TEMPERATURE CONTROL

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To

MY WIFE

AUTHOR'S PREFACE

During recent years a great deal of attention has been given to the subject of temperature control. This has been intensified by the knowledge that many factors involved in practical work are directly influenced by temperature. The tempering of steels, chemical processes of various kinds, and the measurement of physical constants such as refractive indices call for temperatures within narrowly defined limits.

This need has led to the development of thermostatic control which enables the heat source to be adjusted when there is a displacement of temperature from the desired value. For some purposes hand control of the temperature may be sufficient, but modern requirements, both in scientific and industrial practice, demand a much more precise and accurate form of control. In fact, all industrial processes of major importance arrange for this to take place automatically by methods which are large scale developments of laboratory methods.

It must be realised, however, that there are limitations to such control, since however sensitive the regulator may be, the controlled temperature will oscillate between two points depending upon the efficiency of the heat source and the sensitivity of the control unit. Thus if a furnace is badly lagged with consequent large heat losses, or if the convection currents are great, then the ability of the control unit to function within predetermined limits will be influenced by the efficiency of the furnace or heat source. Accordingly, the factors involved in such a problem must include the source of heat supply, the precision in the desirable control, limitations as to cost, and the space available for the installation of the control equipment.

In the following pages an attempt has been made to corrolate some of the methods employed, since the sources of information on this practical subject are widely scattered in the literature and are not generally accessible. The treatment does not claim to be exhaustive, but aims at providing methods which are dependable and simple. Practical and tried efficiency has been preferred to methods of more doubtful value, and the information given must be regarded more as a guide than as a complete solution to every control problem. This must be so when we remember that there are so many variable factors involved, such as the heat supply, the type control available and the surrounding conditions.

Many physical effects have been utilised for thermostatic purposes including the expansion of solids, liquids and gases, thermo-electric and photo-electric effects, electrical resistance of solids and salts, and vapour pressure. Some are, of course, applied more easily than others, and it will often happen that the cost of associated equipment renders an attractive method prohibitive. The range chosen for consideration extends from 0° C. to about 1500° C., no attempt being made to deal with very low temperature, since work in this sphere is highly specialised, and the sources of information are more readily accessible. The term "thermostat" usually describes a control device within the range considered, while "cryostat" is employed when the range extends below 0° C.

It is hoped that the information provided will be of real service to the worker who has need of some form of constant temperature control, for it is certain, that no other piece of apparatus can wastefully absorb so much time as a control method unsuitable for its purpose. Some workers, however, may find it more desirable to purchase the equipment than to make it, and, for these, the laboratory type of control has been supplemented by descriptions of industrial or commercial forms. In order to make the guide as useful as possible, appendices have been added dealing with the essential auxiliary equipment required; copious references to original papers will also be found throughout the work.

The author is specially indebted to Mr. N. Portman, B.Sc., for reading the MS. and to the following firms for the loan of blocks: Cambridge Instrument Co., Griffin & Tatlock, Sun-Vic, Ltd., British Thermostat Co., Bellingham and Stanley, G.E.C., Ltd., Gallenkamp Ltd., London, and The Patent Impermeable Millboard Co. for the data supplied for Table VIII.

A. J. ANSLEY.

November, 1941.

CONTENTS

CHAPTER I

GENERAL CONSIDERATIONS FOR TEMPERATURE CONTROL

THERMOSTATS, the apparatus employed to maintain constant temperatures, may be conveniently divided into three classes: those for use at

(*a*) low temperatures (0° C.—100° C.);
(*b*) medium temperatures (100° C.—350° C.);
(*c*) high temperatures (350° C.—1,500° C.).

These divisions are, of course, arbitrary, and in practice, some instruments can be employed for any temperature above that of the atmosphere, although designed for one special purpose.

It should be remembered that the term "constant temperature" varies somewhat in meaning according to the specific work undertaken. The variation of a few degrees from a predetermined value may be permissible in one process while accuracy within a few thousandths of a degree is necessary with another. Further, the criterion of efficiency of any such system will be the rapidity with which it re-adjusts the temperature to its original value. It is sometimes possible to maintain the temperature sufficiently constant for practical purposes by insulating the apparatus thermally. Such insulation can never be perfect, so that where precise control is essential, a thermostat is necessary in addition.

CONTROL UNIT TERMS

The Differential.—This is most conveniently provided by immersing the apparatus whose temperature it is desired to control, either in a liquid or an air bath from which it may be removed without disturbing any essential components. The automatic control depends in many cases on the principle that a change in heat causes a volume change in some substance, which directly or indirectly regulates the heat supply. The ideal thermostat control would, of course, permit no variation from the desired temperature, and the equipment must be designed to restrict any such variation to within the smallest allowable limits. This variation called the "differential" is the numbers of degrees above or below the set temperature at which the control mechanism operates.

Hunting of the Unit.—This deviation from the desired temperature value is due to insensitive response of the regulator to temperature changes. Consequently, the design of such units must aim at reducing this time-lag to a minimum. On the other hand, if instability of action on the part of the control unit, or "hunting" as it is termed, occurs, rapid oscillations of temperature take place. Such fluctuations are not completely avoidable but, by careful instrument design, they may be reduced to a minimum. The points to be remembered in control design are:

(*a*) the required temperature of the thermostat;
(*b*) the temperature extremes of its surroundings;
(*c*) the extent to which the required sensitivity may be combined with ease of adjustment and simplicity of operation.

Range of Unit.—The range of such control will depend largely on the medium through which control is affected, and the highest and lowest temperatures over which the control can operate. This constant determines the operational value of the control unit, which unfortunately, in many cases, is limited by constructional difficulties.

Adjustment of Control.—When a temperature change takes place in the medium surrounding the control mechanism, it is desirable that it shall rapidly restore the temperature to its original value. This deviation can be measured by a convenient means such as a thermometer. It should be remembered, however, that a time-lag is present in the response of the control, due to the inertia of the unit. The thermometer also introduces a similar lag, so that it does not give immediate information when enough adjustment has been made. In practice, the tendency is to arrange a very violent response of the heating system (through the control) to any deviation from the true value causing an "overshoot" of the desired temperature. Such an actuation of the control will thus necessitate reversal of control action, with a consequent delay of attainment of the desired temperature, and the production of "hunting." Thus any adjustment should be such that heating will be introduced by a gradual, steady amount, thus avoiding instability and violent fluctuations.

The use of many diverse physical phenomena as the basis for various type controls, suggests that each has relative advantages and disadvantages when compared with the others. Industrial requirements are largely based on economic working, which in practice means that any form of control must be of robust construction requiring the minimum of attention and upkeep. The employment of skilled workers is thus diverted from this task, and development of these instruments for this particular purpose has been influenced by these considerations.

The laboratory and research worker's requirements are much more readily met. Delicacy both of construction and adjustment of the control presents no difficulties to these workers. Robustness may be sacrificed at the gain of sensitiveness, which makes possible the employment of methods unsuitable for workshop conditions. In this respect the laboratory worker gains sensitivity, with the introduction of a smaller differential. For instance, the use of a unit functioning at 20° C. with a differential of $\pm 1°$ C. gives a permissible variation of $\pm$ 5%. On the other hand, another set at 500° C. with the same differential gives a variation of only $\pm$ 0·5%. The relative accuracy of control will be readily appreciated, and this will have a deciding influence on the final selection of any thermostatic instrument.

There are three things which affect the rate of change of temperature : the temperature of the surroundings, its own temperature and the " setting " of the control mechanism. So that the amount of heat required to keep the apparatus at constant temperature is not only dependent on the difference between observed and desired temperature of the bath—which should normally be zero—but also on the " steadiness " of its surroundings.

Metal Expansion Controls.—Control units which employ expansion of metal strips find employment in wax and oil baths, glue pots, electric irons of various types, drying chambers, incubator ovens, shoe making machines and vulcanising processes, heated greenhouses and soil temperatures and thermo-couple cold junction control. In these processes the " time-lag " response need not be minutely small.

These bimetallic strips are specially treated by special "ageing" processes in order to minimise changes in crystal formation developed by heating and constant use.

A frequent method of employment is to use a brass tube anchored rigidly to one end of the mounting on the apparatus; at the other an invar rod is fixed. The expansion and contraction with changing temperature of the brass tube causes axial movement of the free end of the invar rod which acts on the switch mechanism. This expansion will, of course, be of the differential type and is used for control of a temperature range between 0° C. and 120° C.

In some forms the whole mechanism is mounted in a glass envelope containing an inert gas in order to reduce arcing and oxidation of the contacts. The latter are mounted in such a manner that they produce a wiping action on opening and closing. These type controls can usually carry 1 ampere at 220 volts A.C. or D.C.

Liquid Controls.—Liquids may be employed in a similar manner, or by utilising their vapour pressures. In commercial practice both forms employ similar apparatus; i.e. a phial containing the liquid and a bellows-type expansion chamber. When used as a liquid-metal expansion combination, the apparatus is completely filled with suitable liquid. The principal limiting factor is the boiling point of the liquid, which should not attack the chamber walls, nor vapourise at working temperatures, and be of chemical stability throughout. The expansion of the liquid is uniform over all temperatures and the differential is the same at all points over the temperature range. In mounting the apparatus the relative positions between the bulb and the bellows is not important.

TABLE 1.

COEFFICIENTS OF CUBICAL EXPANSION OF LIQUIDS

$\alpha/°$ C. at 18° C.

Liquid	$\times 10^{-5}$
Alcohol (amyl)	93
(ethyl)	110
Aniline	85
Ether (ethyl)	163
Glycerine	53
Mercury	18
Paraffin	90
Turpentine	94
Toluene	109

Vapour Pressure Control.—The utilisation of vapour pressure for control purposes has found wide application in industry. It is superior to the direct expansion of a liquid method owing to the extensive range which can be obtained by increasing or decreasing the liquid charge contained in the sensitive phial or capsule. These devices operate through the pressures created by the vapourisation of the liquid; and further increase in bulb temperature increases the supply of gas. This pressure, operating through a bellows system, causes motion against an opposing force, such as a compression spring. With a corresponding fall in temperature the gas condenses, releasing the pressure, so that the opposing force is greater and the mechanism operates in an opposite direction. The equipment is so arranged that the liquid is vapourised from ordinary temperatures to a maximum of about 200° C., the volume of gas employed for operational control not being sufficient to create bursting pressures.

In practice, the bulb temperature is above that of the bellows; and the bellows is so mounted that some portion of it is above the connection between the capillary tube and the bulb. The gas then generated can go into the uttermost portion as a pocket, the pressure here then acts on the liquid. The latter moving up the capillary causes expansion of the bellows system.

The disadvantage of this type is that since vapourisation of the liquid is a straight line function, the differential of the control over a wide temperature range will vary considerably. Such equipment is supplied in a set temperature range, depending on the requirements of the process to be controlled. The ranges may be varied by using different liquids and charge amounts for the capsule.

This method finds wide application in industrial processes, in dyeing pots, drying rooms, incubators, linotype pots, liquid baths, to mention but a few.

Methods employing electrical phenomena, such as thermo-electricity and change of resistance with temperature have found wide application in both scientific and industrial processes. This is due to their wide operating range 0°–1,600° C. coupled with sensitivity and adaptability. The use of galvanometer bridge circuits in conjunction with these phenomena makes for control sensitivity not found in other methods.

Thermo-electric Control Methods.—Thermo-electric methods, however, are not so expensive as resistance methods, but both methods are equally useful for their considered range. The former method employs two dissimilar wires jonied together at one end, whilst the free ends are connected to an electrical indicating device. If the junction is heated, an electric current will flow along the wires.

The magnitude of the electromotive force producing this current will depend on two factors :

(*a*) The difference in temperature between the hot and cold junctions.
(*b*) The metals employed in the loop of wire.

In Table 7, page 72, the values of thermo-e.m.f./° C. represents the e.m.f. which would be obtained if the metal stated was used with platinum to form the junction. E.M.F.s between any of the tabulated metals can be found by subtracting the values. It should be noted that these are average values, due to the non-linearity of the temperature-e.m.f. curve ; the actual value varies with temperature.

The factors influencing the selection of various metals will be the available thermal power, strength, cost, and the ability to withstand corrosion and high temperature.

The couple may be a combination of rare or base metals, and selection is determined primarily by the temperature to be controlled or measured.

But for the question of cost, platinum and its alloys would be universally used, as their non-oxidability, high melting point and strength make them specially suited for their work. In the case of rare metal combinations, the small diameter of the wires results in a somewhat delicate couple for very high temperature work. Base metals, due to their cheapness, can be made of wire of more generous proportions.

The approximate temperature range covered by these couples are :

Couple	Temperature Range
Copper Constantin	300° C.
Iron Constantin	900
Chromel-Alumel	1,100
Platinum—(Platinum 90% + 10% Rhodium)	1,400

The e.m.f.s produced at various temperatures are appended.

TABLE 2.

THERMO-COUPLE E.M.F.s IN MILLIVOLTS.

Cold Junction at 0° C.

Couple.	0	100	200	300	400	500	600	700°
Pt./Pt. Rhodium 13% . .	0	0·645	1·45	2·385	3·385	4·44	5·56	6·725
Copper-Constantin .	0	4·33	9·35	14·97	21·08	27·45	—	—
Chromel-Alumel	0	4·1	8·13	12·21	16·39	20·64	24·9	29·14
Iron-Constantin .	0	5·6	11·2	16·9	22·5	28·3	34·2	40·6

Couple.	0	800	900	1,000	1,100	1,200	1,500	1,400°
Pt./Pt. Rhodium 13% . .	0	7·945	9·21	10·515	11·85	—	—	—
Copper-Constantin .	0	—	—	—	—	—	—	—
Chromel-Alumel	0	33·31	37·36	41·34	45·14	48·85	52·41	55·81
Iron-Constantin .	0	47·3	—	—	—	—	—	—

Copper Constantin Couples.—This is one of the most widely used and most accurate of the base metal couples. It will maintain its calibration if not overheated, but above 300° C. rapid deterioration sets in unless the couple is made of heavy gauge wire. The thermo-e.m.f. is 45 mv/° C., and experience has shown that a precision of 5°–10° C. can be expected in the neighbourhood of 500° C.

Iron Constantin Couples.—The e.m.f.-temperature relationship of this combination is a closer approximation to a straight line than the copper-constantin type. Two disadvantages are present with this combination.

(*a*) At low temperatures the iron tends to rust in humid atmospheres.

(*b*) After prolonged exposure to high temperatures parasitic currents develop in the iron and are believed to be partially due to change of crystal structure and prolonged heating.

Chromel-Alumel Couples.—These are extremely accurate and dependable, and can be used up to 1,100° C. continuously. The e.m.f.-temperature curve above 100° C. is mainly a straight line.

Installation of Couples.—When couples are installed it is important that they are in immediate contact with the heat source desired to control. Special protective refractory and metal sheaths are necessary to withstand the corrosive action of fumes and materials met with in practice. It is essential that the couple head should not be subjected to high temperatures and the positioning of the connecting leads should receive careful attention.

For damp conditions rubber insulated or lead covered cable should be employed, and when exposed to relatively high temperatures asbestos covered wire is substituted. For accurate work it is essential to employ some form of cold junction control. Terminals should be kept clean since corrosion will introduce an increase of resistance to the circuit. Base metal couples may be insulated with asbestos string or tubing painted with a solution of carborundum, firesand and sodium silicate mixed to a thick paste. When heated above 600° C. the insulation will, of course, disintegrate, the carborundum vigourously attacking the metals. The connecting leads should be about 2 sq. cms. cross sectional area, but where the circuit resistance exceeds 4 ohms a heavier gauge wire must be employed.

The Cold Junction.—Since the electromotive force generated by a thermo-couple depends on the difference in temperature between the hot and cold junctions in the thermo-electric circuit, any variation in the temperature of the cold junction will affect the output of the junction. In order, therefore, that the cold junction may be maintained at constant temperature, some form of control must be employed. A very simple method is to employ a thermos flask filled with oil, the vessel being surrounded by a heat insulating material. A thermometer, by which the temperature of the cold junction may be determined, may be inserted through a cork in the neck of the flask. Another method is to control the temperature by burying the junction under a floor of a building rather than in the open. The junction may be enclosed in a $\frac{5}{8}$ inch diameter steel sheath, pointed at its lower end, the thermo-couple leads being connected to a suitable head fixed at the top of the tube.

The e.m.f. produced by the thermo-element has both to be standardised and interpreted in terms of temperature. For this purpose a potentiometer method is employed; in this, a known e.m.f. provided by a standard cell is balanced against the e.m.f. of the couple.

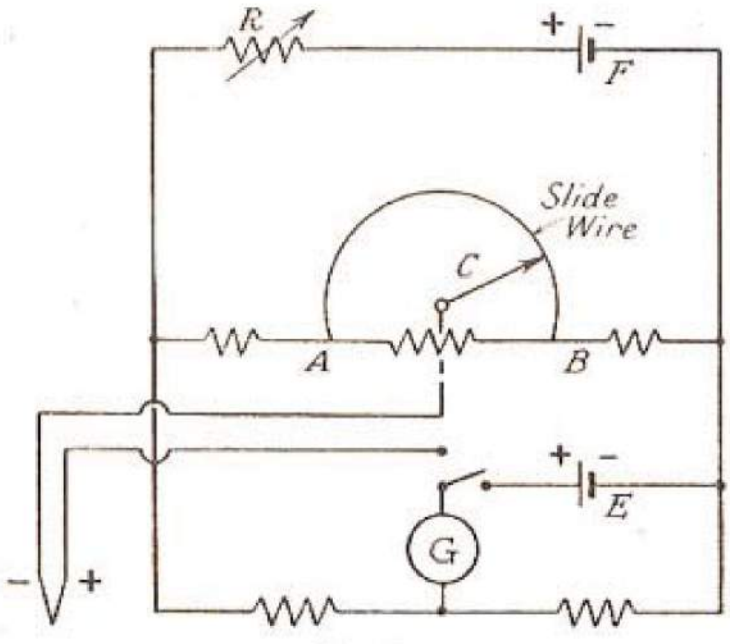

Fig. 1*a*.

The circuit diagram is shown in Fig. 1*a*, and a typical instrument employed as in (*b*). The current supplied by battery *F* is controlled by the adjustable resistance *R* to a predetermined value, so that the voltage drop across any portion of *AB* is known. Adjustment is made by varying the position of the movable contact arm *C*, until the galvanometer *G* shows no deflection; in this position the e.m.f. of the couple is equal to that of the cell *F*. Any variation in the current supplied by the latter will adversely effect the readings since the potential across the slide wire will then vary. To standardise the battery circuit, the standard cell *E* is connected across the galvanometer circuit, and adjustment of *R* will bring the instrument once again to the zero position. Then the e.m.f. produced by balancing the couple against *F*, will also be equal to that of the standard cell *E*.

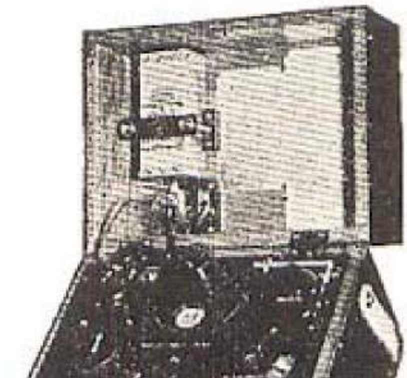

Fig. 1*b*.

A calibration chart giving the e.m.f.-temperature value may conveniently indicate the temperature of the thermo-couple.

This type control finds extensive application in metallurgical research, in chemical plants, in brick, tile, pottery and glass works, and in the annealing and hardening processes using high temperatures in foundry work. Platinum resistance thermometers may also be used for similar control problems.

The Platinum Resistance Thermometer.—When a pure metal is heated its electrical resistance increases with the temperature. In practice, platinum is generally employed because of its high degree of purity and melting point, while at the same time, it does not corrode.

The wire is wound on a mica or steatite frame, enclosed within a suitable protecting sheath depending on the nature of the medium into which it is to be placed. Leads are carried from the frame to a large terminal block situated at the sheath head. The resistance coil is adjusted to have a definite resistance at the melting point of ice, 0° C., (R_o) and the boiling point of water, 100° C. at 760 mms. pressure (R_1).

The Fundamental Interval.—The quantity R_1–R_o is called the "Fundamental Interval" of the thermometer. This value is adjusted to be one or ten ohms, so that 1° C. is equal to a change of resistance of the coil approximately 0·01 and 0·1 ohm respectively.

Since the final reference scale is the gas-scale, the relationship between the variation in resistance of a wire with temperature and the gas-scale should be known. Callender introduced the term "platinum scale," assuming that the increase of resistance of platinum was uniform at all temperatures. He showed that the difference between the true temperature t, as measured by the air-thermometer, and the platinum thermometer temperature p, was given by the following formula:

$$t - p = \delta \left\{ \left(\frac{t}{100} \right)^2 - \left(\frac{t}{100} \right) \right\}$$

where t = temperature on the gas-scale
p = temperature on the platinum-scale
δ = coefficient of the wire specimen.

