The use of an adjustable magnetic shunt for the elimination of this temperature correction may be illustrated as follows: The deflection D of the galvanometer may be considered proportional to the product of the flux F of the magnet by that, f, of the moving coil, or $D = kFf$. But f is directly proportional to the electromotive force e to be measured and inversely to the resistance of the circuit, whence

$$f = k' \frac{e}{r_{15}[1 + \alpha(t - 15)]},$$

where r_{15} is the resistance of the circuit at 15° C., α its temperature coefficient, and t its temperature. We have, therefore,

$$D = kk'F \frac{e}{r_{15}[1 + \alpha(t - 15)]}.$$

Since F remains sensibly constant with temperature, it follows that in order to have the same deflection for a given value of e, it is sufficient to cause F to change proportionally with the resistance of the circuit.

This is realized in practice, as in the instruments of Chauvin and Arnoux, by the use of a small bar of soft iron which may be brought nearer to or farther from the poles of the magnet, which operation produces a change in the magnetic flux through the movable coil. The motion of the iron bar is controlled by a screw whose head is graduated in degrees of temperature. The temperature of the auxiliary thermometer embedded in the galvanometer case is read and the magnet-control screw set to the indicated temperature, when the galvanometer readings are then corrected for temperature coefficient.

An automatic magnetic balancing of the increase in resistance of the galvanometer coil with temperature has been introduced into the Thwing galvanometers, as shown in Fig. 31. The coil rotates about one of its ends in a uniform field between two plane pole pieces. The two magnets that are connected in parallel by these pole pieces differ from those ordinarily used in being thin and therefore flexible. These magnets are pressed together somewhat by the long arm of a strong lever, the short arm of

which rests upon a post which is part of the aluminium case. The fulcrum is a bar of invar. Changes in temperature expand or contract the aluminium part, closing or opening somewhat the gap between the poles of the magnet, and the whole may be adjusted so that the change in flux through the coil may balance its change in resistance.

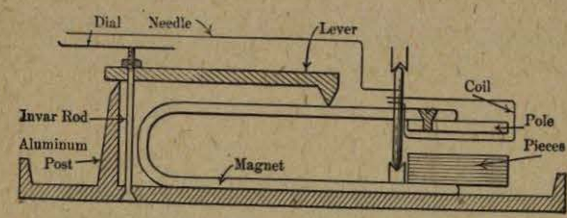

Fig. 31. Thwing's Compensating Device.

The Siemens and Halske method of temperature compensation is by a suitable combination of series and shunted resistances of copper and manganin in the swamping resistance of the instrument.

It should perhaps be emphasized at this point that the elimination of the temperature coefficient of the indicating galvanometer does not do away with making proper corrections for changes in temperature of the cold junctions of the thermocouple (see page 155).

Galvanometer Requirements for Industrial Practice. — In many industrial operations it is desirable to be sure of temperature measurements to within 10° C., often over a very considerable temperature range. This accuracy can be obtained with certain forms of the pyrometer galvanometer both with platinum couples and with some of the base-metal couples, but only when certain conditions are fulfilled by the maker and the user of the instrument. We may emphasize some of the desirable and necessary features of the galvanometer, as follows:

The instrument, if of the moving-coil pointer type, should be dust-free, of sufficient sensibility and range, and at the same time it should have an open, nearly equidistant scale which is well marked and easily read, without parallax, for example, by means of reflection of the pointer in a mirror alongside the scale. The deflection should be aperiodic or deadbeat, and the open-circuit reading should remain constant even after large deflections long maintained. There should be, in the case of suspended-coil instruments and in some pivot types, a suitable leveling device which has been accurately adjusted, and in these instruments particularly the case and other supporting parts should be free from warping. The zero position of the pointer should be readily adjustable. The instrument should either be free from errors due to changes in its temperature or else some form of compensation provided, and there should be no possibility of thermoelectric effects in the wiring within the instrument. The effects of jarring due even to shocks of considerable intensity and changes in the surrounding magnetic field should be without material influence on the readings. For pivot instruments particularly, it should be noted that the same E.M.F. always gives the same deflections. Finally, as we have before stated, the resistance of the galvanometer must be sufficiently high for the type of couple with which it is to be used. The effect of variations in the temperature of the cold ends of the thermocouple will be treated later. When a new couple is substituted, it should be noted that the E.M.F. scale of the galvanometer will still be correct, barring the effect of change in resistance of the circuit, but unless the new couple is identical in its electrical properties with the old, the temperature scale of the instrument will no longer hold.

