Vapor-pressure Pyrometers. — Use is made of the fact that the pressure of a saturated vapor, or one in the presence of its liquid, depends only on the temperature of the vapor, and is independent of its volume. Readings of such a pyrometer may reduce to those of a pressure gauge. There is an apparent advantage over the gas thermometer, in that the volume of the containing vessel plays no part. This vessel must be gas-tight, however, in both types. For relatively low temperatures, where ether or water may be used, to 350° C. for water, several industrial forms using this principle have been developed, that have given satisfaction in special installations, notably the thalpotassimeter of Schaffer and Budenberg and the instruments of Fournier.

The difficulty of rendering them gas-tight and permanent when mercury or other substance suitable for higher temperatures is used appears to be a serious obstacle to the general introduction of this type of instrument as a pyrometer.

Other Pyrometric Methods. — We have by no means exhausted the list of methods for measuring high temperatures that have been suggested or tried. Without dwelling on any of them, we may mention a few that may possibly be of service in particular cases. The variation of boiling point with pressure of such substances as naphthaline, benzophenone, and sulphur, first studied in detail by Crafts, in 1882, will give a continuous temperature scale of very great range, although a relatively complicated pressure apparatus is necessary. Again, the velocity of sound in any medium is a function of its temperature; and, as early as 1837, a method of temperature measurement using this principle was devised by Cagniard-Latour with dry air as the medium. Other phenomena of less promise which have been made use of or suggested, are: heat conduction, rotary polarization, magnetic moment, dissociation, conductivity of gases and vapors, the corpuscular emission in vacuo from current-bearing metals, and an application of Clapeyron's Equation.

CHAPTER X.

RECORDING PYROMETERS.

Among the different methods for the measurement of high temperatures, some of them may be made continuously recording. This is as useful for industrial applications as for scientific investigations. In research laboratories one endeavors as much as possible to take observations automatically, escaping the influence either of preconceived ideas or of carelessness of the observer; in industrial works the use of such processes gives continuous control over the work of the artisans, such as the presence of no foreman can replace.

In recent years, one of the most important practical advances that have been made in pyrometry is the development of several types of simple, convenient, and reliable instruments for the registration of temperatures in industrial operations. It will be impossible to describe them all here, but we shall pass in review several, as well as calling attention to the historical development of the subject. Forms of temperature-recording apparatus, suitable for laboratory investigations of problems involving temperature changes, but too complicated for any but the most elaborate technical installations, have been in existence for a good many years, and the recent introduction of more simple apparatus has greatly stimulated technical research as well as afforded means for the exact control of a great many industrial operations that were heretofore left to chance.

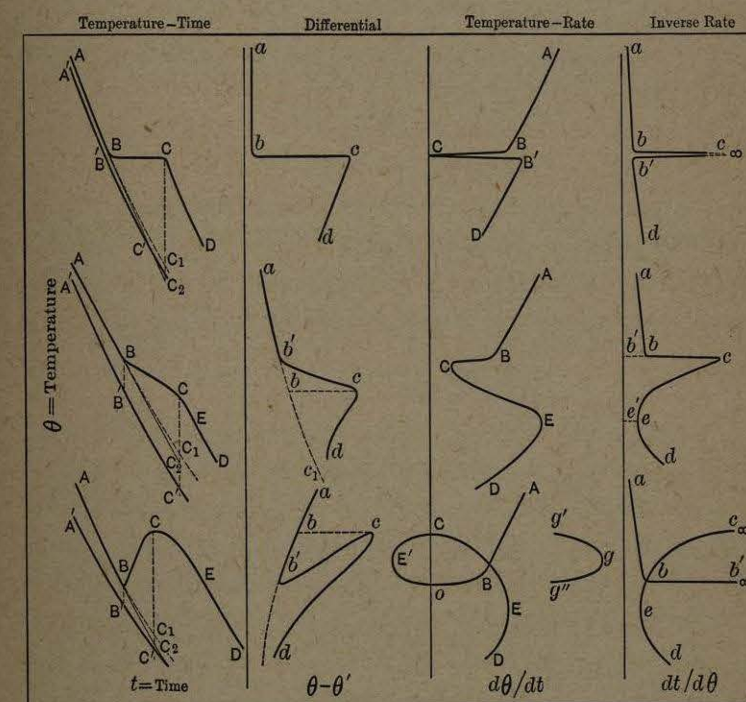
Forms of Temperature Records. — There are several ways in which the change of temperature with time may be recorded, and the method adopted will depend upon the problem in hand. The simplest and the one of most universal application and general utility both in the works and laboratory is the *time-temperature* curve; that is, the time appears as one coördinate, and the temperature, or some quantity proportional to it, as the other on the record sheet. Most temperature recorders are constructed on this basis. For a given temperature interval, there is evidently a limiting sensibility beyond which any such recorder cannot go without unduly increasing the size of the record sheet unless it is operated in steps, when of course the apparatus becomes only semi-recording and requires the occasional intervention of the operator.