For pure platinum δ is equal to 1·5, but varies with the degree of purity. To obtain the difference between the gas and platinum scales, the resistance of the wire must be found at three known temperatures. Those employed are 0° C., 100° C., and 444·6° C., the latter being the melting point of sulphur.

TABLE 3.

REDUCTION OF PLATINUM SCALE TO AIR-SCALE TEMPERATURES

Centigrade scale. δ platinum wire constant = 1·5.

Platinum Temperature	Air-Scale Temperature	Platinum Temperature	Air-Scale Temperature
50	49·6	600	654·4
100	100·0	650	716·2
150	151·2	700	779·4
200	203·1	750	844·3
250	256·0	800	910·8
300	309·7	850	979·1
350	364·5	900	1049·5
400	420·2	950	1122·0
450	477·0	1,000	1197·0
500	534·9	1,050	1274·5
550	594·0	1,100	1355·1

CHAPTER II

LIQUID EXPANSION CONTROLS

THE expansion of a liquid with increase of temperature has been largely utilised for temperature control; mercury, toluene, paraffin, ether, alcohol, aniline and glycerine being employed because they possess relatively high coefficients of expansion. Invariably, the expansion of one of these liquids is communicated to a column of mercury with which it is in immediate contact and this causes an alteration in the control of the available heat supply.

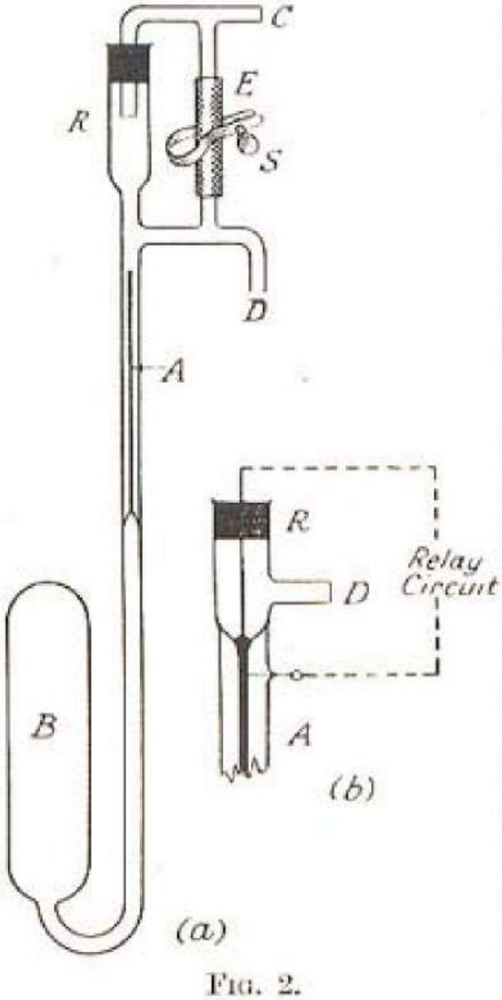

FIG. 2.

One of the earliest forms of such a control was designed by Marie and Marquis,[1] who employed an ordinary thermometer tube filled with acetone, electrical contact being established by means of platinum wires sealed into the stem. The usual form of apparatus, however, consists of a large cylindrical bulb *B* (Fig. 2*a*), partially filled with toluene, or other liquid having a high coefficient of thermal expansion, and sealed to a capillary tube *A*, which contains the mercury column. On the expansion of the toluene the mercury is caused to rise in the tube *A*, while decrease in temperature causes a contraction of the control liquid, by which action the heat supply is brought once again into operation.

To avoid temperature lags due to lack of sensitiveness of the regulator the expansion chamber *B* should be of generous proportions, while the tube *A* should be as small as is compatible with effective operation. Decreasing the bore of the

[1] *Comptes Rendus*, 136, 614. 1903.

capillary or contact tube will increase the sensitivity, but a diameter less than 1 mm. may cause irregular working. This is, in general, due to the fact that the time lag in most systems is such that the mercury overshoots or undershoots the contact point very rapidly. Especially is this the case on a rising temperature, the mercury remaining in contact with the contact wire for an indefinite period, causing the thermostat to operate at a new temperature. Thus, while it is desirable to obtain a large relative displacement in *A*, a limitation will be present due to the inherent practical difficulties of the system.

This type of regulator is usually constructed of glass and, although this material is objectionable because of its mechanical weakness and low thermal conductivity, its transparency more than off-sets any advantage gained by the employment of metal. When the latter is employed, practical difficulties arise in the detection of bubbles of gas in the regulating system. Their compressibility makes accurate control impossible, and their presence may only be detected by their indirect effects. They may, of course, be removed by tapping the area in which they are localised, or by the admission of a fine wire into the apparatus in order to destroy the trapped gas.

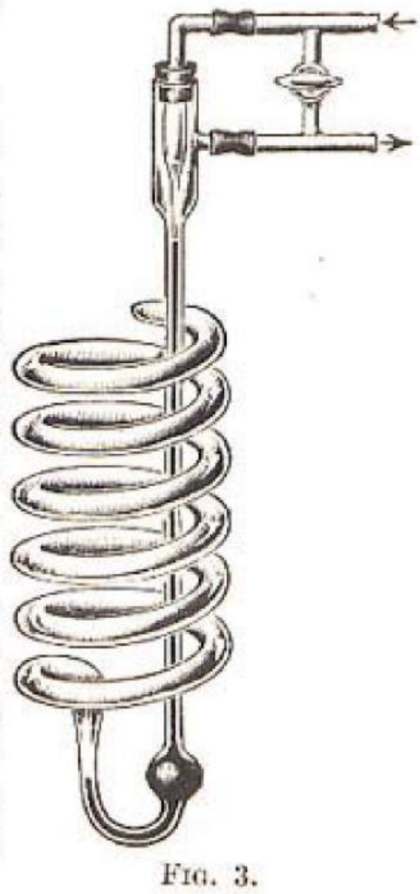

FIG. 3.

In order to increase the response of the control to temperature fluctuations, the regulator surface should be as large as possible. When, however, the available space in the thermostat does not permit the form shown in Fig. 2*a*, the Lowry type may be modified for this purpose. The original form (Fig. 3), consists of a spiral of glass tubing, some 6 mms. in diameter, the open end of which is sealed to a capillary tube as before. In order to conserve space and at the same time to increase the area of surface contact, the spiral may be arranged to lie close to the walls of the containing vessel, the inner diameter of the spiral being such as to permit the insertion of the necessary apparatus within it.

Metal-Liquid Combination.—It is obvious that a much more rapid response would be obtained from a metal regulator, rather than from glass. Accordingly, many workers have sought to combine the advantages of the glass and the metal types, particularly in obtaining transparency in the region of the contact points. De Khotinsky[1] used nickel plated steel for the main body of the regulator, since this has the advantage of a conductivity approximately 66 times that of glass, while mercury was employed as the control liquid, thereby improving the qualities of the control. In order to make visible the contact between the platinum point and the small mercury meniscus, a capillary tube *B* (Fig. 4), ground to fit the metal parts exactly, is attached by means of cement to the body of the control. Copper has also been employed,[2] the metal being deformable into the desired shape if molten lead is poured into the tube and allowed to solidify before being bent. The copper is then sealed to the glass by means of a suitable cement, taking care to thicken the edge of the glass tube prior to fixing.

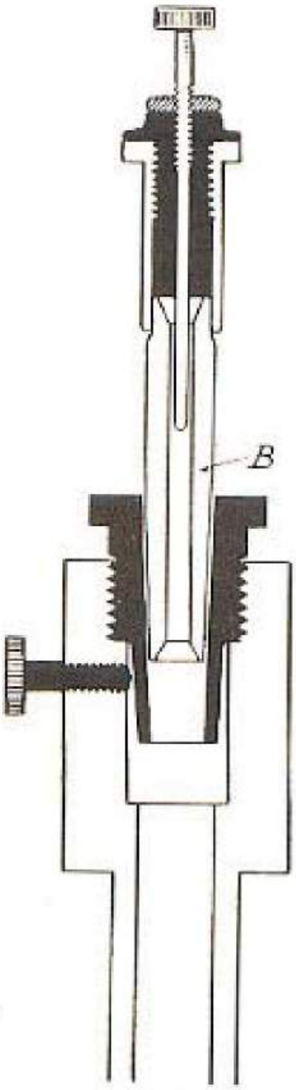

FIG. 4.

Alternatively, the copper may be soldered to a metal directly plated on the glass.[3] After this has been accomplished the end of the copper away from the glass is closed with a metal cap through which a small hole is bored to allow escape of air. The system is then filled with toluene through the glass end of the regulator and, when all air has been expelled, the small hole is closed by driving in a copper plug which is then wiped with solder.

Gas-Control.—Prior to the introduction of electrical heating thermostatic regulators controlled a gas supply but, with slight modification, the same apparatus may also be used for electrical heating. For gas control the tube shown in Fig. 2*a* is employed, the tube *B* being filled with the liquid of high expansion coefficient, while the capillary tube *A* is filled with mercury.

[1] *Jour. Amer. Chem. Soc.*, 38, 251. 1916. [2] *Rev. Sci. Instr.*, 6, 82. 1935.
[3] See author's *Introduction to Laboratory Technique.*

In operation, the gas supply passes through the tube *C*, which is fixed by means of a well-fitting cork in the end of the regulation chamber *R*, and thence through the side tube *D* to the burner. The bulb *B* is immersed in the liquid bath and, consequent on the temperature rise due to heat from the gas burners, the liquid in the bulb expands and causes the mercury level in *A* to rise, thereby partially cutting off the gas supply. If, however, such an action is too rapid the flame is liable to be extinguished, but by arranging an additional side tube *E* —which is generally of rubber—the gas is by-passed to the burner.

The amount of gas controlled by the adjustable clip *E* should be such that, when the end of *C* is closed by the mercury, the thermostat is just maintained at the desired temperature. When the end of the tube *C* is closed by the rise of the mercury column, the amount of heat given to the thermostat will decrease, thereby causing the mercury to fall in the capillary tube and, at the same time, the toluene will contract and the tube *C* will be opened again, allowing an increased supply of gas to be available for the heating of the thermostat. Thus the temperature of the bath will vary between certain limits, depending on the sensitiveness of the regulator and the external conditions of the bath. Any improvements in this form of control aim at bringing these factors within as small a range as is practicable.

Electrical Control.—When this regulator is employed for electrical control the mercury column is used to " make " or " break " an electrical circuit, which in turn controls the heat supply. The modifications required are as follows: The gas tube *C* (Fig. 2*a*), is entirely dispensed with as is also the by-pass tube *E*, leaving only one inlet tube entering the regulator head *R*. Sealed into the capillary *A* (Fig. 2*b*), is a platinum wire which makes contact with the mercury column in the tube.

A rubber bung is inserted at *R*, and carries a platinum wire —sometimes tungsten or nichrome is used—passing through it. The wire should be made adjustable so that the point of contact with the mercury surface may be under control. The wires protruding from the apparatus are then led to terminals situated at some convenient position on the apparatus and are ultimately connected to the relay circuit of the thermostat.

Filling and Adjusting the Regulator.—Remove the inlet tube *C* (Fig. 2*a*), and close the upper end of the regulator tube *R* by means of a rubber bung. To the end of the tube *D* attach a piece of rubber tubing carrying a stop-cock and, by means of the tubing *E*, attach a water or other suction pump to the regulator. Exhaust the apparatus with the tap attached to *D* closed. Then close *E* and open *D* whilst the end is held under a quantity of the liquid with which it is desired to fill the expansion chamber. When some of the latter has passed into the apparatus close *D* and again exhaust by means of the pump, but with the control tube in a beaker of warm water, so that as the liquid is heated air will be expelled. Close *E* again, and open *D* under the toluene so that a further quantity of liquid will enter. This operation should be repeated until the tube *B* is almost full. The cork *R* should be removed and some mercury poured into the tube. Replace the cork and, whilst holding the tube at an angle so that the mercury leaves the end of the capillary free, exhaust once again; replace the tube upright and admit more air. This operation should be repeated until sufficient mercury has been admitted to fill the narrow tube and form a layer some 2 cm. deep in the tube *B*. Surplus liquid collected at the surface of the mercury at *R* may be removed with filter paper. The amount of mercury must now be adjusted for the temperature at which the regulator is to be employed. Accordingly, the tube should be placed in a bath of water maintained for a few minutes at the desired temperature. If too much mercury has been introduced the excess is removed by means of a pipette, until the remainder just occupies the lower end of the tube above the capillary. If too little mercury is present, the tube should be placed within a beaker containing warm water, so that the mercury surface rises above the end of the capillary and a further amount of mercury added. Once again the tube should be adjusted for the toluene level; the final adjustment of the latter being completed by the use of the inlet tube *C*.

An alternative method which, if performed carefully, can be carried out more expeditiously is as follows: The bulb *B* should be held some distance above a small flame or immersed in very hot water so as to expel some air, and at the same time the end of the tube *D* is placed under the surface of some toluene. On cooling, the latter will be drawn into the bulb *B*.

The tube is then rewarmed which will cause further expansion of air and more liquid will enter the tube on cooling. This process should be repeated until sufficient quantity of the liquid has entered the tube.

Preparation of Toluene.—It should be remembered that great care must be exercised when handling toluene since it is very highly inflammable. For this reason, some workers may feel disposed to substitute another liquid, such as aniline, having a high coefficient of expansion. To avoid difficulties in the operation of the regulator when toluene is employed, and which usually develops after the instrument has been in use for some time, the liquid should be treated to eliminate all traces of water. This is done by standing the liquid over anhydrous calcium chloride, and then over freshly cut sodium metal for twenty-four hours. The toluene is then decanted into a distillation flask, distilled, and is ready for insertion into the regulator tube.

Improvements in Toluene Regulator Tubes.—As the tube has to be adjusted for use at a predetermined temperature, each change of temperature range necessitates an addition to, or removal from, the control liquid. In order to avoid this inconvenience Polisser[1] has suggested that a number of tungsten contacts be fused into the capillary tube and inclined at an angle of 45° to the bore. Intermediate temperature settings are thus obtained by tilting the regulator slightly until the mercury thread just reaches the appropriate contact.

Parks,[2] however, employed a tight fitting plunger in the regulator head and, by raising or lowering the latter, the temperature could be adjusted within $\pm$ ·02° C. of the desired value. Such an arrangement is a convenient addition to the control and in the type employed by Yee and Davis[3] the plunger is made adjustable while the adjustment head is fixed. The apparatus is constructed of thin-walled pyrex tubing, ·8 mm. thick, having an outside diameter of 35 mms. (Fig. 5). Indentations, about 25 mms. wide at the mouth and 25 mms. deep are provided, the thickness of the indentation walls being 0·2 mm. which accounts for the rapid response of the regulator to temperature fluctuations. To avoid air being trapped in the pockets of the latter when the regulator

[1] *Jour. Amer. Chem. Soc.*, 52, 636. 1930.
[2] *Ind. & Eng. Chem.* (Anal. Ed.), 5, 357. 1933. [3] Ibid., 8, 477. 1936.

is being filled, the indentations are pointed upwards towards the centre of the tube. The adjustment mechanism, directly sealed to the tube *C* which extends almost to the bottom of the tube *A*, consists of a length of Jena KPG tubing, some 5 mms. bore and 50 mms. long, a brass cap *E* is attached with wax to the top of this tube and through it a finely threaded brass rod carrying an invar steel plunger *F* passes. The diameter of the latter is only slightly smaller than the inside diameter of the tube, but it can move freely therein without the use of a lubricant.

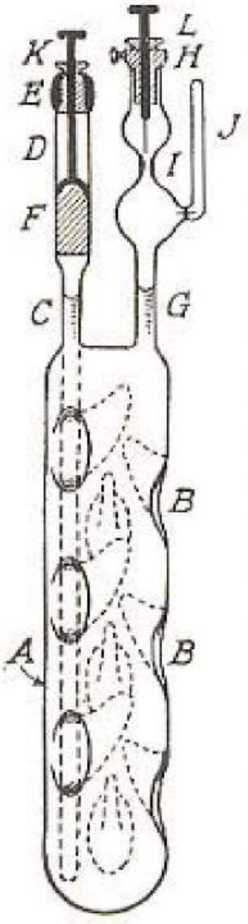

Fig. 5.

To the top of *G* is fitted another brass cap *H*, through which is passed a rod carrying a fine nichrome wire which makes contact with the mercury at *I*, where the fine capillary opens into the upper bulb. The other electrical contact is made through the wire fitted to the side arm *J*, while *K* and *L* are lock nuts. Mercury is introduced into the regulator by means of a funnel with a fine capillary stem reaching to the bottom of the tube *C*. Care should be taken to avoid trapping air bubbles in the tube *A*. When the mercury reaches half-way up the tube *D* the funnel is removed and the plunger replaced. The latter is not air-tight and, although no mercury can escape, the bottom of the plunger should be arranged so as to be slightly below the point *I*, and since there is positive pressure against the plunger, air is prevented from entering.

Prevention of Surface Contamination.—A further defect of the liquid regulator using mercury with electrical contacts, is the possible contamination of the surface with oxide due to sparking at the electrodes. If the spark is at all intense deterioration is very rapid and ultimately causes failure in the regulator action. In order to reduce this arcing, for it is not possible to eliminate it altogether, many suggestions have been proposed. Ramsey[1] designed a regulator (Fig. 6), in which the immediate contact is enclosed in a chamber containing an inert gas. It is constructed of pyrex glass having at *C* a tungsten wire which extends about 1 cm. into the capillary

[1] *Ind. & Eng. Chem.* (Anal. Ed.), 5, 219. 1933.

of bore 1 mm. The side arm *B* of the contact chamber is bent as shown and sealed. Clean, dry mercury is added at *E* until it reaches somewhat above the stopcock, which is about level with the contact point in the capillary. Hydrogen, supplied from a Kipp's generator, is admitted to the contact chamber by means of a three-way stopcock. The latter thus permits the contact chamber to be connected to the gas or air supply. By applying suction at *E*, when connection is

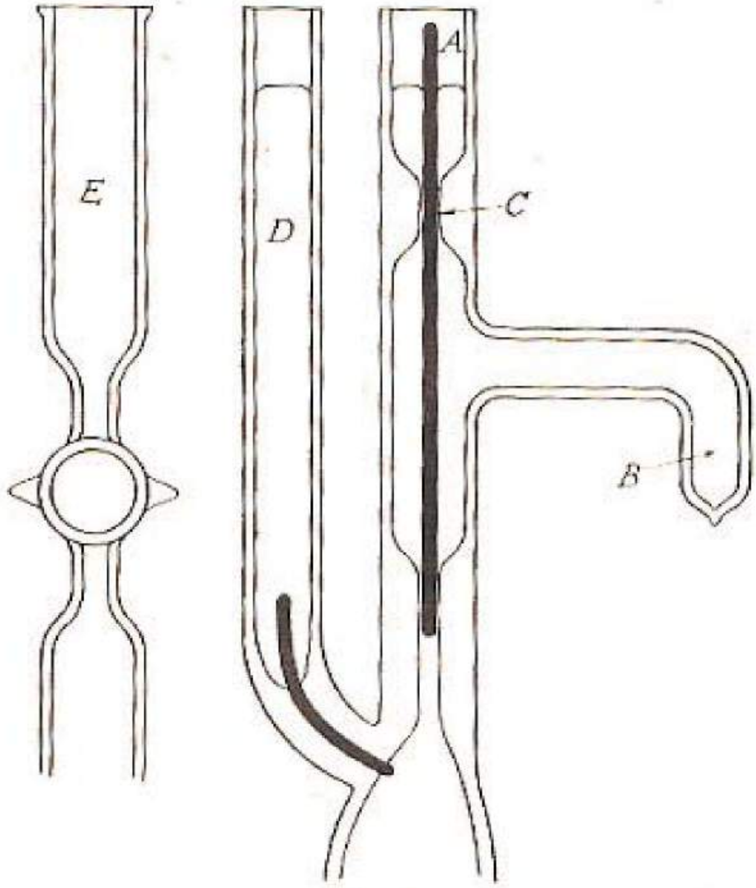

FIG. 6.

made with the hydrogen source, and releasing when opened to the air, the chamber may be thoroughly washed out and finally filled with gas until the mercury stands about 1 cm. below the wire in the capillary. Then the stopcock regulator is closed, the chamber is connected with the air by means of the three-way cock and is immediately sealed off.

