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THE CONTROL OF TEMPERATURE
BY THE VARIATION OF BALANCE
IN A WHEATSTONE BRIDGE

THESIS FOR THE DEGREE OF M. S.
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THE CONTROL OF TEMPERATURE
BY THE VARIATION OF BALANCE IN
A WHEATSTONE BRIDGE

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THESIS

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INTRODUCTION

In the manufacturing structure of present-day industries, many processes in the fabrication of the products require that the temperature be known within a very small percentage of its absolute value. Not only is the measurement of temperature important, but also that temperature must be kept constant in many cases. In other words, many manufacturing processes depend directly upon the control of temperature within very narrow limits.

Many instrument manufacturers have recognized this need for control devices and have placed on the market apparatus which employs the better known methods of thermometry, associated with the necessary equipment for controlling the temperature of drying racks, heat treatment furnaces, isolated "temperature boxes," and many other installations which require a constant temperature.

In these instruments, however, the manufacturers have either overlooked or ignored one of the simplest and most accurate of thermometric devices, the electrical resistance thermometer. This device is not unknown in the scientific field; Seimans first introduced it in 1871, and its development was carried on by many scientists, notably Callendar, Griffiths, Thompson, E. H. Mueller, H. C. Dickenson, and T. S. Sligh. This simple device has not been applied to the field of temperature control.

This thesis is not, therefore, the introduction of a new and different apparatus, but is a presentation of the adaptation of the principles of electrical resistance thermometry to the problem of the control of temperature. In their proper order will be considered the various general thermometric principles, the theory of resistance thermometry, the problem of temperature control, and, finally, the construction, calibration and operation of a temperature control

calibration and operation of a temperature control apparatus depending for its operation upon the variation of resistance due to the heating of a resistance coil which forms one arm of a Wheatstone bridge circuit and the unbalanced conduction of the bridge circuit resulting from that resistance variation. The sections on thermometry, temperature, and resistance thermometry are included for the purpose of giving a clearer into the nature of the problem discussed in this paper.

PART I

TEMPERATURE

There are two distinct questions associated with the concept of temperature; one is practical, the other is theoretical. Our primary ideas of temperature come from our senses; we know what we mean by the words "hot" and "cold", or by saying that one body is "hotter than another." For scientific purposes, however, words require definition. We are guided in this matter, as in all other scientific questions, by our knowledge of facts of observation.

When two bodies at different temperatures are intimately associated, e.g., a hot stone is dropped into a pail of water, our experience is that ultimately they come to the same temperature as far as our senses can tell; the hot body becomes colder and the cold body hotter. In the case of a block of ice immersed in water, the ice melts, forming cold water, which then mixes with the other water, the final result being water colder than the original water.

From our knowledge of the nature of heat phenomena, we learn that in this process one body loses heat and the other gains heat, the condition of thermal equilibrium being one in which each body gains as much heat as it loses. It is distinctly assumed in this statement that only two bodies are concerned in the transfer of heat, all other bodies being rendered in some way impervious to heat. The body that in the process loses heat is said to have the "higher temperature" while the body that gains heat is said to have the "lower temperature;" and, when thermal equilibrium is reached, the two bodies are said to have the "same temperature." Consequently, the temperature of a body may be defined, as it was by Maxwell, as "its thermal state considered with reference to

its power of communicating heat to other bodies."

Experience also proves that if we have three bodies A, B, and C, if A is at the same temperature as B and as C, then B will be at the same temperature as C. This fact is the basis of all methods of thermometry. For instance, if A and B are two bodies in thermal equilibrium, and if C is an ordinary mercury thermometer in equilibrium with A, then if C is placed in B, it will indicate the same "reading," showing that B is in equilibrium with it. This emphasizes an essential feature of the use of a thermometer: it must be in such a relation with the body whose temperature is desired that these two bodies are in a complete thermal equilibrium.

Experiments have shown that we have at our disposal in the laboratories many methods by which definite thermal states can be secured. For instance, when a rod of copper is placed in a mixture of ice and water, it always assumes the same length, regardless of where or when the experiment is performed; a piece of platinum will, in such a bath, always have the same electrical resistance, etc. We therefore believe that we are dealing with a definite thermal condition. The same is true of the steam rising from boiling water if the pressure of the air on the surface of the water is unchanged, and of countless other so-called "changes of state."

THERMOMETRY

The practical question of thermometry is to devise a method by which numbers may be given the temperature of any state of thermal equilibrium and, obviously, the method should be such as to assign a greater number to the higher temperature. The theoretical question is to learn what physical properties of the molecules of a body it is that

determines its temperature. Great difficulties instantly arise. Assume that we have adopted a thermometer and a thermometric scale and that it is possible to insert the thermometer into a flame in such a manner that it and the flame come into equilibrium; then, if there are two such types of flames under two conditions, we obtain numbers by the thermometer readings. Are they temperatures? Supposing one reading is 1500° and the other is 1000° ; does this mean that, when the two flames are placed in thermal communication, the former will lose heat and the latter gain heat? In such a case as this there are at least two causes of uncertainty: (1) Is the state of the flame such as to justify one in using the word "temperature" in connection with it? (2) Is the condition of the thermometer when it ceases to change such that it is in thermal equilibrium with the flame? This same uncertainty arises when one considers inserting a thermometer in an arc light, in an electric spark, in a vacuum tube carrying an electric discharge, and in numerous other cases.

Therefore in the preliminary discussion of temperature and thermometry we shall exclude all such cases, since they have no bearing upon this problem, and shall assume: (1) That the bodies to which temperature numbers are assigned are in thermal equilibrium free of all electrical and chemical changes, and (2) that the presence of the thermometer does not give rise to any such changes. Thermal equilibrium between the body and the thermometer is brought about by the processes of heat-conduction. The process of radiation is involved in those methods of thermometry in which the thermometer is not inserted in the body. It is convenient, therefore, to divide the subject of thermometry into two parts, one involving the insertion of the thermometer into the body, and therefore heat-conduction; the other, the use of the thermometer at a distance and therefore radiation.

CONDUCTION METHODS

In order to assign a number to a thermal state, it is impossible to make use of our temperature-sense, but an obvious method is to make use of some physical property of a definite piece of matter, which property changes in amount as heat leaves this body or is added to it and which can be measured; e.g., the length of a selected copper rod; the volume of a definite quantity of mercury held in some solid; the pressure of a definite volume of nitrogen; the electrical resistance of a definite platinum wire; etc. Such an instrument is called a thermometer. Of course it would cease to be useful if (1) its thermometric property ceased to change as heat was abstracted from it, or (2) it underwent such changes owing to its use that, when replaced in the same thermal state after such use, it gave a different reading. In some cases this second cause of trouble may be obviated.

Having selected a definite physical property of a definite body, for instance, the length of a copper rod, this length may be measured at two definite thermal states to which arbitrary numbers are assigned. Let the numbers be t_1 and t_2 , where t_2 is greater than t_1 , and let the measured quantities be a_1 and a_2 ; the ratio $\frac{a_2 - a_1}{t_2 - t_1}$ is chosen as the measure of a "degree." Then, for a number to be given the temperature of any thermal state, let "a" be the measured quantity in that state, the "t" the temperature of that state may be defined as

$$t = t_1 + \frac{a - a_1}{\frac{a_2 - a_1}{t_2 - t_1}} .$$

It is obvious that this is only one of a number of ways in which a method can be devised for assigning a number to the temperature; but it is certainly the simplest. This definition of "t" leads at once

to the proportion

$$\frac{t - t_1}{t_2 - t_1} = \frac{a - a_1}{a_2 - a_1};$$

and a reason for adopting it, apart from its simplicity, is that, when various "thermometers" are used, experiments made, taking advantage of a large number of definite thermal states, prove that the values of "t" do not differ widely. Of course they differ, but not as much as they would if a less simple definition were adopted.

In this connection another definition is useful; this is the "mean coefficient of change of 'a' between t_1 and t_2 with reference to t_1 ." This is obviously

$$\frac{a_2 - a_1}{a_1(t_2 - t_1)}$$

and may be written "a".

"Absolute zero" on such a scale is, by definition, the value "t" assumes when, in the formula, "a" is put equal to zero. This is quite regardless of whether or not it is physically possible to reduce "a" to zero by any means. Calling this calculated value " t_0 ", we have

$$t_0 = t_1 - \frac{a_1}{\frac{a_2 - a_1}{t_2 - t_1}} = t_1 - \frac{1}{a}.$$

The "absolute temperature" on such a scale is defined to be " $t - t_0$ "; and calling this t_a , we have

$$t_a = \frac{1}{a} + \frac{a - a_1}{\frac{a_2 - a_1}{t_2 - t_1}}.$$

On the Centigrade system, which is now universally adopted, the two standard thermal states selected are those of "equilibrium of ice and water" and "equilibrium of water and steam," both under a pressure of 76 centimeters of mercury; and to this interval of temperature

the number 100 is given. Hence, on the Centigrade scale,

$$\alpha = \frac{a_2 - a_1}{100a_1},$$

$$t_a = \frac{1}{\alpha} + 100 \frac{a - a_1}{a_2 - a_1}.$$

If the ordinary scale, not the absolute one, is used, it is necessary to assign also a number to either of the thermal states, and in all the scientific measurements it is customary to give the number zero to the temperature of "melting ice." Thus,

$$t = 100 \frac{a - a_0}{a_{100} - a_0},$$

$$t_0 = - \frac{100a_0}{a_{100} - a_0}.$$

Certain obvious facts should be noted:

1. If different properties of different bodies are selected for thermometric purposes, that is, if different thermometers are used, different values of "t" will be obtained for the same thermal state.
2. The value of absolute zero will be different for different thermometers.
3. The value of absolute zero does not have any physical importance.
4. To say that a body expands uniformly with changes in temperature has no meaning unless the particular thermometer used to give the numerical values of the temperature is specified.

