Most of the recent exact work employing the principle of this method has been done by taking the observations of θ directly on a potentiometer and $\theta - \theta'$ on the same or an auxiliary galvanometer. In this case of direct reading, the simpler arrangement of thermocouples indicated in Fig. 157, due to Burgess, may advantageously replace Roberts-Austen's (Fig. 158), or the modification shown in Fig. 159, such as used by Carpenter and others. The first dispenses with one thermocouple and the drilling of a second hole in the sample.

This method is evidently capable of attaining maximum sensitiveness, since the galvanometer connected to the differential thermocouple, giving $\theta - \theta'$ *vs* t, may be made as sensitive as

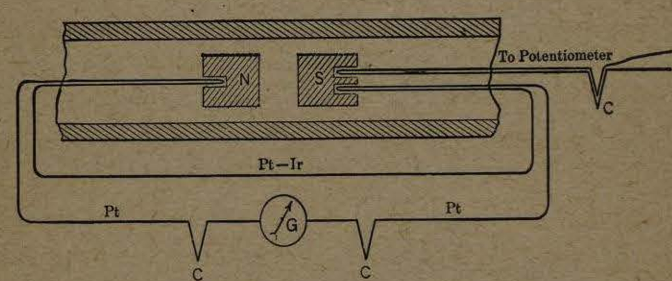


Fig. 159. Arrangement used by Carpenter.

desired independently of the θ *vs* t system. There is the further advantage that no limits are set to the range of temperatures over which a given precision in $\theta - \theta'$ may be had. There is, however, a limitation on the certainty of interpretation of results by this method, especially when the rate of cooling is rapid, due to the fact that it is practically impossible to realize the ideal condition of having $\theta - \theta' =$ a constant, or keeping the cooling curves of the test piece and neutral parallel for temperature intervals within which there are no transformations of the test piece. The rate of cooling, and hence the value of $\theta - \theta'$, is influenced by several factors, among the most important of which are the mass of each substance, — the unknown and the neutral, — its specific heat, conductivity, and emissivity, as well as the relative heat capacities of the furnace and inclosed samples. The $\theta - \theta'$ *vs* t

line is, however, always a smooth curve, except for the regions in which there are transformations in the substance under study.

The autographic system of recording may also be used, and it is possible to construct an apparatus by means of which both the θ *vs* t and $\theta - \theta'$ *vs* t curves shall be recorded simultaneously on the same sheet by the same galvanometer boom. In order to accomplish this, we have made use of a Siemens and Halske recording millivoltmeter having a total range of 1.5 millivolts and a resistance of 10.6 ohms. The E.M.F. generated by the differential thermocouple, proportional to $\theta - \theta'$, is recorded directly by this instrument. 1° C. corresponds to from 16 to 19 microvolts between 300° and 1100° C. for a platinum-iridium couple, or to about 1.8 mm. on the record paper. In series with the Pt-Ir thermocouple giving temperatures is a suitable resistance, about 200 ohms in this case, so that the galvanometer boom may be kept within the limits of the paper when recording values of θ. The circuit is made alternately through the direct and the differential thermocouple circuits in series with the recorder by means of a polarized relay actuated by the same battery that depresses the galvanometer boom when the mark is made on the paper. The thermocouple circuits may be those of either Figs. 157, 158, or 159, but with the galvanometer G_2 indicating temperatures suppressed.

It is evident that by recording the two curves, $\theta - \theta'$ *vs* t and θ *vs* t, on the same sheet there is some sacrifice in the ability to detect small and rapid transformations, since the spacing is doubled. Usually also, with such an arrangement, the galvanometer will not be completely aperiodic for one or the other system. On the other hand, it is of great advantage to have the curves together and obtained independently of inequalities in clock rates, which are a serious source of error in locating transformation points exactly when two separate instruments are used. The same result may be effected by shunting the galvanometer when on the temperature side. This of course cuts down very greatly the resistance of the thermocouple circuit, a disadvantage unless a sensitive galvanometer of high resistance is used. Such galvanometers suitable for mechanical recording are not yet available. In Thwing's recording pyrometer, two galvanometers, one giving temperatures and the other differences, impress their records on a single chart driven by one clock.