To set the regulator for control at the desired temperature it is allowed to attain this temperature by immersion in hot water with the stopcock open. Then, with the circuit breaker connected at *A* and *D* via the mercury, slight suction or pressure is applied at *E* until the mercury barely touches the tungsten wire when the cock is closed. In order to avoid the necessity of opening and refilling with mercury when too little has been introduced into the contact chamber the side arm is bent as shown at B. This permits trapping some of the mercury away from the main body and thereby lowers the mercury level sufficiently to break contact.

It has been observed by Gouy[1] and Sligh[2] that, if the contact point is made to oscillate up and down for a distance of about 1 mm. in the regulator tube, more sensitive control is obtained than if the contact remains stationary. It is evident that even under such conditions, contamination of the mercury surface must inevitably take place, and it is feasible to suggest that a

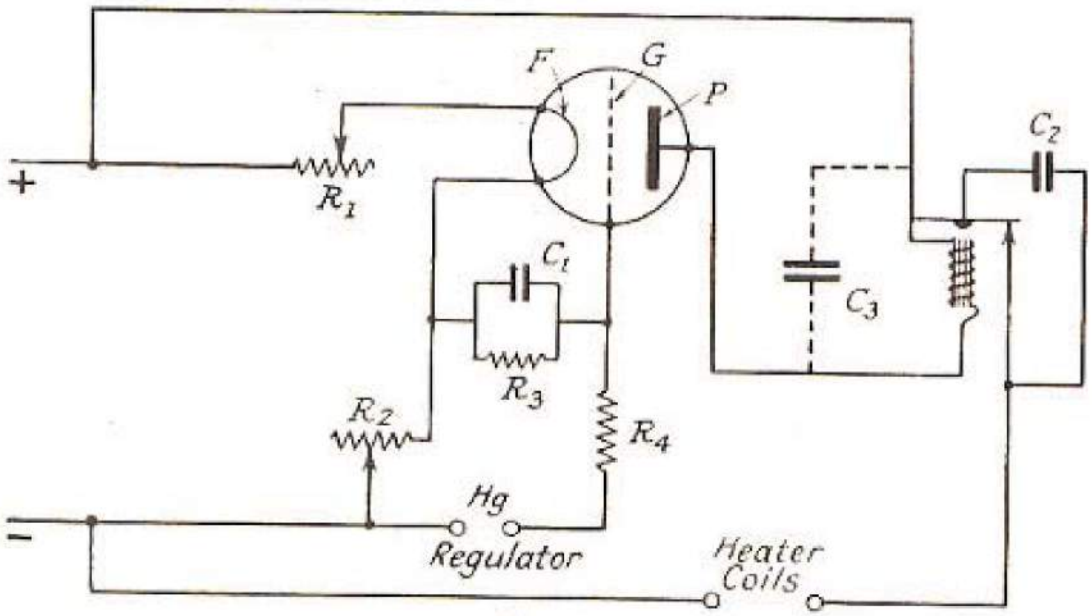

FIG. 7.

far more convenient method of minimising oxidation is to reduce or limit the amount of current passing through the regulator. Accordingly, Beaver[3] and also Cooke and Swallow[4] suggest that a maximum current value of 0·003 ampere should be employed in the control circuit and that by means of an amplifier this current can be increased to operate a relay.

A typical circuit arrangement is shown diagrammatically in Fig. 7. A 120 volt D.C. supply has two resistances, R_1 and R_2, connected across it with the filament of the valve in series, the value of the resistances being 120 ohms and 2 amperes capacity. F, G and P are respectively the filament, grid and plate of the valve. Resistances of 1 megohm, are placed at

[1] *Jour. Chem. Phys.*, 6, 479. 1897. [2] *Jour. Amer. Chem. Soc.*, 44, 60. 1922.
[3] *Ind. & Eng. Chem.*, 15, 359. 1923. [4] *Jour. Sci. Instr.*, 6, 287. 1929.

R_3, R_4, while C_1, C_2 and C_3 are condensers of 0·1, 0·5 and 8 microfarads respectively. The regulator is wired to the grid of the valve via the resistance R_4 and to one terminal of the supply mains, and by this means the current passing through the regulator will be very small. If sparking across the relay contacts points become too great, adjustment of the value of C_2 will be necessary.

Micro-Liquid Thermostat.—When very small quantities of liquid have to be maintained within very small limits of

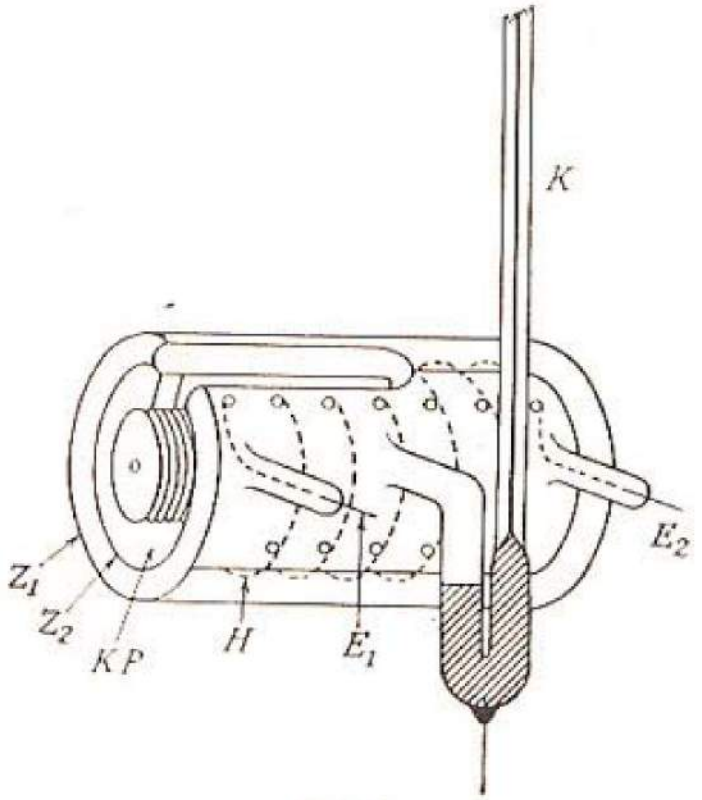

FIG. 8.

temperature change, the problem of control becomes more difficult. The design of such a regulator by Heigemann[1] for use in connection with the measurement of high and low frequency conductivities of electrolytes is worthy of mention. The thermostat was constructed of two glass cylinders Z_1 and Z_2 (Fig. 8), placed one within the other, one end being closed so as to form a containing chamber for toluene. Arranged laterally with the walls and projecting therefrom were a number of equally spaced glass pins, which served the purpose of anchoring lugs for the electric heater, contained within the toluene. The heater consisted of platinum wire H some 1·5 metres in length and 0·1 mms. diameter, which

[1] *Annalen der Physik*, 25, 347. 1936.

terminated at the terminals E_1 and E_2. Attached to the body of the thermostat was a U tube containing mercury, to which was sealed a capillary tube K so arranged that, on the expansion of the toluene, the mercury rise in the tube K was about 5 cms. for a temperature change of about 0·1° C.

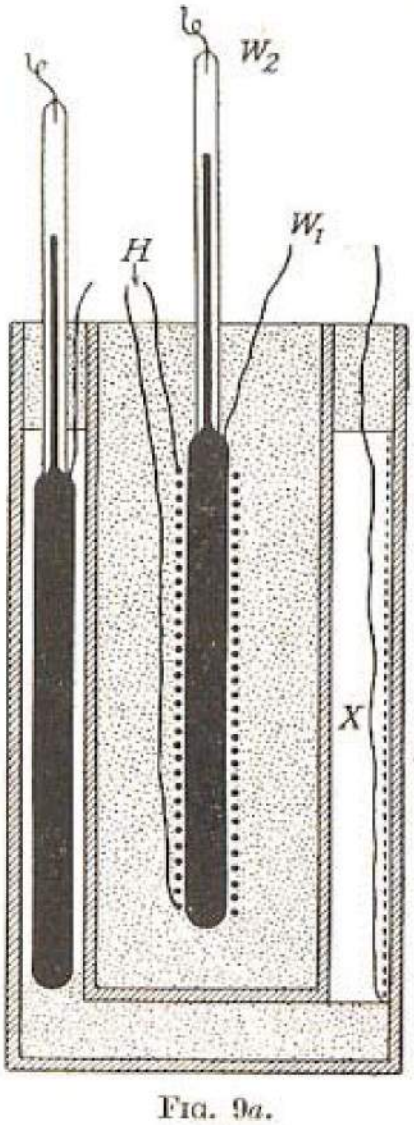

FIG. 9a.

Finally, the terminals were connected to a circuit containing a relay which operated, in turn, the main current passing through the heater H. The actual conductivity cell was placed in the thermostat with its stem projecting through the slot S formed by the walls of the regulating chamber, the intervening space between the stem and the end of the tube being carefully plugged to prevent leakage of the circulating liquid. The end of the thermostat was then closed by means of a rubber end plate K and, to allow the liquid to pass, holes were bored in the latter and tubes inserted to enable the water supply to be connected to it. In practice it was found that the temperature of the thermostat remained constant to $\pm$ 0·001° C. over hourly periods.

Utilising the expansion of mercury Stott[1] controlled the temperature of an electric furnace by an arrangement of which a diagrammatic view is shown in Fig. 9*a*, while (*b*) shows the wiring diagram. Situated in the centre of the apparatus is a mercury thermometer the bulb of which is wound with a small heating coil of 30 S.W.G. insulated manganin wire, held *in situ* by means of cellulose acetate varnish. The thermometer is inserted in a cylindrical pot P and well insulated by magnesia lagging. The bulb has a platinum wire W_1 sealed at its end, and the capillary tube of 1 mm. bore to which it is attached also contains a thin platinum wire W_2 at the end of which a small ball of the same metal has been melted. This

[1] *Jour. Sci. Instr.*, 8, 313. 1931.

wire is arranged so that, at a temperature of 125° C., the mercury just reaches the platinum ball. The usual expansion chamber is fitted at the head of the capillary and the intervening space filled with inert gas. The heating coil *H* is arranged in series with a resistance and shunted across the terminals of the furnace, or it may conveniently be connected to adjustable resistances in the voltage circuit. The wires W_1 and W_2 are connected to the input side of a relay operating a mercury-in-glass switch, and the latter is so arranged that, on the mercury coming into contact with the platinum ball, the main current is reduced.

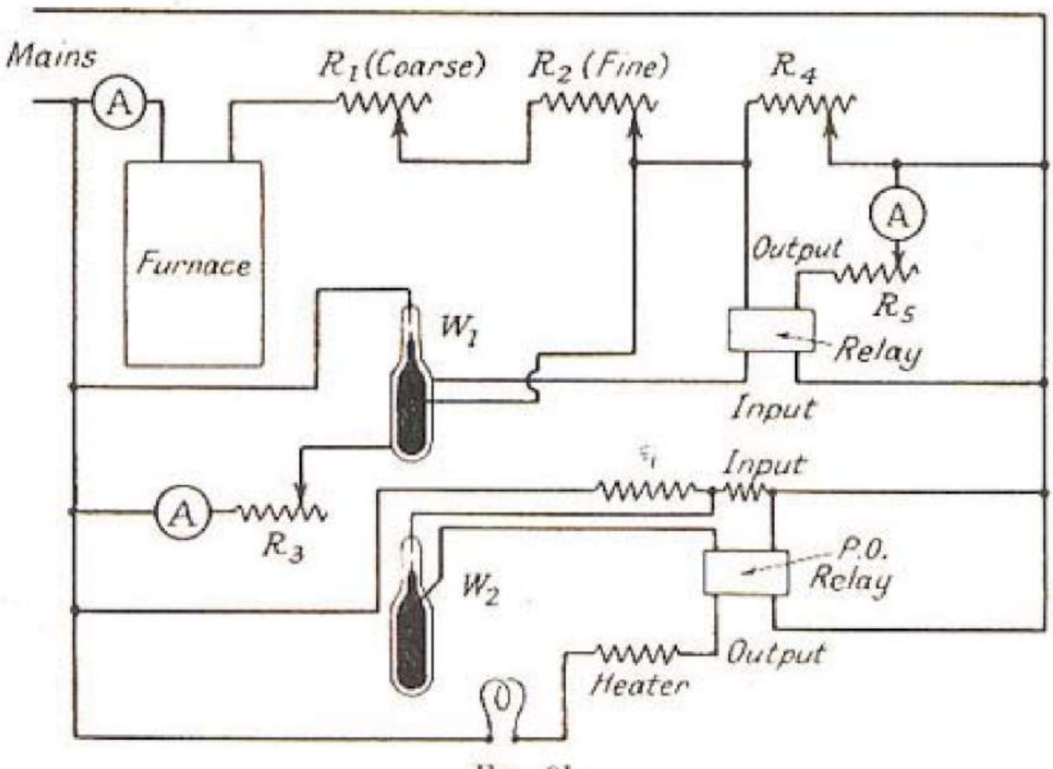

Fig. 9*b*.

To secure a constant current to the furnace, and in order that the external room conditions will not cause difficulties, the apparatus is placed within a larger, but similar, pot P_1, and the temperature is maintained at 50° C. in the annular space *X* by means of the heating coil wound on the outer wall of the inner pot. The current from this coil passes through the output circuit of a post-office relay controlled by a mercury thermometer. When operating on a 100-volt supply the resistance of this heater should be between 80 and 100 ohms. The circuit diagram is shown in Fig. 9*b* and by means of the adjustable resistances R_1 and R_2, it is possible to calibrate the furnace temperature for a given value of R_3.

FIG. 10.

The resistances R_4 and R_5 should be adjusted so as to make the "on" and "off" periods of the regulator about equal, in order not to overload the main relay. Ammeters may conveniently be inserted in the circuit as an aid to better control.

A commercial application of the use of the expansion of liquids is found in the mercury contact thermometer, such as that made by I.A.C. Ltd., of London. The thermometer is filled with mercury in the usual manner and calibrated over the desired temperature range. A platinum wire is sealed into the lower region of its mercury column, and normally is connected to a terminal at the head of the instrument. Another platinum wire, from the top of the stem, passes along the tube and has a small length of iron wire attached to its extremity. Arranged in the tube at a convenient position is a small platinum spiral through which the previous wire passes and, regardless of the position of the latter, contact is always made via the spiral and the wire. The end of the spiral is taken to the remaining terminal of the instrument head. By means of an external magnet the position of the iron wire in the stem may be adjusted to make contact with the mercury in any desired position, and the length of platinum wire is chosen so that its lower tip will always reach the surface of the mercury at the lowest required temperature. In practice, the iron tip is set for the required temperature of the control and the instrument is used in the usual manner; leads being taken from the thermometer terminals to a relay circuit controlling the heating current. A typical instrument is shown in Fig. 10.

Another interesting application is that employed in the temperature control of

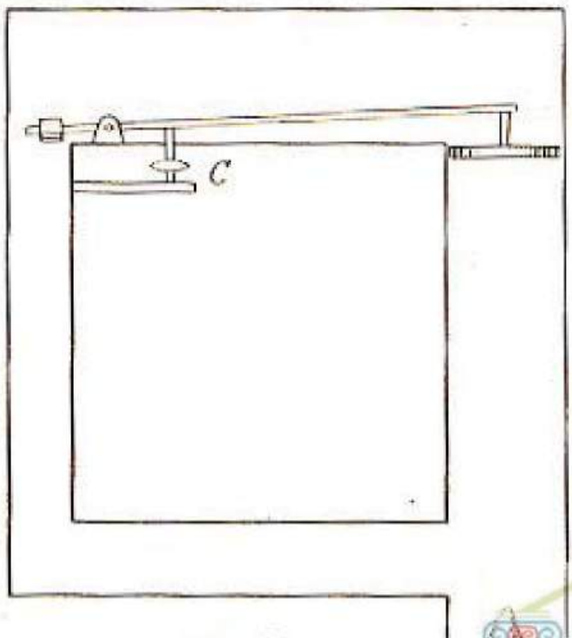

FIG. 11.

hot air ovens and incubators. The liquid is placed in a metal capsule *C* (Fig. 11), placed within the heated space, and the expansion of the liquid causes movement of a weighted lever which opens or closes a gas or electric control. It may be arranged that, on the expansion of the capsule, movement takes place which causes the opening or closing of a damper. In this way, gases may proceed directly through a vertical flue at the side of the oven, or may be by-passed so as to flow around the oven and heat it, the direction of flow being controlled by the capsule-operated damper. The latter closes the top of the direct vertical flue exit when the temperature falls. When equilibrium is once again attained, the damper just hovers above the exit and permits a portion of the hot gases to escape.

CHAPTER III

VAPOUR BATHS AND VAPOUR PRESSURE METHODS OF TEMPERATURE CONTROL

THE use of vapours for temperature control has found greater application in laboratories than in industrial processes, but recent developments indicate that the use of vapours is being increasingly employed in commercial forms of control. This method possesses the advantage that steady temperatures over long periods can be assured.

For laboratory purposes the method usually employed is to arrange that the vapour from a boiling substance is caused to surround the body to be maintained at a predetermined temperature. This must be carried out in such a manner that the rising vapour is constantly kept in contact with condensed liquid in order to preclude superheating. The liquids are usually operated at atmospheric pressure since the boiling points are already known for that pressure. Since the boiling point varies with pressure—that at atmospheric pressure being known—intermediate temperatures may be produced by using the same liquid at different pressures. Such a procedure is not generally necessary since a large number of chemicals with a wide range of boiling points are readily available. It is also possible to produce intermediate temperatures by mixtures having various proportions; while dissolved solids in a liquid bath cause the boiling point to be raised.

The following table gives details of suitable substances for vapour baths. It should be noted that, while some have toxic and inflammable qualities, they may be conveniently employed provided reasonable care is exercised.

TABLE 4.

Boiling Point, °C., 1 atmosphere.	Name.	Formula.	Remarks.
4·6	Methyl Bromide	CH_3Br	
7·4	Dimethylamine	C_2H_7N	Toxic.
12·2	Ethyl Chloride	C_2H_5Cl	Anæsthetic properties.

Boiling Point, °C., 1 atmosphere.	Name.	Formula.	Remarks.
20·8	Acetaldehyde	C_2H_4O	Inflammable, explosive
36·2	Pentane	C_5H_{12}	mixture with air.
38·0	Ethyl Bromide	C_2H_5Br	
42·6	Methyl Iodide	CH_3I	
46·3	Carbon Disulphide	CS_2	Toxic.
50·5	Glyoxal	$C_2H_2O_2$	Toxic.
54·3	Ethyl Formate	$C_3H_6O_2$	
56·1	Acetone	C_3H_6O	
57·1	Methyl Acetate	$C_3H_6O_2$	
61·2	Chloroform	$CHCl_3$	Anæsthetic.
64·5	Methyl Alcohol	CH_4O	
76·8	Carbon Tetra-chloride	CCl_4	Toxic.
77·1	Ethyl Acetate	$C_4H_8O_2$	
78·5	Ethyl Alcohol	C_2H_6O	Toxic, explosive mix-
79·6	Benzene	C_6H_6	ture with air.
83·7	Ethylene Dichloride	$C_2H_4Cl_2$	Toxic.
88·0	Trichlorethylene	C_2HCl_3	Toxic.
91·5	Isobutyl Bromide	$C_4H_9Br_2$	
97·8	Methylene Bromide	CH_2Br_2	
97·8	Propyl Alcohol	C_3K_8O	
100	Water	H_2O	
110	Toluene	C_7H_8	
115·3	Pyridine	C_5H_5N	
117·7	n-Butyl Alcohol	$C_4H_{10}O$	Bad smell.
118·1	Acetic Acid	$C_2H_4O_2$	Not to be used with metal containers.
123·5	Isoamyl Formate	$C_6H_{12}O$	Commercially known as Amyl Alcohol.
132·0	Chlorbenzene	C_6H_5Cl	
147·6	n-Amyl Acetate	$C_3H_{14}O_2$	
142·6	Xylene	C_8H_{10}	
144·8	Methyl Lactate	$C_4H_8O_3$	
145·0	2-Chlorœthyl Acetate	$C_4H_7ClO_2$	
150·4	Bromoform	$CHBr_3$	Toxic.
159·0	Turpentine	$C_{10}H_{16}$	
170·0	Methyl Aceto-Acetate	$C_5H_8O_3$	
182·0	Phenol	C_6H_6O	Not to be used in metal containers.
184·4	Aniline	$C_6H_5NH_2$	Toxic.
189·5	Carbon Tetra-bromide	CBr_4	Toxic.
190·8	o-Cresol	C_7H_8O	
192·0	Deca-Hydro-naphtalene	$C_{10}H_{18}$	(Dekalin).

