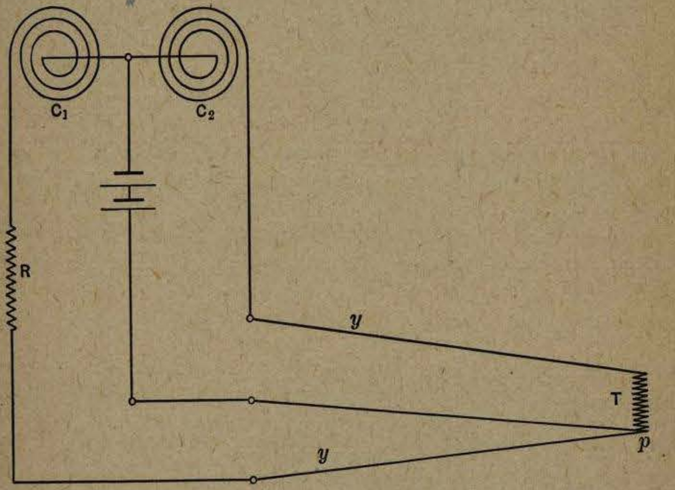

Fig. 80. Northrup's Ratiometer.

The Cambridge Deflectional Instrument. — The Cambridge Scientific Instrument Company also have recently devised a deflectional method for the measurement of temperature with resistance thermometers, in which the temperature is indicated by the "out-of-balance" current in a Wheatstone bridge, provided with compensating leads; the arms of the bridge are all fixed resistances except the one which forms the resistance thermometer. As designed, provision is made for exactly setting the zero of the indicator for a balance of the bridge, for adjusting the current to give the required deflection for the temperature range, and is provided with an "ice coil" for balancing the thermometer at 0° C.

The Whipple indicator shown in Fig. 81 is a dial instrument using the Wheatstone bridge principle. The galvanometer needle has to be brought to rest by turning a knob, when the dial reading gives temperatures directly.

The Leeds and Northrup Indicators. — This firm has brought out several patterns of balance and deflection indicator instruments based for the most part on the use either of the differential galvanometer (page 209) or the Kelvin bridge (page 215).

A very convenient deflection indicator with adjustable scale is shown in Fig. 82. The dial may be set to any desired temperature, and the position of the deflector needle indicates how much higher or lower the furnace is than the required temperature. The deflector has a very open scale, permitting readings to be taken from a distance. The workman has to concern himself only with deflections of the needle from the vertical. The accuracy is independent of voltage fluctuations, and the instrument may be run, if desired, from the ordinary lighting circuit. Temperature intervals as small as two degrees are readable.

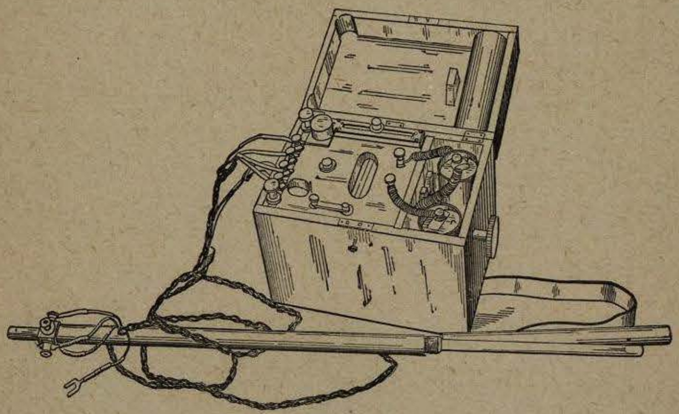

Fig. 81. Whipple Indicator.

Calibration. — For platinum thermometers which are to be used with some form of calibrated resistance-measuring apparatus, such as described above, it is only necessary, in order

to calibrate the thermometer, to take its readings at three temperatures, as at the ice point, the steam point, and the boiling point of sulphur, when, if the wire is of pure platinum, the temperatures found by using Callendar's method of computation (see page 201) will be correct to as close as they are known in terms of the gas scale to 1100° C.

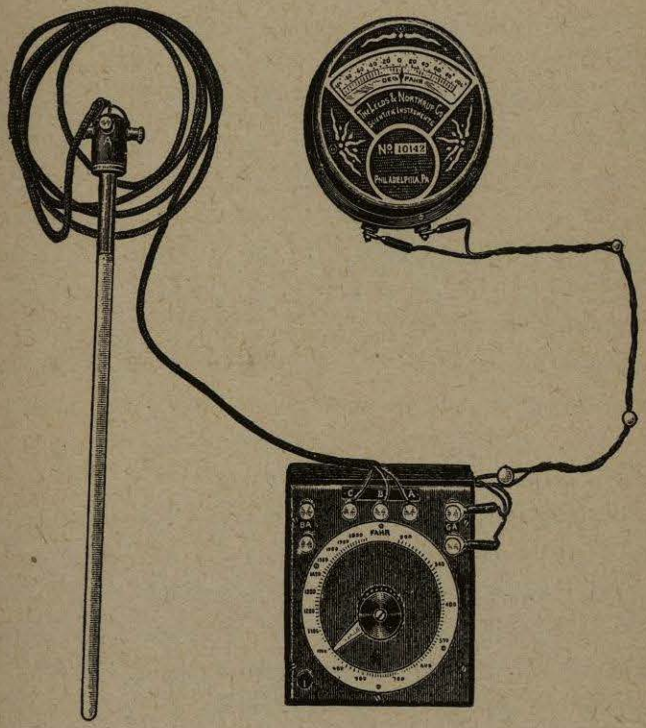

Fig. 82. Deflection Indicator of Leeds and Northrup.

There is advantage in using a fourth calibration point, as the silver freezing point, or that of Ag_3-Cu_2, in calculating the value of δ (page 201) for impure wires that are to be used at high temperatures. For the whole range of temperatures with such a wire, both the sulphur and silver points may be obtained, when δ takes the form $a + bt$.

For thermometers to be used with direct-reading temperature indicators, it is necessary to compare their readings with those