In certain investigations in the laboratory it is of interest to have the rate of change of temperature in terms of the temperature, or the *temperature-rate* curve. Thus, in the study of definite phenomena, such as fusion and allotropic transformations, and in order to recognize their occurrence, use is ordinarily made of the accompanying absorption or liberation of heat, which is manifested by a variation in the rate of heating or cooling. Methods of recording the temperature-rate curve have been devised by Le Chatelier and by Dejean.

In the two preceding methods, any accidental variation in the temperature of the furnace, due to drafts or other outside causes, or to change in rate of heating or cooling, will be recorded. This is most desirable in those cases in which the changes in temperature of the furnace or its contents are wanted. But in those cases in which the transformations going on within the substance itself within the furnace are wanted, as, for example, when taking the cooling curve of a sample of steel, the accidental fluctuations in the heat content not inherent to the sample must be eliminated in exact work. This may be done, as shown by the late Sir Roberts-Austen, by taking the *differential-temperature* curve, or recording the temperature of the sample in terms of the successive differences in temperature between the sample under observation and another body, called the neutral, possessing no transformation points, and placed within the furnace close to the sample.

Although there are other methods of reading and interpreting temperature curves, the above are the only ones that have heretofore been made self-recording. We shall describe types of apparatus using all three methods.

Types of Cooling Curves. — It is of interest to be able to recognize the appearance of a transformation region as defined, for example, on cooling by the various methods above mentioned. In Fig. 134 are illustrated these various forms of temperature curves, in which θ = temperature and t = time for the three following cases: in the first line, the heat evolution balances the radiation and other losses during the transformation or the tem-



TYPES OF COOLING CURVES

Fig. 134. Types of Cooling Curves.

perature remains constant, as in freezing of a pure substance well inclosed; in the second line, the most common, the transformation takes place over a definite temperature interval or there is imperfect heat insulation; and in the third, there is recalescence, or the reaction or transformation evolves heat so rapidly as to cause a rise in temperature. The nomenclature is the same for all the curves, and they may be compared by noting the corresponding letters.

We have included also the *inverse-rate* curve of Osmond, obtained by noting the time intervals necessary to cool equal decrements of temperature plotted in terms of temperature. Although this curve cannot be recorded automatically without elaborate apparatus, the inverse-rate method is one in very common use in metallographic practice. Rosenhain uses still another form of curve, the *derived-differential*, or the temperature difference between sample and neutral for equal temperature decrements plotted in terms of temperature. The observations are taken as if for the differential curve.

On the whole, the most complete, satisfactory, conveniently recorded, and readily interpreted results are obtained over long temperature intervals by the simultaneous recording or observing of the time-temperature and differential curves; or, as we shall see, it is possible to combine these two into a single curve giving differences between sample and neutral in terms of temperature. The time may also be indicated if desired in this latter case by a suitable interrupter.

The inverse-rate curve may be taken with great precision on a chronograph in connection with a potentiometer, the observer pressing a key at equal steps on the dials, and this method may be made as accurate as desired if automatic control of the furnace is provided. The form of the curve obtained is exactly the same as that with the derived differential method. These two methods may be applied simultaneously to advantage on the same sample, as is the practise at the Bureau of Standards.

Methods of Recording. — The recording may be effected either photographically, or by some electrical or mechanical means for which we may use the term "autographic". The latter possesses the advantage that the experimenter may watch any part of the record, and can therefore control the operation and at any moment vary the conditions affecting the experiment or process; whereas, with the photographic apparatus, it is usually necessary to wait until the plate is developed to see what has happened. The manipulation by the photographic method is usually also more delicate and time-consuming and the adjustment less sure,

and the record often requires further graphical interpretation, for all of which reasons the photographic method is not adapted for most industrial needs. The autographic method is in general not adapted for interpreting phenomena taking place within an interval of a few seconds, so that for very rapid temperature changes it is usually necessary to employ the photographic method. An autographic recorder is usually the less readily adjusted for very variable rates, and most types of such apparatus are limited to one or two speeds. This is not a serious inconvenience, however, except in case of the use of the same instrument for very diverse purposes.