One instrument may often serve for use with several couples of the same or of different types. It is then very important to avoid bad contacts in switches, and with very low-resistance outfits considerable errors that are not readily detectable may creep into the measurements. A galvanometer suitable for use with a Pt-Rh couple may very properly be used with a low-resistance base-metal couple of higher E.M.F. by putting additional resistance into the circuit if necessary, but a galvanometer suitable for use with the base-metal couple may be totally unfit for use with one of Pt-Rh.

The Galvanometer Method in the Laboratory. — On account apparently of its relatively low cost, and also because of its speed of operation, the galvanometer method of measuring temperatures with the thermocouple has been used frequently in scientific investigations of considerable delicacy. It should be borne in mind, however, that, even with the best pointer instruments carefully calibrated, which are much used in metallurgical and physiochemical researches, an accuracy of 5° is barely attainable with Pt-Rh couples, and this only by paying attention to the numerous sources of error we have emphasized above.

A sensitive d'Arsonval galvanometer read by reflection upon a straight graduated scale, or by means of a telescope and scale, has also been a favorite method of working. In this way the sensitiveness over the pointer method may be increased greatly, but in general the accuracy will not be very materially improved, as practically all of the troubles inherent to the galvanometer method are usually still present, whatever the method adopted for reading the deflection of the galvanometer coil. By slight modifications, the exactness of the galvanometer method may be increased, as for instance keeping the cold junctions at a definite and known high temperature and depending on the sensitive galvanometer for a smaller temperature interval; or better, by opposing the greater part of the E.M.F. of the couple with a known E.M.F. furnished by a standard cell and resistance or volt box. This last, however, is the simplest case of the potentiometric methods which we shall now study.

Potentiometric Methods. — The fundamental principle on which the many potentiometric methods are based is the adjusting of the electric circuit so that no current flows through the thermocouple. This is accomplished by balancing the E.M.F. generated in the thermocouple by an E.M.F. whose numerical value may be varied at will and measured. Since the two E.M.F.'s are in opposition, the measurements may be made to have all the advantages of a null or zero method, which is usually desirable in precision work.

Apparatus Required. — A complete installation for work to 1° C. consists of:

1. A *standard cell,* which should not have any current pass through it, and serves to determine, as term of comparison, a difference of potential between two points of a circuit through which there is a current given by an accumulator. The cell used may be a Latimer-Clark, whose electromotive force for small changes in temperature is

$$e = 1.433 \text{ volts} - 0.00119\,(t^\circ - 15^\circ).$$

This cell is made up as follows: zinc, sulphate of zinc, mercurous sulphate, mercury. The zinc sulphate should be perfectly neutral; for that, the saturated solution of the salt is heated to 40° or more with an excess of zinc oxide to saturate the free acid, is then treated with mercurous sulphate to remove the excess of zinc oxide dissolved in the sulphate, and finally crystallization is produced at 0°; one thus obtains crystals of zinc sulphate which can be immediately used.

This element is very constant. With a surface of zinc electrode equal to 100 sq. cm. and a resistance of 1000 ohms, the dropping off of the electromotive force of the cell in action does not reach $\frac{1}{1000}$; with 100 ohms only, this would be $\frac{1}{200}$. Practically it is possible, with a resistance of 1000 ohms, to limit the surface of the electrodes to 30 sq. cm., and to do away with the use of accumulators. But then the theoretical advantage of the absolute rigor of the method employed is lost.

There are other forms of standard cell which possess the advantages of portability and small temperature coefficient, rendering them better adapted for ordinary use than the original Clark form. The Carhart-Clark cell is made with unsaturated mercurous sulphate and has the E.M.F.

$$e = 1.439 - 0.00056\,(t^\circ - 15^\circ).$$

In the Weston normal cadmium cell, which has generally replaced the Clark as a standard of E.M.F., and has been officially recognized as the standard by the London Electrical Conference of 1908, cadmium and cadmium sulphate replace the zinc and zinc sulphate of the Clark cell; its E.M.F. at 20° C. is 1.0183 and its temperature coefficient to two terms as found by Wolff is:

$$E_t = E_{20} - 0.0_4406\,(t - 20^\circ) - 0.0_695\,(t - 20)^2.$$

In the portable form of the cell the cadmium sulphate is unsaturated. This portable cell has no appreciable temperature coefficient, so that no precautions as to temperature control have to be taken. This cell also recovers rapidly after maltreatment. Its E.M.F. is 1.0187 volts at 20° C., although different cells will differ slightly, i.e., by ± 0.0005 volt. Hulett has tried using a large-area cadmium cell simultaneously as a battery and standard E.M.F. with considerable success.

