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PYROMETRY

BY

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AND

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SECOND EDITION

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PREFACE TO THE SECOND EDITION

Since the First Edition of this text was published in 1927, there has been little fundamental change in the basic principles underlying the operation of devices used in the measurement of high temperatures. Perhaps the most significant event has been the universal adoption of the international temperature scale. In this period, however, remarkable advances have been made in the production and measurement of extremely low temperatures. Likewise the use of pyrometric equipment in the measurement and control of temperature in industrial processes has increased enormously. This wider demand on the part of industry has led to improvement in the design of the equipment so as to attain greater reliability and accuracy. In including descriptions of the newer equipment it has seemed judicious in many cases to retain the material pertaining to the older apparatus, owing to the large number of installations still existent.

The authors wish particularly to thank the many manufacturers of equipment who have so willingly cooperated in supplying information relative to their products. It is also a pleasure to express appreciation to our colleagues, particularly Dr. Lars Thomassen, for their helpful interest.

WILLIAM P. WOOD,
JAMES M. CORK.

ANN ARBOR, MICHIGAN,
July, 1941.

PREFACE TO THE FIRST EDITION

Industrial developments during the last quarter century have made the accurate measurement of temperature one of the most important phases of the processes involving the production or application of heat. In many plants the entire time of one or more skilled technicians is occupied in maintaining the pyrometric system. This condition has been reflected in colleges and universities by the establishment of separate courses in temperature measurement. Such courses are usually offered by the Engineering or Physics departments.

While there are a few reference books on pyrometry there is no work which is organized in such a manner as to be of great utility as a textbook for college students. Instructors have been forced to handle the subject entirely by lecture or by personally prepared sets of notes. This manuscript, therefore, has been assembled with the needs in mind of the student as well as of the man more experienced in the uses and the theory of pyrometry. Questions and problems are added at the end of some of the chapters. Outlines for laboratory experiments are included. These are largely suggestive and may be modified to meet local conditions.

We wish to express our great appreciation for the assistance which has been rendered by the manufacturers of pyrometric equipment and others in the preparation of this manuscript. The publications of the U.S. Bureau of Standards have been drawn upon freely, particularly, *Technologic Paper* 170. Other references to be mentioned are "Dictionary of Applied Physics," Glazebrook, Volume 1; "The Measurement of High Temperatures," Burgess and Le Chatelier; "Tempera-

tur Messung," Henning; "The International Critical Tables"; and the three symposia on pyrometry, the first held by the British Iron and Steel Institute in 1904, the second by the Faraday Society in 1917, and the third by the American Institute of Mining and Metallurgical Engineers in 1919. Wherever tables or illustrations have been used from these sources the name is appended.

Especial thanks are due our colleagues, Professors A. H. White, C. Upthegrove, W. F. Colby, and G. G. Brown for helpful criticism of various parts of the manuscript.

THE AUTHORS.

ANN ARBOR, MICHIGAN,
August, 1927.

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PYROMETRY

CHAPTER I

TEMPERATURE SCALES

Temperature.—Purely mechanical phenomena may be completely described in terms of three quantities, considered by agreement as fundamental, such as mass, length, and time. To describe those phenomena involving heat, it becomes necessary (aside from the kinetic theory) to introduce a new fundamental quantity. Such a quantity is temperature. Maxwell defined temperature vaguely as follows: "The temperature of a body is its thermal state considered with reference to its ability to communicate heat to other bodies." This definition presupposes an understanding of the term "heat" and may thus be considered illogical. Since the knowledge of the properties of matter can be gained only through sense perception, every fundamental quantity must ultimately be defined in terms of certain received sensations. The temperature of a body may thus be qualitatively defined as the property of a body that determines the sensation of warmth or coldness received from it. Experience shows, however, the inadequacy of the sense organs in quantitative measurements. The same body might be regarded as either warm or cold, depending upon the circumstances of observation. It therefore becomes necessary to adopt by agreement some device for obtaining a quantitative expression of temperature.

Heat.—Temperature having been defined, it becomes easy to define heat, regardless of its ultimately true nature. Thus heat may be spoken of as that something

(form of energy) which, if present in a body in larger quantities, results in more acute sensations of warmth or higher temperatures. Observation readily shows that along with the more acute sensation of warmth there is a marked change in all the other physical properties of the body. Among these changes, the following might be noted in particular:

1. Increase in dimensions
2. Increase in pressure, if confined
3. Change in e.m.f. developed during contact with some other substance
4. Change in electrical resistance
5. Increase in the amount of radiation from the surface of the body
6. Change in color of the body
7. Change in state

Many of these changes are accurately measurable, and any one of them might be used by agreement as a measure of the accompanying temperature change and, hence, be the basis of a temperature scale. As a matter of fact, every one of the changes noted above has been used at some time or other as the basis of temperature scales. It must be noted, however, that inasmuch as they employ different properties of the substance, temperatures measured on one scale should not necessarily agree with the same temperatures measured on a different scale. Only on that scale accepted by agreement would the temperatures be correct.

It would, of course, be desirable to obtain a temperature scale that was independent of the particular properties of any substance. Such a theoretical scale was proposed by Lord Kelvin, and it may be approximately attained in practice.

Thermometry by Quantities of Heat.—A system of thermometry might be founded on the measurement of quantities of heat rather than on the change in some physical property of a substance, although this method

would be found rather inconvenient. Thus, if any two definite temperatures be agreed upon as fixed points, such as the freezing and boiling points of pure water under standard conditions, the unit of heat may be taken as the quantity of heat needed to raise the temperature of a certain unit of mass of water from one of these temperatures to the other. For convenience, this unit of heat may be related to the quantity of heat needed to melt unit mass of ice at the lower fixed temperature. Now the temperatures of two bodies of the same mass and material may be considered as being proportional to the quantities of ice melted by each when dropped into an enclosure of ice at its melting point. To affix definite numbers to the temperatures, the dropped body must in one case be given an initial temperature equivalent to that of the higher fixed point. If this be called 100, as in the centigrade scale, then the other temperatures may be directly evaluated. This method, of course, assumes that the specific heat of the test body is constant at all temperatures, which is not true for any substance. This method of mixtures used in connection with mercury thermometers was, however, one of the very early methods of estimating the temperature of very hot bodies.

The Normal Hydrogen Thermometer.—At a meeting of an International Committee on Weights and Measures in 1887, the need for a standard scale of temperature was recognized and acted upon. The merits and the disadvantages of the various devices then available for the measurement of temperature were considered carefully, and it was finally agreed that the constant-volume gas thermometer should be the international standard and that all temperatures should be expressed in terms of this scale. It was further agreed that the gas to be employed between the freezing point and the normal boiling point of water should be hydrogen and that the pressure at 0°C. should be 100 centimeters of mercury.

The resolution adopted was as follows: "The International Committee on Weights and Measures adopts as the standard thermometric scale for the international service of weights and measures, the centigrade scale of the hydrogen thermometer, having as fixed points the temperature of melting ice (0°C.) and of the vapor of distilled water boiling (100°C.) at standard atmospheric pressure, the hydrogen being taken at an initial manometric pressure of 1 meter of mercury."

Although hydrogen could be used satisfactorily over the specified range, it became necessary to use other gases to extend the range to very low or to very high temperatures. At high temperatures, it is difficult to obtain a container that is impervious to hydrogen, and in this range nitrogen is used. The pressure at 0°C. is commonly taken as 50 centimeters of mercury or less in order that the pressure at high temperatures may be correspondingly reduced. For low temperatures, helium is used, since it remains a gas at temperatures below that at which the hydrogen has liquefied. The manipulation and the corrections to be applied to the gas thermometer will be discussed later. To extend the standard scale of temperature, the freezing and the boiling points of several pure substances were determined by the gas thermometer. This work was carried out by various national laboratories, and the data were not always in agreement, leading to small differences in the temperature scales adopted.

By 1920, several national laboratories had abandoned the international hydrogen scale, both as an ultimate standard and as a working standard.

The Thermodynamic Temperature Scale.—Carnot, in 1824, showed that any reversible thermodynamic engine, which took in some quantity of heat H_1 at a temperature T_1 and, after doing a certain amount of work W, gave to a condenser at some lower temperature T_2 a quantity of heat H_2, should have an efficiency as follows:

$$\text{Efficiency} = \frac{H_1 - H_2}{H_1} \tag{1}$$

It further follows from the second law of thermodynamics that the efficiencies of all reversible engines working between these two temperatures must be the same regardless of the nature of the working substance. Lord Kelvin suggested that this might serve as the basis of a temperature scale and this scale would have the advantage that it would not be dependent upon any particular property of matter. If the quantities of heat absorbed or ejected at any temperature be taken as proportional to that temperature, then the expression for efficiency may be written

$$\text{Efficiency} = \frac{KT_1 - KT_2}{KT_1} = \frac{T_1 - T_2}{T_1} \tag{2}$$

On this scale, then, any two temperatures have the ratio of the quantities of heat absorbed and ejected by a cyclic reversible engine working between these temperatures. The numerical values of temperatures may be assigned by agreeing upon the values of two fixed points, as in any of the other temperature scales.

Now it happens that, if an actual gas be considered as taken about a Carnot cycle and the expression for the efficiency obtained by considering the gas ideal, the following expression is obtained:

$$\text{Efficiency} = \frac{T_1 \log_e \frac{V_2}{V_1} - T_2 \log_e \frac{V_2}{V_1}}{T_1 \log_e \frac{V_2}{V_1}} = \frac{T_1 - T_2}{T_1} \tag{3}$$

where T_1 and T_2 are measured on the gas scale.

The ideal gas must obey both the Gay-Lussac law and the law of Joule (*i.e.*, its internal energy must be a single valued function of the temperature only). Thus, the gas thermometer, which is very exact for most of the permanent gases, indicates temperatures on the thermodynamic

scale to the degree that the gas obeys the foregoing laws. The corrections to be applied to the temperatures observed on the gas thermometer to reduce them to thermodynamic temperatures may be calculated from a knowledge of the divergence of the gas from the above-mentioned laws.

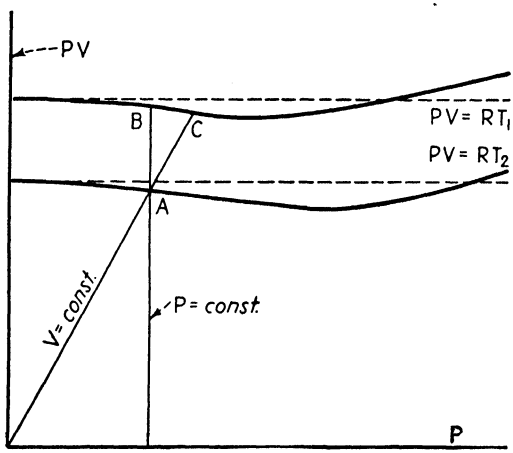


FIG. 1.—Isotherms representing the ideal and actual behavior of gases with increase of pressure.

The deviation of actual gases from the "ideal" behavior is illustrated by the isotherms in Fig. 1. Instead of the horizontal lines corresponding to the gas equation

$$PV = RT, \tag{4}$$

isotherms of the form shown represent the real gases at ordinary temperatures, with the exception of helium and hydrogen. Even helium and hydrogen yield similar curves at sufficiently reduced temperatures. Holborn and Otto[1] suggest the following empirical equation:

$$PV = A + BP + CP^2 + DP^4 + EP^6 \tag{5}$$

where A, B, C, D, and E are constants characteristic of a substance at a particular temperature. At low temperatures, B and C may both be negative, giving the parts of the curves with negative slope. Many other empirical

[1] L. Holborn and J. Otto, *Zeit. Physik*, **33**, 1, (1925).

equations have been suggested to represent the behavior of a gas. Thus Onnes[1] proposed

$$PV = A\left(1 + \frac{B}{V} + \frac{C}{V^2} + \cdots\right) \tag{6}$$

where the constants A, B, and C are functions of the temperature and are called the "Virial" coefficients.

It is apparent from Fig. 1 that temperatures as measured by the constant-volume gas thermometer might be differently expressed when measured by the constant-pressure thermometer. As the pressures are reduced to vanishingly small values, the intercepts and hence the temperatures, as measured by the two devices, must become identical. Moreover, under this condition the temperatures by either device must approach the ideal gas or thermodynamic temperatures. Such temperatures now universally used are followed by the symbol °K. (for Kelvin). Thus the normal freezing point of water is 273.16°K. The corrections[2] to the constant-volume nitrogen scale for an ice-point pressure of 200 millimeters of mercury amount to about +0.015° at 200°K., − 0.003° at 320°K., +0.003° at 400°K., and +0.068° at 600°K. For helium thermometers at low temperatures the corrections for an initial pressure of 1,000 millimeters of mercury at the ice point are of the order of −0.006° at 100°K. and −0.019° at 200°K.

Temperature Measurement by Secondary Standards. By painstaking experimentation with the gas thermometer, the melting points and the boiling points of many pure substances from the boiling point of helium (−268.9°C.) to the melting point of palladium (1554.4°C.) have been evaluated. It was hoped that these definitely established temperatures might be regarded as fixed points on an equal basis with the two original fixed temperatures. In carrying out actual temperature measurement, the constant-volume gas thermometer is unwieldy, and other

[1] H. Kammerlingh Onnes, *Commun. Univ. Leiden*, **170***b*.

[2] J. R. Roebuck and T. A. Murrell, *Temperature*, p. 60, Reinhold Pub. Corp. (1941).

secondary devices whose scale laws have been established by calibration at the known fixed temperatures are used. The type of secondary device used is determined by the temperature range to be covered and the nature of the subject to be investigated.

For the range from the very lowest temperatures up to 1500°C., noble-metal thermocouples may be employed. From −190°C. to 1100°C., resistance thermometers of platinum may be used satisfactorily. Above 700°C., temperature measuring devices based upon the radiation laws are employed. These pyrometers, when calibrated by the fixed points established by the gas thermometer, may be used at higher temperatures by extrapolating the scale law discovered for them over the known range.

Temperature in Kinetic Theory.—Experiments on the mechanical equivalent of heat have shown that the addition of heat to a body must mean only an increase in the energy of the particles of which the body is composed. How can an assemblage of particles take on an increased energy? This may be accomplished by an increase in the translatory, rotational, or vibrational motions of the particles, together with a possible change in the potential energy of the system.

In the constant-volume gas thermometer, a measurement of the pressure serves as an indication of the temperature. Pressure is by definition the force per unit area of surface, and force may, in turn, be defined as the momentum communicated per second. It is evident that momentum can be communicated to a surface only by the translatory motion of the particles. Hence, although the addition of heat to a body may increase the energy of the particles in every possible manner, only the increase in the translatory kinetic energy is significant in determining the increase in temperature. This dependence of the temperature T upon the average kinetic energy of the particles (K.E.) is given by the following simple relationship:

$$T = \frac{2(\text{K.E.})}{3k} \tag{7}$$

where k is the Boltzmann gas constant, whose value is numerically 1.3708×10^{-16} erg per degree centigrade per particle. In this sense one may speak of the temperature of even a single particle.

Accuracy in Temperature Measurement.—The magnitude of the error present in the evaluation of a high temperature may be appreciable. In the first case, all measurements depend upon the correctness of the value of the fixed points employed in calibrating the indicator. That these points are not always certain may be illustrated from the fact that in the case of the sulphur boiling point values have been assigned by observers using the gas thermometer from 443.7 to 444.7°C. At higher temperatures, the discrepancy increases so that in the case of the melting point of palladium values have been reported ranging from 1549 to 1556°C. The value 1549.2°C. reported in the monumental work of Day and Sosman has been shown to be in error. By comparing the radiation emitted by a black body at this temperature with the radiation emitted from a black body at the temperature of freezing gold, 1063°C., Schofield[1] concludes that the freezing point of palladium is 1554.4°C. ± 1°.

At very high temperatures, the uncertainty is greatly magnified. The radiation laws that underlie the operation of both optical and radiation pyrometers were originally based upon experiments by Lummer and Pringsheim[2] regarding the radiation from a black body whose temperature was measured by thermocouples. The more recent investigations of the radiation laws make use of the best known values of the fixed points. To any uncertainty in the constants of the radiation laws and to the errors in the fixed temperatures must be added

[1] F. H. Schofield, *Proc. Roy. Soc.* (*London*), **155**, 301 (1936).
[2] O. Lummer and E. Pringsheim, *Wied. Ann*, **63**, 395 (1897).

the uncertainty in extrapolating a law far beyond the limits for which it has been verified.

The melting point of rhodium has been found by Roeser[1] and Wensel at the U. S. Bureau of Standards to be 1966° ± 3°C. In the case of the melting point of tungsten, the value may be given as 3410 ± 20°C. The melting point of graphite has been reported as 3700 ± 100°C.

The ability to reproduce readings with a given instrument is a matter of importance. This has been accomplished in many instruments by remarkable improvements in design. As an illustration in the case of the disappearing-filament optical pyrometer, Fairchild and Hoover,[2] by eliminating diffraction effects, etc., report a reproducibility of readings at the melting point of gold 1063°C. of 0.2°C. or better.

In the region of extremely low temperatures, the absolute values are not known within 0.01°C. In spite of this, it is permissible to express a temperature as 0.0045°K., meaning by this the ability to reproduce this value in terms of the absolute zero.

The International Temperature Scale.—At the Seventh General Conference on Weights and Measures, the representatives of 31 nations unanimously adopted a new international temperature scale. The definition of this scale as adopted follows:

"Definition of the International Temperature Scale

"1. The Thermodynamic Centigrade scale, on which the temperature of melting ice, and the temperature of condensing water vapor, both under the pressure of one standard atmosphere, are numbered 0° and 100°, respectively, is recognized as the fundamental scale to which

[1] W. F. Roeser and H. T. Wenzel, *U. S. Bur. of Standards, Jour. of Research*, **12**, 519 (1934).

[2] C. O. Fairchild and W. H. Hoover, *Jour. Opt. Soc. Am.*, **7**, 543 (1924).

all temperature measurements should ultimately be referable.

"2. The experimental difficulties incident to the practical realization of the thermodynamic scale have made it expedient to adopt for international use a practical scale designated as the International Temperature scale. This scale conforms with the thermodynamic scale as closely as is possible with present knowledge, and is designed to be definite, conveniently and accurately reproducible, and to provide means for uniquely determining any temperature within the range of the scale, thus promoting uniformity in numerical statements of temperature.

"3. Temperatures on the international scale will ordinarily be designated as '°C,' but may be designated as '°C (Int.)' if it is desired to emphasize the fact that this scale is being used.

"4. The International Temperature scale is based upon a number of fixed and reproducible equilibrium temperatures to which numerical values are assigned, and upon the indications of interpolation instruments calibrated according to a specified procedure at the fixed temperatures.

"5. The basic fixed points and the numerical values assigned to them for the pressure of one standard atmosphere are given in the following table, together with formulas which represent the temperature (T_p) as a function of vapor pressure (p) over the range 680 to 780 mm of mercury.

"6. Basic fixed points of the International Temperature scale—

	°C
"(*a*) Temperature of equilibrium between liquid and gaseous oxygen at the pressure of one standard atmosphere (oxygen point)	−182.97

$$T_p = T_{760} + 0.0126(p - 760) - 0.0000065(p - 760)^2.$$

"(*b*) Temperature of equilibrium between ice and air-saturated water at normal atmospheric pressure (ice point)	0.000
"(*c*) Temperature of equilibrium between liquid water and its vapor at the pressure of one standard atmosphere (steam point)	100.000
$T_p = T_{760} + 0.0367(p - 760) - 0.000023(p - 760)^2$.	
"(*d*) Temperature of equilibrium between liquid sulphur and its vapor at the pressure of one standard atmosphere (sulphur point)	444.60
$T_p = T_{760} + 0.0909(p - 760) - 0.000048(p - 760)^2$.	
"(*e*) Temperature of equilibrium between solid silver and liquid silver at normal atmospheric pressure (silver point)	960.5
"(*f*) Temperature of equilibrium between solid gold and liquid gold at normal atmospheric pressure (gold point)	1063

"Standard atmospheric pressure is defined as the pressure due to a column of mercury 760 mm high, having a density of 13.5951 g/cm^3, subject to a gravitational acceleration of 980.665 cm/sec.^{2} and is equal to 1,013,250 dynes/cm^2.

"It is an essential feature of a practical scale of temperature that definite numerical values shall be assigned to such fixed points as are chosen. It should be noted, however, that the last decimal place given for each of the values in the table is significant only as regards the degree of reproducibility of that fixed point on the International Temperature scale. It is not to be understood that the values are necessarily known on the Thermodynamic Centigrade scale to the corresponding degree of accuracy.

"7. The means available for interpolation lead to a division of the scale into four parts.

"(*a*) From the ice point to 660°C the temperature T is deduced from the resistance R_T of a standard platinum resistance thermometer by means of the formula

$$R_T = R_0(1 + AT + BT^2).$$

The constants R_0, A, and B of this formula are to be determined by calibration at the ice, steam, and sulphur points, respectively.

"The purity and physical condition of the platinum of which the thermometer is made should be such that the ratio R_T/R_0 shall not be less than 1,390 for $T = 100°$ and 2.645 for $T = 444.6°$.

"(*b*) From $-190°$ to the ice point, the temperature T is deduced from the resistance R_T of a standard platinum resistance thermometer by means of the formula

$$R_T = R_0[1 + AT + BT^2 + C(T - 100)T^3].$$

The constants R_0, A, and B are to be determined as specified above, and the additional constant C is determined by calibration at the oxygen point.

"The standard thermometer for use below 0°C must, in addition, have a ratio R_T/R_0 less than 0.250 for $T = -183°$.

"(*c*) From 660°C to the gold point, the temperature T is deduced from the electromotive force e of a standard platinum *vs.* platinum-rhodium thermocouple, one junction of which is kept at a constant temperature of 0°C while the other is at the temperature T defined by the formula

$$e = a + bT + cT^2.$$

The constants a, b, and c are to be determined by calibration at the freezing point of antimony, and at the silver and gold points.

"(*d*) Above the gold point the temperature T is determined by means of the ratio of the intensity J_2 of monochromatic visible radiation of wave-length λ cm, emitted by a black-body at the temperature T_2, to the intensity

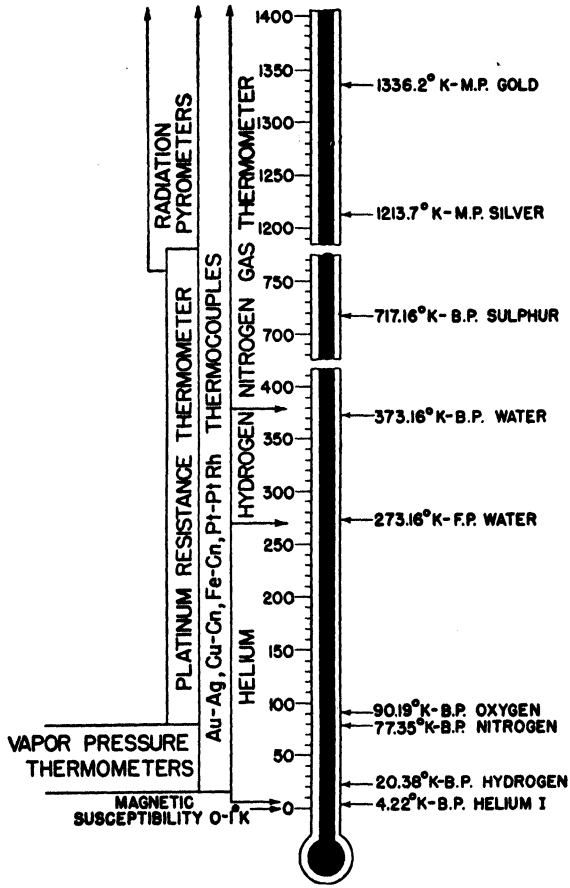


FIG. 2.—Fixed temperatures and useful ranges of various devices for the measurement of temperature.

J_1 of radiation of the same wave-length emitted by a blackbody at the gold point, by means of the formula

$$\log_e \frac{J_2}{J_1} = \frac{c_2}{\lambda}\left[\frac{1}{1336} - \frac{1}{T + 273}\right].$$

The constant c_2 is taken as 1.432 cm degrees. The equation is valid if $\lambda(T + 273)$ is less than 0.3 cm degree."

The International Committee meeting every six years should have convened in 1939, at which time certain minor revisions might have been considered. A number of suggestions have been proposed by Dr. H. T. Wensel[1] of the U. S. Bureau of Standards that might be considered at any future meeting, to make the scale slightly more useful but in no way to alter its general structure.

The distribution of these fixed temperatures and the usable range of the various temperature-measuring devices is shown graphically in Fig. 2.

[1] H. T. Wensel, *Jour. Applied Phys.*, Vol. 2, No. 6, 373 (1940).

CHAPTER II

FLUID THERMOMETERS

Fluid thermometers include all the types of instruments that indicate variations in temperature by means of a measurable change in volume or pressure of a fluid held in a gastight container.

Mercury in Glass Thermometers.—The earliest devices for comparing temperatures made use of the change in volume of a confined fluid as it was being warmed. In the first instruments used in the early part of the seventeenth century, the expansion and contraction of air were used as an indication of the temperature. The introduction of mercury, together with the use of enlarged bulbs, is attributed to Fahrenheit in the early part of the eighteenth century. His scale was based upon three quite arbitrary, fixed points, namely: the temperature of a certain mixture of ice and salt was taken as 0, that of a mixture of ice and water as 32, and that of the human body as 96. On this scale, the temperature of boiling water was found to be 212, although this was not used as a reference point. The numbers 32 and 212 are retained on the modern Fahrenheit scale. More accurate observations show the temperature of the human body to be 98.6 instead of the value 96 assigned to it by Fahrenheit.

In measuring temperatures by an instrument of this sort, it is evident that the underlying assumption is as follows: Those changes in temperature that produce equal apparent changes in the volume of a given amount of mercury enclosed in a glass container shall be considered equal temperature changes.

It is conjectured that Réaumur, in warming a mixture of alcohol and water from the freezing point to the boil-

ing point, found an increase in volume of 80 parts in 1,000. He consequently divided his scale into 80 divisions, taking 0 as the freezing point. This scale, applied to mercury thermometers by other observers, gives the present Réaumur scale in common use in certain countries and in certain industries.

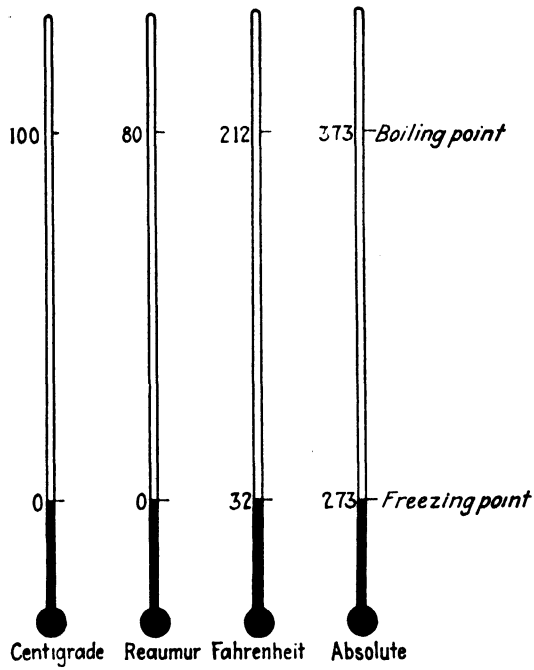


FIG. 3.—Fixed points on the various temperature scales.

In the centigrade scale, whose origin is attributed to Celsius, the values of 100° and 0° were assigned, respectively, to the freezing point and boiling point of pure water. These numbers were later inverted, giving the present centigrade scale. A certain temperature may thus be expressed in the three scales as follows:

$$T_c = \frac{5}{9}(T_f - 32) = \frac{5}{4}T_r \qquad (1)$$

where the subscripts of T denote the corresponding scale readings. Figure 3 shows the numbers assigned to the two fixed points on the various scales.

The properties of mercury make it a very desirable thermometric substance when used in a glass container. Since mercury is a liquid, the change in volume of a large volume of mercury in the bulb, induced by a slight temperature change, may be confined to the capillary stem and made readily apparent. The volumetric coefficient of expansion of mercury is large and fairly uniform when expressed in terms of the fundamental scale to be described later. Its low freezing point $-40°$ and high boiling point 356°C., which may be extended further by added pressure, make a fairly wide working range. Mercury is not compressible, and its surface tension is such that it does not adhere to the glass. It is readily observable because of its high reflecting power. To extend the upper range of the thermometer beyond 356°C, the stem of the thermometer may be filled with nitrogen and sealed at a low temperature. The increasing volume of mercury compresses the nitrogen and raises the boiling point of the mercury. At sufficiently high temperatures, however, the glass will soften and become stretched because of the high pressure. By using quartz containers, the upper temperature limit may be extended to 650°C.

Glass suitable for thermometers should possess certain characteristics. A thermometer made and calibrated, using freshly blown glass, is found to develop scale errors after a time because of the shrinkage of the glass. Bulbs are therefore aged until the final constant volume is attained before they are filled. Most glasses show a hysteresis effect; *i.e.*, upon being heated and subsequently cooled to the starting temperature, they do not regain their original volume completely at once but are left slightly enlarged, giving a depression of the freezing point.

Other Liquid Thermometers.—For use at higher temperatures, thermometers of this type have been constructed, employing liquid tin as the fluid in a container made of porcelain or platinum. With opaque containers,

the scale may be read by lowering a scale from the top to make contact with the top surface of the molten tin. For temperatures below the freezing point of mercury, the bulb may be filled with toloul, alcohol, or pentane, the freezing points of which are, respectively, −97°C., −113°C., and −200°C.

The Beckmann Thermometer.—In order to measure as precisely as possible small temperature changes with the convenience of the mercury in glass thermometer, E. O. Beckmann proposed the thermometer now so well known by his name and illustrated in Fig. 4. In order that a single instrument may be used at different temperatures, there is a reservoir for superfluous mercury at the top of the capillary tube. The bulb contains a large amount of mercury, and the capillary tube is of fine bore such that a change in the mercury thread of about 4 centimeters corresponds to a temperature change of 1°. Each degree is usually divided into 100 parts, and by means of a lens it is customary to estimate tenths of a division so that temperature changes are expressed to the thousandth of a degree. The total length of the scale is usually about 5°, and hence the thermometer must first be adjusted so that its workable range covers the desired interval. This is accomplished by heating to a temperature slightly above that to be measured. As the temperature begins to fall, a brisk tap will break the mercury thread at the entrance to the reservoir. If more mercury is needed in the bulb, the thermometer is inverted while it is heated so that the mercury in the reservoir joins the thread of mercury in the capillary tube. By carefully returning the thermometer to the upright position, as much mercury as desired may be

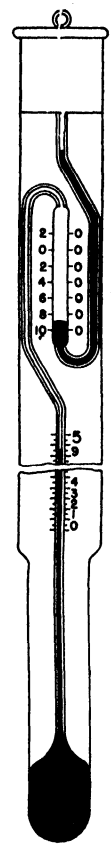


FIG. 4.—The Beckmann thermometer.

drawn into the bulb. Although these instruments are often used because of their simplicity, other less cumber-

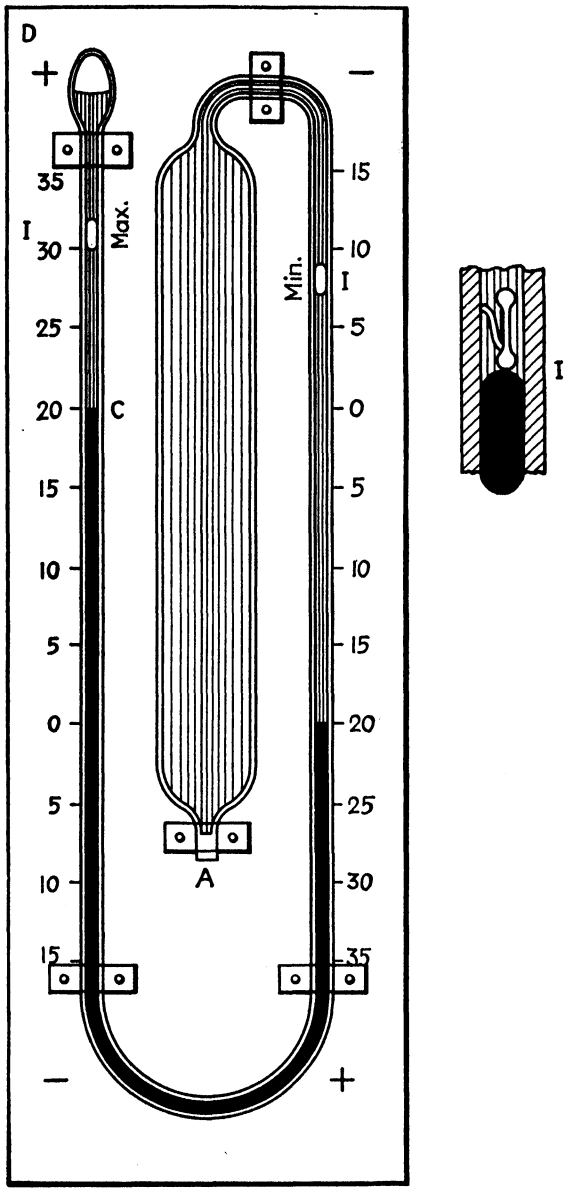


FIG. 5.—The Six maximum and minimum thermometer.

some thermometric devices are usually available that will give not only relative but absolute temperatures.

Maximum and Minimum Thermometers.—Various types of fluid thermometers have been devised to register the highest and the lowest temperatures during a particular interval of time. One of the most widely used of these arrangements is that due to **Six,** shown in Fig. 5. Bulb *A* and part of bulb *D* are filled with a liquid such as alcohol or creosote, and the connecting capillary tube is filled with mercury. The capillary tubes are uniform in bore and calibrated in degrees. Above the mercury on each side are small iron floats that serve as indexes of the temperature. Each iron float is carried along by the advancing front of mercury, but enough friction exists with the walls of the tube to cause it to remain in its highest position as the mercury recedes. The alcohol is able to pass freely by the stationary index. As the temperature is raised, the alcohol in bulb *A* expands, pushing the mercury ahead and carrying the index giving the maximum reading in tube *C*. At the same time, the index on the right is left behind, giving the minimum reading. A small magnet may be employed to reset the indexes.

Other maximum thermometers make use of a constriction in the glass of the stem, so that the thread of mercury can push up on expansion but does not follow back as the temperature recedes. This same principle is used in clinical thermometers. The thermometer is reset by mechanical force.

The Gas Thermometer.—Although the liquid in the solid-container type of thermometer is convenient to use, still, because of the relatively large coefficient of expansion in the container compared to the fluid and the limited working temperature range, thermometers of this type have not been adopted as fundamental in temperature measurement. If a given amount of gas be enclosed in a bulb, the temperature of which is raised, with the volume of the gas kept constant, its pressure will increase. If the pressure of the gas be kept constant, its volume will

increase. This change in volume of the gas compared to the change in volume of the container for the same temperature change is very large. For various reasons, as mentioned earlier, it was agreed by the International Committee on Weights and Measures in 1887 that the former of these changes, when taking place in an apparatus set up under certain prescribed conditions, should serve as the fundamental temperature-measuring device. This may be called the "normal hydrogen thermometer." Figure 6 shows a constant-volume gas thermometer. In the normal hydrogen thermometer, the gas used is hydrogen, and the pressure of the gas at 0°C. is prescribed as 100 centimeters of mercury.