The following pyrometers have been made recording:

The constant-volume gas thermometer;

The thermoelectric pyrometer;

The electrical resistance pyrometer;

The total-radiation pyrometer;

The transpiration pyrometer.

The optical pyrometer of the Morse type could be made semi-recording, but the other optical and discontinuous types of pyrometer could be made recording only with very great difficulty.

Recording Gas Pyrometer. — The transformation of the gas pyrometer into a recording instrument is extremely simple and has been long since effected. It suffices to join permanently the tube from the porcelain bulb to a registering manometer to realize a recording pyrometer theoretically perfect. But practically these instruments possess many disadvantages that have prevented their introduction generally, and they have been replaced for the most part by other types more suitable both for laboratory and technical plants.

Above 1000° the permeability of the porcelain for water vapor is sufficient to soon render them useless. Investigations made by the Paris Gas Company have shown that in furnaces heated to 1100° the penetration of water vapor is sufficiently rapid so that in a few days liquid water collects in the cold parts of the apparatus.

Absolute impermeability of the apparatus, which is quite indispensable, since its operation supposes the invariability of the gaseous mass, is very difficult to obtain. Frequently the glazing of the porcelain has holes in it. The numerous joints entering into the registering apparatus, and above all the metallic parts of the apparatus, may be the seats of very small leakages difficult to locate.

The connection of the metallic parts with the porcelain tube is generally made with wax, always with substances of organic origin, which, in the vicinity of industrial apparatus, generally bulky and thick-walled, cannot be protected against radiation save by a water jacket. This is a serious inconvenience.

In laboratory apparatus of small size the protection of the joint is easier, but then the large dimensions of the bulb, as has been indicated, are a serious disadvantage. One cannot, in a small furnace, find a large volume whose temperature is uniform.

Another most serious disadvantage of the recording gas pyrometer is the difficulty of its calibration. Already with the mercury manometer the dead space is a source of complications. However, this may be measured and allowed for. With the registering manometer the dead space is much greater, and besides variable with the deformation of the elastic tube. Thus the calibration can be made only empirically, employing baths of fixed fusing or boiling points, an operation almost always impossible of realization with an apparatus of very fragile porcelain, or by using a large tube furnace whose temperatures are given by another type of pyrometer calibrated at the requisite fixed points. The recording gas thermometer is therefore of little practical interest.

Electrical Resistance Recording Pyrometer. — There have been several satisfactory solutions of the problem of rendering the resistance pyrometer self-registering.

Callendar's Slidewire Recorder. — In order to render his pyrometer recording (Figs. 135 and 137), Callendar employs the following very simple device: Two of the branches of a Wheatstone bridge used to measure the resistance of the heated coil are made of a single wire, on which slides a rider to which is brought

one of the galvanometer leads. To each position of the rider, when the galvanometer is at zero, corresponds a resistance, and consequently a definite temperature of the coil. The position of the rider may be easily registered by attaching to it a pen

