THERMOSTATS

AND TEMPERATURE-REGULATING INSTRUMENTS

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BY

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PRINCIPAL C. A. EDWARDS, D.Sc., F.R.S.

As a token of admiration and gratitude.

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PREFACE TO SECOND EDITION

THE application of automatic temperature-controllers for laboratory and industrial purposes has increased tremendously during the past few years, and is likely to continue to do so. Design has correspondingly improved.

Greater attention has been devoted also to determining the basic principles of temperature-control. In view of the increasing complexity of the subject, the main objectives towards which efforts are being directed at present are :—

(*a*) To establish a nomenclature which will be generally acceptable ;

(*b*) To classify the processes to be controlled and the methods of control ;

(*c*) To develop a theory of temperature-control in terms of time-constants which will yield solutions to practical problems, and which will define a " figure of merit " to describe the effectiveness of a given method of control in a given process.

A number of contributions to the subject have been made. As, however, these theories are not as yet sufficiently comprehensive, a final discussion of the subject is not possible. Some of the more important views put forward have been included in the Appendix ; and the reader who wishes to pursue the subject further is recommended to consult the original papers, which are listed at the end of the Appendix.

It is hoped that this new edition will give the reader some indication of the progress that has been made in recent years in various aspects of the subject. It may be emphasized here that an instrument cannot of itself be expected to provide the solution to a problem of temperature-control, but is merely a scientific tool employed to help solve the problem.

References to the literature of the various types of regulators are given at the end of the respective Chapters.

R. G.

SWANSEA,
December, 1942.

CONTENTS

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INTRODUCTION

THE maintenance of a constant temperature-value is a necessity in many technical processes and laboratory experiments. The temperature to be controlled and the closeness of control will vary widely in different circumstances; in all cases, however, the basis of control is the same. Random disturbances affect the temperature, and it is necessary to employ some form of thermostat if the temperature is to be maintained at a constant value. Three main components have to be considered in connection with the thermostat.

It is necessary, in the first place, to measure or ascertain the value of the temperature by means of a pyrometer or temperature-sensitive element; very frequently too much is expected of the pyrometer. It must not be forgotten that "contact" pyrometers measure the temperature in the immediate vicinity of their hot tip or bulb, and not the general temperature of the oven or furnace, although they are sometimes affected by their surroundings as a result of radiation. In a well-insulated space, such as can be arranged under laboratory conditions, this variation of temperature should of course be extremely small, or negligible, but in industrial furnaces there may sometimes be large temperature-gradients. It is essential, therefore, that the pyrometer or *sensitive element* be placed in the correct position, so that the temperature measured is the true one, or at least bears a constant, known relation to the true value. Various forms of sensitive element are used for automatic temperature regulation, and these are dealt with in the text.

The second component that has to be considered is what may be termed the *control gear*. This component reacts to the changes taking place in the sensitive element and alters the amount of heat liberated by the third component, situated in or around the controlled space; this last component may be termed the *heating element*.

The correct relationship between these three components is the basis of successful temperature-control.

When there is a change of temperature in the controlled space, a certain time must elapse before the sensitive element, which records this change, acquires the new temperature. When this occurs, the control gear is set in operation to regulate the amount of heat liberated by the third component. The regulator is not able to stop this operation as soon as enough adjustment has been made, because of the time-lag. The shorter the time required for the space to return to the normal value compared with the time-lag, the further will the temperature overshoot before the regulator responds to the condition when the space has reached the normal temperature-value. There is a danger of setting up an oscillation of increasing amplitude if the rate of return to normal value is too rapid. Complete elimination of fluctuations of temperature would, of course, dispense with the need for the appropriate controlling actions.

Three factors influence the rate at which the regulator changes temperature: (*a*) the temperature of its surroundings, (*b*) its own temperature, and (*c*) the "setting" of the control mechanism.

The operation of the control mechanism might be arranged to depend either on the amount by which the temperature departs from the controlled value, or on the rate of change of temperature. Possibly the second differential of the temperature with respect to time might be used, or an integral, or some function of these. Again, these latter might be used to decide the setting of the control mechanism or the rate of change of setting, etc. There are many complex possibilities.

Let us now assume a simple case where the thermostat operates, as explained in Chapter II, by the movement of a column of mercury as the result of temperature-changes. The make-and-break of the circuit occurs between the mercury and a wire placed near its surface. Make and break seldom occur at the same level, due to various causes such as contamination of the mercury surface, surface tension, and other effects. There is a "backlash"; and "hunting" of the temperature over the range of the backlash is unavoidable. An alternative method of control is to make the action continuous by arranging for the resistance to change continuously with the level of mercury instead of from infinity to zero, as in the make-and-break system. A similar continuous action takes place in a form of thermostat frequently used for controlling gas-supply (p. 15).

Considering next the heating element in relation to the other components: as the heating element has a certain heat-capacity, it will require time to cool down or heat up from a particular temperature. In the meantime (as we have seen) the temperature of the space will have continued to rise or fall, and with it the temperature of the sensitive element.

The resultant effect of all these actions is a swing from side to side of the required controlled temperature. Time-lags of several minutes may occur, particularly under industrial conditions. This "hunting" or periodic fluctuation of the temperature due to the heater, etc. may be minimized by improving the thermal contact between the heater and the sensitive element. In practice this is usually done (when the construction allows) by vigorous circulation or agitation of the medium in which the two components are placed. A further step has been taken in one type of thermostat (p. 44) by placing a part of the sensitive element very close to the heater, and in a direct stream of air from it. The tendency in this design is to control the mean temperature of the heater. The final step is to identify the heating and sensitive elements by using the one for both purposes. As will be shown later in the discussion on the theoretical aspects of temperature-control, this method in certain circumstances is not always advantageous.

CHAPTER I

THERMOSTATS BASED ON THE EXPANSION OF GASES WITH TEMPERATURE.

GASES have the largest coefficient of expansion of known substances, and there is relatively little difference in the magnitude of the coefficient for different gases.

When one of the permanent gases is used as the expanding medium in a thermostat, the temperature-range over which the instrument is applicable is limited only by the strength and porosity of the envelope at high temperatures. The number of forms of thermostats of this class is comparatively small, partly because high sensitivity can be obtained only with difficulty, and partly because the instrument has to be of the "sealed-in" type to avoid the effect of changes of barometric pressure on the volume of the gas in the thermostat bulb.

The simplest form of this type of thermostat consists of a vessel containing the expansible gas, which is inserted into the space to be controlled. The change of volume of the gas with change of temperature causes movement in a column of mercury, thus making or breaking —either directly or through the medium of relays—an electric circuit controlling the heating of the space. The vessel which contains the gas should have as large a surface area as possible, and have sufficient volume to reduce to negligible amounts the effect of room temperature-variations on the capillary and contact-tube volumes. The range of temperature-values which can be controlled with this type of instrument is great, but the sensitiveness is not high nor easily increased. Fig. 1 shows diagrammatically a form of regulator of this type.[1] A bulb *E* is filled with hydrogen and communicates with a mercury column contained in a barometer tube. The bulb is usually placed in the heated space, and the barometer tube outside. Into the walls of the tube are sealed two platinum wires *A* and *B*, serving to lead the current into and out of the mercury respectively; the mercury is in series with the electrical heating circuit. The circuit breaks at the junction of hydrogen and mercury at *A*. The mercury does not tarnish, since no compound of hydrogen and mercury forms on sparking. A point of advantage with this form of thermostat is that regulation of temperature is independent of variations of atmospheric pressure, because the gas is completely enclosed. The regulator is not free, however, from errors due to variations in room temperature unless precautions are taken to select suitable capacities for the bulb and connecting-tube, and to ensure the correct volume of mercury below and above the level of the platinum contact. Nevertheless these errors are not large.

The height of the mercury in the contact tube at *A*, and consequently the temperature at which make and break occur, are regulated by means of the lower stopcock. The tube is furnished with two small bulbs *C* and *D*. The mean pressure in the large bulb *E* is so chosen that the mercury in the top bulb *D* occupies about half the volume

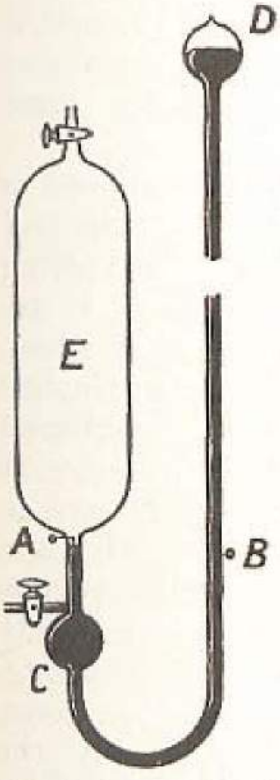

FIG. 1.—Gas-expansion thermostat.

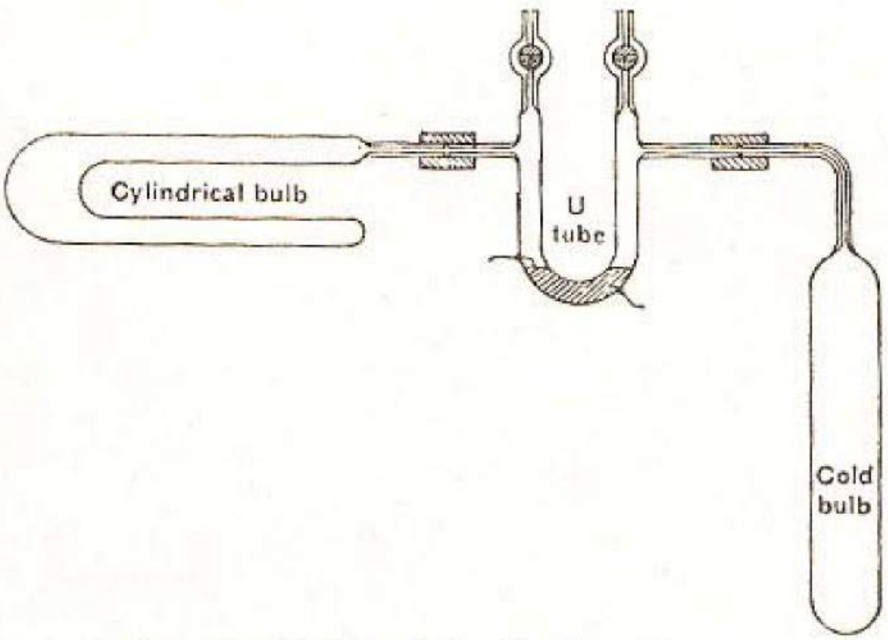

FIG. 2.—Principle of the Haughton-Hanson thermostat (original design).

of this bulb. It is convenient to make the pressure of the gas in *E* about equal to mean atmospheric pressure ; the length of the vertical tube is then that of an ordinary barometer tube, so that possible leakage of hydrogen through defective taps is minimized. The lower small bulb *C* would supply sufficient mercury to fill the upper small bulb *D* in the event of overheating, without allowing the lower level of the mercury to be depressed to the bottom of the tube ; if this happened, bubbles of gas from *E* would pass over and destroy the vacuum on the upper bulb *D*.

Haughton-Hanson Thermostat.—An instrument of this class which is fairly extensively used in laboratory work is the Haughton-Hanson [2] type of thermostat (Fig. 2). In principle this thermostat consists of a double-walled silica vessel (known as the " hot " bulb), which is well lagged thermally and wound on the outside with resistance wire for heating purposes. The air space between the two walls is connected by capillary tubing to a U-tube containing mercury in which suitable electrical contacts are sealed. The other side of the U-tube is connected to another bulb, referred to as the "cold" bulb. This latter bulb is kept at a constant temperature, and serves to eliminate the effect of variations of atmospheric pressure on the system, since it makes the system totally enclosed. Fluctuations of temperature in the "hot" bulb cause changes in the air pressure in it, resulting in displacement of the mercury in the U-tube. An electrical circuit is completed or broken, which has in it a relay controlling the current flowing in the furnace winding. Since this thermostat was introduced, details of the apparatus have been modified and alternative designs suggested for some of the parts. The more important of these will now be considered.

Modified U-tube.—The form of control tube at present used is shown in Fig. 3. The tube *A* is connected to the "hot" bulb and *B* to the "cold" bulb. *C* is connected to a slow-heating and cooling device to be described later. The ends of the tubes *D* and *F* are connected by rubber tubes to thistle funnels, with the aid of which mercury can be let into the U-tube and into *D*. The latter adjustment [3] enables the controlled temperature of the thermostat to be altered to a small extent by means of small changes in the air pressure in the "hot" bulb. Admitting mercury into *D* raises the pressure in the bulb and causes the temperature to fall slightly. Removing the mercury has the reverse effect. It is advisable to give the furnace some time, preferably about 24 hours if heated from the cold, to allow steady conditions to be attained before making final temperature adjustments.

On cooling the thermostat from high temperatures to, say, room temperature, mercury in the U-tube tends to be sucked back into the "hot" bulb unless precautions are taken. It is obvious, of course, that in heating to and cooling from the control temperature, the bulb should be put into communication with the atmosphere by suitable manipulation of the taps, but in the event of inadvertent wide fluctuations of temperature of this order, sucking-back is liable to occur. If the limb of the U-tube is more than large enough to take the whole volume of mercury, then the air can find its way past the mercury column; this, however, is not a complete safeguard against sucking-back, and it is advisable to provide a trap, which may take the form of a porous diaphragm interposed in the tube, or a means of obtaining a complete change in direction of the air-stream, as illustrated at *E* in Fig. 3. These traps are not, however, completely satisfactory, and the safest procedure is to remove the mercury from the U-tube (by opening the tap at *F* after lowering the thistle funnel connected to it) before opening any part of the apparatus to the atmosphere.

A further point to be guarded against is that the U-tube should not be subjected to possible heating by direct sunlight, for this may heat one limb first and then the other during movement of the sun.

Contamination of the mercury due to sparking at the contact surface can be a troublesome feature, causing erratic working of the thermostat. The sparking can be minimized by introducing a condenser in parallel with the contacts, or better still a Westinghouse rectifier across them; but the effective remedy is to decrease the current that has to be broken at the contacts by the use of a thermionic valve or similar relay, as described later (see p. 24).

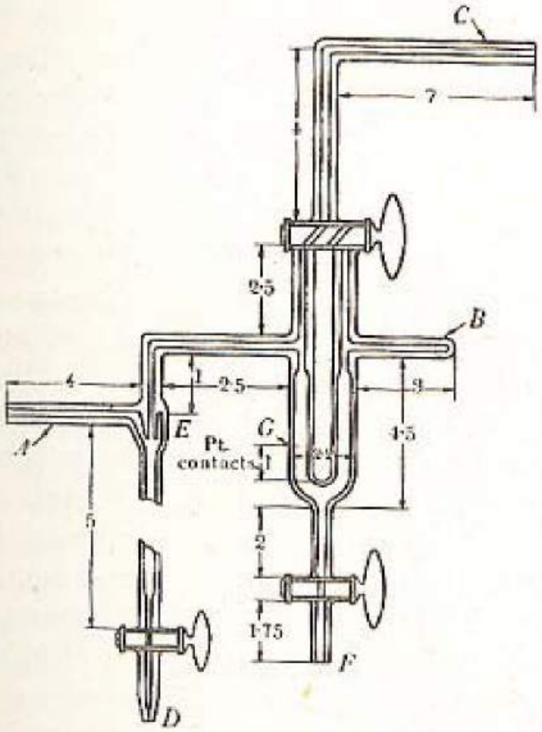

Fig. 3.—Control tube for modified Haughton-Hanson thermostat. (All dimensions in centimetres.)