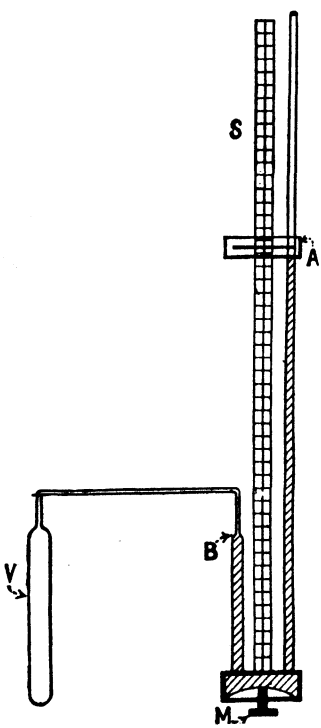


FIG. 6.—Constant-volume gas thermometer.

The fixed temperatures for the normal thermometer were agreed upon as the boiling and freezing points of distilled water under standard conditions. It is thus evident that the scale law of this device may be stated as follows: Those changes in temperature that produce equal changes in the pressure of a given amount of hydrogen in glass are equal temperature changes. Thus, a curve in which pressure is plotted against temperature should appear as a straight line, as shown in Fig. 7. To calibrate the thermometer, its pressure is adjusted to 100 centimeters of mercury when the bulb is placed in melting ice and this value of pressure designated P_0. The bulb is now placed in a steam bath under standard conditions, and the pressure P_{100} measured when the volume is adjusted to the original value. The pressure change per

degree a is then

$$a = \frac{P_{100} - P_0}{100} \tag{2}$$

To measure an unknown temperature x, the pressure corresponding to it, P_x, is measured. Then x is given by

$$x = \frac{P_x - P_0}{a} \tag{3}$$

The zero temperature coefficient

$$\alpha_0 = \frac{\Delta P}{P_0 \Delta T} = \frac{a}{P_0} \tag{4}$$

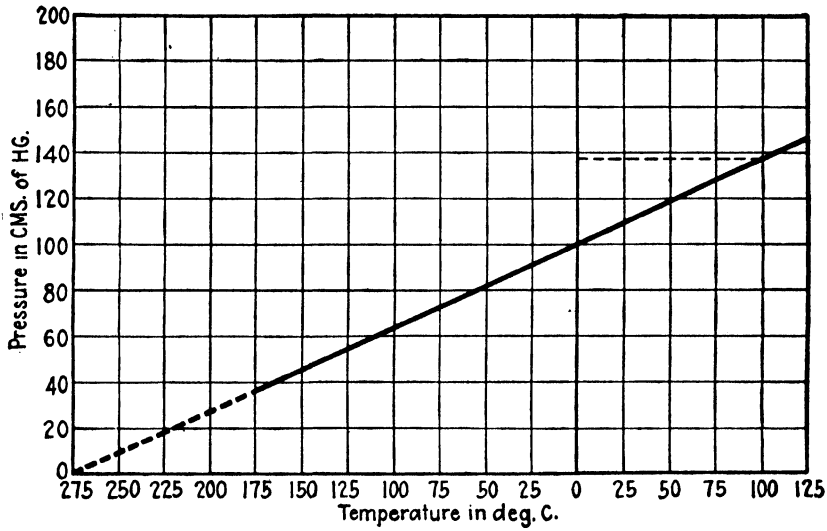


FIG. 7.—Pressure temperature relationship in normal thermometer.

(*i.e.*, the change in pressure per degree divided by the pressure at 0°) is also a constant and has the value 0.00366, or about 1/273.16 for all gases. The true pressure coefficient α, or the relative change in pressure per degree, is not a constant for an ideal gas but must decrease at higher temperatures, since P, being in the denominator, increases.

In the operation of the instrument, shown in Fig. 6, certain errors are always introduced and must be accounted for. As the temperature of the bulb is raised, the actual volume of the bulb increases for two reasons: (1) because

of the thermal expansion of the bulb; and (2) because of the fact that at the higher temperature the increased pressure within causes an elastic expansion, *i.e.*, the volume of the bulb and hence, also, that of the contained gas is greater at the higher temperature. The effect due to the thermal expansion of the material of the bulb in the case of glass amounts to a correction of about 0.75 per cent. The correction is about the same for platinum. The correction due to the pressure expansion is difficult to compute and in precise work is overcome by using a bomb-type heating device in which the same pressure may be maintained as that within the bulb.

An additional correction arises from the fact that the capillary tube that connects the gas bulb to the manometer has its temperature changed only slightly as the temperature of the bulb is raised to its highest value. Hence, some of the air that resided in the bulb at the lower temperature will be crowded into this so-called "dead" space at the higher temperature. Care should be taken to observe the temperature of the mercury in the manometer so that pressures are always expressed in terms of mercury under standard conditions. The effect of some of these corrections may be shown by writing an equation in which the total amount of gas in the bulb and dead space at the lower temperature is set equal to the combined mass at the higher temperature. If there is no change in pressure, the density ρ of a gas at any temperature T is related to the density ρ_0 at 0°, as follows:

$$\rho_T = \frac{\rho_0}{1 + \alpha T}$$

Hence, it follows that

$$V_0\rho_0 + v\frac{\rho_0}{1 + \alpha T_1} = V_0\frac{1 + gT}{1 + \alpha T}\rho_0\frac{P}{P_0} + v\frac{\rho_0}{1 + \alpha T_1}\frac{P}{P_0} \quad (5)$$

where the letters have the following significance:

V_0 = volume of bulb at zero.

ρ_0 = density of gas at zero.

v = volume of dead space.
T_1 = temperature of dead space.
α = temperature coefficient of the gas.
g = temperature coefficient of the container (volume).
P_0, P = pressure at 0° and T°, respectively.
T' = final temperature of bulb.

The equation may be solved for T or for α, depending upon whether or not the operation is a calibration using fixed temperatures or the measurement of an unknown temperature. Neglecting those terms involving the product of expansion coefficients, the temperature T may be expressed as

$$T = \frac{\Delta P \left[1 + \frac{v}{V} + \alpha T_1\right]}{\alpha P_0 \left[1 - \frac{Pg}{P_0}(273 + T_1) - \frac{\Delta P}{P_0} \cdot \frac{v}{V_0} + \alpha T_1\right]} \tag{6}$$

Since the value of α_0, as defined above, is numerically about $1/273$, it must follow that at a temperature of -273°C. the pressure is 0. Should a constant-pressure gas thermometer be used and the changes in volume be taken as an indication of the temperatures, then, also, for those gases that obey Boyle's law, measurements from 0 to 100° indicate that at -273°C. the volume of the gas would become zero. This temperature is therefore called the absolute zero, and centigrade thermometer readings may be expressed in the absolute scale by adding to each reading the value 273.16.

From elementary kinetic theory, the pressure of a gas is related to the effective velocity of the gas particles as follows:

$$P = \frac{1}{3}\rho v^2 \tag{7}$$

where ρ is the density of the gas and v^2 the average squared velocity of the particles. If the pressure is zero,

it would then follow that the particles were at rest, since ρ is not zero. The notion of zero volume, which would follow from the constant-pressure gas thermometer at the absolute zero, is untenable. It would be better to say that at that temperature the volume is the minimum volume of the gas particles at rest; such a volume as enters as a correction term in van der Waals' equation of state.

That temperatures measured by a constant-volume gas thermometer should agree with those of the normal thermometer, provided the gas obeys Boyle's law, may be shown to follow by allowing the temperature of a certain amount of gas to change from T_0 to T, first under the condition of constant pressure and secondly under the condition of constant volume. By taking T_0, as 0°C. and writing expressions for the product PV at the temperature T, it follows that

$$(PV)_T = P_0V_T = P_0V_0(1+\alpha_v T) = P_TV_0 = P_0V_0(1+\alpha_p T)$$
$$= P_0V_0\left(1+\frac{T}{273}\right) = \frac{P_0V_0}{273}T_k = RT_k \quad (8)$$

where T_k denotes the absolute temperature. Most gases obey Boyle's law very closely at temperatures distant from their condensation point. When they are used for temperatures close to the condensation point, the error in the normal thermometer is surprisingly small. Kammerlingh Onnes[1] tested this effect by comparing a hydrogen thermometer with a helium thermometer at temperatures close to the condensation point of hydrogen. He found that the error was very small at temperatures distant from the condensation point by 0.5°C. or more.

Limitations of the Gas Thermometer.—At low temperatures, the gas thermometer is usable close to the condensation point of the gas employed. For very low temperatures, then, helium has an advantage. Because of the awkwardness of the large bulb, however, Kammer-

[1] H. Kammerlingh Onnes, *Proc. Acad. Sci. Amsterdam*, **10**, 743 (1907).

lingh Onnes[1] generally found it preferable to use the gas thermometer only to calibrate noble-metal thermocouples or resistance thermometers for use in this temperature range. At high temperatures, the bulb must be made of a material whose expansion coefficient is accurately known, and at the same time the bulb must neither emit gases nor allow them to diffuse either into or out of the bulb. Using bulbs made of platinum and iridium alloys and using nitrogen as the working gas, Day and Sosman[2] were able to make determinations of certain fixed points up to the melting point of palladium, 1553 $\pm$ 3°C. In spite of the greatest care, the errors in working with a gas thermometer at this temperature were large. Since the gas thermometer is so difficult to work with, it is more convenient to calibrate other secondary devices in terms of the gas thermometer and use them in the actual temperature measurement.

The fact that the gas scale is fundamental by agreement should not be overlooked, however, and, since it has not been used above 1550°C., higher temperatures can only be measured by extrapolating certain laws that have been found to hold true below this value. Hence, for these higher temperatures, an element of uncertainty exists, and it is only by extrapolating with several different laws, that have been independently verified in the known region and by obtaining in each case the same value at the higher temperature that confidence is placed in the result. The uncertainty attendant upon extrapolations of this sort is well illustrated by the following early experiment in high-temperature measurement carried out by Wedgewood.[3] He attempted to measure temperature by the shrinkage caused by that temperature upon a certain sample of clay. The measuring of the shrinkage for the known temperature interval from

[1] *Loc. cit.*

[2] A. L. Day and P. B. Sosman, *Am. Jour. Sci.*, **29**, 93 (1910).

[3] J. Wedgewood, *Phil. Trans.*, **72**, 305 (1782); **74**, 358 (1784).

the freezing to the boiling point of water sufficed for a calibration of the instrument. By comparing this shrinkage with that which took place when the clay was placed in a furnace at the temperature of melting iron, he expressed the melting point of iron as about 12000°C., a value about 10500° too large.

Vapor-pressure Thermometers.—The pressure of a saturated vapor in equilibrium with a pure liquid varies rapidly with the temperature. By establishing the relationship between the vapor pressure and the temperature, it becomes possible to utilize this property to measure temperature. It is employed to good advantage, particularly at very low temperatures. Any one substance can be used only over a very limited range in temperature.

The relationship between vapor tension P and temperature T may for some substances be represented by the simple expression

$$\log P = A + \frac{B}{T} \tag{9}$$

where A and B are constants. To represent better the behavior of many substances, it is necessary to insert additional terms.

At the very lowest temperatures, helium, whose normal boiling point is 4.215°K., may be used. It is found that the vapor tension—temperature curve has a distinct discontinuity at 2.186°K. This leads to the conclusion that there are two different phases of liquid helium. Below 2.186°K., the substance is called helium II, and above that temperature it is called helium I. The following equation is found[1] to represent satisfactorily the vapor tension of helium I:

$$\log P = 1.217 - \frac{3.024}{T} + 2.208 \log T \tag{10}$$

[1] G. Schmidt and W. H. Keesom, *Physica*, **4**, 963 (1937).

where P is expressed in millimeters of mercury and T is in degrees Kelvin.

For certain other substances, Henning and Otto[1] add an additional term CT to Eq. 9 above. The values of the constants A, B, and C, together with the workable range of temperature, are shown in Table I.

TABLE I

P is in millimeters of mercury

Substance	Normal boiling point, °K.	Range, °K.	A	B	C
Helium I.....	4.216°K.	2.18–4.2			
Hydrogen.....	20.382	14–21	4.80204	− 46.104	+0.0167335
Neon.....	27.073	24–28	8.74637	−126.780	−0.0436834
Nitrogen.....	77.352	65–78	7.78174	−341.619	−0.0062649
Oxygen.....	90.18	66–91	7.86224	−408.740	−0.0049832

These data are shown graphically in Fig. 8. Such information is of particular value in determining the

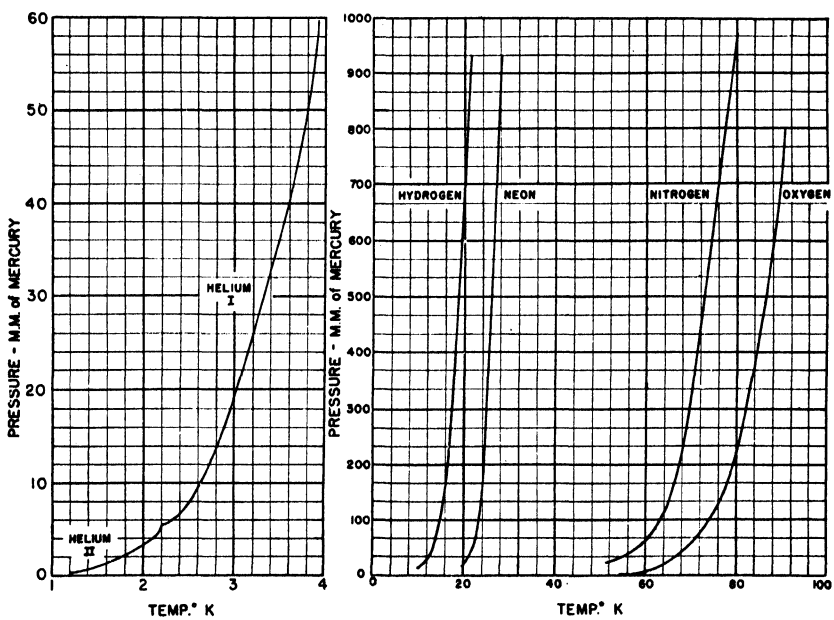


FIG. 8.—Pressure-temperature relationships for various elements.

[1] F. Henning and J. Otto, *Phys. Zeit.*, **37**, 633 (1936).

temperature of cryostats maintained at low temperatures by baths of boiling liquids. By changing the pressure above the bath, the temperature can be altered as desired.

Vapor-pressure thermometers have certain distinct advantages. A wide change in pressure corresponds to a relatively small change in temperature, giving a high sensitivity. The pressure is independent of the amount of liquid present and of the material, the volume, and the shape of the container. The thermometer indicates the temperature of the coldest point of the apparatus, and all other surfaces in contact with the bulb should be warmer than the region whose temperature is to be measured.

Fusion Pyrometers.—It is possible to obtain a series of materials with progressive melting points differing from each other by certain known amounts. By molding these materials in the form of cylinders or cones and arranging them in order on a tray, it becomes possible to estimate temperatures by observing the collapse of the figures. Metals, salts, or clays are suitable for this work. Seger,[1] in 1886, developed a series of materials by using mixtures of Al_2O_3, SiO_2 and SiO_3, B_2O_3 in varied proportions, such that they possessed melting points from 1800 to 590°C. with small steps between successive members. These samples are made in the form of small pyramids and are called Seger cones. These appliances are satisfactory where it is desirable simply to heat a furnace to some definite temperature and then allow it to cool. The cones are very cheap, and only those whose melting points lie in the neighborhood of the final temperature need be used.

The Bourdon Thermometer.—In a thermometer probably used first by E. Bourdon, a thin, flexible metal tube in the form of a spiral is filled with a highly expansive liquid. As the temperature is raised, the increased volume can be accommodated only by the tube's straightening out or unwinding. The free end may carry

[1] H. Seger, *Tonind.-Zeit.*, **10**, 145 (1886).

a pointer that moves over a scale indicating the temperature. Such thermometers have been widely used in meteorological work and are readily adapted to recording devices (Fig. 72).

EXPERIMENT

GAS THERMOMETER

OBJECT: Temperature measurement and pressure coefficient of air.

Place a 0 to 100°C. thermometer close to the bulb of a gas thermometer, and read thermometer when observing the following pressures.

Find the pressure of the gas when the bulb is surrounded by melting ice.

Repeat at the boiling point of water.

Compute the boiling temperature of water for the existing barometric pressure.

Immerse the bulbs of both thermometers in a Thermos bottle filled with water warmed to about 40°C. Read the mercury thermometer, and making any corrections necessary for errors at 0 or 100°C., express the temperature. Read the pressure of the gas thermometer, and by means of the previous readings, calculate the gas temperature. Should the two readings agree? Discuss.

From the first two readings, calculate the zero-temperature coefficient of pressure of the gas. Repeat the calculation where the volume of the dead space and expansion of glass is considered. Discuss errors such as the presence of water vapor in the gas.

The total mass of gas in the bulb and dead space at the low and high temperatures must be the same. If V_0 denotes the volume of the bulb at 0°C., P_0 the pressure of the gas at 0°C., v and T_1 the volume and temperature of the dead space, ρ_0 the density of air at zero degrees, α coefficient of pressure of the gas under constant volume, and g coefficient of cubical expansion of glass, the two expressions for the total mass of gas at 0°C. and T°C., follow:

$$V_0\rho_0 + \frac{v\rho_0}{1+\alpha T_1} = \frac{V_0(1+gT)\rho_0}{1+\alpha T} \cdot \frac{P}{P_0} + \frac{v\rho_0}{1+\alpha T_1} \cdot \frac{P}{P_0}$$

Simplifying and solving gives

$$\alpha_0 = \frac{\Delta P + gTP + \Delta P \frac{v}{V_0}}{P_0T - \Delta P \frac{v}{V_0} T - PgTT_1 + \alpha P_0 TT_1 - \Delta PT_1}$$

which reduces to $\Delta P/P_0T$ when g and v are negligible.

Problems

1. A mercury in glass thermometer has a spherical bulb of 1-centimeter diameter. The cylindrical capillary has an internal diameter of 3 millimeters. What is the approximate distance on the stem for 1°, assuming that the volumetric coefficients for glass and mercury are 0.000024 and 0.000182 per degree centigrade, respectively?

2. In a constant-volume hydrogen thermometer with the bulb in melting ice, the pressure is adjusted to 1,000 millimeters of mercury. With the bulb in steam above boiling water when the barometer stands at 746 millimeters, the pressure in the thermometer is found to be 1,364.2 millimeters of mercury. What does this indicate for the value of the absolute zero?

3. Neglecting corrections, what pressure would be expected in the thermometer of Prob. 2 when the temperature of the bulb is 400°C.? What would the expected pressure be at 400°C. if the thermal expansion of the glass bulb is considered (α glass = 0.000024°C.$^{-1}$)?

4. On a rectangular coordinate plot, lay off centigrade temperatures as abscissas and Fahrenheit temperatures as ordinates. Interpret the slope of the line and the intercepts on the axes. Read from the diagram the Fahrenheit temperature at absolute zero, the temperature at which both thermometers read the same, and the temperature at which the readings are the same but opposite in sign.

CHAPTER III

THERMOELECTRIC PYROMETERS

A simple thermoelectric pyrometer consists of a thermocouple, an indicator or recorder of some type, and suitable lead wires connecting the two. A thermocouple is made by welding two dissimilar metal wires together at one end. If the opposite ends are connected to the two terminals of an instrument indicating e.m.f. and the junction is heated, an e.m.f. will be generated in the wires, the value of which may be read on the instrument. If the cold ends of the thermocouple are maintained at a constant and known temperature and if the wires are of suitable composition, there will be a uniform increase of e.m.f. as the temperature of the hot end of the couple is increased. It is then possible to calibrate this system and make of it a temperature-measuring device.

THERMOCOUPLES

Thermoelectric Currents.—The existence of these so-called thermoelectric currents was discovered by Seebeck[1] in 1821 while he was experimenting on the difference of potential that was thought to exist when two metals were placed in contact. It was noted, for instance, that if the ends of a copper and an iron wire were fused together and one of the junctions heated (over a particular temperature range), an e.m.f. was generated, and current flowed from the copper to the iron wire at the hot end and from the iron to copper at the cold end. Two sources of e.m.f. combine to cause the flow of this

[1] T. J. Seebeck, "Fundamental Principles," *Pogg. Ann.*, **6**, 133, 263 (1826).

current. One of these sources is known as the Peltier e.m.f. and the other as the Thomson e.m.f.

The Peltier E.m.f.—Peltier[1] discovered in 1834 that when an electric current is passed through the junction of two metals there will be either an evolution or an absorption of heat at the junction, depending upon the direction in which the current is made to flow. This indicates that

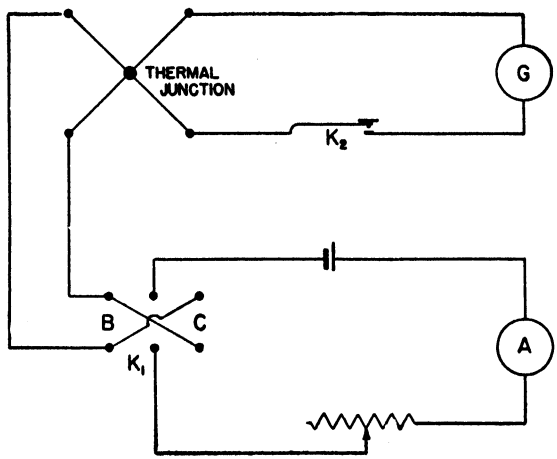


FIG. 9.—Arrangement to demonstrate the Peltier effect.

there is a difference of potential at the junction of the two metals, and when the current is made to flow against this e.m.f. excess heating is produced, whereas if made to flow in the direction that the e.m.f. would produce a current, a cooling effect appears. The existence of this effect may be demonstrated by an arrangement as shown in Fig. 9. An electric current may be sent through a thermal cross of two dissimilar metals in either direction by closing the switch K_1 toward B or toward C. On quickly opening K_1 and closing K_2, a deflection of the galvanometer will be observed that is proportional to the temperature of the thermal junction in each case. Since, for both directions of flow, there is an ohmic heating effect that is proportional to the square of the current and since the Peltier heating

[1] A. Peltier, *Compt. rend.*, **1**, 360 (1835).

or cooling effects are dependent upon the first power of the current, it is evident that the maximum difference in deflections will occur for a particular current. This so-called Peltier e.m.f. is responsible for a portion of the e.m.f. observed in all thermocouples.

The Thomson E.m.f.—While studying the nature of thermal electromotive forces, Lord Kelvin[1] was led to conclude that in a closed circuit made up of dissimilar wires there are other sources of e.m.f. than are accounted for by the Peltier effect. His further work finally brought out the fact that a difference of potential exists in a single section of wire when there is a temperature gradient between the ends. For instance, if a section of copper wire is heated at one end, an e.m.f. will be set up from the hot to the cold end. As in the case of the Peltier e.m.f., the intensity and direction of the Thomson e.m.f. vary in different metals. The presence of this e.m.f. was demonstrated by observing the temperature variations on both sides of a heated point in a wire when an electric current was made to flow first in one direction and then in the other. It was observed that the temperature rose on one side and fell on the other when the current was passed in one direction. On reversing the current, the side that was heated previously was cooled, and the other side was warmed. This may be demonstrated by an apparatus such as that shown in Fig. 10.

An electric heating coil H is free to move between A and B on metal rod MN. A and B are the junctions of a differential thermocouple and are insulated electrically from metal rod MN. G is a galvanometer that registers differences in temperature at A and B. D is a reversing switch by means of which a current of a few amperes may be caused to flow through MN in either direction. Heating coil H is first adjusted to such a

[1] W. T. Thomson, *Trans. Roy. Soc. Edinburgh*, **21**, 123 (1854); *Phil. Mag.* **4**, (II), 214, 281, 379, 433 (1856): *Compt. rend.* **39**, 116 (1854).

position that the temperature is the same at A and B, with no current passing through MN. When a current is caused to flow from M to N, the temperature at A will be observed to assume a value lower or higher than that at B, and the reverse effect will be noted when the direction of the current is reversed. These temperature variations indicate the existence of e.m.fs. in MN due to the temperature gradients.

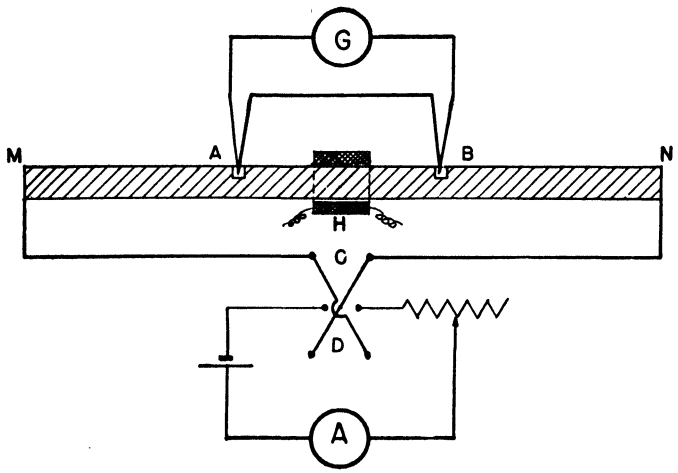


FIG. 10.—Arrangement to demonstrate the Thomson effect.

Nature of Electrothermal Effects.—At the present time, no theoretical explanation of these electrothermal effects is completely in accord with all experimental data. By considering the complete thermocouple attached to a dynamo-electric machine with a negligible ohmic resistance in the circuit, the arrangement may be considered as a reversible heat engine. If one junction is heated above the other, heat will be absorbed at the hot junction, a certain part of this will be used to do work in the dynamo-electric machine now functioning as a motor, and a certain amount of heat will be ejected at the cold junction similar to the condenser or low-temperature reservoir of a heat engine. Now, if this process be considered as obeying the first law of thermodynamics, one equation is obtained involving for

the complete process two Peltier coefficients P_1 and P_2 and two Thomson coefficients σ_1 and σ_2. These coefficients are defined as follows: P represents the number of heat units evolved or absorbed at the junction when unit quantity of electricity q flows across the junction; σ represents the heat evolved within a metal when unit quantity of electricity flows from one region to a neighboring region differing in temperature by 1°. Then the energy converted into work is

$$Eq = P_1q - P_2q + q\int_{T_1}^{T_2} \sigma_a dT - q\int_{T_1}^{T_2} \sigma_b dT \quad (1)$$

The second law of thermodynamics for any cycle, when considered reversible, is

$$\int \frac{dW}{T} = 0$$

or, in this case, $$\frac{P_1}{T} - \frac{P_2}{T} + \int \frac{\sigma_a dT}{T} - \int \frac{\sigma_b dT}{T} = 0 \quad (2)$$

The solution of these thermodynamic equations gives

$$P = T\frac{\partial E}{\partial T} \quad (3)$$

and

$$\sigma_a - \sigma_b = T\frac{\partial^2 E}{\partial T^2} \quad (4)$$

Hence, for any thermocouple whose e.m.f.-temperature relation is given by a second-degree equation such as $E = a + bT + cT^2$, the Eq. (4) for the difference in Thomson coefficients for the two metals would appear to be given by $2c$, and the Peltier coefficient P from Eq. (3) would equal $b + 2cT$. Now, should c be negative and b positive, there would be some value of T beyond which the Peltier effect would reverse.

For a couple whose calibration curve for e.m.f. temperature is a straight line, such as most of the base-metal couples in use ($E = a + bT$), the Peltier coefficient P would equal bT, and the total Thomson effect $\sigma_a - \sigma_b = 0$ at all temperatures. Experiment seems to indicate that

the Thomson effect for a pure metal may actually reverse at certain temperatures. Such experimental values are shown in Table I.

TABLE I.—VALUES OF THE THOMSON COEFFICIENT σ FOR SEVERAL METALS

If σ is positive, heat is absorbed as current flows from higher to lower temperature.

$\sigma = \alpha + \beta T \cdot 10^{-2} + \gamma T^2 \cdot 10^{-5}$, σ in microvolts per degree centigrade

Substance	Temperatures		α	β	γ
	Low	High			
Silver	−168	−123	−0.112	9.47	42.0
	123	525	−3.08	−3.02	
Aluminum	− 13	119	−0.04	0.475	
	71	322	0.268	0.080	
Bismuth	25	32	6.76	2.8	
Constantan	87	481	20.0	2.55	−10.05
Copper	−172	− 60	−2.244	−2.5	− 6.4
	− 60	127	−1.42	−0.74	
	252	678	−1.37	−0.235	
Iron	− 51	115	4.00	8.4	
	32	182	7.66	4.1	
	91	441	7.78	8.61	
Lead	45	342	0.03	−0.47	0.55
Platinum	− 72	128	9.10	−0.475	4.75
Tin	−171	112	−0.09	0.50	
	51	256	0.35	0.093	

These phenomena should be explainable by the free-electron theory, which has met with considerable success in the field of thermal and electric conductivities. As the temperature of the metal is increased, the number of free electrons per unit volume might be expected to increase directly. The average kinetic energy of the electrons should also increase, but the mean free path of the electrons would decrease. The combination of these effects will influence the flow of electrons from one region to another within a given metal or across the contact surface by which it is connected to another metal. The first two effects would aid, whereas the last-

named effect would hinder, electron diffusion. Since these combined effects might vary for different metals in different degrees with temperature, a reversal of the Peltier coefficient would be possible. A reversal of the Thomson effect might also be possible if the combined effect for a given metal varies irregularly with temperature.

Lead appears to have a very small Thomson effect and is therefore generally taken as a reference metal

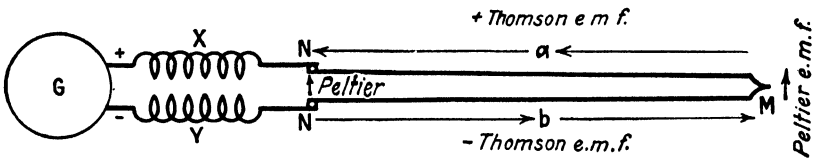


FIG. 11.—Sources of e.m.f. in a thermocouple.

in thermoelectric power tables, although any other metal, such as platinum, could be used.

Preparation and Operation of Thermocouples.—In order that a thermocouple be useful in temperature measurement, it is essential that the algebraic sum of the Peltier and Thomson e.m.fs. be sufficiently large and show a direct variation with temperature. Such a system is illustrated in Fig. 11. M is the hot junction of the couple, N the cold junctions, a the positive wire, b the negative wire, G the galvanometer, and x and y the lead wires.

Cold-junction errors will be discussed more fully later, but it will be well to point out at this time just why it is necessary that the cold junctions N in Fig. 11 must be kept at a constant temperature. The leads x and y are usually copper wires. At the points N, these copper wires are in contact with wires a and b of the couple, the connection being completed through the galvanometer. Such a situation means that there are small Peltier e.m.fs. at points N. If these points are allowed to fluctuate in temperature, these Peltier e.m.fs. will vary and may cause errors in the e.m.f. which

is being produced because of the temperature of the hot end of the couple.

Further, if the temperature of the cold junction rises, the hot end remaining constant, the Thomson e.m.f. in wires *a* and *b* will be affected, producing a further error. The temperature of the cold junctions should remain constant unless suitable compensation for the error is provided.

Another question grows out of this consideration. What will be the effect of heating one or both wires of a thermocouple at some point between the hot and cold junctions? Consider, for instance, that the hot end of a certain couple is at 700°C., the cold junctions at 0°C., and the wires heated to 1000°C. at some point between the two junctions. Unless there is inhomogeneity of the metal or conduction of heat along the wires to one or both the junctions, the e.m.f. generated will be that produced by the hot junction as if there were no intermediate heating of the wires. The reason for this is easily explained. When the wires are heated to 1000°C. at an intermediate point, the Thomson e.m.f. only will be affected. From the point at 1000°C. to the hot end of the couple, there will be a Thomson e.m.f. generated because of the 300°C. difference between the two points. Between the point at 1000°C. and the cold ends at 0°C., an opposite Thomson e.m.f. will be generated because of the 1000°C. difference between the two. The resultant e.m.f. will be the algebraic sum of the two e.m.fs. generated in the wires, which, of course, will be the e.m.f. generated by a temperature of 700°C. at the hot end of the couple. In other words, the e.m.f. generated by a thermocouple, except in situations where there is inhomogeneity or noticeable heat conduction along the wires, is due only to the difference in temperature between the hot and the cold junctions of the couple, and the temperature indicated is only that at the hot junction.

Thermoelectric Power of Thermocouples.—The e.m.f. produced by thermocouples is always very small. There is, of course, considerable variation in the different types of couples, the maximum range for metals commonly used being about 0 to 0.065 volt as the temperature varies from 0° to 1100°C. (2012°F.). Figure 12 represents the e.m.f.-temperature relation of metals and alloys commonly used in making thermocouples,

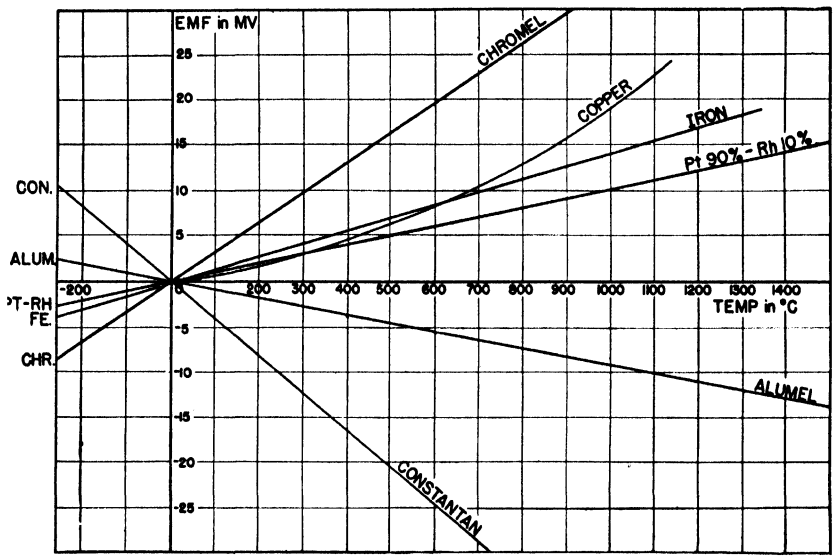


FIG. 12.—E.m.f.-temperature relationship for certain metals with respect to platinum.

versus platinum, the cold junctions being at 0°C. It will be noted that the upper curves represent materials that are positive and the lower curves those that are negative to platinum. The e.m.f. of a combination of any two of these materials at a given temperature may be ascertained by measuring in millivolts the vertical distance between the two curves. In all cases, the upper curve indicates the positive element of the couple.

The e.m.f. per degree rise in temperature is sometimes referred to as the thermoelectric power of a couple and furnishes a convenient means of comparing the same or different types of couples over various ranges. It

is obtained by determining the first derivative with respect to temperature of the expression $E = f(T)$, where E is e.m.f. and T is temperature. The same information may, of course, be found approximately from inspection of curves such as are found in Fig. 12.

Required Properties for Thermocouples.—Although some reference has been made in the discussion so far to the thermoelectric requirements of thermocouples, other properties should be considered. Little beyond a brief enumeration of desirable properties will be made at this point, since it is more convenient to cover them in detail in the discussions dealing with particular types of thermocouples.

1. *Direct Variation of Temperature and E.m.f.*

2. *Resistance to Corrosion and Oxidation.*—It is quite obvious that the elements of the thermocouples must have a reasonable amount of resistance to these actions. A bare iron wire, for instance, will deteriorate too rapidly.

3. *Development of Relatively Large E.m.fs.*—The accurate determination of the e.m.f. of a couple that has an extremely low thermoelectric power requires a delicate instrument. In general, a couple possessing a larger thermoelectric power will have a greater utility.

4. *Constancy of Calibration.*—Changes in the calibration of thermocouples may result from various causes. Couples should not be made from metals or alloys that deteriorate rapidly upon exposure to temperatures in the range over which they are expected to operate. Contamination by furnace fumes and oxidation will cause inhomogeneity of couples and consequent variations in e.m.f.-temperature relationships.