Any one thermometer may be calibrated in terms of another and the demands of scientific statements require that all temperatures quoted in reports should refer to the same instrument. In order to comply with these demands, a definite temperature scale has been adopted for this report. This scale is known as the "Centigrade scale" and was adopted

because of its general use in scientific investigations which are dependent upon temperature.

RADIATION METHODS

The thermometric methods just described are evidently not applicable to extremely hot states, e.g., the carbon poles of an arc light, furnaces, etc. Instead, therefore, of attempting to secure thermal equilibrium between a thermometer and the hot body, application may be made of the facts that all bodies are radiating energy, that the amount of energy radiated varies with the temperature of the body, and that this energy may be measured. It is easily observed that the surfaces of different bodies, when at the same temperature, emit different amounts of radiation, but Kirchhoff proved, from theoretical considerations, that if a hollow is made in a solid body maintained at a constant temperature, the radiation out of the body through a small opening in the wall is independent of the nature of the solid and is a function of temperature alone. Such radiation is called "black-body radiation"; and it is, as Kirchhoff proved, greater than is emitted from the surface of any body at the same temperature, provided this emission is due solely to the thermal state of the body, that is, is not due to what has been called "luminescence." If it were possible to obtain a body that would absorb all the radiation incident upon it, it would be called a black body and its surface would emit the same radiation as the enclosure just described, at the same temperature.

The radiation from such an enclosure is, then, a measure of its temperature, and it is possible to define, in any way deemed desirable, a new scale of temperature in terms of the radiation "E" emitted per unit of time through an opening of unit area. Simple observation

proves that the radiation "E" increases with the increase of temperature "t", so possible scales would be

$$t = AE, \text{ where } A \text{ is an arbitrary constant,}$$

$$t = AE^2 + BE, \text{ where } A \text{ and } B \text{ are constants,}$$

$$t = AE^3 + BE^2 + CE, \text{ where } A, B, C, \text{ are constants, etc.}$$

Naturally one would select such a definition as would make "t" on this new scale have, if possible, the same value as "t" on some standard scale, e.g., a gas thermometer using the Centigrade scale, for those thermal states that are not so hot as to preclude the use of such a conduction instrument. Experiments have shown that if the definition adopted is

$$E = A(t + 273)^4$$

where A is a definite constant, this condition is satisfied. This new scale may be called "radiation temperature." Obviously, it may be used for temperatures far beyond the range of gas thermometers.

Further, if the radiation from the surface of any body is measured, this same formula in the form $AS^4 = E$ may be applied, and the numerical value of S may be deduced. The value of S is called the "black-body temperature" of the body, but this number is obviously less than 273 plus its true temperature. The true temperature may be obtained in certain cases, however, by an indirect method. If the body is one whose properties are conditioned by its temperature, we have the law:

$$\text{Reflection coefficient} + \text{transmission coefficient} + \text{emissivity} = 1.$$

Let us assume that these first two may be measured. The emissivity is, by definition, the ratio of the emission of the body to that of a black body at the same temperature. Hence, calling the

reflection coefficient "R", the transmission coefficient "T" and the black-body temperature of the body "S"

$$\frac{S^4}{(t + 273)^4} = 1 - R - T$$

and therefore "t" may be calculated.

Other radiation methods have been evolved. If that part of the radiation from a black body is due to waves having wave-lengths in the range from λ to $\lambda + \Delta\lambda$ is called " $E_\lambda \Delta\lambda$ ", experiments prove that for radiation in the visible spectrum, through a range of temperatures where a gas thermometer may be used

$$E_\lambda = c_1 \lambda^{-5} e^{-\left[\frac{c_2}{\lambda(t + 273)}\right]}$$

where "t" is the gas-thermometer temperature and " c_1 " and " c_2 " are definite constants. Therefore the formula may be used to define a new temperature scale, especially for hot bodies; and the value of "t" obtained agrees with both those given by the radiation method and the conduction method previously described.

Both the radiation formulas for black bodies:

$$\text{Total radiation} \quad E = A(t + 273)^4 \quad (\text{Stefan's Law})$$

$$\text{Partial radiation} \quad E_\lambda = c_1 \lambda^{-5} e^{-\left[\frac{c_2}{\lambda(t + 273)}\right]} \quad (\text{Wien's Law})$$

have a thermodynamic foundation. It may be proved from thermodynamic reasoning, with certain assumptions, that the total and partial radiations from a black body obey the laws

$$E = AT^4 \quad \text{and} \quad E_\lambda = c_1 \lambda^{-5} e^{-\left[\frac{c_2}{\lambda T}\right]}$$

where "T" is Kelvin's absolute temperature. Therefore radiation methods will give us a knowledge of Kelvin's temperature for very hot bodies, for in order to define the Kelvin scale, it is sufficient to assign an

arbitrary number to some one thermal state, e.g., 373.36 to that of boiling water; then "E" may be measured for a black body having that temperature and "A" may then be calculated; or, using two known values for "T" for definite thermal states, " c_1 " and " c_2 " may be found, consequently the constants being known, "T" will be given by measurement of "E" or "E".

The results of experiments of porous-plug expansion are to show that over the range of temperature between melting ice and boiling water, absolute temperature $T = t + 273$, approximately, where "t" is the temperature measured by an ordinary thermometer of the Centigrade system, and radiation experiments prove that the same is true approximately for higher temperatures, as far as a gas thermometer can be used, that is, the constants in the foregoing formulas are the same regardless of what method is used to obtain them.

In this particular problem, the temperature range used is approximately that from melting ice to boiling water (0° C. to 100° C.). In this range the effect of radiation is neglected and it is assumed that temperature will be measured by the heat-conduction method. Further, the heating apparatus is so constructed that radiation is replaced by convection, or the transfer of heat is by circulation of heated air.

THEORY OF TEMPERATURE

In the discussion of both conduction and radiation methods, care has been taken to exclude from consideration bodies in which chemical or electrical actions are going on and bodies that were not in what has been called statical equilibrium. The question now arises as to whether or not it is allowable to speak of the temperature of such bodies. Light is thrown upon this from the dynamical study of the

properties of bodies, considering them formed from molecules. It has been proved that for a gas in a state of equilibrium, that is, when it is not flowing or in a turbulent condition, there is an intimate connection between its mean kinetic energy per molecule and its temperature. If "m" is the mass of each of its molecules, and if "u", "v", and "w" are the components of the velocity of the center of mass of any one molecule in the three coordinate planes, we may write for the mean kinetic energy of translation of the molecules

$$\text{K.E.} = \frac{1}{2} (mu^2 + mv^2 + mw^2).$$

It has been proven that $mu^2 = mv^2 = mw^2 = RT$, where "R" is a definite constant and "T" is Kelvin's absolute temperature. If we consider the Centigrade system and use other deductions from the kinetic theory as applied to actual gases, it is found that $R = 9.3 \times 10^{-17}$ approximately. Further, if the molecules have kinetic energy of rotation, each of the "degrees of freedom" has an amount of mean kinetic energy equal to $\frac{1}{2}RT$. So far as the mean kinetic energy of translation is concerned, this equals, therefore, $\frac{3}{2}RT$; and the same is true of solids, liquids, and the "free electrons" in solids. It is clear, then, that for a body not in a state of statical equilibrium it is not allowable to use the word temperature. This means that the word should not be used with reference to a single molecule or to such phenomena as occur in most flames, or in an electric spark or discharge. It is true that bodies placed in flames, sparks, etc., may assume definite temperatures, but this does not affect the statement just made.

From the standpoint of experiment, the fundamental question is to determine when a body is in a state of statical equilibrium and, therefore, has its properties conditioned by temperature. Unfortunately

this cannot be done with certainty in all cases; general principles are the only guides.

There are, however, certain cases in which the body is not in thermal equilibrium, and where the word "temperature" may be used. Consider a pail of water placed on a stove; we say that its "temperature rises," thus attaching a meaning to the word at that instant. Again, consider a current of air moving with uniform velocity; if a thermometer were to move with the air at the same velocity; it would register the true temperature of the gas, but this temperature is not that which would be indicated by a thermometer at rest in the moving air, nor is it the temperature of the solid walls of the tube through which the air is flowing. We may obtain the temperature of conditions which are merely relative to the position and movement of the temperature and the air. We may often think of certain limits of temperature between which a certain body must lie when it is not in a condition of equilibrium; thus, one limit would be that which corresponds to its mean molecular kinetic energy of translation. But, in general, it is safest to limit the use of the word "temperature" to bodies in the state of equilibrium and then even to those bodies for which there is reason for believing that their state is conditioned by their mean molecular kinetic energy.

However, in this paper there will be no attempt to consider the effects produced and the data gathered with any regard to this property of mean molecular kinetic energy. This property merely is introduced as a method by which one may determine the approximate action of any particular body with reference to its temperature. The calibration of the device later considered is not in any way associated with this particular theory.