When it is desired merely to detect the existence of a transformation without measuring its temperature exactly, the sensitive form of recording millivoltmeter may be connected directly to the differential thermocouple without other accessories, as was done by Hoffmann and Rothe in studying the transformations of liquid sulphur.

Saladin's Apparatus. — It is sometimes of advantage to be able to record and discuss the data independently of the time, and so express $\theta - \theta'$, the difference in temperature between sample and neutral, directly in terms of θ, the temperature of the sample. This may evidently be accomplished by replotting the results obtained from the curves of the previous differential methods which involve the time. It was reserved, however, to Saladin, engineer of the Creusot Works, to invent, in 1903, a method that would record photographically the θ *vs* $\theta - \theta'$ curve directly, thus obviating any replotting. His method possesses also the advantage of having the photographic plate fixed in place. The forms of curve obtained in this way are illustrated in Fig. 134.

The arrangement of the apparatus in its simplest form, due to Le Chatelier, is shown in Fig. 160. Light from the source S strikes the mirror of the sensitive galvanometer G_1 whose deflections measure the differences in temperature $(\theta - \theta')$ between the sample under study and the neutral body. The horizontal deflections of the beam of light are now turned into a vertical plane by passing through the totally reflecting prism M placed at an angle of 45 degrees. A second galvanometer G_2, whose deflections are a measure of the temperature of the sample and whose mirror in its zero position is at right angles to that of G_1, reflects the beam horizontally upon the plate at P. The spot of light has thus impressed upon it two motions at right angles to each other, giving, therefore, on the plate a curve whose abscissæ are ap-

proximately proportional to the temperature θ of the sample and whose ordinates are proportional to $\theta - \theta'$. The sensitiveness of the method depends upon that of the galvanometer G_1, which may readily be made to give 5 or 6 mm. for each degree cen-

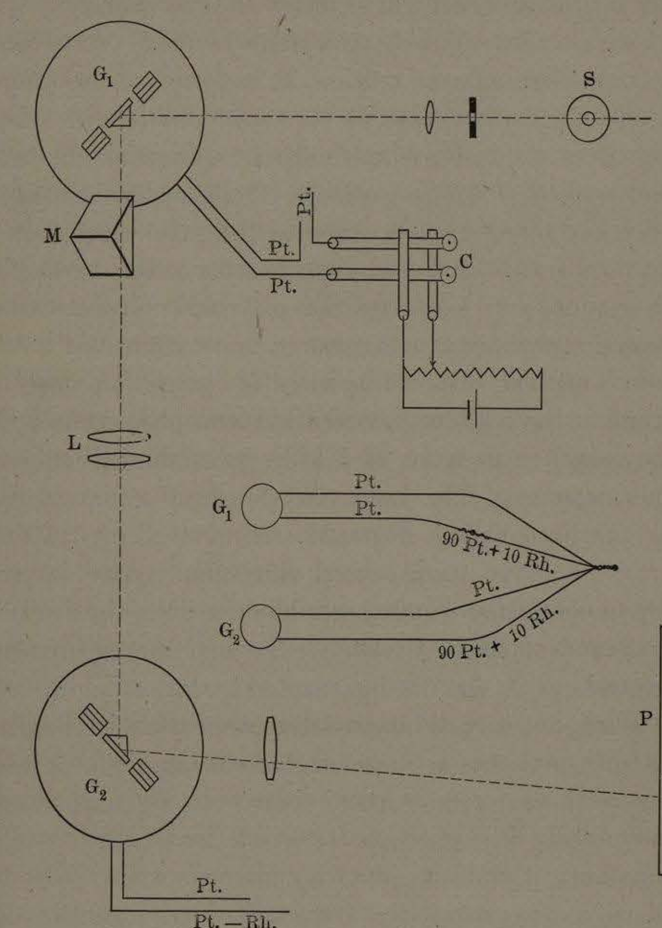


Fig. 160. Saladin's Apparatus.

tigrade. The arrangement of the thermocouple circuits is the same as in Figs. 158 or 159. If so desired, the time may also be recorded by means of a toothed wheel driven by a clock and placed in the path of the beam of light. Compact forms of this apparatus, which is used considerably in metallurgical laboratories, are made by Pellin, Paris, and by Siemens and Halske, Berlin. The lens between G_1 and G_2 may be suppressed.