5. *Reproducibility of Couples.*—In laboratory work, this point is not of great importance. In plant work, however, where a large number of couples are being used and where several couples may be read on one instrument that is graduated in degrees of temperature only, it is very essential that there be no marked variation

in couples of the same type. Any great variation necessitates the application of a correction, and that is difficult in a large installation.

Noble-metal Thermocouples.—Becquerel,[1] in 1826, first applied the discovery of Seebeck to the measurement of high temperatures. He used a platinum-palladium couple but obtained no satisfactory results. Considerable work was done by other investigators, but the thermoelectric pyrometer was not successfully used until after the investigations of Le Chatelier.[2] He finally perfected and introduced the couple whose positive element consists of 90 per cent platinum and 10 per cent rhodium, the negative element being a pure platinum wire. Barus,[3] at about the same time, recommended the use of a couple whose positive element consists of 90 per cent platinum and 10 per cent iridium and whose negative element is pure platinum. This latter couple develops a greater e.m.f. than the couple of Le Chatelier, but there is a gradual distillation of the iridium from the alloy wire, especially at high temperatures. This causes the e.m.f. to drop gradually and necessitates frequent recalibration of the couple. The effect of varying the percentage of rhodium in the platinum alloys[4] used in the noble-metal couple is shown in Fig. 13. It is apparent that the thermoelectric power increases rapidly with concentration for small amounts of rhodium but attains almost a saturated value at about 15 per cent.

From what has just been said, it is evident that the first types of thermocouples to come into general use were made of the noble metals. After the successful

[1] E. Becquerel, *Ann. chim. phys.* (2) **31,** 371 (1827).

[2] H. Le Chatelier, "Thermoelectric Pyrometer," *Compt. rend.*, **102,** 819 (1886); also, *Jour. phys.* (2), **6** (January, 1887).

[3] C. Barus, *U. S. Geol. Survey Bulls.* 54 and 103; *Phil. Mag.* (5), **34,** 15, 376 (1892); *Am. Jour. Sci.*, **36,** 427 (1888), **47,** 366 (1893), **49,** 336 (1894).

[4] F. R. Caldwell, *U. S. Bur. Standards Jour. Research*, **10,** 373 (1933).

application of these couples, a considerable period elapsed during which no other type of couple was introduced, although the fact was appreciated that the cost of couples made of platinum was almost prohibitive in many cases. More recent years have seen the development and successful application of the cheaper base-metal couples. The range of base-metal couples

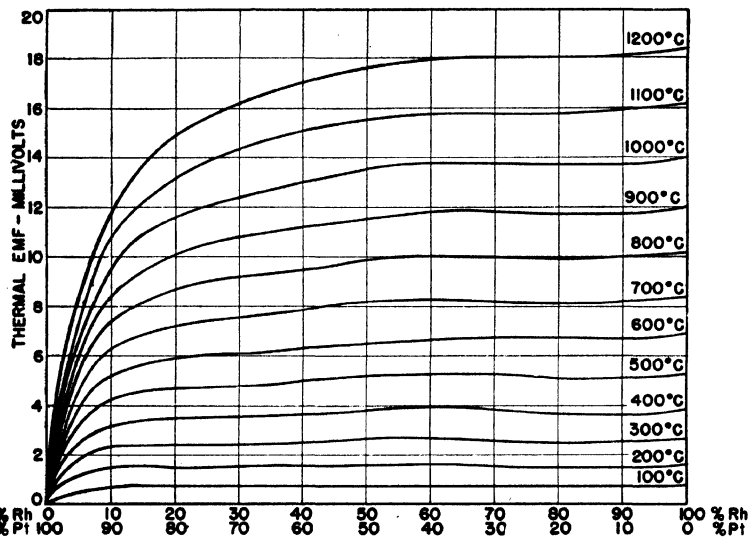


FIG. 13.—E.m.f. of platinum platinum-rhodium thermocouples with varying amounts of rhodium.

is in all cases less than that of noble-metal couples, and since their determinations are less accurate, many applications yet remain for the noble-metal couples. Laboratory work requiring high precision, the hardening of high-speed steel, maintenance of standards for base-metal couples, and control of high-temperature kilns are included among these.

Preparation.—Noble-metal couples may be purchased already mounted, or, if desired, the wire may be bought from the platinum refiners and made into couples in the laboratory. Figure 14*A* shows a noble-metal thermocouple with its primary mounting before insertion

in the protecting tube. Figure 14*B* shows the completely assembled thermocouple with protecting tube and head.

The ends of the two elements should be fused together. This may be done by means of an electric arc or a small oxygen-illuminating gas flame. Acetylene should not be used, since the wires become embrittled through the formation of platinum carbide. The welding flame is conveniently produced by a small torch. The flame of the torch should be about 4 centimeters long. The torch is supported by suitable means and the two ends

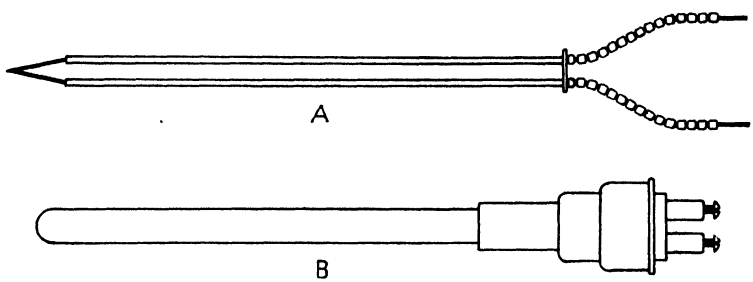


FIG. 14.—*A*. Thermocouple with primary mounting. *B*. Thermocouple in protecting tube.

of the wires held in the flame until they fuse together in a small head. No flux should be used.

Calibration.—Before calibration, a noble-metal couple should be annealed electrically for a period varying from 30 minutes to 2 hours, at about 1500°C. The purpose of the annealing is to produce homogeneity in the wire. In case there are hard and soft spots, parasitic e.m.fs. are set up that may introduce errors. The annealing operation is carried out by suspending the couple between two binding posts in a 110-volt circuit. The current required depends upon the size of the wire, varying from about 10 to 14 amperes as the diameter of the wire varies from 0.4 to 0.6 millimeters. In the case of old and badly contaminated couples, the time of annealing may have to be increased to several hours.

If there is any doubt as to the homogeneity of a noble-metal couple and if precise work is required, a homogeneity test should be applied. Uncontaminated reference specimens of each type of wire are required for this. One end of the standard wire is placed in contact with the corresponding wire of the couple to be tested. This junction is then heated, and any e.m.f. between the cold ends of the couple wire and the reference wire is recorded. This procedure is carried out at several points along the couple wire. If the couple wire is homogeneous, no e.m.f. will be generated. In a similar manner, the other element of the couple is explored. For detailed description of this test, see *Technological Paper* 170 of the U. S. Bureau of Standards, page 228.

An inhomogeneous couple indicates the temperature of the hot junction only when the region of inhomogeneity lies completely on one side or the other of the region of temperature gradient on the couple.

The temperature-e.m.f. relation of the platinum, platinum-rhodium thermocouple in the range 300 to 1200°C. is expressed by the equation

$$E = a + bT + cT^2 \qquad (5)$$

where E = e.m.f., T = temperature in degrees centigrade of the hot junction of the couple (cold junction at 0°C.), and a, b, and c are constants. The constants are different for each couple and require three standard points for their determination. These points are usually the melting or freezing points of three metals (see Experiment 4). The e.m.fs. of the couple at these three points are obtained and inserted in the first member of the equation. Three equations are thus obtained that are solved simultaneously for a, b, and c. The following is a typical expression for a couple of this type:

$$E = -0.323 + 0.008276T + 0.0000016387^2.$$

Using this equation, a calibration curve of temperature

versus e.m.f. may be prepared. Above 1200°C., the following corrections must be added to the temperatures given by the equation.

TABLE II

Temperature Computed from Parabolic Equation, Degrees Centigrade	Correction to Add, Degrees Centigrade
1200	0
1300	2
1400	6
1500	14
1600	25
1700	39

The calibration that has just been described is termed the primary calibration and may be made by a standardizing laboratory. In the secondary calibration, the actual couples to be used are compared with a standard couple that has been previously calibrated.

Two types of noble-metal couples are commonly used. In one, the alloy wire contains 10 per cent of rhodium while the other contains 13 per cent of rhodium. The latter has a somewhat higher thermoelectric power as shown in Fig. 13.

Base-metal Thermocouples.—In installations requiring large numbers of thermocouples, the cost of using platinum, platinum-rhodium couples would be very high. For this reason, if for no other, there has been an insistent demand for couples that will give reasonable service and be made from the less expensive metals. Many combinations of metals and alloys have been investigated, but until the present time comparatively few successful base-metal couples have been developed. No space will be given here to the fundamental investigations in connection with this type of couple. This work has been carried out to a great extent in industrial laboratories, and much of the material has not been published. In the present discussion, the more important types of base-metal couples will be listed and their characteristics and applications discussed.

Much of the effort along this line has been made with a view of producing as nearly as possible what is termed a "straight-line" couple. In such a couple, the temperature is a linear function of the e.m.f., and the relationship, when plotted, is a straight line represented by the equation

$$E = a + bT \tag{6}$$

The advantages of such a couple are very evident. The calibration curve requires the establishment of only two standard temperatures, one of which might well be the ice point. Another important advantage lies in the fact that in checking couples of this type it is necessary to check only one point. In other words, the per cent error is nearly constant. Much time in checking large installations is thereby saved. Perhaps the most useful feature of straight-line couples is in the application of cold-junction corrections. This involves merely the addition or the subtraction of the difference between the actual temperature of the cold junction and the temperature at which the original calibration was carried out. For instance, suppose a couple originally calibrated at a cold-junction temperature of 0°C. is being used with a cold-junction temperature of 15°C. In order to obtain the correct temperature at the hot junction, it is necessary only to add 15°C. to the indicated temperature. If the cold junction were at −15°C., the 15° difference would be subtracted from the indicated temperature.

Base-metal couples are made in sizes ranging from 0.02 up to 0.25 inch in diameter. The couples may be bought completely mounted, or the wire may be purchased and couples made by the user. The mounting of base-metal couples is similar to the methods used in the case of noble-metal couples (see Fig. 14).

A study of Fig. 12 will reveal the various types of base-metal elements that could be advantageously used

in thermocouples. The following combinations are the ones usually found in practice:

1. Chromel (+)..... Alumel (−)
2. Iron (+)..... Constantan (−)
3. Copper (+)..... Constantan (−)
4. Chromel-X (+)..... Copel (−)

The *chromel-alumel* couple is used very widely at the present time. The chromel, or positive, element is an alloy consisting of about 90 per cent nickel and 10 per cent chromium. The alumel, or negative element, carries about 94 per cent nickel, 2 per cent aluminum, 3 per cent manganese, and 1 per cent silicon. This couple may be used intermittently for temperatures up to 2400°F. (1315°C.) and continuously for temperatures up to 2000°F. (1094°C.). Its calibration curve is very nearly a straight line, so that cold-junction errors may be corrected by mere additions or subtractions of the differences between actual cold-junction temperature and the cold-junction temperature of the calibration curve. They are very durable and will give good service for several months with very little attention. It is possible to purchase coils of chromel and alumel wire from which couples can be made as needed, without calibrating each couple. Before making any couples, however, for precision work, samples from such coils should be checked against a standard such as platinum. This will ensure that the millivoltage values of the alloy wire are correct and that there are no wide variations in different specimens of the same material. The procedure indicated above should be followed in the case of any alloy wire that is to be used as a thermocouple element. The e.m.f. per degree centigrade is about 0.04 millivolt. These couples, as well as noble-metal couples, should never be used in a reducing atmosphere without adequate protection.

The *iron-constantan* couple is also widely used. The positive element consists of carefully made pure-iron wire and the negative element, of the 60 per cent copper and 40 per cent nickel alloy known as constantan.

This couple may safely be used up to a temperature of 1800°F. (982°C.) providing proper precautions are made to prevent oxidation and contamination of the wires. Two methods are used to accomplish this. One is to pack the secondary protecting tube of the couple with a material that is slightly reducing in nature, such as a 97 per cent alumina and 3 per cent charcoal

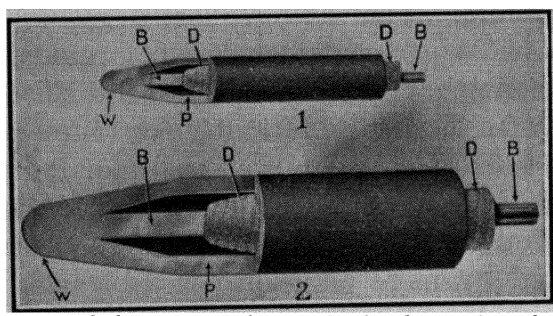


FIG. 15.—Thermocouple having one element in the shape of a tube surrounding the other element. (*Foxboro Co.*)

mixture. Figure 15 represents the other method of construction. An iron tube is made the positive element of the couple and the constantan wire or rod placed inside the tube, the two being fused together at one end. Asbestos cord is used to insulate the two elements. The iron tube furnishes protection to the constantan element and is not so quickly deteriorated by oxidation. For severe furnace conditions, however, even this sort of couple must be protected by an outer tube. The thermoelectric power of this couple is about 0.055 millivolt per degree centigrade.

The *copper-constantan* couple is useful for temperatures up to 1000°F. (537°C.). Its greatest utility is in the lower ranges, for its calibration curve remains nearly straight at temperatures in the neighborhood of the boiling point of water, and its thermoelectric power is

high enough so that accurate readings of temperature may be made in that range. It is generally possible to dispense with the protecting tube when this couple is being used for low-temperature work.

An interesting application of the copper-constantan couple is in the measurement of temperatures below zero. Adams[1] states that it is possible to make temperature measurements as low as −253°C. with this couple. Values of the temperature-e.m.f. relationship for low temperatures have been determined by the above investigator. In using a couple in this range, it should be kept in mind that there is a reversal of the direction of the e.m.f. as the temperature passes downward through zero, the cold junction remaining at zero.

The *chromel-X*, *copel* couple is also suitable for the range of temperature below 1000°F., having a thermoelectric power about twice as great as that of the base-metal couples mentioned above. Chromel-X is an alloy carrying about 64 per cent nickel, 25 per cent iron, and 11 per cent chromium. Copel contains 45 per cent nickel and 55 per cent copper. The chromel alloys alumel and copel are made by the Hoskins Manufacturing Company of Detroit. Constantan may be bought on the open market under trade names such as Advance and Ideal.

The junctions of base-metal couples are made by fusing the ends of the two elements together by means of an electric arc or an oxygen-illuminating gas torch. In the case of the larger wire sizes, it is advisable to twist the two wires for a few turns before welding. This gives added mechanical strength to the couple and brings the two ends to be fused conveniently close together. If an electric arc is used, the two couple wires are fastened to the positive terminal of a 110-volt, direct-current line. The negative terminal is connected

[1] L. H. Adams, "Pyrometry," p. 165, Symposium, *Am. Inst. Mining Met. Engrs.*, (1920).

through a resistance to a graphite pencil, about ¼ inch in diameter, having an insulated handle. When the ends of the wires have been brought together, the junctions are touched with the graphite pencil. As soon as an arc is formed, the pencil is drawn away. This method is very good for the repairing of broken couples. If the junction is to be made by means of an oxy-gas flame, it should be first coated thoroughly with borax. This is accomplished by heating the ends of the wires to a dull red heat and then dipping them into a dish of powdered borax. The process should be repeated until there is a heavy coating of transparent borax around the junction. The full heat of the torch is then applied, and the ends of the wires will fuse down to a round bead that shows almost no signs of oxidation.

The calibration of base-metal couples is usually carried out by direct comparison with a standard couple of the same type, or with a platinum, platinum-rhodium couple. The question of checking large numbers of couples, such as is the problem in industrial plants, is well discussed in *Technological Paper* 170 of the U. S. Bureau of Standards, from which the following is taken:

"**Standardization of Base-metal Couples.**—It is difficult to secure equality of temperature between the hot junctions of two base-metal couples or between a base-metal and a rare-metal couple. One arrangement for precision calibration is to place the junction of the rare-metal couple in a small saw cut made in the hot junction of the base-metal couple and pinch the jaws of the saw cut until good thermal contact is secured. Small base-metal couples may be fused directly to the rare-metal couple. The rare-metal couple is protected by porcelain tubes to within a few millimeters of the hot junction, and the end of the porcelain tube is sealed to the couple by a small amount of kaolin and water-glass cement or by pyrex glass. This prevents contamination of the rare-metal couple, with the exception of the small

length of 2 or 3 millimeters, which is necessarily exposed to the metal vapors. If the furnace is uniformly heated in this region a small amount of contamination will not cause any error. The method, however, is not feasible for work on a large scale. With fused or squeezed junctions the double potentiometer may be used in calibrating base-metal couples.

"1. *Use of a Muffle Furnace.*—Several base-metal couples and the standard rare-metal couples mounted in non-porous porcelain tubes are packed together as closely as possible and tied into a bundle with asbestos cord. The hot junctions are inserted into a length of very heavy iron pipe capped at one end and the open end from which the couples protrude is tightly packed with asbestos wool. The iron tube and couples are mounted in the furnace and the e.m.f. measurements are made as soon as temperature equilibrium is reached. If the muffle furnace is large enough, the iron tubes protecting the base-metal couples need not be removed. A satisfactory size of furnace measures 8 by 8 by 30 inches deep. Precision work is impossible in this method of calibration. Even when every precaution is taken to reduce temperature gradients, differences in temperature of 10 or 20°C. frequently will be found to exist between the different couples mounted side by side. This accuracy, however, is sufficient for many industrial processes.

"This method may be greatly improved by employing a large copper block drilled with holes into which the hot junctions of the couples are inserted. The heavy protecting tube is removed from each couple during the test.

"2. *Use of Molten-metal Bath.*—A satisfactory method for calibrating base-metal couples on a large scale is by use of a bath of molten metal. An iron pot about 12 inches in diameter, or larger, and 15 inches deep is filled with tin or lead covered with powdered graphite.

This may be heated in a gas furnace or an electric furnace wound with nickel alloy, such as nichrome or chromel. Into the tin bath dip about six iron tubes closed at the lower end and immersed to a depth of 12 inches. The tubes are just large enough to permit easy insertion of the base-metal couple with its iron protecting tube. The standard couple is mounted in one of the six tubes and the base-metal couples are placed in the others. As soon as temperature equilibrium is reached the e.m.fs. are measured, that of the standard couple giving the temperature of the bath. A large number of base-metal couples may be tested one after the other at this temperature, and the process is then repeated at another temperature. The tin bath may be used satisfactorily in the range 300 to 1000°C., since tin is a metal of low volatility. Data obtained by the above method are plotted, temperature *versus* e.m.f. for each couple, and a smooth curve drawn representing the calibration. For some types of base-metal couple, the curve is slightly S-shaped, showing small inflections near the critical points of the metals of which the couple is constructed. In precision work the calibration must be made at short-temperature intervals over these critical regions to determine the exact form of the temperature-e.m.f. curve.

"3. *Single-point Calibration or Check Point.*—It is frequently desirable to check a base-metal couple at a single point. If the couple is indicating e.m.fs., say 2 per cent higher at this temperature than the usual e.m.f. of that shown by the original calibration data, it is customary to assume that it reads 2 per cent high at all temperatures. This method of calibration at best is only approximate, and experimentally it is frequently found that a couple reading 2 per cent high at 800°C. indicates correctly at 1000°C. Single-point calibrations are of value, however, especially as a check upon the behavior of a couple in any particular temperature range.

"A convenient standard temperature for this work is the melting or freezing point of sodium chloride (common salt), chemically pure. This material melts or freezes at 801°C. The salt may be used in a duriron crucible heated in a gas or electric furnace. The base-metal couples are immersed without protecting tubes from 4 to 6 inches in the bath. Melting or freezing point curves may be observed as already described. These curves are rather oblique on account of the low thermal conductivity of the salt, as discussed in the section on melting-point methods. The exact portion of the curve representing the true freezing point is reached when crystals begin to form along the entire length of the immersed end of the couple. The couple may be used as a stirring rod during the freezing. If the salt has not been previously fused, it must be melted the first time with a cover on the crucible as the imprisoned water in the salt crystals will cause the salt to sputter out badly. After the first melt, however, there will be no trouble in the use of this material. Molten salt reacts somewhat with most base-metal couples, but the reaction is so slow that the couple will not be injured. No serious change in the melting point resulting from heating the salt in contact with iron for several hours has been found.

"4. *Checking Thermocouples in Fixed Installations.*—It is frequently desirable to check the readings of a thermocouple without removing it from the furnace in which it is installed. Tests of this nature are of extreme importance in the technical industries. They are also difficult to perform with precision, and the precision which is obtainable in a laboratory test cannot be expected in tests of this nature. An ordinary calibration in the laboratory of a base-metal couple which has been in use in a fixed installation for some time, while furnishing results apparently of high precision, does not, however, necessarily hold when the couple is

returned to its original installation. This is on account of the heterogeneity developed in a base-metal couple after prolonged heating.

"The presence of heterogeneity could be detected by a homogeneity test, but such tests on a large scale are not worth while for base-metal couples except for investigational work and, moreover, do not show how to correct the readings satisfactorily. Such a test would simply indicate that the couple should be thrown away, whereas in its permanent installation it still has a useful life. The throwing away of base-metal couples in a fixed installation as soon as heterogeneity sets up would be a very costly and unnecessary procedure, except in the comparatively rare cases where the highest possible accuracy is required. The degree of heterogeneity developed depends upon the type of installation, depth of immersion, location, and character of temperature gradient, etc. These quantities are fairly definite and fixed for any particular installation. If, however, the couple is removed from the installation and calibrated in the laboratory, these quantities are altered and the conditions under which the couple is actually operating cannot be reproduced. The calibration of the laboratory may give results quite different from the calibration which would be obtained if it were possible to duplicate exactly all the physical characteristics of the permanent installation. Hence, it is evident that if inhomogeneous couples are ever to be used, it is important that they be calibrated or checked in their fixed installation.

"The exact method of procedure depends upon the type of installation. A standard checking couple is employed complete with a high-resistance galvanometer, 'heat-meter,' or portable potentiometer. The hot junction of the checking couple is placed as closely as possible to the hot junction of the couple under test, and the readings of the two couples compared. The

main objection to the method is the difficulty in getting the two hot junctions together. One method is that of drilling a hole in the furnace at the side of each couple permanently installed large enough to permit insertion of the checking couple. The hole is kept plugged, except when comparison tests are being made. The checking couple is inserted in the furnace through this hole to the same depth as the couple under test. The hole should be located as close to the permanently installed couple as possible.

"In many installations the base-metal couple and protecting tube are mounted inside another protecting tube of iron, fire clay, carborundum, or some other refractory which is permanently cemented or fastened into the furnace wall. Frequently, there is room to insert a small test couple in this outer tube adjacent to the fixed couple. A third method, much less satisfactory, is that of waiting until the furnace has reached a fairly constant temperature and of making observations with the couple under test. Then remove this couple from the furnace, and insert the checking couple to the same depth.

"If desired, comparisons can be made preferably by either the first or second method at several temperatures, and a curve may be obtained for each permanently installed couple showing the corrections necessary to apply to its readings.

"It may be thought that this method of checking couples is unsatisfactory, because in most furnaces used in industrial processes large temperature gradients exist and there is no certainty that the standard couple is at the same temperature as the couple under test. This objection, however, is not serious, because if temperature gradients do exist, in the furnace, of such a magnitude as to cause much difference in temperature between two similarly mounted thermocouples located near each other, the accuracy required by the measuring

instruments need not be great, and the reading of the standard couple can be accepted for the standardization of the fixed couple just as satisfactorily as if the true temperature of the fixed couple were known. If temperature gradients exist of such a magnitude that two correctly calibrated couples similarly mounted near each other read, say, 20°C. apart, it may be certain that neither couple is registering the temperature of material within the furnace to this degree of accuracy."

Use of Thermocouples in Molten Metals.—The rapidity with which readings can be made as well as the relative accuracy of temperature determinations by means of thermocouples would seem to make them ideal for measuring the temperatures of molten metals. In the lower temperature ranges, no difficulties are experienced, but as temperatures rise above 2000°F. (1093°C.), the problem of providing suitable protection for the couple becomes acute. Correct calibration of the couple also becomes more difficult.

Metals Melting below 2000°*F.*—Base-metal couples may be used for this service, and for intermittent readings it is not necessary to use a protecting tube unless there is a decided reaction between the molten metal and the thermocouple elements. More rapid readings will, of course, be obtained without the protecting tube. However, where a couple is to be used for continuous indication of temperature, as in the case of lead baths for heat treatment of steel, a protecting tube must always be used. Figure 16 represents the construction of a couple for intermittent use in molten metals. It is unnecessary to use a welded couple in this service, since the end of the couple frequently reacts with the metal bath and grows steadily shorter. The diameter of the elements is relatively large, and, as is shown in the illustration, the parts of the elements that are immersed in the molten metal may be readily replaced. Where protecting tubes are necessary, a

material must be used that does not react with the metal. In most cases, however, a protecting tube of wrought iron or mild steel is entirely satisfactory. Where the use of these metals is doubtful, protecting tubes of chromel or nichrome are indicated.

Metals Melting above 2000°*F.* The application of thermocouples in this temperature range has been largely in connection with the temperatures of molten cast iron and steel but may equally well deal with any other metals or alloys of high melting point. The problem has been attacked by two methods. In the first case, attempts have been made to develop new and more refractory thermoelements. Other investigations have been along the lines of furnishing sufficient protection to noble-metal couples so that they may be used at these high temperatures. Some success has been reached in both attempts, although there still is no rapid and foolproof procedure for making these temperature measurements.



FIG. 16.—Thermocouple for use in molten metals. (*Pyrometer Instrument Co.*)

The Fitterer[1] couple uses for its elements a rod of silicon carbide supported inside a hollow cylinder of graphite. The rod of silicon carbide is embedded in the graphite at the hot end, and the graphite tip at this point is replaceable. At the cold end, the graphite and the silicon carbide are electrically insulated from

[1] G. R. Fitterer, *Trans. A.I.M.E.* **105**, 290 (1933).

each other, and the temperature of the cold end is controlled by cooling water. These couples can be made of any desired length and have a very high thermoelectric power—approximately 0.3 millivolt per degree centigrade. Further information regarding the development and application of this couple in the steel industry may be obtained by reference to the *Proceedings of the Open Hearth Committee* of the A.I.M.E. for the years 1936, 1938, and 1939.

Thermocouples of tungsten and molybdenum for use in molten steel have been described by Osann and Schröder[1] and by Leiber.[2] Both these metals oxidize at high temperatures, so must be used in a protecting tube. The thermoelectric power of this couple is very low, and it exhibits a reversal of e.m.f. at about 600°C. (1112°F.) that complicates its use below 1200°C. (2192°F.).

Holtby[3] discusses the use of a tungsten-graphite couple in measuring the temperatures of molten cast iron. The results appear to be quite satisfactory. The thermoelectric power of this couple is less than that of the platinum−10 per cent rhodium couple below 400°F. but is about twice as great at 2000°F. This reduces the errors introduced by cold-junction variations, provided the cold-junction temperature does not rise above 212°F.

Steelmakers in Britain report successful results with the use of a so-called "quick-immersion" thermocouple that is dealt with at length in a paper by Schofield and Grace.[4] A platinum platinum-rhodium thermocouple enclosed in a silica sheath about 1 millimeter in wall thickness is placed inside a thin-walled steel protecting tube. The couple is carried to the center of the

[1] J. B. Osann and E. Schröder, *Arch. für das Eisenhüttenw.*, **7**, 89 (1933).
[2] G. Leiber, *Arch. für das Eisenhüttenw.*, **11**, 63 (1937).
[3] F. Holtby, *Trans. Am. Foundrymen's Assoc.*, **XLVII**, 4, 854 (1940).
[4] F. H. Schofield and A. Grace, *Iron Steel Inst. Special Rept.* **25**, 235 (1939).

steel bath and immersed in the steel for about 20 seconds while a reading is taken. Of course, the steel tube disappears, and the further usefulness of the silica sheath is usually destroyed, but the tube and the sheath have furnished sufficient protection for the couple during the 30 to 40 seconds that it is in the furnace. The cost of replacement of the silica sheath is small. It is stated that the couple can be reassembled in about 3 minutes.

The Thermopile.—When very small temperature differences are to be measured, several thermocouples may be connected in series so that their electromotive forces are cumulative. Such an arrangement is termed a thermopile. One of the first applications of this device was in infrared spectroscopy, in which the hot junctions of the thermopile were arranged in a line so as to be covered by the image of the slit, and the cold junctions were shielded from the radiation. In radiation pyrometers where the image of the source is a disk, the thermopile is equally adaptable. In this case, the component wires are arranged as the spokes of a wheel with the hot junctions close together but not touching at the hub. By using special elements of Hutchins alloys, consisting of bismuth 97 per cent, antimony 3 per cent, and bismuth 95 per cent, antimony 5 per cent, so that each couple has a sensitivity of about 120 microvolts per degree, Pfund[1] has constructed very fine thermopiles of the wheel type for use in radiation measurement. It is essential in this use that the thermal capacity of the junctions be small and that they be thermally insulated. To best reduce heat loss, they are often placed in an evacuated enclosure.

Perhaps the ultimate in detecting small differences in temperature was attained by Lange.[2] In his investigation, it was desired to detect the difference in temperature between two adjacent calorimeters, and a small

[1] A. H. Pfund, *Rev. Sci. Instruments*, **8**, 417 (1937).

[2] E. Lange and J. Monheim, *Zeit. physik Chem.*, **A149**, 51 (1930).

thermal capacity for the thermopile was not essential. By using 1,000 pairs of iron and constantan wires, with the hot junction in one calorimeter and the cold junctions in the other it became possible to detect a temperature difference of 2×10^{-7}°C.

INSTRUMENTS FOR MEASUREMENT OF E.M.F.

Instruments for the measurement of e.m.f. generated by thermocouples fall into three classes: (1) the gal-

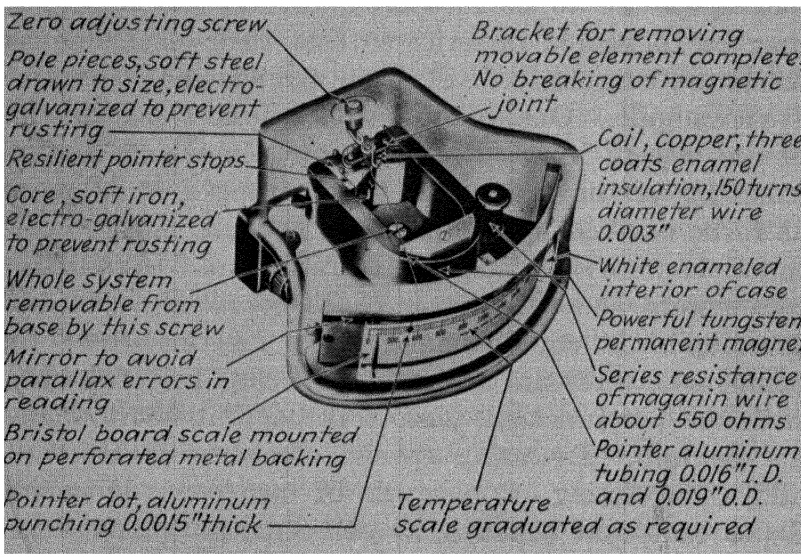


FIG. 17.—Phantom view of millivoltmeter. (*Brown Instrument Co.*)

vanometer type, or millivoltmeter; (2) the potentiometer type; and (3) types involving a combination of the first two.

Millivoltmeters.—All millivoltmeters operate on the d'Arsonval principle, which involves a moving coil mounted between the poles of a permanent magnet. This moving coil carries a long needle or pointer that swings over a scale graduated in either millivolts or temperature. Figure 17 shows a phantom view of such an instrument. In most instruments, the coil is supported by two jeweled bearings, but in one or two

types the coil is supported by one pivot that is placed at the center of gravity of the whole moving system. If the pivot system is used, the jewel cups or bearings must be very carefully made in order that friction may be almost entirely eliminated. The movement of the coil and the needle are proportional to the thermoelectric current that passes through the coil, and this current is proportional to the e.m.f. produced by the thermocouple. By the use of an internal series resistance and an extra binding post, it is possible to have the scale graduated for both base- and noble-metal thermocouples. The coil turns against the torque of a double spiral spring that returns the pointer to the zero position when the circuit is broken.

Resistance of Millivoltmeters.—It has already been pointed out that the e.m.fs. generated by thermocouples are very small, and it is easily appreciated that any satisfactory millivoltmeter must be a comparatively sensitive instrument. Some of the earlier forms were so delicate that it was only with extreme care that they could be moved from place to place, and whenever they were used, it was necessary to level them carefully. As the use of thermoelectric pyrometers became more common, the construction of the instruments was made more robust, and it became possible to make them portable. As has already been stated, the turning moment of the moving coil is proportional to the current. If, therefore, the total resistance of the circuit is kept low, the current will be proportionally larger, and it will be possible to build a sturdier instrument. As a result of this, the early forms of portable millivoltmeters were all made with low total resistance.

The principal objection to the use of millivoltmeters lies in the fact that the e.m.f. indicated is less than the actual value developed by the couple. This follows from the fact that the indicator requires that a current be delivered by the couple which necessarily results

in some fall of potential in the couple. This can be cared for by arbitrarily calibrating the scale to read the correct e.m.f. with a certain fixed line and couple resistance. If the resistance of the line or the couple varies, however, an error is introduced. These difficulties are all largely overcome if the millivoltmeter resistance is high and that of the couple low.

Assume that a millivoltmeter is graduated to read differences in e.m.f. at its terminals. Let e_o represent the e.m.f. drop across the indicator; e, the true e.m.f. of the couple; R_g, the resistance of the millivoltmeter; R_c, the resistance of the thermocouple and R_1, the resistance of the leads. The relation between e_o and e is then

$$e_o = \left(\frac{R_g}{R_g + R_c + R_1}\right) e$$

This expression follows from Ohm's law, which states that the e.m.f. drop between two points in a simple closed circuit is proportional to the resistance between the two points. It is very evident that, if R_g is large compared to R_c and R_1, the ratio $\frac{R_g}{R_g + R_c + R_1}$ becomes nearly equal to 1, and the reading of the millivoltmeter does not differ much from the true e.m.f.

To illustrate, compare the behavior of millivoltmeters having resistances of 600 ohms and 10 ohms, respectively. The line and couple resistance is 2 ohms. Substituting in the above expression, it is found that in the case of the 600-ohm instrument $e_o = 0.996\ e$, and in the case of the 10-ohm instrument $e_o = 0.830\ e$. In the first case, the actual readings are only 0.4 per cent low; in the second case, they are 17 per cent low. The 600-ohm instrument might be used without arbitrary calibration, which would not be practicable for the 10-ohm instrument.

Assuming that both instruments are calibrated for a fixed external resistance, compare their behavior when

line and couple resistance vary. Let the line and couple resistance be represented by R', the specific line and couple resistance for which the instrument is calibrated by R_o', the reading of the instrument by e', the e.m.f. of the couple by e, and the actual e.m.f. drop across the terminals of the instrument by e_o. It follows that when $R' = R_o'$, $e' = e$. The general relation between e' and e may be obtained as follows:

$$e_o = \frac{R_g}{R_g + R'} e \tag{5}$$

or,

$$e = \frac{R_g + R'}{R_g} e_o \tag{6}$$

When $R' = R_o'$ $e' = \frac{R_g + R_o'}{R_g} e_o = e$ (7)

Substituting the general value of e_o in Eq. (7),

$$e' = \frac{R_g + R_o'}{R_g} \cdot \frac{R_g}{R_g + R'} e = \frac{R_g + R_o'}{R_g + R'} e \tag{8}$$

Table III represents the results computed from Eq. (8) when R' has values of 1, 2, 3, and 4 ohms, respectively, the value of R_o' being 2 ohms.