PART II

ELECTRICAL RESISTANCE THERMOMETRY

One of the simplest and most accurate means of temperature measurement is the use of the electrical resistance thermometer. The temperature coefficient of electrical resistance of pure metals is high and, therefore, the resistance increases rapidly with rising temperature. In 1871, Siemens suggested the use of this property as an accurate means of temperature determination. Owing to practical difficulties, particularly the contamination of the metal and consequent permanent change in its resistance and its resistance-temperature characteristic, this method fell into disrepute as a practical standard until revived later by Callendar and Griffiths, and subsequently by Holborn and Wien, all of whom showed that the earlier difficulties were not inherent in the method but incident to the mode of protection of the resistance coils. Following the work of these investigators, the problem of temperature measurement by this means has been the subject of careful study and has assumed an importance second only in practical adoption to the thermoelectric method. It is well, at this time, to consider some of the features of electrical resistance thermometry.

It is generally recognized that the standard temperature scale should be the thermodynamic scale as it permits the evaluation of high temperatures on the basis of the radiation laws of Stefan and Boltzmann, of Rayleigh, and of Wien and Planck, on a scale consistent with that obtained by means of the gas and mercury thermometers at low temperatures.

For the standardization of the resistance thermometer, we are limited, for all practical purposes, to the fixed points of the standard

scale falling within the range of practical usefulness of the resistance thermometer. These are, in the case of the platinum thermometer, the freezing point of mercury at $-38.83^{\circ}\text{C}.$, the melting point of ice at $0^{\circ}\text{C}.$, the transition point of sodium sulfate at $32.384^{\circ}\text{C}.$, the vapor of water boiling under standard atmospheric pressure at $100^{\circ}\text{C}.$, the boiling point of naphthalene at $217.96^{\circ}\text{C}.$, the boiling point of benzophenone at $305.9^{\circ}\text{C}.$, and the boiling point of sulphur at $444.5^{\circ}\text{C}.$

The temperature on the international scale is then deduced from the formula

$$t - pt = \delta \frac{t}{100}^2 - \frac{t}{100}$$

where $pt = 100 \frac{R - R_0}{R_{100} - R_0}$ and R , R_0 , and R_{100} are the measured resistance of the thermometer at the temperatures t° , 0° , and 100° respectively.

Over the limits of this scale, the variation of the platinum resistance thermometer scale from the standard scale of the International Bureau lies within the limits of experimental error and for most practical purposes the correspondence is sufficiently close as low as the boiling point of oxygen, $-182.9^{\circ}\text{C}.$, and as high as the boiling point of copper, $1083^{\circ}\text{C}.$ in reduced atmosphere. The accuracy within these wide limits, as determined by various experimenters, has shown some variation and might well be made the subject of a careful and thorough investigation. For use in making resistance thermometers, the platinum should be of such purity that the value of " δ " in the above equation is not greater than 1.52 and $\frac{R_{100}}{R_0}$ should not be less than 1.386.

ADVANTAGES OF ELECTRIC RESISTANCE METHOD

The resistance method of temperature determination possesses for the practical range of the instrument, as indicated in the foregoing,

several very important advantages over all other methods of measurement. The temperature coefficient of pure platinum is such that for an increase of temperature from 0° to 300° C. the resistance of the spiral is more than doubled and this increase is maintained at practically the same rate up to the highest temperatures. Knowing the high degree of accuracy with which electrical resistance may be determined by relatively simple apparatus, the great sensitiveness of this method is at once apparent. Using the usual Wheatstone bridge method in one or another of its forms, the temperature scale on commercial instruments can be arranged for any desired interval. Taking a common type of galvanometer, the instrument may be graduated directly in degrees, for any desired range, say from 600° to 700° C. Such a scale can be read without difficulty to one-fourth of one degree. In comparison with the thermoelectric instrument in which the scale must always start at zero, the increase in sensitiveness of the electrical resistance method is very great. A further advantage of the electrical resistance method is the avoidance of the cold-junction errors inherent in the thermoelectric device.

LIMITATION OF ELECTRICAL RESISTANCE METHOD

For practical purposes, the range of the electric resistance thermometer covers the field from -200° C. to $+900^{\circ}$ C. For the measurement of temperature by this method, an outside source of current is necessary, and for most commercial instruments of the direct-reading type, a storage battery is used to provide this current. The care of the storage battery under circumstances where direct current is not available for charging is one disadvantage of this system. This may be overcome by the use of dry-cells, but owing to the inconstancy of the dry-cell voltage, the remedy is rather worse than the disease.

CONSTRUCTION AND PROTECTION OF RESISTANCE SPIRALS

Platinum is most generally used as the resistance metal. It can be readily obtained in a chemically pure state and is applicable to a wide range of temperature. Iridium, palladium, and rhodium have all been suggested but are not in commercial use. The cost of platinum is rather prohibitive and therefore nickel is sometimes used. However, nickel is not recommended for temperatures higher than 250° C., owing to the change in the resistance-temperature characteristic curve as the transition temperature of nickel is approached. According to Marvin¹ the equation $\text{Log } R = a + mt$, where "R" is the resistance of the nickel, "a" and "m" are constants determined by the physical, chemical and electrical properties of the nickel, and "t" is the temperature of the nickel, holds very closely for the range from 0° to 300° C. for the resistance of nickel. Molten tin was recommended in 1916 by E. F. Northrup and R. C. Sherwood², who found that the resistance-temperature relation gives a straight-line curve up to temperatures between 1500° and 1700° C. This material is useful, however, only for temperatures above +231.9° C., the melting point of tin.

One common method of mounting the resistance wire is that devised by Callendar. It consists of crosses, serrated mica plates on which the platinum wire is spirally wound. This form is used by the Leeds and Northrup Company and by the Cambridge Scientific Instrument Company, though in some cases Leeds and Northrup replace the mica frame by steatite, a heat-resisting, insulating compound. With this form of

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1. Electrical Resistance of Nickel to 300°C. Physical Review 30:522-528
 2. Journal of the Franklyn Institute. 1916

spiral, it is necessary, in order to protect the platinum from contamination when exposed to high temperatures, gases, or acid fumes, to mount it in an impervious tube such as glazed porcelain, usually protected on the outside by a tube of iron or nickel. For very high temperatures, the Leeds and Northrup Company uses a form of potential lead thermometer. Heavy wire is used in the coil and is freely suspended between steatite disks. Owing to its very low resistance, special precautions are necessary with this instrument to obtain a satisfactory degree of sensitivity.

Another type of spiral is that manufactured by the Hanovia Chemical and Manufacturing Company, in which the platinum spiral is wound on a thin tube of transparent quartz with an outer jacket of the same material melted down onto the inner core so that the platinum wire is firmly imbedded in the quartz. This construction gives an instrument of very small volume in which the resistance wire is thoroughly protected from the influence of dirt and reducing gases. Owing to the small volume of this instrument, this form of thermometer follows temperature changes very rapidly and each spiral can be accurately adjusted to a standard resistance within approximately 0.05 per cent. This standardization of the resistance coil obviates the necessity of auxiliary manganin or constantan coils in the headpiece used with other types of resistance thermometers. For the most accurate calorimetric work, this construction is not to be recommended, owing to the slight changes in the constants of the equation. This change, however, is not of sufficient magnitude to impair the accuracy for ordinary laboratory and industrial measurements. As mounted for industrial use in a steel or copper tube, or in a perforated sheath for air temperatures, the quartz-mounted resistance thermometer forms a very rugged and convenient instrument.

When measuring at high temperatures, the resistance of the

leads to the thermometer, graduating from the high temperature to be measured down to the comparatively cool headpiece, require special precautions to avoid the introduction of errors. In the quartz thermometer above described, this source of error is eliminated by terminating the leads immediately above the spiral and continuing the electrical connection with the headpiece through heavy metal rods of low temperature coefficient. The method originally suggested by Siemens and adopted by Leeds and Northrup Company for industrial use consists of a third lead of the same wire connected to one of the thermometer leads. This loop is connected in series with the balancing rheostat or resistance in the bridge and accurately compensates for the lead resistance when zero-deflection instruments are used. In an instrument which is calibrated against a very accurate standard, this method is unnecessary since the difference in resistance of the two bridge arms is compensated for in the calibration.

COMMON TYPES OF MEASURING APPARATUS

Any of the usual methods of measuring electrical resistance may be applied to resistance thermometry. For precision work, where high laboratory standards of accuracy are required, either the Kelvin double bridge may be used or the potential drop measured across the terminals of the thermometer. A very sensitive arrangement is the thermometer bridge designed by the Governmental Bureau of Standards³ and manufactured by the Leeds and Northrup Company, using a four-lead thermometer to compensate for the temperature rise in the thermometer leads.

For most industrial instruments, however, the method in general use is almost entirely some modification of the Wheatstone bridge. All of the resistance coils of the bridge are of fixed values

3. Bulletin of the Bureau of Standards 13(4):547-561. 1916

and the variations in the thermometer temperature are graduated on the galvanometer scale. By selecting the corresponding resistance value for the adjacent arm of the bridge, the temperature scale is so arranged as to begin at any desired value of temperature.

The other system in use is that of the ohmmeter. This method is used somewhat by the Leeds and Northrup Company. In it a variable resistance, that of the thermometer, is balanced against a known resistance by means of a zero-point galvanometer reading. The temperature scale is usually indicated by a dial and pointer on the resistance box. For temperature indicating in shop practice, Leeds and Northrup use a slide-wire balancing resistance graduated in degrees of temperature with a center-zero voltmeter as an indicator. The slide-wire resistance is adjusted to correspond to the temperature desired and the indicator shows a deflection, plus or minus, as the temperature is higher or lower than that for which the balancing resistance is set.

In the direct-reading type of instrument, a recording galvanometer is often substituted for the indicating type, very much similar to the recording devices used with thermocouples in heat-treatment furnaces.