When steels and metallic alloys in the solid state are being investigated, advantage may be taken of the thermoelectric behavior of the sample itself to record the critical regions with Saladin's apparatus. Thus Boudouard measures $\theta - \theta'$ by means of platinum wires set into crevices at each end of the sample, taking advantage of the fact that the transformation will usually be progressive along the sample. This modification eliminates the neutral piece and one platinum or alloy wire, but, as Le Chatelier has shown, is less accurate than the usual form of Saladin's apparatus; and its indications may even be indeterminate or ambiguous, as the reaction may start midway between the embedded wires or at either end.

Saladin's method, it should be noted, is a perfectly general one for recording the relations between any two phenomena which may be measured in terms of E.M.F. or as the deflections of two galvanometers. The Leeds and Northrup Company have recently modified their autographic recorder, p. 393, to trace the θ *vs* $\theta - \theta'$ curve, using several differential couples in series in order to obtain the required sensibility.

Registration of Rapid Cooling. — None of the experimental arrangements so far described is adapted for measuring the very rapid cooling, i.e., several hundred degrees in a few seconds, met with in such processes as quenching or chilling. The development of methods for measuring rapidly varying temperatures will undoubtedly be of great use in the solution of many physical and metallurgical problems involving products whose properties depend on cooling velocities. Only a few preliminary investigations into this field, however, have as yet been made.

Le Chatelier's Experiments. — Le Chatelier, in an investigation of the quenching of small samples of steel, and the effect of various baths, made use of a galvanometer having a period of 0.2 second and a resistance of 7 ohms, whose deflections, produced by the current from a thermocouple inserted into the specimen undergoing the quenching, were recorded on a photographic plate

moving vertically at a speed of 3 mm. per second. A half-second's pendulum vibrating across the path of the beam of light, from a Nernst glower as source, gave a measure of the time. He succeeded in recording satisfactorily temperature intervals of 700° C. in 6 seconds, using as samples cylinders 18 mm. on a side, and obtained results of great interest to the theory and practice of hardening steel samples by quenching in baths of various kinds of liquids. Le Chatelier recognized the desirability of increasing the precision and sensitiveness, and of improving the technique, of this method, and suggested the advantages of using for the registration an oscillograph arrangement, or a string galvanometer of very short period such as Einthoven's, in which the displacements of a silvered quartz fiber of high resistance in an intense magnetic field are measured photographically.

Benedicks' Experiments. — Following the suggestions of Le Chatelier, Benedicks has carried out a series of researches on the cooling power of liquids, on quenching velocities, and on certain constituents of steel. The errors in cooling curves of metals have also been studied recently by Hayes.

Benedicks' apparatus, as arranged for taking the time-temperature curve of steel samples during quenching, is shown in Fig. 161. The principles here applied may evidently be used in other kinds of experimentation involving rapid cooling.

The specimen *A* is heated in a small electric furnace *B*, which is provided, in its lower part, with a narrow opening parallel to the longitudinal axis, through which passes a holder *C*, which turns about an horizontal axis, being given a definite torque by a spiral spring *D*, and maintained vertical by an electromagnetic control *E*. Through a bore in *C* a thermocouple is led into the interior of *A*, and the cold junction is contained in the ice box *F*, from which the wires are led to a commutator *G* by means of which either the thermocouple *A* or the calibrating apparatus *b*, *c*, etc., may be connected to the measuring instrument *J*, this being a small string galvanometer by Edelmann of Munich. The light from the arc lamp *K*, passing through the microscope of the galvanometer, fitted with a projection eyepiece, gives an image of the movable string on the registration apparatus L, provided with a rotating cylinder which carries the sensitive paper.