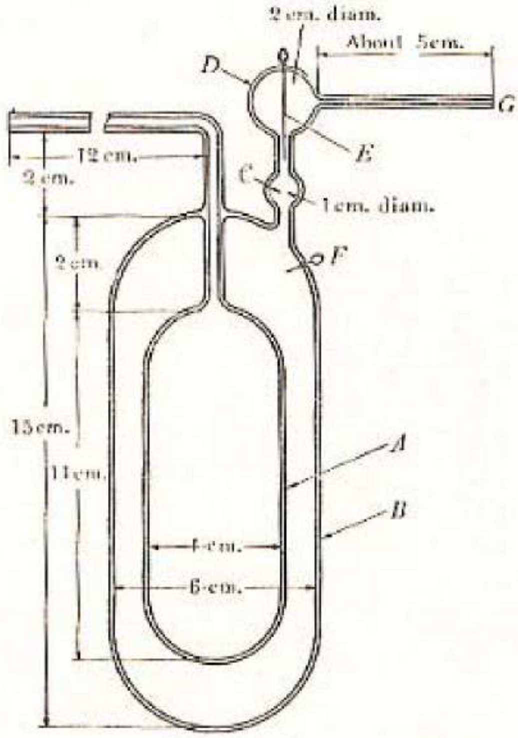

Fig. 4.—"Cold" bulb in modified Haughton-Hanson thermostat.

Re-designed Forms of "Cold" Bulb.—As previously stated, the temperature of the "cold" bulb should be kept at a constant value. For short periods of time, this can be done most effectively and efficiently by immersing the bulb in melting ice contained in a thermos flask. When, however, the furnace is to be used for longer periods than that during which the ice will remain unmelted in the flask, it is necessary to use other methods. One of these methods is to enclose the bulb in a liquid the temperature of which is controlled. In one form the inner glass bulb *A* (Fig. 4) is connected to the U-tube, and the annular space between it and the outer bulb *B* is filled with mercury. The mercury just rises into the small bulb *C* when the apparatus is at the lowest temperature it is likely to reach when not in use. The space above this is filled with hydrogen. The bulb *D* enables the mercury to rise in the tube connecting C and D, without an excessive accompanying rise in pressure in the hydrogen atmosphere. A platinum wire E reaches into the tube joining C and D and makes contact with the mercury. A second platinum wire F makes contact with the mercury in the bulb. The tube G is used for filling the apparatus and is then drawn off so as to leave it about 2 cm. long.

The outer bulb B carries a heating winding over the lower two-thirds of its length, the resistance of the winding being about 50 ohms for 110-volt supply. This is in series with a 500-ohm resistance. When the mercury makes contact with the upper platinum wire, the heating coil is shunted by a 45-ohm resistance and the current of the heating coil decreased. A condenser of about 0·1 μF capacity across the contacts helps to reduce sparking. There is a small fluctuation of the order of 0·1° C. in the temperature of the bulb. For the highest accuracy it is advisable [4] to lag the tube connecting the bulb with the platinum contact.

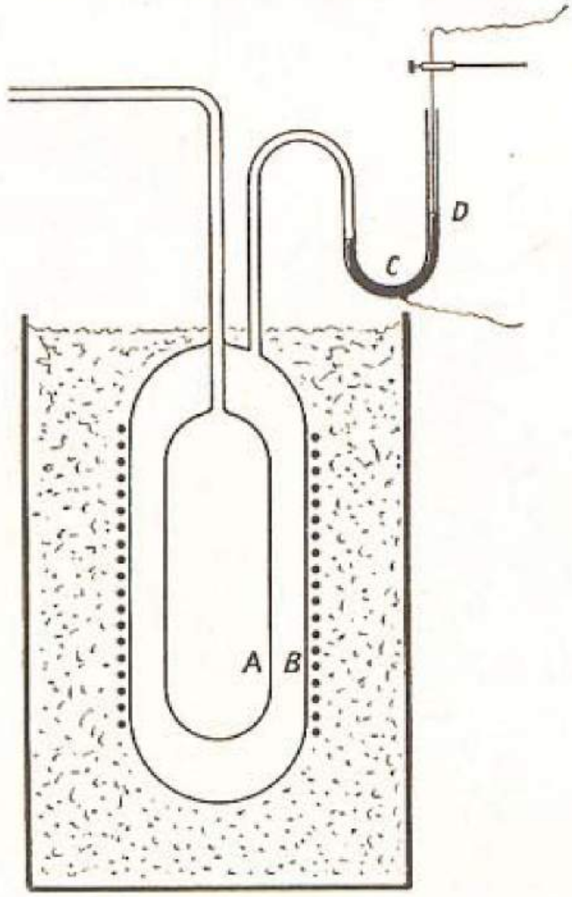

FIG. 5.—Device for maintaining temperature of "cold" bulb constant and fine adjustment of temperature-setting.

A similar device for "cold" bulb temperature-control has been suggested [5] in which the mercury is replaced by toluene. (Both liquids have their advantages, *e.g.* mercury has the greater thermal conductivity, while toluene has the higher coefficient of expansion.) In this device (Fig. 5) a U-tube C containing mercury communicates with the bulb B. Expansion and contraction of the toluene with change of temperature makes and breaks the circuit at the contact D, which controls the heating current passing through the coil surrounding the outer vessel B. When contact is made, the heating current is decreased, due to a part of the heater winding being shorted.

Accurate setting of the temperature to be regulated can be made by adjusting the position of the contact D. This device can be used to alter rapidly and accurately the temperature of regulation of the thermostat furnace from one setting to another. The effect on the temperature of the furnace of known movements of the contact can be determined experimentally at various temperatures, and the values obtained used for adjustment purposes. Rapid changes to lower temperatures can then be made by allowing the furnace to cool down, with both taps on the main control U-tube open, until the temperature falls to within a few degrees of the required figure; allowing the furnace to settle down; and then adjusting the contact by the required amount.

In one particular apparatus a movement of 1 cm. of the platinum contact altered the temperature of the thermostat approximately 1° C., and with this arrangement it was possible to adjust the temperature over a range of 50° C. with an accuracy of 0·1° C.

When the thermostat is allowed to cool down to room temperature after use, it is necessary to prevent air sucking back into the bulb *B*. This is done by allowing the furnace to warm up until nearly all the mercury is in the open limb of the U-tube. The greater part of the mercury is then removed by means of a dropping-tube. Toluene is added until the open limb is almost full. The tube of a siphon connected to a reservoir of toluene is then inserted into the limb of the U-tube and the toluene allowed to be sucked over.

This is a somewhat troublesome operation, and a further slight drawback in the use of this particular cold-bulb device is that it requires a supplementary source of current at low voltage and a relay to operate it.

Yet another form [6] of "cold" bulb is that in which the device acts not merely in this capacity but also replaces the U-tube, and safeguards the apparatus against sucking-back of the mercury in case the furnace is accidentally cut off. The capillary tube from the "hot" bulb is connected to the open limb of a mercury barometer, into which the contacts are sealed. As mentioned in connection with the simple form of gas-expansion thermostat, 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 cause the errors due to changes in room temperature to cancel each other. To avoid mercury being sucked back from the barometer tube into the "hot" bulb when the furnace is allowed to cool, the tubing joining the "hot" bulb to the barometer is carried to such a height that if the whole system were evacuated the mercury would not reach to the top of the tube.

This form of "cold" bulb is very accurate, but it suffers from the disadvantages of having a long, fragile barometer tube, and the necessity of knowing the coefficient of expansion of the glass and also the volumes of the tubes, etc. The data need, however, only be known to within a few per cent.

Auxiliary Furnace.—The Haughton-Hanson type thermostat functions by keeping the mean voltage at a definite value, which is such that the heat input due to the current produced in the furnace by that voltage is just sufficient to compensate for radiation and other heat losses. If we have a second main furnace which will be affected by changes in room temperature to the same extent as the thermostat furnace, and connect it in parallel with the terminals of the thermostat furnace but in series with the relay, resistances, etc. the temperature of the second furnace will be regulated at the same time as that of the first. Theoretically, there is no limit to the number of furnaces which can be run in this way. The mean temperature of the main large furnace over very long periods of time is independent of variations of room temperature. Over short periods, however, some variation of temperature may occur. If, for instance, the temperature of the room should rise, the equilibrium of the subsidiary small thermostat furnace would be affected in a comparatively short time, during which the temperature of the main furnace would be sensibly unaltered, owing to its greater size. As a result, however, the power input in both furnaces would be reduced by the action of the thermostat, and the temperature of the large furnace would drop in a short time, until the power was applied to the inner portion of the furnace close to the point at which the temperature was measured. Much later, of course, the large furnace would tend to regain the original temperature.

Where the highest possible accuracy is desired, the thermostat furnace itself should be used, but the second furnace can be used where a variation of 2° C. is unimportant. An advantage of using a second furnace is that the tube of such a furnace is cheaper and easier to replace than the special silica bulb of the thermostat furnace.

Slow-Cooling and Heating.—In conjunction with the Haughton-Hanson thermostat, slow-cooling or heating devices can be used to regulate the rate of cooling or heating of the thermostat furnace. It may be stated at the outset that these devices cannot be used with the barometer-tube type of "cold" bulb.

In the original design, a bulb is connected to the U-tube by capillary tubing so that either limb of the U-tube may, by turning the two-way tap on that tube, be put into communication with the bulb. When it is desired to cool the furnace slowly, the whole bulb is immersed in hot water or oil contained in a vacuum flask. As the temperature of the air in the slow-cooling bulb falls, air is extracted from the limb of the U-tube away from the furnace. This reduces the pressure on the gas in the hot furnace bulb, and the expansion which otherwise would take place is, owing to the breaking of the circuit, automatically balanced by a fall in temperature of the furnace. For slow-heating the bulb is connected to the other limb of the U-tube.

This method of slow-cooling or heating is suitable for rates of change of temperature greater than 20° C. per hour over a comparatively short time, the rate of cooling being controlled by the size of the bulb, the temperature of the liquid, or the lagging of the vessel.

Another ingenious method of slow-cooling consists in connecting the two sides of the U-tube together by means of a very slow leak. The amount of mercury is adjusted so that when the platinum contact-point at *G* (Fig. 3) is just making contact, the mercury in the other limb is at a higher level. To maintain this difference in level, a definite pressure on the furnace side of the U-tube is necessary. The leak tends to reduce the pressure and, therefore, the furnace has to heat up in order to prevent this reduction of pressure, doing so automatically because the heating circuit is completed as the mercury rises to make contact with *G* on lowering of the pressure. Conversely, if the mercury level in the limb on the furnace side is higher than in the other, the action of the leak is such that the furnace has to cool to keep the mercury in the neighbourhood of *G*. The rate of heating or cooling can be controlled by altering the head of mercury, or altering the value of the leak. The chief obstacle preventing extensive use of this device is the difficulty of obtaining suitable leak tubes which are not fragile.

Use of Electrolytic Cell.—The arrangement for slow-heating or cooling now used at the National Physical Laboratory makes use of an electrolyte cell.[7]

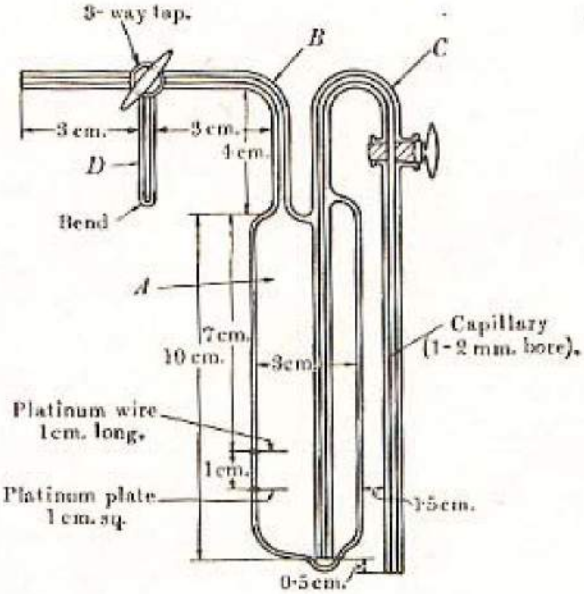

FIG. 6.—Electrolytic cell for Slow-cooling. (N.P.L.)

The bulb *A* (Fig. 6) is filled with a saturated solution of chromic acid in equal parts of water and sulphuric acid. One electrode is in the form of a platinum plate 1 cm. square, and the other a platinum wire to form the anode. The use of a plate instead of a wire for the cathode enables higher currents to be used before hydrogen is evolved. In the cell illustrated, a current of about 8 milliamperes can be used without excessive evolution of hydrogen. The oxygen evolved is passed by the tube *B* to one or other side of the U-tube of the thermostat. If it passes into the cold-bulb side of the U-tube, the rise in pressure will have to be balanced by a rise in temperature on the furnace side, and consequently the furnace heats up. Alternatively, if the gas is passed into the hot-bulb side, this will have to cool in order to maintain constant pressure. The rate of heating or cooling is governed by the quantity of gas evolved, which depends on the current passing through the electrolytic cell. The cell can be run off the D.C. mains with a potential-divider to control the current. The resistance of the cell varies with the amount of gas clinging to the electrodes, etc., and the behaviour of the cell is greatly improved if a ballast resistance of 500 ohms or more is introduced in series with the plate. This has also the effect of enabling finer control of the current to be obtained.

The tube *C* (Fig. 6) is used for filling and emptying the apparatus. If the tube cell is designed with a tap at the bottom, difficulty is experienced with the tap either leaking or sticking due to the chromic acid attacking the lubricant.

With this cell arrangement it is possible to obtain rates of heating and cooling up to 20° C. per hour at a temperature of about 600° C.

When slow-heating is being carried out, the pressure on both sides of the U-tube rises steadily, and it is advisable to open the whole apparatus to the atmosphere every 200° or 300°, so as to prevent the pressure from becoming excessive. With slow-cooling, on the other hand, this is unnecessary, as the pressure remains constant.

General Notes : *Required Values of Resistances.*—It was originally considered necessary to have a number of resistances to control the current, in order to enable the maximum and minimum currents to lie fairly closely to the mean current which would keep the thermostat at the required temperature. It has been found by experience that this is unnecessary and that two values of maximum current (either full on, or with a small resistance in the circuit) and two values of minimum current, one of which is zero, give all the control necessary. The resistances which are put in series with the thermostat are: on the " maximum " current position, zero or 10 ohms; and on the " minimum " current position 20 ohms or infinity. The resistances can be controlled by two switches.

The joints in all connecting tubing should, if possible, be free from rubber connections.

A convenient relay for use with this thermostat is of the mercury-in-glass type, the I.A.C. RNK being one form which has a pilot relay working the main circuit-breaker. As previously stated, the use of a thermionic-valve arrangement to work a relay considerably lessens troubles due to sparking at the U-tube contacts.

References to Chapter I.

(1) Bousfield, *Trans. Faraday Soc.*, 1911, **7**, 260 ; *ibid.*, 1912, **7**, 3.
(2) Haughton-Hanson, *J. Inst. Metals*, 1915, **14**, 145 ; *ibid.*, 1917, **18** 173.
(3) Jenkins, *ibid.*, 1929, **41**, 255.
(4) Hindley, *ibid.*, 1929, **41**, 258.
(5) Durant, *ibid.*, 1929, **41**, 249.
(6) Adcock, *J. Sci. Instr.*, 1925, **2**, 273.
(7) Grogan, *ibid.*, 1928, **5**, 217.

CHAPTER II

THERMOSTATS BASED ON EXPANSION OF LIQUIDS—LABORATORY TYPES.

THE expansion of liquids with increase of temperature is used as a means of control in a number of laboratory and commercial thermostats of various forms. The movement of a column of liquid with the expansion and contraction of a volume of liquid, contained in a bulb immersed in the heated space or bath, is arranged to control a burner gas-supply or to actuate contacts in an electrical heating-supply circuit. The liquids are usually of the volatile class, as these have a high coefficient of expansion. Regulators controlled by mercury expansion are described in a later chapter.