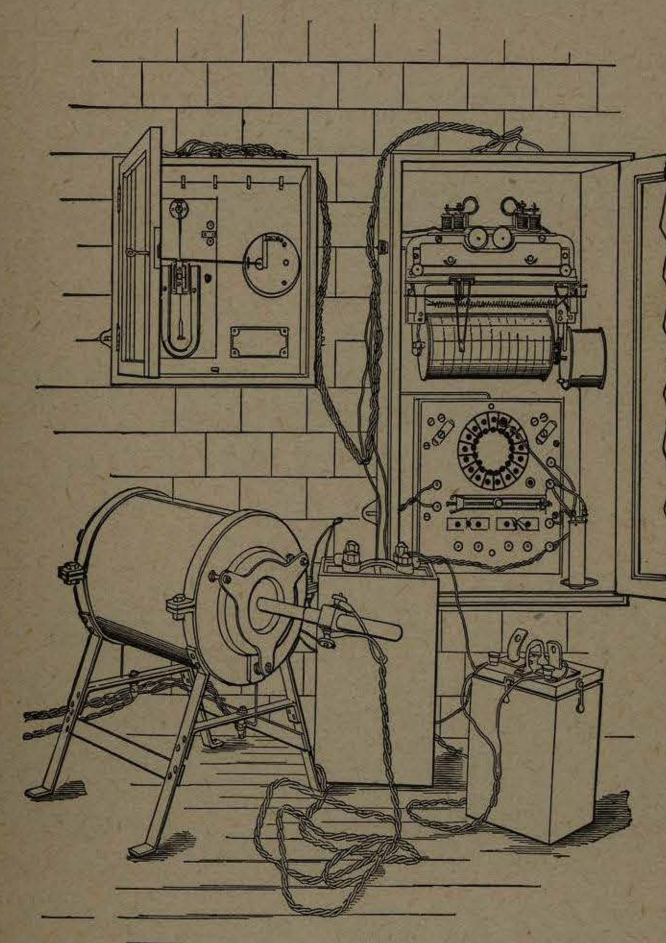


Fig. 135. Callendar's Recorder.

writing on a sheet of paper which moves perpendicularly to the length of the wire. In order to have the curve thus obtained correspond to that of temperatures, it suffices that the position of the rider be at each instant adjusted so as to keep the galvanometer at zero.

This result is obtained by means of a clock movement controlled by a relay that the galvanometer works in one direction or the other, according to the direction of the deflection that it tends to take on from the zero point. It is a movable-coil galvanometer whose needle carries an arm which, making contact, causes a current to pass. The curve traced by this instrument is in rectangular coördinates, which is of practical convenience in reading off temperatures.

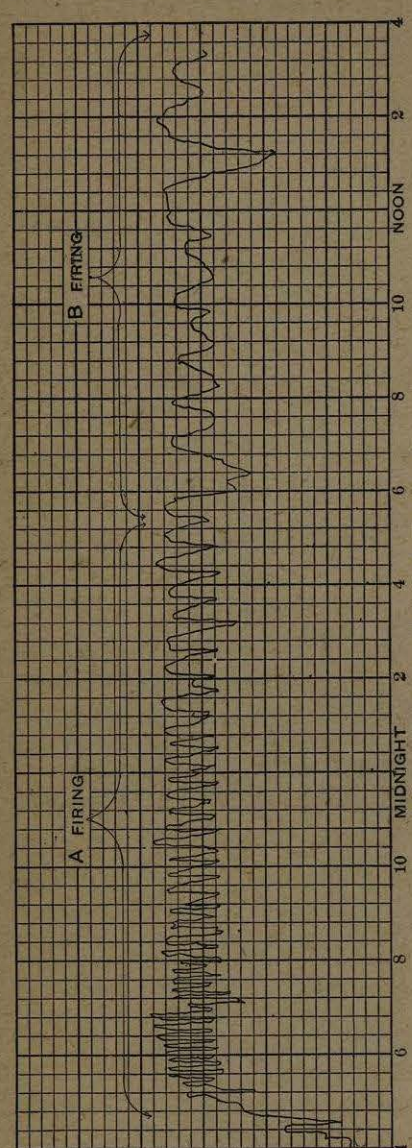


Fig. 136. Record with Callendar Recorder.

Fig. 136 gives an example of a curve recorded by this apparatus, showing the effect on the temperature of an annealing oven by firing by an old hand and by a new one. It will be noted that a continuous pen record is obtained.

This recorder possesses an interesting detail which assures good working and which could well be adopted in other similar cases. The pointer of the galvanometer needle does not hit against a fixed conductor, to which it would stick on account of heating by the passage of the current and especially the extra current at break. This conductor consists of the metallic circumference of a wheel which

is given a slow, constant rotary motion, rendering all adherence impossible. This artifice renders possible working the relays by means of a sensitive galvanometer, which would not otherwise be realizable.

This registering apparatus is necessarily very costly, but until recently was the only sensitive one generally available with which a record of high temperatures could be obtained by purely mechanical means without the intervention of photography. This apparatus labors further under the disadvantages inherent to a somewhat complicated mechanism, requiring the intervention of skilled labor to adjust it; nevertheless, it has proved of extreme usefulness in many technical operations requiring exact temperature control, especially in large works.