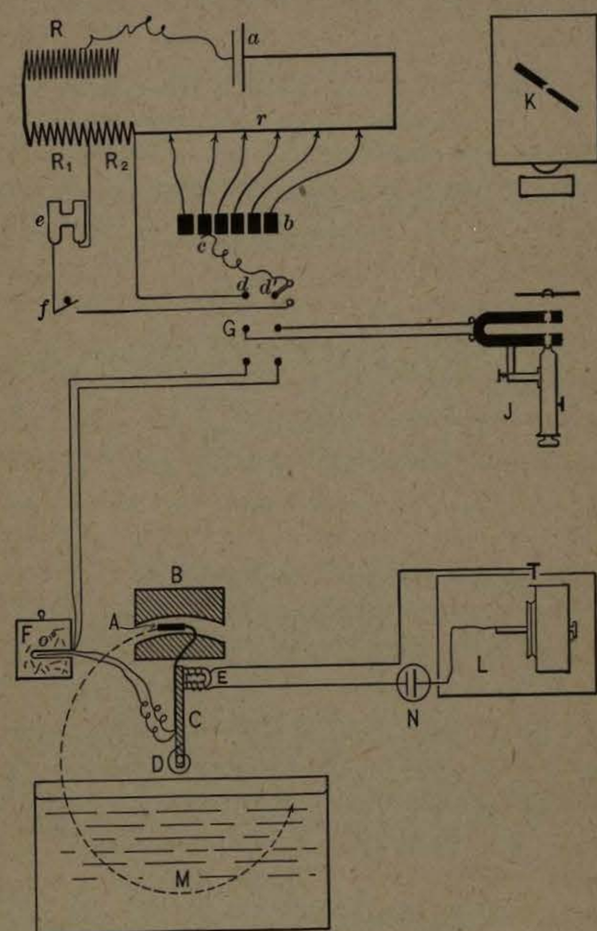


Fig. 161. Apparatus of Benedicks.

Finally, the electromagnet release E is connected with an accumulator N and a contact T on the shutter before the cylinder L.

The process of registration is therefore as follows: The cylinder L is set in rotation, and as the edge of the sensitive paper passes

the window T the shutter rises. At the same instant the circuit of E is closed, releasing the arm C. This automatically and quickly quenches the specimen A in the cistern of water M beneath.

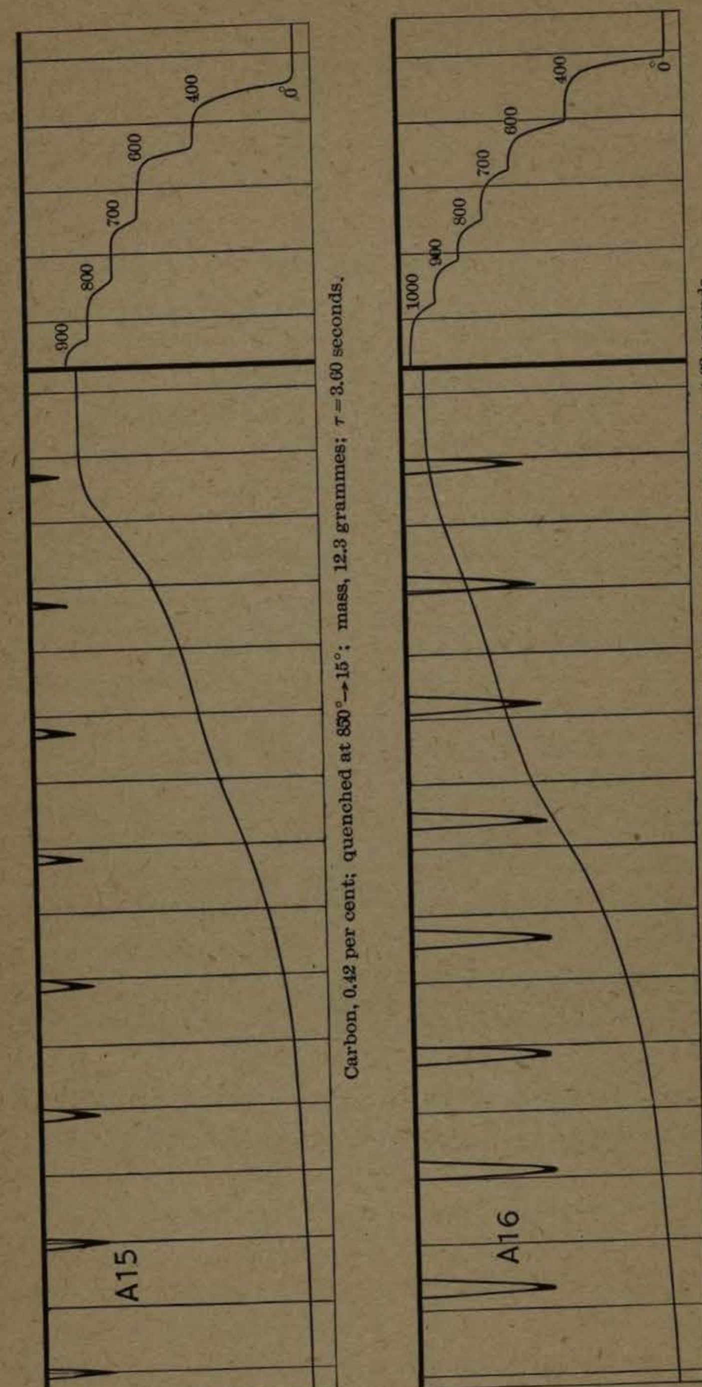
Precautions have to be taken in insulating the thermocouple wires leading into the specimen and in insuring good contact of the couple junction against the specimen with a water-tight joint. Capillary tubes of fused quartz, which will also stand sudden temperature changes, were used for insulating, and water was prevented from entering joints by means of compressed air introduced into the containing tube C of the thermocouple wires.