Liquids for Use in Regulators.—The liquid commonly used is toluene. When the temperature to be regulated greatly exceeds 100° C., however, the toluene must be replaced by another liquid, such as aniline or mercury. This modified form is not as sensitive as that containing toluene, in that the coefficient of expansion of mercury, for example, is much less than that of toluene, one litre of mercury increasing in volume by 0·18 ml. for 1° C. rise in temperature, whilst 1 litre of toluene increases by 1·1 ml. for the same rise of temperature.

Coefficients of expansion at a temperature of about 25° C. of a few suitable liquids are given in the accompanying table :—

Increase in Volume of 1 litre for 1° C. Rise in Temperature.		Specific Heat.
	ml.	
Water	0·25	1·0
40 per cent. Calcium chloride solution	0·50	0·63
Mercury	0·18	0·03
Carbon tetrachloride	1·1	0·2
Toluene	1·1	0·4
Ethyl alcohol	1·1	0·5
Ethyl ether	1·1	0·55
Chloroform	1·3	0·23
Benzene	1·2	0·40

Liquid-expansion Regulator Designs.

In the form of regulator extensively used in the laboratory, the toluene or other liquid is contained in a glass bulb or series of bulbs. Where it is desired to have a larger exposed surface, a glass spiral or a long length of closed-ended tube, bent into a convenient form, may be used. Various other means have been suggested to increase the ratio of the exposed surface to the volume of sensitive liquid. and so increase the response to temperature-changes. A simple method is to make a number of thin-walled indentations or depressions in the walls of the bulb; the bulb is not made more fragile by this means. To ensure that air is not trapped beneath the indentations when the regulator is being filled, the tips of the indentations may be pointed slightly upwards; care should then be taken that air is not trapped in them when the regulator is immersed in the bath liquid, as this will nullify their usefulness to some extent. Another suggestion to increase the sensitivity of the bulb is to place in it a good-conducting metal foil such as copper.

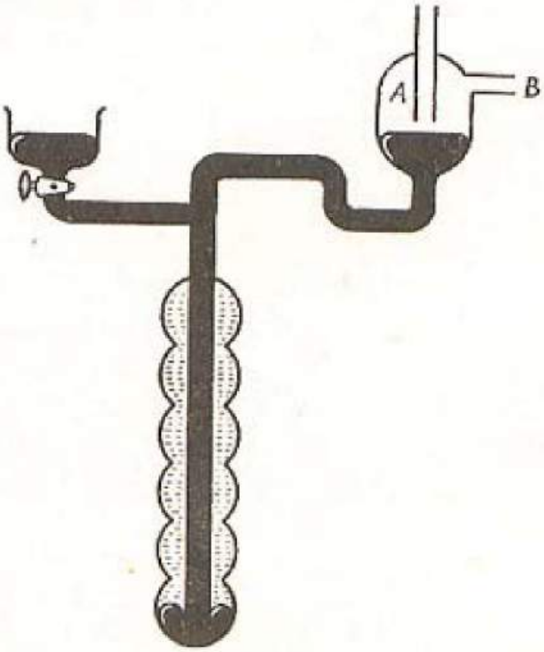

FIG. 7.—One form of toluene-mercury thermostat for use with gas-heated bath.

FIG. 8.—Arrangement to prevent creeping of toluene to mercury contact-surface.

When liquids other than mercury are used as the heat-sensitive liquid, it is usual to arrange that a column of mercury is moved by the liquid in order to provide a more positive means of control when using gas, and a conducting path when using electrical heating. If toluene is used as the sensitive liquid it should, before use, be kept in contact with mercury for several weeks with occasional shaking, followed by redistillation over sodium, although the latter treatment is not recommended by some authorities. Fig. 7 shows one arrangement of the bulbs and mercury column. Hermetically sealed into the bulbs is a tube containing mercury, reaching to the lowest bulb, where it dips into a small quantity of mercury.

Where the same continuous tube contains both toluene and mercury, as in some forms of thermostat, it is difficult to prevent the toluene from creeping around between the mercury and glass walls on to the surface of the mercury, unless a device [1] similar to that illustrated in Fig. 8 is introduced. By this means the ends of the tubes connected with the mercury and toluene dip well into the respective liquids and the side tubes facilitate filling with the appropriate liquids. The lowest tube in Fig. 8 is connected to the bulbs containing the remainder of the toluene.

It may be mentioned here that the regulator bulb need not necessarily consist of glass. Monel metal has been recommended [2] on account of its strength, resistance to corrosion, and greater rapidity of response to temperature-changes. When electrical heating is used with the bulb of metal, it is necessary, as will be seen later, that the upper part of the regulator shall consist of glass. The junction between the glass and Monel metal may be made by nickel plating. The glass is first coated with a silver mirror, copper-plated and then soldered to the Monel metal bulb. The joint is next plated with a thin layer of copper and finally with a thick coat of nickel.

When once fitted up, the quantity of toluene in a regulator is not usually altered; but the level of mercury has to be altered for adjustment purposes. This may be done in various ways, one way being, as shown in Fig. 7, to connect the column of mercury by a side tube to a reservoir of mercury. A sensitive method of adjustment is to dispense with the reservoir and to close the side tube with an airtight rubber bung through which passes a glass plunger dipping into the mercury. The diameter of the plunger is only slightly less than the internal diameter of the side tube. Raising or lowering the plunger moves the mercury column. The space between the mercury and bung in the tube is filled with a mixture of one part water and two parts glycerine. This serves to exclude air and at the same time lubricates the plunger.

Gas-heating Type (see Fig. 7).—Where gas is used as the source of heat for the bath, the mercury column emerges into a bulb into which the gas is delivered by the tube *A* close to the surface of the mercury and then passes away to the heater by a side tube *B*. The tube *A* should be centred and cut off square. Another method is to taper and grind the tube so that a long, narrow hole is formed, making an angle with the mercury surface.

On increasing the temperature of the toluene, expansion takes place, forcing up the mercury in the tube and partially or wholly closing the inlet tube and so regulating the quantity of gas supplied to the burner. On cooling, the reverse takes place, admitting more gas to the heater. A by-pass, consisting of a very small hole in the side of the tube *A*, prevents total stoppage of gas and consequent extinction of the burner-flame. If all the gas supply passes through the thermostat, trouble arises due to the gas pressure forcing the mercury away from the tube orifice; so that, for more sensitive control, the greater part of the gas supply should be by-passed, and a small quantity for regulation passed through the thermostat.

The lower end of the inlet tube can be widened out slightly so as to prevent any tendency for the mercury to stick in the narrow tube (see Fig. 9A).

Flickering of the flame sometimes occurs when a single tube is being closed by the mercury, and it is difficult to avoid extinction of the flame. If the single tube is replaced by a number of smaller tubes in parallel, contained in a wider glass tube, this trouble is lessened. Improvement also results when a reservoir is interposed between the control and the burner.

To prevent the formation of a scum on the mercury surface, the top of the mercury tube could be covered with a thin sheet of

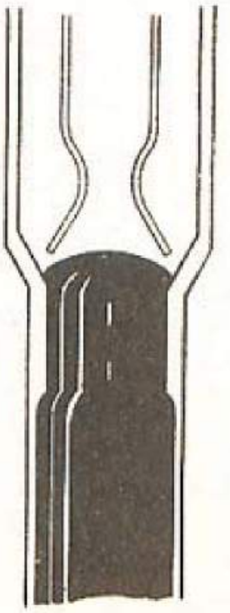

FIG. 9A.—Gas-entry tube splayed out to prevent mercury sticking.

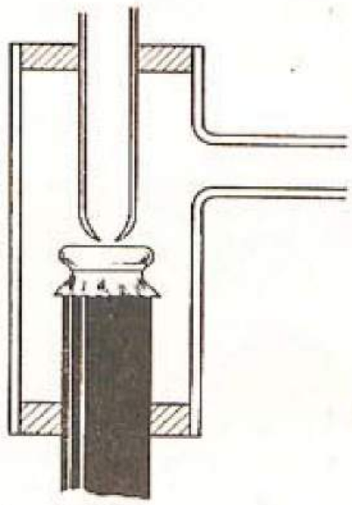

FIG. 9B.—Rubber cover on mercury to avoid scum-formation.

rubber (see Fig. 9B). The expansion of the liquid with rise in temperature would press this rubber against the inlet tube and close it.

Electric-heating Type.—When the bath is heated electrically, the thermostat tube containing the mercury has at its upper end a capillary tube, as shown in Fig. 10, instead of a bulb as in the gas-heating type. Extending into this capillary tube is an adjustable contact-wire connected to a relay of some form. Permanently immersed in the mercury at some convenient point is a second contact, which is also connected to the relay through a suitable energizing battery. When therefore the mercury rises in the capillary, due to expansion of the toluene, and makes contact with the adjustable contact, the circuit is completed and the relay operates to cut off the current in the bath heating-coil. The mercury level or the contact, or both together, may be adjusted to obtain the correct temperature-setting.

To allow of rapid changes in the temperature-setting of the thermostat, instead of one adjustable contact a number of tungsten contacts, as suggested by Polisser,[3] could be fused into the capillary tube, which is inclined at an angle of 45°. Intermediate temperature-settings would then be obtained by tilting the thermostat slightly when the bath is at the correct temperature, until the mercury thread just reaches the nearest contact. This contact is then connected to

FIG. 10.—Toluene thermostat for electrically-heated bath.

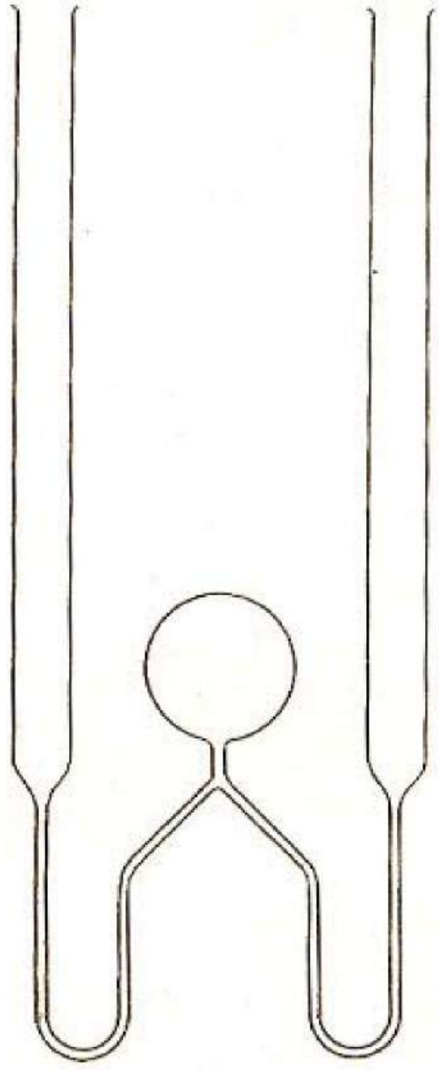

FIG. 11.—Goodhue form of regulator.

the relay. By inclining the contact tube in this way it is claimed that the sensitivity is increased.

An interesting and simple form of regulator which has no sealed-in contacts for the leads, and in which make and break occur between two columns of mercury, has been designed by Goodhue,[4] and is included here as an interesting alternative to the normal type described. The operation of the regulator depends on the principle of the differential manometer, and temperatures from about 15° C. to 40° C. can be maintained with its aid. Fig. 11 illustrates diagrammatically this type of regulator. The vertical tubes would in practice be suitably disposed to make the construction more compact in form. The bulb of about 3 cm. diameter is first completely filled with isopentane or other volatile liquid, and then half the volume of the isopentane in the bulb is replaced, with the aid of a capillary tube, by some inert gas such as nitrogen or hydrogen. Finally mercury is added to both limbs. The bulb is then heated to displace sufficient isopentane so that both columns of mercury just meet at the apex of the inclined fine-bore tubes when the regulator is cooled nearly to the control temperature required. Further adjustment can be made by the addition of mercury. Fine adjustment can be facilitated by the aid of a small plunger in one limb. The electric current is broken with rise in temperature, so that a relay is not really necessary. The sensitivity of the regulator will be governed by the amount of inclination of the inclined tubes. This form of regulator is somewhat difficult to set up and has a narrow range of temperature-control. The form of regulator described in the earlier part of this section is used almost universally for electrical-heating control.

Contacts.

One of the chief difficulties, and one which largely governs the sensitivity of the normal toluene-mercury type of thermostat, is that of obtaining a suitable arrangement for making and breaking the electrical circuit in the regulator.

Failure at the electrical contact may leave the heater operating at its maximum capacity, causing the bath temperature to rise and forcing the mercury and sometimes even the toluene out of the bulb, and necessitating a large amount of work to set in order again. Contact-failure is generally due to fouling of the mercury surface.

If the mercury does not wet the contact wire, an extremely small rise or fall of the mercury thread will be sufficient to make or break the circuit. Mercury adheres to platinum, so that if this material is used as the contact wire the breaking of the circuit takes place at an appreciably lower temperature than the make. The use of iron, tungsten, nickel or nichrome in place of platinum effects an improvement in this respect, and the make and break occur at temperatures closer to one another. Decreasing the bore of the contact tube tends to increase the sensitivity of the thermostat, but a tube diameter of less than 1 mm. may cause erratic working, for the following reason: the time-lag in most systems is such that the mercury overshoots and undershoots the contact-point, and when the mercury is forced up between the wire and the glass in a small capillary, the mercury column is apt to break and the thermostat then begins to operate at a new temperature.

Gouy Oscillating Contact.—Gouy[5] observed that if the contact needle, instead of being fixed, is given an oscillating motion of 20 seconds' period along the axis of the tube, the sensitivity of the regulator is improved.[6] Incidentally, the period of oscillation need not necessarily be this figure.

Energy is in this way periodically supplied to the bath when contact is made between the mercury and the needle. An increase in the temperature of the thermo-regulator bulb results in a rising of the meniscus, which causes a decrease in the length of time during which energy is periodically supplied to the bath, thus tending to stabilize the bath temperature. Gouy stated that the use of this device greatly reduced the errors due to the compressibility of the thermostatic fluid and to the distortion of the mercury meniscus as it moved up and down.

Sligh[7] has made a theoretical analysis of the fixed and oscillating types of contact and has put forward equations to represent the conditions which might be expected with the use of each type. The equations are based on the assumption of a constant time-lag, coupled, as it were, with a bath of perfect conductivity.

Mathematical Representations: (a) Fixed Contact.—The periodic change in temperature as the regulator operates with a fixed contact is expressed by the equation

$$\Delta\theta_p = \frac{tW}{M} + \Delta\theta',$$

where $\Delta\theta_p$ is the total change in temperature during one cycle of "make" and "break," that is, the amplitude of the periodic oscillations of temperature; and t is the time-lag of the thermo-regulator in seconds. This quantity is defined as the number of seconds which would elapse between the time when the total energy input to the bath has reached a value corresponding to a given meniscus position and the time when the meniscus assumes this position, supposing the rate of energy input to be approximately constant. It is assumed that the lag of the bath as a whole with respect to the heater is less than the lag of the thermo-regulator with respect to the heater. W is the maximum electrical input supplied by the regulator in watts, and does not refer to the average input.

$\Delta\theta'$ is the contact lag; that is to say, the change in temperature required to change the contact of the thermo-regulator from "make" to "break." This quantity can be very variable. M is the heat capacity of the bath in joules per degree.