Boiling Point, °C., 1 atmosphere.	Name.	Formula.	Remarks.
197·2	Ethylene Glycol	$HOCH_2CH_2OK$	
218·0	Turpineol	$C_{10}H_{18}O$	
218·0	Naphthalene	$C_{10}H_8$	
290·0	Glycerol (ine)	$C_3H_8O_3$	
298·0	Benzyl Ether	$C_{14}H_{14}O$	
302·0	Diphenylamine	$(C_6H_5)_2NH$	
314·0	Phenyl Benzoate	$C_{13}H_{10}O_2$	
326·0	Hexachlorobenzene	C_6Cl_6	
356·7	Mercury	Hg	Vapour, very poisonous.
401·7	Benzidine	$C_{12}H_{12}N_2$	
444·5	Sulphur	S	
730·0	Zinc Chloride	ZnCl	Not to be used in metal containers.

Petroleum Ether		Range ° C.	
,,	,,	40–50	Explosive mixture with air.
,,	,,	40–60	
,,	,,	50–60	
,,	,,	60–80	
,,	,,	80–100	
,,	,,	100–120	

Water Type Boiler.—Various forms of boilers have been devised for this purpose, but the principal precaution is to ensure that impurities are absent from the bath substance. It is sufficient to boil the substance rapidly at first, in order to drive over impurities, and then it is possible to adjust the heat supply so that the vapour will produce steady conditions. In order to obtain steady ebullition a small quantity of mercury may be added to alcohol baths.

R. S. Edwards[1] employed the form of bath shown in Fig. 12. For use at 100° C. a separate boiler was employed: the steam was brought into the jacket at *A* by means of flexible tubing and allowed to escape at *B*. In order to drain off condensed steam from the jacket a tap was provided at *T*. For temperatures above 100° C. the heat supply was situated directly under the vapour bath, the substance being placed in the bottom of the vessel. To obtain steady boiling it was found desirable to place an asbestos cone round the lower half of the vessel, as in Fig. 12*b*, while the upper portion was jacketed with an air condenser to condense the vapour.

[1] *Pro. Roy. Soc.*, (A), 117, 245. 1928.

Sulphur Type Boiler.—For sulphur, the boiling point being 445·5° C., certain modifications had to be made. The container, usually of iron, was surrounded by an asbestos cylinder *E*, and the hot gases from the burner at the base passed up through the interspace and escaped at *D*. A coil

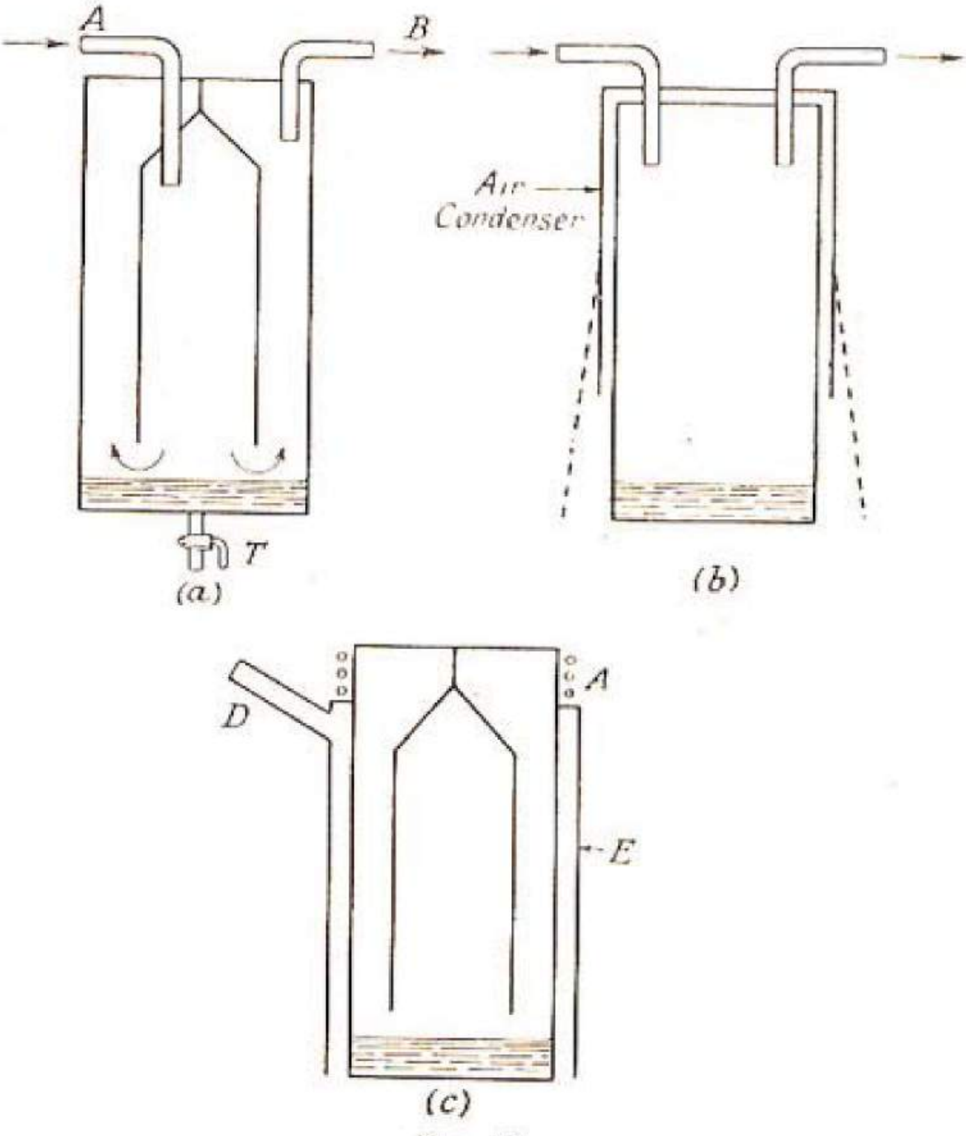

Fig. 12.

of metal tubing *A* was wound round the top of the jacket, through which a current of cold water was circulated, thereby condensing the sulphur vapour. In order to protect the immersed apparatus from the vapour, a metal cone *B* was suspended from the top of the bath container. The connections to the apparatus were made by passing tubes through the lid.

Lambert and Clark[1] devised the apparatus shown in Fig. 13, which consisted of a long glass tube with a bulb *B* at one end,

[1] Ibid., 117, 183. 1928.

and containing the liquid to be boiled. Asbestos paper and water are ground into pulp and moulded round the bulb and, when dry, a suitable number of turns of nichrome wire were wound in the position CC_1.

This heating coil was connected in series with a control rheostat and the main current supply. A further thick coating of asbestos was moulded over the heating system and finally the whole heating apparatus was lagged by packing with slag wool in the metal container *M*. The exposed outer glass surface of the vapour bath was protected by the cylindrical aluminium tube *D*, which may be provided with slits for observational purposes. In order to minimise the effect of convection currents around the vapour bath, the top of the tube *D* is covered with an asbestos board *E*. The open end of the tube *A* was closed by a rubber bung *F*, which carried a glass hook *H* in order to support the immersed apparatus. *G* is a water-cooled condenser to condense escaping vapours, and *J* an accurate thermometer. These workers in order to obtain control within fine limits, used a manostat to maintain the air pressure constant. A description of this Wade and Merriman manostat will be found in Appendix III.

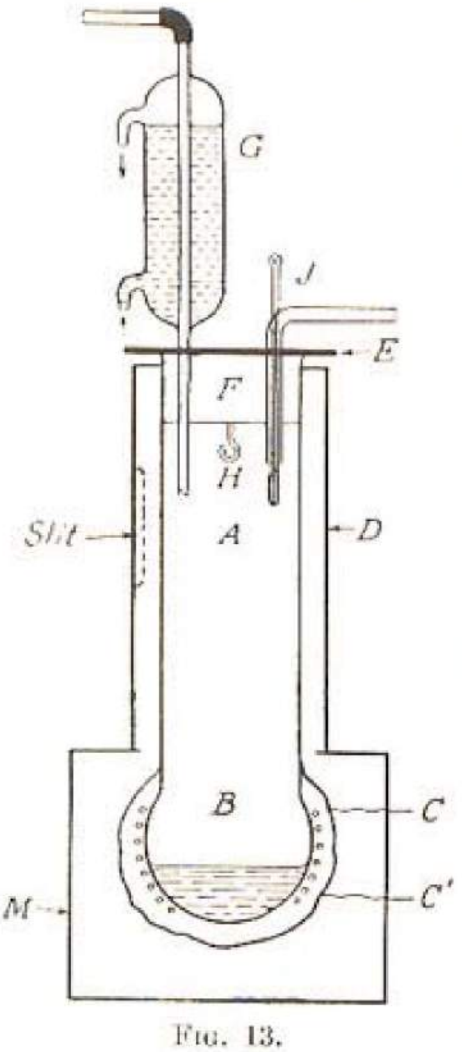

FIG. 13.

In order to carry out pH measurements at elevated temperatures the author devised the bath shown in Fig. 14. It consists of a double-walled copper tank *A*, of 24 S.W.G., the outer compartment being completely closed except for the two circular openings *BB*. A ridge inside the tank supports a perforated copper disc *CC*, to which the conductivity cells are attached. The support *D* is fitted with bearings and carries the motor-driven paddle stirrer *E*, and, to enable the hydrogen which passes into the cell also to be at constant temperature, a copper coil *F* rests on the bottom of the inner compartment. The ends of the coil reach the top of the thermostat tank, and the hydrogen supply is connected thereto by means of rubber tubing. In order to condense the escaping vapour a

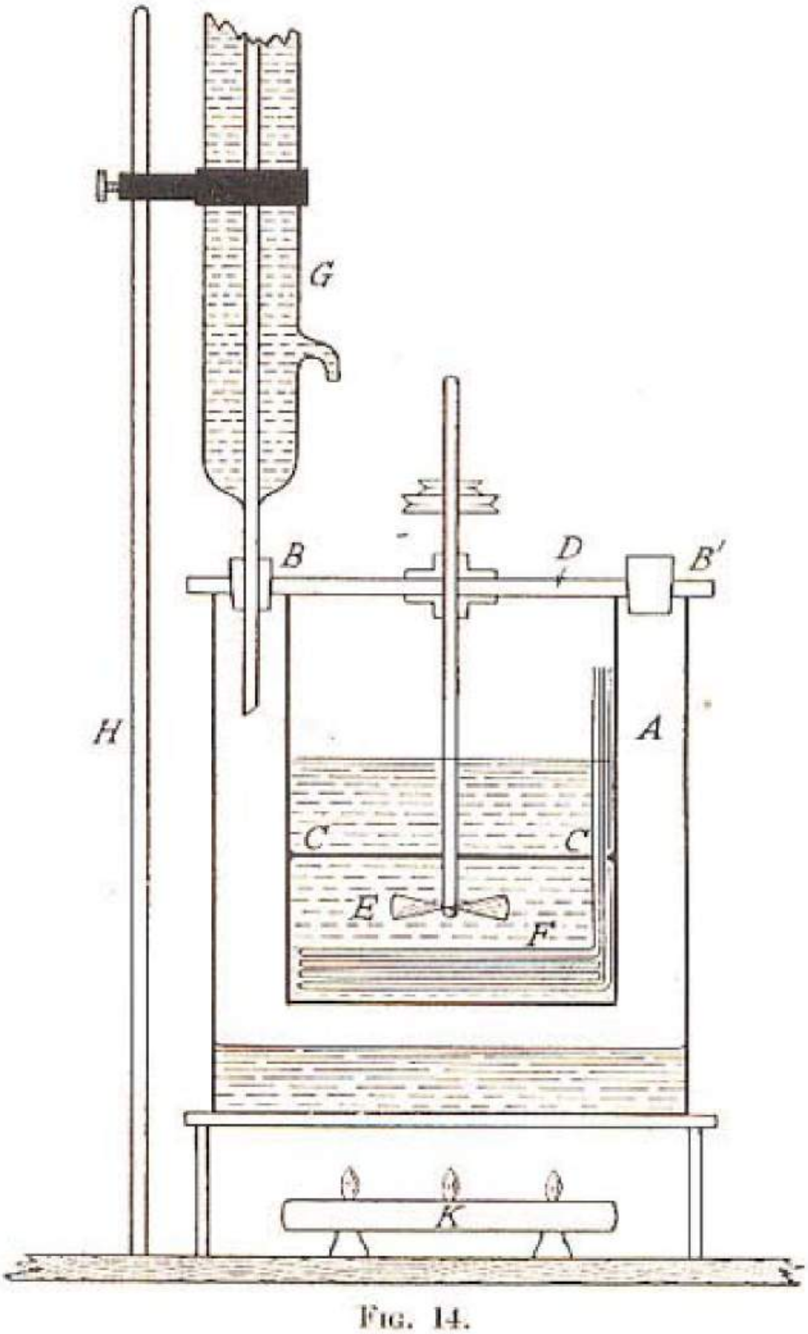

FIG. 14.

water-cooled condenser *G* is conveniently fitted to *B*, and held in place by the retort stand *H*. A gas ring situated at *K* with small jets is employed for heating. The correct liquid for the desired temperature range is poured into the outer jacket and the opening *B′* is then closed. The cells are then placed in position on the plate *C*, and the inner container is filled with water to a convenient depth. The liquid in the outer vessel is heated to boiling which raises the temperature of the water in the inner compartment to the same value.

In this form of apparatus, exposed liquid surfaces should be eliminated, by employing a closely fitting lid and to ensure constancy of temperature over long periods precautions must be taken to prevent the effect of any variation of atmospheric pressure, since the boiling point is dependent thereon. This may be accomplished by sealing the bath in an air-tight manner, and compensating for changes in the atmospheric pressure by the addition or removal of quantities of air as required.

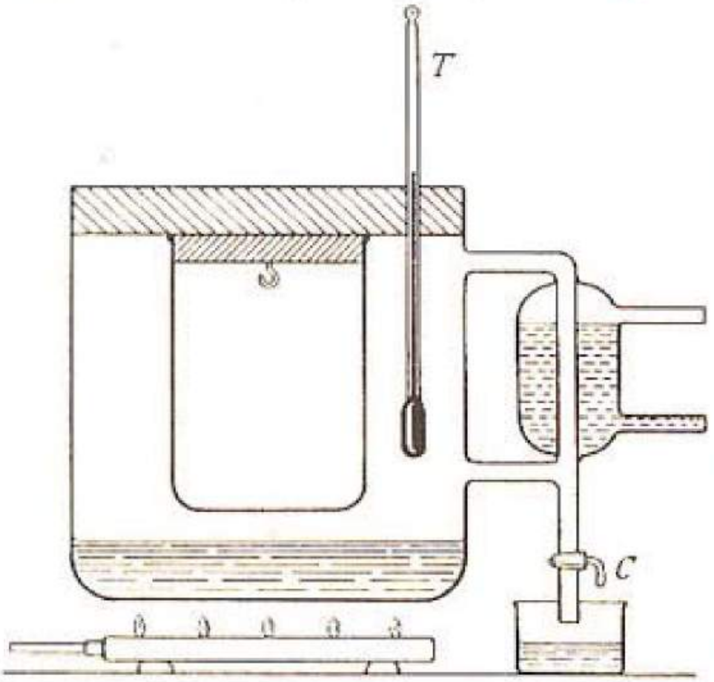

Fig. 15.

A method designed by Fock is shown in Fig. 15. It consists of a double walled copper vessel, the intervening space between the two vessels containing mixed liquids and their vapour. A closely fitting lid, heavily heat-insulated, is employed to eliminate external temperature differences, while the object to be kept at constant temperature is situated in the inner compartment. The mixture is boiled and the vapour passes into the condenser and from thence flows into a conveniently situated vessel. When the desired temperature has been obtained, as indicated by the thermometer T, placed in the vapour bath, the condenser tap C is closed. Thus when mixtures are employed for bath purposes, the concentration will remain constant, since on the vapour condensing the condensate will return to the bath. By this means a liquid may be boiled at constant temperature.

An interesting form of bath was developed by the chemical workers Nelson and Haller[1] and is shown diagrammatically in Fig. 16. It consists essentially of a boiler B, containing a liquid boiling at constant temperature, a heating unit and a

[1] *Ind. & Eng. Chem.* (Annal. Ed.), 9, 402. 1937.

side tube for a reflux condenser. The boiling flask was a Kjeldahl flask suitably adapted for the particular purpose in view. The space between the molecular still and the temperature bath was filled with a mineral oil of high boiling point to function as a heat conductor between the vapours of the boiling liquid and the material in the still. Heating was carried out by inserting a suitable length of nichrome wire in the boiling liquid and connected by leads to an external source of current supply. It was found advantageous to insert a resistance in series with the main current and the heater. The height from the base of the still to the bottom of the bath was approximately 17 cms. while the space between the still and bath was approximately 2 cms. wide throughout.

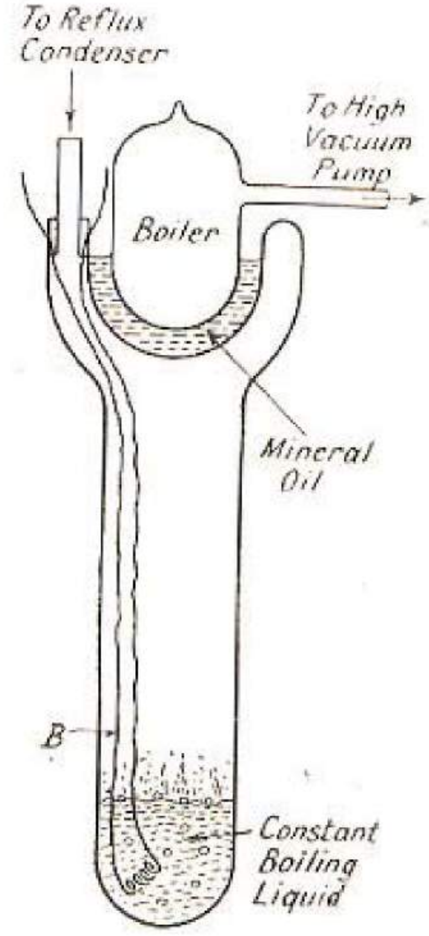

FIG. 16.

Commercial Applications of Principle.—A commercial form of apparatus using vapour pressure is shown in Fig. 17. The projection at the left of the case houses a flexible chamber, in the form of metallic bellows, which is charged with a volatile liquid such as ether, alcohol or turpentine. One face of the chamber presses against a spiral spring of requisite strength, the other being maintained against the housing case. In use, an increase of temperature causes a corresponding increase of vapour pressure within the chamber and the expansion of the latter takes place against the spiral spring. This motion is then communicated through a lever system to a movable contact piece which makes or breaks contact with another stud. In some arrangements the studs are replaced by a mercury-in-glass switch. Suitable leads are provided to take the main current to the studs or switch. By means of the control knob *B*, the spring tension may be varied and this increases or decreases the operative temperature of the control device. This adjustment, however, is only permissible within certain limits, since in order to obtain sufficient flexibility in the chamber walls, thick metal cannot be employed.

The apparatus is usually placed within the chamber whose temperature it is desired to control, but, in the modified form

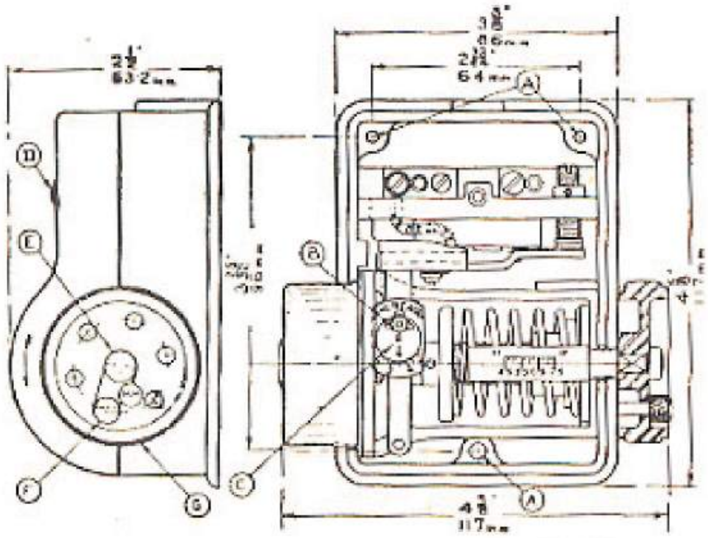

Fig. 17.