For use in the laboratory, it is to be noted that some of the extreme sensitiveness of the resistance method of measuring temperatures is necessarily lost by rendering it recording; but such loss is not serious enough to prevent this, the most sensitive method of recording, to be of great use in many laboratory investigations. A sensibility of 1 in 5000 may easily be maintained, and with care considerably higher sensibility. The relatively large volume of the bulb, or thermometric coil, is sometimes a disadvantage, as in taking cooling curves of steel specimens. Callendar calls attention also to the following points: The scale of the instrument is uniform and independent of the E.M.F. of the battery, being determined by the resistance of the bridge wire in relation to that of the thermometer, and these may be constructed to give any desired temperature range. It is a great advantage in practice that the scale never requires adjustment, but is always correct to about 1 in 1000, provided the bridge wire is correct and uniform.

For ordinary work, thermometers are generally provided with an "ice bobbin" or balancing coil, for adjusting the resistance of the thermometer at 0° C. The ice bobbin for each thermometer is connected to its appropriate terminals when the thermometer to which it belongs is in use. If the thermometer is required to cover an extensive range of temperature, and it is desired to keep the sensitiveness very great, a series of auxiliary resistances or "zero coils," generally ranging from 0 to 20 ohms, may be provided, which enables the range to be extended to twenty times that of the 1-ohm bridge wire. With a 26-ohm thermometer the range thus obtained would be 200° C., or 2000° C. with a 2.6-ohm pyrometer.

The most important points to test in a slide-wire recorder are the adjustment of the zero of the galvanometer and the zero of the slide wire. The former is effected by turning the torsion lead of the suspension until the galvanometer boom swings clear of the contact wheel; and for the latter, the slide wire itself may be shifted with respect to the record paper, the pyrometer and compensation terminals being short-circuited and the battery switched on.

This recorder, as well as the others we shall mention, may be arranged to register any of the component factors in electric power, and may therefore serve also as a thermoelectric recorder.

When so used for the measurement of temperatures by means of thermoelectric couples by the method of opposition, the strength of the currents available to work the relays is much more feeble than in the preceding applications, so that a great sensibility cannot be obtained. Fig. 136 shows a Callendar recorder as made by the Cambridge Instrument Company, arranged for the thermoelectric measurement of temperatures in connection with an electric resistance furnace. In Fig. 137 is shown the wiring diagram for a Callendar recorder arranged for commercial work.

Deflectional Recorders. — The thread recorder, shown in Fig. 152, or other type of recording millivoltmeter designed primarily for use with thermocouples, may also be used to register relatively small intervals of temperature when used as the deflecting galvanometer of a Wheatstone bridge for a resistance thermometer, provided the sensitiveness of the recording instrument is sufficient. This is readily accomplished, since a high-resistance galvanometer is not required nor desired. In Fig. 138 is shown such an arrangement as used by Callendar. The