The changes in the mean bath temperature, $\Delta\theta_m$, produced by changes in the thermal head, $\Delta\varphi$, and by changes in the maximum electrical input controlled by the regulator, ΔW, are represented by

$$\Delta\theta_m = \frac{t}{2M} \cdot \Delta W - tK\Delta\varphi,$$

where φ is the portion of the thermal head of the bath (*i.e.* the difference in temperature between the exposed portion of the bath and its surroundings) which is compensated by the thermo-regulator. This does not include the portion of the thermal head which is compensated by the fixed heating. φ is considered positive when the bath loses heat to the surroundings. K is the cooling constant of the bath in degrees per second. The corresponding formulæ for the oscillating contact are as follows :—

(b) Oscillating Contact.—For changes in mean bath temperature, $\Delta\,\theta_m$, due to changes in thermal head, $\Delta\,\varphi$, and changes in average electrical distribution along the path of the moving contact, $\Delta\,W$,

$$\Delta\,\theta_m = \frac{M\,K\,\varphi}{a\,W_1\,W_2}\,\Delta\,W - \frac{M\,K\,\Delta\,\varphi}{a\,W_2},$$

where a is the sensitivity of the thermo-regulator, *i.e.* the movement of meniscus in cm. per degree change in temperature ; and W is the electrical energy distribution along the path of the oscillating element, expressed in watts per cm., *i.e.* a change of 0·1 cm. in the position of the meniscus would change the average power input by $W/10$ watts.

The subscripts 1 and 2 denote values before and after changes in the length in centimetres of the path of the oscillating contact over which energy is being delivered to the bath.

The expression for the variation in bath temperature as the regulator operates was not derived, but Sligh states that from experiment this variation was found to be small.

For successful operation of an oscillating-contact thermo-regulator, the following conditions are necessary :—

(1) The periodicity of the oscillation should be small in comparison with the lag of the bath, say one-fifth of the value, but not so small as to produce sustained waves on the mercury surface. There seems to be no advantage in reducing the period beyond that necessary to damp the periodic fluctuations in bath temperature sufficiently to render their effects imperceptible.

(2) The length of path of the oscillating element should be large in comparison with the movement required to make or break contact with the mercury surface ; one mm. seems to be sufficient in most cases.

(3) The energy distribution along the path of the oscillating element should be large in order that great range and close regulation may be secured under a wide range of external conditions. The upper limit to this energy distribution is fixed by the fact that the smallest amount of energy which may be supplied during a single cycle should not exceed that which is required during that cycle. If this condition is violated, motion of the meniscus beyond the limits of the stroke of the oscillating element would result.

White [8] considers that it is unnecessary to add the temperature-lag of the bulb at the end of the stroke. With the ordinary mercury-contact thermostat regulator, it is sufficient, he considers, if the total lag, expressed as a temperature-difference, is not over twice the "backlash" equivalent, but already gives twice the correct result when the ratio of the lag to the equivalent is 20. The backlash equivalent indicates, in degrees, the difference in temperature at which contact "makes" and "breaks," the former taking place for a higher temperature than the latter. The maximum inconstancy normally occurring in an ordinary thermostat for any given rate of heating is the periodic oscillation of temperature for equal resultant up-and-down rates. White expresses this oscillation by the equation

$$\frac{\Delta U_B}{V L} = \frac{v T}{2 v L} - \tan h \frac{v T}{2 v L},$$

from which the ratio of $v T$, the oscillation, to the temperature-lag, $v L$, or to the backlash equivalent, U_B, can be found for any ratio of ΔU_B to $V L$. V is the rate of heating due to the heater alone, v the instantaneous actual rate, here equal to $\frac{V}{2}$, and L is the time-lag.

Advantages of Oscillating Contact.—The principal advantages of the oscillating-contact type of regulator over the fixed-contact type may be summed up as follows:—

(1) A large amount of available energy can be used to compensate for any possible wide fluctuation in external conditions without a sacrifice of closeness of control.

(2) A bath temperature is obtained in which the periodic variations about the mean due to operation of the regulator are very greatly reduced.

(3) Troubles due to soiling of the mercury, surface sticking, etc., are greatly reduced. Nevertheless it must be stated that the mercury tends to become fouled sooner with this form of contact than with the stationary form, and requires fairly frequent cleaning.

The advantages to be secured by the use of the oscillating type of regulator are due to the fact that the time at which a given movement of the meniscus may affect the energy input is rendered independent of the physical constants of the bath, and is made dependent only upon the periodicity of the oscillating element of the regulator. Further advantages accrue from the provision of a means for applying successive corrections, at short time-intervals, to the value of the energy input, instead of corrections at such longer time-intervals as will permit of wider excursions of bath temperature above and below its mean value.

The Gouy contact was the first device to bridge the gap between simple on-and-off control and continuous control. It is used in modified form in many present-day controllers.

The mercury surface may be oscillated,[2] instead of the contact wire, to effect a similar result to the Gouy arrangement. Such movements have been produced [9] by trapping pockets of air with the mercury in the arm carrying the stop-cock and reservoir, and by supporting the regulator in such a way that the vibrations of the motor used to stir the bath liquid are imparted to it.

The Mercury Surface.—Whatever type of contact is used, it is necessary, for high sensitivity and satisfactory working, to maintain a clean mercury surface at the contact. This requirement is not easily attained, and many methods have been tried.

Elimination of oxygen from the space around the contact would be a satisfactory method. With this object in view, the air has been replaced by hydrogen or nitrogen. This method is satisfactory as long as the gas is present, but is cumbersome because of the apparatus and care required to maintain the gas. There is a risk of forming an explosive mixture with air which may be admitted inadvertently when hydrogen is used. Generators have been specially designed [10] to supply the necessary hydrogen. If the regulator is sealed [11] it is difficult to change the position of the contact-point and also impossible to oscillate it. It does not, however, prevent the mercury surface from being agitated by vibration of the regulator. Sealing [12] the cap of the regulating capillary with a drop of mercury fails if the regulator is jarred, because the drop then works downward.

It may be mentioned here that all regulators which depend for their action on the expansion of a column of liquid are sensitive to fluctuations in barometric pressure if the liquid is open to the atmosphere. Variations in the controlled temperature of the order of $\pm 0{\cdot}2^\circ$ C. arise from this cause. By sealing the gas space above the liquid surface to maintain the inert atmosphere, variations due to this cause are therefore prevented. Another method [13] of eliminating atmospheric pressure variations may be mentioned which is to place in the bath a vessel of about one-litre capacity containing air, and to connect it by a tube with the top of the regulator. The junction between the tube and regulator can be effected by arranging a mercury seal around the top of the regulator into which the tube dips. The latter method does not, of course, prevent the mercury surface from coming into contact with oxygen.

Prevention of Sparking at Mercury Surface.—Sparking at the point of contact can be reduced by using a small current in the circuit and placing a condenser as a shunt across the contact-points or, alternatively, connecting a Westinghouse rectifier across them. Contact can be arranged to take place away from the mercury surface, and Fig. 12 illustrates the use of floats with contacts attached at their upper ends. Both methods, however, decrease the sensitivity of the regulator.

Less sparking takes place if the usual procedure of making and breaking the relay circuit is reversed; *i.e.* if, when contact is made, the relay is short-circuited and the armature released. The energy of the relay coil is then dissipated through a closed circuit instead of

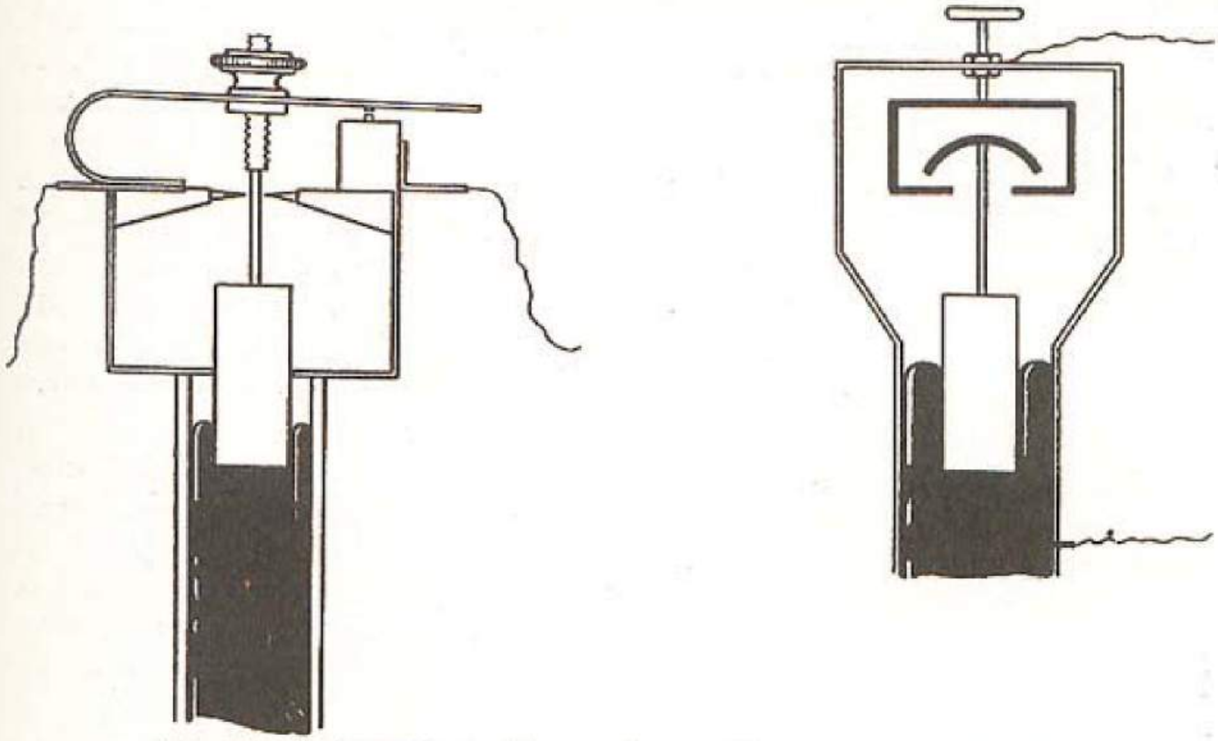

FIG. 12.—Some methods of preventing sparking at mercury surface.

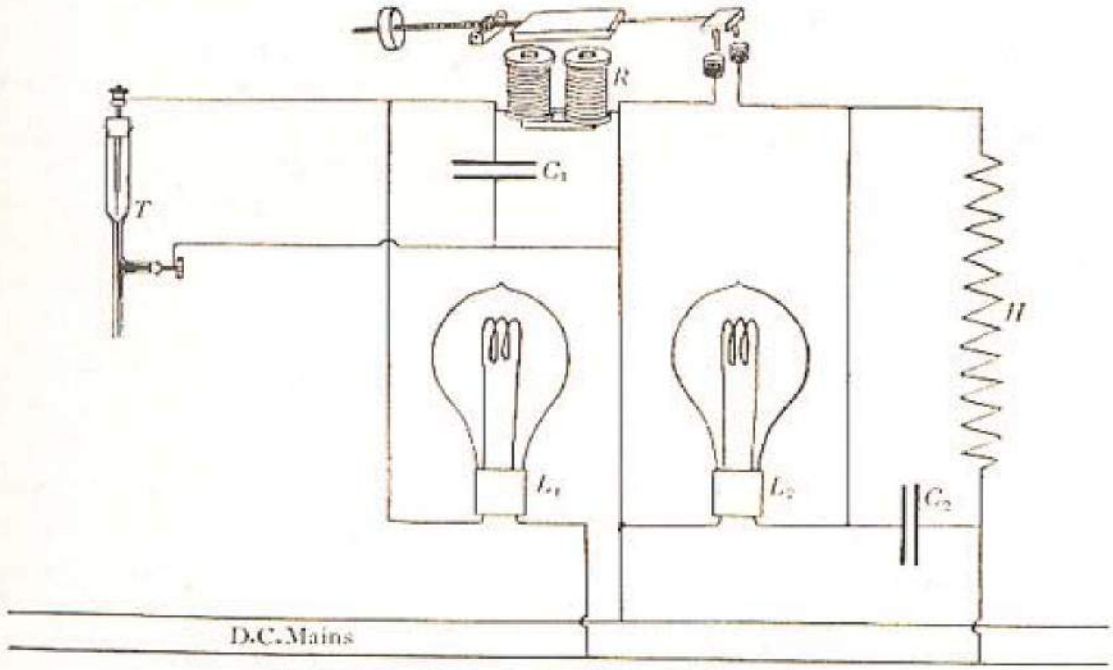

FIG. 13.—Sumner circuit for D.C. mains.

through an open circuit, and the hot inductive spark is eliminated. Sumner [14] describes a similar method when using D.C. mains for operating the relay circuit (Fig. 13). The relay coils R and the regulator T are in parallel, the relay being energized by the current through the lamp resistance L_1 when the contacts are open, and being short-circuited when the contacts close. The inductance of the coils opposes the tendency to formation of spark when contact is broken in the regulator, condenser C_1 reducing this tendency still further. The current through the heating circuit H is controlled by the relay, which short-circuits the lamp L_2 when energized. The condenser C_2 tends to reduce the spark at the relay contacts.

Triode-Valve Relay.—Two methods now widely used to reduce sparking are the application of either the triode-valve system, [2, 15-19] or the hot cathode grid-controlled gas-filled [20] tube, as a relay (see p. 93). By these means the current at the make-and-break contact is reduced to a minimum, whilst still providing a sufficient current through the medium of the relay to operate a relay valve controlling the heating supply of electricity or gas.

The use of one of these relays naturally introduces complications, and where simplicity is desired one of the other methods described has to be adopted.

In the triode-valve system, the adjustable contact of the regulator is connected to the grid of a thermionic valve, and thereby controls its plate current. The plate or anode current may then be made sufficient to operate a robust relay.

Winton [21] uses the valve-relay method in conjunction with an unusual form of regulator contact. This consists of a wire tipped with burnt sealing-wax, thus forming a contact of varying resistance (Fig. 14). This variable resistance forms one arm of a potential-divider, the other arm of which is of fixed resistance, and is so connected that it can vary the grid bias of a thermionic valve from zero to a fixed value. The anode current of the valve passes through a heating resistance in the bath and is thus automatically adjusted to a value which will keep the temperature of the bath constant. The valve must of course be capable of dealing with the necessarily large current to provide sufficient heating for the bath.

Certain difficulties may arise in the use of such a variable-resistance contact, unless precautions are taken. There is a tendency for dirty mercury to cause sticking; this may be overcome to a large extent by vibrating the regulator in some way. Capillary-electric phenomena (which lead to instability) associated with extreme sensitivity may occur unless the mercury is connected to the positive side and the wire to the negative side of the potential-divider. To avoid passing too large a current through the contact, a resistance of about 5 megohms should be placed in the arm of the potential-divider.

Beaver and Beaver [2] use a triode-valve relay in conjunction with an oscillating contact. The oscillations are produced by agitating the regulator from the vibrations of the stirring motor of the bath.

