measurements of current, it was necessary to attend to a series of details of construction, previously neglected. Here are the most important among these, as noted by Le Chatelier for suspended-coil galvanometers:

1. The *movable coil* should possess a resistance as little variable as possible with the surrounding temperature in order to avoid corrections always very uncertain. The coils of copper wire ordinarily used to augment the sensibility should be absolutely discarded; use should be made of coils of German silver or of similar metal with small temperature coefficient such as manganin.

2. The spaces which separate the coils, from the poles of the magnet, on the one hand, and from the central soft-iron core on the other, should be sufficiently great to avoid with certainty any accidental friction which would prevent the free movement of the coil. The rubbings to look out for do not come from the direct contact of the frame with the magnet: these latter are too visible to escape unseen. Those which are to be guarded against come from the rubbing of filaments of silk which stand out from insulating covering of the metallic wires, and from the ferruginous dust which clings to the magnet. It is here, it would seem, that the most serious source of error is met with in the use of the movable-coil galvanometer as measuring instrument. There is no warning indication of these slight rubbings which limit the displacement of the coil without, however, taking from it its apparent mobility.

3. The suspending wire should be as strong as may be to support the coil without being exposed to breaking by shocks; on the other hand, it should be very fine, so as not to have too great a torsion couple. Two different artifices help to reconcile somewhat these two opposed conditions: the use of the mode of suspension of Ayrton and Perry, which consists in replacing the straight wire by a spiral made of a flattened wire, or more simply the use of a straight wire flattened by a passage between rollers.

The first method offers the greatest security from shocks; it is, on the other hand, more difficultly realizable; minute precautions should be taken to prevent any rubbing between adjoining spirals. The second method allows more easily having the large angular displacements which are indispensable when it is desired to take readings upon a dial.

The most essential property necessary for the wires is absence of permanent torsion during the operations. These torsions cause changes of zero which may render worthless all the observations if account is not taken of this, which complicates matters considerably if such correction has to be made. This result is reached by using wires as long as possible, having not less than 100 mm. length, and by avoiding giving to them an initial torsion, a precaution that should be kept constantly in mind, which it often is not. When one wishes to adjust the coil to the zero of graduation, one turns often haphazard either one of the wires; it may be then that each of the wires is given an initial torsion of considerable magnitude and of opposite sign. If the two wires are not symmetrical, as is ordinarily the case, the permanent deformation resulting from this exaggerated torsion will cause a continual displacement of the zero which may last for weeks and months, increasing or decreasing during the observations according to the direction of displacement of the coil. This torsion is easy to obviate at the time of construction, but it is not possible to verify later its absence in the case of round wires or spirals except by dismounting the apparatus. On the contrary, by the use of stretched flat wires it is very easy upon simple examination to determine the existence or absence of torsion. This is another reason for employing them.

Finally, use must be made of wires having a very high elastic limit. For that it is necessary that the metal has been hardened, and besides that the metal does not undergo spontaneous hardening at ordinary temperatures. Silver, generally employed as suspension wire, is worthless. A metal, as iron, which even after annealing possesses a high elastic limit, would be perfect if it were not for its too great alterability. One cannot be sure of having uniform hardening, because the soldering of wires, indispensable to assure good contacts, anneals them throughout a certain length. German silver is the metal the most frequently used in galvanometer suspensions destined for pyrometric measurements. The alloy of platinum with 10 per cent of nickel seems preferable; after annealing it has a high elastic limit, and possesses a tenacity much higher than that of German silver. Its disadvantage is to possess a limit of elasticity twice as great, which reduces by one-half the deflections of a given cross section of wire. Phosphor bronze also gives good results.

4. *Installation of the apparatus* for the galvanometers, in which the coil is carried by two opposed *stretched* wires, necessitates special precautions.

In the first place, it should be located beyond the influence of jarrings of the ground, which render reading impossible; then it is necessary that its position remain *rigorously* fixed. If, in fact, the two extreme points of suspension of the wires are not exactly in the same vertical, and if the center of gravity of the coil is not exactly in the line of the two points of suspension, two conditions which can be never rigorously realized, the apparatus constitutes a bifilar pendulum of great sensibility. The slightest jarring suffices to provoke very considerable angular displacements of the coil. To avoid them, the apparatus should rest upon a metallic support attached to a wall of masonry. When the apparatus is placed, as is often the case, upon a wooden table resting upon an ordinary wooden floor, in order to obtain a deflection of the coil, and in consequence a displacement of the zero, it suffices to walk around the table, which causes the floor to bend slightly, or to provoke a current of air, which, in changing the hygrometric state of the legs of the table, causes it to tip somewhat.