The calibrating apparatus consists of a sliding commutator c, b, the blocks of which are connected to fixed points on a slide wire r in such positions as to give electromotive forces corresponding to definite temperatures, 400°, 600°, etc., of the thermocouple when the resistances R, R_1, and R_2 are properly adjusted; variations in the battery a are controlled by the standard cell and resistance R. This arrangement allows calibrating the galvanometer immediately before each experiment and give the calibration data on the same sheet as the quenching curve.

The string galvanometer had a resistance of 6700 ohms; its sensitiveness may be adjusted to follow that of the thermocouple, although this is not necessary. The time correction of this galvanometer is such, fortunately, that the directly registered curve is simply a parallel curve to the one which would be obtained if the deflections were absolutely instantaneous; or in other words, no correction for the inability of the instrument to respond instantaneously is necessary. There remains, of course, a small unknown time correction due to the lag of the thermocouple with respect to the test specimen.

In Fig. 162 are shown curves for a steel of 0.42 carbon quenched both from 850° and 950° C.; the time τ is taken to 100° C. The calibration curves are also shown in the figure.

Recording Radiation Pyrometers. — Any phenomenon whose magnitude may be measured by the deflection of a galvanometer may be rendered self-registering by optical means. Total or



Carbon, 0.42 per cent; quenched at 850°→15°; mass, 12.3 grammes; τ = 3.60 seconds.

Carbon, 0.42 per cent; quenched at 949°→15°; mass, 12.4 grammes; τ = 4.63 seconds.

Fig. 162. Quenching Curves with Benedicks' Apparatus.

monochromatic radiation falling on the exposed strip of a bolometer may, therefore, be made to record its intensity, which is, as we have seen, a function of the temperature of the radiating body. Langley, in 1892, rendered his bolometer a recording instrument, the records being taken photographically. This system of recording has been used mainly for the mapping of solar spectra, and incidentally for the estimation of the sun's temperature and in other astrophysical investigations; and although it might be used in laboratory investigations in recording high temperatures in terms of either total or monochromatic radiation, it has not come into any general use for such purposes. The experimental arrangements are necessarily very elaborate

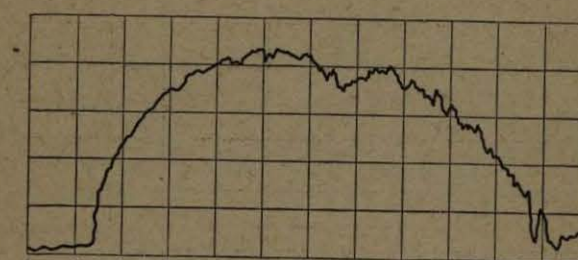


Fig. 163. Solar Radiation Record.

and delicate, for descriptions of which the reader should consult the Annals of the Astrophysical Observatory of the Smithsonian Institution. Callendar has applied also his slide-wire method of recording electrical resistances to Langley's bolometer. The curve of Fig. 163 gives the record of solar radiation for a day.