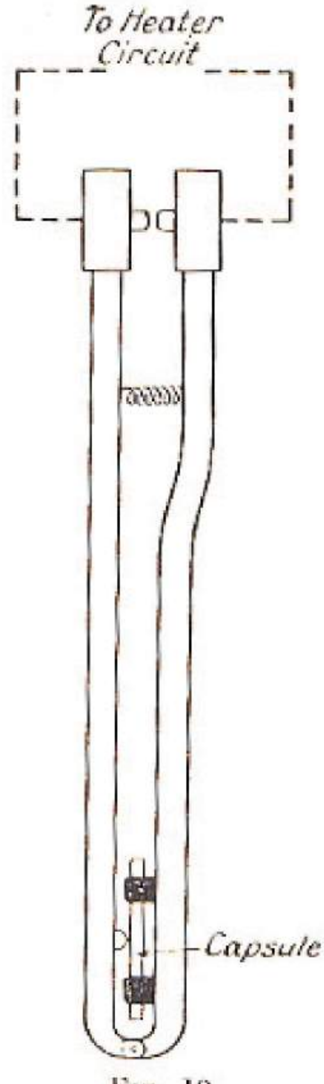

Fig. 19.

shown in Fig. 18*a*, only the control phial need be placed within the chamber. In this case the volatile liquid is placed within a metal cylinder, some 6 inches long and $\frac{3}{16}$ inch diameter, and connection is made to the switch control by means of a metal capillary tube. The action is similar to the previous arrangement, the vapour trapped in the fine bore tubing producing sufficient pressure to operate the switch arm. Fig. 18*b* shows the external arrangement. Another commercial form is shown in Fig. 19. A volatile liquid is placed within a small hermetically sealed copper capsule. The latter is fixed in a cup, situated near the junction of a pair of hinged arms. On the increase of temperature, the capsule wall is caused to expand, the movement being communicated to the lever system. Temperature control over a range of several degrees can be obtained and regulated by means of a fine-pitch adjusting screw.

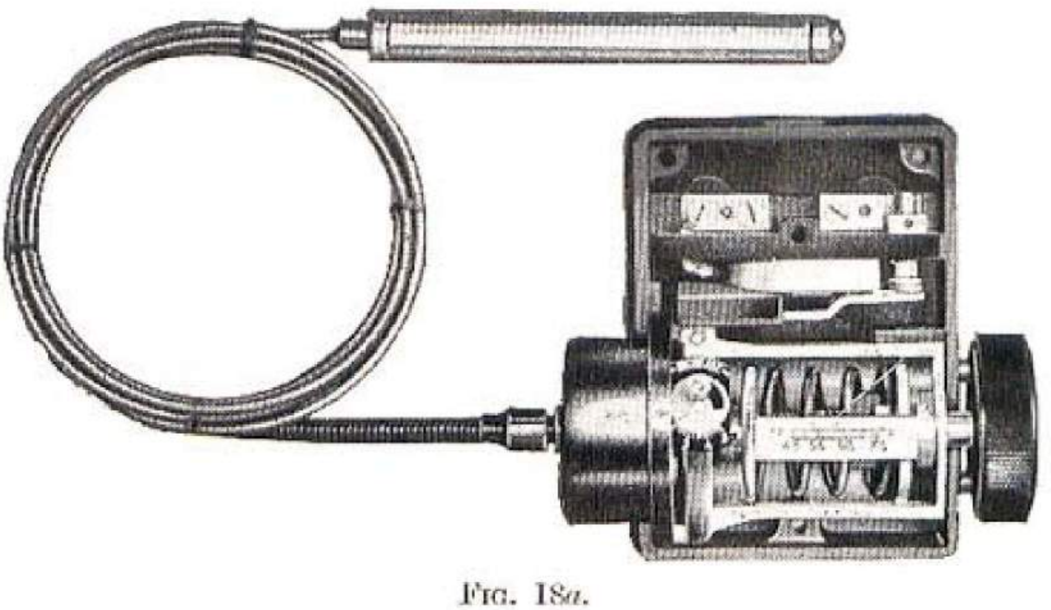

Fig. 18*a*.

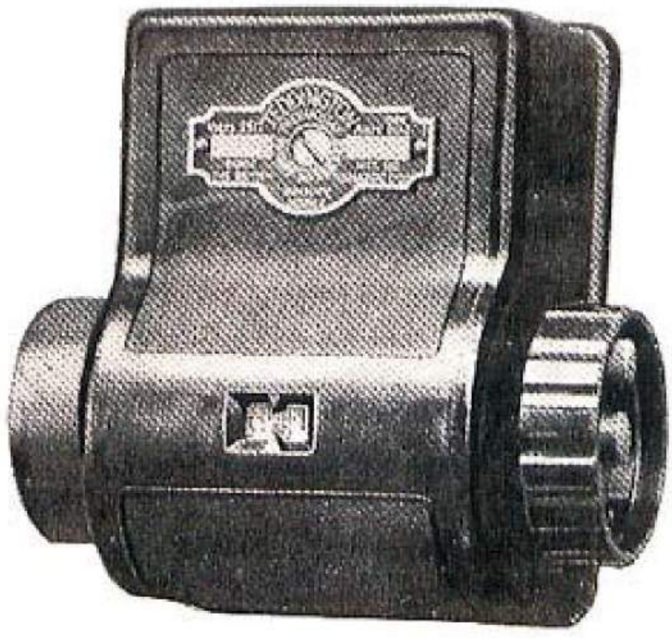

Fig. 18*b*.

[*To face page 31*.

CHAPTER IV

METAL EXPANSION CONTROLS

SOLIDS, such as metals, have found widespread use in temperature control work, because of the simple construction involved, dependability of the apparatus as well as long life. In fact, the earliest regulators used by Bonnemann[1] and Ure[2] were made of metal. In its simplest form the expansion of a rod of metal is made to operate a system of levers or controls which in turn regulate the temperature of the system. In order, however, to obtain the greatest sensitivity over a predetermined range, it is desirable that the greatest expansion per unit length of bar should be obtained, thus metals having large expansion coefficients are always employed.

The values of the coefficients of linear expansion (a) are appended in the following table:

TABLE 5.

COEFFICIENT OF LINEAR EXPANSION PER °C. AT ORDINARY ATMOSPHERIC TEMPERATURES.

Metal.	Coefficient of expansion × 10^{-6} (a)
Aluminium	25·5
Brass (Cu. 66, Zn. 34)	18·9
Bronze (Cu. 32)	17·7
Copper	16·7
Duralumin	22·6
Iron—Cast	10·2
Iron—Wrought	11·9
Invar	18·8
Nickel	12·8
Nickel steel (20%)	19·5
Phosphor bronze (Cu. 97·6, Sn. 2, P, ·2)	16·8
Silver	10·5–11·6
Steel	21·4
Tin	23·0
Zinc	26·3

[1] *Dingl. polyt. Jour.*, 16, 285. 1825.

[2] Ibid, 42, 173. 1831.

The choice of a metal will be determined not only by its expansion coefficient, but also, by considering possible corrosion when in contact with liquids, cost, and constructional difficulties.

Wire Expansion Control.—Chevenard has designed a control in which the expansion of a wire caused by an increase in a current passing through it, enables an adjustable resistance to operate on the main heating current.

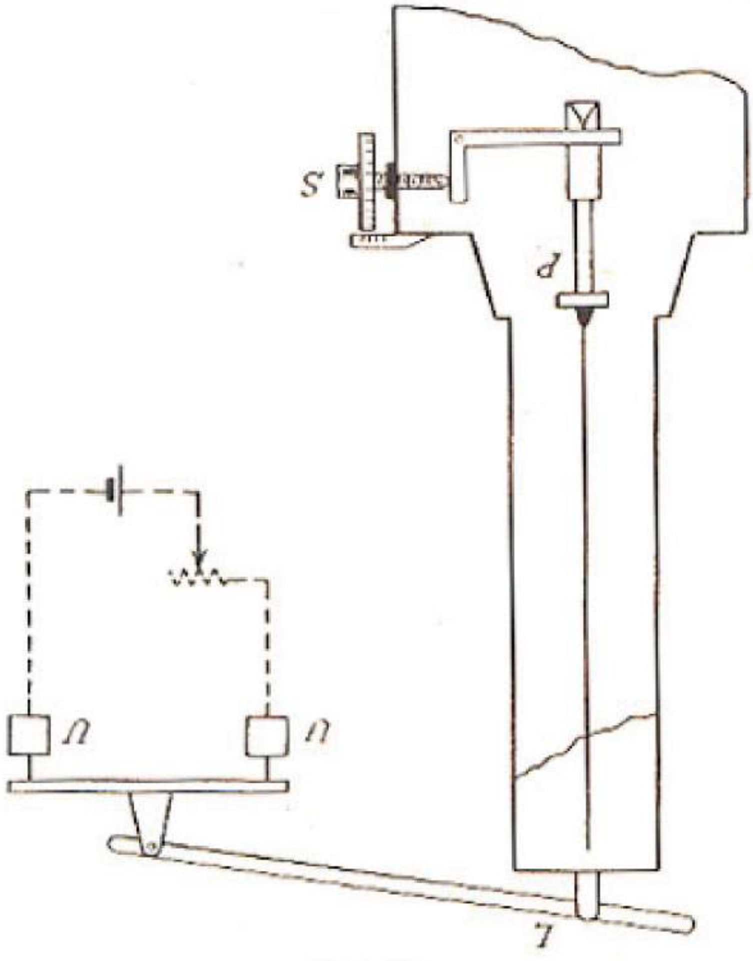

FIG. 20.

The wire, preferably of nichrome, passes through a vertical pyrex tube. One end of the wire terminates at the screw head *P* (Fig. 20), whilst the other is linked to a pivoted lever *L* at the head of the tube. This lever is connected to another pivoted beam, at the ends of which are prongs which dip into mercury cups. The latter are connected to the main circuit in which an adjustable resistance is placed. By means of the screw *S* the wire may be adjusted for equilibrium at the required temperature, i.e. the prongs *UU* are in such a position, that they will break the surface immediately the current passing through the nichrome wire exceeds a predetermined value. In order that fluctuations in the atmospheric temperature shall not affect control, compensation is provided by making the link lever bi-metallic, so that as it bends with change of temperature, the point of contact between the mercury level and prongs advances or recedes.

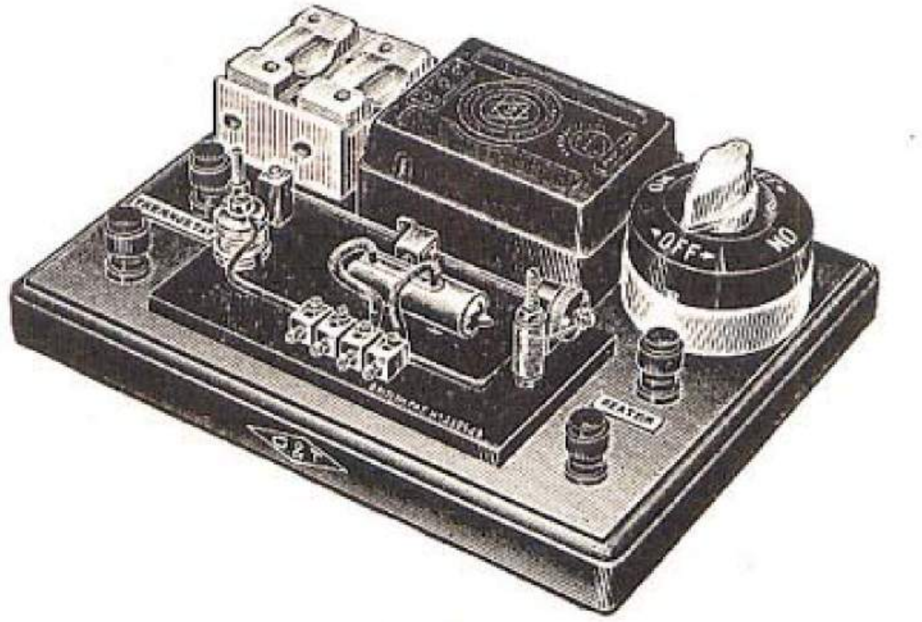

Fig. 21.

This form of control has been adopted by Griffin and Tatlock for commercial purposes, the exterior of the equipment being shown in Fig. 21, while Fig. 22 gives the circuit diagram. The action of the relay depends on the expansion of the wire *AB*, when heated by the passage of a current. The resultant

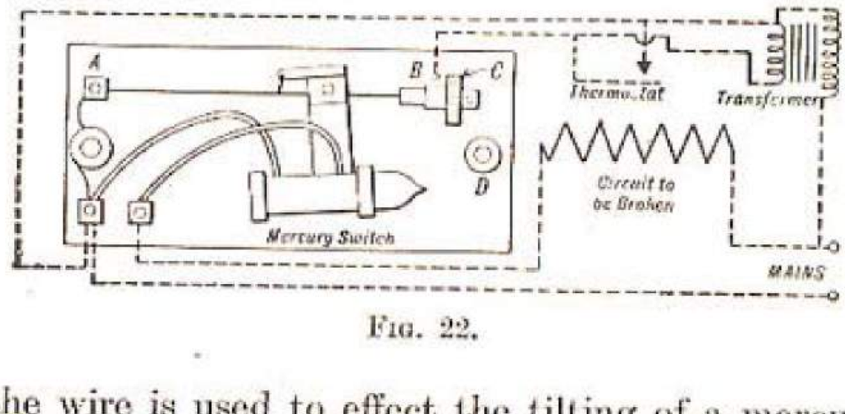

Fig. 22.

sag in the wire is used to effect the tilting of a mercury tube switch which then makes or breaks the main circuit. In the diagram it is to be noted that the thermostat is connected in parallel with the wire element. When the thermostat contact is completed the wire element is short circuited and the current through it being thereby reduced, the wire cools and contracts. The effect of this contraction is to tilt the mercury switch, and thus to operate the main circuit. This cycle is indefinitely repeated while the apparatus is in operation. It is practicable to connect the thermostat in series with the wire element, but then the potential across the contacts is equal to that of the mains supply.

Bi-metallic Controls.—Generally speaking, the employment of a rod of single material is not usual since the increase of length over a short length is not great for normal operating temperatures. Consequently, it will be found that rods of different materials are coupled together, thereby increasing the effective expansion for the corresponding range. These are known as bi-metallic types and generally consist of a brass tube surrounding a rod of invar, the two being connected rigidly at one end. The brass tube is anchored to the case at the other end, and its expansion with temperature causes axial movement of the free end of the invar rod, which operates the control mechanism.

Such a movement is used for the control of hot-air ovens, and the method adopted by Hearson, as in Fig. 23, is typical. The unit consists of two metal rods *A*, having a widely differing coefficient of expansion, provided with a central rod *B*. These rods are fitted so that the sum of their lineal expansion coefficients is made available for operating the pivoted lever *L*, which also controls the electrical circuit containing the heating elements of the oven. The lever is pivoted about the thermostatic unit, and passing through the rod at this end is a line threaded screw *P*, by which contact is made between *L* and the expansion unit. At the other end an insulator *S* is fixed, which, when the rod is raised or lowered, applies pressure on the spring tongue *XT*, thus making or breaking the electrical heating circuit. In order to facilitate rapid adjustment of the control, a graduated head is attached to the expansion unit external to the air oven. In operation, the screw *P* must rest on the rod *B*, and it is rotated till the spring tongues just make contact with the tipped contact screws, which are part of the heating circuit. These are so arranged that two separate heaters can be brought into the circuit, both together or individually. On switching on the current, the heating will commence and continue until the chamber attains approximately the temperature indicated on the graduated scale *C*.

When this state is reached the free end of the lever will be found resting on the contact springs, so that one or more currents become interrupted. In this manner, control is effected, but if the temperature reached is not within the desired amount, small movements of the control head will enable a finer adjustment to be made. It is possible by this mechanism to control temperatures over a range 50°–250° C.

As an alternative, a cantilever is often largely favoured, the deflection of the free end being used for control purposes.

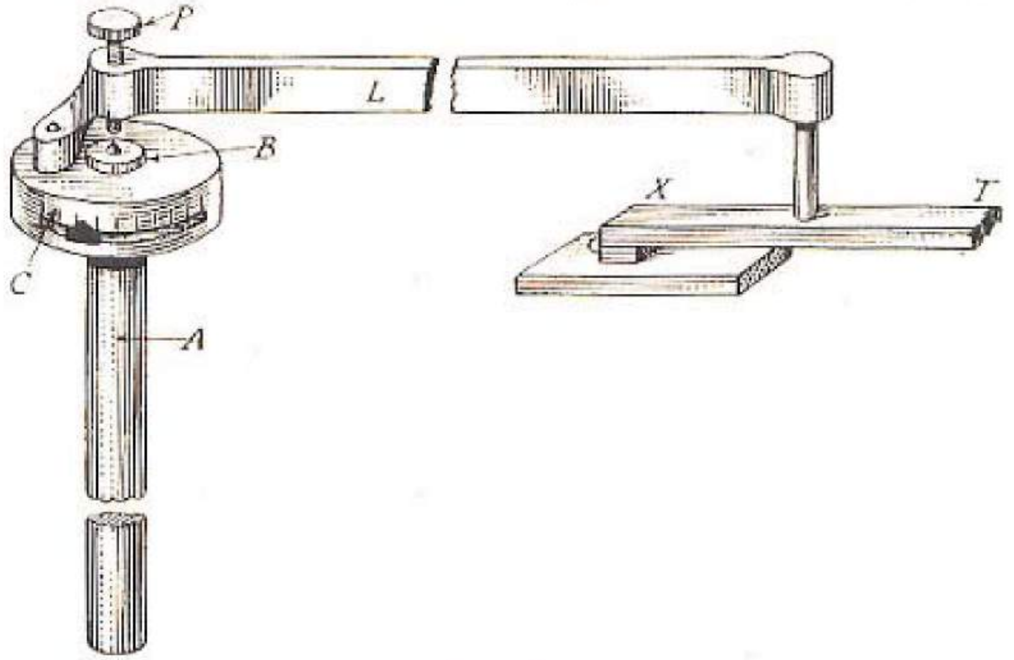

Fig. 23.

The metals in this case are in strip form, two dissimilar metals being fused or welded together, with the result that temperature variation produces a distortion or bending of the strip. The process of jointing has to be carried out with extreme care, since the continual expansion or contraction results in considerable strain in the bi-metal strip, and, unless the joint is perfect, the resulting distortion quickly tears them apart. The strength of the individual components is also of great importance, since, if the metals are not sufficiently strong, permanent deformation will result, and the strip will not return to its original setting on cooling.

The accuracy of a bi-metallic strip depends principally on the elastic properties of the combination; it is therefore essential to use the material hardened by cold-rolling and carefully heat-treated to obtain the highest possible strength and elasticity. Subsequent treatment which will adversely affect these properties should be avoided. Any remaining strains, consequent on manufacture, may be removed by heating to about 50° C. above the intended working temperature and slowly cooling.

Generally the low expansion strip consists of an alloy of nickel and iron, having a 3% nickel content, the material being known as Invar. Various combinations of metals have been used and the high expansion metals may be brass, monel metal, or mild steel. A very good combination is brass and invar, marketed under the trade name "Thermoflex," and made by Wilkinson, Shustoke, Warwickshire. It is possible to obtain silver on copper, silver on brass, copper on brass.

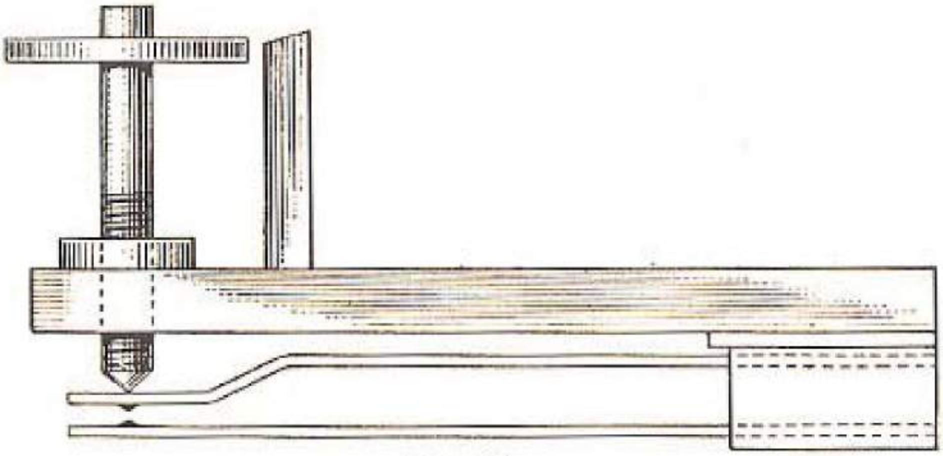

FIG. 24.

Although it is possible to pass heating currents directly through the bi-metal strip, since such currents have to be limited to a small value, this method is unsatisfactory in practice. It is usual, therefore, to operate a relay by means of the bi-metal strips ; this is always the case when the current exceeds 1 ampere. A typical mounting for such a strip is shown in Fig. 24, the contact distance being controlled by the adjustable screw head.

It is an advantage to know the amount of movement in the element for a given change of temperature. With a straight bi-metal strip held as a cantilever at one end, the deflection at the free end varies as the square of the length and inversely as the thickness.