Coils freely suspended from above have not these disadvantages.

Types of Suspended-coil Galvanometer. — A series of galvanometers have been studied especially in view of pyrometric measurements; we shall pass them rapidly in review.

For laboratory researches the usual swinging-coil galvanometer as made by Carpentier is often used in France. One must make sure that these instruments satisfy well the indispensable

conditions which we have mentioned, which is not always the case when these instruments have been constructed with reference to the ordinary experiments of physics.

This laboratory apparatus, the only one which existed at the time of the first investigations of Le Chatelier, was not transportable, and could not be arranged for experiments in industrial works. It was then necessary to devise a special model of galvanometer easy to carry about and to put in place. The apparatus (Fig. 26) is composed of two parts, the galvanometer and the transparent scale with its light. The two parts are symmetrical,

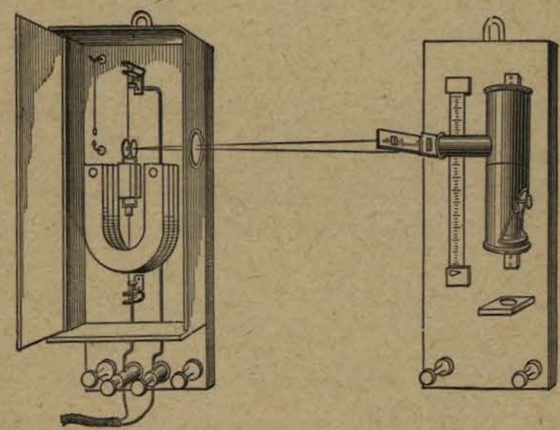

Fig. 26. Le Chatelier's Thermoelectric Galvanometer.

and, for transportation, may be fixed back to back on the same plank carrying a handle. For observations they are fastened to a wall by means of two nails driven in at a suitable distance apart. The suspension wires, in case of breakage, may be immediately replaced. They carry, soldered to their two ends, small nickel spheres, which one has only to slip on to forked pieces attached to the top and bottom of the coil, and to the supports of the apparatus, respectively. The mirror consists of a plano-convex lens, silvered on the plane face, which gives much sharper and brighter images than the ordinary small mirrors with parallel faces.

Carpentier has also made for the same purpose a galvanometer in which the readings are taken by means of a microscope. It is an easily transportable apparatus and very convenient. It has the fault to be subject to a displacement of the zero resulting from the unsymmetrical heating of the body of the microscope by the small lamp which lights the reticule. The stretched wires are replaced by large spirals which offer an absolute resistance to rupture by shock during transportation.

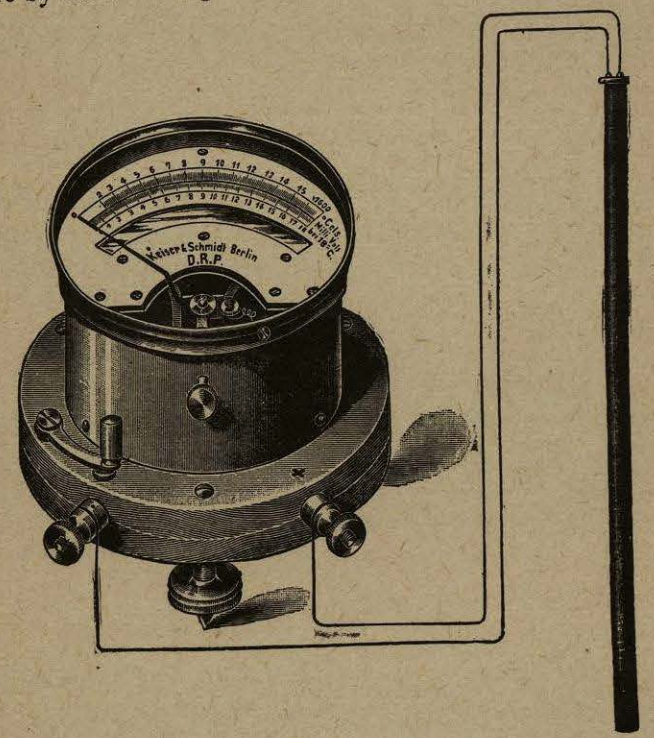

Fig. 27. Keiser and Schmidt Outfit.

The use of this apparatus necessitates an arrangement which permits, during the observations, putting the galvanometer on open circuit so as to verify the zero reading.

In the three preceding galvanometers the measurement of the deflection of the coil is made by optical means; in the following, the measurement is made by means of a needle swinging over a scale.