The radiation pyrometers of the Féry type are readily made self-registering, it being only necessary to substitute for the indicating galvanometer a suitable deflection-recording instrument, such as the Cambridge thread recorder or a Siemens and Halske recording millivoltmeter of the required range and sensitiveness. In Fig. 164 is shown the record of the temperature of a pottery "biscuit" kiln as taken with a Féry radiation pyrometer and Cambridge thread recorder. A Callendar slide-wire recorder could also be used to register very high temperatures if too great sensitiveness be not demanded.

The Morse or Holborn and Kurlbaum instruments may be made semi-recording; that is, a registering ammeter may be put in the lamp circuit and made to record each temperature to which the pyrometer is set by the observer. This method would have some advantages in the control of those industrial operations for which this type of pyrometer is best adapted.

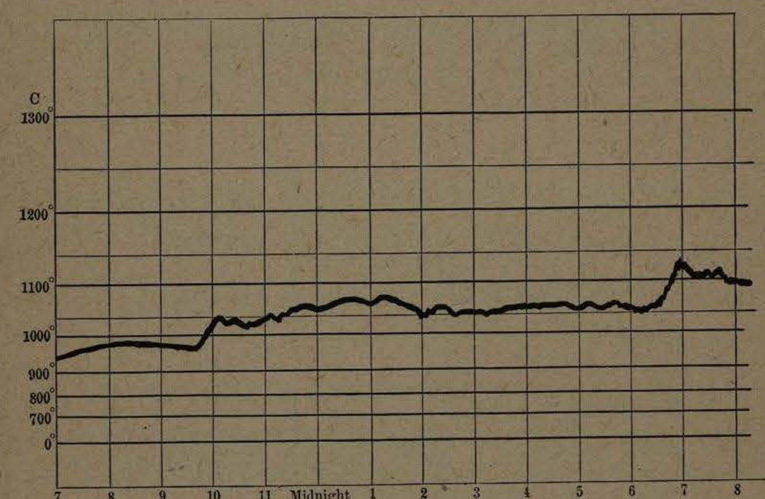


Fig. 164. Temperature Record of Pottery Kiln.

Recording Accessories. — We may mention, finally, a number of auxiliary pieces of apparatus and methods which are useful in special cases.

Range Control. — It is sometimes desirable to limit the range of the recorder to some restricted temperature interval and thereby gain greater sensibility with a more open temperature scale. This may be done in several ways. We shall use as illustrations the scale-control box of Peake as applied by the Cambridge Company to their thread recorder. In its more complete form this device is shown in Fig. 165, for use with thermocouples provided with Peake's compensating leads (page 176).

A 6-volt accumulator passes a current through a series of fixed resistances, R_3, R_4, R_7, and a portion of a variable resistance R_2, the potentiometer circuit.

A second circuit, the pyrometer circuit, consisting of the couple, leads, R_6 and R_5, and the recorder, is connected to tap onto the ends of the coil R_4 in the potentiometer circuit. Thus the potential drop in R_4, due to the current from the accumulator, is opposed to the electromotive force of the couple, and, therefore, at some particular temperature, say 750° C., the two just balance, and no current will flow through the pyrometer circuit. If now the

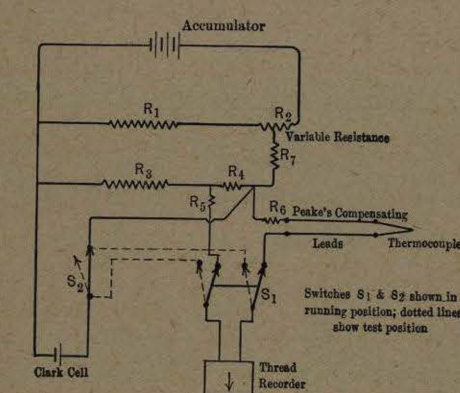


Fig. 165. Peake's Scale Control Box.

temperature of the couple falls, a current will flow in one direction through the recorder, whilst if it rises a current will flow in the reverse direction. Thus the zero or undeflected position of the recorder pointer may be made in the center of the scale, and will correspond in the above case to 750° C., whilst the resistance R_5 may be so adjusted that one end of the scale will correspond to 600° C., and the other to 900° C.