TABLE III

Line resistance, ohms	Error in indicated reading, per cent		Error in degrees at 1000°C.	
	600 ohms	10 ohms	600 ohms	10 ohms
1	+0.16	+ 9.1	+1.6	+ 91.0
2	±0.00	± 0.0	±0.0	± 0.0
3	−0.17	− 7.7	−1.7	− 77.0
4	−0.34	−14.3	−3.4	−143.0

U. S. Bur. Standards Tech. Paper 170.

Variable line resistance is caused by a number of things, among which may be mentioned oxidation of the wire, poor contacts, variable depth of immersion,

temperature variations in the line, and partial fracturing of lead wires.

Methods of Compensation for Errors Due to Line Resistance. *Use of Test Sets.*—As long as a close check of the resistance in a pyrometer circuit is maintained, it is entirely possible to use a millivoltmeter of low resistance. For this purpose, some form of Wheatstone bridge is necessary. By using this, increases of resistance may be detected and means taken for their elimination before any damage is done through incorrect readings of millivoltmeters. It is advisable for any plant using millivoltmeter indicators having either high or low resistance to keep such a test set on hand, for by their use it is possible to locate breaks, grounds, or crosses in the circuits as well as to detect variations in resistance. The location of faults requires a little more complicated arrangement of circuits, but full directions for such setups are usually included with the instrument.

The Use of Series Resistance.—In cases where it is known that there will be considerable variation in line resistance, it is possible to purchase millivoltmeters that carry a variable resistance in series with the moving coil. The instrument is originally calibrated to read correctly with a line resistance equal to the total resistance available in the contained rheostat. As the line resistance increases, the resistance in the instrument is gradually cut down. For instance, if such a millivoltmeter is calibrated to read correctly with a line resistance of 15 ohms and the actual line resistance is 5 ohms, the series resistance in the instrument will be reduced to 10 ohms. It is thus quite easy to keep the instrument reading correctly, providing the resistance in the line is frequently checked by means of a test set.

Potentiometers.—A potentiometer is a device for measuring potential differences by totally or partially balancing an unknown e.m.f. against a potential difference whose value is known. If the two e.m.fs.

are exactly balanced, the instrument is called a zero or null-point potentiometer; if the e.m.fs. are only partially balanced and if the difference is indicated by a properly calibrated galvanometer, it is called a deflection potentiometer.

Figure 18 represents a simple potentiometer setup, and by its use the principle may be demonstrated.

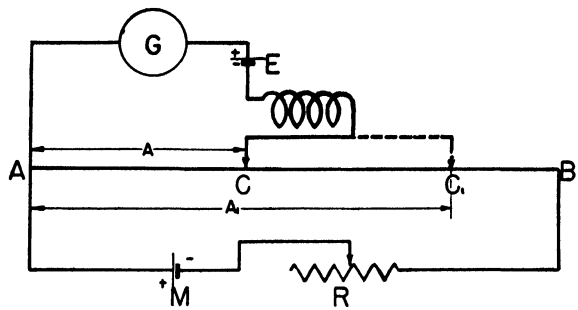


FIG. 18.—Diagram of slide-wire potentiometer.

AB represents a simple slide wire along which contact C is free to move. There is a potential drop from A to B due to battery M. For the present purpose it will be assumed that this drop is constant. E represents an unknown source of e.m.f. It is easily seen that, provided the potential drop from A to B is greater than the unknown source of e.m.f. E, there will be some point C where E is exactly balanced by the drop in the slide wire from A to C, and at which the galvanometer will register zero. Now, if p represents the resistance per unit length of slide wire, A the distance AC, and i the current in AB, the following equation may be written:

$$E = \mathrm{A}pi. \tag{9}$$

Next substitute for E a standard cell E_s, the e.m.f. of which is known. There will be some point C_1 at a distance A_1 from point A, where the galvanometer will again indicate zero. Then the equation may be written

$$E_s = \mathrm{A}_1 pi \tag{10}$$

Dividing Eq. (9) by Eq. (10) and solving for E,

$$E = E_s \frac{A}{A_1}$$

and the exact value of E may be ascertained.

If the potential drop from A to B could be maintained at a constant value and the slide wire AB divided up into equal linear divisions, it would be possible to measure unknown sources of e.m.f. directly, since the linear distance from A to C would be exactly proportional to the potential drop between these points. It is possible to maintain a constant potential drop, as mentioned above, if an adjustable rheostat R is placed in the primary battery circuit. The procedure would then be as follows:

Insert a standard cell in the unknown e.m.f. circuit in place of E, and set the sliding contact C at a value which is some simple multiple of the certified e.m.f. of the standard cell. This will, of course, cause a deflection of the galvanometer. Now adjust the rheostat R until the galvanometer is brought back to zero. When that is done, the instrument is direct reading and e.m.fs. are directly proportional to the indications on the scale. Unfortunately, the current in the slide wire does not remain constant for a great while, so that readjustment of the rheostat R against the standard cell is necessary at frequent intervals while unknown e.m.fs. are being measured.

The Portable Potentiometer.—Figure 19 illustrates the instrument board of the Leeds and Northrup portable potentiometer, and Fig. 20 represents its wiring diagram. In this instrument, the standard cell is connected over a fixed portion of the main circuit, whose resistance is of such value that when the galvanometer is brought to zero by adjusting the rheostat, the potentiometer is direct reading. This adjustment should be made at frequent intervals while the instrument is being used. Readings of unknown e.m.fs. are made by closing the

thermocouple switch and adjusting the dial until the galvanometer is brought to zero. The graduations on the dial may be in either millivolts or temperature for a particular type of thermocouple, and by the insertion of shunt circuits it can be made a multiple-scale instrument.

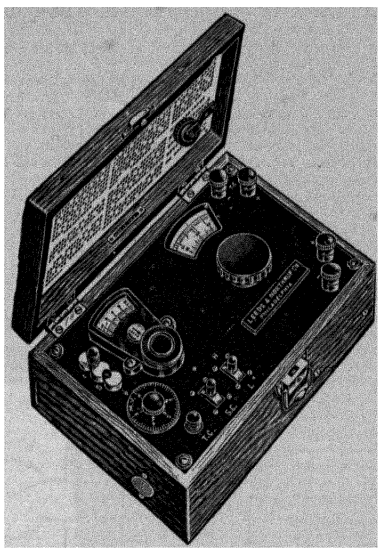


FIG. 19.—Portable potentiometer. (*Leeds and Northrup Co.*)

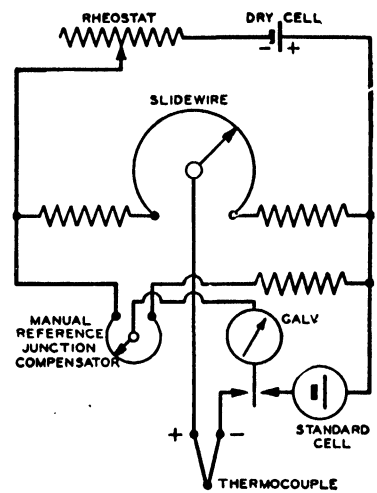


FIG. 20.—Circuit diagram of portable potentiometer. (*Leeds and Northrup Co.*)

The Precision Potentiometer.—Figures 21 and 22 represent, respectively, the instrument panel and the circuit diagram of a precision potentiometer. This instrument must be used in semipermanent installations and requires as auxiliaries a sensitive galvanometer, a standard cell, and a battery to maintain the working current in the measuring circuit. A study of the circuit diagram reveals that the fundamental principle of the instrument is the same as in the portable potentiometer, but the degree of accuracy in measurement of e.m.f. is much greater. This increase in accuracy is accomplished largely by using a greatly extended slide-wire in the measuring circuit and a more sensitive galvanometer. The instrument has three ranges of direct measurement:

0 – 1.61 volts in steps of 0.00005 volt, 0 – 0.161 volt in steps of 0.000005 volt, and 0 – 0.0161 volt in steps

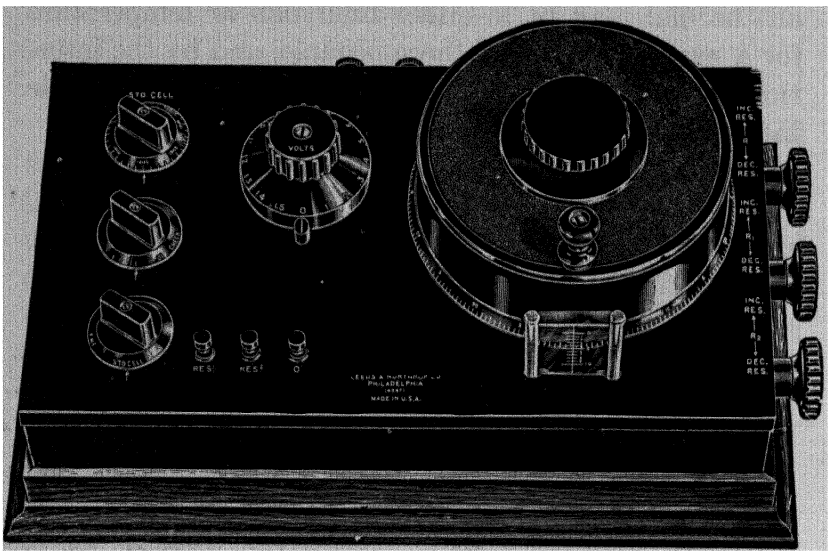


FIG. 21.—Precision potentiometer, type K-2. (*Leeds and Northrup Co.*)

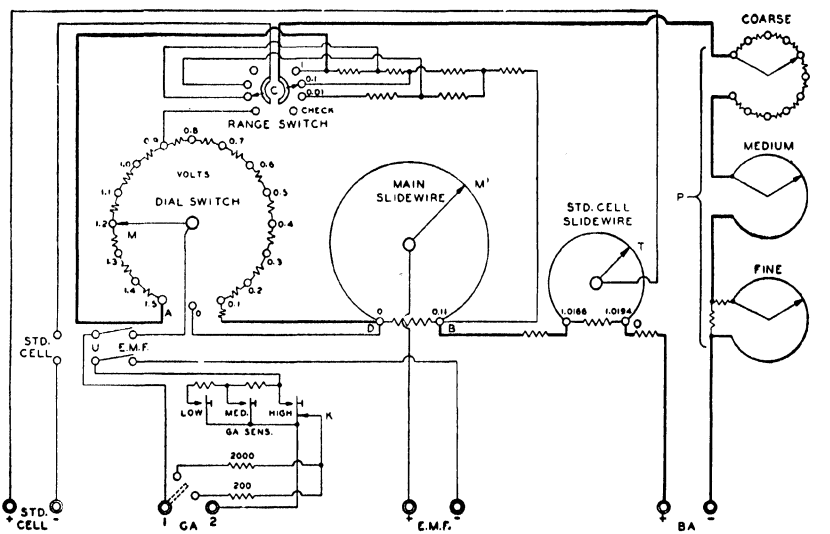


FIG. 22.—Circuit diagram of precision potentiometer. (*Leeds and Northrup Co.*)

of 0.0000005 volt. It is very useful in checking less accurate instruments, in checking thermocouples, and in making accurate temperature measurements.

The Portable Precision Potentiometer.—This instrument combines the portability and operating conveniences of the smaller portable potentiometer with the precision of a laboratory instrument. It is shown in Fig. 23. The measurements are made by means of a dial switch and a slide-wire, and the sensitivity is as great as though the entire range were spread over a 16-foot slide-wire. The lamp- and scale-type galvanometer is self-contained, and the over-all accuracy is about four times as great as that of the smaller portable instrument. It is very useful for checking in both shop and laboratory.

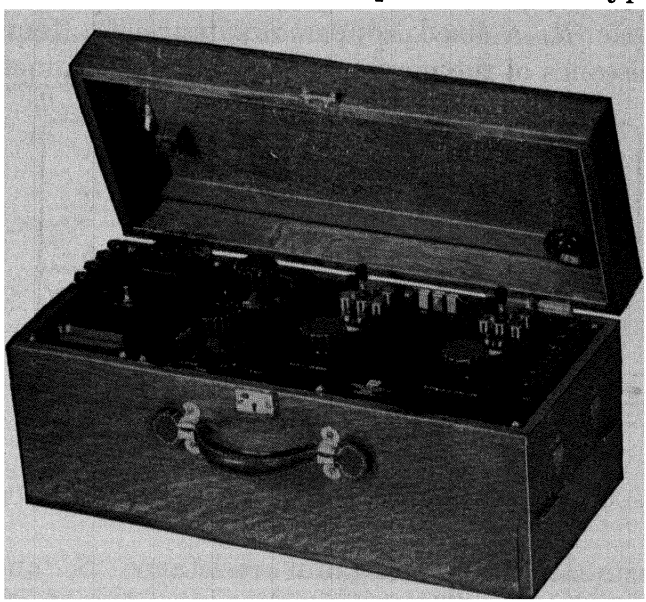


FIG. 23.—Portable precision potentiometer. (*Leeds and Northrup Co.*)

Semipotentiometers.—The essential factor in the operation of a potentiometer is a constant current in the main battery circuit. By arranging the wiring in a potentiometer in such a manner that the galvanometer with a shunt may be thrown into the main battery circuit, it is possible to adjust this current to a predetermined proper value. The galvanometer is next thrown into the unknown e.m.f. circuit and used as a

null-point instrument. This arrangement thus has the desirable feature of a potentiometer in that it measures the e.m.f. independent of the resistance of the source.

The Pyrovolter.—Figure 24 represents the wiring diagram of the Northrup pyrovolter which in principle is a semipotentiometer. The use of this instrument involves two settings shown by diagrams 1 and 2 on the figure. In diagram 1 is a battery *Ba*, a variable resistance *R*, a fixed copper resistance *Cu* (equal to the resistance of the moving element in galvanometer *G*),

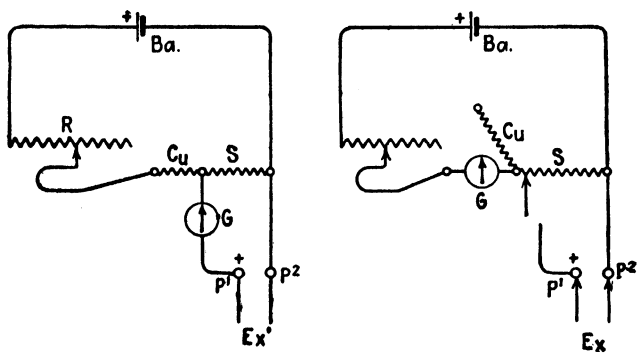


FIG. 24.—Circuits in instrument using Northrup's method. (*Pyrolectric Instrument Co.*)

an accurate fixed manganin resistance *S*, and the galvanometer *G*. The unknown source of e.m.f., usually a thermocouple, is connected at E_x. The galvanometer in this setting serves as a null-point instrument in determining when a balance is established between E_x and the drop in potential across *S*, which is varied by means of rheostat *R*. This balance having been obtained, a button is depressed that changes the system to the form shown in diagram 2. The galvanometer *G* is here substituted for the resistance *Cu*, which has resistance and temperature coefficient equal to that of the galvanometer. The galvanometer will therefore deflect proportionally to the current that is flowing through *S*, and its scale may be marked to indicate the e.m.f. drop across *S*. The e.m.f. across *S*,

however, was made equal to that of the unknown source in operation 1; so the galvanometer is indicating the value of the unknown e.m.f. By changing the value of S to other fixed values, additional ranges are given.

Northrup's method may be applied to continuously deflecting instruments by the addition of an extra key switch and a rheostat. After the e.m.f. of a thermocouple has been determined as described in the preceding paragraph, the galvanometer is connected in series

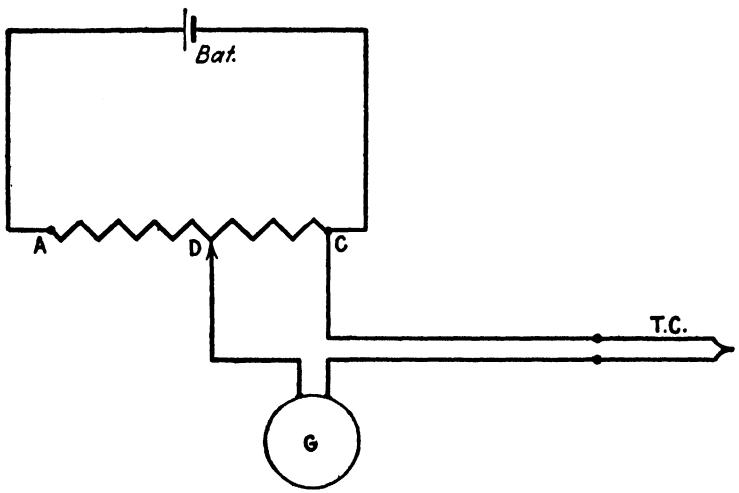


FIG. 25.—Simple circuits in deflection potentiometer.

with the extra resistance and the thermocouple. The extra resistance is then varied until the reading of the galvanometer is the same as when the e.m.f. was determined by the pyrovolter. In this way, variations in line and couple resistance may be compensated.

Deflection Potentiometers.—In the deflection potentiometer, only part of the e.m.f. of the thermocouple is balanced against the resistance through which the main battery current is flowing. The remaining portion of the e.m.f. is indicated by a galvanometer that is in series with the thermocouple. For instance, the instrument might be constructed in such a way that a dial would indicate the whole millivolts and a galvanometer would indicate fractions of millivolts. Figure 25 repre-

sents the simple wiring diagram of a deflection potentiometer. AC is a slide-wire along which contact D moves. The points on AC represent integral e.m.f. drops or the corresponding number of degrees of temperature. G is the galvanometer that indicates the fractional parts of the divisions on the slide wire.

It can be shown that readings of the galvanometer are proportional to the e.m.f. only when the sum of the resistances of the galvanometer, the thermocouple, and the potentiometer are constant. This is not usually the case, since it is necessary to vary the dial settings on the potentiometer from time to time. In order to compensate this error, a variable resistance is placed in the galvanometer circuit—in some instruments it is made an integral part of the dial—so that turning the dial adjusts the e.m.f. setting and at the same time adjusts the compensating resistance in the galvanometer circuit. Precision instruments of this type have been developed by H. B. Brooks[1] of the U. S. Bureau of Standards.

THE COLD-JUNCTION CORRECTION

As has been stated, it is very necessary that the cold junction of a thermocouple be at the temperature for which it was calibrated. As soon as there is a departure from this temperature, the readings of the indicator are incorrect, unless some means of compensation are employed. In the case of simple installations, it is possible to obtain the true temperature at the hot junction by adding to it a value obtained by multiplying the difference between the actual cold-junction temperature and the correct cold-junction temperature by a factor K that depends upon the type of couple being used and the temperatures of the hot and cold junctions. The factor K varies from 0.3 to 1.5 but may be taken as approximately 1.0 for base-metal couples and 0.5 for noble-metal couples. The variation in K

[1] H. B. Brooks, *U. S. Bur. Stand. Bull.* 8, 419 (1912).

depends upon differences in slope at low temperatures of the temperature-e.m.f. curve.

Most instruments for the measurement of the e.m.f. of thermocouples are provided with some sort of device for cold-junction error compensation. Some of these require setting by the operator, and some are automatic. In any event, it is desirable to maintain the cold junction at as constant a temperature as possible. One method for accomplishing this is to jacket the head of the couple and maintain a circulation of tap water around it. This method is cumbersome and very little used. It is evident that if the couple were made of sufficient length it would be possible to carry the cold junction well away from the furnace and provide some means for maintaining it at a fairly constant temperature. It is not practicable or advisable to make such a long couple in single sections, so recourse is had to so-called "compensating leads." In most cases, these leads are multiple-strand, flexible wires made from the same material as the corresponding thermocouple elements. The leads are tightly attached to the elements of the couple proper and extend from there to the cold junction, which may be either at the indicating instrument or at some particular point where the temperature remains nearly constant. In the case of noble-metal couples, it is too expensive to use such leads, but the difficulty is partly offset by the use of Bristol compensating leads that consist of a copper wire and a copper-nickel alloy wire. The copper wire is attached to the platinum-rhodium element of the couple and the copper-nickel wire to the platinum wire of the couple. These leads may be actually termed compensating leads.

Among the methods used for maintaining a constant cold-junction temperature, the use of a thermostatically controlled chamber and the placing of the cold junction underground may be mentioned. The idea of a thermostatically controlled chamber needs no discussion.

The temperature at a depth of 10 feet underground remains constant within ±2°C. in most localities the year round. An iron pipe closed and pointed at the bottom is driven into the ground, and the two cold junctions, well insulated, are inserted in the top of the pipe and pushed down to the bottom. They must, of course, be well soldered to the copper leads that convey the e.m.f. to the indicating instrument. It follows that there are four wires in the pipe—the two compensating lead wires coming from the couple and the two copper leads going to the instrument. It is well to have some means of determining the temperature at the bottom of the pipe, so that adjustments of the indicator may be made for any variations which occur.

Millivoltmeter Compensation.—In the case of millivoltmeters, a zero adjusting screw makes it possible to move the needle to any desired point. If, therefore, the cold-junction temperature is known, it is necessary only to move the needle to this temperature, or the e.m.f. corresponding to it, while the instrument is on open circuit. As long as the cold-junction temperature does not vary, the indicated readings will be correct. Any variation of the cold-junction temperature, however, means a new adjustment of the needle. The Bristol compensator makes this adjustment automatically through the use of a bimetallic spring, and many of the millivoltmeters now on the market include this feature. The metals in this spring possess different coefficients of expansion, so that as the temperature varies the spring tends to coil or uncoil, thereby moving the galvanometer needle to the new position. In order to make use of this compensation, the cold junctions of the couple should actually be at the instrument.

Potentiometer Compensation.—Figure 20 represents the wiring diagram of the Leeds and Northrup portable potentiometer equipped with a manually operated, cold-junction compensator. The e.m.f. generated by

the thermocouple, or its corresponding temperature, is indicated on the slide-wire. In parallel with the main slide-wire is a smaller one called the manual reference junction compensator. These two slide-wires, with the galvanometer, form a typical Wheatstone-bridge circuit. If the cold-junction temperature is that of the reference point of the e.m.f. scale, the reference junction dial is placed at zero and readings are made directly by moving the slide-wire dial to the proper position. If the temperature of the cold junction varies, the reference junction dial is changed accordingly. This requires a new setting of the slide-wire dial to maintain the galvanometer at zero. In this way, the proper hot-junction temperature will be indicated, although there may be variations in e.m.f. due to variations in the cold-junction temperature.

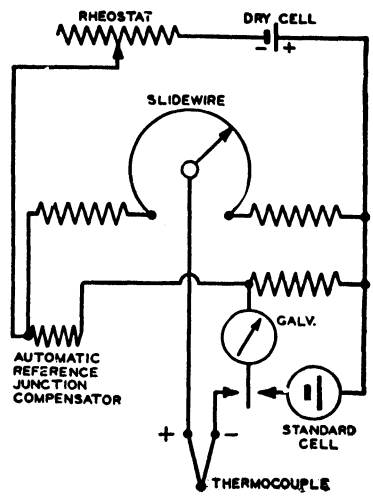


FIG. 26.—Circuit diagram of potentiometer equipped with automatic cold-junction compensator.

For use with any one thermocouple an automatic compensator, as shown in Fig. 26, may be used. This consists of a coil of nickel wire whose resistance changes with temperature. The circuit is still a Wheatstone bridge, and as the resistance of the nickel coil varies, the position of the main slidewire dial has to be changed in order to secure a balance in the measuring circuit.

Compensation by Means of a Shunt.—Figure 27 illustrates the use of a shunt across the terminals of a thermocouple as a means of securing partial compensation for the cold-junction error. As the cold-junction temperature increases, the e.m.f. of the couple decreases, but at the same time the resistance of the shunt increases, so that the product of the new increased resistance

times the decreased current is the same as before and thus no variation will be observed in the indication of the potentiometer.

Compensation by Means of a Wheatstone Bridge.—Figure 28 represents the wiring diagram for cold-junction compensation in indicators produced by The Foxboro Company. The Wheatstone-bridge circuit in one of the lines is easily identified. Three arms of the bridge are

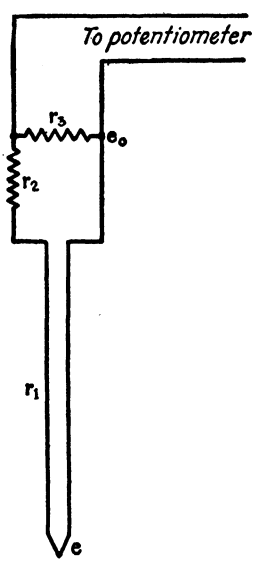


FIG. 27.—Wiring diagram of shunt method of cold junction compensation. (T. P. 170. *U. S. Bur. Stand.*)

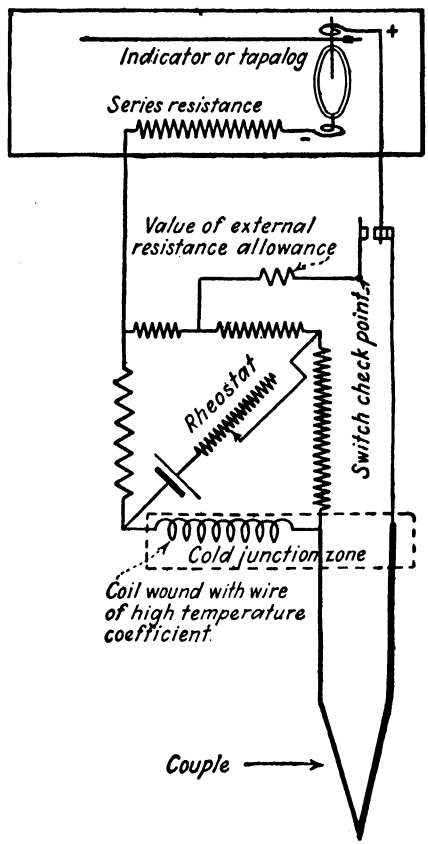


FIG. 28.—Wheatstone bridge method for cold junction compensation. (*The Foxboro Co.*)

made of manganin wire, and the fourth, which is in the cold-junction zone, consists of nickel wire that has a high temperature coefficient. The cold junction of the couple is brought to the instrument by means of compensating leads. As the cold-junction temperature varies, the

resistance of the coil of nickel wire varies in such a manner as to vary the balance of the Wheatstone bridge, with the result that more or less e.m.f. is impressed over the millivoltmeter, depending on whether the cold-junction temperature rises or falls. The compensation is dependent upon the constancy of the current flowing in the arms of the bridge, thus making a preliminary setting necessary. This is accomplished by closing the

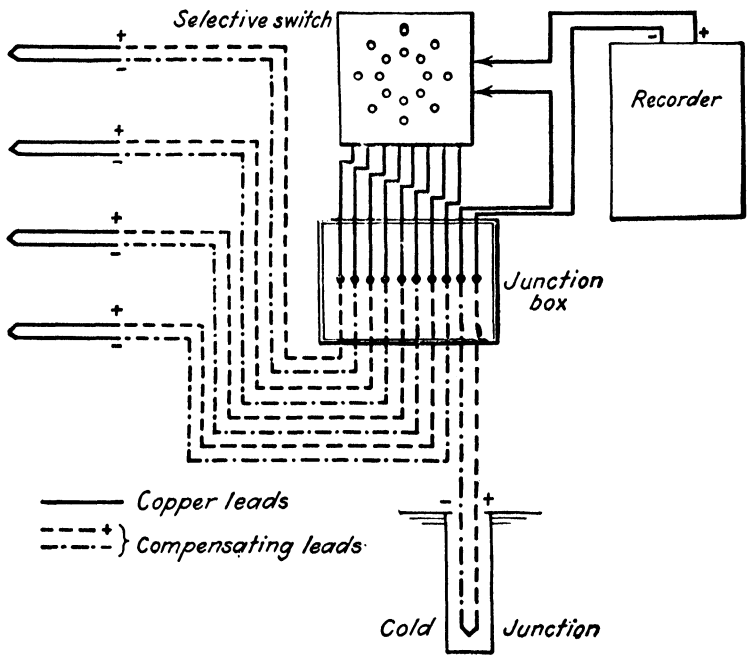


FIG. 29.—Wiring diagram of installation using junction box. (T. P. 170. *U. S. Bur. Stand.*)

switch at the check point and adjusting the rheostat until the millivoltmeter needle swings to the zero point on the scale. This setting has to be checked occasionally.

Use of a Junction Box.—In large installations of thermoelectric pyrometers, the location of cold junctions becomes somewhat of a problem. If the cold junctions were all located at the instruments and the instruments were all assembled in one locality, the cost of compensating leads would be very high. In order to eliminate this large number of compensating leads, a so-called

junction box is sometimes used. The wiring diagram is shown in Fig. 29. The box is made of heavy metal in order that the temperature within may remain practically constant.

The buried cold junction in this case is not the actual cold junction of the thermocouples that may be switched into circuit with it but is the cold junction of an auxiliary couple whose hot junction is in the junction box. It will be seen that the actual cold junctions of the couples are in the junction box and that if the temperature of the junction box rises their e.m.f. will drop. The rise in temperature of the junction box, however, increases the e.m.f. of the auxiliary couple, and this, being connected in the circuit in such a way that its e.m.f. is additive, impresses into the circuit enough e.m.f. just to compensate for that which is lost in the main thermocouple circuit by the rise in temperature of the junction box.

By means of this installation, it is possible to locate the indicator or recorder at any distance from the furnaces, using only one set of copper leads.

THERMOELECTRIC PYROMETER INSTALLATION

A brief consideration of some points in connection with the installation of thermocouple systems may not be out of place. One thing that should always be kept in mind is the fact that the e.m.fs. and the currents generated by thermocouples are small, and, therefore, the resistance of the lines should be kept at the lowest figure possible. Nothing smaller than No. 12 copper wire should be used, and switches should have a much higher ampere rating than the value of the current in the line indicates unless the potentiometer is used. Sometimes to be desired are 100-ampere switches.

A couple placed in one corner of a large furnace may not give anything like an adequate indication of the average temperature of the furnace. It is unwise to outline an arbitrary procedure, but a good rule is to place the

hot end of the couple as near the work as possible and near a point where average temperature conditions exist. In large furnaces, it is better practice to use two or more couples. In this way, the temperature at more than one point is obtained, and better control is possible. Some furnaces have a couple in each corner and one in the middle. This makes possible the production of a very even temperature throughout the furnace chamber if each couple actuates a correspondingly situated heating element.

The length of the couple that lies within the heated zone is of great importance. This is sometimes called the "depth of immersion." If a couple is insufficiently immersed, conduction to the outer, cooler sections is so high that the reading of the couple will be low. It is good practice to insert the couple just as far as possible. This will ensure satisfactory results, as a rule, but in cases where it is suspected that the immersion is not sufficient, the temperatures along the protecting tube should be explored, and if there is a large temperature gradient near the hot end of the couple, means should be taken to produce a sufficient immersion.

Some couples are purposely immersed an insufficient distance. This is done when the temperature of the furnace is so high that there is danger of fusing the couple and tube. Although the temperature read is low, it is possible, by correlation with physical changes of material within the furnace, to obtain a fairly accurate idea of the temperature for future operations.

Figures 30 and 31 represent typical installations of thermocouples. In Fig. 30, the couple is shown placed in a muffle furnace. The hot end is sufficiently immersed, and the portion going through the muffle is protected by a sleeve. Figure 31 shows a right-angle installation of a thermocouple in a lead pot. When a gas is passing through a flue or furnace, its actual temperature is not indicated by a thermometer or thermocouple placed

in the gas stream unless the walls are at the same temperature as the gas. Even if there is considerable difference between the temperatures of the walls and gas stream, a condition of equilibrium will be reached,

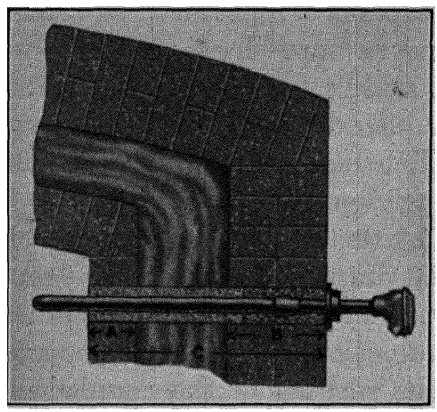


FIG. 30.—Thermocouple installed in a muffle furnace. (*Republic Flow Meters Co.*)

and the thermometer or thermocouple will indicate a temperature somewhere between the temperatures of the walls and gas. This is due to radiation of heat from the walls to the temperature-measuring instrument and

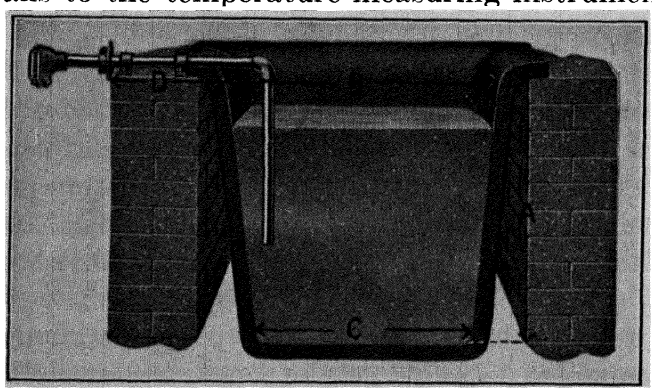


FIG. 31.—Thermocouple installed in a lead pot. (*Republic Flow Meters Co.*)

to a loss of heat by the instrument to the surrounding gas, by convection. Suitable correction for this condition should be made.

Figure 32 is a line diagram illustrating an installation of six thermocouples with indicator and recorder con-

nected in parallel. A double-pole switch below the indicator enables one to check individual couples when desired, and the recorder keeps a permanent record of the temperature variations of all six couples. Cold-junction variations are controlled by a zone box. Each couple has its own individual lead wires.

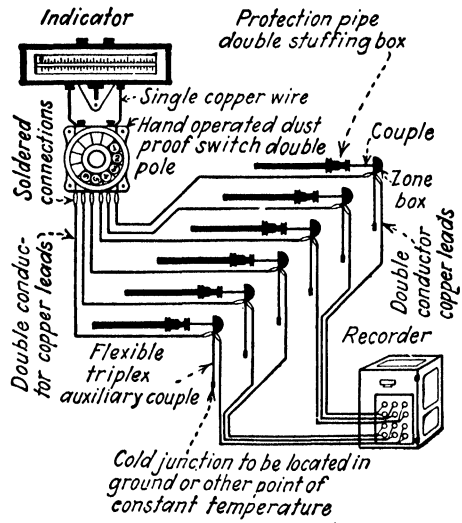


FIG. 32.—Thermocouple installation using individual lead wires. (*The Foxboro Co.*)

EXPERIMENT 1

OBJECT: To study the Peltier effect.

If an e.m.f. exists at the contact surface of two dissimilar metals, then a current passed in such a way as to oppose this e.m.f. would produce heat at a greater rate than the ordinary power expression RI^2. If passed in the reverse direction, a cooling effect might be expected if the heat withdrawn from the junction is greater than the RI^2 liberated.

Cross a short iron wire with a constantan wire, and fuse together. Antimony and bismuth or many other pairs of metals would do as well. Connect this thermal-cross to a battery througha reversing switch, as shown in Fig. 9. Connect the other terminals of the thermal-cross so that by means of a double-throw switch the heating current is broken and a galvanometer is connected to the junction. Observe the deflection of the galvanometer with the reversing switch in each position. Vary the value of the current and the time of heating. Explain results.

Experiment 2

Object: To observe the Thomson effect in metals.