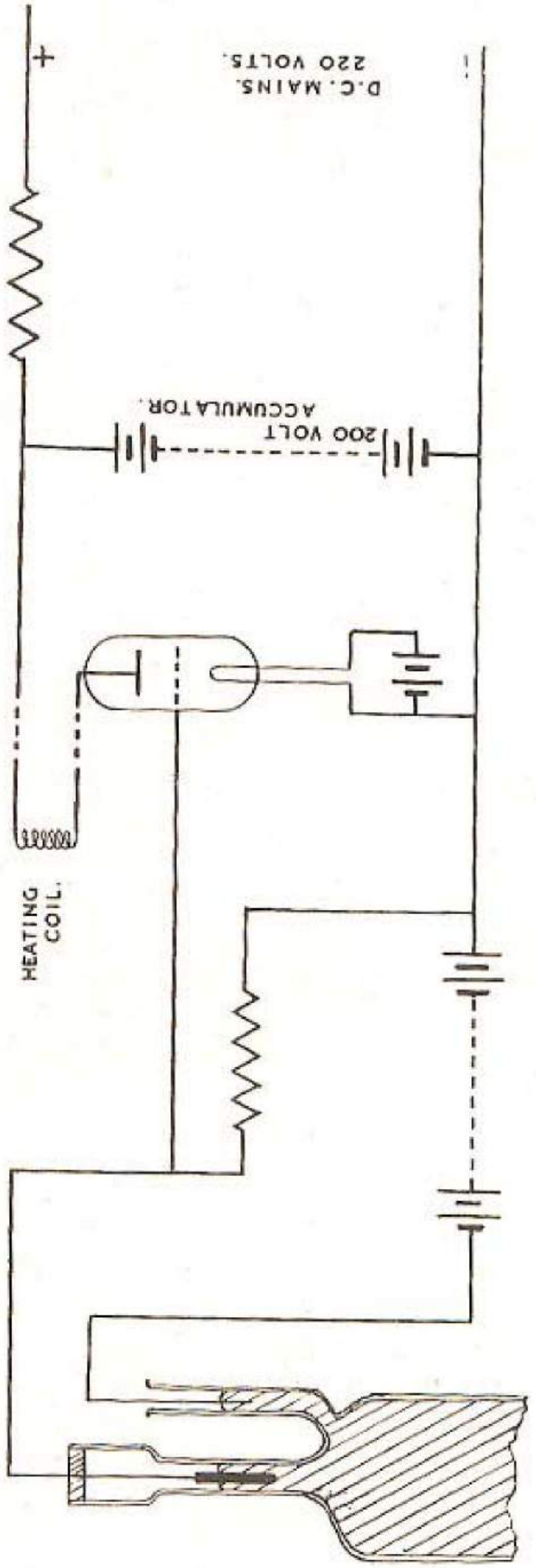

FIG. 14.—Winton variable-contact resistance and thermionic-valve relay.

As the frequency of the make and break may be too high, causing the relay to act too frequently, a condenser of about 0·1 μF. capacity in parallel with a grid-leak is connected between the grid of the valve and the negative terminal of the filament. By varying the capacity of the condenser or resistance of the grid-leak, the speed of the relay can be regulated to any desired period. A period of twice a second is of the right order for baths of about 30 litres or more capacity; for baths of smaller capacity shorter periods are desirable.

Baths and Accessories.

For laboratory purposes, the object to be maintained at a constant temperature may be placed either in an air-chamber or immersed in a liquid, and the temperature of the air or liquid is regulated by means of the thermostat.

Air-Bath.—Temperature-controlled air-chambers are particularly suitable when solubility measurements [18] or corrosion [22] work, etc.[23, 24] have to be carried out.

Owing to the small thermal capacity of air, it is difficult to obtain uniformity of temperature at different points in the enclosure. Efficient mixing of the air is necessary, but a continuous, uni-directional flow across the working space is to be avoided, since under the latter conditions a temperature-gradient is set up in the space by the air-stream, which is continuously losing heat.

If a single large source of heat is used, and particularly if this source be incandescent, there is a risk that direct heating of the contents of the space may occur by radiation. A number of small heating elements is preferable, and heaters of the wire-grid type very often meet the case. The risk of fire, however, is present with this type of heater, and the use of a number of small heating lamps may sometimes be preferable. In this way the temperature of the heating elements need only be a few degrees above the control temperature.

The use of a double-walled vessel, with the space between the double walls thermostated and the whole of the air in the inner chamber thoroughly stirred, permits of very close uniformity and constancy of temperature. Tian [22] describes a multiple-walled chamber with the regulator and heating on the outside container.

Thermostated Air-chamber.—A detailed description of a thermostated air-chamber (see Figs. 15 and 16) has been given by W. H. J. Vernon.[23] The chamber is of wood, 96 ins. long, 45 ins. high and 39 ins. wide, lagged with cork slabs. Two fans, situated one at each end of the chamber, force air over a group of heating lamps set in front of each fan. The two opposing air-streams meet in the middle of the chamber and pass downwards over the regulator bulbs. A portion of each stream then passes through two holes in the working floor, under which it returns.

In the work for which the Vernon thermostat was primarily

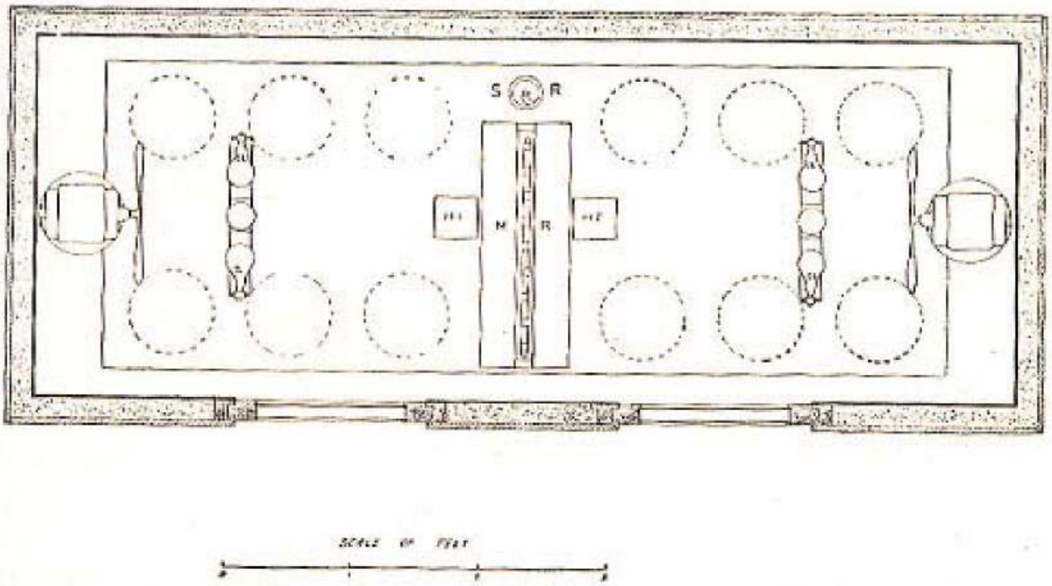

FIG. 15.—Plan of thermostated air-chamber, showing section through fans, heating-lamps, main and subsidiary toluene regulators.

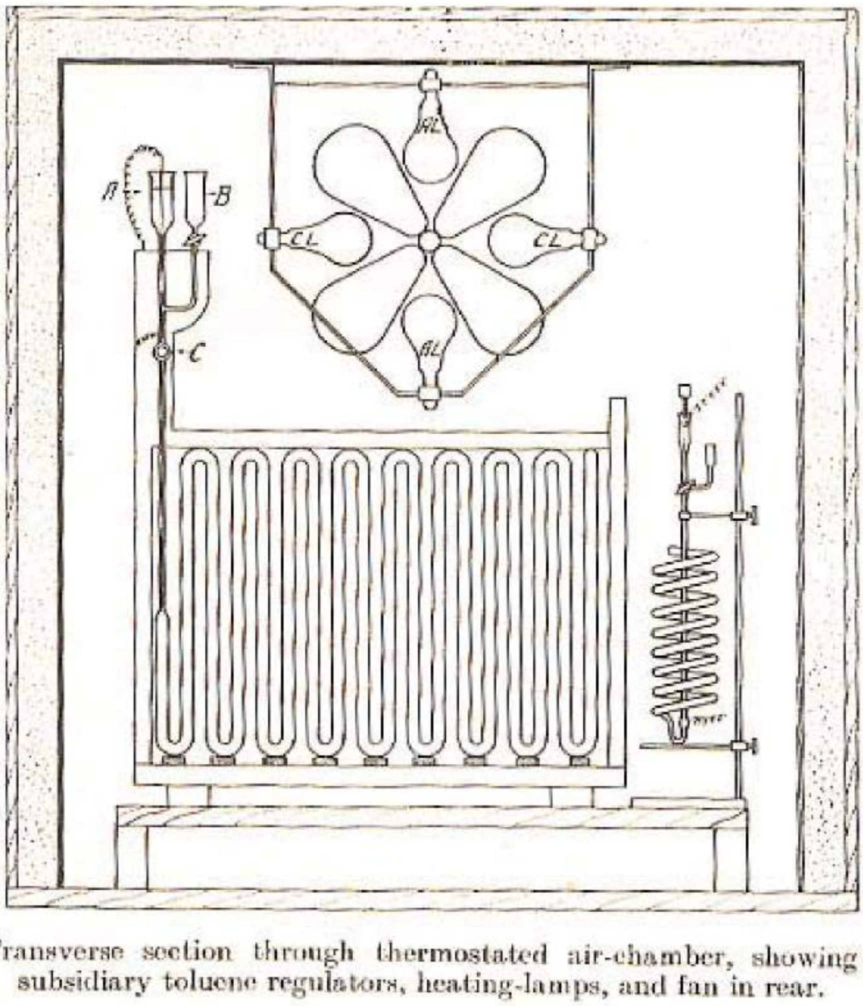

FIG. 16.—Transverse section through thermostated air-chamber, showing main and subsidiary toluene regulators, heating-lamps, and fan in rear.

used liquids are listed below, with upper and lower temperature limits :—

	Temperature-range, ° C.
Water	0 to 80
Kerosene	−40 ,, 75
Brines	−40 ,, 120
Light lubricating oils	30 ,, 200
Commercial vegetable fats ...	100 ,, 300
Glycerine	100 ,, 270
Tempering oil	50 ,, 300
High-temperature lubricating oil	100 ,, 300
Lead–tin alloy	200 ,, 600
Fused inorganic salts	200 ,, 1600

When water is used as a bath liquid, a slimy growth is apt to form after some time. This may be prevented by suspending in the bath a muslin bag containing mercuric iodide, or by dissolving a little mercuric chloride in the water. Evaporation of the water may be minimised by maintaining a layer of olive oil on the surface.

Brines and aqueous solutions of salts may attack the walls of the containing vessels on account of hydrolysis, and moreover with brines the maximum limit of temperature is only about 20° C. above that of boiling water.

Sulphur has a tendency to fume and therefore requires the use of a hood; also care has to be taken in handling it when hot. Otherwise it makes quite a good bath liquid and is often used.

Paraffin oils and bath waxes [25, 26] must of course be heated with due regard to the fire hazard. "Hard" hydrogenated vegetable oil is a good bath-liquid, since no tarry masses are produced in use and the risk of fire is small. So-called "hard sesame oil," an opaque, white solid, melts at 60° C. to a clear oil and has a weak "flash" at 320° C. This substance does not stick to iron or glass on solidifying, but cracks and falls apart into fragments, and it is superior to vaseline, paraffin or other hydrocarbons as a bath liquid. Hard hydrogenated cotton-seed oil is more widely obtainable than the sesame product.

The upper temperature limit of the oils is set by the decomposition which occurs at higher temperatures, large volumes of gas with a disagreeable odour being given off and spontaneous ignition often occurring. For moderately high temperatures, the difficulties may be obviated to some extent by enclosing the oil or paraffin in a metal vessel communicating with the air through a single tube, through which the stirrer spindle passes, the tube serving as a kind of reflux condenser. With an oil bath it is possible to have a number of tubes closed at the lower end and let into the bath through the cover, thus forming a number of air-baths of considerable capacity and with excellent uniformity of temperature.

Lard is said to be more satisfactory than heavy mineral or vegetable oils. An iron pot serves as a containing vessel.

The eutectic of diphenyl-diphenyl oxide may be used as a bath liquid up to 200° C.

Beattie recommends the eutectic mixture of lithium, sodium and potassium nitrates, which consists of 30 per cent. lithium nitrate, 14 per cent. sodium nitrate and 56 per cent. potassium nitrate by weight, and which melts at 120° C. A less expensive mixture consists of 27·3 per cent. of lithium nitrate, 18·2 per cent. of sodium nitrate and 54·4 per cent. of potassium nitrate, a mixture which is fluid at 135° C., although some solid separates. The specific gravity of the latter liquid is 1·85. It is advisable to allow the liquid to act on steel turnings for several weeks before using, in order to minimise corrosion and other effects.

Many other inorganic salts are available for use as bath fluids.

Metaphosphoric acid, melting at a temperature of 150° C. to a clear liquid, can be used as a bath liquid, but is improved by the addition of 85 per cent. orthophosphoric acid. A variety of mixtures of the two acids can be employed, but the most serviceable is that consisting of 4 parts of 85 per cent. orthophosphoric acid to 1 part of metaphosphoric acid. This mixture can be used in the temperature-range 100-340° C. The mixture is mobile at room temperature and, in common with other mixtures of these two substances, possesses a very small temperature-gradient, as expansion takes place on increase of temperature, which serves to circulate the liquid. It is advisable to heat the mixture to a temperature of 260° C. and to remove all the water vapour before putting into use.

When substances which are solid at ordinary temperatures, such as metals [28] and alloys,[29–32] are used as bath liquids, precautions have to be taken that the bath is heated from the top when melting, so that liquefaction occurs from the surface of the solid downwards. If melting starts at the bottom, the expansion may cause fracture of the containing vessel. It should also be remembered that the vapours of some metals, such as antimony and lead, are poisonous.

Other objections to baths of metal are their relatively low heat capacity and high specific gravity.

Containers.—The size and shape of the bath will be determined by the contents, and liberal allowance should be made for adequate circulation of the fluid. The material of which the bath is constructed is determined also by the contents: glass, iron, galvanized iron, zinc and copper baths are used. Enamelled iron usually cracks and rusts after a short time, especially if used at the higher temperatures.

Glass-sided troughs [33, 34] can be readily made to any form with the aid of metal angle or channelling framework. Lead-oxide base cements [34] are most suitable for the joints.

Methods of Stirring the Bath Liquid.—Vigorous and adequate mixing and stirring of the liquid is essential in all thermostatically controlled baths, in order that temperature-gradients set up in the region of cooling and heating may be smoothed out and the temperatures equalized. The rapidity of stirring just insufficient to produce wavelets and floating bubbles is generally found adequate. A Beckmann thermometer is convenient for exploring the bath for temperature-differences; but it must be remembered that rapid local temperature-fluctuations may occur which are integrated by a thermometer even of this type (because of its high thermal mass) and may therefore be undetected. It must also be realized that a stationary reading cannot always be taken to indicate a constant temperature. Despite vibration of the thermometer, "sticking" of the mercury may persist. Further, a "soaking" effect may arise. This occurs if the thermometer is left at room temperatures for some time; on returning to higher temperatures it rises too high, and subsequently *very* slowly sinks.

Fluctuations in temperature of the bath may occur, due to a number of causes; these factors have been dealt with in greater detail elsewhere (Introduction). There is a lag between the occurrence of a temperature-change in the bath and a compensating change in the heating current, and a lag before this change of current affects the temperature of the bath. These two effects produce periodic fluctuations or "hunting" of the temperature. Slight irregularities in stirring may produce shifting temperature pockets in the bath, and this effect is aggravated if the heating is concentrated in a small localized area.

There are various means of stirring, to which brief reference will now be made.

Air-jets.—The use of air-jets is often a convenient method of stirring. For low-temperature work the air must be dried to remove moisture which otherwise would condense in the bath. The disadvantages of the air-bubbling method are the evaporation losses it causes; the heat carried into the bath in low-temperature work; and the heat taken from the bath at other temperatures by the air-stream. When the bath is in the form of a tall, cylindrical, vacuum-walled vessel, the use of an air-jet is often particularly convenient.

Screw Propellers.—These stirrers mix the liquid well if several are used on the same shaft, but they are not very effective in driving the liquid over more or less pre-determined paths. The most suitable way of using screw propellers is to fix them so that the liquid shall be drawn from the top of the bath, where it has been exposed to the effects of disturbing influences, past the heating coils, then past the propeller, where it is thoroughly mixed, and finally discharged past the regulator bulb into the bottom of the bath. In this way a maximum rapidity of response to temperature-changes is secured which is essential to precise control, and the attempered liquid is brought into the working space in the bath with the minimum exposure to outside influences. As a general guide it will be found that good regulation is obtained with stirring set up by a propeller in a tube operating at such a speed that all the bath liquid passes through the tube three or four times a minute.