All in all, the resistance thermometer over the range for which it is applicable provides the most convenient and reliable method of temperature determination, particularly where the measurements are required at one central point or some distance from the heat. They possess, generally speaking, greater freedom from errors liable to be overlooked in other types of instruments. With reasonable care in use, they are little subject to disturbances in operation, can be calibrated for any temperature range desired, and with suitable protection almost any degree of sensitivity can be secured for any desired temperature range.

PART III

TEMPERATURE CONTROL

The meaning of temperature control can be extended to cover not only the control of temperature but also the control of processes through a knowledge of the temperature involved. The list of industries in which temperature control is used in one way or another would cover nearly the entire industrial field. Suffice to say that temperature control enters into the manufacturing of nearly all commercial products.

GENERAL DISCUSSION OF THE PROBLEM

Some of the factors entering into the difficulty of temperature regulation are: Inconstancy of the heat supply, variation of internal absorption or generation of heat, variation of heat loss by radiation, and the unsteady supply or composition of the material to be heated. As each of these items is closely associated with temperature variation, there is little room for doubt that heat control is best accomplished with and through a knowledge of the temperature and the temperature variations. There are connected with this problem four general questions: How are the temperature and its variations to be best determined; where (in what part of the furnace, drying rack, or oven) is it to be determined; what is the best way in which the temperature may be indicated so that it will aid in control; can automatic temperature control be accomplished?

DEVICES USED FOR CONTROL

Automatic Alarm. -- An ordinary galvanometer movement can be fitted with two contacts on pivoted arms, between which the meter pointer

swings. No relay is necessary for the small current and voltage required to operate a bell or other alarm-signal device. The automatic alarm cannot be used in an installation where very accurate temperature control is necessary, since it merely warns of too high or too low temperatures and requires manual adjustment of the heating units.

Manual Signaling. -- The development of manual signaling has taken place, for the most part, in heat treatment plants having extensive pyrometric installations of such proportions that a central pyrometer station is necessary. With such an installation, only the thermocouples or other thermometric devices and the signal lights are located in the furnace room. Colored lights are used to flash the condition of the furnace temperature to the operator at the furnace. Here again accurate temperature regulation is impossible.

Automatic Signaling. -- Automatic signaling is, in fact, a combination of automatic alarm and manual signaling. The temperature is controlled manually as in the foregoing methods.

Automatic Temperature Control. -- The devices for automatic control of temperature may be classes as two general types, mechanical and electrical. The mechanical devices are those operating on the thermostatic principle and are ordinarily operated by means of movement of bimetallic springs, or the thermal expansion of rods or fluid columns. The electric devices, in general, are operated on the thermoelectric principle. The heating of a joint between two dissimilar metals generates an electromotive force which is measured by a potentiometer or a Wheatstone bridge. The control equipment in such a device may become very complicated in an effort to incure control within very close limits of the given temperature.

PRESENT METHODS OF CONTROL

At the present time there are on the market instruments for the control of temperature which are quite accurate in their operation. Of these devices, there seems to be two general types of thermometric methods in use, one being the mercury column and the other the thermocouple. These devices are manufactured by nationally known firms and be discussed, both with regard to their operation and their advantages.

Hiergesell Brothers, of Philadelphia, manufacture a regulating device known as the "Thermo-Regulator", consisting of a mercury column or thermometric instruments with contacts so placed as to be inserted in the mercury column, and an associated, special relay. The Thermo-Regulator responds to temperature variations as small as 0.05° C. It acts through a specially constructed relay without the necessity of using batteries, receiving its operating voltage and current from the commercial electric lines. The mercury is adjustable to operate the relay at any degree or fraction of a degree from -17° to 150° C. The adjustment of the thermometer is the undesirable feature. The thermometer is so constructed as to have a mercury reservoir at the bottom and also at the top of the glass stem. To increase the operating range of the instrument the lower bulb must be heated, driving some of the mercury into the upper reservoir. When cooled to the working range, the mercury breaks contact with the upper electrode at the temperature desired. For a lower setting, the instrument is heated in a horizontal position until the mercury thread makes contact with the pool in the top storage bulb. For any setting, accuracy is determined by the operator's ability to measure the temperature of the bulb by means of a certified standard thermometer.

The General Radio Company, of Cambridge, Massachusetts, is the maker of a temperature control box which employs a thermometric device of the above type. This apparatus controls the temperature within the box to within $\pm 0.1^{\circ}$ C. against changes in room temperature from 11° to 20° C. The operating temperature within the box is from 40° to 60° C., a very limited range. This range, however, is sufficient for the use for which the device was designed, i.e., the increase of frequency stability of a piezo-electric oscillator by controlling the temperature of the quartz crystal.

The General Radio Company also manufacture a temperature control box fitted with a bimetallic thermostat. This unit has the same operating range but the accuracy in this case is much less, being $\pm 1^{\circ}$ C.

Another type of control unit is that employed by Leeds and Northrup Company, of Philadelphia, and the Brown Instrument Company, also of Philadelphia. These manufacturers use thermocouples to measure the temperature by the generation of an electromotive force, created by heating a union of two dissimilar metals. The controlling device consists of a form of potentiometer and sufficient associated equipment to make the operation entirely automatic. The undesirable features of this method are that the thermocouple generates very small electromotive forces, the thermocouple unit has a natural thermal lag, the control equipment is rather complicated, and a reliable source of direct current, usually a primary cell, is necessary in the operation of the device. The thermocouples in general use are constructed of two wires, one of iron and one of constantan, which are joined firmly at the "hot" or measuring end. The greatest electromotive force generated by any commercial thermocouple is about 50 millivolts. Further, the thermocouple is not sensitive to small temperature changes or quick variations of temperature. This is

due to the natural lag of the unit. The thermocouple also must be associated with a cold-junction compensation device which is a correction applied to the thermocouple system to compensate for changes in room temperature and the temperature of the thermocouple leads. The advantage of this device is that a record is made continually of the temperature of the thermocouple. This is a part of the complicated mechanism previously mentioned. The device is much more reliable at high temperatures. The usual type of thermocouple is designed for the range from 150° to 1600°C . and is not easily adapted to the lower temperature range. The control device is accurate to approximately one-half of one percent of the range or about 1.5° in a 300° range. This accuracy is not sufficient for this problem.

TEMPERATURE CONTROL WITH RESISTANCE THERMOMETRY

In a previous section of this paper, the electric resistance thermometric device has been discussed. The problem which is the subject of this paper is the adaptation of the electric resistance method of temperature measurement to the field of temperature control. It has been made evident that the last word has not been written in connection with this subject. Therefore, attention is again directed to the simplicity of the device.

Electrical resistance thermometry is one of the most accurate and simplest devices known for temperature determination. Since several other thermometric devices have been used in the control of heat, it is only natural to believe that this device might be similarly used. Some of the difficulties and opinions arising in the connection with this subject will be discussed.

In the first place, by using a form of Wheatstone bridge,

it is possible to measure continuously the resistance of a coil even when its resistance is changing due to heat or elongation. This fact is the basis of the construction of this thermometric device. Therefore, a resistance coil must first be procured.

The resistance coil which can be used is one of platinum. Any laboratory instrument manufacturer can construct a platinum resistance thermometer similar to the original device of Callendar, or even one of the more advanced designs such as the calorimetric thermometer designed by the Bureau of Standards.

The three resistance units of the bridge circuit can be any commercial type, the resistance of each being accurately determined.

Now, consider what means may be used for the control of the temperature. The galvanometer ordinarily used with the Wheatstone bridge can be fitted with contacts to close or open a circuit at the desired time. The resistance of the thermometer coil will increase with an increase of its temperature. This causes an unbalanced condition in the bridge circuit and a current will flow in the galvanometer circuit. This current energizes the coil of the galvanometer causing the contacts to open or close a local circuit which will shut off the heating device. As the temperature of the thermometer coil decreases, the resistance of the coil also decreases. After a condition of balance has been reached, the resistance of the thermometer coil continues to decrease, causing a current to flow through the galvanometer circuit in the opposite direction to the first current. This will cause the contacts on the galvanometer to close and the heating element will be turned on. By placing a manual control on the heating element in addition to the automatic device, the temperature can still further be adjusted until the electrical control device is very constant and the opening and closing of the control

circuit occurs infrequently. However, without the manual control, this device will operate very effectively.

A source of direct current is required to supply the bridge circuit with the necessary current for its operation. The current flow through the thermometer coil has a direct effect on the operation of the entire device. The direct current may be obtained from suitable primary cells or from a rectifier operating from alternating current.