Arrange a differential thermocouple along a metal conductor, by drilling two small holes about 10 centimeters apart and inserting the junctions of the couple so that they are insulated from the metal conductor (see Fig. 10). About halfway between the junctions, arrange an electric heater of a few turns of resistance wire so that it may be moved along the conductor. Slide the heater along the conductor until the galvanometer connected to the differential couple shows no deflection. Now pass a current of a few amperes through the conductor, and observe the galvanometer. Reverse the current, and note the effect. Explain results.

Experiment 3

Object: Determination of the e.m.f.-temperature relationship of a copper-iron thermojunction.

Procure a 2-foot section each of No. 14 copper and iron wire.

Construct a thermojunction of these two by twisting the ends together and fusing in the electric arc, or an oxy-gas flame.

Attach to this junction the hot junction of a calibrated chromel-alumel or iron-constantan couple, and place the combined junctions in a furnace whose temperature may be rapidly and easily varied. A small electric resistance furnace is best for this purpose. The chromel-alumel or iron-constantan couple in conjunction with a suitable indicator is used to determine the temperature of the two hot junctions.

Immerse the cold junctions in a thermos bottle containing cracked ice, and connect each couple to a millivoltmeter or potentiometer. Gradually raise the temperature of the furnace, and take simultaneous readings of temperature and e.m.f.

Plot the e.m.f.-temperature curve of the iron-copper couple, and fit it with an equation. Solve for the constants.

Experiment 4

Object: Calibration of a platinum, platinum-rhodium thermocouple by the use of fixed temperature points.

The fixed points required in this calibration are the melting points of zinc, aluminum, and copper. Samples of these metals, with certified melting points, may be obtained from the U. S. Bureau of Standards.

The crucibles used should be of such size as to hold conveniently 50 cubic centimeters of molten metal, this being a convenient amount of metal to use with the ordinary sizes of noble-metal thermocouples

The sample of metal is first melted. In doing this, the crucible should be heated in such a device (either a gas or electric furnace) that a layer of fine graphite can be maintained over the top of the crucible and the surface of the metal. The apparatus, shown in Fig. 105, Chap. VIII, is particularly well adapted to this calibration. The top of the crucible should have a hole of suitable size for the introduction of the protecting tube of the couple. The protecting tube should be of glazed porcelain or fused quartz.

After the metal has become molten, carefully insert the protecting tube without the couple. Care must be exercised, or the protecting tube will be broken. After the tube has been successfully lowered into the molten metal, the couple may be inserted in the protecting tube. The cold junction of the couple should be packed in a thermos bottle containing cracked ice. As the metal cools, take e.m.f. readings at intervals of 15 seconds, and prepare a curve of e.m.f. versus consecutive time. There will be a halt in this curve at the freezing point of the metal. Calculate the average e.m.f. during this halt. As soon as the metal is nearly solid, remove the couple and protecting tube.

The above procedure is carried out with each one of the three metals.

The e.m.f.-temperature relation for the couple is represented by the equation

$$e = a + bT + cT^2.$$

e = e.m.f.
T = temperature of hot junction of couple.
a, b, and c are constants.

Since e was determined at three temperatures, it is possible to determine a, b, and c by solving the three simultaneous equations.

In this manner, determine the final equation for the couple that is being calibrated.

Experiment 5

Object: Effect of cold-junction temperature upon the e.m.f. of a thermocouple.

Fasten together the hot junctions of two platinum, platinum-rhodium thermocouples. Place their cold junctions in separate thermos bottles filled with cracked ice. One of the couples is used merely to obtain the correct temperature, but any other carefully calibrated thermocouple will serve this purpose. Place the attached hot junctions in a furnace whose temperature may be easily and quickly varied. Obtain the data necessary to plot an e.m.f.-tem-

perature curve for the platinum, platinum-rhodium couple over the range from 0 to 700°C. Repeat over the same range, but maintain the cold-junction temperature at 30°C.; at 60°C. This may be done by carefully heating a 500-cubic centimeter beaker of water into which the cold junction is placed.

The first curve obtained is the one usually found in tables. Suppose this couple were being used with such a table but with the cold junction at some other temperature, T_c°C. The true temperature T would be

$$T = \text{indicated temperature} + KT_c$$

Evaluate K from the data, showing that it is not a constant. How does it vary with cold- and hot-junction temperatures?

When K is greater than 1, what must be the slope of the e.m.f.-temperature curve at low temperatures?

Problems

1. The hot and cold junctions of a thermocouple remain at constant temperatures. If the resistance of couple and leads changes from 2 to 3 ohms, the e.m.f. across the millivoltmeter drops 0.2 per cent. Calculate the resistance of the millivoltmeter.

2. A millivoltmeter with a resistance of 15 ohms is calibrated to read correctly when couple and lead resistance equals 3 ohms. If couple and lead resistance increases to 5 ohms, calculate the percentage error in readings of the millivoltmeter.

3. A thermocouple has its cold-junction variations compensated by means of a shunt. The resistance of the couple and leads is 60 ohms, and the resistance of the shunt is 100 ohms. Assuming that the hot junction remains constant, while the cold junction is warmed, calculate the increase in resistance of the shunt that will just compensate for a 0.2 per cent decrease in e.m.f. so that the potentiometer reading does not change.

4. The resistance of a thermocouple and its leads is 3 ohms. The hot junction remaining constant, the e.m.f. of the couple is read successively by a potentiometer and a millivoltmeter. The potentiometer indicates 25 millivolts, and the millivoltmeter indicates 24.2 millivolts. Calculate the resistance of the millivoltmeter.

5. A thermocouple having a resistance of 0.4 ohm is connected through leads of a resistance of 1.5 ohms to a recording millivoltmeter with a resistance of 300 ohms. An indicating millivoltmeter is to be connected in parallel with the recorder. What resistance must the indicator have in order that the readings of the recorder shall not be in error more than 1 per cent? The lead resistance between the instruments is to be 1 ohm.

6. The resistance of thermocouple and leads in a pyrometer installation is 2 ohms. Temperature is indicated by means of a millivoltmeter of 20 ohms resistance. The instrument is calibrated to read correctly under the above conditions. A recorder of 20 ohms resistance is installed in the foreman's office near by, the recorder being connected in parallel with the indicator and the total resistance of the leads between the two instruments being 1 ohm. Calculate the percentage error in the readings of the two instruments when thus connected.

7. The chromel wire of a chromel-alumel thermocouple has a resistance of 0.0828 ohm per foot. The resistance of the alumel wire is 0.0432 ohm per foot. The corresponding lead wires have the same resistance per foot as the couple wires. How far away (distance measured along the wires) must a millivoltmeter calibrated for an external resistance of 15 ohms be placed in order to indicate e.m.f. correctly? Is the resistance of the millivoltmeter important under these conditions? Explain. If a millivoltmeter (600 ohms resistance) that was not calibrated for the external resistance was placed the same distance away from the hot junction, what percentage of error in its readings would be observed?

8. An iron constantan couple is calibrated with its cold junction at 0°C. What e.m.f. will be read from the thermocouple if the hot junction is at 200°C. and the cold junction at 25°C. (see tables in Appendix). Determine the constant K in the expression

$$T_{\text{true}} = T_{\text{approximate}} + KT_c.$$

Do the same for a noble-metal couple.

9. A chromel-alumel couple is calibrated in degrees Fahrenheit with its cold junction at 75°F. What correction will have to be made to the indicated e.m.f. of the couple if the cold junction is actually at 45°F. (see tables in Appendix)?

CHAPTER IV

RESISTANCE THERMOMETERS

Resistance-temperature Relations.—Measurements upon the electrical resistance of a metallic conductor as the temperature of the conductor is increased indicate that the resistance increases with the temperature. The relationship between resistance and temperature, as measured by the gas thermometer, is in general not linear, as might be represented by the equation

$$R = A' + B'T \tag{1}$$

but is closely expressible by an equation of higher degree, such as

$$R = A + BT + CT^2. \tag{2}$$

The dependence of R upon T should be explained by any satisfactory theory of electric conduction. On the basis of the free-electron theory, Drude[1] obtained the following expression for the electrical resistivity ρ of a metal; $\rho = aT/Nlu$, a being a constant, N the number of free electrons per cubic centimeter, l the mean free path of the electrons, and u their average velocity at the temperature T. As T increases, N and u supposedly increase, and l probably decreases.

If a resistance coil be constructed and its resistance measured at certain known temperatures, then the resistance at other temperatures might be used to measure those temperatures. This device is called a resistance thermometer. Its use was first proposed by Siemens[2] in 1871. It was at first thought that the

[1] P. Drude, *Ann. Phys.*, **1**, 566 (1900).

[2] W. Siemens, *Proc. Roy. Soc.* (London), **19**, 351 (1871).

relative change in resistance per degree (called the temperature coefficient of resistance) for all pure metals was the same at the temperature 0°C. Some 15 of the common metals have an average value of 0.0039 per degree Centigrade for this coefficient, but individual values vary by as much as ± 0.0005 from this amount. Since platinum does not readily oxidize at high temperatures and since it has a relatively large and uniform change in resistance with temperature over a wide temperature range, it is used extensively as the resistor material in thermometers of this type. Nickel is sometimes used for work at lower temperatures, and palladium may be used at temperatures as high as 600°C.

In the early coils made by Siemens,[1] the platinum wire was wound on a pipe-clay tube and the coil placed in an iron protecting tube. When heated to a high temperature, the platinum was changed in resistivity through some chemical action provoked by the presence of the clay. For this reason, this method of temperature measurement was in ill repute until 1886, when it was revised by Callendar, who sealed the platinum coil within the bulb of an air thermometer and demonstrated its reproducibility with continued heating and cooling.

Platinum Temperature.—If the resistance of a coil of platinum wire be measured when placed in melting ice and when placed above water boiling under standard conditions of pressure, the values obtained, designated, respectively, as R_0 and R_{100}, may be represented on a resistance-temperature diagram. A straight line through these points, shown by curve A in Fig. 33, whose equation is $R_T = R_0(1 + \alpha_0 T)$, would then represent the relationship between R and T if the change in R was proportional to the change in T. The constant α_0 is called the zero temperature coefficient of resistance and is given by the expression $(R_{100} - R_0)/100R_0$. For pure platinum, it has a value of 0.003915. Thus, any unknown tempera-

[1] *Loc. cit.*

ture that would cause the thermometer to have a resistance R_T would be $T_{pt} = (R_T - R_0)/\alpha_0 R_0$. Temperatures found in this way are called platinum temperatures and are, of course, not correct, since a linear relationship between R and T does not exist. The actual relationship between R and T for platinum is

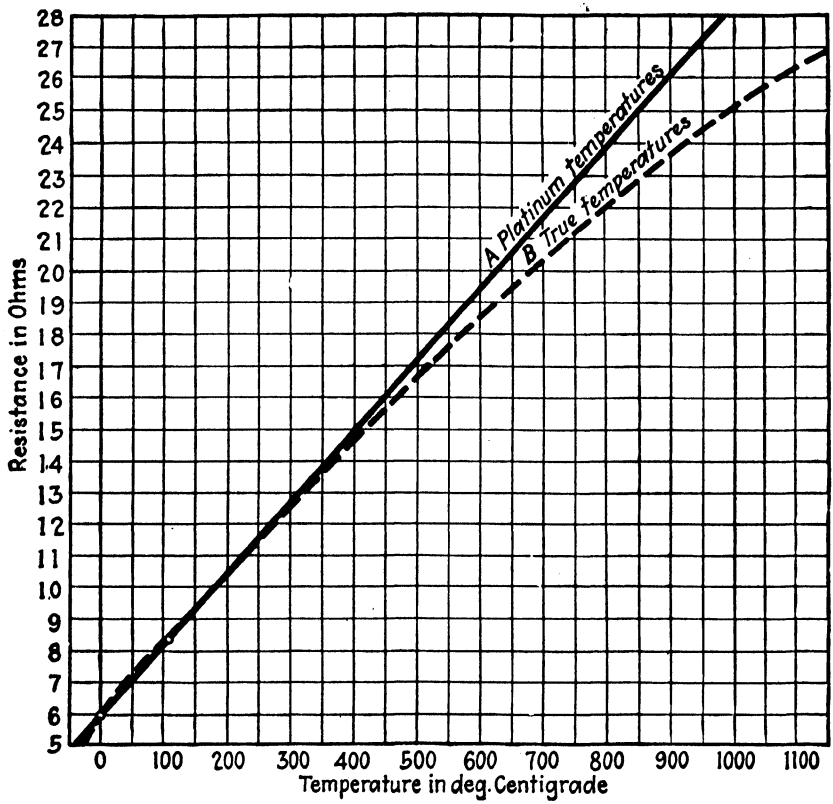


FIG. 33.—Resistance-temperature curves for platinum.

shown in curve B in Fig. 33. For pure platinum, this curve is closely represented by the following equation:

$$R_T = R_0(1 + \alpha T + \beta T^2)$$

in which $\alpha = +0.00392$ and $\beta = -0.000000588$.

It is thus evident that between 0 and 100°C. the platinum temperature is greater than the true temperature, whereas above 100°C. it is less. To find

experimentally the values of α, β, and R_0, an additional fixed temperature must be included in the calibration. For this purpose, the boiling point of sulphur (444.6°C.) under conditions of standard pressure is generally used. The sulphur boiling point T at pressure P is

$$T = 444.6 + 0.0909(P - 760) - 0.000048(P - 760)^2.$$

Callendar's Correction.—Callendar[1] suggested that since it is easy to obtain the platinum temperature T_{Pt}, it would be convenient to obtain an expression for the difference between the true and the platinum temperatures for any value of the platinum temperature. At 100°C., the values of the resistances for platinum temperature and true temperature are the same, so the values may be equated

$$R_0(1 + \alpha_0 T_{pt}) = R_0(1 + \alpha T + \beta T^2) \qquad (3)$$

Substituting the temperature (100°C.) in Eq. 3 gives

$$\alpha_0 = \alpha + 100\beta \qquad (4)$$

and

$$\alpha = \alpha_0 - 100\beta \qquad (5)$$

Substituting this value of α in Eq. 3 gives

$$T - T_{pt} = \frac{-(100)^2\beta}{\alpha_0}\left\{\frac{T^2}{(100)^2} - \frac{T}{100}\right\} = \delta\left\{\frac{T^2}{(100)^2} - \frac{T}{100}\right\} \qquad (6)$$

It is clear that if the difference $T - T_{pt}$ can be evaluated, the correction to be added to the platinum temperature to obtain the true temperature has been obtained. To secure the first approximation, the value of the platinum temperature is substituted in the right-hand member of Eq. (6). This gives a value of $T - T_{pt}$ that is used to revise the original T_{pt} and the substitution repeated. A few such substitutions will give very nearly the correct value for the difference.

[1] H. L. Callendar, *Phil. Trans. Roy. Soc.*, **178**, 161 (1887).

The value of δ in Eq. 6 is about 1.5 for platinum, varying somewhat with the purity. Using 1.5 as the value of δ, the correction to be added to platinum

TABLE I

Platinum Temperature, Degrees Centigrade	Temperature by Normal Thermometer, Degrees Centigrade
−200	−191
−100	−·97
0	0
+100	+100
200	203.1
300	309.8
400	420.2
500	534.9
600	654.4
700	779.4
800	910.7
900	1049.4
1000	1197.0
1100	1355.0
1200	1526.7
1300	1716.0

temperature to obtain true temperature is about −0.4°C. at 50°C. and about +20°C. at 400°C. Table I gives the values for these corrections for a particular thermometer over a wide range of temperatures. Callendar and Griffiths[1] found that the platinum resistance thermometer, when carefully calibrated, using the boiling point of sulphur and the boiling and freezing points of water, could be used at temperatures as high as 1000°C. with negligible error by extrapolating with the formula developed at the lower temperatures. Henning,[2] however, has shown that the parabolic formula does not apply for platinum below −40°C. As already indicated, for temperatures from −190°C. to the ice point, the International Conference adopted the more complicated equation

$$R_T = R_0[1 + AT + BT^2 + C(T - 100)T^2] \qquad (7)$$

[1] H. L. Callendar and E. Griffiths, *Phil. Trans.*, **D182**, 119 (1892).
[2] F. Henning, *Ann. Physik.*, **40**, 635 (1913).

where the additional constant C is determined by an added resistance measurement at the normal oxygen boiling point (−189.97°C.).

Palladium may be used for temperatures as high as 600°C. with the parabolic formula, but above this a fourth-degree equation is necessary to represent its behavior.

Nickel in the ordinary temperature range may be treated by the Callendar formula. The values of α and β are +0.00544 and +0.0000060, respectively.

Resistance-thermometer Construction.—The requirements of a satisfactory resistance thermometer are: (1) that the resistance at any particular temperature be a constant value, unchanging with time; (2) that the bulb is able to assume quickly the temperature of its surroundings; and (3) that the protecting tube in which it is placed be able to withstand the shocks both mechanical and thermal to which the thermometer is subjected. The effect of even small traces of an impurity in a pure metal is to increase greatly its electrical resistivity. In the case of platinum at −200°C., the presence of 10 per cent of rhodium was found by Dewar and Fleming to change the resistivity by a factor of 400 per cent. So great is this change at low temperatures that a measurement of the resistivity is one of the most accurate tests for the presence of impurities. The thermometer, therefore, must be placed in protecting tubes that will keep it free from contamination throughout the temperature range in which it is used. As generally constructed, the resistance of the thermometer at 0°C. is from 10 to 20 ohms. Since the resistivity of platinum is about 0.00001 ohm-centimeters, it is necessary to use a considerable length of fine wire to obtain this resistance.

The wire must not, however, be so fine that it is too fragile to work with. The details of winding this wire in such a way that no mechanical strains are

introduced by the large temperature changes and the accompanying expansions have been the subject of much investigation. The wire is generally wound on a light mica form made of two rectangular pieces of mica intersecting at right angles at their centers along the long dimension. The edges of the mica sheets are notched to hold the wire. The several leads are insulated with perforated mica washers. The platinum leads terminate in the head of the thermometer and are fused to stranded copper leads carefully adjusted to equality, which connect the thermometer to the measuring

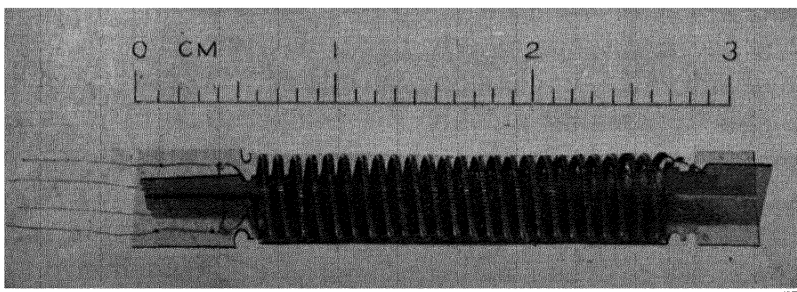


FIG. 34.—Coil of a platinum thermometer. (*C. H. Meyers, U. S. Bureau of Standards.*)

apparatus. Care should be taken to avoid the possibility of any unbalanced thermal e.m.f. Mica appears to be very suitable for the forms of these coils. At high temperatures, it becomes dehydrated and flaky but is still satisfactory. The wire is annealed at about 1000°C. by passing an electric current through it both before and after winding. Dickinson and Mueller[1] have described a thermometer having a very small thermal capacity and time lag in operation. The winding form was in this case a flat rectangular sheet, and the case was a flattened metal cylinder insulated from the platinum coil by very thin mica sheets.

Figure 34 shows a 25-ohm platinum thermometer of unusually small dimensions as described by C. H.

[1] H. C. Dickinson and L. F. Mueller, *U. S. Bur. Standards Bull.* 9, 483 (1913), *U. S. Bur. Standards Sci. Paper* 200 (1913).

Meyers.[1] The resistance element consists of a double helical winding 2 centimeter long and 0.5 centimeter in diameter. The thermometer is filled with helium and hermetically sealed, thereby reducing the time lag.

Resistance Measurement by Wheatstone Bridge.—Some form of Wheatstone bridge is generally used to measure the resistance of the thermometer. Since the thermal capacity of the thermometer bulb is small,

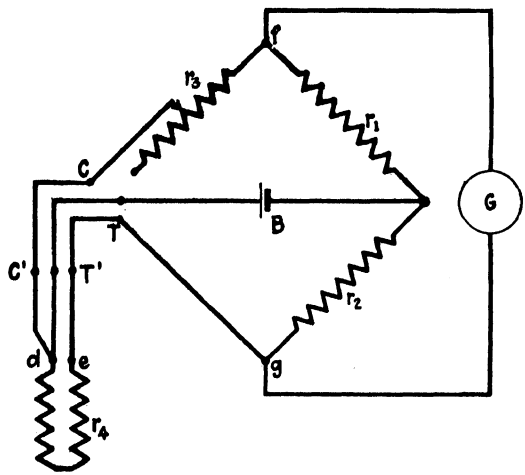


FIG. 35.—Resistance thermometer with Wheatstone bridge. Siemens' three-lead compensation.

the measuring current through the bulb must be kept small to avoid heating from that source. This may be accomplished by the use of a small e.m.f. on the bridge or by having a high series resistance in that arm of the bridge containing the resistance thermometer. For reasons given below in connection with compensating leads, a one to one ratio is generally maintained between the resistances of the parallel branches of the battery circuit. A typical bridge setup is shown in Fig. 35, in which r_4, B, and G denote the resistance thermometer, battery, and galvanometer, respectively. The resistances r_1 and r_2 are made equal at some value such as 1,000 ohms. The bridge is balanced by changing r_3 until the gal-

[1] C. H. Meyers, *Bur. of Standards Jour. Research*, **9**, 807 (1932).

vanometer shows no deflection. Since the value of r_3, only a few ohms, is then equal to the resistance of the thermometer r_4, it is important that the adjustment of r_3 be made without introducing any variable contact resistance. Unless the bridge is especially constructed for this purpose, the smallest division of the resistance r_3 may be 1 ohm. In using, therefore, a one to one ratio to obtain more precise resistance values, r_3 may be shunted by a resistance of several hundred ohms R. Then, by adjusting r_3 to the nearest whole ohm value above that of r_4, a small variation in R allows the true resistance of r_4 to be calculated to the nearest 0.01 or 0.001 ohm.

Many special types of Wheatstone or Kelvin bridges have been made especially for resistance-thermometer work in which it is possible to read directly to 0.001 or 0.0001 ohm, with no series contact resistance introduced.

Compensation for Connecting Wires. 1. *Siemens' Three-wire Method.*—The resistance bulb is commonly used at a considerable distance from the bridge, and the connecting wires that may be of different material are subjected to varying temperatures along their length. To compensate for the introduction of this uncertain resistance, various devices have been employed. In the three-wire compensation method, shown in Fig. 35, the thermometer has three identical lead wires coming from it. Two of these are attached at one end of the platinum coil and one lead wire at the other end. Thus, by connecting the free end of one of the wires of the pair to the battery, it is evident that one of the lead wires is thrown in series with r_3 and one in series with r_4. By using a one to one bridge ratio, therefore, any resistance variation in the leads produces no error, since any change in one lead is balanced by a similar change in the other.

2. *Dummy Pair—Four-wire Method.*—Another method of compensation sometimes employed is to have, in

addition to the two wires attached to the ends of the platinum coil, another pair of identical wires fastened together at their distant ends and lying side by side with but not in electrical contact with the leads from the platinum coil. With such an arrangement, the battery terminal in Fig. 35 would be connected at point C instead of point d, and the dummy pair would be in series with r_3, so that any change in the thermometer leads would be offset by a similar change in the dummy pair that is connected in the measuring arm of the bridge. The effect of the varying resistance of the lead wire is, of course, greater if the resistance of the coil is low. For this reason, if no compensating arrangement is used, the resistance of the coil should be as large as practicable.

3. *Four-wire Compensation—Unequal Lead-wire Resistance.*—It may often happen that not all the lead wires have the same resistance. To compensate in this case, it is necessary that two wires come from each end of the platinum coil as in the thermometer shown in Fig. 36. If these leads be numbered a and b from one end and c and d from the other, the thermometer may be connected to a bridge, as shown in Fig. 35, where a is the wire dc', c is eT', and b is connected to the battery, lead d being unconnected. When balanced

$$r_4 + c = r_3 + a \tag{8}$$

Now interchange a and c and b and d, and adjust r_3 to its new value r_3', if necessary, giving

$$r_4 + a = r_3' + c \tag{9}$$

Adding Eqs. 8 and 9, $$r_4 = \frac{r_3 + r_3'}{2} \tag{10}$$

and the value of the resistance r_4 is found, independent of the resistance of the leads. The interchange of terminals may be accomplished by a double-throw switch.

Resistance Measurement by Potentiometer.—By connecting the resistance thermometer in series with a standard resistance, it is possible to express its resistance in terms of the standard. The resistance ratio will be the ratio of the falls in potential across the two conductors when carrying the same current. The resistance thermometer is then constructed with two connecting wires from each end, one of each pair being a potential lead. If the e.m.f. is now measured by a potentiometer,

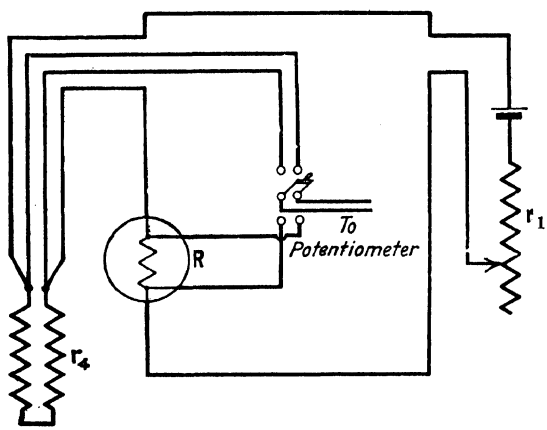


FIG. 36.—Resistance thermometer with potentiometer.

the variation of the resistance of the connecting wires can produce no effect. This method is frequently used to measure small changes in the temperature of a bath where the heating effect due to the measuring current is negligible. Figure 36 shows a wiring diagram of an arrangement of this sort.

Range and Accuracy of the Resistance Thermometer. Resistance-temperature measurements upon pure platinum between 0 and 100°C. indicate an absolute zero on the platinum scale of about −269°C. When impurities are present, the apparent absolute zero goes toward lower temperature values. Although the melting point of platinum is 1755°C., resistance thermometers have rarely been used above 1200°C. At this temperature,

great care must be taken to keep the platinum free from impurities.

A coil whose resistance at 0°C. is 20 ohms has a resistance of about 27.7 ohms at 100°C. If the resistance measurement, therefore, could be made to the 0.01 ohm, a temperature variation of 0.13°C. could be observed. Considering the fact that this accuracy is obtainable over such a wide temperature range, combined with the fact that it may readily be made a recording instrument, the value of the resistance thermometer is apparent.

At temperatures near the absolute zero, alloys of phosphor-bronze and of other pure metals with small amounts of lead show remarkably good linear relationships between resistance and temperature.

Unbalanced Wheatstone Bridge.—It is possible to use the resistance thermometer with a Wheatstone bridge so that the galvanometer deflections are used to indicate the temperature of the thermometer. The deflection of the galvanometer depends upon the difference in potential between f and g (Fig. 35). This is determined by the amount that r_4 differs from r_3 and the currents through the branches of the bridge. By inserting a definite fixed resistance in place of r_4, the current may be adjusted to a standard value by varying a resistance in series with B until the galvanometer deflection is a certain definite value. Having established the proper current, the resistance thermometer may be replaced in the circuit. The galvanometer deflection now indicates temperature directly. It is possible to have two or more temperature ranges on the galvanometer scale associated with two or more values respectively of the fixed resistance. If two scales are provided, a typical way of arranging them might be that of having one give values from 0 to 500°C. and another give values from 400 to 900°C. This method is thus free from the necessity of constantly balancing the bridge as long as the current remains unchanged. Since the difference of

potential between f and g is proportional to the temperature of the thermometer bulb, it may be used in connection with any indicating, recording, or controlling device in the same way as a thermocouple.

The Bolometer.—In 1881, Langley[1] developed a form of resistance thermometer of very great sensitivity and made in such a form that it could be used to obtain the energy distribution in the spectrum of a hot source. This device, as modified by Lummer and Kurlbaum in 1892, in measuring the total radiation from a heated body was constructed as follows: A system of strips, joined end to end so that they made a continuous electric conductor, was stamped out of a very thin metallic foil. This grating made use of one-half of the foil sheet. Another similar grating was placed over the first but electrically insulated from it in such a way that the open space in the first grating was occupied by the closed space in the second. One of these gratings was placed in the arm r_4 (Fig. 35); the other took the place of r_1. This system, when exposed to radiation, was warmed with an accompanying rise in resistance so that, if the bridge had been balanced, it would become unbalanced from the cumulative effects of both gratings. The arms r_2 and r_3 were similar gratings not exposed to the radiation to be measured and, hence, were of constant resistance. By this means, a change in temperature as small as 0.0001° could be measured. Due to the extreme thinness of the foil, the thermal capacity of the receiver was very small, so that equilibrium was quickly established.

An interesting application of the differential resistance thermometer is in the measurement of the extremely small quantities of heat associated with radioactive disintegrations. Such an arrangement for evaluating the average energy per fission of the uranium nucleus has recently been described.[2]

[1] S. P. Langley, *Am. Jour. Sci.*, **21**, 187 (1881).
[2] M. Henderson, *Phys. Rev.*, **58**, 774 (1940).

Applications of Resistance Thermometers.—The resistance thermometer is one of the most accurate of temperature-measuring devices, and this feature makes it a valuable instrument for scientific study. It may be used for boiling-point determinations and other phase changes in liquids and gases where great accuracy is required. Readings to 0.001°C. are not uncommon with this instrument, and this range of accuracy extends into the subzero region as well as in the ranges above the boiling point of water. One drawback in its use is that the bulb occupies an appreciably large space, so that it is impossible to read temperatures in very restricted volumes.

In the commercial field, these instruments find a wide variety of uses. Installations may be found in a number of large office and apartment buildings where they are used to indicate temperatures at various points to assist in controlling the operation of heating and air-conditioning systems. Other applications are cargo temperatures in the holds of vessels carrying perishable goods, control of chemical processes, such as the hydrogenation of oils and petroleum cracking processes, the pasteurization of milk, control of temperatures in electric transformers, and many others. Because of the fragility of the bulbs, these instruments cannot be used where there is constant vibration or danger of mechanical shock.

EXPERIMENT 1

OBJECT: To obtain a resistance-temperature curve for a platinum or nickel thermometer, using fixed known temperatures; to obtain the equation of the curve; to find δ in the Callendar correction formula.

Connect the resistance thermometer to a Wheatstone bridge in such a way that the resistance of the connecting wires is compensated. Measure the resistance of the bulb when immersed (*a*) in melting ice, (*b*) when above water, boiling in an enclosed container under standard pressure conditions, and (*c*) when similarly placed with respect to boiling sulphur or naphthalene. From the results obtained, solve for α_0, α, and β. What is the value of δ to be used in the Callendar correction formula for this thermometer? Measure the room temperature

with the resistance thermometer. Explain any difference obtained between this reading and that of a good mercury thermometer.

Problems

1. A certain resistance bulb is found to have resistances of 8.0, 11.09, and 21.01 ohms, when placed in melting ice, boiling water, and boiling sulphur (444.6°C.), respectively. Find the equation of the resistance-temperature relation. Find the value of the δ in Callendar's correction formula.

2. At what temperature would the resistance of the above thermometer be zero if the same equation held at low temperatures? Is this the case?

3. If the resistance of each arm of the bridge shown in Fig. 35 is equal to 20 ohms when the temperature of the platinum thermometer r_4 is 0°C. and a potential difference of 0.5 volt is applied by B at the ends of the parallel paths, what difference in potential would be produced between f and g if the temperature of r_4 is raised to 200°C.? What should be the current sensitivity of the instrument if its resistance is 1,000 ohms in order to detect a change in temperature of 0.1°C.?

4. The resistance of a platinum thermometer is 10 ohms at 0°C., and the resistance of a nickel thermometer is the same at the same temperature. Compute the resistance of each at 100°C. and at 400°C. See the values of the constants given on pages 90 and 93.

CHAPTER V

OPTICAL PYROMETERS

Temperature and Color.—Skilled workmen, in treating metals, long ago recognized the fact that the tint of metals changed as they were heated. By being able to judge this tint accurately and to apply their experience, they were able to heat metals to the proper desired condition of temperature with no additional temperature-measuring apparatus. Although individuals vary somewhat in their judgment of color, the following table approximates a relationship between tint and temperature:

TABLE I

Tint	Temperature, °C.	Temperature, °F.
Lowest visible red	470	878
Dull red	600	1112
Cherry red	700	1292
Light red	850	1562
Yellow	1000	1832
White	1150	2102

The color ascribed to a body is due to the wave length or combination of wave lengths in the radiations coming from it to the eye. To be visible, some radiation must be present whose wave length is shorter than 0.000070 centimeter or 0.7 micron, which is approximately the longest wave length capable of affecting the organs of vision. As the temperature of the radiating body is increased, the radiation is found to include more energy of shorter wave lengths. The shortest wave length capable of affecting the eye is about 0.000037 centimeter

or 0.37 micron, which gives the sensation of a violet color. Although bodies at very high temperature emit radiations of this wave length, they also emit all other longer wave lengths, so that the total result is the sensation of a white or a bluish-white color.

Black-body Conditions.—Although it is evident that the radiations from a body increase with temperature, it may also be shown that the radiations from all bodies are not the same at a given temperature. For instance, if both carbon and polished platinum are heated to such a temperature that the carbon becomes incandescent, it will be noted that the platinum is emitting much less light than the carbon, even though the temperatures of the two bodies are the same. Further investigation shows that all substances have different energy-emitting powers or emissivities at the same temperature. It might appear, therefore, that the measurement of temperature by variations in energy radiation is uncertain. Kirchhoff's conception of a "black body" has removed the difficulty, and at present all optical and radiation pyrometers are calibrated in terms of black-body conditions.

Since all bodies exhibit different emissivities, it is possible to conceive of a body that has maximum emissivity. Such a body is called a black body, and its emissivity is designated numerically as 1. The emissivities of all other bodies are therefore fractions of the emissivity of a black body. Kirchhoff[1] defined a black body as one that absorbs all radiations falling upon it and reflects none. The radiations from such a body would, therefore, be due to temperature only. All other bodies absorb part of the radiations falling upon them and reflect or transmit the rest. Their radiations are not due, therefore, to their own temperature alone.

[1] G. Kirchhoff, *Pogg. Ann.*, **109**, 275 (1860), *Ann. chim. phys.*, **59**, 124 (1860).

The laws of radiation that will be discussed in subsequent sections are all stated in terms of black-body radiations. Although it might seem that the low emissivities of actual surfaces would necessitate large corrections in temperature measurements by optical and radiation pyrometers, it is a fact that a good many commercial operations requiring high temperatures are carried out under conditions that approach very closely those of the black body. The emissivities of a good many substances such as surfaces coated with oxide are very close to the emissivity of the black body.

The black body is experimentally produced by uniformly heating the walls of a hollow opaque enclosure and noting the radiations emitted through a small aperture. The radiations thus produced are due to temperature alone and are not affected by light from other sources.

Stefan-Boltzmann Law.—Newton formulated a "law of cooling" that asserted that the rate of radiation was proportional to the temperature difference between the body and its surroundings. Although this law is still used when the temperature difference between the body and its surroundings is small, it was long ago recognized that it was inadequate when the temperature difference was large. An investigation to determine more accurately the relation between the total radiant energy per square centimeter per second and the temperature of the body was carried out by Tyndall.[1] In this experiment, the radiating body was the opening of a heated hollow enclosure. Thus it gave black-body radiation. From results obtained by Tyndall and from other considerations, Stefan[2] concluded that for a black-body radiator the energy emitted per square centimeter per second was proportional to the fourth power of the absolute temperature of the radiating body. This

[1] J. Tyndall, *Phil. Mag.*, **28**, 329 (1864).