Centrifugal propellers give a wide range of velocities and force the liquid to the outlying parts of the bath.

Reciprocating paddles are ineffective as general mixers unless they are of relatively large size.

Supports for Objects in Bath.—The stands for objects immersed in the baths should be perforated or latticed, in order that they shall not have any appreciable effect upon the circulation of the liquid.

The buoyancy of the immersed articles has to be overcome in some cases by loading or fixing down.

Gas Heating of Bath.—Heating by gas is convenient and possesses the advantage of a low operating cost, but this is outweighed by a number of disadvantages. It is rather difficult to deliver the heat from a gas flame to the exact positions where there is greatest loss of heat. The question of obtaining a burner which will not strike back, not cover the apparatus with soot, and yet burn with a good hot flame over a wide range of gas flows, is very difficult of solution. One method is to provide the major portion of the heat by a Bunsen burner, with a small burner controlled by the regulator to maintain the desired temperature.

Again, the question of danger from fire must not be overlooked, especially when the apparatus is left unattended over long periods of time. Rubber tubing for the gas-supply should be avoided.

Electrical Heating of Bath.—On the whole, heating of the bath by electricity, when available, is to be preferred to gas, for the heat can be delivered in approximately the position where greatest loss occurs and the controls are simple and positive.

Heating by electricity may be achieved by immersing a number of incandescent electric lamps in various positions in the bath, and protecting the sockets from the action of the water by suitable means. Electric lamps are manufactured with long stems especially for heating purposes. A length of tube of 30–40 cm. has a bulb at one end, and at the other, metal contact-pieces, collar, and studs as in an ordinary lamp. Since heating, and not lighting, is required, the lamps can be under-run, thereby increasing their life considerably. A 250-volt lamp on a 200-volt circuit, with a nominal candle-power of 50, is suitable as a unit. To overcome the buoyancy, a ring of lead should be slipped over the head, resting on the bulb.

Coils of bare or covered wire may be wound around the bath or even immersed inside it; but in the latter case, with liquid baths, electrolysis tends to take place, which ruins the coils, even when using alternating current; hence it is always advisable to enclose the heaters for protection.

Convenient heating elements can be made by inserting coils of nichrome wire in test-tubes filled with oil. It is sometimes an advantage to place an auxiliary heater near the regulator itself, and this can be done simply by fusing a length of tungsten wire into a tube of high-melting-point glass and bending to a convenient form.

When oils or similar inflammable liquids are used as bath liquids, it is sometimes advisable to insert a safety device in the heating circuit. Otherwise, the bath may become overheated if one of the components, such as the relay, fails. This safety device can take the form of a fusible link in the electrical heating circuit. The link is placed in a metal or glass sheath which is immersed in the bath, so that when the link melts it breaks the circuit and falls into the bottom of the sheath. Fusible links of numerous components[35] and proportions can be made or obtained to suit any desired temperature.

The method of making the bath liquid an electrical conductor and heating by passing the current between resistant electrodes is not to be recommended, because electrolytic action may take place, and also the heat evolved is badly distributed. Baths of this type have, however, been devised. For instance, S. C. Collins[36] has described an arrangement for the automatic control of such a bath where one of the electrodes which conducts the electricity into the bath is contained in a pocket. The unbalancing of a U-tube arrangement containing ether and mercury, inserted in the bath, causes a glass plate which is attached to the tube to close the mouth of the pocket, and so to cut down the cross-section of the column of conducting liquid.

Insulation of Bath.—Good thermal insulation of the bath is essential, both for the conservation of heat and to minimize the effects of extraneous temperature-changes. The form of insulation will of course be governed to some extent by the method of heating. Cork, either in the form of slabs, fine granules, shavings, or hair felt, can be used for this purpose up to moderate temperatures. Wood serves as an insulator, and its effect can be improved by filling the space in a wooden box surrounding the bath with some other insulating material, such as diatomaceous earth. When the size of the bath can be small, Dewar flasks may be used. A wooden case surrounding the flask serves as a protection and as a means of maintaining the temperature of the air around the flask moderately constant.

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CHAPTER III

THERMOSTATS FOR USE AT ATMOSPHERIC TEMPERATURES, EMPLOYING REGULATORS DEPENDING ON THE EXPANSION OF VOLATILE LIQUIDS.

When the temperature of the space to be controlled is within the range of fluctuation of atmospheric temperature, cooling as well as heating arrangements have to be provided. The space to be controlled may be in the form of an air-oven or liquid bath.

Air-Ovens.—An example of the air-oven type is the Hearson apparatus (Fig. 18). It consists of a water-jacketed chamber, a

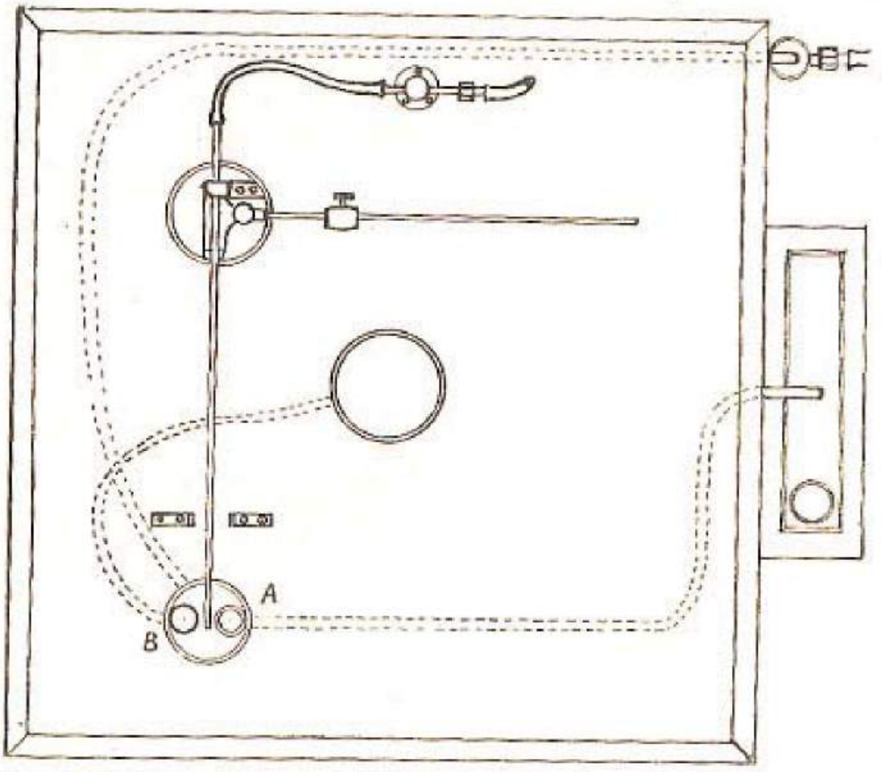

Fig. 18.—Incubator with provision for cooling or heating circulating water.

vessel containing ice, and a heater, the whole apparatus being thoroughly heat-insulated. The regulation of the temperature within the chamber is effected by a small stream of water which runs continuously through the apparatus by one of three courses, the particular course being determined by the thermostatic capsule. These three courses are :—

(1) Heating passage through a boiler.
(2) Cooling passage through ice.
(3) By-pass passage direct to waste.

The stream of water is supplied through a horizontal tube which is bent over at the end, and pivoted so that as it moves from side to side, it passes over the open ends of two adjacent vertical pipes. If the chamber is being heated, the water from the tube passes through the right vertical pipe *A* and through the heater, where it is warmed before entering the water-jacket of the chamber. When the desired temperature is attained and the necessary adjustments have been made, the tube is moved over to the left by the capsule-actuated lever, and the water flows into the space between the vertical pipes and so to waste, without affecting the incubating chamber. If the temperature of the room is higher than that required in the incubator, the horizontal tube will continue to travel towards the left, so that the water runs down the left-hand pipe *B* and passes through the ice-box, where it is cooled, and then into the water-jacket, so lowering the chamber temperature to the desired point, when the capsule will partially collapse and cause the stream of water to pass again between the two pipes.

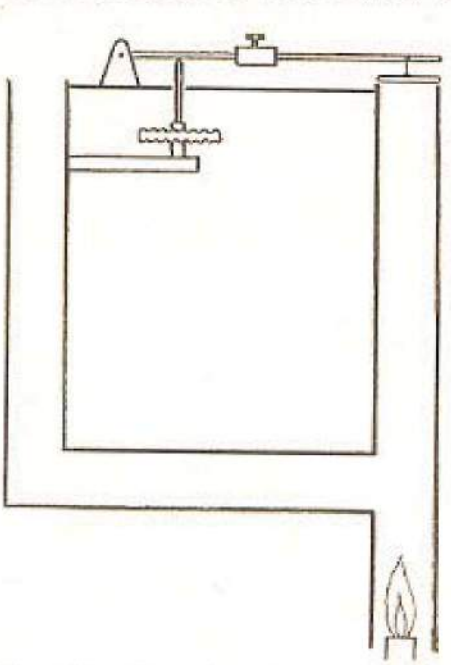

FIG. 19.—Air-oven, showing main heating flue and capsule controlling by-pass flue.

The makers appreciate the fact that should the water supply fail, the incubator control will not function, and they have devised an apparatus to obviate the use of running water where there is any risk of its failure. By means of a two-way switch connected to the capsule lever, current is switched on either to heating coils in the oven or, if cooling is necessary, to a motor which drives a pump to circulate water in the jacket over a supply of ice.

When the temperature required in an oven is always slightly above room temperatures, cooling is unnecessary and a simpler arrangement can be used; for most incubators this meets the temperature requirements. The control generally consists of a capsule containing a volatile liquid placed in the heated space, the expansion of the capsule causing movement in a weighted lever which opens or closes a gas valve or makes or breaks contact in an electrical circuit.

In a form of oven where the heating is by means of a burner, the control can be very simple. For instance, the hot gases from the burner may proceed either 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 (Fig. 19). The direction of flow is controlled by a capsule-controlled damper which closes the top of the direct vertical exit when the temperature falls. When equilibrium is reached, the damper hovers just above the exit and permits a portion of the hot gases to escape.

Water-Baths.—In order to cool water-baths, tap water, previously cooled if necessary, is either added to the bath or passed through pipes immersed in the bath. Efficient stirring must, of course, be maintained. The flow of water to the bath may be controlled by modifying a toluene regulator of the gas type (Fig. 7). Cooled water is used instead of gas, and a rise in the mercury column cuts off the supply of cold water to the bath and diverts it to waste. This method is for small baths only.

Siphon Systems.—Baths which are cooled by the addition of cold water require some means of keeping constant the level of the water in

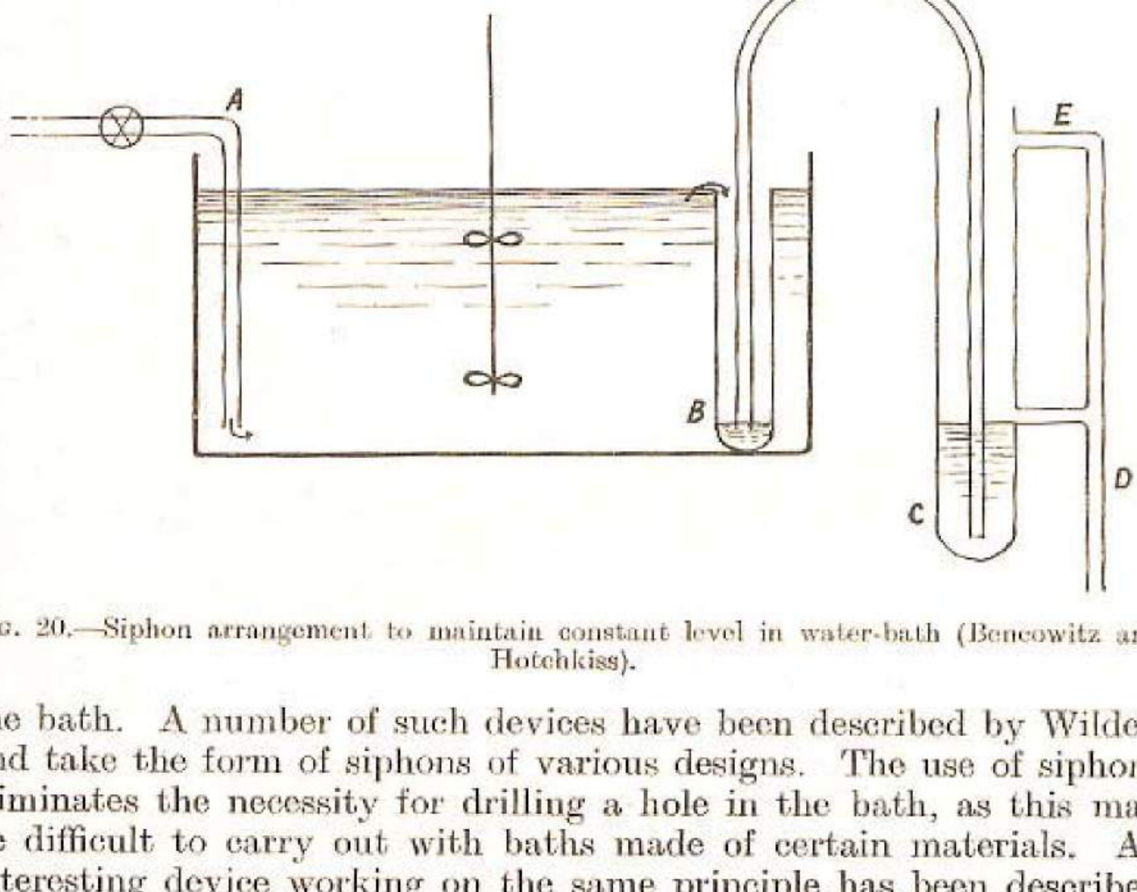

FIG. 20.—Siphon arrangement to maintain constant level in water-bath (Bencowitz and Hotchkiss).

the bath. A number of such devices have been described by Wilde [1] and take the form of siphons of various designs. The use of siphons eliminates the necessity for drilling a hole in the bath, as this may be difficult to carry out with baths made of certain materials. An interesting device working on the same principle has been described by Bencowitz and Hotchkiss [2] and is illustrated in Fig. 20. Cold water is supplied to the bottom of the bath by the pipe *A*. Excess water in the bath flows into the closed-ended tube *B*, from which it is siphoned into *C* and runs to waste through *D*. This occurs when the head of water in *B* is sufficient to cause a displacement in the direction of *C*. The tube *E* is a safety overflow. The siphon does not break, as its ends dip into reservoirs of water in *B* and *C*, and flow only occurs when there is a head of water sufficient to cause a displacement in the direction of *D*.

Othmer Flow-controller.—A controller to regulate the quantity of water added to the bath has been described by Othmer [3] (see Fig. 21). A vapour-pressure bulb, containing ethylene oxide, is immersed in the bath and connected to the flow-controller by a tube containing mercury. The level of the flow-controller is adjusted so that the vapour pressure of the liquid in the sensitive bulb at the set temperature forces the mercury high enough to submerge the inverted V-weir of the central tube.

Cooling water flows into the tube at the upper left side of the flow-controller and, when the mercury is below the level of the weir, down the annular space, up through the inner tube, and out through the discharge tube on the left to waste. As the mercury rises and throttles the flow through the weir, the water rises in the annular space and overflows through the tube on the right side, running directly into the stirred water of the bath.