The values of the E.M.F.'s given above are in international volts, which are legal in the United States and used by the National Bureau of Standards, and are the values effective Jan. 1, 1911, as recommended by the International Committee on electrical standards. The values previously used for the Clark were 1.434 volts at 15° C., and for the normal Weston, 1.0189 volts at 25°, in the United States.

2. A *resistance box,* or one of the forms of potentiometer of which we shall treat immediately. The former includes a fixed resistance of about 1000 ohms and a series of resistances of 0 to 10 ohms, permitting by their combinations to realize in this interval resistances varying by tenths of an ohm. One may, for greater simplicity, but by sacrificing precision, replace this series of small resistances by a single Pouillet's rheostat having a total resistance of 10 ohms. This apparatus consists of two parallel wires of a meter in length and 3 mm. in diameter, made of an alloy of platinum and 3 per cent copper.

3. A *sensitive galvanometer* giving an appreciable deflection for 10 microvolts. Since it is placed in the circuit of the couple, and since this is a case of reduction to zero, use may be made here of a Deprez-d'Arsonval galvanometer of small resistance.

Principle of the Method. — If we have an electric circuit consisting of a standard cell, or other source of E.M.F. of known value E, and a suitable combination of resistances whose total value is R for the whole circuit; and if the thermocouple in series with a galvanometer is connected across a portion r of R so that there is no deflection of the galvanometer, the E.M.F. of the couple is given by the expression

$$e = E \cdot \frac{r}{R}.$$

A modification of this method eliminating the standard cell in actual work with the couple has its advantages. A storage cell at W (Fig. 32) is in series with a rheostat R and a series of coils or combinations of coils and bridge wire represented by AB. The E.M.F. of the standard cell at E is balanced against

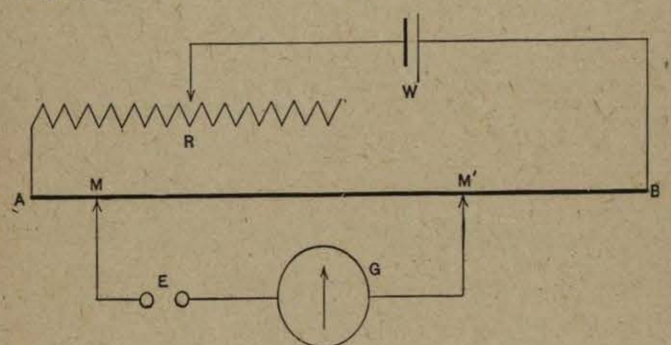

Fig. 32. Principle of Potentiometer.

that of the battery W by varying R, the points of contact M and M' being at A and B and the balance indicated by no current in the galvanometer. The standard cell is now replaced at E by the couple whose E.M.F. is to be measured; M and M' are then varied in position until a balance is again obtained; then

$$e = E \cdot \frac{MM'}{AB}.$$

This is the simplest form of *potentiometer*, of which there are many convenient forms now available for temperature measurements.

Another modification of this method, eliminating the use of a potentiometer or carefully calibrated resistance box, but requiring a calibrated milliammeter and one or more well-known resistances, was first used by Holman in thermoelectric work, and Fig. 33 illustrates the principle. M is a milliammeter and r a small (0.1 ω) known resistance, R a rheostat with fine adjustment, G the galvanometer, and T the thermocouple. The deflection of G is brought to zero by varying R when the product of the current given by M and the resistance r gives the desired E.M.F. With a series of coils to substitute at r, the range of measurable temperature may be indefinitely extended. The precision of this method is limited by that of the milliammeter M. Siemens and Halske sell a convenient form of this apparatus as devised by Lindeck of the Reichsanstalt.

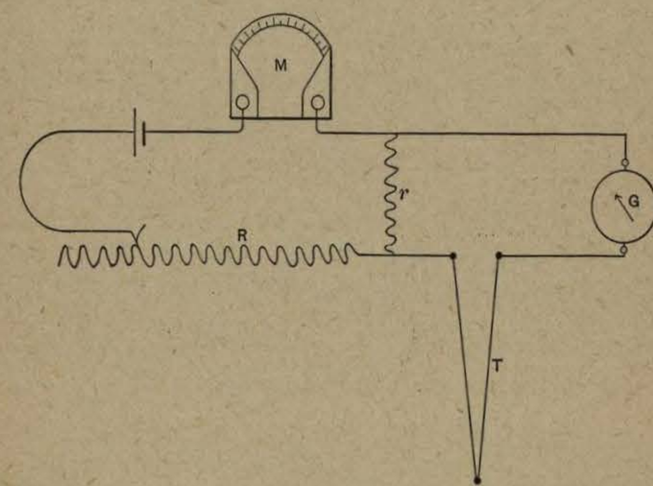

Fig. 33. Holman's Method.