[2] J. Stefan, *Wien. Ber.*, **79**, *A.* 2, 391 (1879).

quantity is represented in Fig. 37 by the total areas under the curves. If the body, however, were placed in an environment at some other temperature, it must also be receiving heat proportional to the fourth power of this temperature, so that the net loss in energy per

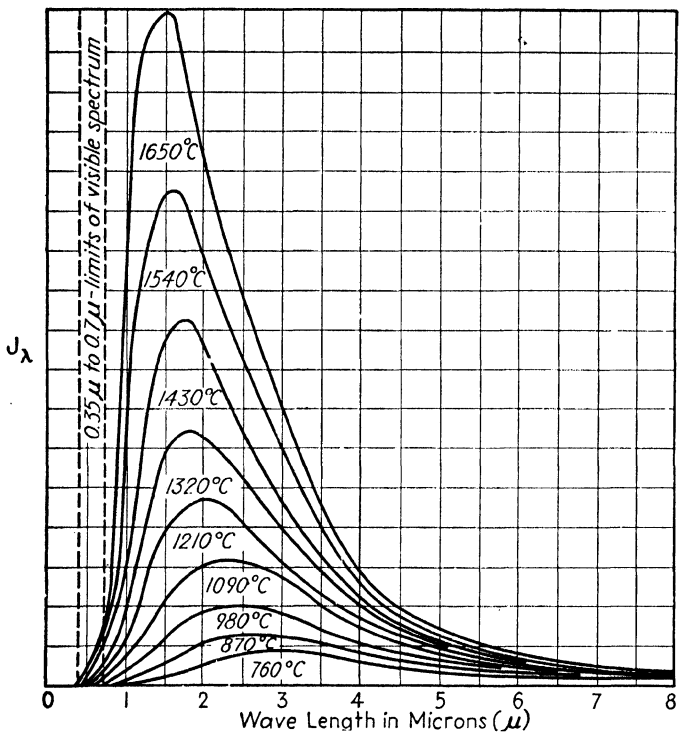


FIG. 37.—Distribution of black body radiation with respect to wave length from sources at different temperatures.

square centimeter per second is given by the following expression:

$$W = \sigma(T_1^4 - T_2^4).$$

σ is a universal radiation constant whose value appears to be 5.735×10^{-12} when W is expressed in joules, and T_1 and T_2 are the absolute temperatures of the radiating body and its surroundings, respectively.

Boltzmann,[1] in 1884, from thermodynamic reasoning, deduced the same result theoretically. This equation

[1] L. Boltzmann, *Wied. Ann.*, **26**, 287 (1884).

has since been experimentally verified by many observers for temperatures as high as 1550°C., with the use of the gas thermometer to measure the temperatures. Having established the validity of such a relationship for temperatures up to 1550°C., then, if some device were at hand for comparing the received energies at higher temperatures, an extrapolation of the law would enable the higher temperatures to be evaluated. Devices for comparing the total radiant energies from bodies are called total radiation pyrometers and will be discussed in the next chapter.

Wien's Law.—An experiment whose object was to determine the intensity distribution of the radiation from a uniformly heated enclosure in terms of the wave length of the radiation and the temperature of the enclosure was carried out by Lummer and Pringsheim.[1] The experiment was later repeated by these observers and others. The enclosure in the original experiment was a hollow carbon cylinder electrically heated. Its temperature was measured by a thermoelement calibrated in terms of the standard nitrogen thermometer. The radiation was allowed to pass out through a narrow opening and to be dispersed by a fluorite prism. A bolometer was used to obtain the energy distribution of the spectrum. The results obtained are pictured in Fig. 37. The ordinate J_λ is a quantity such that $J_\lambda d\lambda$ represents the energy per square centimeter per second carried by wave lengths whose values lie between the limits λ and $\lambda + d\lambda$. Thus, areas on the figure represent energies. It is observed that, as the temperature is increased, the intensity of each wave length increases but does not increase equally. From the figure, when the temperature is increased from 980 to 1650°C., the ordinate at 1.0 micron changes by a factor of 30 and that at 2.5 microns changes by a factor of 5. Thus, at higher temperatures, a larger part of the energy is

[1] O. Lummer and E. Pringsheim, *Wied. Ann.*, **63**, 395 (1897).

carried in shorter wave lengths, which accounts for the observed change in color.

The law connecting the radiation intensity J_λ, the wave length λ, and the absolute temperature of the emitting enclosure was first formulated by Wien,[1] in 1896, from theoretical considerations. The final form of the equation that he obtained is as follows:

$$J_\lambda = c_1 \lambda^{-5} e^{-\frac{c_2}{\lambda T}} \tag{1}$$

where λ and T denote wave length and absolute temperature, respectively, and c_1 is a constant depending upon the arrangement of apparatus, distance from source, etc., whereas c_2 might be considered a universal constant for radiation processes and e is the base of the Naperian logarithm system. By substituting the known coordinates of any two points in Fig. 37 two equations are obtained from which it is possible to obtain values of c_1 and c_2. If λ is expressed in microns (0.001 millimeter) and T in degrees absolute, c_2 is found to have the value 14,330. Since the original work of Lummer and Pringsheim was carried out before the accurate work of Day and Sosman[2] upon the high-temperature scale, the constants of the Wien law have involved considerable uncertainty.

Planck's Law.—The Wien equation was at first thought to represent the experimental facts exactly. More accurate experimental data, however, revealed the fact that there was unquestionably a discrepancy between the experimental and theoretical laws. This was especially noticeable at large values of T and λ. In 1901, Planck,[3] starting with rather radical assumptions regarding the conditions of equilibrium and the energy distribution of the oscillators that he assumed existed in

[1] W. Wien, *Wied. Ann.*, **58**, 662 (1896).
[2] *Loc. cit.*
[3] M. Planck, *Ann. Physik*, **4**, 553 (1901).

the heated enclosure, arrived at a theoretical result slightly different from that of Wien, namely,

$$J_\lambda = c_1\lambda^{-5}\left(e^{\frac{c_2}{\lambda T}} - 1\right)^{-1} \qquad (2)$$

The assumptions made in the development of this formula led to the now famous quantum theory. Many precise experiments have been made to test the validity of this equation. The conclusion seems to be that it fits the experimental facts very closely throughout the entire wave-length range for the temperatures used in the experiments, which have been from 400 to about 1500°C.

Optical Pyrometer.—A valid relationship between the intensity of radiation J_λ of a particular wave length λ and the temperature of the radiating body having been established, measurements of J_λ might be used to compare the temperatures of different radiating bodies, provided the intensity measurements are made for the same wave length. If a device is available for readily comparing the values of J_λ, it might be calibrated in terms of the gas thermometer at temperatures up to 1550°C., and then by extrapolation it might be used to measure temperatures far above the range of the gas thermometer, provided the radiation law is valid for all temperatures.

Various devices have been suggested and used practically to compare values of J_λ in a particular wave-length region, as the temperature changes. This apparatus generally assumes the form of an optical telescope with certain auxiliary attachments and is called an optical pyrometer. In determining the scale law of these instruments, the monochromatic wave length is generally obtained by the selective transmission of a glass plate (usually red, $\lambda = 0.63$ micron) placed in the path of the radiation at the eyepiece of the telescope. In this wave-length region, the difference between the Planck and the Wien equations is small, and therefore

the simpler Wien equation will be used in the following discussion.

Disappearing-filament Optical Pyrometer. *Morse Type.*—Figure 38 shows an optical pyrometer, manufactured by the Leeds and Northrup Company. The essential parts of the apparatus are an eyepiece E; an objective lens L; a red glass R, which absorbs all

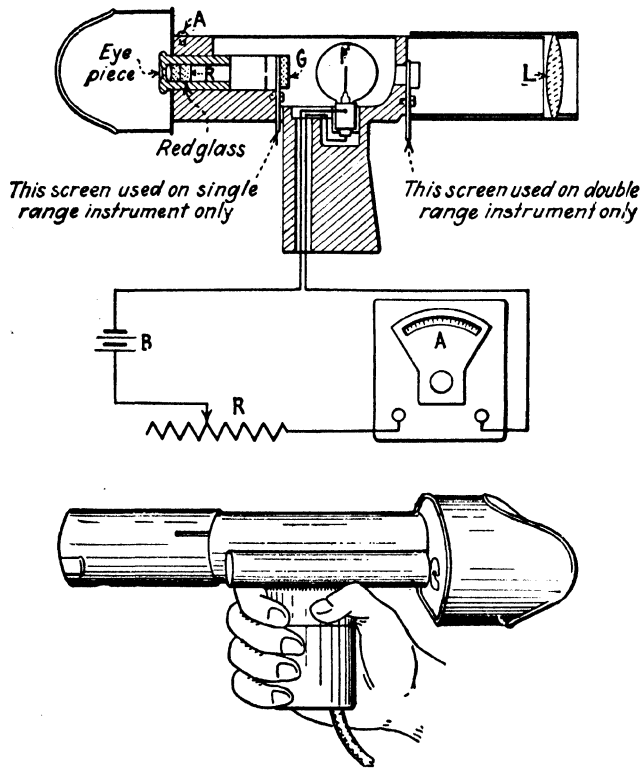


FIG. 38.—Optical pyrometer of disappearing filament type. (*Leeds and Northrup Co.*)

radiations except a narrow wave-length region in the red; the filament of an electric lamp F placed in the common focal plane of both E and L; a milliammeter A to measure the current through the filament F; a battery B; and a variable resistance R.

In the earliest form of optical pyrometer suggested by Le Chatelier,[1] instead of the electric lamp F, the instru-

[1] H. Le Chatelier, *Compt. rend.*, **114**, 214 (1892).

ment was provided with a side arm carrying a standard flame lamp that, by means of a lens and an inclined reflector, produced an image in the common focal plane of E and L. An iris diaphragm was used to reduce the quantity of light entering the telescope in order to obtain an intensity match with the standard lamp. Morse[1] suggested the use of the electric lamp, whose current could be varied to obtain an intensity match with the radiation through the objective. The apparatus used by Morse, however, had no lenses, and these

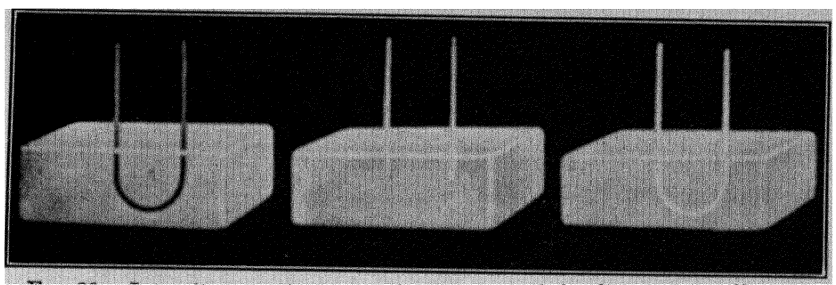


FIG. 39.—Intensity match in optical pyrometer of the disappearing filament type.

were later introduced by Holborn and Kurlbaum,[2] giving an instrument that was similar to that shown in Fig. 38.

In operation, the ocular is first focused upon the lamp filament, and the telescope is then pointed at and focused upon the high-temperature source. The filament, whose temperature, and hence brightness, may be varied by changing R, is superimposed upon the image of the source produced by the objective. The setting of the pyrometer then consists in adjusting R until the tip of the filament, which is generally made with a downward loop, just merges in brightness with the bright background of the image of the high-temperature source, as shown in the center of Fig. 39. The reading of the milliammeter for this condition of intensity match is then used as an indication of the temperature of the source.

[1] E. F. Morse, *Am. Machinist*, **26**, 1514 (1903).

[2] L. Holborn and F. Kurlbaum, *Ann. Physik*, **10**, 225 (1902).

Scale Law of Morse-type Disappearing-filament Pyrometer.—The relationship that might be expected to exist between the temperature of the source and the readings of the milliammeter may be approximated as follows: When the pyrometer is properly focused, the energy per square millimeter per second through the image formed by the objective in the plane of the filament is equal to the energy per square millimeter per second radiated by the filament normal to its surface. The former value may be expressed from Wien's law as

$$J_\lambda = c_1\lambda^{-5}e^{-\frac{c_2}{\lambda T}} \tag{3}$$

The latter is related to the temperature of the filament by a similar relationship, if the filament be considered as a radiating black body

$$J_\lambda = c_1\lambda^{-5}e^{-\frac{c_2}{\lambda T_f}} \tag{4}$$

where T is the temperature of the source and T_f the temperature of the filament. The temperature of the filament need not be known, since it is related to the energy supplied to it and radiated from it by the Stefan-Boltzmann law. The filament temperature will take such a value that the rate of receiving heat is equal to the rate at which it is lost. By neglecting the loss by thermal conduction and the gain by radiation from surrounding bodies, it therefore follows that

$$\sigma A T_f^4 = RI^2 \tag{5}$$

where A is the area of that part of the filament whose resistance is R. Now, if the resistance of the filament be considered constant together with σ and A, it follows that

$$c_1\lambda^{-5}e^{-\frac{c_2}{\lambda T}} = C_1'\lambda^{-5}e^{-\frac{c_2}{(\lambda kI^{1/2})}} \tag{6}$$

By taking the logarithm of each member and combining

the constants, the equation may be written in the following simple form for a definite wave length:

$$\frac{1}{T} = \frac{A}{I^{\frac{1}{2}}} + B \qquad (7)$$

where A and B are constants. Thus, a straight line

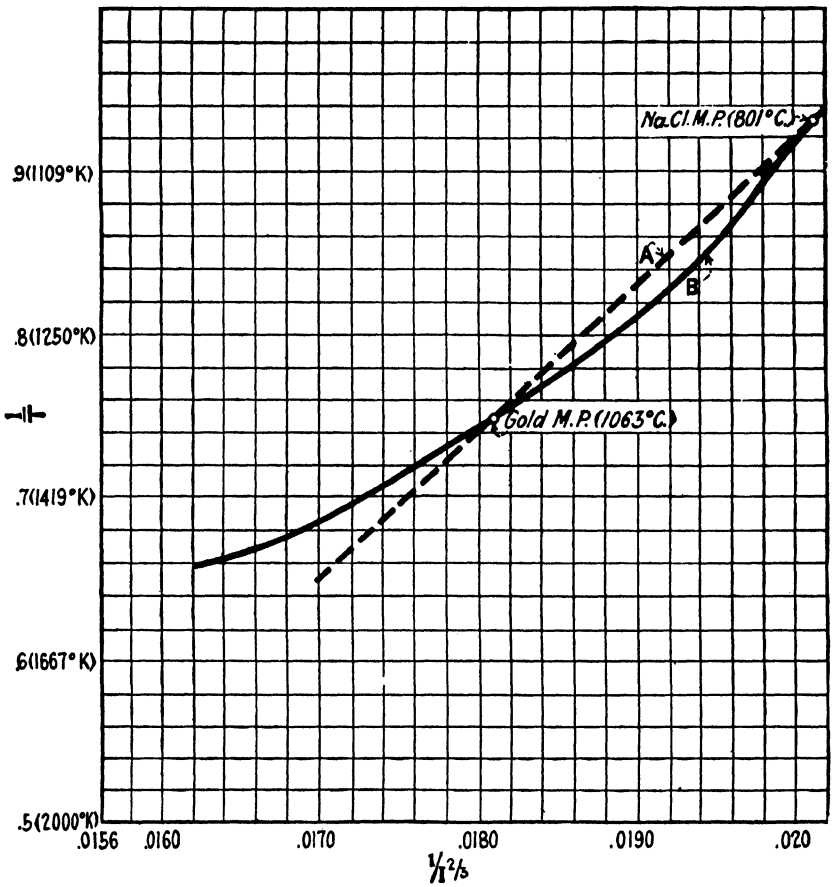


FIG. 40.—Scale law for Leeds and Northrup optical pyrometer.

should be obtained if the reciprocal of the temperature is plotted against the reciprocal of the square root of the corresponding current value. It should then be possible by knowing the current values for any two known temperatures to obtain a complete calibration of the instrument. However, R is probably not constant but varies directly with T for many metals. If this be assumed,

then the exponent of I becomes $\frac{2}{3}$ rather than $\frac{1}{2}$.

$$\frac{1}{T} = \frac{A}{I^{\frac{2}{3}}} + B \tag{8}$$

In Fig. 40, A is such a curve where the known temperatures are the melting point of gold, 1063°C., and the melting point of sodium chloride, 801°C. Curve B shows the actual relationship between I and T. Several reasons may be given to account for the difference between the two curves, actual and ideal. It may be accounted for by the fact that the assumptions made in the development involved approximations that were not quite permissible. It is practicable to express

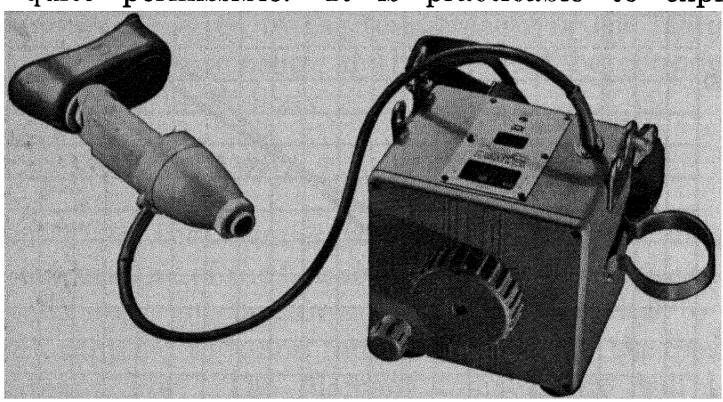


FIG. 41.—Optical pyrometer with potentiometer indicator. (*Leeds and Northrup Co.*)

the relationship between milliammeter readings and temperature by the following empirical equation

$$I = A + BT + CT^2 \tag{9}$$

Thus, to calibrate the instrument completely, the current at three known temperatures is obtained and the constants A, B, and C determined.

Optical Pyrometer with Potentiometer Indicator.—The Leeds and Northrup Company has introduced an instrument of the disappearing filament type in which the indication of the filament current is obtained by a potentiometric adjustment. The complete assembled instrument is shown in Fig. 41. A schematic arrange-

ment of the circuit is illustrated in Fig. 42. The success of the operation is dependent upon the fact that the electromotive force of a standard cell is constant and reproducible to better than 0.05 per cent and that the current required to heat a filament to a definite brightness may by the proper selection of the filament be constant within prescribed limits. Resistances R_4 and R_2 are chosen of such values that when R_1 is adjusted to give a brightness match between the filament and source at some definite temperature, the fall in potential across R_4 and that part of R_2 indicated is exactly equal to the

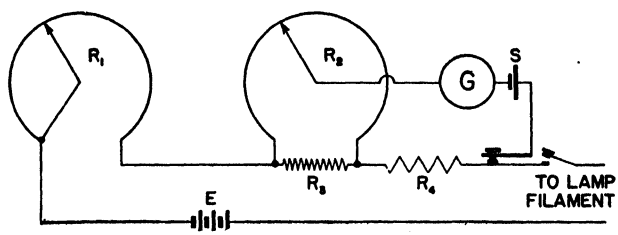


FIG. 42.—Circuit diagram of optical pyrometer with potentiometer indicator. (*Leeds and Northrup Co.*)

electromotive force of the standard cell S. In this position, the galvanometer G reads zero. A scale calibrated directly in degrees is carried with the dial of R_2. To adjust the filament current, the dial R_1 is turned, and since a clockwise motion of this dial reduces the resistance and thus increases the current through the lamp filament and the other resistances, a clockwise motion of R_2 is also necessary to balance the standard cell. It is thus possible to obtain an exact brightness match and an approximate adjustment of the standard cell by a single rotation of the large knob shown in Fig. 41. The final more exact adjustment of R_2 alone is obtained by the small knob shown in the figure.

The values of the current are thus obtained independent of the deflection of an indicating instrument with its accompanying uncertainties. However, the relationship between the temperature and the adjusted position

of the dial R_2 is purely empirical and depends upon the reproducibility of the filament.

F. and F. Optical Pyrometer.—Another disappearing filament optical pyrometer in which the intensity match is obtained in a different way is shown in Fig. 43. This instrument is called an F. and F. optical pyrometer and is manufactured by the Scientific Materials Company. As before, the instrument is provided with an eyepiece, an objective, a red absorbing glass, a milliammeter, a

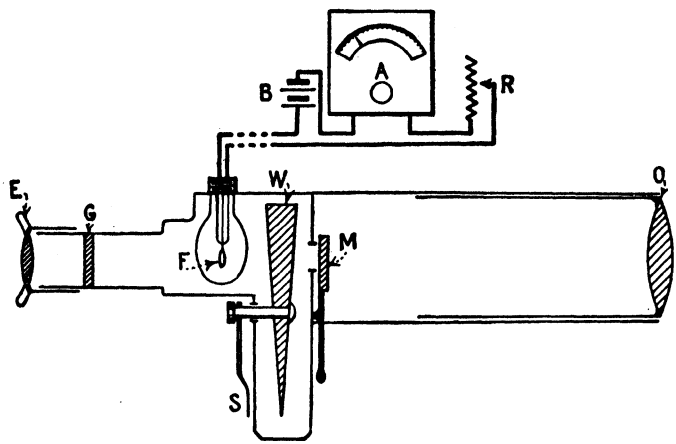


FIG. 43.—F. and F. optical pyrometer.

lamp filament, and a variable resistance. In addition, a wedge of absorbing glass W, located between the objective and the filament, is mounted in such a way that by rotating the handle S the thickness of the absorbing wedge may be varied, thus altering the intensity of radiation through the objective. This method of obtaining a brightness match between the source and standard lamp was first employed by Féry. Attached to S is a pointer that moves over a circular scale whose reading may be noted. In operation, the filament current is first adjusted to a predetermined constant value and is maintained continuously at that value. The pyrometer is focused upon the source and intensity match obtained by turning S until the filament and

background are indistinguishable. The angular reading of S may be expressed directly in temperatures. The range of the pyrometer may be changed either by moving the arm M, which puts an additional absorbing glass between the filament and the objective, or by changing the constant value of the filament current.

Absorption of Radiation.—If radiation of intensity I_0 is incident upon a thin layer of absorbing material, an amount of radiation I will emerge from the distant side of the absorbing layer. The intensity of the emergent radiation is less than that of the incident radiation by the amount absorbed and transformed into heat by the absorbing layer. The amount absorbed is proportional to the following factors: thickness of the absorbing layer, intensity of the incident radiation I_0, and the absorbing power of the material μ.

Thus, $dI = -\mu I dx$ where the minus sign indicates that the radiation decreases as the thickness dx increases. For a layer of finite thickness t, the above equation is integrated between the limits zero and t for the thickness and the corresponding limits for the radiation I_0 and I.

$$\frac{dI}{I} = -\mu dx \tag{10}$$

from which $$I = I_0 e^{-\mu t}.$$

μ is termed the coefficient of absorption and is numerically equal to the reciprocal of that thickness of material that would reduce the emergent I to 1/2.718 of the incident radiation intensity I_0. This same equation applies equally well in other branches of physics where absorbing media are encountered such as for x-rays, sound, etc., when the appropriate absorption coefficient is used.

Scale Law of the F. and F. Optical Pyrometer.—The energy that is radiated by the filament per unit area per second is constant if the filament current is kept constant. When an intensity match is obtained in adjusting this pyrometer, the energy radiated per square millimeter

per second by the filament must equal that of the background of the filament that comes through the objective and the absorbing wedge. Because of absorption in the absorbing wedge, only the fraction I/I_0 of the radia-

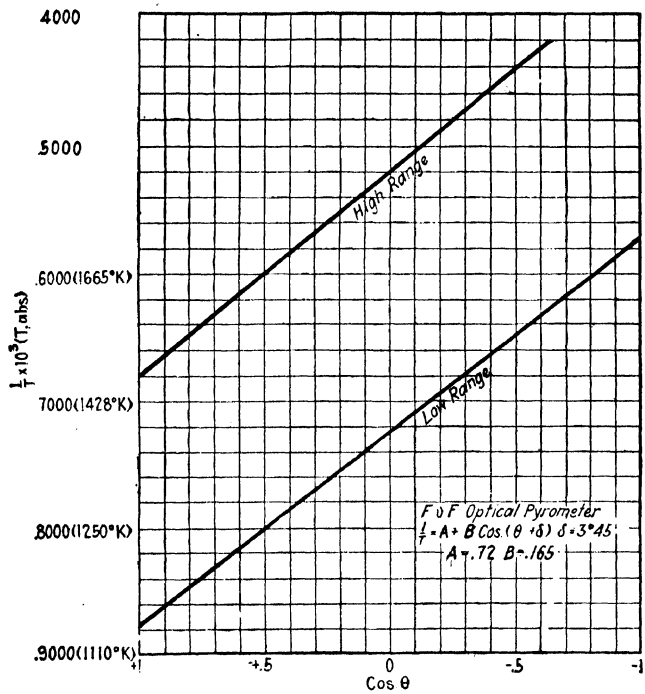


FIG. 44.—Calibration of an F. and F. optical pyrometer.

tion that would be expected by the Wien law is present. Thus

$$J_\lambda \text{ (filament)} = \frac{I}{I_0} c_1 \lambda^{-5} e^{-\frac{c_2}{\lambda T}} = e^{-\mu t} c_1 \lambda^{-5} e^{-\frac{c_2}{\lambda T}} = k \quad (11)$$

from which it follows, by taking the logarithm of the last two terms and grouping constants, for a definite wave length that

$$\frac{1}{T} = A't + B'. \quad (12)$$

A' and B' are constants. Now, from the geometry of the hemicircular wedge, the thickness t for any angular

setting θ equals the maximum thickness t_0 times the quantity $(r - r \cos \theta)/2r$. Substituting this value in Eq. (12) gives

$$\frac{1}{T} = A \cos \theta + B \tag{13}$$

A and B are constants whose value may be determined by knowing the angular settings corresponding to any two known temperatures. The value of expressing the scale law in this way is evident, since a complete calibration of the instrument may be obtained by using only two fixed points. Figure 44 shows the actual calibration of an F. and F. instrument using certain fixed melting points for the calibration. The lines are remarkably straight for both high and low ranges showing the validity of the above development.

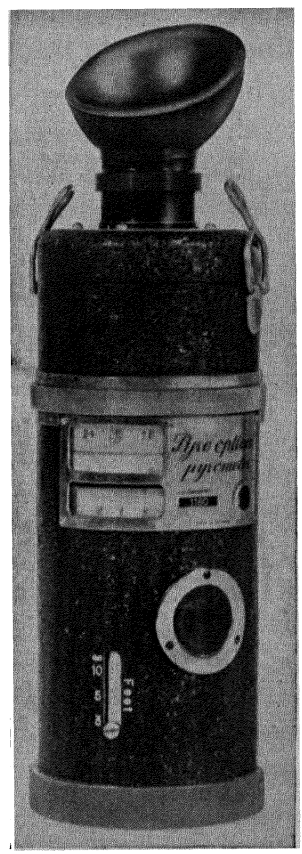


FIG. 45.—Pyro optical pyrometer. (*Pyrometer Instrument Co.*)

The Pyro Optical Pyrometer.—A compact instrument operating on the same principle as the F. and F. optical pyrometer has been developed by the Pyrometer Instrument Company and is shown in assembled form in Fig. 45. A diagrammatic section showing the construction of the component parts is presented in Fig. 46. A standard flashlight battery supplying a current of about 60 milliamperes lights the lamp. By means of totally reflecting prisms a small circular disk of light from the pyrometer lamp is made to fall at the center of the real image of the object formed by the objective lens. The

lamp current is set at some predetermined value. The radiation from the source whose temperature is being sought is varied by the rotation of an optical wedge placed between the objective lens and the image. The drum on which the optical wedge is mounted also carries the temperature scale that is read through a window on the outside of the instrument. Brightness match is obtained when the small inner disk becomes indistinguishable in its background.

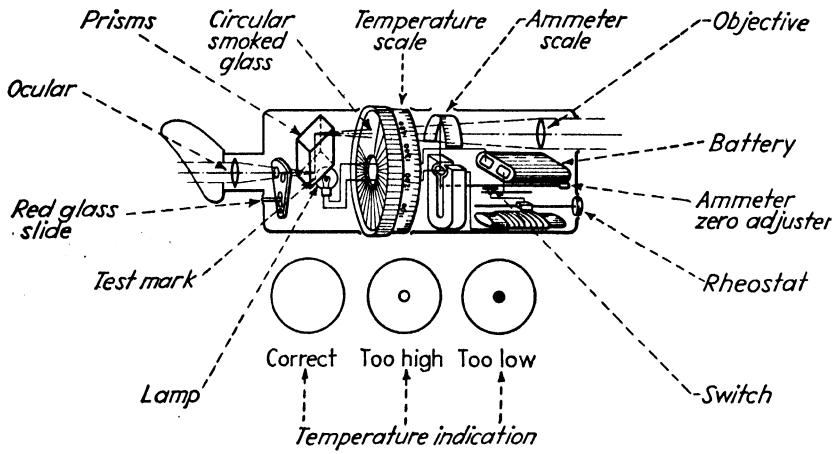


FIG. 46.—Isometric section of Pyro optical pyrometer. (*Pyrometer Instrument Co.*)

The proper filament current must be checked from time to time as the lamp ages. This can be done by having a master lamp that is not used continuously but that can be inserted when desired. With this standard lamp and its prescribed current, the temperature of a fixed source is determined. The service lamp is now put back and, leaving the temperature scale set at the known value, the current is varied through the filament until brightness match is obtained. This value of the current is then the new value required to make the instrument direct reading. A red glass in the eyepiece transmits only a narrow wave band so that the Wien law of radiation is applicable. Additional absorb-

ing glasses may be interposed near the objective to give a higher range in temperature.

Polarizing Type of Optical Pyrometer. *Wanner Optical Pyrometer.*—Figure 47 shows the detailed construction of a Wanner optical pyrometer. This instrument makes use of polarized light and is different from the two preceding instruments in that the monochromatic radiation is obtained by a direct-vision spectroscope rather than by the use of colored glasses. The eyepiece E carries an analyzer A for polarized light. The field of view consists of two half circles separated by a common diameter. One of the half disks is illuminated by radiation coming from a semistandard electric lamp

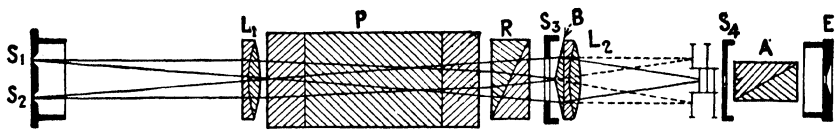


FIG. 47.—Wanner optical pyrometer.

through the slit S_2; the other half is illuminated by radiation coming from a standard amyl-acetate lamp through the slit S_1. The light from these two sources is polarized in passage by the Rochon prism P, each source giving two components polarized at right angles. The two perpendicularly polarized beams from each slit give rise to eight beams after passing through the biprism B. The optical system is so adjusted that all these beams except one from each slit is lost by reflection against the walls of the telescope tube. The beams that are allowed to pass are polarized at right angles to each other. Thus, the analyzer may be set so as to allow either half circle to appear light or dark.

In operation, the pyrometer is first sighted toward a standard amyl-acetate lamp burning under specified conditions. The analyzer is set to some definite angular position and the current through the electric lamp varied by adjusting a series resistance until both halves of the circular field are of the same brightness. The

filament current is now observed and this value is maintained until a future check shows that it has changed. A change will gradually occur through deterioration of the filament as it is operated at a rather high temperature. The amyl-acetate lamp may now be removed and the pyrometer sighted upon the high-temperature source. The analyzer is rotated until the two half circles are

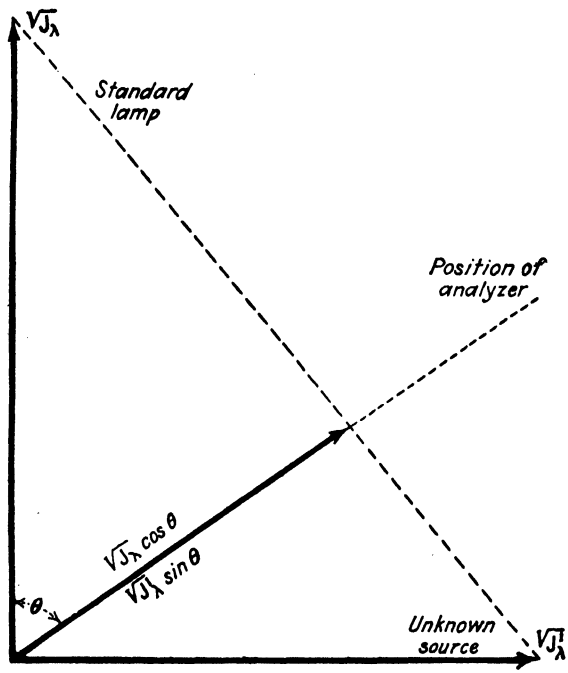


FIG. 48.—Vector diagram for Wanner pyrometer.

of the same brightness. From the angular reading when the half circles of the analyzer are of equal brightness, the temperature may be found.

Pyrometers of this principle, with slightly improved construction, are now manufactured by several other makers, notably Scientific Materials Company, Pittsburgh, and Cambridge and Paul Instrument Company, England.

Scale Law of the Wanner Optical Pyrometer.—When the brightness of the two half-circular fields is the same, the analyzer must be in such a position that the projec-

tions upon this direction of the two perpendicular vectors, representing, respectively, the amplitudes of vibration, are the same. Since the electric lamp is continually operated by the same current, its radiation intensity J_λ and, hence, also the corresponding amplitude of vibration that is proportional to the square root of the intensity are constant. This is represented in Fig. 48 by the vertical vector.

The horizontal vector represents the amplitude of vibration of the radiation from the source of unknown temperature. This radiation may be related to the temperature of the source by the Wien law. Thus

$$\sqrt{J}_{\lambda(\text{standard lamp})} \cos\theta = \sqrt{J'}_{\lambda(\text{source})} \sin\theta = \sqrt{c_1\lambda^{-5}e^{-\frac{c_2}{\lambda T}}} \sin\theta \quad (14)$$

From this equation, it follows by taking logarithms that the angular readings are related to the corresponding temperatures by the following:

$$\frac{1}{T} = A \log \tan^2\theta + B \quad (15)$$

where A and B are constants. Thus, if any two temperatures and their corresponding angular settings are experimentally determined, the instrument is completely calibrated, since $1/T$ plotted with $\log \tan^2 \theta$ gives a straight-line curve. Figure 49 shows a typical curve of this type, where the temperatures were certain standard calibration temperatures. The points lie almost in a straight line. The range of the pyrometer may be extended by the use of absorbing glasses to reduce the radiation coming through the slit S_1 or by using a different angular setting of the analyzer during the adjustment of the proper current through the electric lamp.