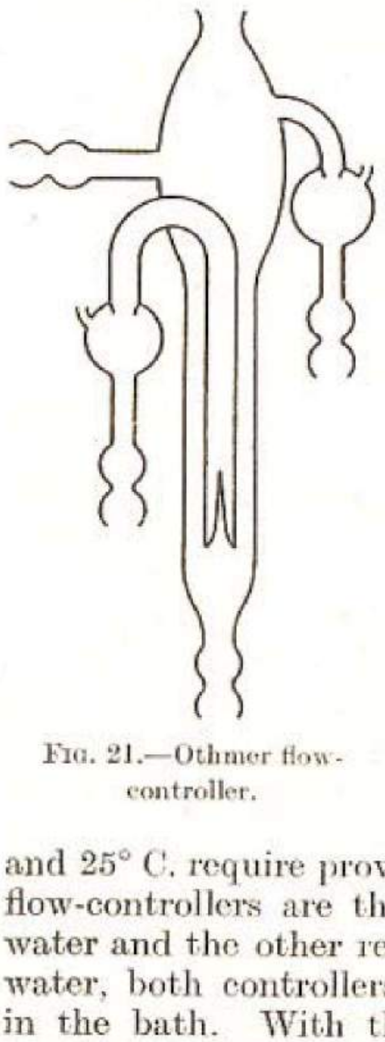

FIG. 21.—Othmer flow-controller.

Both outflow tubes have insealed tips to facilitate visual inspection of the comparative amounts flowing in each, and are vented to prevent siphoning.

Control with a reverse action to that described is made by interchanging the connections on the left and right arms. For temperatures above that of the room, any temperature-point below that of the hot water available may be maintained with this arrangement. Hot water discharges through the left arm to supply the heat required. Ethyl ether is a suitable sensitive liquid for this range of temperature.

Baths for temperatures between 15° C. and 25° C. require provision for both heating and cooling. Two liquid flow-controllers are therefore used, one diverting a stream of cold water and the other reversed in action and diverting a stream of hot water, both controllers being connected to the same sensitive bulb in the bath. With the two weirs at the same height, increase of vapour pressure in the bulb raises the mercury level to throttle both simultaneously. This increases the cold-water flow and decreases the hot-water flow to the bath, the respective flows to waste changing to compensate.

The same controller can be used for other purposes. For regulating the gas supplied to a burner, the gas is introduced through the upper left arm and discharged through the lower left arm, all other openings save the bottom being plugged. Again, in distillation processes, the flow-controller can be adapted to control the stillhead temperature by regulation of the amount of wash liquid returned to a fractionating column.

Schmitt Thermostat.—As an example of a thermostat using the principle of passing suitably tempered water through pipes immersed in the bath, that of Schmitt [4] may be instanced (see Fig. 22). Any temperatures within the range 10° to 40° C. may be maintained. The water passing through the coil in the bath is drawn from a pre-thermostat, which is regulated to a temperature just sufficiently below that of the main thermostat to provide adequate cooling when the water is made to circulate rapidly. The amount of cooling in the main thermostat is controlled by the difference in temperature between the pre-thermostat and the main bath, and by the rate of

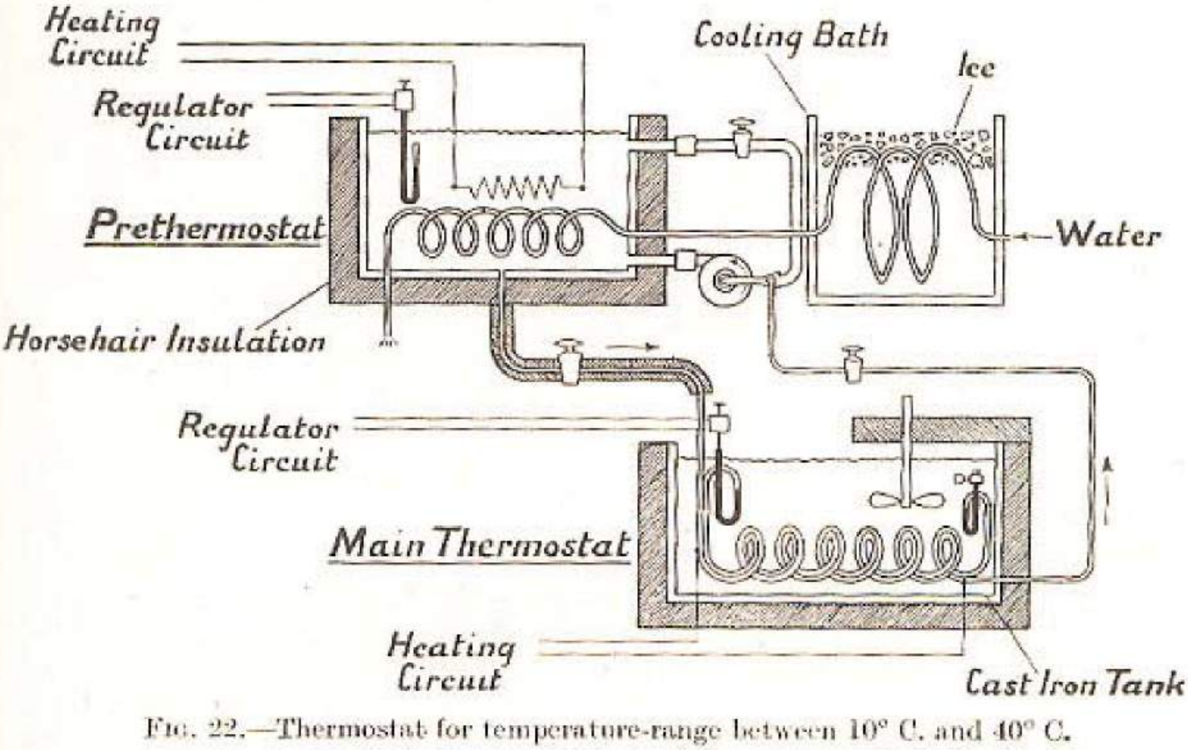

FIG. 22.—Thermostat for temperature-range between 10° C. and 40° C.

flow in the cooling coils, the latter being controllable by a valve. The pre-thermostat is cooled by the passage of ice-water from a constant-pressure system through a copper coil immersed in this bath, compensatory heating being obtained by a heating coil immersed in the bath and controlled by a toluene regulator. The temperature-difference between the two baths depends on the temperature desired. At 20° C. the best results are found to obtain with a temperature-difference of 0·2 to 0·4° C., but whatever this value, the difference must be constant to ± 0·005° C.

Heating of the main bath is accomplished by passing an electric current directly through the cooling coil, which is suitably insulated for the purpose. About 90 per cent. of the heating is continuous. The amount of this heating is regulated so as to be just insufficient to maintain the desired temperature. Additional current, controlled by a regulator wound in a similar form of coil to the heating-cooling coil, can provide supplementary heating more than necessary to maintain a constant temperature.

The system of using the same coil for heating and cooling has a number of advantages. Heat is liberated from the same surface as that from which cooling takes place, so that equilibrium between heating and cooling tends to be completed in the coil rather than in the bath. Since the area of the coil is large, the surface temperature rise is low, thus tending to minimize temperature pockets by reducing the temperature-gradient around the coils. Heating is practically instantaneous and the heat is liberated symmetrically throughout the bath, making violent stirring unnecessary.

A simple means of maintaining fairly constant temperature-values 5° or 10° below room temperature without the use of iced water and circulating coils, has been suggested by Garrett.[5] The terminals of a small fan are shunted across the heater terminals of a relay which is in series with the heater. When the relay circuit is closed by the regulator in the bath, the fan is shunted out of the circuit and a large current passes through the heater. On the other hand, when the relay circuit is opened, the fan runs at full speed but the heater current is cut down, due to the high resistance of the fan motor. The draught of the fan causes accelerated evaporation of the water in the bath, which is designed to have a reasonably large exposed surface. The humidity of the atmosphere should not be excessive, because efficiency of cooling depends upon it.

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CHAPTER IV

ACCURATE ROOM TEMPERATURE CONTROL.

CERTAIN bulky instruments require a constant ambient temperature, and this may often be most conveniently maintained by keeping the room, in which the instrument is situated, at a constant temperature. The need for such control can be exemplified in two cases, viz. that of an interferometer or of a concave grating, where temperature variations of about 0·1° C. are large enough to reduce the resolving power to half its attainable value ; and that of creep tests on metals, where temperature is obviously an important factor.

More accurate control of temperature is desired in such cases than in the adjusting of temperature for comfortable room conditions, where other coarser or simpler forms of thermostats suffice. These latter are described elsewhere.

Conditions similar to those in the laboratory air-baths previously described apply in room control, but on a larger scale. Especially is the concentration of the heating elements in one position to be avoided, unless a high degree of turbulence of the air in the room has been arranged for. Otherwise, the risk of direct radiation from the heater on to the objects in the room is very great with such a concentration.

Vapour-pressure Regulators.—It must be borne in mind that air has a comparatively small heat-capacity, so that for sensitive regulation, the controlling and heating elements have to be carefully considered in their relation to the heat-capacity of the air in the room. It is frequently found that the volume of air to be controlled has a smaller heat-capacity than the thermostat, resulting in a corresponding sluggishness of response to temperature-changes. It follows, therefore, that it is an advantage to use a vapour which has a low heat-capacity as a thermostatic medium in the regulator. The change of vapour pressure with temperature in suitable volatile liquids is quite appreciable, that of ethyl ether, for instance, being about 2 cm. of mercury pressure increase for 1° C. rise. Regulators using these liquids are fairly easy to construct, and by reason of their form it is advisable, for safety, to make them at the place where they are to be used.

A description of the method of construction of one of these regulators has been published by Green and Loring,[1] and since certain precautions are necessary to obtain successful operation a somewhat full description will be given of the method they employed. Fig. 23 shows the regulator, together with the accessories for filling it. All the components are of glassware, apart from the two contacts which are sealed in pyrex, one at *A* consisting of a tungsten wire

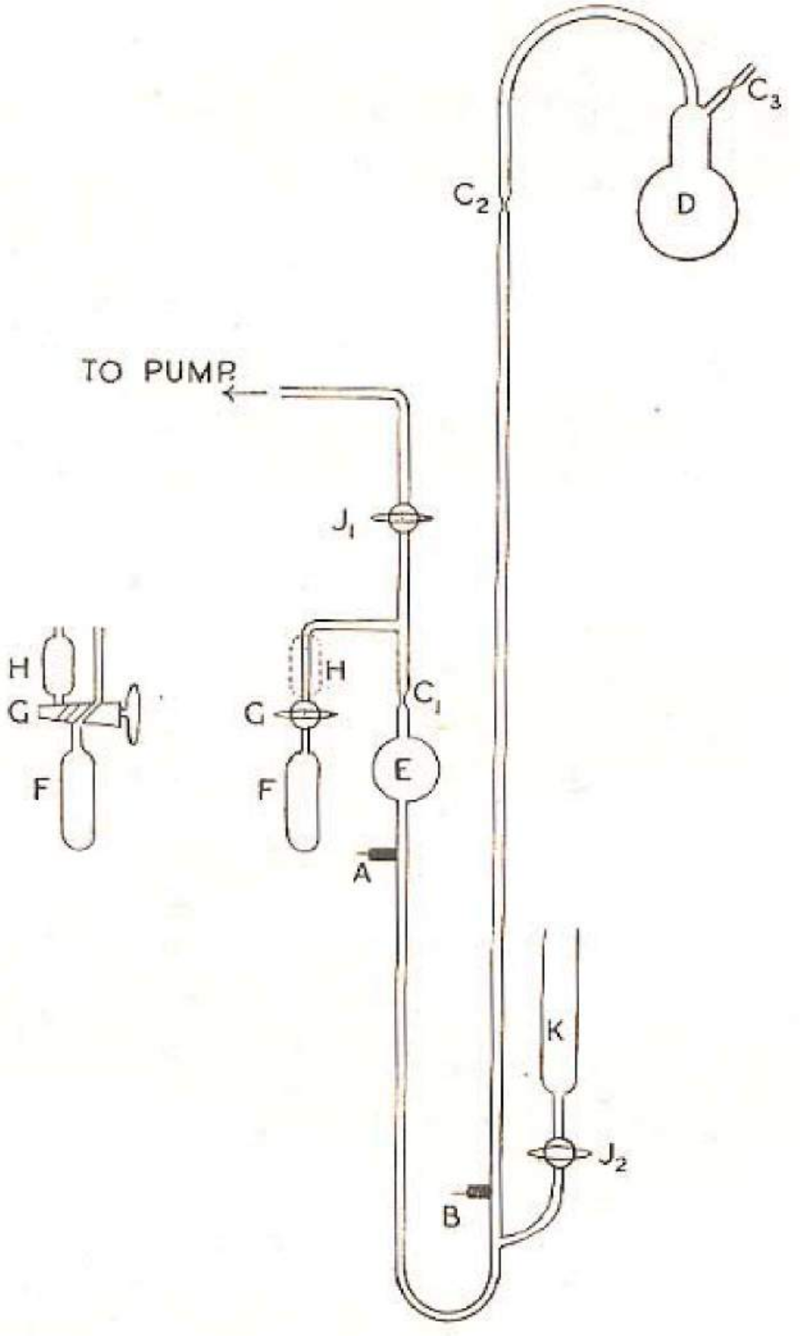

FIG. 23.—Vapour-pressure regulator with accessories for filling.

with a platinum tip, and the other at *B* of tungsten. An important essential, and one on which the successful final operation depends, is that the glassware be thoroughly cleansed. This can be done in the usual way with chromic acid, finally rinsing with distilled water. After the glass system has been cleaned and then dried by sucking dry hot air through the tubes, it is suitably supported to withstand the weight of mercury which is to be placed in it. Mercury is introduced into the retort D, and C_3 is sealed off. The system is then connected to a vacuum pump, with stopcock J_2 closed and stopcock G open to bulb F. When the pressure is as low as the pump will produce (preferably less than 0·1 mm. Hg), heat is applied to the retort D and mercury is allowed to distil into the system. When the mercury has attained a height of 35-40 cm. on each side of the U-tube, the heating is stopped. The bulb H is filled with carefully dried ether and the stopcock G turned to allow it to run into F. G is then closed and a little mercury put into H, to form a seal for G. The stopcock J_1 is closed and G opened to the system, when the bulb F can be very gently warmed (with the hand) until about 2 ml. of ether have collected on top of the mercury column. During this process the mercury column on the ether side drops by about 25 to 30 cm., with a corresponding rise in the other limb. The seal C_1 may now be sealed off, but in doing this care is required, or the ether vapour will blow out on heating ; it can be done in the following way. As much ether as possible is collected away from C_1 by cooling the system about A and E with ice or solid CO_2. The sealing can then be effected in the usual way. The cooling medium is removed and the mercury in D again heated. When the level of the mercury in the limb on the same side as C_2 is about 80 cm. above the stop-cock J_2, the heating is stopped, J_2 opened slightly and the mercury allowed to flow into K, and the stop-cock then closed. C_2 may then be sealed off.

To set the regulator, the following procedure is adopted. Allow it to attain equilibrium in the room where constant temperature is desired, then open J_2 slowly and allow mercury to rise about 1 cm. above the point A. If atmospheric pressure is low, it may be necessary to pump a slight amount of air from K to accomplish this. Close J_2. The regulator is then connected to a relay system governing the heat supply.

Other methods [2, 3, 4, 5] of regulation of room temperature are possible, but in all cases the form of the regulator, the form of heating, and method of mixing of the air have to be carefully considered in relation to each other. The importance of thorough mixing of the air cannot be over-emphasized.