The accuracy of the arrangement depends upon the current in R_4 being maintained constant, and to secure this a Clark cell is connected across the resistances R_3 and R_4. When the accumulator voltage is normal, this cell does not give any current, but if accumulator voltage falls slightly, the Clark cell gives a slight current and tends to keep the voltage across the terminals of R_3 and R_4 nearly constant.

The change in E.M.F. of the Clark cell with temperature also balances very nearly the corresponding changes in the compensating leads, so that the behavior of the apparatus is nearly independent of cold-junction temperature fluctuations. The arrangement may be simplified but rendered less exact by dispensing with the Clark cell.

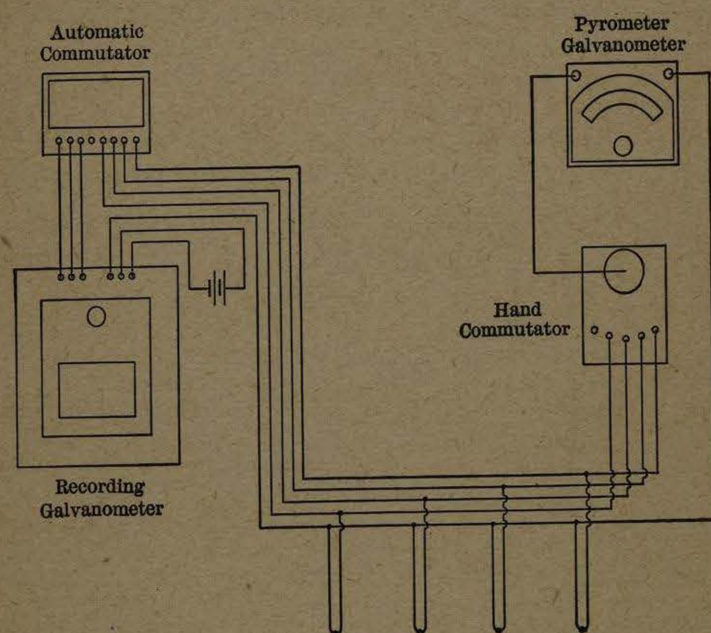


Fig. 166. Recorder and Indicator with Four Thermocouples.

Multiple Records and Circuits. — There are various devices for taking several records on a single sheet by means of one galvanometer. They practically all reduce to some type of automatically driven commutator and are often so constructed that the several records may be distinguished by the spacing or length of dots and dashes. While it is proper to record simultaneously quite different temperatures, it is usually good practice not to try and so record temperatures that frequently overlap

on the sheet, as its interpretation may then become doubtful. It is also often convenient to have on one circuit a recorder, which may be in an office, together with one or more indicating instruments. An arrangement of four thermocouple circuits is shown in Fig. 166, whereby a recorder gives a continuous record for all the couples, and the temperature reading of each of them may also be taken by means of an indicating galvanometer.