Effect of Varying the Distance between Pyrometer and Source.—It might appear that a pyrometer which

reads correctly for a certain distance between the pyrometer and furnace would be in error if the distance were altered. For an increased distance, a smaller amount of energy would be received by the objective. If the pyrometer is kept properly focused, however, the size of the image produced by the objective is decreased so that the energy per square millimeter per second remains

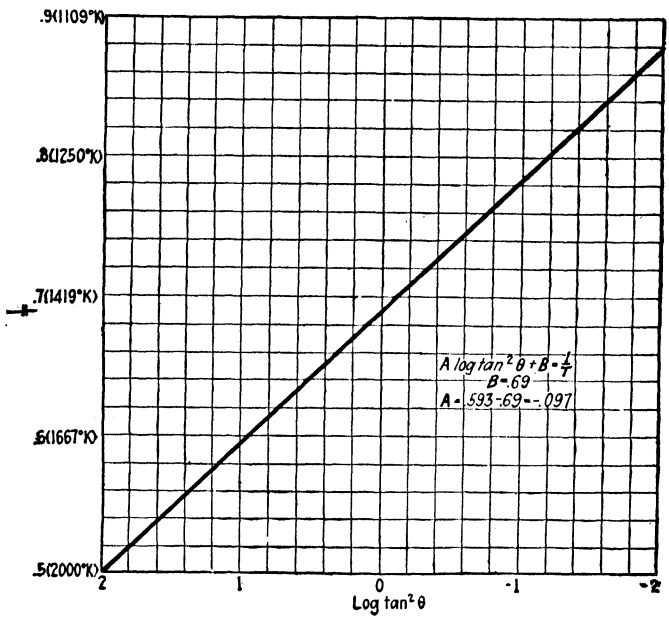


FIG. 49.—Calibration of a Wanner optical pyrometer.

practically unchanged. This may be shown to follow from the simple lens formula

$$\frac{1}{P} + \frac{1}{Q} = \frac{1}{F} \tag{16}$$

where P, Q, and F denote the object distance, image distance, and focal length of the lens, respectively. Also, Q/P equals the magnification produced by the objective. Since P is always a large quantity, changes in P produce negligible changes in Q. Hence, the magnification varies inversely as P. Thus, if P is

increased, the energy received by the objective varies inversely with P^2, and the area of the image formed by the objective also varies inversely as P^2; hence the energy per square millimeter in the image remains unchanged, and the readings of the pyrometer would be independent of the distance. If it should happen, however, that the high temperature source was being viewed through an aperture such that the objective was not completely covered with the radiation from the source at the shorter distance, then, on moving the objective farther away, the energy received by the objective would be constant until such a distance was reached that the objective was completely covered by the radiation coming through the aperture. In this case, then, it would follow that the temperature would appear to increase as the distance of the pyrometer from the aperture increased.

The presence of absorbing gases between the source and objective would, of course, always make the pyrometer read too low, and this effect would increase with the thickness of the gas layer or its density.

Emissivity of Materials and Its Effect upon Optical Pyrometer Reading.—The curves, shown in Fig. 37, show the intensity distribution of the radiation from a uniformly heated enclosure, in terms of wave length and temperature. Such a body is termed a black body, and these curves are spoken of as black-body curves. A black body will absorb completely all radiation incident upon it. It has been shown experimentally, however, that if a mass of metal be substituted for the uniformly heated enclosure at the same temperature, the curve obtained lies below that for the black body. In Fig. 50, along with the intensity wave-length distribution curve for a black body at 1000°C. is shown a similar curve for a mass of gold at the same temperature. It is evident that although the radiation from the gold has the appearance of a black-body curve, it lies well below that

of the black body at the same temperature, particularly in the long wave-length region.

If the radiation intensity from a black body at any temperature in some wave-length region be denoted by 1,

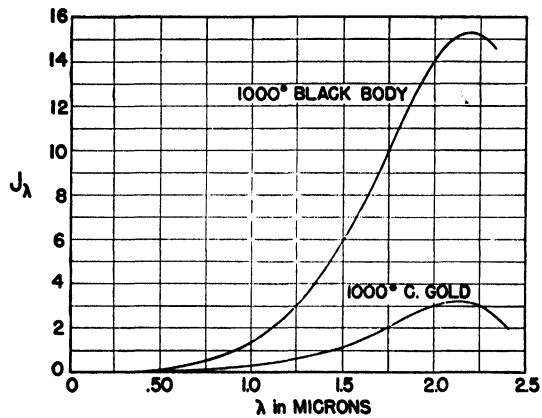


FIG. 50.—Relative radiation from a black body and a gold surface, both at 1000°C.

then the intensity of radiation from the nonblack body at the same temperature in the same wave-length region is less than 1. The ratio of the latter quantity to the former is called the emissivity E_λ of the substance for the particular wave length λ.

TABLE II.—EMISSIVITY OF GOLD AT THE MELTING POINT*

Wave Length, Microns	Emissivity
0.7014	0.184
0.6712	0.203
0.6409	0.232
0.6149	0.263
0.5895	0.304
0.5649	0.347
0.5418	0.390
0.5186	0.434
0.4961	0.473
0.4750	0.503

*C. M. Stubbs and E. Prideaux, *Proc. Royal Soc.*, **87**, 451 (1912).

Table II shows the emissivity of gold for a few wave lengths at its melting point. It is thus evident that if an optical pyrometer had been calibrated in terms of a black-body source, then a nonblack body would have an

apparent temperature less than its true temperature, since the smaller radiation intensity would allow a brightness match with a smaller filament current. If the emissivity E_λ of the substance, however, is known, then it becomes possible to calculate the true temperature from the apparent temperature. Since the actual radiation intensity from the nonblack body is E_λ times the radiation that would be given by a black body at the same temperature, then from Wien's law it follows that

$$J_\lambda \text{ (actual)} = c_1\lambda^{-5}e^{-\frac{c_2}{\lambda T_{\text{apparent}}}} = E_\lambda c_1\lambda^{-5}e^{-\frac{c_2}{\lambda T}} \quad (17)$$

where T_{app} and T represent the apparent and true temperatures, respectively. Taking logarithms of the last two members this becomes

$$\frac{1}{T} - \frac{1}{T_{\text{apparent}}} = \frac{\lambda}{c_2}\log_e E_\lambda = \frac{0.63}{14{,}330}(2.302)\log_{10} E_\lambda = \frac{\log_{10} E_\lambda}{9{,}880} \quad (18)$$

For any given set of conditions, the right-hand member of Eq. (18) is a constant that may be evaluated as a whole by measuring any true temperature and its corresponding apparent temperature. Knowing this constant value, the true value corresponding to any apparent temperature may be found. It is apparent that the difference between the true and apparent temperatures for any value of E_λ becomes greater as the temperature increases. As an illustration, if the emissivity of a substance were 0.5, a true temperature of 1000°C. would have an apparent temperature of 948°C., and temperatures of 1500°C. and 2000°C. would appear as 1398°C. and 1826°C. Figure 51 shows a graphical method of illustrating the relation of true and apparent temperatures for any value of emissivity. Another ingenious graphical method due to Pirani[1] is shown in Fig. 52, in

[1] M. Pirani, *Phys. Ges. Verh.*, **12**, 301, 1054 (1910) and **13**, 19 (1911).

which a straight line through the observed temperature shown in columns s'' or s' and the emissive power A will,

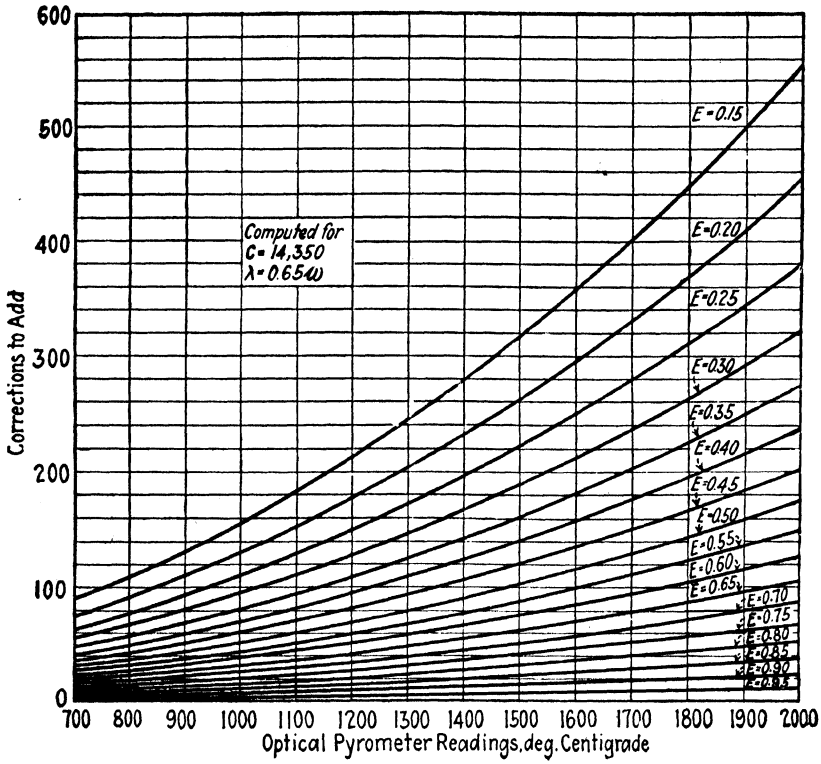


FIG. 51.—Corrections due to emissivity, in readings of optical pyrometers. (T. P. 170, *U. S. Bur. Standards.*)

TABLE III.—EMISSIVITY FOR WAVE-LENGTH REGION 0.65 MICRONS

	Substance	Emissivity
Gold	Solid	0.13
	Liquid	0.22
Platinum	Solid	0.33
	Liquid	0.38
Copper	Solid	0.11
	Liquid	0.15
Tungsten	Solid	0.4
Carbon	.....	0.9

when extended, give the true temperature from columns T' or T''. If a pyrometer is to be used for a single

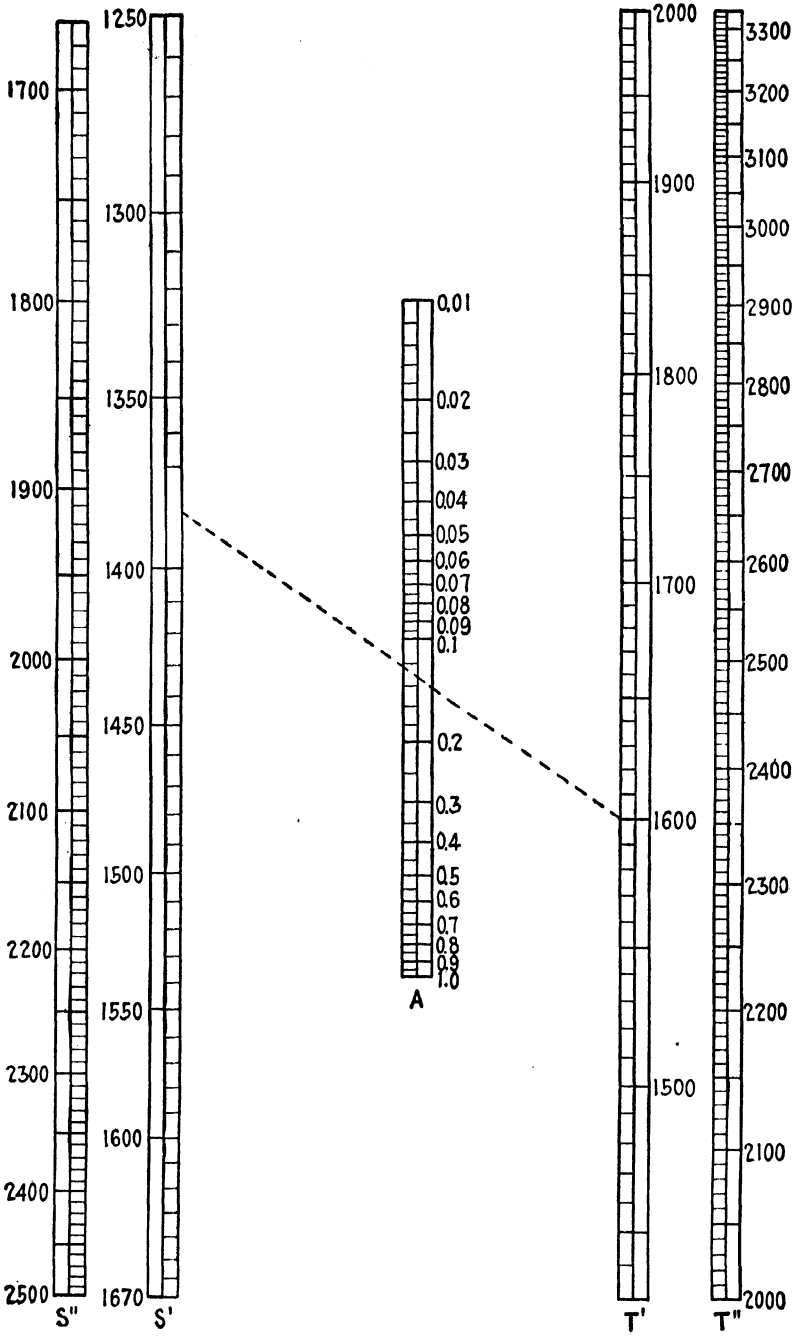


FIG. 52.—True and apparent temperatures. Pirani method.

purpose where the emissivity is constant the scale may be corrected so that it gives directly the true temperature.

Table III shows the emissivity of a few unoxidized metal surfaces for the wave length 0.65 micron at temperatures close to the melting points for the first three metals.

Change in Emissivity with Temperature.—The change in emissivity of a metallic surface with temperature has been the subject of many investigations.[1] The results obtained by Stephens[2] for a platinum surface

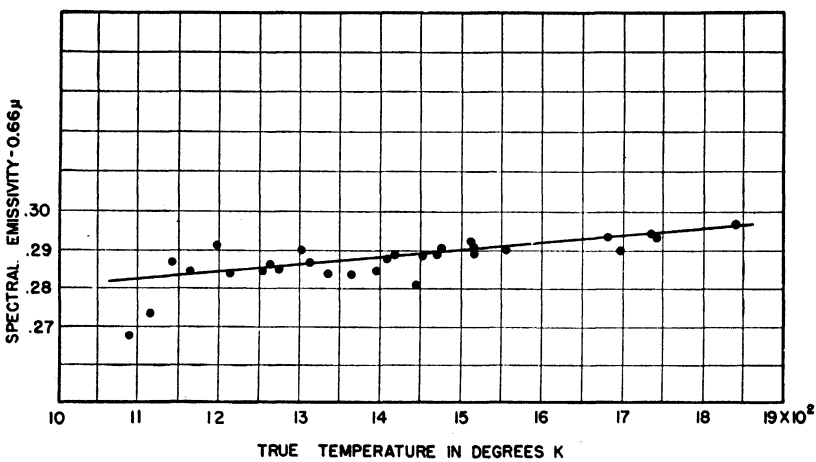


FIG. 53.—Variation in emissivity of platinum with temperature at a wave length of 0.66 micron.

are shown in Fig. 53. In this investigation, the inside of a heated hollow cylinder is viewed through a small aperture in the side, giving the true temperature; the same pyrometer, sighted upon the outer cylindrical surface, gives the apparent temperature. A slight increase in emissivity is observed as the temperature increases. Certain of the earlier reports had indicated a decrease in emissivity at higher temperatures.

Lambert's Law.—The energy radiated from a unit area in unit time might be expected to vary directly with the cosine of the angle θ between the normal and the

[1] A. G. Worthing, *Phys. Rev.*, **28**, 183 (1926).

[2] R. E. Stephens, *Jour. Optical Soc.*, **29**, 158 (1939).

emitted radiation. However, the effective emitting area perpendicular to the radiation at the angle θ is the actual area multiplied by the cosine of θ. Hence it would follow that the intensity of radiation is independent of the emitting angle. That this relationship, known as Lambert's law, does not quite hold in actual practice is shown in Fig. 54 by Stephens for a platinum

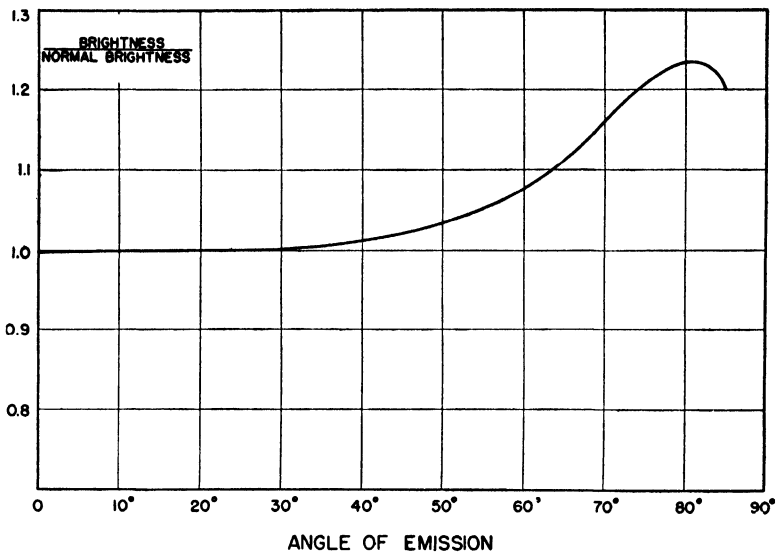


FIG. 54.—Deviation from Lambert's law for radiation from a platinum surface.

surface at 1392°K. It is apparent that at an emergent angle of 80 degrees the deviation is a maximum and exceeds the normal intensity by about 20 per cent.

The Optical Wedge.—Mendenhall[1] has shown that even for materials whose emissivity is small, blackbody conditions are closely approached if the pyrometer is sighted upon the inside surface of a hollow wedge of the material having a small angular opening. Let E_λ, E_λ', and R_λ denote, respectively, the emissivity of a black body, the emissivity of the material of a nonblack body, and the reflecting power of the material of the nonblack body, all for some wave length λ. Kirchhoff

[1] C. E. Mendenhall, *Phys. Rev.*, **33**, 74 (1911).

showed that the following relationship existed:

$$R_\lambda + E_\lambda' = E_\lambda = 1 \tag{19}$$

i.e., that a good reflector is a poor emitter and vice versa. Hence, in Fig. 55, the radiation coming from A to the pyrometer objective is made up of some radiation emitted by the region A, some emitted by B and reflected by the region at A, some emitted at C and reflected

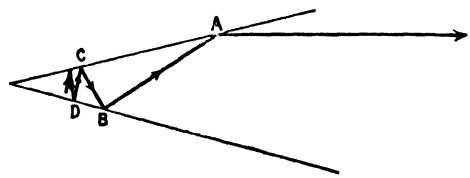


FIG. 55.—Radiation from a hollow wedge-shaped enclosure.

successively at both B and A, etc. Thus, the total emissivity of the region A is

$$\begin{aligned} &E_\lambda' + R_\lambda E_\lambda' + R_\lambda^2 E_\lambda' + R_\lambda^3 E_\lambda' + \text{etc} \\ &\quad = E_\lambda' + R_\lambda - R_\lambda^2 + R_\lambda^2 - R_\lambda^3 + R_\lambda^3 \text{ etc} \\ &\quad - R_\lambda^n = 1 - R_\lambda^n = 1 \text{ (approximately)} \end{aligned} \tag{20}$$

For an angular opening of 10 degrees, n may be as large as 20, and R_λ^n becomes negligible, so that even if E_λ' is small, the total emissivity is close to that for a black body. Hence, if metals are viewed when enclosed in a furnace or when covered with an oxide coating or a rough surface, black-body conditions are approached, and true temperatures approximately given directly.

Nichols and Howes[1] have reported certain oxides that, when heated, gave off radiation in the blue region of the spectrum many times greater than that from a black body at the same temperature. The radiation was, however, deficient in other wave lengths. This has been explained as not pure temperature radiation but a case of luminescence excited by the presence of some activating material, as the effect exhibited fatigue in time.

[1] H. L. Howes and E. L. Nichols, *Jour. Optical Soc. Am.*, **6**, 42 (1922).

The Effect of Absorbing Media upon the Reading of Optical Pyrometers.—It was previously noted on page 117 that radiation passing through any absorbing matter would be reduced in intensity. Hence, if a window or smoke screen is interposed between the pyrometer and the high-temperature source, the apparent temperature will be less than the true temperature. Since the ratio of the actual intensity I to the intensity that would be obtained with no absorber I_0 was shown to be equal to $e^{-\mu t}$, it follows that the quantity $e^{-\mu t}$ plays the same role as emissivity in Eq. (18). Thus, the true and apparent temperatures are related as follows:

$$\frac{1}{T} - \frac{1}{T_{\text{apparent}}} = \frac{\lambda}{c_2} \log_e e^{-\mu t} = \frac{-\lambda \mu t}{c_2} = -\frac{0.63 \mu t}{14{,}330} \quad (21)$$

Thus, if it is necessary that the absorbing substance be present, its effect may be accounted for by knowing any pair of true and apparent temperatures, since the right-hand member of Eq. 21 is constant. When an absorbing glass is interposed to extend the range of an optical pyrometer, it is therefore necessary to obtain a calibration at only one point in order to evaluate the whole scale. In practice, an error is generally present, because the radiation is not strictly monochromatic.

The Effect of Reflection upon the Reading of an Optical Pyrometer.—In an optical pyrometer, brightness match is obtained between the filament and the image formed by the objective, regardless of the history of the radiation before coming to the objective. The radiation might, therefore, come from a reflecting surface that is itself cold. The apparent temperature of the body would in this case be much greater than its true temperature. For example, a wall in sunlight might have an apparent temperature of 2000°C. Hence, care must be taken that the body whose temperature is being determined is not reflecting radiation from another bright source.

Extension of Range of Optical Pyrometers.—The working range of an optical pyrometer may readily be extended beyond that which was originally intended. This is particularly easy with certain types of pyrometers such as the Wanner or the F. and F. With the instrument first mentioned, if the analyzing eyepiece is set at a smaller angular reading than the normal while the filament current is being adjusted by comparing with the standard amyl-acetate lamp, then the normal filament current value is increased, and the scale readings mean higher temperatures than normally. With the latter instrument, to extend the range, the constant filament current is maintained at a value above the normal. The filament, however, should not be made to carry an excessive current so that it deteriorates rapidly. Certain other methods of extending the range may be used with any of the pyrometers.

Absorbing Screen.—The effect of interposing an absorbing layer has been mentioned. The true temperature is greater than the apparent temperature with the absorber, and if the readings of the pyrometer are obtained in a single case with and without the absorber, any subsequent apparent temperature may be converted to true temperature, as shown by Eq. (21).

Sectored Disk.—Another method of extending the range of the pyrometer is to place between the pyrometer and the high-temperature source a sectored disk that is rotated at a sufficiently high speed to avoid flickering. If the ratio of the open to the total space of the disk is denoted by R, then R represents the fraction of the total radiation from the high-temperature source that is received by the objective. It, therefore, may be treated like the similar terms, emissivity in Eq. (18) and I/I_0 or $e^{-\mu t}$ in Eq. (21), giving

$$\frac{I}{T} - \frac{I}{T_{\text{apparent}}} = \frac{\lambda}{c_2} \log_e R \qquad (22)$$

Since R is measurable, T may be found from T_{apparent} without any additional experiment, provided λ and c_2 are known. Disks of this sort may be made by having two identically sectored disks clamped together on the same axis so that they may be shifted with respect to each other, making R any desired fraction. From the emissivity diagrams it may readily be observed that in order to make T_{apparent} small with respect to T, R must be a very small fraction.

Effective Wave Length of Absorbing Glass.—Since it is impossible in practice to obtain absolutely mono-

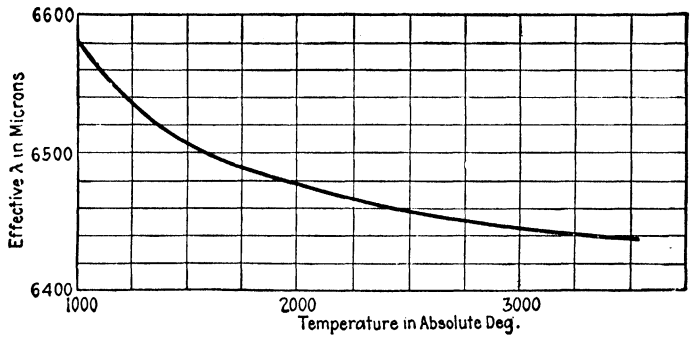


FIG. 56.—The effective transmission wave length of an absorbing glass as a function of the temperature of the source.

chromatic filter glass, it is necessary to determine what wave length in the spectral band transmitted is to be employed in the calculation. The quantities that are actually compared in pyrometry are the integral luminosities as observed through the filter glass. In general, it has been found that the "effective" wave length of a transmission glass shifts toward shorter wave lengths for higher temperatures. Figure 56 shows the effective transmission wave length obtained with a typical filter glass as the temperature is increased.

Color Temperature.—In the field of illumination engineering, the term "color temperature" is significant. The color temperature of an illuminant is the temperature of a black body or hollow enclosure whose emission in the visible spectrum most closely matches that of the

illuminant. For temperatures not too high, agreement is determined by direct visual comparison. At higher temperatures, it is difficult to control the temperature of the black body, and other methods are used to supplement visual comparison. These indirect methods involve the calculation of the color temperature from a measure-

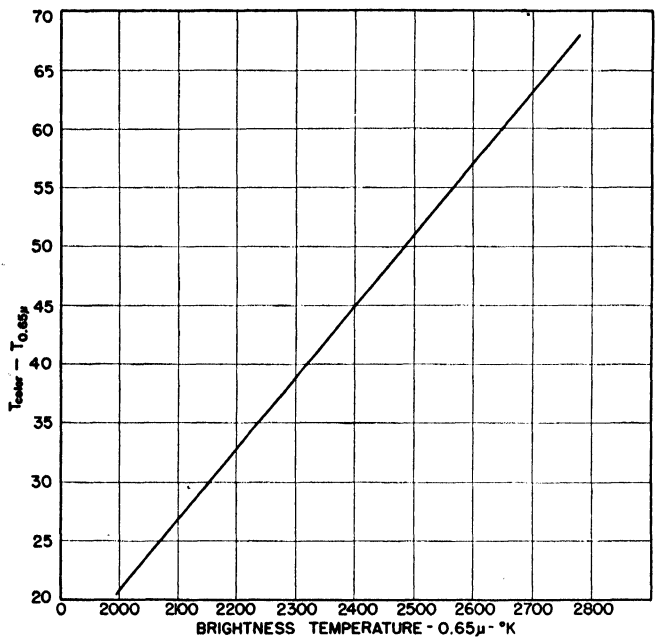


FIG. 57.—Difference between brightness and color temperatures for a particular tungsten filament.

ment of the distribution of the spectral energy. In one of these, known as the red-blue ratio method, the color temperature is the temperature of a black body having the same ratio of radiant energies at two selected wavelengths as the illuminant. In another method, the illuminant is said to have a color temperature equivalent to that of a black body whose spectral distribution most nearly fits that of the illuminant.

At the U. S. Bureau of Standards, an attempt has been made to establish[1] a scale of color temperature

[1] H. T. Wenzel, D. B. Judd, W. F. Roeser, *U. S. Bur. Standards Jour. Research*, **12**, 527 (1934).

based upon the fixed freezing points of platinum, rhodium, and iridium 2046°K., 2239°K., and 2727°K. This work involved the color matching by a Lummer-Brodhun photometer of the radiation from several 400-watt projection bulbs with the radiation from black bodies immersed in the freezing metals. The voltage on each lamp for color match at each temperature was noted. This group of lamps is to serve as a primary standard of color temperature and is to be used only to calibrate other working standards. Intermediate color temperatures T_c can be found by a simple empirical expression such as

$$T_c = 620 + 243.6\sqrt{V} \tag{23}$$

where V is the voltage applied to the lamp terminals.

By sighting an optical pyrometer on the inside of the turns of the tungsten filament, the brightness temperature at 0.65 micron can be observed. The brightness temperature of the filament is less than the color temperature. This difference as observed for a particular lamp is shown in Fig. 57.

Burgess Micropyrometer.[1]—In order to determine the melting points of minute samples of materials, Burgess devised an instrument of the disappearing-filament type employing a compound microscope instead of the usual telescope. The apparatus is shown in Fig. 58. The microscope is focused upon a platinum strip in an enclosure so that black-body conditions are approximated. A small piece of the sample under investigation is now placed upon the platinum strip that is heated by passing an electric current through it. A small lamp filament in the eyepiece is visible, superimposed upon the image of the platinum strip. By varying the current through the filament, it may be made to disappear in the field of view, as was the case in the Morse-

[1] G. K. Burgess, "The Measurement of High Temperatures," p. 343, John Wiley & Sons, Inc., 1911.

type pyrometer. The current through the lamp filament at the instant of the melting of the "sample," which is also in the field of view, serves as an indication of the temperature. The instrument may be calibrated by using certain specimens whose melting points are known

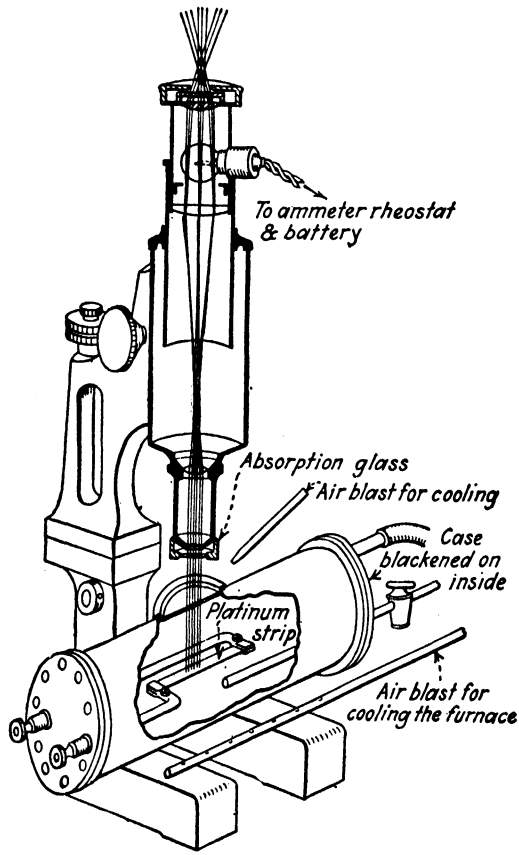


FIG. 58.—Burgess micropyrometer.

and interpolating for other values. The ordinary optical pyrometer may be used in this connection if it be sighted upon the sample and heated strip and the reading at the instant of melting observed. A microscope focused upon the sample may be used to judge the instant of melting.

Care of Optical Pyrometers.—In those pyrometers in which the constancy of calibration depends upon the

constancy of the filament of the lamp, great care should be taken to avoid excessively large currents. The lamps are normally operated much below their rated power input so that their life is much prolonged. They should be turned on only while the reading is being taken. In the Wanner instrument, comparison with the standard lamp should be made at frequent intervals. When not in use, pyrometers should be covered to avoid the accumulation of dust coverings upon the optical parts of the instruments that might produce errors in the readings. Care should be taken in focusing those instruments of variable focus, for the independence of distance follows only when the pyrometer is properly adjusted.

Accuracy in Optical Pyrometry.—Optical pyrometry has grown to mean almost exclusively high-temperature measurements with the disappearing-filament type of pyrometer. This type is simple in construction, affords great accuracy, and is adapted to a diversity of conditions. Although the optical pyrometer may still be regarded as a secondary device, the experimental values of the radiation constants have been so precisely established that it seems reasonable to make use of it in checking the high-temperature gas scale. The precision, accuracy, and wide range of usefulness of the disappearing-filament optical pyrometer depend on perfect disappearance of the filament with high resolving power and magnification by the eyepiece. By designing the instrument to avoid diffraction effects, Fairchild and Hoover[1] state that it is possible to obtain a precision of 0.2°C. or better at the melting point of gold. To test the consistency of the high-temperature scales in use in various research laboratories in this country and England, Forsythe[2] in 1923, *i.e.*, before the adoption of the international temperature scale, compared the current-temperature relations for cer-

[1] *Loc. cit.*

[2] W. E. Forsythe, *Astrophys. Jour.*, **58**, 294 (1923).

tain lamps found in these various laboratories. These high-temperature scales are based upon assumptions regarding the melting point of a metal and a value of the c_2 radiation constant. Thus the basis of the scale at the General Electric Research Laboratory and the U. S. Bureau of Standards was $c_2 = 14{,}350$ and the melting point of gold, 1063°C. At the National Physical Laboratory, England, the basis was $c_2 = 14{,}350$ and the melting point of palladium, 1555°C. The agreement of the scales was found to be very good, differences being only a few degrees over the range from 1000 to 2400°C.

In the use of secondary standards consisting of tungsten ribbons in evacuated bulbs, the filament appears less bright than it actually is because of loss of light at the two surfaces of the glass. This loss is usually accounted for in the original calibration. In case a source is being viewed through a thickness of glass or other material appreciable corrections often need to be made. The magnitude of these corrections has been discussed by Benford.[1] If the transmission of the glass is treated as an emissivity, then the corrections can be taken from Fig. 51 on page 128.

The Optical Pyrometer and the International Scale of Temperature.—For temperatures above the melting point of gold (1063°C.), the optical pyrometer is recognized by international agreement to be the fundamental temperature-measuring device. The absolute temperature T of any source emitting an intensity of radiation J_λ at the wave length λ is given by the expression from Wien's law

$$\log_e \frac{J_\lambda}{J_\lambda'} = \frac{c_2}{\lambda}\left[\frac{1}{1336} - \frac{1}{T}\right] \qquad (24)$$

where J_λ' is the intensity of emission of a black body at the temperature of the gold point. The constant c_2 is arbitrarily assigned the value 14,320 micron degrees.

[1] F. Benford, *Jour. Optical Soc. Amer.*, **29**, 162 (1939).

EXPERIMENT 1

OBJECT: To calibrate an optical pyrometer and obtain its scale law.

Sources of Known Temperatures:

1. *Standard Broad Filament Lamps.*—It is now possible to obtain a broad filament lamp that may be calibrated so that its effective black-body temperature is expressible in terms of the current through it. Tungsten serves particularly well for the material because of its high melting point and relatively large emissivity. Since lamps of this sort need not be operated near their rated power, their original calibration will change very little with time.

2. *Furnace with Thermocouple.*—A cylindrical furnace carrying at the center of the tube a plug of carbon might be used as standard high-temperature source. The temperature of the plug may be noted by a *Pt. Pt-Rh* thermocouple up to 1500°C.

3. *Fixed Melting Points.*—The melting points of various substances may be taken as known temperatures. For each of these temperatures, a crucible containing the corresponding substance is placed in the furnace so that black-body conditions are approximated. The substance is now heated well above its melting point, and readings of the pyrometer, when focused upon the surface, taken every half minute as the substance cools. A pyrometer reading-time curve will now indicate the pyrometer reading at the melting point as a horizontal part of the curve.

4. *Melting Points from Electrically Heated Strips.*—Instead of using a quantity of a substance in a crucible, a strip of the material may be connected between two heavy electrodes so that a large current may be passed through it. A convenient source of supply is the secondary of a step-down transformer having a resistance in the primary for control. A slight notch should be put in the strip at one point to insure a position of maximum temperature upon which the pyrometer is focused. The whole strip should be enclosed so that approximately black-body conditions prevail. The current is now gradually increased through the strip and the pyrometer made to follow the increase in temperature to the melting point of the strip.

The pyrometer to be calibrated may be focused upon any one of these high-temperature sources.

Pyrometers. *Leeds and Northrup Pyrometer.*—The scale law of this instrument has been developed on page 113 as

$$\frac{1}{T} = \frac{A}{I^{\frac{1}{2} \text{ or } \frac{2}{3}}} + B$$

Using any two of the known temperatures, observe the corresponding

pyrometer currents, and solve for A and B. Now calculate the pyrometer currents to be expected at some other temperatures. Note the difference between calculated and true temperatures, and draw curves (using $1/T$ and $1/I_{\frac{1}{2} \text{ or } \frac{2}{3}}$ or T and I as coordinates) that show the calculated and observed values. If agreement is not good at calculated points, solve for the constants A, B, and C in the empirical equation

$$I = A + BT + CT^2$$

Assume the temperatures known at three points. Now try other known points, and observe discrepancies between calculated and observed values. Explain why the first equation may be inaccurate. If the instrument is provided with a double range, check the higher range of the instrument at one point. Can you now calculate what the other higher range readings will be if the lower range readings are known? What error is present?

F. and F. Optical Pyrometer.—Set the current through the lamp at the prescribed value, and read the scale of the pyrometer for the various known temperatures. It is preferable that the scale be marked in angular degrees. Assuming two of the temperatures known, solve for A and B in the scale-law equation derived on page 119.

$$\frac{1}{T} = A \cos \theta + B$$

Does the equation allow the temperature to be correctly calculated for other angular settings? If the scale is marked only in temperatures, the scale law could be checked by fastening on an additional circular scale. How could the zero of this scale be located? Suppose the filament current had been set at a value larger than that prescribed, what would have been the effect upon the apparent temperature?