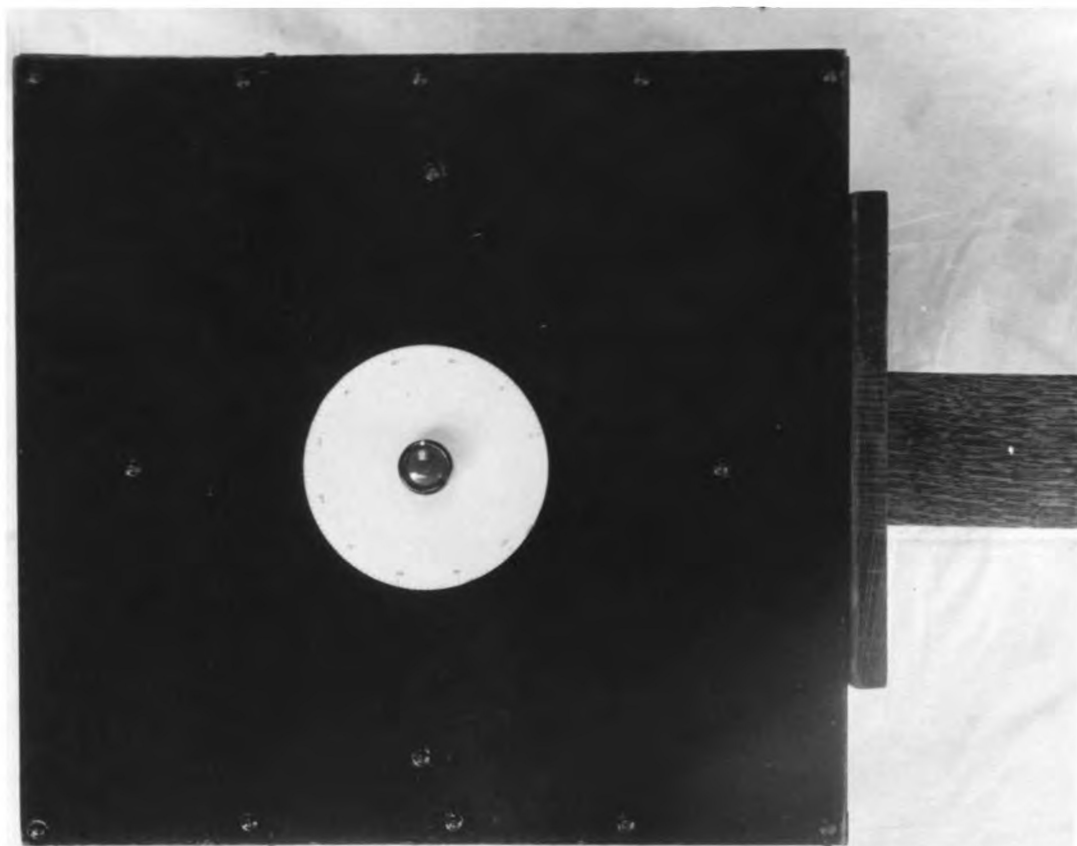
PART IV

THE EXPERIMENTAL DEVICE

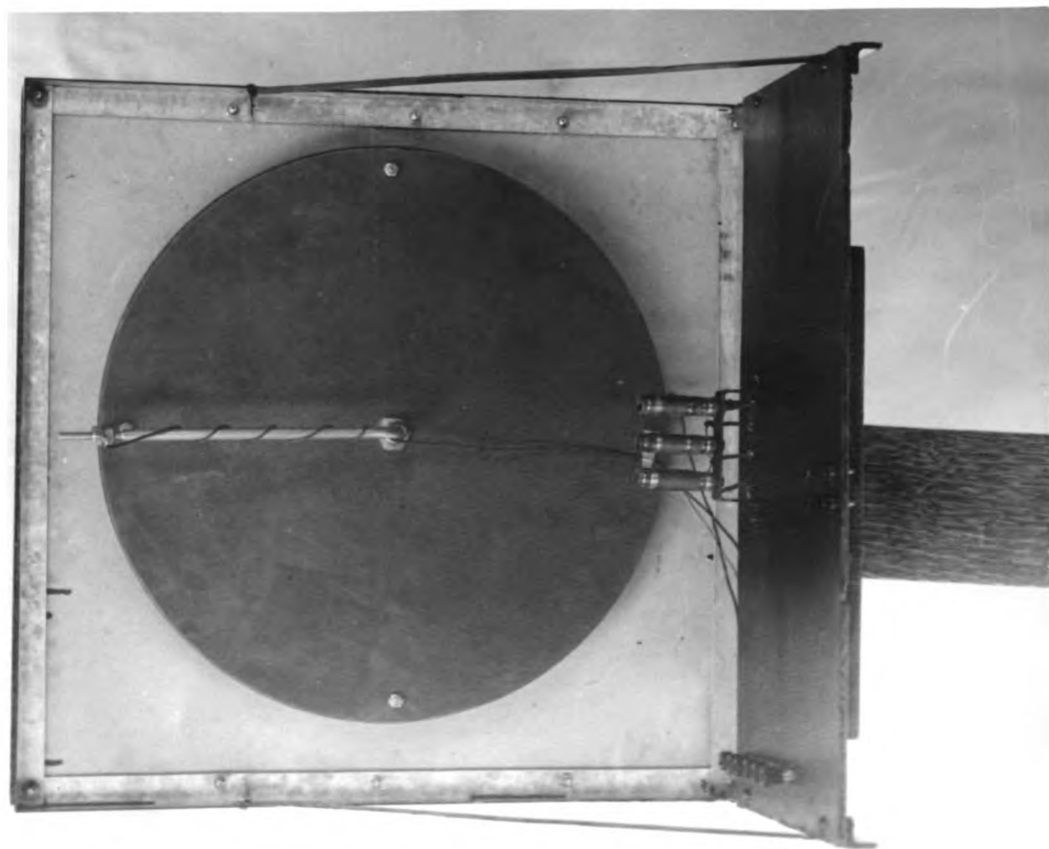
CONSTRUCTION

The construction of the temperature control equipment may be considered as consisting of three distinct parts: the resistance thermometer, the Wheatstone bridge, and the control equipment. Any one of these three can be used separately although the Wheatstone bridge and the resistance thermometer have a correlated relation, the balancing resistance arm. The discussion of the apparatus will be considered in the above order.

The construction of the resistance thermometer is determined by the type of service for which it is to be used and the temperature range to which it is to be subjected. This leaves a wide field of choice as to the type of construction. The resistance thermometer used in this particular device was patterned after Callendar's original thermometer, consisting of a cross of mica plates wound with the resistance spiral. The temperature range covered by this device is from 0° to about 100° C. Therefore, in an effort to reduce the cost of equipment and still retain maximum operating efficiency and accuracy, nickel wire was used in place of the platinum spiral of Callendar's resistance thermometer. Nickel wire serves equally as well as platinum if the temperature of the resistance coil does not exceed 300° C. Between 300° and 400° C. lies the transition point where the slope of the temperature-resistance curve changes. When the slope of this curve changes the value of "a", the temperature coefficient of resistance, also changes. The use of nickel wire lends a greater resistance change per degree temperature change than does platinum, hence for the range covered in this instance the

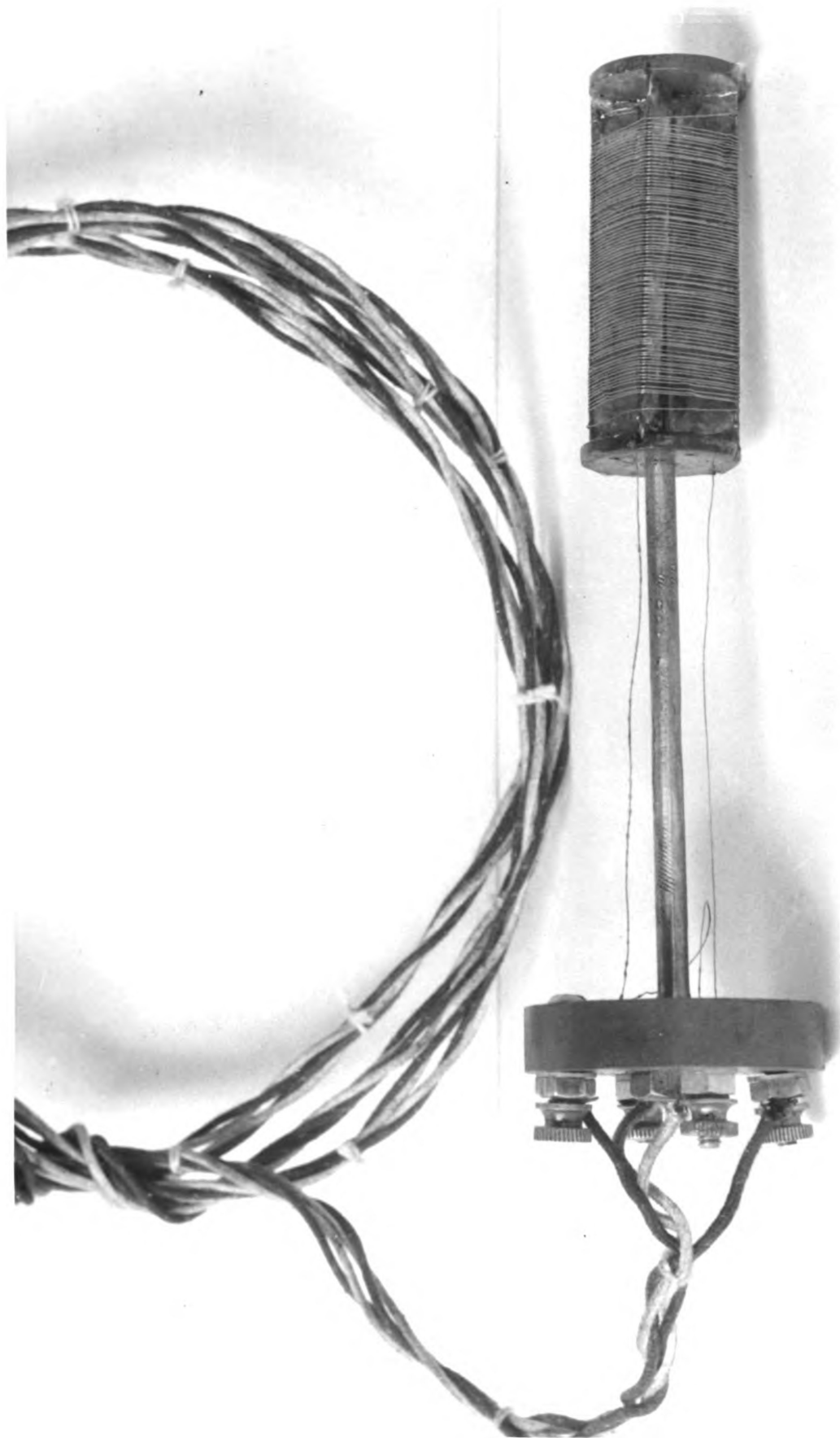


FRONT VIEW



REAR VIEW

THE BRIDGE ASSEMBLY



THE THERMOMETER COIL

thermometer and bridge is sensitive to smaller changes of temperature. The fiber end pieces were added to the mica frame to obtain rigidity of the frame. The brass mounting rod and fiber head were added for convenience and to facilitate electrical connections.