Various other special forms of apparatus for the exact measurement of thermocouple E.M.F.'s have been devised, but they are all modifications, more or less complicated, of the above. We shall treat of some of them under potentiometers.

Potentiometers for Use with Thermocouples. — Although the galvanometric method is suitable for many technical thermoelectric measurements of temperature, it is generally necessary to resort to potentiometric methods when an accuracy of 10° C. or better is required, as is the case in many laboratory operations. This exact work is usually best done with thermocouples of the platinum metals, so that the problem of best design of potentiometers for temperature measurement is quite a definite one. The need of sufficiently sensitive and accurate devices for the measurement of small E.M.F.'s in thermoelectric pyrometry has acted as an incentive for the great improvement, in recent years, of apparatus suitable for this purpose, and there are now available a considerable number of potentiometers meeting the requirements for very exact temperature measurements by this method, as well as less costly instruments giving an accuracy between that obtained with the galvanometer method and the more elaborate potentiometric installations.

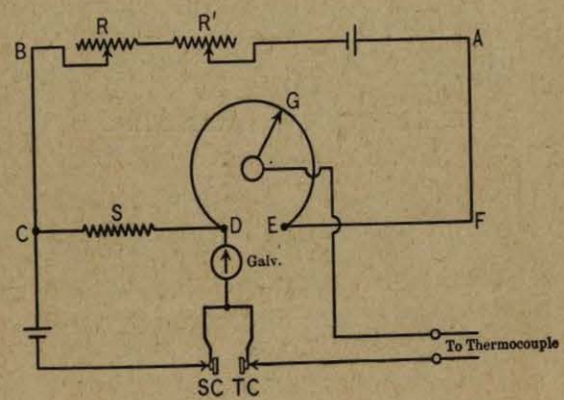

Fig. 34. Potentiometer Indicator Circuits.

The potentiometer indicator of Leeds and Northrup, shown in Fig. 34, illustrates a type of instrument of intermediate precision, but without the disadvantages of the galvanometric method, it being possible to get results to about 3° C. with this apparatus, using Pt-Rh thermocouples.

This indicator consists of a Weston standard cell, a secondary dry battery, and a galvanometer connected up as a potentiometer, the whole being mounted in a box of convenient size, making a portable testing outfit (Fig. 35). The dry cell is continuously on the closed potentiometer circuit $ABCF$, which includes the two regulating rheostats R and R' and a fixed resistance S. The current in the potentiometer circuit is adjusted by changing R

and R' with the key at SC until the galvanometer shows no deflection. Pressing the key to TC, the pointer G is set on the slide wire DE, calibrated in millivolts, until again the galvanometer remains undeflected, indicating a balance in the thermocouple circuit.

Precision Requirements. — Some of the requirements which must be met in potentiometer construction we may emphasize. For work to 0.1° C. with Pt-Rh couples, for example, we must

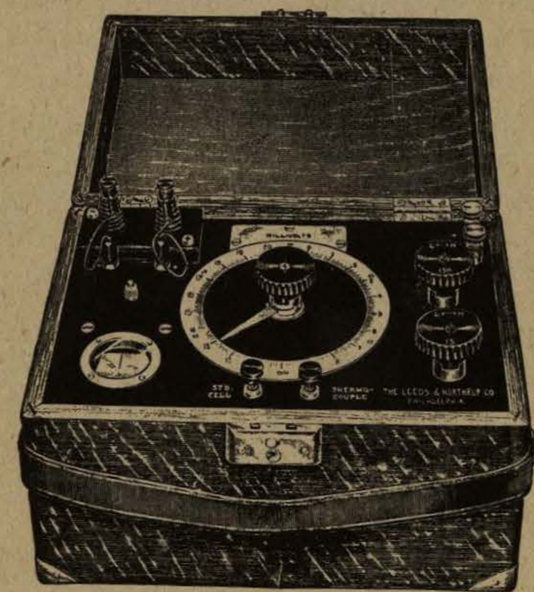

Fig. 35. Potentiometer Indicator.

have a sensibility of 1 microvolt (millionth of a volt) throughout the range of the instrument, which may be of 20 millivolts, necessitating an accuracy of 1 in 20,000 in all adjustments affecting the final value of the E.M.F. Contact or thermal E.M.F.'s, such as develop even for slight temperature differences in the various parts of such an apparatus, are to be avoided in the electric circuits, as far as possible, by proper choice of materials, design, and method of manipulation; for example, using thin metal contacts, putting sliding contacts in battery circuit, and working with the galvanometer circuit closed. In order to in-