After a study made by Holborn and Wien at the Physikalische

Reichsanstalt in Berlin of the Le Chatelier thermoelectric pyrometer, the firm of Keiser and Schmidt devised a needle galvanometer (Fig. 27) which works fairly well, although the early forms of this instrument were of too low resistance for many industrial purposes and its temperature coefficient is unduly high. It has the disadvantage of being somewhat fragile. The suspending wire of the coil does not seem to have more than $\frac{1}{20}$ mm. diameter; the mounting of the apparatus is quite complicated. Repairs cannot readily be made either in the laboratory or works.

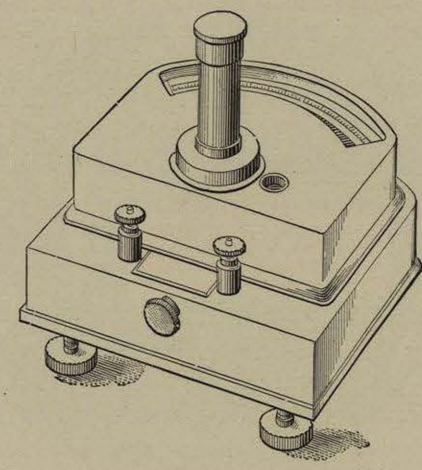

Fig. 28. Siemens and Halske Pyrometer Galvanometer.

The firm Siemens and Halske has also devised an excellent model of needle galvanometer suitable for temperature measurements (Fig. 28). Its resistance is 340 ohms, or 400 ohms in the later forms; the scale has 180 divisions, each corresponding to 10 microvolts. There is also a second graduation which gives the temperature directly with the couple sold with the apparatus. Commutators allow of putting the apparatus successively in communication with different thermoelectric couples, if it is desired to take simultaneously several sets of observations. This instrument is provided with a good level, and has a small temperature coefficient. Hartmann and Braun also manufacture excellent instruments of this type. Their wall pattern is shown in Fig. 29.

Pellin of Paris has made, from designs of Le Chatelier, a needle galvanometer of simple construction which can be repaired where it stands. The very long suspension wire is of 10 per cent nickel platinum; it has $\frac{1}{10}$ mm. diameter and is drawn out flat.

The lower wire is made of a spiral of the same wire of $\frac{1}{20}$ mm. diameter, which is situated in the interior of the iron core so as to

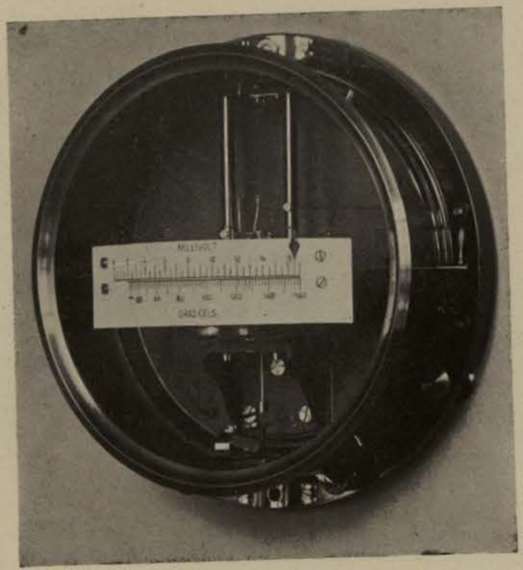

Fig. 29. Hartmann and Braun Wall Type.

insure uniformity of temperature. When the spirals of the suspension are unequally heated by radiation from the room or for other reason, there results considerable displacement of the zero. A spirit level permits of rendering the apparatus vertical, but it is prudent, by reason of the length of the suspension wire, to make sure directly of the absence of rubbing on the coil. For this a slight jar is given to the apparatus; the point of the needle should take up and keep for a long time a slow oscillatory movement in the direction of its length; the transverse oscillations ceasing rapidly indicate friction upon the coil.

Pivot Galvanometers. — The development of satisfactory pivoted moving-coil electrical instruments with spring control, whose indications as given by a pointer on a scale do not change with time, is very largely due to Weston. It is only recently, however, that pivoted millivoltmeters of sufficiently high resistance and range to use with platinum couples have been made. The characteristics of the design of one type of such instruments are shown in Fig. 30, illustrating Paul's mono-pivot construction.

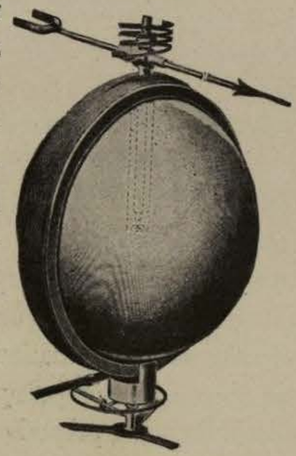

Fig. 30. Paul's Unipivot Mounting.