The nickel wire used was supplied by Driver-Harris Company, of Harrison, New Jersey. This wire has a resistance of 0.940 ohms per foot and a diameter of 0.0080 inch. The temperature-resistance curve is shown in Plate IV.

The Wheatstone bridge is a modification of the conventional type, having two ratio arms of equal resistance and in the other two arms the thermometer coil and its balancing resistance. The two ratio arms and the balancing resistance each have a resistance of twenty ohms. Heaviside, in his "Electrical Papers," shows that maximum sensitivity of the bridge circuit is obtained when the resistance of the thermometer coil and the three arms are all equal to each other. Due to the variation of the thermometer coil resistance and the attendant change of the balancing resistance, this relation does not at all times exist. However, the variation in resistance over the entire range, from 0° to 100° C., is small enough that the sensitivity of the bridge may be considered practically constant. Any decrease in sensitivity is compensated for in the calibration of the device.

In order to control the bridge circuit and obtain a balanced condition, the balancing resistance must be made variable. This may be done in either of two ways. The resistance may be a rheostat and variable in itself, or the resistance in both the balance arm and the thermometer arm may be changed simultaneously by a form of potentiometer, the contact of which is connected to the galvanometer circuit. The latter method was adopted and the potentiometer was so constructed that as the resistance

in the thermometer arm was decreased, the balance resistance was increased at the same rate. The use of this method of variation of the balancing resistance lends to distinct advantages: one, it avoids the necessity of a heavy contact on the variable resistance to heavy the current in the first mentioned method of variation, and two, it decreases the resistance value necessary in the variable unit. As the temperature varies from 0° to t° C., the resistance of the thermometer coil increases according to the law:

$$R_t = R_0 [1 + \alpha(t - 0)]$$

where " R_t " is the resistance at " t° " and " R_0 " is the resistance at 0° , " α " is the temperature coefficient of resistance. By using the potentiometer, the variable resistance is decreases both in value and in size of contact point. When the temperature of the thermometer coil is 0° C., the contact is at the left end of the slide wire. The resistance of the balance arm is then " R_c " and the resistance of the thermometer arm is the sum of the resistance of the thermometer coil, " R_0 ", and the resistance of the slide wire, " R_s ". At 100° C. the contact is at the right end of the slide wire. The resistance of the balance arm is then $R_c + R_s$ and the resistance of the thermometer arm is $R_0 [1 + \alpha(100 - 0)]$. Then for these two conditions, since the ratio of the ratio arms is 1:1,

$$R_c = R_s + R_0 ,$$

$$R_c + R_s = R_0 [1 + \alpha(100 - 0)] .$$

Solving these two equations simultaneously, the resultant necessary resistance of the thermometer coil and of the slide wire potentiometer is determined.

$$R_0 = \frac{R_c}{1 + 50\alpha}$$

$$R_s = 50 R_0 = \frac{50 R_c}{1 + 50\alpha}$$

PLATE I



BRIDGE ARRANGEMENT

The slide wire resistance was constructed in circular form for convenience and compactness. A scale was used which was divided into one hundred and fitted with a vernier which made it possible to read to 0.1 of a scale division or 0.001 of the total resistance of the slide wire. This scale was used primarily for ease in calibration.

The bridge circuit, as well as the thermometer connecting head, was equipped with terminals for compensating leads. The purpose of these leads is to compensate for the resistance of the leads to the thermometer coil from the thermometer coil arm of the bridge circuit. The leads themselves have appreciable resistance and by using similar leads between the two sets of compensating lead terminals that resistance is balanced in the balancing arm of the bridge. The bridge circuit used in this device is shown in Plate I.

The control circuit might be any of the usual commercial types used in connection with thermoelectric devices. These types of control devices employ a galvanometer movement and associated equipment which will function as a galvanometric control. In this particular instance, two types of control devices were considered: one, a galvanometric relay sensitive to very small amounts of current, and second, a vacuum tube amplifier with a relay sensitive to 0.075 milliamperes in the plate circuit of the tube.

The use of the galvanometric relay is not warranted, since the current flow through the galvanometer circuit due to a change of temperature of 0.01° C. is too small to affect even the most sensitive of galvanometric relays. Maxwell, in his Treatise on Electricity and Magnetism, shows that the current in the galvanometer circuit is

$$i_g = \frac{E}{D} (r_2 r_3 - r_1 r_4)$$

$$\text{where } D = rr_1r_2 + r_1r_2(r_3 + r_4) + rr_1(r_g + r_4) + rr_2(r_g + r_3) \\ + (r + r_1 + r_2)(r_3r_4 + r_g r_3 + r_g r_4),$$

r_1 and r_2 = the resistance of the ratio arms,

r_3 = the resistance of the balancing arm,

r_4 = the resistance of the thermometer coil arm,

r = the resistance of the d.c. supply circuit,

r_g = the resistance of the galvanometer circuit, and

E = the battery or d.c. supply voltage.

Since the only variable in the right hand member of the above equation is r_4 , and its variation is small for 0.01° C. change of temperature, the galvanometer current is very small. In order to use this apparatus to control temperature within 0.01° C., some other means of detecting small current changes in the galvanometer circuit must be used.

If, in the galvanometer circuit, there is placed a resistance, say of 1000 ohms, the small current through that resistance will cause a measurable voltage drop. The second device considered, the vacuum tube voltage amplifier, can readily detect and amplify this small voltage drop when it is applied to the grid circuit of the average receiving type radio tube. This change in grid voltage will cause a corresponding change in plate current, which could be made to flow through a resistance in the plate circuit, causing a larger voltage drop than that in the grid circuit. By using several stages of amplification it is possible to increase this plate current change until it has reached a sufficient value to operate a sensitive relay. The number of stages necessary are determined by the current necessary to operate the relay and the amplification per stage of the amplifying tubes. This method requires an extensive outlay of equipment and is very critical at the point of

plate-current cut-off and, therefore, is not practical in the commercial sense. However, it is an effective method and will lend itself readily to the problem. A typical vacuum tube amplifier circuit is shown in Plate **II**.

The vacuum tube amplifying device used in connection with the resistance thermometry equipment designed for this thesis did not incorporate the usual undesirable features of the average vacuum tube voltmeter which is biased to the plate-current cut-off.

Plate III shows the schematic diagram of the amplifier device. The vacuum tube used was the type '**27**', manufactured by the R. C. A. - Victor Corporation. It's characteristics are as follows:

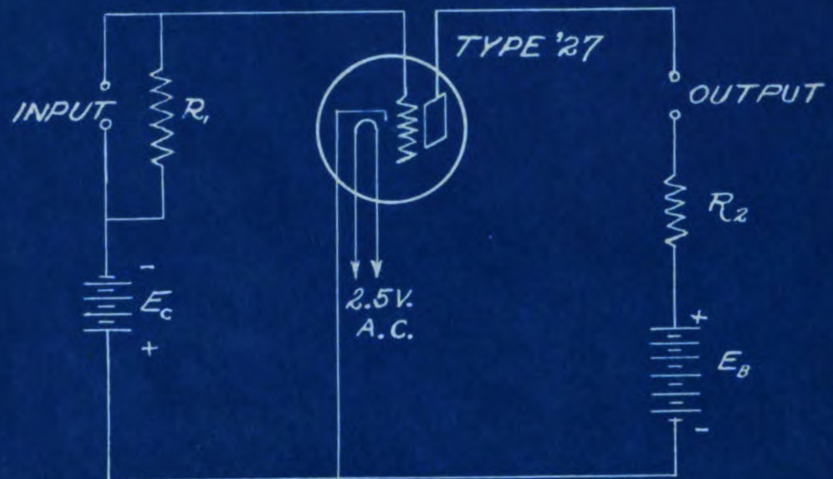
Heater voltage	2.5 volts AC or DC			
Heater current	1.75 amperes			
Plate voltage	45	90	135	180 volts
Grid voltage (C-bias)	0	-4.5	-9	-13.5 volts
Plate current	4	5	5.5	6 milliamperes
Plate resistance	10000	10000	9000	9000 ohms
Amplification factor	9	9	9	9
Mutual conductance	900	900	1000	1000 micromhos
Undistorted Power Output		30	78	134 milliwatts

Approximate direct inter-electrode capacitances:

Grid to plate	3.3 $\mu\text{uf.}$
Grid to cathode	3.6 $\mu\text{uf.}$
Plate to cathode	2.8 $\mu\text{uf.}$