Thus if L = the length of the strip,
a = the difference in mean co-efficient of expansion of the two metals over the temperature range required,

T = degrees change in temperature,
H = the thickness of the strip,
X = the deflection at the free end,

then $X = \frac{3L^2aT}{4H}$.

It will be seen that when the bi-metallic strip is used in this way, greater sensitivity is obtained when the strip is long and narrow.

Commercial Bi-metallic Units.—A compact form of control used for regulating directly 1 ampere at 250 volts A.C. or D.C. is manufactured by the Sun-Vic Thermostat Co., and is shown in Fig. 25. This device has been successfully used to control the temperature of aquariums, viscometers, standard cells, wax, oil, and glue baths, and in vulcanising and photographic processes. It consists of a small bi-metallic strip hermetically sealed into a glass tube. The thermostat is set during manufacture to the required operating temperature, and since no arcing at the contacts takes place, this setting remains entirely permanent. The totally sealed construction permits the device to be immersed in water and other fluids. The differential obtained with this control does not exceed $\pm 1°$ C. when controlling 1 ampere at 250 volts, whilst various settings are obtainable for different temperature ranges.

Another form of regulator made by the G.E.C. is shown in Fig. 26. This consists of a bi-metallic element, one end of which is fixed, the other carrying a moving contact and armature of soft iron. The latter is attracted by the poles of a magnet suitably mounted on the frame and lying in a plane parallel to the bi-metal strip and close to it; whilst the fixed contact is situated midway between the limbs of the magnet near the poles. With such an arrangement a "snap" action is provided since the pull exerted by the magnet on the armature increases rapidly as the latter approaches it. The design is such that on increase of temperature the strip bends away from the magnet, and the construction enables operation between 30°–210° F., the adjustment for the temperature being carried out by the control knob fixed at the end. This adjustment is effected by mounting the "fixed" end of the bi-metal on a hinged bracket which is caused to rotate through a small angle when the adjusting knob is rotated. The bi-metallic strip (1) carries the soft iron armature (2) at its free end and the contact (3). The fixed contact (6) is surrounded by a porcelain arc shute (4), the function of which is to prevent the arc striking over to the frame which is at the same potential as the moving contact (3). The permanent magnet (5) is clamped to the frame with its poles embracing the contacts. The end of the bi-metallic strip more distant from the contacts is clamped to the angle bracket (7) by movement of which the contact is forced to a greater or less degree against the fixed contact. Thus under such circumstances, a greater or less rise of temperature is required to enable the bi-metal to open the contacts, depending on the position of the bracket. The latter is caused to rotate by the rod (8) which bears on the surface of the cam (9) which is in turn rotated by the knob (10). The whole mechanism is then fitted in a tubular pocket in a water heater enabling the device to be protected from any fouling matter.

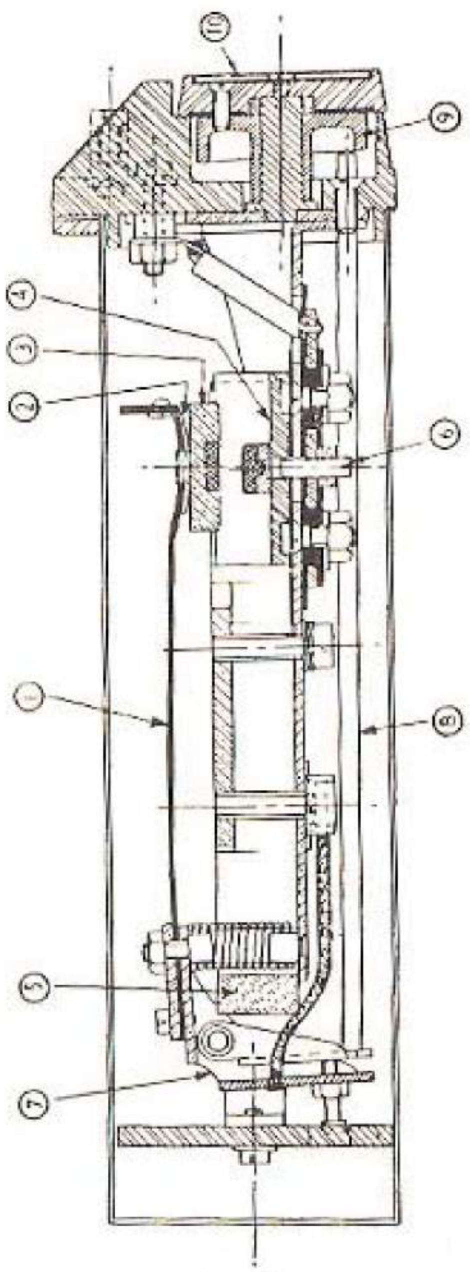

FIG. 26.

The same method is employed by the British Thermostat Co., but, in order to increase the sensitivity of the unit, the bi-metallic strip is increased in length by forming the fixed end into a series of concentric circles as shown in Fig. 27. The operating procedure is as before.

Black[1] has developed the bi-metallic helix type for controlling an air oven. When heated, the helix *D* (Fig. 28), one end of which is fixed, receives a twisting movement which is conveyed to the contact arm by means of a steel spindle

[1] *Jour. Sci. Instr.*, 5, 376. 1928.

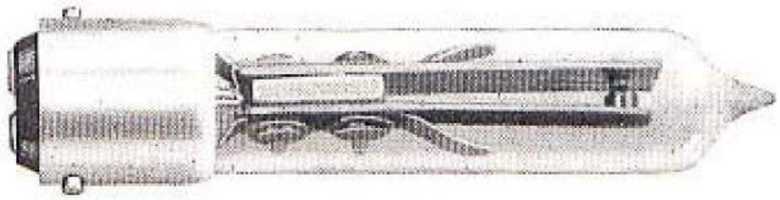

FIG. 25.

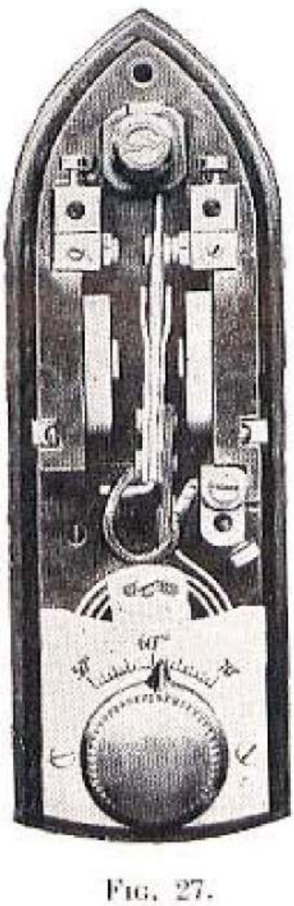

FIG. 27.

[To face page 42.

of $\frac{1}{16}$ inch diameter. On reaching the required temperature, the arm makes contact with the screw *S*, thus closing the relay circuit which cuts off all or part of the heating current.

Rough adjustment for the temperature may be made by clamping the contact arm on the spindle and the final adjustment by means of the contact screw. The main body of the regulator consists of a brass tube, some 8 inches long and 0·5 inch diameter. This is fitted with two similar end pieces *BB*,

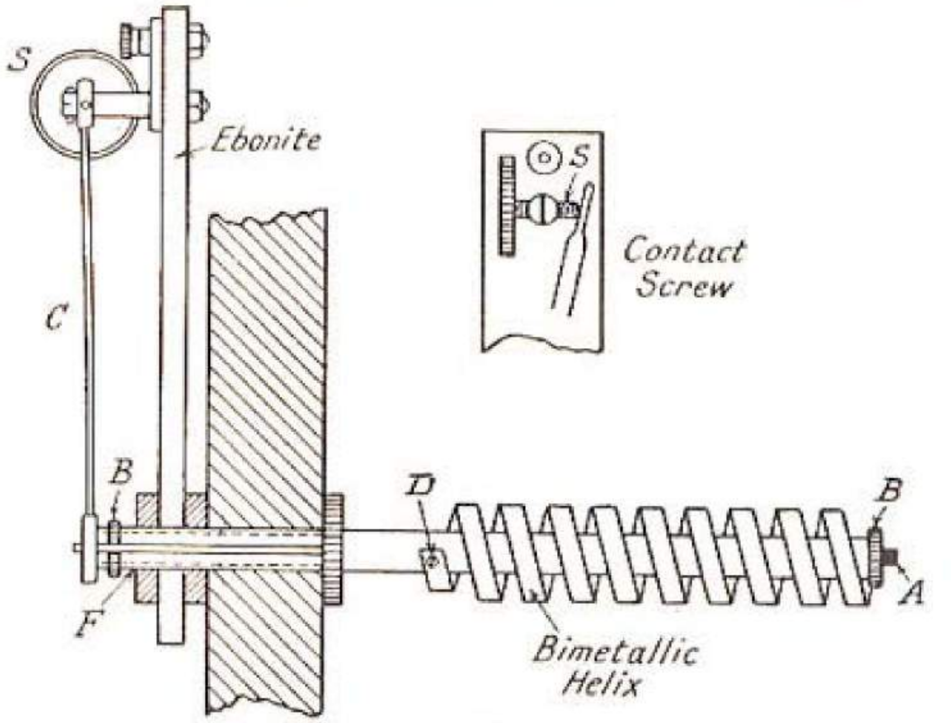

Fig. 28.

which form bearings with the collars *F*, sweated to the steel spindle *A*. The tube should be threaded for a suitable distance so that with the aid of knurled nuts it may be fastened in position. A piece of ebonite 6·75 inch × 1 inch × 0·25 inch thick is fitted to the outer tube and this carries the contact screw and a terminal at its outer end. The helix is constructed from bi-metal strip 30 inches long, 0·25 inch wide and ·02 inch wound into a helix of 1 inch diameter. This material may be obtained from Wilkinson Ltd., or the British Thomson Houston Co., Rugby. For the contact arm to operate in the direction shown, the helix should be wound with the brass surface on the inside, one end of which is fixed to the tube by the screw *D*, and the other attached to the spindle by means of the clamp.

The contact screw should be tipped with tungsten or platinum, and a condenser of value 2μF, with a resistance of 200 ohms in series should be connected across the gap to prevent sparking. The sensitivity of the instrument is such that for a difference in temperature of 1° C. the tip of the contact arm moves through a distance of 1 cm.

A commercial form of air bath made by the Cambridge Instrument Co., also employs bi-metallic control. It consists of four heater coils in series with two high resistance carbon filament lamps giving a green and red light respectively, and

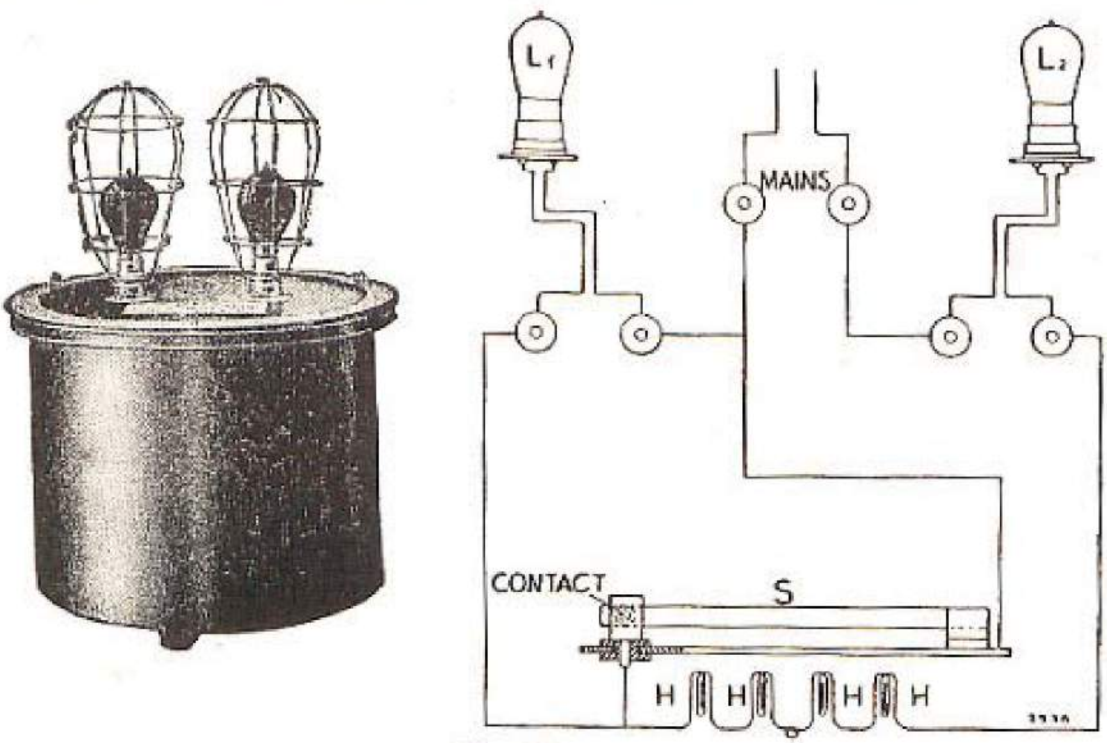

Fig. 29.

situated outside the apparatus (Fig. 29). A bi-metallic strip having an adjustable contact is so arranged that when a definite temperature is reached, the deflection of the beam causes breaking of an electrical circuit, which at the same time brings both lamps in circuit. The resistance of the lamps decreases the number of watts dissipated in the heater coils, and the temperature falls until the strip makes contact and shunts one lamp, thus again increasing the heating effect due to the coils. The control strip, heaters and the cold junction (the thermostat being designed for the control of the latter), are immersed in an air bath, placed in an outer metal tank, the space between the two containers being well lagged to prevent heat loss. This apparatus was developed to maintain the temperature of the "cold" junction of a thermo-electric circuit constant, since the electromotive force developed by a thermo-couple depends on the difference of temperature between the "hot" and "cold" junctions of the system. If the temperature of the cold varies, the readings of the galvanometer will vary, although the hot junction may be at a constant temperature, but with this device the "cold" junction temperature can be controlled to within about $\pm$ 0·5° C.

CHAPTER V

GAS EXPANSION CONTROLS

Although gases have the largest coefficients of expansion of known substances, and there is relatively little difference in the magnitudes of the coefficients for different gases, this phenomena has not found wide application for control purposes. When one of the permanent gases is employed, the range over which it is possible to work is only limited by the porosity and strength of the containing vessel, usually of glass, at high temperatures. Further, the instrument has to be so designed that the effect of changes in barometric pressure on the volume of the gas in the bulb are avoided. From the practical standpoint, however, since this form of control is constructed entirely of glass, its usefulness is rather confined to the laboratory.

In principle, the gas, which is contained in a glass envelope, is utilised to move a mercury column which makes or breaks an electrical contact. This envelope containing the gas, should have as large a surface as possible exposed, and have sufficient volume to reduce to negligible amounts the effects of room temperature variations on the capillary and contact tube volumes.

Bousfield[1] developed a simple form of control as shown in Fig. 30. A bulb *E* is filled with hydrogen and sealed to a barometer which has two bulbs *A* and *H*. The barometer tube contains mercury, the correct quantity for any desired temperature being admitted into the apparatus by means of the tap *C*. Hydrogen may be introduced into the bulb *E* by means of the tap *F*, and, by leaving *C* open, the gas may thoroughly wash out the bulb. For electrical contact purposes, two platinum wires *X* and *Y* are sealed into the apparatus; the former at the point of contact of the gas and mercury surface. The mercury at this junction does not tarnish since no oxidation occurs on sparking. The wires *X*, *Y*, are connected in series with the heating system.

[1] *Trans. Far. Soc.*, 7, 260. 1911.

The mean pressure in the bulb E is so chosen that the mercury in the small bulb A occupies about half the volume of E. By making the gas pressure in the latter equal to mean atmospheric pressure, the length of the vertical tube is about that of an ordinary barometer tube. The lower bulb H supplies sufficient mercury to fill the bulb A, in case of overheating, without allowing the lower level of the mercury to be depressed to the bottom of the tube, for if this occurred gas bubbles would pass over and destroy the vacuum in the upper bulb.

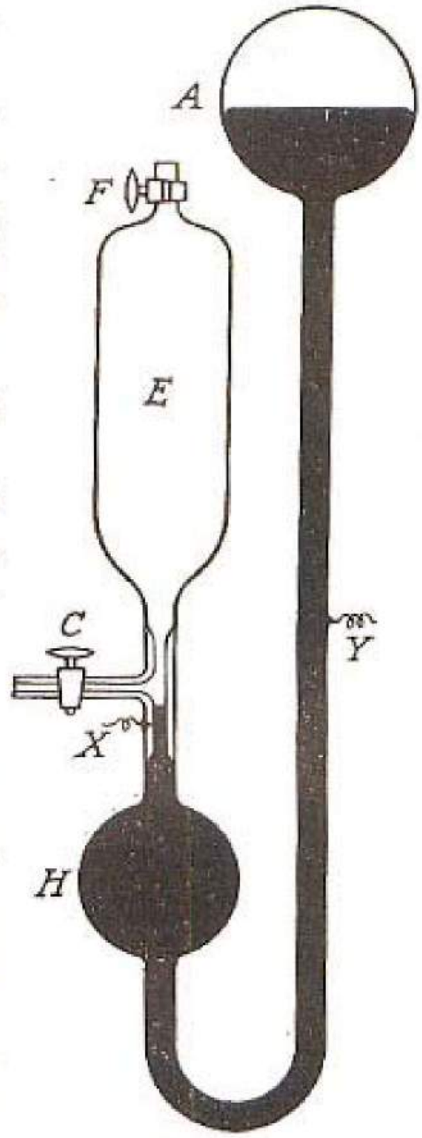

FIG. 30.

Carpenter and Stoodley's[1] design was somewhat different, as in Fig. 31.

It consisted of a U shaped glass tube—containing mercury—the right hand limb A being a capillary tube 1 mm. diameter; the remainder of the apparatus being constructed of 3·5 mm. internal diameter tubing. S is an adjusting screw tipped with iron wire, which also serves as a terminal. Connection is also made by means of platinum wire sealed through the end of the side limb B in the horizontal portion of the U-tube. The left-hand limb is connected by a rubber tube R to the control bulb, immersed in the tank whose temperature it is desired to control, a tap T being provided for the purposes of adjustment. By inclining the limbs of the mercury filled U-tube, a more precise control of the mercury was effected. In order to accomplish this, the apparatus was mounted on a hinged board, the angle of inclination being maintained by a "Shadbolt stay." The completion of the circuit through the mercury-iron contact energises a relay which opens the main heating current until contact is re-established. Scrupulous cleanliness of both mercury and glass is necessary to ensure reliability and sensitivity. In use, the bath desired to be

[1] *Jour. Sci. Instr.*, 5, 100. 1928.

controlled is heated to within 1° C. of the required temperature with the tap T open to the air. Air is then blown through the tube E until the mercury is within ·5 mm. of the contact. The tap is then closed, final adjustment being made with the adjusting screw.

Houghton and Hanson[1] using this principle have developed a form of apparatus for the control of temperatures up to 1,000° C. Their original paper[2] gave details of control up to

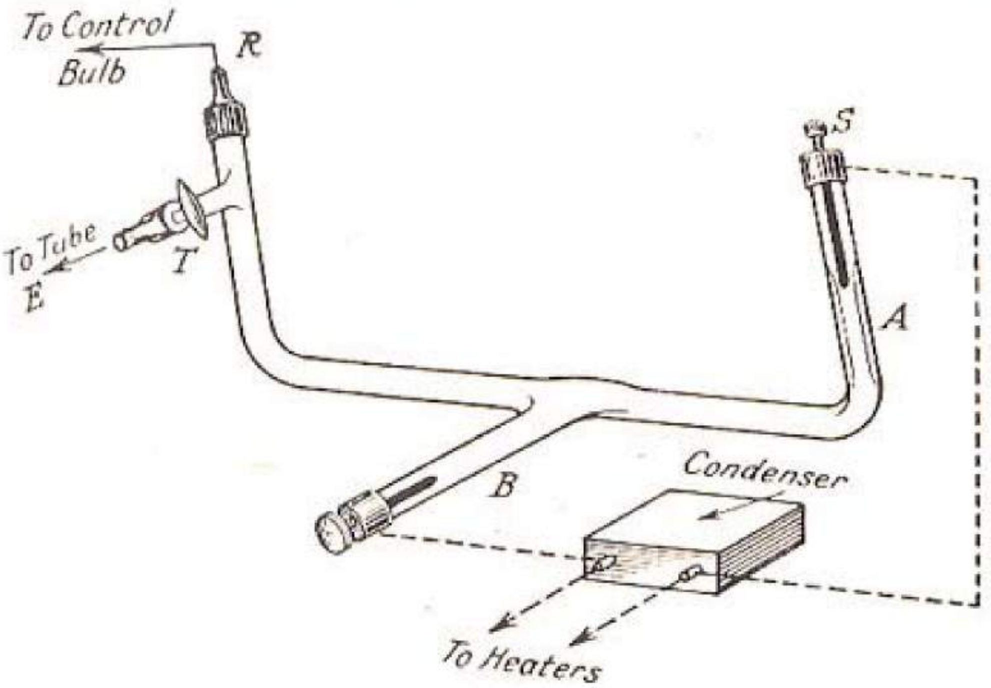

FIG. 31.