The indicator is a low-reading moving-coil voltmeter, the circular coil of which is pivoted at the center of a spherical iron core, and carefully balanced so that its position is unaffected by vibration or want of exact leveling. The pivot works in a finely polished jewel, from which it is completely lifted on depressing a plunger projecting through the top of the instrument, thus rendering the apparatus proof against rough handling in transit. A moving coil of low resistance is used in conjunction with a large resistance of negligible temperature coefficient included in the instrument, so that any error due to change of temperature of the indicator is thus reduced to a minimum. The movement of the coil is controlled by a spring, and the index may be set to zero, should this be necessary, without opening the instrument, an external adjustment being provided for this purpose. The unipivot principle entirely eliminates the delicate suspensions previously used, which frequently caused trouble by accidental breakage, this necessitating the entire readjustment of the apparatus.

In general, we may point out that for this type of galvanometer the case must be dust-free to avoid the collection of particles in the very small clearance of the moving coil, mounted between the pole pieces of a powerful permanent magnet. When well designed the magnetic circuit does not change its qualities appreciably in years, and such instruments are very little affected by extraneous magnetic fields, and are very robust, being capable of standing relatively rough handling. They require no leveling and several types have no adjustment whatever. It is usually well, however, to have a set screw to lock the pointer or coil system, unless, as is sometimes the case, lifting the instrument clamps the pointer. It is also convenient to be able to adjust readily the zero position of the galvanometer, and also to be able to eliminate mechanically the effects of temperature change on the readings of such an instrument. There are many millivoltmeters on the market of sufficient range and sensibility for the thermoelectric measurement of temperature, but only a very few of them are properly designed for such usage, and great care should be taken, in purchasing a pivot galvanometer, to find out if the instrument in question is suited for the work in hand. It has been the custom of some dealers in pyrometric apparatus to make use, for example, of pivot millivoltmeters of absurdly low resistance in connection with relatively high resistance thermocouples (see page 119). A millivoltmeter may, therefore, be suitable for use with one type of thermocouple and not with another.

In order to enjoy the practical conveniences of the pivot type of galvanometer, at least when using platinum thermocouples, some sacrifice of precision, range or sensibility has to be made. It appears to be as yet impracticable, for example, to make open-scale instruments with a range of 18 millivolts and increase the resistance above 170 ohms, and the range of the best makes is from 90 to 160 ohms. In this case, as we have seen, the reading of the galvanometer will depend somewhat upon the length of leads and upon the depth of immersion of the couple in the heated space.

There are a great many manufacturers of low-resistance pivot millivoltmeters, some of which are suitable for use with base-metal couples of sufficiently low resistance. Among the manufacturers of pivot instruments suitable for use with platinum couples are Paul of London, Siemens and Halske, and the Cambridge Scientific Instrument Company. The first makes a unipivot galvanometer, and the others double-pivot instruments of the Weston type.

Temperature Coefficient of Galvanometers. — It is desirable that the readings of indicating galvanometers be as little affected as possible by temperature changes in the instruments themselves. In the earlier pyrometer galvanometers this matter was generally overlooked, but in many of the newer instruments provision is made for eliminating this effect. Some of the instruments most commonly used in pyrometric practice have temperature coefficients ranging from 0.03 per cent to 0.25 per cent per degree C., depending on the type and maker. They all read too low for an increase in temperature. That this is a serious source of error is evident from an example. If an instrument having a temperature coefficient of 0.1 per cent per degree C. is calibrated at 15° C. and is used at 35° C., as may readily happen in practice, its readings will be low by 2 per cent, or 20° C. at 1000° C., due to this cause alone.

The simplest method in theory for the elimination of this effect is to use wire having no temperature coefficient, such as manganin, for the coil and auxiliary resistance of pyrometer galvanometers. Manganin has the further advantage that its Peltier effect against copper is almost zero. It appears, however, to be difficult to get sufficient sensibility in this way due to the high specific resistance of manganin.

There are various other devices for cutting down or eliminating this effect, some based on the choice of materials for and the ratio of the coil and balance resistances, and others on the variation of the strength of the magnetic field between the pole pieces, effected either by hand or automatically.

In the single-pivot indicators of 100 ohms total resistance, of R. W. Paul of London, for example, the resistance of the copper moving coil is only 10 ohms, the balance being of manganin, reducing the temperature variation in the resistance of this galvanometer to the order of 0.047 per degree C.