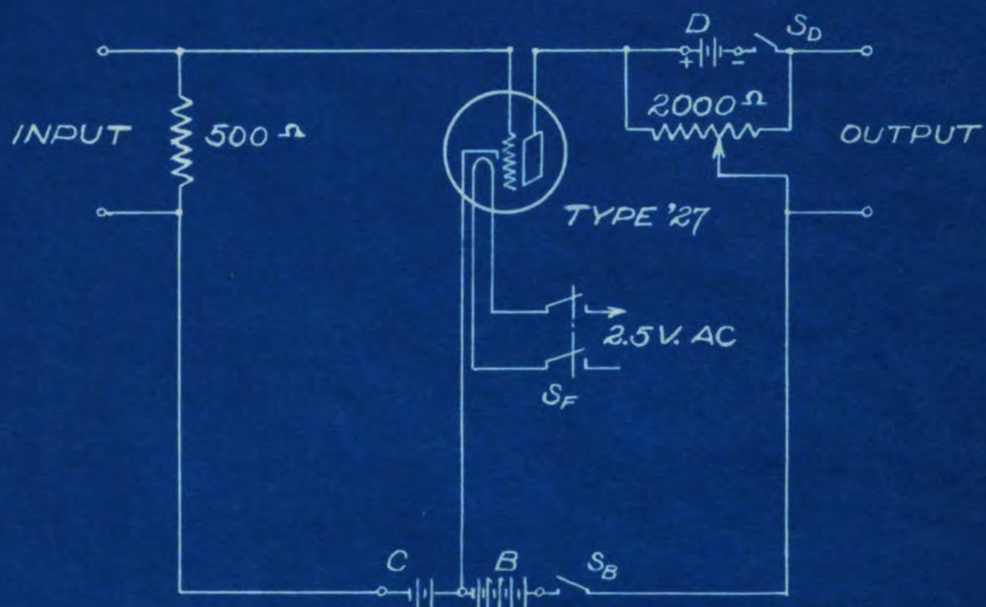
The grid circuit is so designed that the bias voltage on the grid of the tube may be adjusted to give the most satisfactory operation and the maximum change in plate current for a given current applied to the grid input terminals. The value of the grid resistance is not critical

PLATE II



TYPE OF VACUUM TUBE
VOLTAGE AMPLIFIER

PLATE III



VACUUM TUBE AMPLIFIER
CONTROL CIRCUIT FOR USE
WITH RESISTANCE THERMOMETER

and allows further adjustment of the grid circuit. The characteristics of the tube are such that a small direct current, when applied to the grid input terminals, causes a change in plate current which is very large in proportion to the current in the grid circuit. The battery and potentiometer designated by "D" in Plate III serves to balance out the effect of the normal plate current through the output circuit. With this addition, the plate current may be adjusted to any desired value.

The advantage of this device over the usual vacuum tube voltmeter biased to the plate-current cut-off are (1) the adjustment of the balance battery-potentiometer circuit is very much less critical than the adjustment of the grid voltage necessary to bias the tube exactly to the cut-off, and (2) the tube is operating on the straight-line part of the grid-voltage--plate-current curve, which gives a maximum value of amplification. The voltmeter biased to the cut-off must operate on the lower, curved portion of the grid-voltage--plate-current curve, giving a much smaller amount of amplification for a given change of grid voltage.

The plate current output terminals are connected to a sensitive relay. It is recommended that a d.c. milliammeter be connected in series with the relay at all times to allow the operator to adjust the output current from time to time as the temperature of the cathode within the tube changes. The relay used was a Weston Photronic Cell Relay which operated on 0.075 milliamperes to open the external circuit. A 0-1 milliamperes meter was used in series with the relay to allow the necessary adjustments to be readily made.

Another type of control device which might be used is the "Thyratron", a tube manufactured by the General Electric Company, of Schenectady, New York. This type of vacuum tube is essentially a grid controlled arc rectifier, having three or more elements, one of which is

the control grid, which are enclosed in a gas or vapor filled glass shell. The tube most suited for this problem is the Thyatron, Type FP-54, known as a low grid current diotron. This tube is a four element vacuum tube specially designed to have a very high input resistance and a very low d.c. grid current. It is exceedingly useful for measuring or amplifying very small currents, or voltages in very high resistance circuits. The FP-54 has been carefully constructed to insure high leakage resistance from the control grid to the other elements of the tube. Inasmuch as the license notice does not include license for the use of the tube in thesis investigations, it could not be incorporated herein. Additional information concerning this vacuum tube may be had from the General Electric Company.

CONSTRUCTIONAL DATA

Resistance of Slide Wire and Thermometer

From the solution of the simultaneous equations on page 31 the resistance of the slide wire and of the thermometer coil were obtained.

$$R_c = R_s + R_o$$

$$R_c + R_s = R_o[1 + \alpha(100 - 0)]$$

R_c was fixed at a value of twenty ohms, α was given as 0.005375 ohm per degree temperature rise per ohm. Therefore,

$$20 = R_s + R_o$$

$$20 + R_s = R_o[1 + 0.005375(100)]$$

$$20 - R_s = R_o$$

$$20 + R_s = 1.5375 R_o$$

$$40 = 2.5375 R_o$$

$$R_o = \frac{40}{2.5375} = 15.8 \text{ ohms at } 0^\circ \text{ C.}$$

$$R_s = 20 - R_o$$

$$= 20 - 15.8$$

$$= 4.2 \text{ ohms}$$

To limit the range somewhat more than previously estimated the thermometer coil was constructed with a resistance of 16.45 ohms at 0° C. and the slide wire was constructed with a resistance of 3.55 ohms. The range of temperature for these values is from 0° C. to 80° C. , as shown by substitution in the formula

$$R_c + R_s = R_o[1 + \alpha(t - 0)]$$

$$20 + 3.55 = 16.45[1 + 0.005374 t]$$

$$t = \frac{0.43}{0.005375} = 80^\circ \text{ C.}$$

The Resistance Thermometer Coil

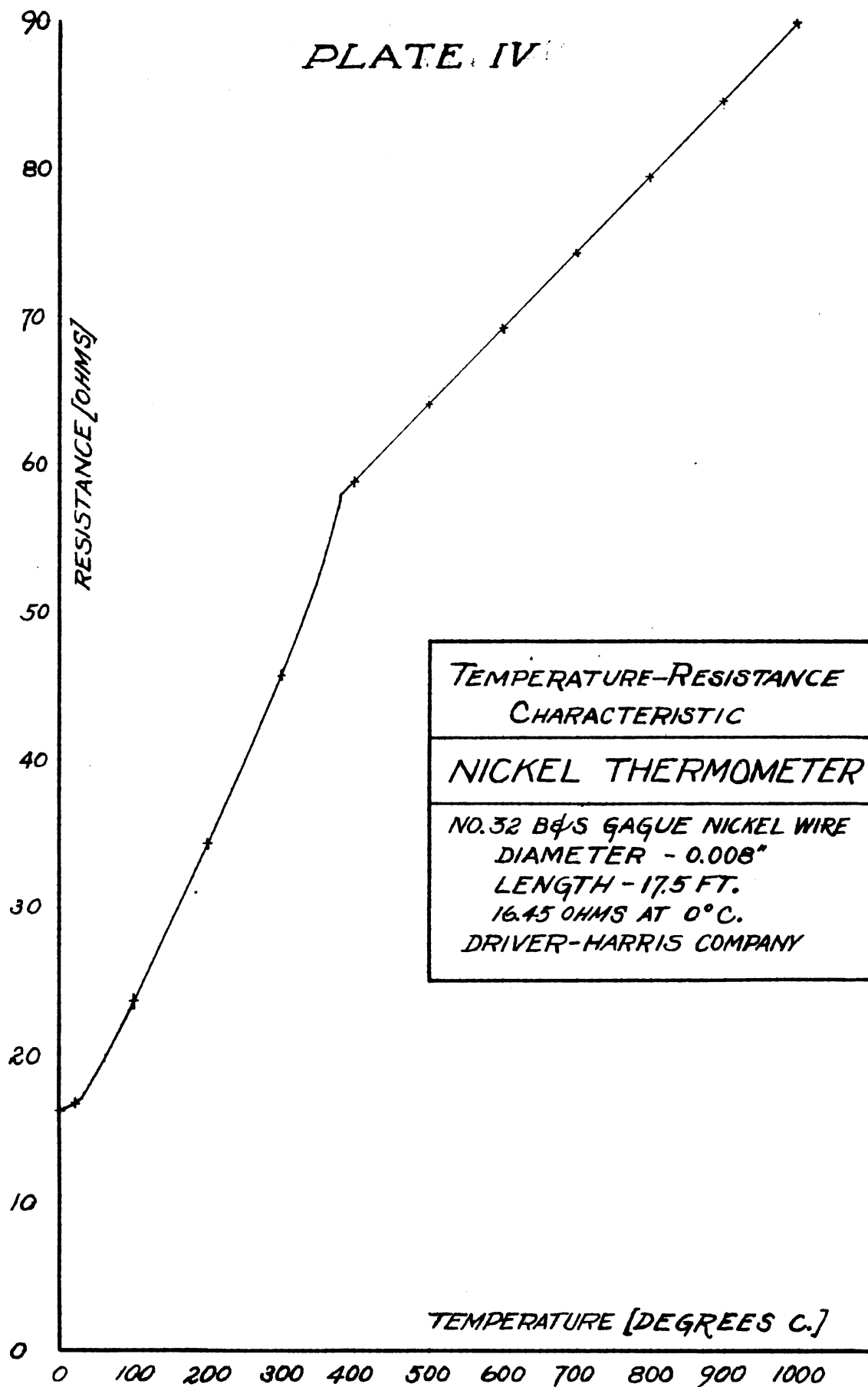
Wire Pure (98.8%) Nickel, Driver-Harris Company.
Size No. 32 B. and S. gage.
Diameter 0.0080 inch.
Resistance 0.940 ohm per foot.
Length 17.5 feet.
Total resistance 16.45 ohms at 0° C.
Temperature coefficient of resistance 0.005375 from 0° to 100° C.