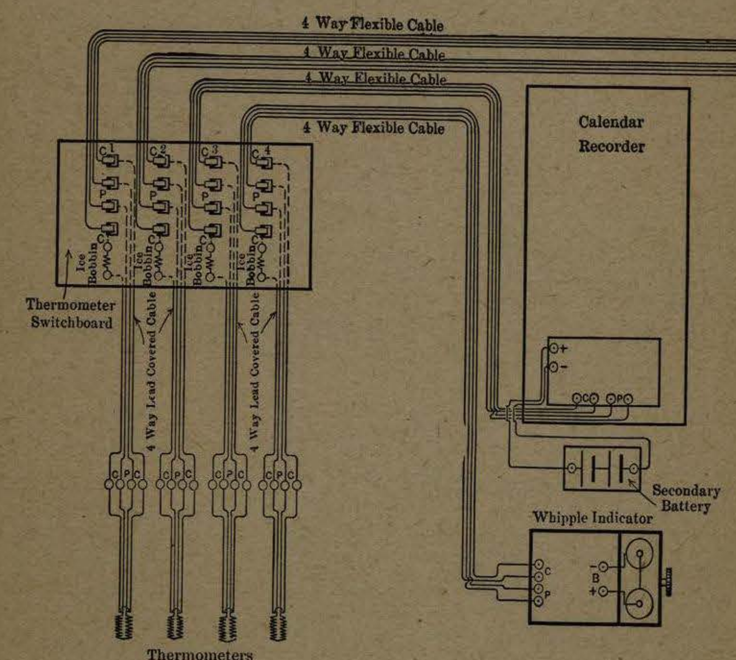


Fig. 167. Recorder and Indicator with Four Resistance Pyrometers.

A switchboard may also be used permitting interchangeability of pyrometers, as illustrated in Fig. 167, where four resistance-thermometer circuits are provided for, to be used with various instruments as required. See also Fig. 70.

In general, it may be said that almost any industrial requirement of combination of pyrometer circuits, recording and indicating instruments and alarms may be solved satisfactorily in practice.

Furnace Control and Thermostats. — In certain operations, — for example, in taking heating and cooling curves, — it is advantageous to raise or lower the temperature of the electric furnace continuously at a uniform rate. This is readily accomplished for an alternate-current supply by the use of a salt-water rheostat fed on heating from a Mariotte bottle. The metal electrodes may be cut to shape to favor the uniformity of rise in temperature; during the cooling the water is siphoned off. The whole apparatus may be made completely automatic, if desired, so that a series of heating and cooling curves may be taken at any desired rate without the intervention of the observer. It is well to keep the temperature of the rheostat down by circulating water through it in a coil of pipe.

It is often desirable to maintain a furnace at constant temperature. The method used will depend largely upon the temperature in question.

In the range over which liquid baths may be used, to 350° C. with suitable oils, they are satisfactory when properly stirred and provided with thermostatic control. With a sensitive gas regulator a constancy of 0.05° C. may be maintained, and with electric control a somewhat better uniformity.

A uniform temperature over a large volume may be established by means of a vapor in equilibrium with its liquid. This system is not available for high temperatures, and it is difficult to maintain a constant temperature over long periods of time.

For high temperatures air baths only can be employed, the most usual form being the electric resistance tube furnace. Special windings and delicate control are required if it is desired to maintain a considerable volume at constant temperature. Various devices have been suggested for the automatic control of furnace temperatures, based usually on the use of relays actuated either electrically or optically. Most of the recorders we have described may be fitted with such an accessory.

We may also cite the optical regulator of Kolowrat which will keep an electric furnace constant to 2° or 3° at 1000° C., and may be applied to either thermoelectric or resistance measurement of

temperature. The light from a powerful source, a Nernst lamp, is reflected from the galvanometer mirror onto a scale representing temperatures. When in adjustment an increase in temperature of the furnace throws the spot of light onto a thermopile which operates a series of relays cutting in resistance to the heating circuit and cooling the furnace slightly. This resistance is cut out when the spot leaves the thermopile.

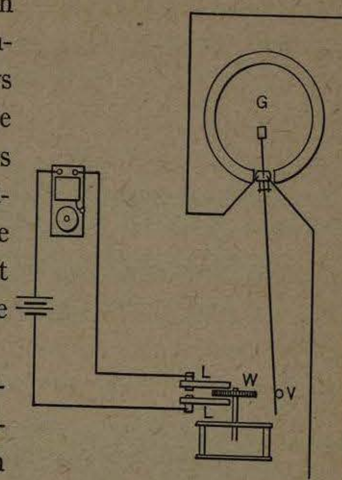


Fig. 168. Darwin Temperature Alarm.

Among the many electric thermostatic controls we may mention that of H. Darwin, which may also be used as an alarm (Fig. 168). When the galvanometer needle GV is deflected from the stop V, due to a rise in temperature, the needle engages the wheel W driven by clockwork and makes a circuit at L, which may be either that of an alarm, as shown, or that of a regulating circuit by means of relays.