The necessary extreme turbulence of the air in the room is achieved by Deighton [2] by the aid of eight or more electric fans suitably distributed in the room. One fan blows air over the elements of the fire or heater. This is made of low heat-capacity by supporting three sets of nickel-chrome wire resistances on light, rectangular uralite frames. These resistances are placed one behind the other, vertically. The expansion liquid used in the thermostat itself is paraffin, acting on a column of mercury in a U-tube. The U-tube contains the contacts. The paraffin is enclosed in a long " compo " pipe which is fixed around the room about a yard from the floor, ending, at the end remote from the U-tube, in a heat-absorber of gilled copper tubing of a form similar to the old type of motor-car radiator. This heat-absorber, fixed immediately behind the heater, is a special feature of the thermostat, and acts as a "brake" controlling the motion of the mercury in the contact tube after make and break of the current. The heater, owing to its small heat-capacity, cools rapidly when the current is cut off, and when this occurs, the fan in front of the heater blows cool air on to the heat-absorber, causing contraction of the paraffin in it and thus offsetting the continued rise of the mercury due to lag. Similarly, at "make," the heater warms up quickly and hot air is blown on the heat-absorber, causing the lag to be taken up as before. The size of the heat-absorber should be arranged so that the relay operates every 10 to 25 secs. It is essential that, if variations of atmospheric pressure are not to affect the thermostat, the whole of the "compo" tube and heat-absorber be filled with paraffin and free from air bubbles before sealing. A more uniform temperature in the room can be obtained if the heaters are split up as previously suggested and some of the heat is generated in the opposite part of the room. Suitable insulation of the walls of the room also assists in maintaining uniformity of temperature.

Solid-expansion Thermostat for Room Temperature Control.—Mention may be made of a thermostat[3] which, while not dependent on liquid-expansion but rather on solid-expansion, is, however, used for room temperature control such as is considered in this chapter. The sensitive element, a stainless steel strip 80 ft. long, ½ in. wide and 0·010 in. thick, is supported on pulleys around the walls of the room at a height of about a yard from the floor. Variations in length of the strip, magnified fifty times, cause a low-voltage relay to act which, in turn, through a magnifying lever of 6 to 1, causes the operation of a contactor to control a number of heating elements. In this way, slow movement of the first lever is converted, through the medium of the relay, into a rapid make and break in the second contactor, which controls a larger power-supply relay.

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CHAPTER V

MERCURY-EXPANSION THERMOSTATS.

The mercury-expansion regulators described in this chapter are in a different category from those described in Chapter III in that, in the latter, the regulators considered are those which are solely used to control the temperature of an air or liquid bath for laboratory work. In this chapter will be considered miscellaneous applications of the expansion of mercury in a somewhat different manner, for both laboratory and industrial purposes.

Mercury Thermometer Type.—One of the earliest, and still used, forms of thermostat, is that of a simple mercurial thermometer into which are fused two platinum wires connected in series with a battery and relay. One platinum wire is sealed into the bulb and the other at a predetermined point at a certain height which represents a definite temperature; the mercury thread completes the electrical circuit at that temperature. A suitable relay operates air, steam or gas valves as required. This form of instrument was originally designed for such purposes as maintaining greenhouses at a fairly even temperature, the relay opening a cold air valve when the maximum temperature was reached.

By sealing in a number of platinum contacts at various points along the length of the bore of the thermometer, any of these contacts may be selected, according to the temperature required.

An adjustable form of instrument is available, in which one terminal is connected to a small spiral of platinum wire inside the bore. A glass capsule containing a short piece of iron is located at the top of the thermometer tube, to which is attached a length of platinum wire passing through, and making contact with, the platinum spiral and forming the upper contact. The capsule can be moved up and down in the tube by means of a permanent magnet applied externally, and hence the regulator can be arranged to make contact at any temperature within the range of the instrument. (See Fig. 24.)

These thermostats may be made to operate control-valves through a thermionic relay.

A maximum and minimum thermometer can be fitted with adjustable contacts and used to indicate by audible or visible means whether the temperature is too high or too low. Another way in which this can be achieved with the ordinary type of mercury thermometer thermostat is to have "high" and "low" points. For the "high-point" alarm an open circuit is used, which the mercury itself closes as it reaches the upper platinum wire. For the "low-point" alarm a closed circuit is used, which the mercury opens as it recedes below the lower platinum wire. The alarm device is actuated by means of a relay which completes a secondary circuit when the mercury circuit is broken.

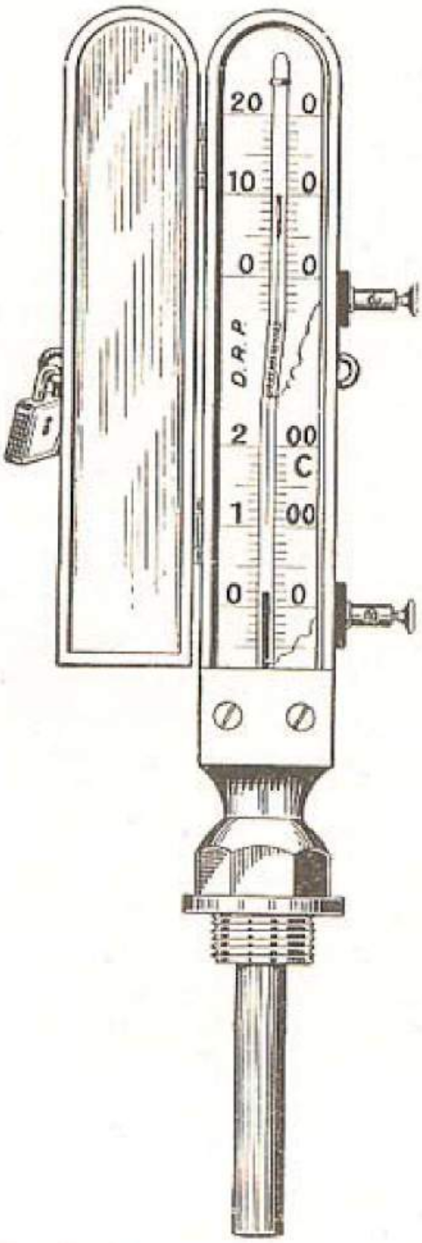

FIG. 24.—Isenthal's adjustable-contact type mercury-thermometer thermostat.

An apparatus depending upon the expansion of mercury to regulate temperature in a somewhat different manner, viz. by utilizing its mass, will now be described. This apparatus consists of a double-walled vessel, the space between the walls containing a liquid having a higher boiling-point than the temperature at which the space inside the walls is required to be kept constant. In this liquid is immersed a vessel full of mercury, with the outlet drawn out to a capillary tube, also full of mercury. The open end of this capillary tube dips into mercury contained in a cup which is attached to a ring encircling the outer vessel. This ring is balanced about a diameter by two pivots in the sides of the vessel, and is attached by means of a lever to the gas-cock. The ring is balanced for a required temperature by means of weights on its opposite side to compensate for the mercury ejected up to this temperature. When the temperature increases or decreases beyond the required temperature, mercury flows out of or into the vessel in the bath, unbalances the ring, and correspondingly moves the lever which controls the gas-supply valve. One of the principal difficulties in the use of this thermostat is that of obtaining a freely-moving gas-cock.

Voltage Regulator.—A regulator has been devised by V. H. Stott,[1] which, whilst not controlling the temperature directly, does so indirectly by keeping constant the root-mean-square voltage applied to the furnace terminals. It must be pointed out that the temperature of the furnace will not be maintained at a constant value where there are large fluctuations of room temperature over long periods. With the regulator in normal operation, the voltage remains at a certain minimum value (subject to mains fluctuations) for about

10 seconds, after which it is raised some 20 per cent. and remains at the higher value for about the same length of time. The cycle is repeated indefinitely, and the times during which the maximum and minimum voltages are applied are adjusted automatically so as to maintain a constant mean square voltage per cycle. The ratio of the maximum to the minimum voltage may be varied to suit

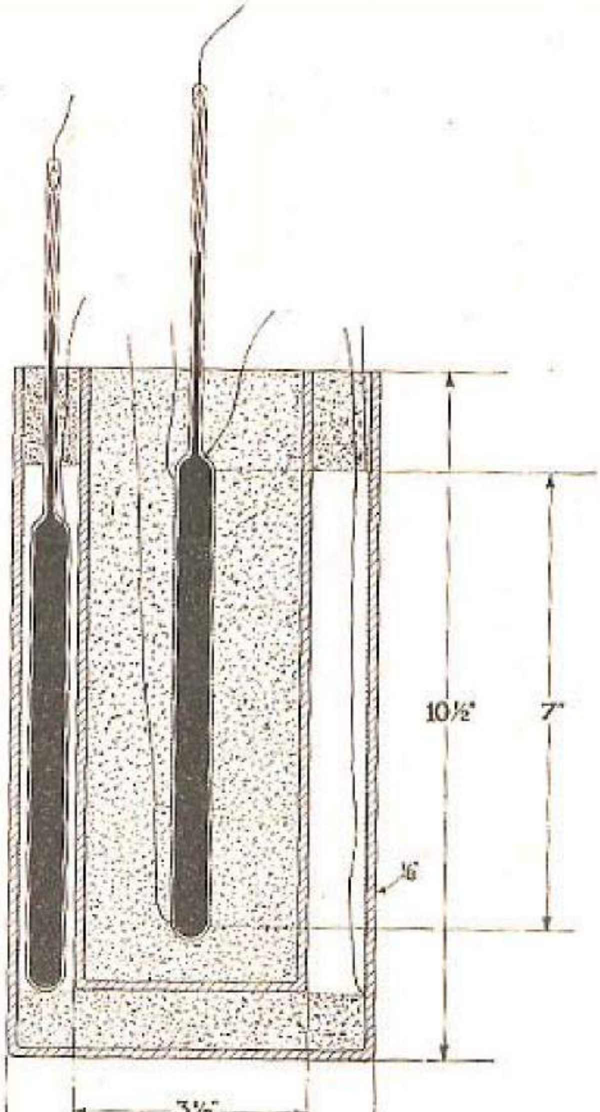

Fig. 25.—Arrangement of mercury thermometers in Stott regulator.

different circumstances. As the extra voltage becomes greater, the time of a completed cycle of control becomes less, the two magnitudes being roughly inversely proportional. The cyclic period is too small to affect the temperature of a furnace of ordinary size.

The regulator (Fig. 25) consists of a bulb containing mercury, wound with a heating coil which, in series with an adjustable resistance, is shunted across the points in the furnace circuit where voltage control is required.* A platinum wire is sealed into the bulb and another into a capillary tube projecting from the bulb. The bulb and capillary function like a mercury thermometer. The platinum wires are connected to the input side of a delicate relay containing a mercury-tilting switch. The output side of the relay is associated with the furnace circuit in such a manner that contact of the mercury with the upper platinum wire reduces the main furnace current. With suitable adjustment of the maximum and minimum currents, the temperature of the central thermometer is maintained automatically at 125° C. Energy proportional to that supplied to the central thermometer is supplied to the furnace. In order that this energy may be affected as little as possible by variations in the

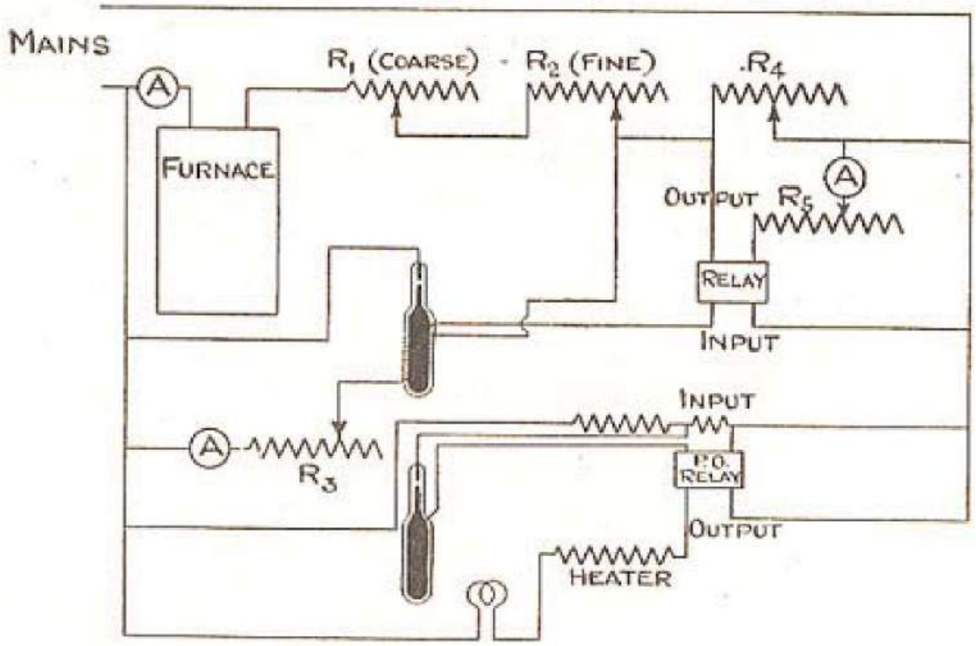

FIG. 26.—D.C. connections of Stott regulator.

temperature of the room, the bulb with its capillary is placed in a large vessel, the annular space between the two being kept at a temperature of 50° C. by means of a heating coil on the inner surface of the outer pot. The current through this heating coil passes through the output circuit of a post-office relay controlled by a mercury thermometer, so that thermostatic action is achieved.

The wiring diagram for D.C. mains is shown in Fig. 26. In the case of A.C. mains, direct current must be used to operate the relays. For a given value of R_3 it is possible to calibrate the furnace temperature, when in final equilibrium, in terms of R_1 and R_2. It is necessary to see that the proportional change of voltage produced by the regulator is considerably greater than any such change likely to occur in the mains voltage.

* These points may either be the terminals of the furnace, or rheostats may be included for convenience of control.

It is possible to adapt the apparatus for slow-heating or cooling.

After some experience with this thermostat, it was found that the end heat losses were greater than was originally supposed. They may be eliminated by using a narrower and taller outer pot and arranging the lagging so that there is an air space round the top and bottom of the inner pot, as well as round the sides. The narrower pot is placed eccentrically so as to leave room for the outer bulb. The eccentric arrangement also facilitates the circulation of air by convection.

Reference to Chapter V.

Stott, *J. Sci. Instr.*, 1931, **8**, No. 10, 313-316.

CHAPTER VI

CLASSIFICATION OF CONTROL EQUIPMENT.

BEFORE proceeding to a consideration of some industrial types of regulators, it may be advisable to explain some of the terms used in connection with these regulators or controllers. Despite the tremendous variety of these instruments, the majority are based on three main methods of control, which may either be in their original form or in combination with each other; a limited number of mechanisms employ derivations of these systems.

(1) **The "On-and-Off" Method of Control.**—Other terms applied to this category are: "two-position," "open-and-shut," "fixed-position" and the various "——stats." The French term is very apt: "*tout ou rien.*"

The on-and-off method of control is the most primitive and is characterized by the fact that the controls—meaning valves or contacts—can be in one of two positions. In one position the temperature is too low, and in the other too high. A sudden movement of the controls takes place from one position to the other. It is evident that a permanent oscillation of temperature must result, with an amplitude and frequency depending on the characteristics of the plant and on the extent of the variations in the conditions caused by the control. In the "three-point control," three positions are provided, one lying about half-way between the other two. The temperature is just correct when the controls are in the middle position. When the conditions change, to make the temperature depart from the desired value by a certain small amount, movement of the controls takes place. On-and-off control using simple globe or balanced-disc valves is simple and cheap, particularly where large valve-sizes are required. The on-and-off method of control is the one normally used in laboratory thermostats using electrical heating.

(2) **The Proportional Method.**—This type is also called "corresponding control" and "throttling control," the latter due to the definitely allocated band of values (termed the "throttling band") in which the mechanism acts. This band may either be "narrow," say less than 10 per cent. of the scale width, or "wide," in which case the band of proportional response may extend in some cases over the full scale-range of the instrument. In the "on-and-off" system, small deviations of temperature cause the same movement of the controls as large deviations, and it would sometimes be more con-