Temperature Resistance Data

Temperature	Resistance
0°	16.45
20°	16.71
100°	23.90
200°	34.4
300°	45.7
400°	58.9
500°	64.7
600°	69.4
700°	74.3
800°	79.1
900°	84.2
1000°	90.0

Coil dimensions: Width 1 inch.
 Height 1 inch.
 Length 1.75 inches.
 Spacing 40 turns per inch.

PLATE IV



The Slide Wire Potentiometer

The slide wire potentiometer was constructed in circular form to lend compactness and convenience. The frame consisted of a circular, pressed cardboard disc, 15.5 inches in diameter with a groove around the periphery to hold the resistance wire in place. The wire itself was "Advance" resistance wire, manufactured by Driver-Harris Company, and furnished by the Physics Department of Michigan State College. Its resistance was 0.960 ohm per foot and its diameter was 0.0150 inch. This wire was wound around the circumference of the pressed cardboard disc. Contact was made by a telephone relay spring which was modified by bending until a sharp edge was presented to the wire. The spring was carried on a one-quarter inch brass rod which was bent to a 90° angle to supply the shaft for the dial mounting. The wire was terminated at bolts spaced thirty degrees apart on the circumference of the disc. The total resistance of the potentiometer, as given by the formula

$$\begin{aligned} R_s &= \frac{360 - 30}{360} 2\pi r\rho \\ &= \frac{330}{360} \times 2\pi \times \frac{7.75}{12} \times 0.94 \\ &= 3.49 \text{ ohms.} \end{aligned}$$

The resistance wire, having a temperature coefficient of resistance of ± 0.00001 per degree Centigrade, is not affected by the change of temperature of the room in which the measurements are being made.

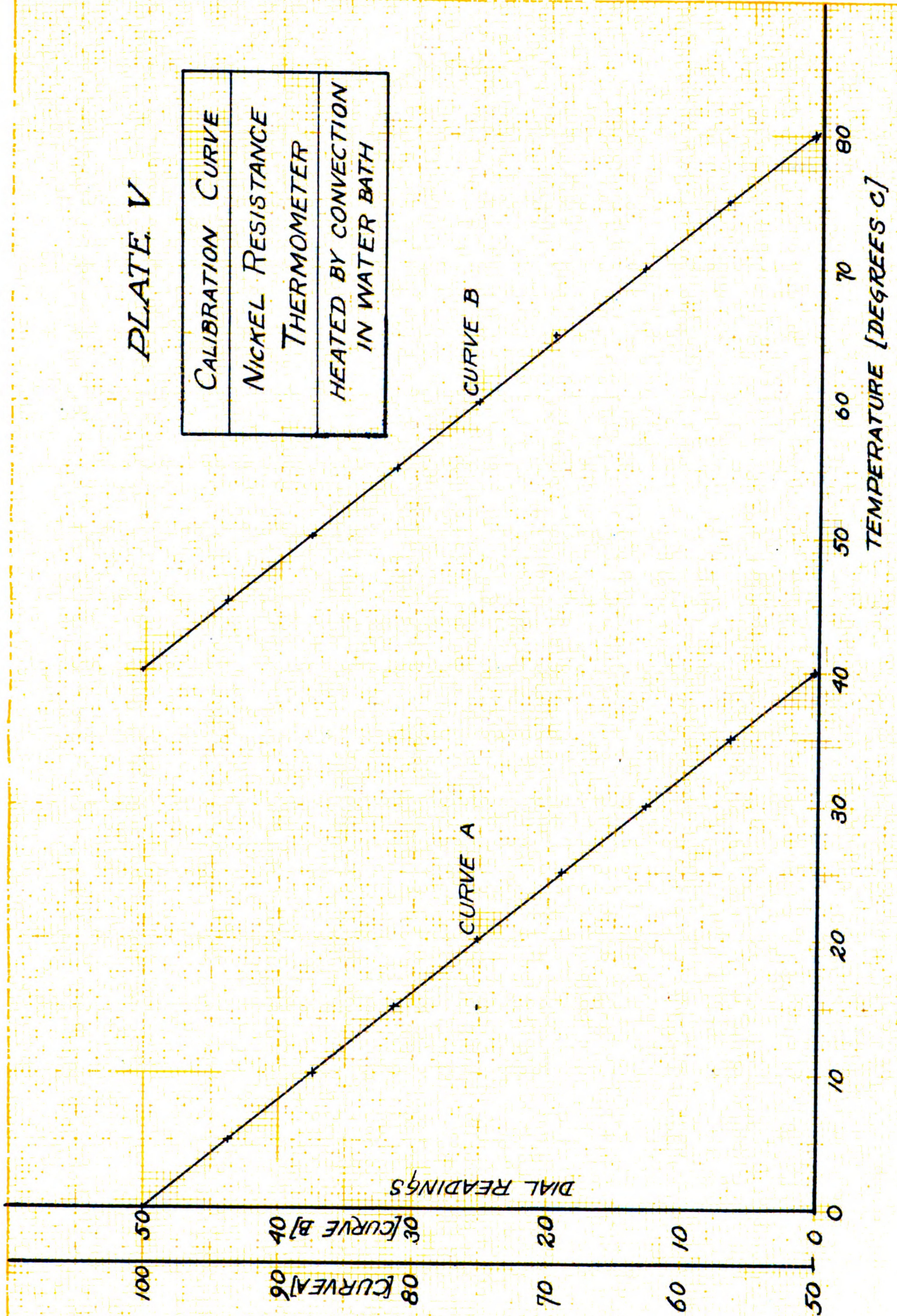
Mean Calibration Data

The following data was obtained by taking the mean of six calibration tests. Each calibration test was made by immersing the thermometer coil and the bulb of an accurate mercury thermometer in a water bath containing ice. The bath was slowly heated. As the temperature of the bath increases, readings of the dial were taken at every five degrees Centigrade. The greatest deviation of any point in the six tests did not vary from the average calibration curve more than three percent.

Temperature	Dial Reading
0°	100
5°	92.775
10°	87.55
15°	81.33
20°	75.1
25°	68.875
30°	62.55
35°	56.425
40°	50.2
45°	43.975
50°	37.75
55°	31.525
60°	25.3
65°	19.075
70°	12.85
75°	6.725
80°	0.4

PLATE V

CALIBRATION CURVE
NICKEL RESISTANCE
THERMOMETER
HEATED BY CONVECTION IN WATER BATH



OPERATION

The use of this device is both simple and convenient. With the control circuit connected to the galvanometer circuit, the device becomes an automatic temperature control apparatus. The calibration curve and dial allows the device to be set for any desired temperature within the temperature range, i.e., between zero and eighty degrees Centigrade. As the temperature of the thermometer coil increases, its resistance also increases. When the temperature of the coil has reached the value set on the dial, the bridge circuit is balanced. Any further increase of temperature causes a current to flow through the input resistance of the vacuum tube amplifier in such a direction as to make the grid of the tube less negative. Then, the plate current increases a sufficient amount to operate the Weston Photronic Coil Relay in the plate circuit which, in turn, operates a power relay, breaking the current supply to the heating coils. The coils then cool, the resistance of the thermometer coil decreases, the bridge circuit is again in a balanced condition and the relay contacts close. With this device, the temperature oscillates about a fixed temperature which is set on the dial. The entire cycle of operation is based upon the sensitivity of the controlling circuit to the small current produced in the galvanometer by a small change of temperature. This sensitivity may be further increased by adjusting the current in the plate circuit by means of the potentiometer "P" of Plate III until that current is but a little less than the current necessary to operate the relay.

By using a galvanometer in place of the control circuit, the device becomes a resistance thermometer. To measure the temperature it is only necessary to adjust the dial until the bridge circuit is in a

balanced condition, as indicated by zero deflection of the galvanometer. Reference to the calibration curve will show the temperature of the thermometer coil. By using the thermometer in the same manner as a mercury thermometer and observing the principles of accurate temperature measurement, this temperature reading will be the temperature in the immediate vicinity of the thermometer coil.

CONCLUSION

As outlined in the introduction, the purpose of this thesis was to investigate the possibility of temperature control by the use of the resistance thermometer. It is reasonable to believe that the resistance thermometer can be used for this purpose with as great a degree of accuracy as any of the other means of automatic temperature control. However, the equipment necessary and the adjustments which must be made does not, in a commercial sense, warrant its use.

The resistance thermometer bridge circuit requires an external source of direct current to furnish the galvanometer current during a period of unbalance. In addition, the vacuum tube circuit requires a source of low voltage of sufficient current capacity to supply the filament with 1.75 amperes at 2.5 volts. Alternating current, stepped down, is the simplest supply for this purpose. Sources of direct-current voltage must also be supplied for the grid bias, the plate voltage, and the plate balancing voltage for the tube. These must be high-grade, dry cells for the grid bias and plate balancing voltages and a standard 45-volt B-battery for the plate voltage.

As a result of the work carried out in connection with this thesis, as outlined in the preceding pages, the conclusion is that until more sensitive equipment for the control circuit can be devised, this apparatus is not warranted either from a commercial or a practical viewpoint.

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