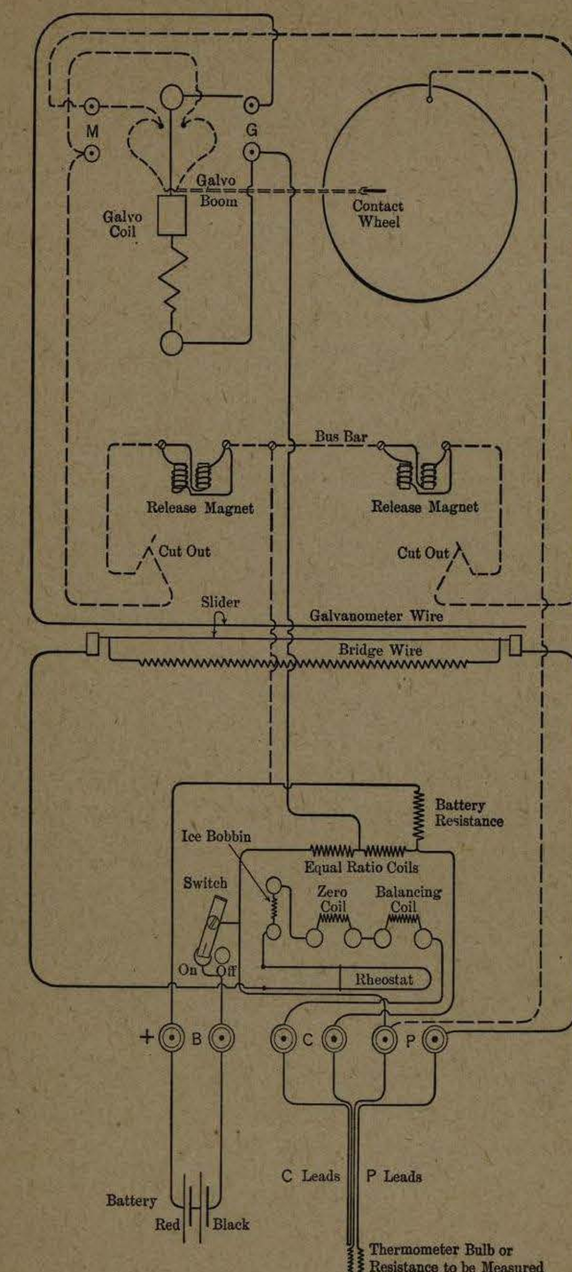


Fig. 137. Wiring Diagram, Callendar Recorder.

Siemens and Halske recorder (Fig. 149) may also be had with a very sensitive scale, i.e., 1.5 millivolt, for example, for a galvanometer resistance of 10.5 ohms.

Some form of platinum-thermometer bridge with a slide wire is required, and a rheostat capable of fine adjustment. This rheostat is connected in series with a storage cell and serves to adjust the scale of the record. One terminal of the recorder is connected at G between the ratio arms of the bridge B_1G and B_2G, and the other to the sliding contact on the bridge wire.

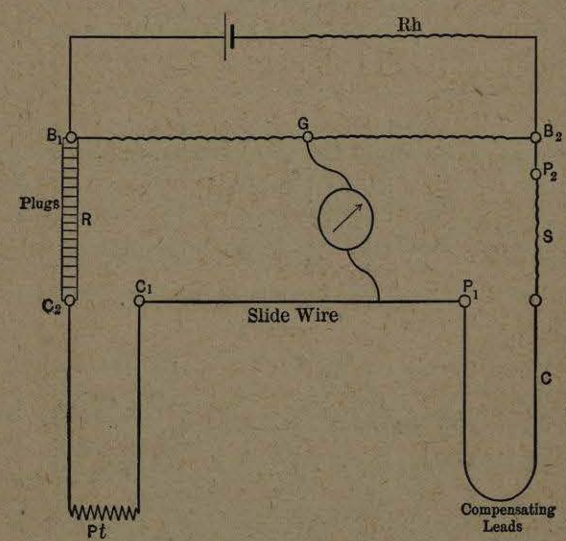


Fig. 138. Circuits for Deflectional Recorder.

The compensator leads are connected in series with the balancing coils. With this arrangement the resistance $S + C$ is nearly constant, so that if the galvanometer deflection is adjusted to be correct when the thermometer is at 0° C., or any convenient temperature, the scale will be very nearly correct when the thermometer is at any other temperature, the plugs R being suitably adjusted. A much greater sensibility can be obtained in this way than with thermocouples using such a recorder. Thus it is possible to get a scale of 50 mm. to 1° C. if desired. Such great sensibility, however, would only be necessary in extremely delicate thermostatic control. The scale of the galvanometer is not strictly one of equal parts, and this has to be allowed for in exact work.

The Leeds and Northrup Recorders. — This firm has developed two types of resistance recorders suitable for temperature measurements, one having an electromagnetic control and the other mechanical. The former has been perfected to a definite instrument and the latter is still undergoing improvement in details. Both are of the balance type and give pen records proportional to temperatures in rectangular coördinates; in both the recording mechanism is entirely independent of the galvanometer system, and the accuracy uninfluenced by changes in the galvanometer constant.