500° C., but with further improvements and modifications by these, and other workers, the range has been extended. In principle, the apparatus consists of a double walled vessel, well lagged and wound with nichrome wire. The air space between the two walls is connected through a U-tube containing mercury to another bulb which is maintained at a constant temperature. The former is known as the "hot-bulb" and the latter the "cold-bulb." Changes in the "hot-bulb" temperature cause fluctuations in the mercury in the U-tube, and this movement is used to control the heating of one or more furnaces, by making or breaking the heating current.

The bulb B (Fig. 32), is wound with nichrome wire over two-thirds of its length, and is connected in series with a

[1] *Jour. Sci. Instr.*, 9, 310. 1932.
[2] *Jour. Inst. Metals*, 14, 145.1915. Ibid, 18, 173. 1917.

500 ohm resistance, which, when the mercury makes contact with the upper platinum wire, is shunted by a 45 ohm resistance. A 0·1 μF condenser connected across the contacts reduces sparking. The "cold-bulb" is most conveniently immersed in melting ice in a thermos flask, which maintains its temperature at a constant value.

Houghton Thermostat Refinements.—Grogan[1] devised a method whereby the rate of cooling and heating of this thermostat might be made possible. The arrangement is shown in

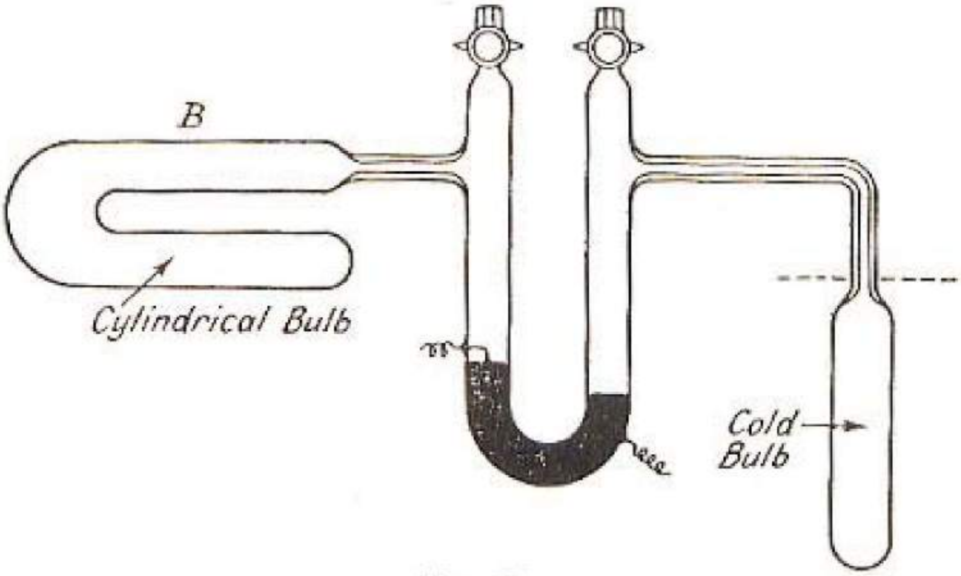

FIG. 32.

Fig. 33, and consists of an electrolytic cell, which by means of a three-way tap is enabled to be connected either to the atmosphere or the thermostatic system. By another three-way tap connected to both arms of the mercury contact U-tube, the cell is made to deliver gas to either bulb. To produce slow cooling the cell is connected to bulb *A* and a suitable current passed through the cell. To produce slow heating the cell is connected to the bulb *B* which is working at constant temperature. The electrolytic gas raises the pressure in *B*, while the pressure in *A* rises equally, the increase in absolute temperature being proportional to the increase in pressure. When slow heating is in progress the thermostat works under constantly increasing pressure.

To avoid leakage it is necessary to restore the pressure to normal occasionally. The heating will then continue as before, but at an increased rate owing to the change in initial absolute temperature.

[1] *Jour. Sci. Instr.*, 5, 217. 1928.

A saturated solution of chromic acid in equal parts of water and sulphuric acid is used ; the maximum value of the current being that which just does not cause liberation of hydrogen at the cathode. In the cell described the limit is 6 milliamperes, which gives a rate of cooling at 600° C. of over 15° C. per hour.

F. Adcock[1] has modified this type of cold bulb eliminating the usual form of U-tube. The tube from the "hot-bulb"

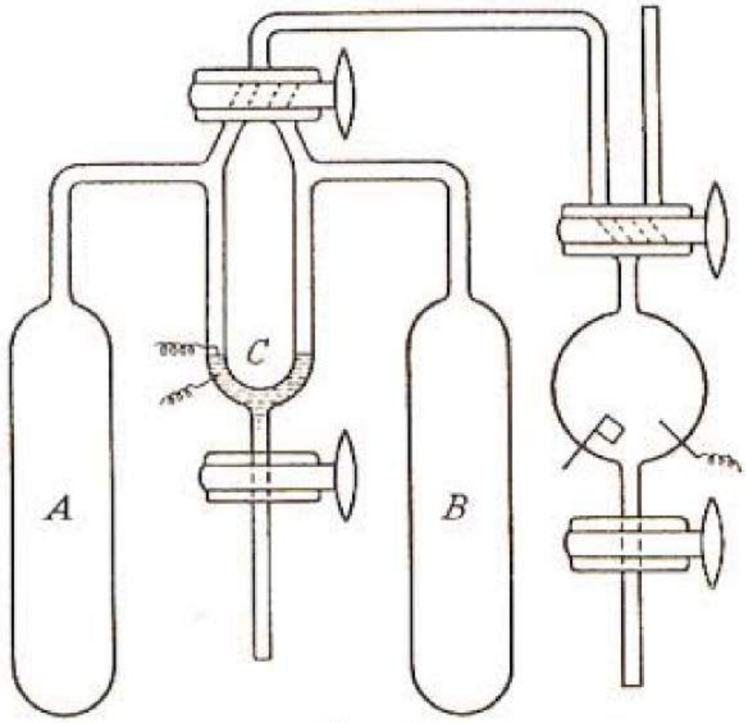

FIG. 33.

is connected to the open limb of a mercury barometer, into which contacts are sealed. By using suitable capacities in the "hot-bulb" and the connecting tube, and the correct volume of mercury below and above the level of the platinum contact, it is possible to eliminate the changes in room temperature. An additional advantage is obtained if the tube joining the "hot-bulb" to the barometer is carried to such a height that on evacuating the whole system the mercury will not reach the top.

It should be noted that considerable errors may be introduced if the thermostat is mounted in such a position that direct sunshine falls on one limb of the U-tube and not on the other. Precautions should therefore be taken to ensure that adequate protection from heat rays are afforded when setting up this equipment.

[1] *Jour. Sci. Instr.*, 2, 273. 1925.

CHAPTER VI

CHANGE OF RESISTANCE WITH TEMPERATURE CONTROL

THE change of resistance with temperature of a material has been utilised for temperature control devices. Salts, oxides, non-metallic and metallic materials have been employed, but more especially the latter. The resistance of metals increases with temperature, while salts, oxides and non-metallic materials have a negative coefficient of resistance, i.e. the resistance usually decreases rapidly as the temperature approaches the melting point. Above the melting point further decrease is slight, while the reverse occurs on cooling. This change is constant over long periods, and, in some cases, near the melting point, salts decrease their resistance from about 1,000 to 5,000 ohms per centimetre cube, down to 1 to 5 ohms per cube when the temperature passes through a range of 10°–15° C. near the melting point of the solid.

Many commercial forms of control have utilised the temperature-coefficient change in specific resistance, by making a coil of special resistance wire the arm of a Wheatstone bridge network. Such an arrangement has the advantage that it is extremely compact, reliable and of low cost. C. W. Siemens[1] was the first to employ the principle in measuring temperatures, using platinum wire, but it was not until the work of Callendar[2] and Griffiths[3] that successful devices were produced for temperature control work. The wire generally employed is nickel, but when the temperatures are in the neighbourhood of 1,000° C. then platinum is much more suitable. The prepared element is exposed to the temperature which it is desired to control, and forms one arm of a Wheatstone network, which is balanced at a temperature corresponding to the zero of the indicating instrument. As the temperature rises, the degree of unbalance of the bridge is indicated by the galvanometer, which can thus be calibrated in degrees of temperature.

[1] *Proc. Roy. Soc.* (A), 19, 443. 1871.
[2] *Phil. Trans.* (A), 178, 161. 1887. *Phil. Mag.* (5), 32, 104. 1887.
[3] *Phil. Trans.* (A), 182. 1891. *Nature*, 53, 39. 1895.

In order to obtain accurate control, an adjustable resistance should be included in the battery circuit, to compensate for variations in battery voltage; this should be adjusted on making observations. To compensate for the temperature of the connecting leads, three leads are employed between the resistance element and bridge as indicated in Fig. 34*a*. A further development of this circuit is shown in Fig. 34*b*, and is known as the cross-coil resistance thermometer. C_1 and C_2 are two identical coils forming the moving system of the galvanometer or indicating instrument, while R_1 is a fixed resistance

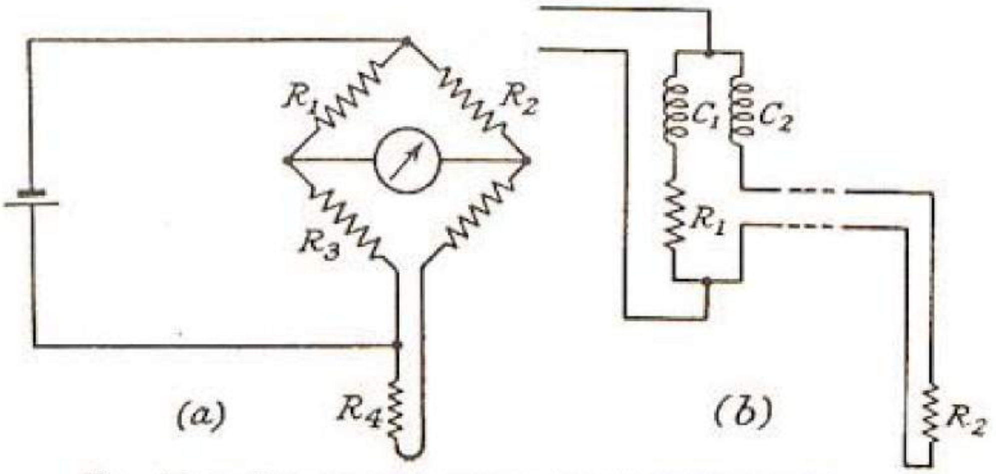

FIG. 34*a*.—Compensating circuit for connecting leads.
FIG. 34*b*.—Basic circuit of cross-coil resistance thermometer.

in series with C_1 and R_2 the sensitive coil element. At a predetermined temperature the resistances R_1 and R_2 are equal, and since the coils C_1 and C_2 are identical, the currents flowing in the two coils are equal. Since the galvanometer coils are wound in opposite directions, so that they tend to cause deflections in opposite directions under these conditions, no deflection will occur. If the resistance of R_2 changes with increase or decrease of temperature, the balance between the two coils will be disturbed and a deflection proportional to temperature change will result.

Some typical forms of commercial resistance thermometers are shown in Fig. 35; for those, however, who are interested in constructional details reference should be made to original papers or articles.[1]

Using the platinum resistance thermometer many methods have been developed to render its control automatic and accurate, a modern development being the use of the thyratron

[1] *Jour. Opt. Soc. Amer.*, 6, 865. 1922. *Jour. Sci. Instr.*, 2, 228. 1924.

or grid controlled valve. The general arrangement of such a scheme is shown in Fig. 36, where it is used with a valve regulator for the control of a very rapid moving current of air, the temperatures ranging from 100° C. to 300° F. The cold air is forced by means of fans through a pipeline, and, from thence, it passes through a specially constructed furnace

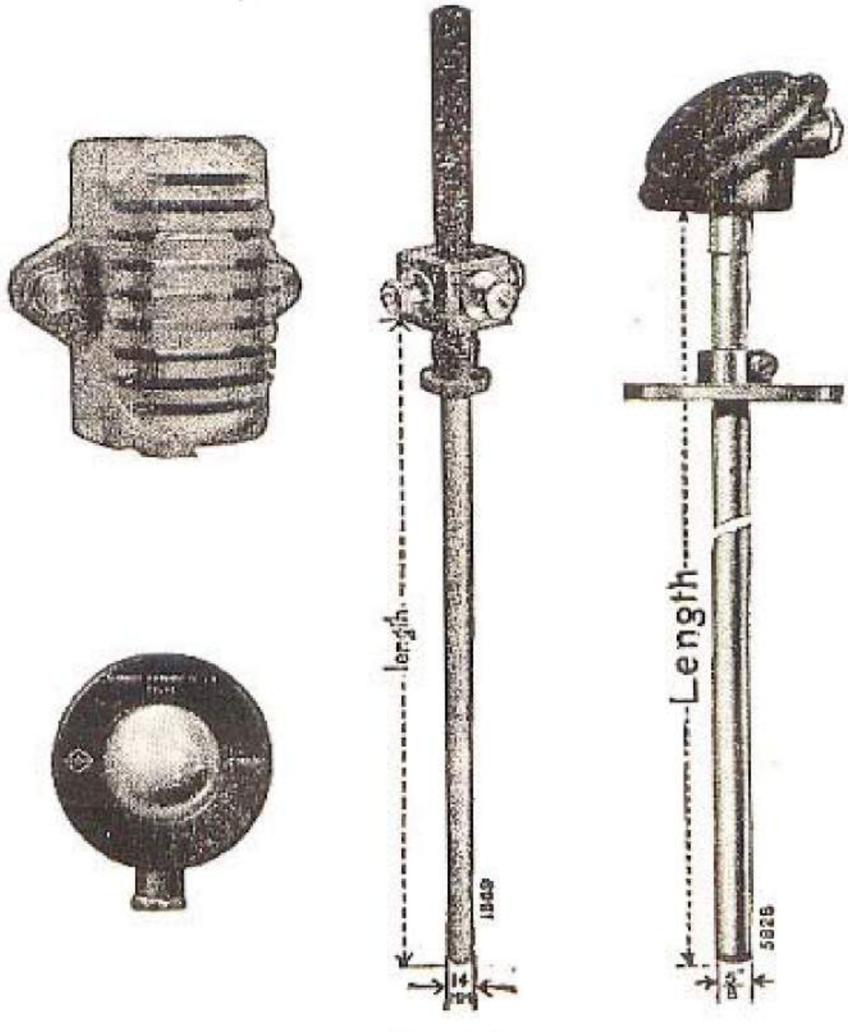

Fig. 35.

containing the windings *H*. After leaving the latter, the heated air comes into immediate contact with a resistance thermometer of minimum heat capacity, connected to a bridge circuit operating thyratrons through an amplifier. The rectifying valves, according to the state of unbalance of the bridge deliver a greater or smaller direct current, which in turn, polarises the chokes in the connection circuit windings. The choke then admits additional currents to the windings according to the state of magnetisation, and the circuit thereby being completed, control of air temperature is carried out.

A similar device has been described by L. Podolsky[1] for control where the possible variations were extremely severe. Control was effected by variations of one of the bridge arms, and with correct temperature, no voltage is present across the bridge. Temperature variations unbalance the bridge, and apply a voltage to the insulating transformer, which is then impressed on the grid of the rectifier valve. An increase in temperature causes the grid bias to increase and thus restrict the flow of current on the half-cycle, when the anode is normally conducting, i.e. the positive half-cycle. A corresponding

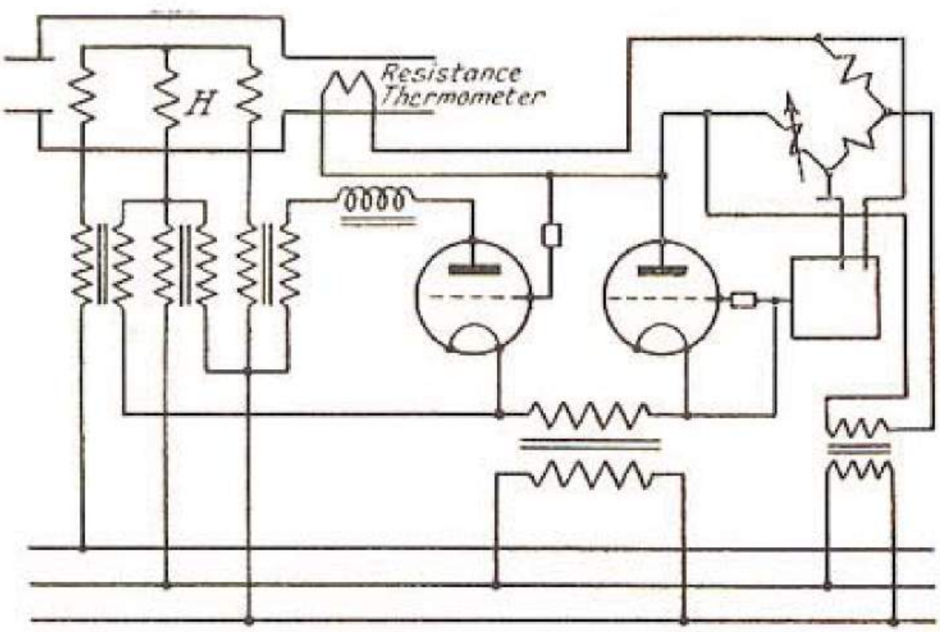

FIG. 36.

decrease permits the tube to conduct, thereby closing the power relay ; this apparatus (Fig. 37), has been used to control the temperature of a furnace at 500° C. to within ±5°.

J. M. Sturtevant[2] has recently described a thyratron controlled resistance thermometer circuit, this being an improvement on the original arrangement of Benedict[3] and Winton.[4] Using a water bath of 160 litres capacity, control to ± ·003° C. was obtained at 29° C. with the arrangement shown in Fig. 38. Alternating voltage of appropriate phase with respect to the supply line was impressed on the bridge ; the output of the latter being made up of one component varying with the balance of the bridge whose phase is the same as that of the impressed voltage, and another component approximately

[1] *Electronics*, 6, 180. 1933.
[2] *Rev. Sci. Instr.*, 9, 276. 1938.
[3] Ibid, 8, 252. 1937.
[4] *Jour. Sci. Instr.*, 6, 214. 1929.

90° out of phase with the impressed voltage. The bridge is transformer coupled to a single stage of audio-amplification, the output of the amplifier being fed into the grid of a power valve. The latter is transformer-coupled to the grid of a mercury vapour filled thyratron, the transformer serving to isolate the thyratron from the rest of the circuit, thus avoiding feed-back. In practice, it is advisable to shield the bridge and the amplifier thoroughly, since the amplification is so high that pick-up voltages may give rise to endless trouble. For the same reason, the transformer T_1 should have long shielded

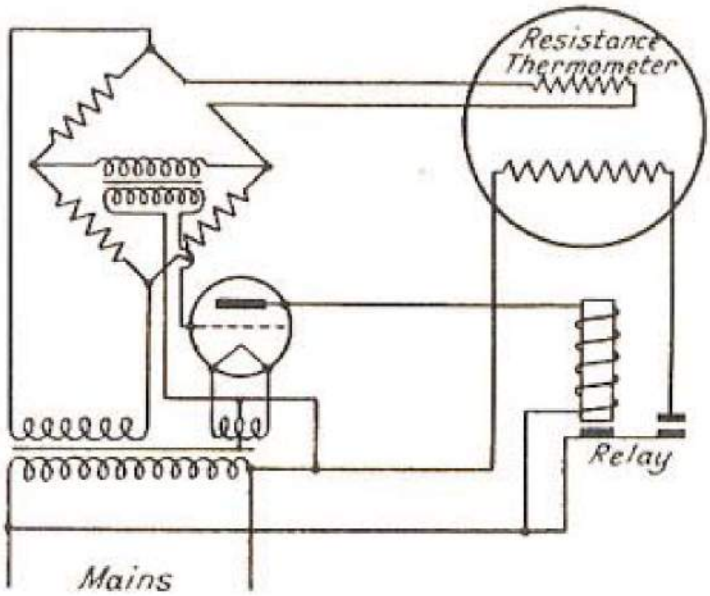

Fig. 37.

leads so that it may be readily placed in such a position that it is not inductively coupled to any other transformer. To realise this position, the primary of the transformer should be shorted and the instrument moved about until no voltage is observed on the grid of the thyratron.