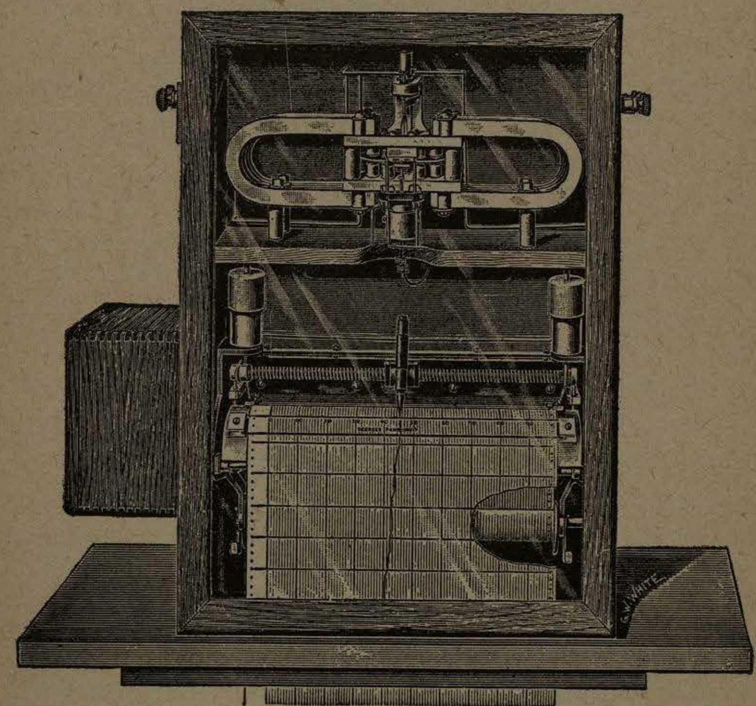


Fig. 139. Leeds and Northrup Recorder.

The general appearance of the recorder with electromagnetic control is shown in Fig. 139. As usually constructed, this recorder is made for any range over 100° F. to 1800° F. with a sensibility of $\frac{1}{5}$ per cent and a constancy of repetition of $\frac{2}{5}$ per cent. The pen will follow temperature changes at the rate of $\frac{1}{5}$ per cent of the total range per second, giving a continuous terraced record.

The complete recorder consists of four essential parts: a differential galvanometer, with a plunger magnet attached to it, for operating periodically the contactor; a clock which drives the paper and operates the contacting plunger magnet; a simple mechanism consisting of a screw and two electromagnets of the plunger type for traveling the pen and the balancing contact; and a paper drive, moved by the clock, which feeds a continuous band of paper off a roll and over an apron carrying it under an ordinary stylographic pen.

The mechanical recorder is of the same general design, except that the moving mechanisms are all driven mechanically, with the added factor that, according as the galvanometer needle is more or less deflected, the pen mechanism will be driven faster or slower. This permits following much more rapid temperature changes than with the electromagnetically controlled recorder.

Both of these instruments may also be arranged for use with thermocouples; and the mechanical recorder has besides been adapted to record directly the differential-temperature curve (page 382) by means of a double galvanometer system, the paper moving proportionally to the temperature of the sample and the pen proportionally to the difference in temperature between the sample and neutral.

Carpentier's Electrothermal Recorder. — This system gives rectilinear coördinates by the use of a cylindrical frame containing the paper, which advances continuously and against which the pen carried by the galvanometer boom impinges periodically by means of the following electrothermal mechanism: The galvanometer boom carries a fine wire of platinum-silver through which an electric current, either direct or alternating, may be sent from an auxiliary, or the ordinary lighting circuit. The

recording pen and wire are so attached to the end of the boom by a spring that when no current is passing in the wire the pen is free of the paper; but the passage of a current weakens the tension of the wire, due to its expansion, and the spring then pulls the pen gently against the paper without shock. With a suitable commutator, as many as four contacts per second may be had on the paper; and where several records are to be taken on the same sheet for as many separate thermometers, the same principle of electrothermal control may be applied also to the commutator, giving, when the contact surfaces are so spaced, dots or dashes of different length for each circuit.

This type of recorder and commutator may evidently be used with any kind of pyrometer whose readings may be taken with a galvanometer.

Thermoelectric Recording Pyrometer. — We shall group the thermoelectric recording methods according to the type of curve which they register, — temperature-time, differential, and temperature-rate, — all of which may be realized both with photographic and autographic registering apparatus. Due perhaps to the general convenience of the thermocouple for temperature measurements, there appears until very recently to have been more attention paid to the development of recording methods for this type of pyrometer than for any other, and this in spite of the fact that the thermocouple labors under the disadvantage, as compared with the resistance pyrometer, for instance, in having intrinsically very little energy available for the mechanical operation of a recorder.

It would seem to be mainly for this reason that the early thermoelectric recorders were photographic instruments; and, in fact, it is only in recent years that satisfactory autographic thermoelectric recorders have been devised, and they employ various artifices to maintain the sensitiveness of the registering galvanometer, necessitating usually an intermittent or dotted record, at least with Pt-Rh thermocouples. The difficulty of the problem, in this case, is emphasized when it is recalled that only very weak currents can be had; thus for a precision of 10° C. an