There is a considerable phase shift between the bridge and the rectifier valve due largely to the saturation of the iron in the transformers and the audio re-actor, and this phase shift varies somewhat with the amplitude of the impressed signal. For maximum sensitivity it is necessary that the variable voltage at the grid of the control valve be in phase with the anode voltage of this tube, i.e. the alternating current supply. In practice it is found that with the listed components the phase shift is approximately 90° so that a simple capacitor resistor method of obtaining the proper bridge supply is used.

the voltage drop in the bridge is about 20 volts so that each arm of the bridge has to dissipate 0·5 watts. The value of the resistance R_{12} is adjusted so that the phase of voltages of the order of 15 volts at the grid of the thyratrons is the same as

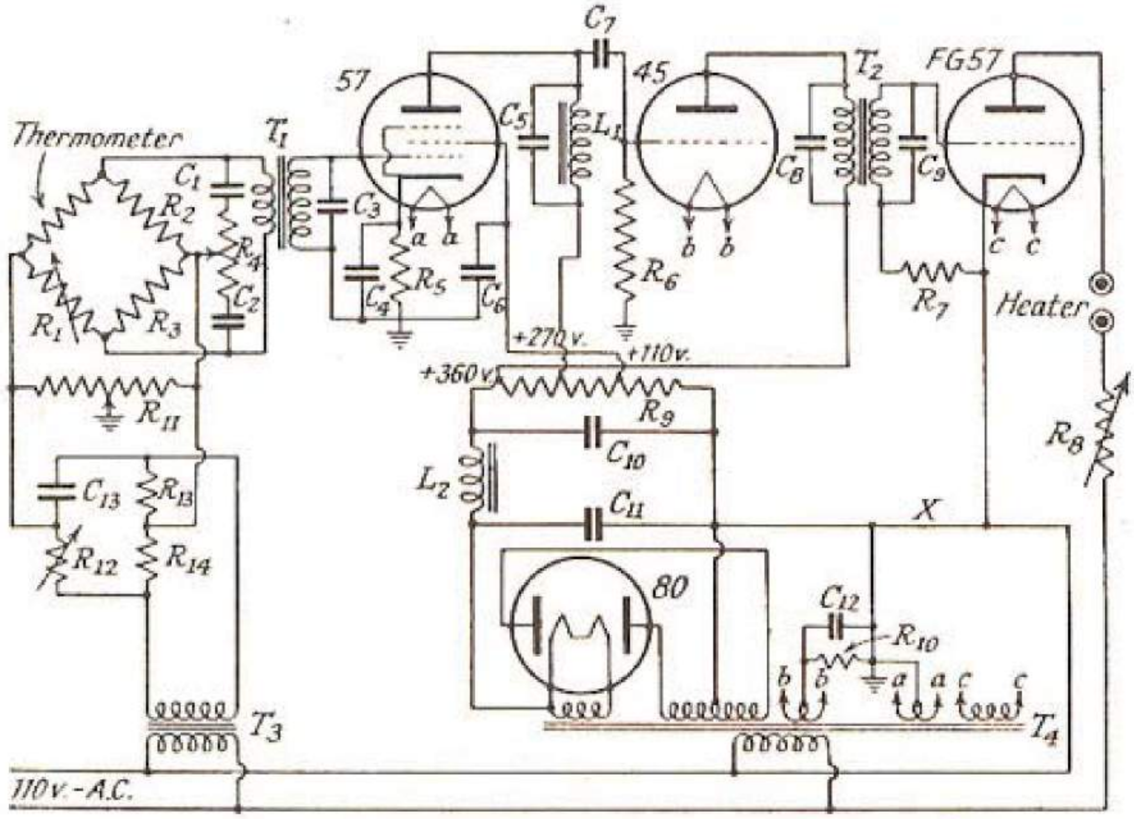

Fig. 38.

R_1=200 ohms, bifilar manganin, variable
R_2, R_3=200 ohms, bifilar manganin
R_4=100,000 ohm potentiometer, 1 watt
R_5=10,000 ohms, 1 watt
R_6=1 megohm, 1 watt
R_7=5,000 ohms, 10 watts
R_9=40,000 ohms, 25 watts
R_{10}=2,000 ohms, 10 watts
R_{11}=5,000 ohm potentiometer, 1 watt
R_{12}=1,000 ohms, 50 watts, variable
R_{13}, R_{14}=75 watt lamps
C_1, C_2=0·25 microfarad
C_3=0·04 microfarad
C_4=8 microfarads, 25 volts, electrolytic
C_6, C_{10}, C_{11}, C_{12}=8 microfarads, 400 volts, electrolytic
C_5=0·01 microfarad, 400 volts
C_7=0·5 microfarad, 400 volts
C_8, C_9=1 microfarad, 400 volts
C_{13}=5 microfarads, 400 volts
T_1=Double-button microphone to grid audio transformer ratio, 22 : 1
T_2=Audio-output transformer, ratio 1 : 1, d.c. resistance 50 ohms, 50 milliamperes
T_3=Isolation transformer, ratio 1 : 1, 100 watts
T_4=Power transformer; secondaries: 700 volts (centre tap), 50 milliamperes; 5 volts, 2 amperes; 2·5 volts (centre tap), 1 ampere; 2·5 volts (centre tap), 1·5 amperes; 5 volts, 4·5 amperes
L_1=Audio reactor, 1,080 henrys at 0·5 milliampere
L_2=Filter choke, 10 henrys at 65 milliamperes

that of the 110 volts supply line. The grid voltages at the thyratron are observed with a cathode ray oscillograph. With the resistance thermometer in the bath, the potentiometers, R_4 and R_{11}, are adjusted so that the bridge can be balanced to give zero voltage at the grid of the thyratron by means of a slide wire inserted in one arm of the bridge. This adjustment serves to neutralise stray electro-motive forces arising from leakage or coupling effects.

The variation with signal amplitude of the phase shift in the amplifier is sufficient so that it is unnecessary to supply more than a very small component of voltage other than that arising from the co-balance of the bridge in order to secure continuous control. This component is obtained by a slight change in setting of the potentiometer R_4, the best setting being that which gives a maximum rate of change with respect to the bridge off balance of the plate current passed by the rectifier. The resistance R_8 is adjusted so that the maximum current that the thyratron will pass is about twice that needed to maintain constant temperature. If the resistance of the thermometer increases beyond the point of bridge balance by more than 0·2% the thyratron abruptly starts to pass maximum current. This results in a complete loss of temperature control so that the temperature of the bath must be within a few tenths of a degree of the desired point before it will be effectively controlled by the thyratron.

J. C. Swallow and E. A. Cooke[1] developed a regulator using a change of resistance with temperature, and which was employed on a 220 volt D.C. supply to control the temperature of an electric furnace to within $\pm$ 0·1° at 600° C. Since, however, it is usual to operate resistance furnaces with an alternating current, a commercial form of such control has been produced by Metro-Vick Ltd. for that type of supply. The apparatus shown in Fig. 39 consists of the usual network, one arm of which is a platinum resistance thermometer of three spiral type. Flexible copper leads are attached to its head in order that it may be conveniently located in any desired position in the furnace. Compensation for resistance variation in these leads is provided by a second pair of leads of the same cable, connected in the opposite arms of the bridge. By means of a variable resistance in the compensating arm of the bridge, control may be effected from 20° to 600° C. Unbalance of the bridge causes the operation of a sensitive relay, and, in order to obviate the tendency of the relay contacts to stick, an auxiliary circuit[2] is arranged which supplies to the relay regulator current impulses sufficient to open the contacts against adhesion. This is arranged by a condenser

[1] *Jour. Sci. Instr.*, 6, 87. 1929. [2] *Proc. Roy. Soc.*, 34, 204. 1922.

which is charged through a resistance and discharges through a neon lamp at 20 seconds interval. Thus each discharge leaves the relay coil perfectly free, so that the contacts may be opened or closed according to the bridge balance. It was found that to avoid any likelihood of sticking, the current must not exceed a few micro-amperes. Accordingly, the relay is arranged so that the closing of its contacts reduced the bias on the grid of the pentode valve, and the resulting increase in

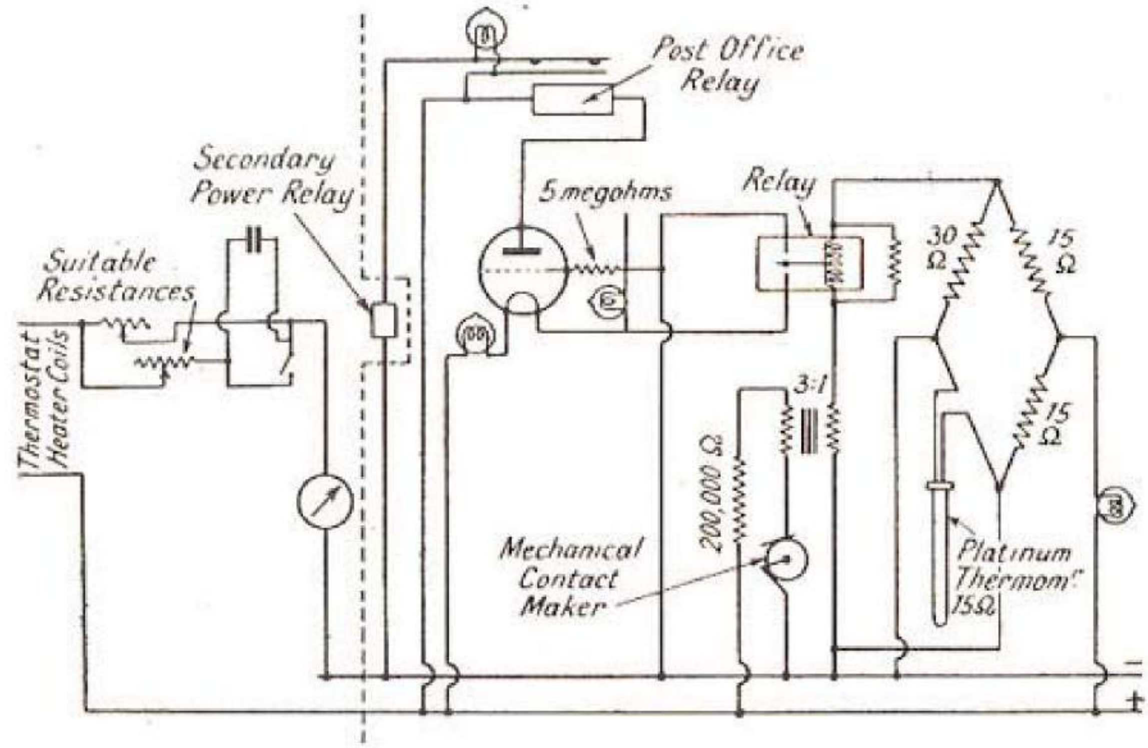

FIG. 39.

anode current operates the power relay; the contacts are now able to carry a maximum current of about 12 mA. In order to minimise variation in the bridge characteristics resulting from ambient temperature variations, Eureka wire is used wherever possible in construction and wiring of this temperature regulator.

Although it has been shown that a separate resistance unit may be employed for control purposes, White and Adams[1] have used the heating coil of the furnace itself as the resistance element, thus forming the basis of the thermometer. Hibben[2] has modified this arrangement. The resistance thermometer was formed by the windings of the furnace R_1 (Fig 40), of resistance approximately 5 ohms, and was one arm of a

[1] *Phys. Rev.*, 14, 44. 1919. [2] *Rev. Sci. Instr.*, 1, 285. 1930.

Wheatstone network. R_2 is an adjustable constantin resistance of 7·5 ohms and of 1 ampere capacity ; R_3, 20 ohms and of 40 amperes capacity and R_4 a similar type resistance carrying the same current at 20 ohms. The bridge was connected across 110 volts D.C. ; the two resistances R_5 and R_7 being inserted for course and final adjustment. Connected across the bridge was also a slide wire in series with a galvanometer. In practice, it is arranged that some mechanical arrangement causes the current regulating switches to move according to

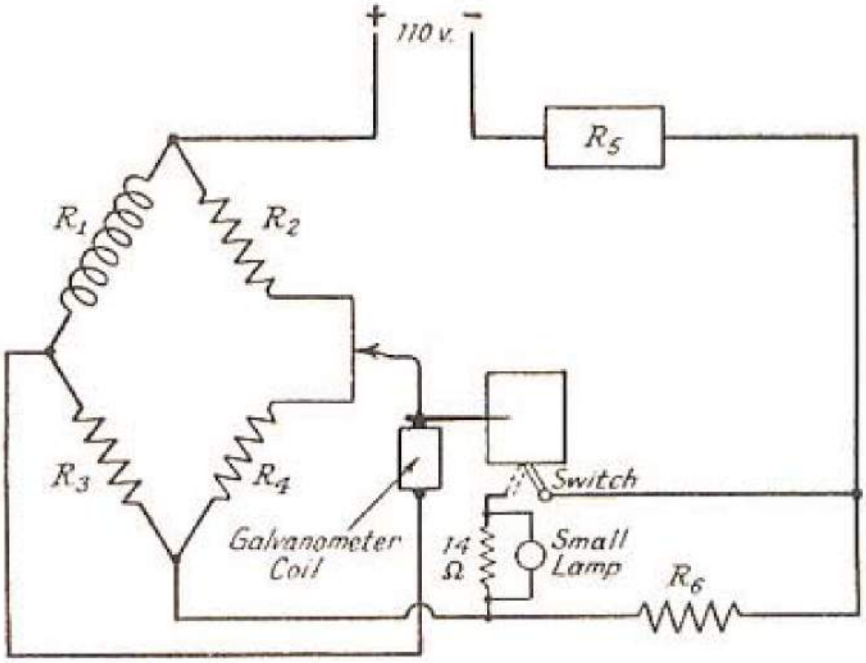

FIG. 40.

the changes in the position of the galvanometer beam, so that it strikes or misses a contact maker which in turn controls a suitable relay.

Barretter Valves.—It it well known that the resistance of iron wire increases rapidly over a limited temperature range. In practice, the wire is enclosed in a glass envelope containing hydrogen, in order to prevent oxidation of the metal. The ends of the wire terminate in the base of the lamp, which hold the necessary contact pieces. The lamp is inserted into the heater circuit, and controls the current passing so that it just glows. Any increase in the applied voltage increases the temperature of the wire, causing an increase in its resistance, thereby decreasing the current through the circuit. A typical characteristic curve is shown in Fig. 41. This device is known as a barretter valve, which operates satisfactorily at a critical current value. Normally, this is a mean current value of 0·3 amperes, and with a variation of between 110–160 volts, the G.E.C. Osram barretter, type 304, will maintain this current value constant over this range. This device is eminently suitable for circuits in which the heating current is not great. In operation, ample circulation should be allowed for this valve, since it becomes extremely hot on circuit. Approximately five minutes should be allowed for the barretter to settle down to its steady current regulation.

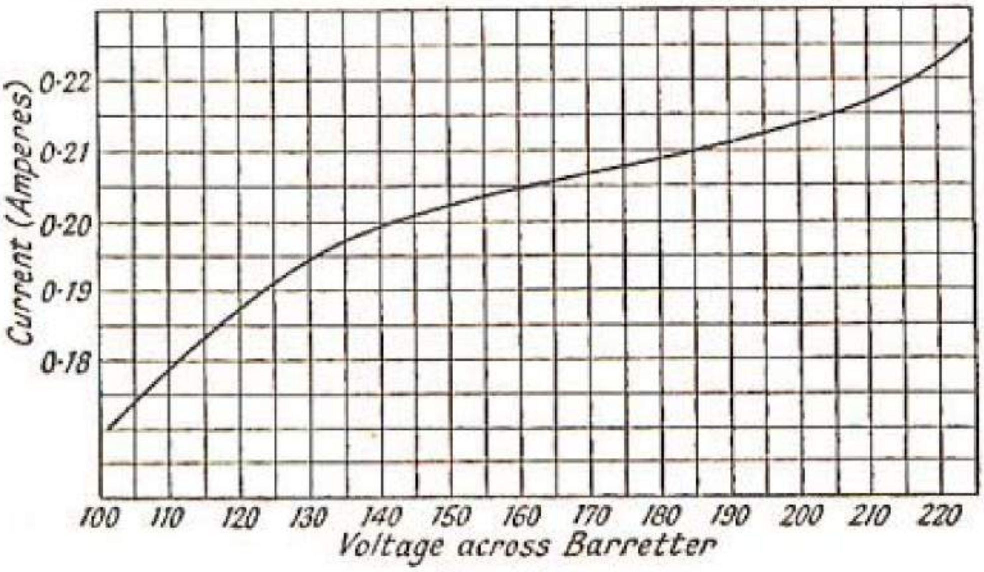

Fig. 41.

Resistance - Current - Voltage Relationship.—Proctor and Douglas[1] using the resistance-current-voltage relationship have devised a simple method for the control of furnace temperatures. It possesses the advantage that there is an absence of temperature lag between the regulator and the heating elements, and it can be used up to the highest working temperature, which is specially useful with molybdenum or tungsten furnaces. The regulator consists of two bulbs *A* and *B* (Fig. 42*a*), filled with air and connected by means of a mercury manometer. Filaments are fitted to each bulb made from 0·4 mm. diameter nichrome wire in coil form, of 14 mm. diameter and 3 mm. pitch; the resistance of each being 10 ohms. The filament in *A* is connected so as to be heated in proportion to the voltage across the furnace, while that in *B* is heated in proportion to that flowing through the furnace. With increase of temperature the resistance will increase with a corresponding decrease between the ratio of the current through the furnace

[1] *Jour. Sci. Instr.*, 9, 192. 1932.

and the applied voltage. Consequently, the current through *A* will increase relatively to that through *B*, and thus cause the air pressure of *A* to increase compared with that in *B*. The mercury level in the left limb of the control apparatus will fall, and on breaking the relay current, power to the furnace will be reduced by the insertion of a series resistance.

For satisfactory operation the air pressures in the two bulbs should be approximately equal at the instant of breaking or

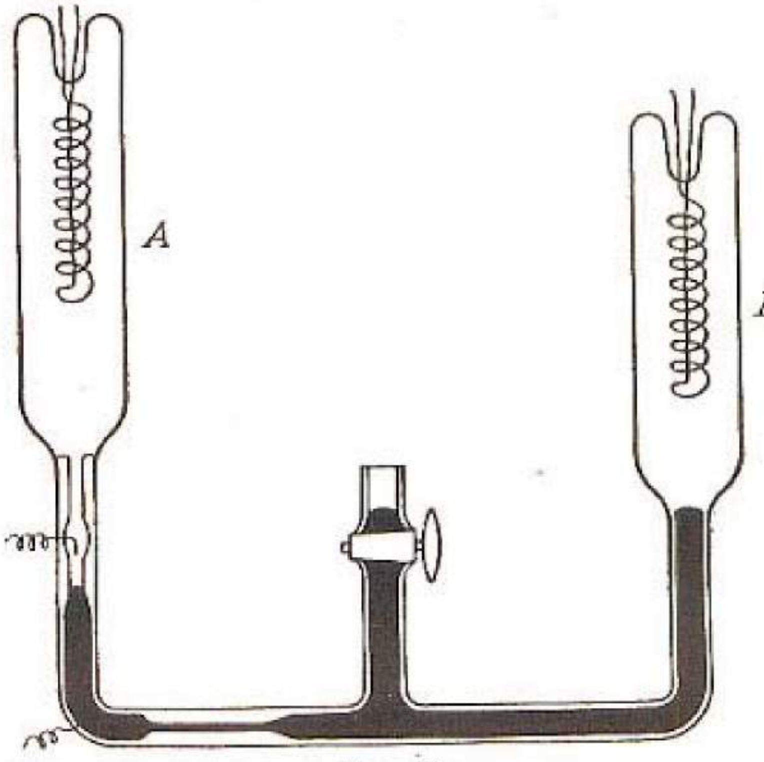

FIG. 42*a*.

making contact. It will be found that if the air pressure in one bulb is considerably in excess of the other, the regulator is affected by changes in voltage across the furnace caused by the operation of the relay. If we assume that that pressure in *B* is greater than in *A*, prior to making contact, and that the circuit is so arranged that the voltage across the furnace also rises—the furnace having a large heat capacity—immediately contact is made heat supplied to the two bulbs will increase in the same ratio, with a corresponding proportional increase in bulb pressure. Thus the difference in pressure between the two bulbs will increase and the mercury level in the large bulb will fall, thereby reducing the furnace voltage. This will cause the gas in the bulbs to cool, the mercury will rise, make contact and then the cycle will be repeated and the relay will chatter continuously. Alternately if the pressure