Wanner Optical Pyrometer.—Adjust the standard amyl-acetate lamp according to directions so that the tip of the flame burns level with the top of the flame gage, and affix to pyrometer. Set the analyzing eyepiece at some particular angular setting, and adjust the current through the electric lamp until the two halves of the circular field of view are of equal brightness. Note the value of the filament current, and keep this constant until a recheck shows it to have changed through deterioration of the lamp filament. The high-temperature source may now be substituted for the amyl-acetate lamp and the eyepiece rotated until brightness match is again obtained. Obtain angular settings for several known tempera-

tures. Using any two of them, solve for the constants A and B in the scale-law equation developed on page 123.

$$\frac{1}{T} = A \log \tan^2 \theta + B$$

Do the calculated and observed temperatures agree at other angular settings? What would have been the effect of using a smaller standard angular setting in obtaining the constant current for the electric bulb? On account of stray light, the pyrometer is not accurate at very small or very large angular settings. Why does the temperature increase very rapidly at large angular positions?

Experiment 2

Object: To find the emissivity of various metals.

Most substances, when heated to some temperature T, emit less energy in every wave-length region than a black body at the same temperature. That factor which, when multiplied by the intensity of the black-body radiation, will give the actual radiation intensity in a particular wave-length region is called the emissivity of the substance for that wave length E_λ. Thus

$$J_\lambda' \text{ (nonblack body)} = E_\lambda J_\lambda \text{ (black body)}$$

Hence, in an optical pyrometer calibrated with the Wien law as a basis of the temperature scale, the apparent temperature T_a will be too low. The actual radiation intensity may be written in terms of the true and apparent temperatures as follows:

$$J_\lambda' = c_1 \lambda^{-5} e^{-\frac{c_2}{\lambda T_{\text{apparent}}}} = E_\lambda c_1 \lambda^{-5} e^{-\frac{c_2}{\lambda T_{\text{true}}}}$$

It thus follows by taking logarithms that

$$\frac{1}{T_{\text{true}}} - \frac{1}{T_{\text{apparent}}} = \frac{\lambda}{c_2} \log_e E_\lambda = \frac{\log_{10} E_\lambda}{9{,}880} \tag{18}$$

when $\lambda = 0.63$ micron

and $c_2 = 14{,}320$

Thus, if any pair of true and apparent temperatures are known, the emissivity of the substance may be found. It was shown on page 132 that a pyrometer, when sighted upon the inside of a hollow wedge of small angular opening, gives approximately black-body temperatures.

Fold a thin strip of the substance under investigation so that it makes a wedge having an angular opening of a few degrees. Con-

nect the ends of the strip to the terminals of a step-down transformer whose current may be adjusted by a series resistance. Set the current through the wedge at some steady value, and read the temperature both inside and outside with the optical pyrometer, as nearly as possible at the same point. Repeat the process at another temperature. Is the emissivity of the substance a constant? What might be the effect due to the fact that the transmission glass does not give monochromatic light? Outline some other methods of obtaining the true temperatures. Only a few metals may be heated in this way without the formation of an oxide coating. What is the effect of the oxide coating?

Experiment 3

Object: To study the effect of varying the distance of source and size of aperture upon the reading of an optical pyrometer.

In an optical pyrometer, when properly adjusted, intensity match is obtained between the radiation from the source observed and that from some standard source. In the disappearing-filament type, the filament is placed in the focal plane of the objective so that the energy per unit area per second radiated from the filament and that through the image of the source are made identical. Now, as the source is taken farther away, the objective receives a total amount of energy varying inversely as the square of the distance for small sources. The magnification of a lens varies how with the object distance? Hence, what is true for the energy per unit area in the focal plane of the objective?

Use as the high-temperature source any furnace or standard lamp whose temperature may be maintained constant during one set of observations. A tungsten lamp in a box having a small translucent window makes a satisfactory source. Make readings of the apparent temperatures at distances of ½, 1, 1½, 2, etc., meters. Interpose between the source and the objective a screen with an aperture such that the solid angle subtended by the objective is not filled with radiation at the shortest distance, and repeat the above readings. Sketch apparatus, and explain results.

Experiment 4

Object: The use of the sectored disk to extend the range of an optical pyrometer.

If a disk whose ratio of open space to total space is R be interposed between a high-temperature source and the optical pyrometer, shown in Fig. 59, the radiation received by the pyrometer will be reduced. Hence, that the apparent temperature of the source will be less than its true temperature would follow from Wien's law. Thus

$$J_\lambda' \text{ (with disk)} = c_1\lambda^{-5}e^{-\frac{c_2}{\lambda T_{\text{apparent}}}}$$

$$= RJ_\lambda \text{ (without disk)} = Rc_1\lambda^{-5}e^{-\frac{c_2}{\lambda T_{\text{true}}}}$$

giving
$$\frac{1}{T_{\text{true}}} - \frac{1}{T_{\text{apparent}}} = \frac{\lambda \log_e R}{c_2} = \frac{\log_{10} R}{9{,}880}$$

for $\lambda = 0.63$ micron and $c_2 = 14{,}320$ (22)

Thus, R plays the same role here as emissivity on page 127, and Figs. 51 and 52 may be used to determine the true temperature T if the apparent temperature T_{apparent} and R are known. If R is

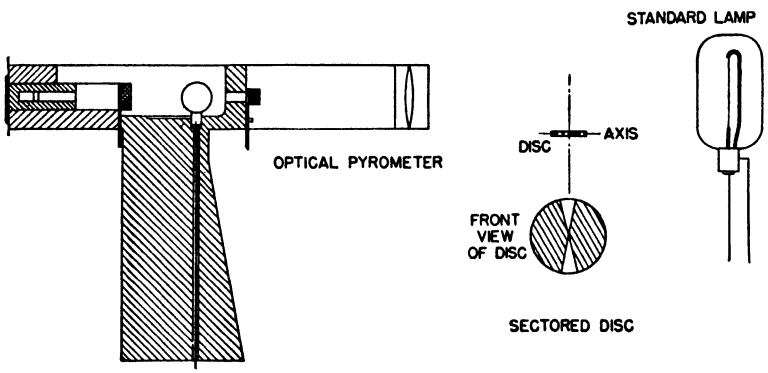


FIG. 59.—Pyrometer with rotating sectored disk and standard source of radiation.

unknown, then any pair of true and apparent temperatures allow the constant value of the right-hand member to be determined, and thereafter any true temperature may be found if its apparent temperature is known.

A pair of similarly slotted disks may be mounted close together on the same shaft so that they may be shifted with respect to each other, giving R any fractional value smaller than one-half. The whole should be rotated at a sufficiently high speed to avoid flickering in the pyrometer. For some particular known value of R, observe the temperature of some constant source with and without the rotating disk in place. Repeat at other temperatures. Is the value of $1/T - 1/T_{\text{apparent}}$ a constant? Explain why it might be expected to change with temperature. What value of R would be necessary to observe the temperature of the sun on an optical pyrometer at 2000°C.? Try it.

EXPERIMENT 5

OBJECT: To measure the coefficient of absorption of a material and study the effect of absorbing media upon the reading of an optical pyrometer.

If radiation travels through an absorbing medium, a certain fraction of it is absorbed in the medium. As was shown on page 117, the amount transmitted I may be related to the amount incident upon the medium by the equation

$$I = I_o e^{-\mu t}$$

where μ is termed the absorption coefficient of the material and t its thickness. Hence, an optical pyrometer sighted upon a high-temperature source through an absorbing layer will receive only I/I_o as much radiation as it should and the apparent temperature of the source will be less than its true temperature. Hence, I/I_o or $e^{-\mu t}$ plays the same part in this connection as R in Eq. (22), and emissivity in Eq. (18), and the true temperature T is related to the apparent temperature T_{apparent} as follows:

$$\frac{1}{T_{\text{true}}} - \frac{1}{T_{\text{apparent}}} = \frac{\lambda \log_e e^{-\mu t}}{c_2} = \frac{-\lambda \mu t}{c_2} = \frac{\mu t}{22{,}730} \qquad (18)$$

where $\lambda = 0.63$ micron and $c_2 = 14{,}320$. Thus, if λ and t are known, the true temperature may be calculated from any corresponding apparent temperature. If these are not known, then any one experiment in which T and T_{apparent} are both observed suffices to evaluate the constant right-hand member of the equation, and the equation may then be used to relate any observed temperature to its true value.

Sight an optical pyrometer upon some constant-temperature source, and observe the temperature. Insert the subject of the investigation, which may be a mica or glass window or a gas layer, and observe the apparent temperature. Repeat with two and three thicknesses of the absorbing material. Does the factor t enter as indicated in Eq. (21)? Now set the temperature of the source at a higher value, and repeat the observations. Express in each case the value of μ obtained. Show in detail how you might extend the range of a calibrated optical pyrometer by means of an absorbing glass. How could you find the true temperature of a furnace when it is necessary to view it always through a mica window?

Experiment 6

Object: To determine the fundamental constant c_2 in the Wien or Planck radiation law.

By resolving the radiation from a hot body with a prism, it would be possible to observe the distribution of energy with wave length and hence the constants in the radiation law. Such an investigation can be carried out only with very elaborate equipment. It is possible, however, to determine this constant with rather simple

apparatus with an accuracy dependent upon a knowledge of the monochromatic transmission of the glass of an optical pyrometer. The same apparatus employed in Experiment 4 as shown in Fig. 59 may be used.

If Eq. (22) is solved for c_2, it follows that

$$c_2 = \frac{\lambda \log_e R(T_{\text{apparent}} T_{\text{true}})}{T_{\text{true}} - T_{\text{apparent}}}$$

Thus, by sighting the pyrometer upon a standard source of temperature, such as a calibrated lamp, the true temperature T_{true} is observed. Now, by interposing a sectored disk between the pyrometer and source the apparent temperature T_{apparent} is noted. The ratio R of open to total space in the sectored disk can be precisely determined. The effective transmission wave length λ of the absorbing glass may be obtained from the maker of the glass. Discuss the accuracy obtainable in the final result for the constant c_2. What are the fundamental dimensions of the quantity?

Problems

1. A Leeds and Northrup optical pyrometer requires currents of 349.3 and 456.2 milliamperes for brightness match at 800 and 1200°C., respectively. What current should be required at 1000 and 1300°C., assuming the scale law of Eq. (8),

$$\frac{1}{T} = \frac{A}{I^{\frac{1}{2} \text{ or } \frac{2}{3}}} + B$$

The actual observed value at 1000°C. is 391 milliamperes. Then what should the value be at 1300°C., using the equation

$$I = a + bT + cT^2$$

2. Why is the difference between the Wien and the Planck laws negligible in optical pyrometry?

3. What relative increase in radiation intensity should be observed at 0.6 micron as the temperature changes from 1000 to 1500°C.? Also at 6.0 microns? What phenomenon does this explain?

4. If, in an F. and F. optical pyrometer, a temperature of 1000°C. requires a setting of 41 degrees (circular measure), and 1400°C. is balanced at 72 degrees (circular measure), what position should be required for a temperature of 1200°C.?

5. In a calibration of a certain Wanner optical pyrometer, a setting of the analyzing eyepiece at 20 is required for a temperature 990°C., and at 1255°C. the setting is 60. What angular settings should be required at 1100 and 1500°C.?

6. If the focal length of the objective lens on an optical pyrometer is 10 inches, what provision should be made for change of focus if the source distance varies from 2 to 30 feet?

7. A certain furnace has an apparent temperature of 1100°C. when measured by an optical pyrometer sighted upon the furnace through a glass window. If an additional window similar to the first is interposed, the apparent temperature is found to be 1060°C. What is the true temperature of the furnace?

8. What is the effective coefficient of absorption of the window material in Prob. 7 if each has a thickness of 2 millimeters.

9. An optical pyrometer sighted upon the inside of a hollow metal wedge reads a temperature of 1450°C.; when it is focused upon the outside, the apparent temperature is 1310°C. What is the emissivity of the metal?

10. The ratio of open to total space in a sectored disk is one-fourth. If an optical pyrometer be sighted through the rotating disk upon a furnace and an apparent temperature of 1500°C. is observed, what is the true temperature?

CHAPTER VI

TOTAL RADIATION PYROMETERS

The Stefan-Boltzmann law was discussed on page 105. It is evident from the simple form of the expression

$$W = \sigma A(T^4 - T_0^4) \qquad (1)$$

that if the energy per second of all wave lengths from any body at the temperature T can be measured, then the temperature is determinable. Devices for comparing the total radiant energies per second from emitting surfaces for the purpose of comparing their temperatures are called "total radiation" pyrometers. Since these radiations always include some energy in wave lengths, both longer and shorter than the visible, they cannot be compared visually. Although they obey the same laws of reflection and refraction as the visible, the absorption may be very different. Substances that are transparent to visible radiation may be completely opaque to the ultraviolet or infrared wave lengths, and vice versa. Thermocouples or photoelectric cells may be arranged to receive the radiation and thus actuate an electrical indicating instrument giving a deflection directly related to the total intensity of radiation.

Féry Radiation Pyrometer.—The first device of this sort was perhaps that proposed by Féry[1] in 1902. This instrument consisted of a telescope arranged with a minute thermojunction in the focal plane of the objective. The terminals of the thermocouple were connected to a sensitive D'Arsonval galvanometer. By first adjusting the eyepiece so that the thermojunction may be seen clearly and then adjusting the objective to bring the

[1] C. Féry, *Compt. rend.*, **134**, 997 (1902).

high-temperature source into proper focus, the hot junction of the thermocouple is automatically brought into correct position.

An objection to an instrument of this sort arises from the fact that the objective lens, if made of glass, absorbs a large part of the radiation incident upon it, especially in the infrared spectral region. Since most of the radiant energy from bodies at temperatures not exceedingly

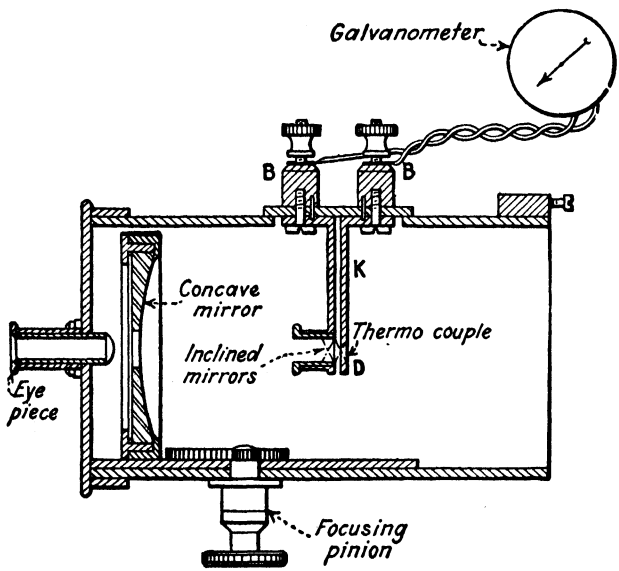


FIG. 60.—Féry total radiation pyrometer.

high lies in the infrared region, the sensitivity of the apparatus is greatly reduced. Further, the fourth-power law or any other simple expression does not apply to the radiation transmitted by the glass lenses. Fluorite (calcium fluoride) has a remarkably small and almost constant absorption coefficient for all wave lengths up to 10 microns and would be a suitable material from which to make the lenses of the instrument. Its use, however, is limited by its expense.

To overcome this objection, Féry[1], in 1904, suggested the use of a concave mirror similar to the astronomical

[1] C. Féry, *Jour. Phys.*, September, 1904.

reflector to replace the lenses. The front surface is made reflecting so that no transmission whatever is necessary. The final complete apparatus as now used in practice is shown in Fig. 60. The radiation is focused upon the hot junction of a thermocouple whose terminals are connected to the galvanometer or millivoltmeter. The cold junction of the thermocouple is shielded from the direct radiation by suitable screens. By means of a rack and pinion screw, the relative position of the hot junction and concave mirror may be changed so as to bring the junction to the focus of the mirror. In order to secure correct focus, a small lens is employed in conjunction with two inclined mirrors. The effect of these mirrors is to give a circular image of the source when in correct position. If not properly focused, the field of view appears as two half circles displaced with respect to each other. Without this arrangement, correct focus would be taken as that position giving a maximum reading of the galvanometer. The area of the opening at the end of the pyrometer tube may be altered by a shutter to certain fixed positions giving as many temperature ranges for the instrument.

The image formed by the objective should be larger than the area of the thermojunction so that the latter is always completely covered with radiation. If this condition is satisfied, the reading of the pyrometer should be independent of the distance between pyrometer and source, since, as the distance increases, the decreased amount of energy received is accompanied by a correspondingly decreased image size so that the energy per unit area in the image is a constant. In practice, however, Burgess and Foote[1] have found that varying the distance does produce a very noticeable effect upon the pyrometer reading. An increase in the size of the image, up to five or six times that of the thermojunction area, was accompanied by an apparent increase in the

[1] G. K. Burgess and P. D. Foote, *U. S. Bur. Standards, Sci. Paper* 250.

temperature of the source. This effect was explained as due to the added heating of the mirror and other parts at the shorter distances, with accompanying radiation from them as radiating sources. There is also the additional effect due to the absorption of the radiation in the air and other gases through which it passes, which would be greater at the larger distances.

The cold junction of the thermocouple is shielded from the direct radiation, and any general temperature changes such as that of the room would change the temperature of both junctions so that the differential effect would remain unchanged, provided the temperature-e.m.f. curve of the thermocouple is a straight line.

Care must be observed that the efficiency of reflection of the mirror is not reduced by the accumulation of dust or other surface coatings. To avoid this, the pyrometer tube should be kept closed except when actually in use, and the mirrors should be cleaned at intervals, following the directions accompanying the instrument. The e.m.f. measuring instrument should have as large a resistance as possible and still be sufficiently rugged.

Scale Law of Féry Radiation Pyrometer.—If it be assumed that the thermocouple of the instrument has a linear relationship between e.m.f. and the temperature difference between hot and cold junctions, and that the deflections are proportional to the e.m.f., then the deflections are proportional to the excess temperature of the hot junction over its surroundings. By Newton's law of cooling, however, this temperature excess is proportional to the rate at which it is radiating heat which is in turn equal to the rate at which it is receiving heat from the high-temperature source. This rate, however, is by the Stefan-Boltzmann law proportional to the fourth power of the absolute temperature of the radiating body. These relations may be summarized as follows:

$$\text{Deflection} = a\ (\text{e.m.f.}) = b(T_H - T_C) = c(T_2^4 - T_1^4) = AT^4 + B \quad (2)$$

where a, b, c, A, and B are constants. Hence, if the above approximations are not in error, a complete calibration of the instrument could be obtained by knowing only two temperatures and the corresponding pyrometer readings. These would suffice for a solution of A and B, and any other deflection could be evaluated in terms of temperature. A convenient way to represent

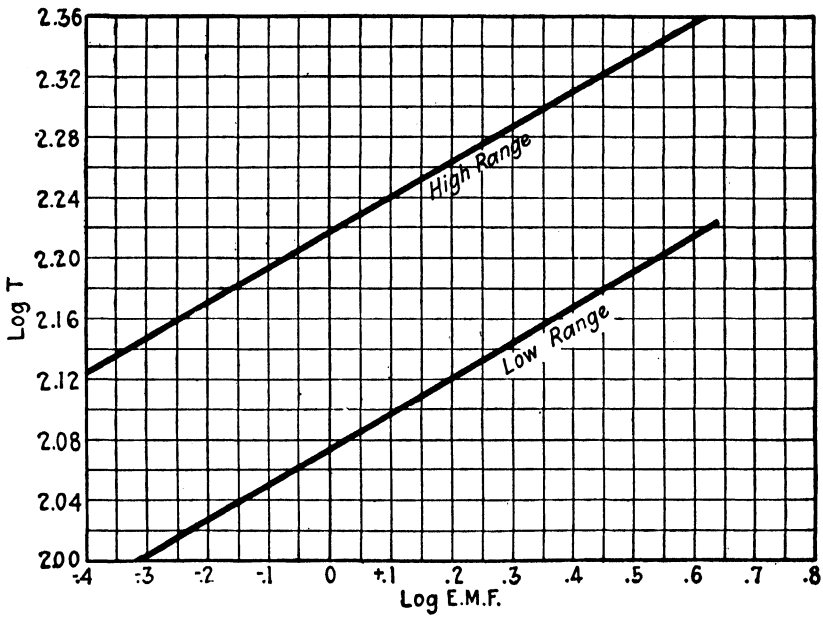


FIG. 61.—Calibration of a Féry total radiation pyrometer.

the calibration would be to plot log (deflection) with log T. This should give a straight line whose slope is 4. The actual values of log (e.m.f.) plotted with log T, as obtained with a typical instrument with two ranges, is shown in Fig. 61. It is observed that the slope of the lines is practically constant, and the average value for $\frac{\log E}{\log T}$ is about 4.25. This value, greater than 4, may be due either to radiation emitted from heated parts of the pyrometer at the higher temperatures or to selective absorption so that the fourth-power law does not apply exactly.

Féry Metal Spiral Radiation Pyrometer.—A modified form of the Féry[1] pyrometer made use of a small spiral coil of metal to replace the thermocouple. The spiral was made of a very light bimetallic strip consisting of two metals having a large difference in their coefficients of expansion. The advantage of this instrument lay in the fact that no galvanometer was necessary, and a pointer affixed to the end of the spiral coil could be made to move over a scale marked directly in temperature. It has the disadvantage, however, of lacking the sensitivity of the thermocouple instrument. Further, the expansion of a metal body depends upon

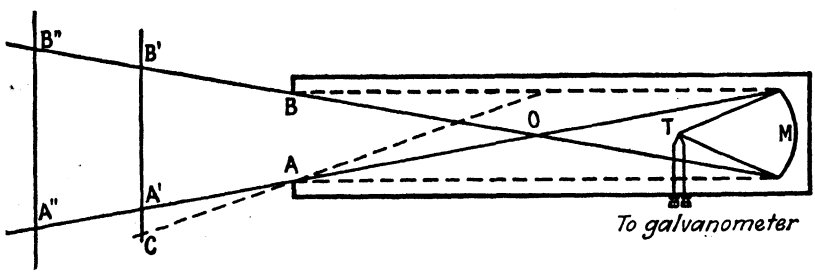


FIG. 62.—Diagram of Foster fixed focus radiation pyrometer.

its previous treatment; that is, it shows a hysteresis effect, and consequently the readings of the pyrometer, when sighted upon a definite source, might be different if the pyrometer has received different treatment previous to the observations. A general heating of the instrument would cause a shift in the zero reading of the pointer unlike the effect for the thermocouple instrument.

Fixed-focus Radiation Pyrometers. 1. *Foster Pyrometer.*—A radiation pyrometer in which it was not necessary to focus the mirror in taking observations was proposed by Foster.[2] This arrangement is shown in Fig. 62. The thermocouple T and the opening of the pyrometer tube AB are placed at the conjugate foci of the concave spherical mirror M. It is evident that if the size of the source is such that it completely fills

[1] C. Féry, *Compt. rend.*, 134, 977 (1902).

[2] C. E. Foster, *Trans. Am. Electrochem. Soc.*, 17, 223 (1910).

the base of the cone $A'B'$, $A''B''$, etc., whose apex is at O, then the energy received at O is constant, regardless of the distance of the source, except for the increased absorption of the air at the greater distance. Regions on the source outside of $A'B'$, etc., can contribute no energy to O, although some energy will enter AB and be absorbed by the blackened walls of the pyrometer tube. Since the energy passing through O is focused upon the thermocouple T, the readings of the pyrometer should be approximately independent of distance. To satisfy this condition, it must evidently follow that the diameter of the source be at least a certain fraction

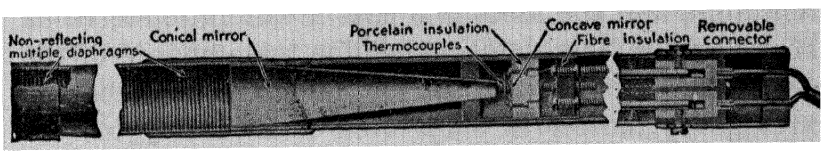


FIG. 63.—Longitudinal section of Thwing total radiation pyrometer. (*Thwing Instrument Co.*)

(usually one-eighth) of the distance between the source and the point O, whose position is generally marked by a wing nut on the side of the pyrometer tube. An attempt is made to ensure that no radiation coming from a point outside $A'B'$, such as C, may reach T by successive reflection. In addition to blacking the walls of the tube, vanes with circular openings at their center are inserted. These vanes prevent any reradiation from the walls of the tube to T, even though they may be warmed considerably by the radiation absorbed by them.

2. *Thwing Pyrometer.*—Another type of fixed-focus pyrometer is that proposed by Thwing,[1] a section of which is shown in Fig. 63. The concave spherical mirror is here replaced by a hollow conical mirror, at the apex of which is placed the hot junction of the thermocouple. As with the Foster pyrometer, the minimum diameter of the source must be equal to the

[1] C. B. Thwing, *Jour. Franklin Inst.*, May, 1908; *Western Electrician*, **41**, 424 (1907).

diameter of the base of the cone whose apex is at O. In practice, the minimum diameter of the source is generally one-eighth that of its distance from O. The vanes prevent radiation from regions outside AB reaching the mirror, and they also prevent reradiation from any warmed part within the pyrometer tube reaching the thermocouple.

To extend the range of pyrometers of this sort to higher temperatures, the pyrometer tube may be replaced by one in which the area of the opening AB is reduced.

Sources of Error in Radiation Pyrometers. 1. *Reflecting Power.*—Most types of radiation pyrometers employ reflectors, and the assurance that a calibration is to be of value at a later date implies the maintenance of the reflecting power of the mirror unchanged. Since the average pyrometer in shop work is favorably located for the accumulation of dust, care must be taken to ensure clean surfaces. The pyrometer tube should be kept closed while not in use, and the mirrors should be occasionally cleaned, following the instructions with the instrument. If the coefficient of reflection of the surface has decreased since its calibration, then the apparent temperature registered will be too low. It follows from the Stefan-Boltzmann law that the ratio of the fourth power of the apparent temperature to the fourth power of the absolute temperature is equal to the coefficient of reflection of the surface. The magnitude of this correction may be demonstrated by assuming values of the reflecting power and the true temperature. Thus, for a reflection coefficient of 90 per cent at 1500°C., the apparent temperature is about 46° too low.

2. *Absorption.*—Since it is very often necessary that the radiation coming to the pyrometer must pass through hot gases and smoke in the neighborhood of the high-temperature source, some of the radiation will be absorbed, and the apparent temperature of the source will be too low. Certain gases, although transparent to

visible radiation, exhibit selective absorption of longer wave lengths to a remarkable degree. A glass window that to visible light offers little absorption is very nearly opaque to the longer wave lengths. Thus, radiation pyrometers cannot be used where radiation from the source must pass through intervening media of appreciable density.

Emissivity.—The total radiation from a heated mass of metal is always less than that from a black body having the same temperature and area of surface. Hence, the apparent temperature of a mass of metal heated in the open, when measured by a pyrometer calibrated for black-body conditions, is generally less than its true temperature. The total emissivity E may be defined as the ratio between the total radiant energy per square centimeter per second from the body under investigation to the total energy per square centimeter per second from a black body at the same temperature. Hence, it follows for the apparent temperature of a nonblack body that

$$E\sigma T^4_{\text{true}} = \sigma T^4_{\text{apparent}}$$

or

$$E = \frac{T_a^4}{T_t^4} \tag{3}$$

As demonstrated on page 132 for the selective emissivity E_λ, so here, also, for the total emissivity E, the inside of a hollow wedge used as a source would emit practically black-body radiation. Thus, the apparent temperature of metals covered with oxide coatings may differ only slightly from their true temperatures. Further, if the metal is in an enclosure, the effect of the wedge may be at least partially obtained so that the apparent temperature may not be greatly in error.

Table I shows the apparent temperature of certain sources when the true temperature is as indicated in column 1:

TABLE I

True temperature, °C.	Apparent temperature, °C.		
	Iron oxide coated	Nickel oxide coated	Copper oxide coated
600	572	495	
700	668	600	590
800	763	705	675
900	858	815	755
1000	953	925	850
1100	1048	1035	
1200	1142	1145	

Range Extension by Variation of Pyrometer-tube Opening.—For extending the range of a radiation pyrometer, provision is generally made for reducing the area that receives the radiation at higher temperatures. The Féry instrument is arranged so that full area, half area, or, indeed, any fraction of the total area may be used. For other types, different-sized openings are affixed to the pyrometer tube to alter the range. If A_1 and A_2 denote any two opening areas, then the temperature T_1 for the smaller area is related to the temperature T_2, with the larger area for the same galvanometer reading as follows:

$$A_1 T_1^4 = A_2 T_2^4$$

giving

$$T_1 = \sqrt[4]{\frac{A_2}{A_1}}\, T_2 \qquad (4)$$

This relationship has been found to be somewhat inaccurate, probably owing to the different amounts of heat being absorbed by the inner walls of the pyrometer tube for the two openings and consequently different reradiations to the thermocouple.

Whipple Closed-tube Pyrometer.—A modification of the Féry pyrometer has been introduced by Whipple[1] in which the pyrometer is placed in the open end of a large fire-clay tube. The other end of the tube is

[1] *Electrician*, **68**, 132 (1911)

closed and may be placed in direct contact with the body whose temperature is to be obtained. This end, when heated, is the source of radiation for the pyrometer. It is evident that a pyrometer of this sort should possess certain marked advantages. No errors would be present through the emissivity of the material of the source, variable distance of the source or absorption of intermediate gases, provided the tube is impermeable to gases. This last condition is, however, difficult to obtain at high temperatures. There is, nevertheless, the possibility that the temperature of the end of the tube will not attain the temperature of the source due to the temperature gradient through the refractory wall. This effect could be largely compensated for in the calibration of the instrument.

Tubes of this sort may often be used to advantage in connection with any type of radiation pyrometer where the heated body is sufficiently large.

The Rayotube.—The idea brought out in the preceding paragraph is used frequently by Leeds and Northrup when installing their recently developed "Rayotube." This is a total-radiation pyrometer wherein the sensitive element is made of a number of fine wire thermocouples connected in series (thermopile) and mounted as the radii of a circle. The measuring junctions are mounted at the center of the circle, the reference junctions being midway between the center and the circumference. With this construction, the measuring junctions and the reference junctions are at the same initial temperature and therefore no reference junction compensation is required in measuring the e.m.f. by means of a potentiometer indicator or recorder.

Two types of this instrument are made, one using a quartz lens and the other a mirror for focusing the radiation upon the sensitive element. Figure 64 illustrates the latter type. The mirror (6) focuses radiation upon the sensitive thermoelement (7). Window (8) is

used to seal the sensitive element from dust, and there is a peephole in the back of the instrument so that it may be sighted on the object. The image of the source

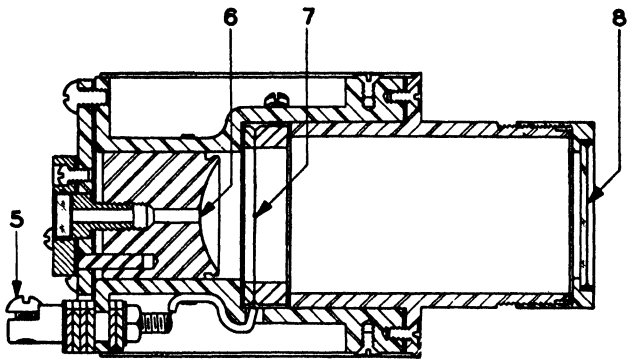


FIG. 64.—Mirror type of Rayotube. (*Leeds & Northrup Co.*)

should completely fill the field of view. In the other type of this instrument, a fused quartz lens is placed between the window and the sensitive element. A

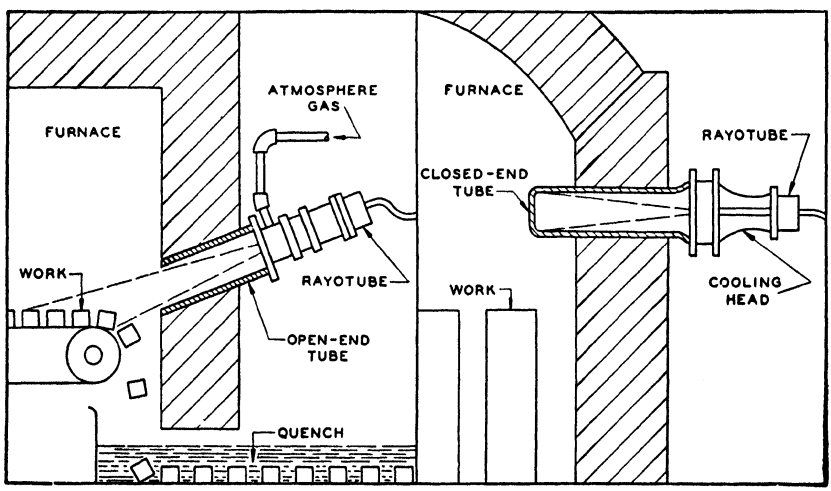


FIG. 65.—Permanent installations of the Rayotube. (*Leeds & Northrup Co.*)

potentiometer is used to measure the e.m.f. in both cases. Figure 65 shows the Rayotube in two types of installation. In (*a*), it is sighted directly upon the work; in (*b*), it is sighted into a closed target tube. This instrument is also available in a portable form.

Pyro Pyrometer.—By using a sufficiently sensitive thermocouple, usually in a vacuum, it is possible to permit a loss of considerable energy as might occur in a refracting lens of quartz and still have adequate sensitivity. Figure 66 is an external view of such an instrument made by the Pyrometer Instrument Co. and offered under the trade name Pyro. The milli-voltmeter, thermocouple, and optical system are all incorporated in a single compact unit thus eliminating all cable connections. The complete instrument is small in dimension and weighs only 25 ounces. To make a read-

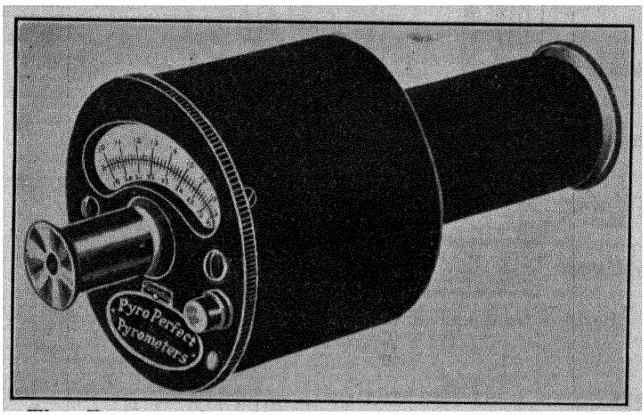


FIG. 66.—The Pyro total radiation pyrometer. (*Pyrometer Instrument Co.*)

ing, it is necessary only to focus the instrument on the heat source, and press the button releasing the indicator. The indicator then swings to the proper point on the temperature scale. By releasing the button, the pointer is clamped in this position, and the reading may be taken after the instrument is lowered from the eye of the observer.

Figure 67 is a longitudinal section of the instrument. The thermocouple is made up of a very thin wire and a thicker supporting wire. An opaque black disk is fastened to the hot junction of the two wires to assist in absorption of the radiations impinging upon it. The hot junction carrying the black disk is mounted in an

evacuated bulb. Radiations enter the barrel of the instrument through the quartz objective lens and are focused upon the hot junction of the thermocouple. By this means, greater e.m.fs. are produced in the couple than is usually the case in radiation pyrometers. The energy of certain wave bands having been absorbed in the quartz, the fourth-power law would no longer apply. The calibration would be carried out at several known

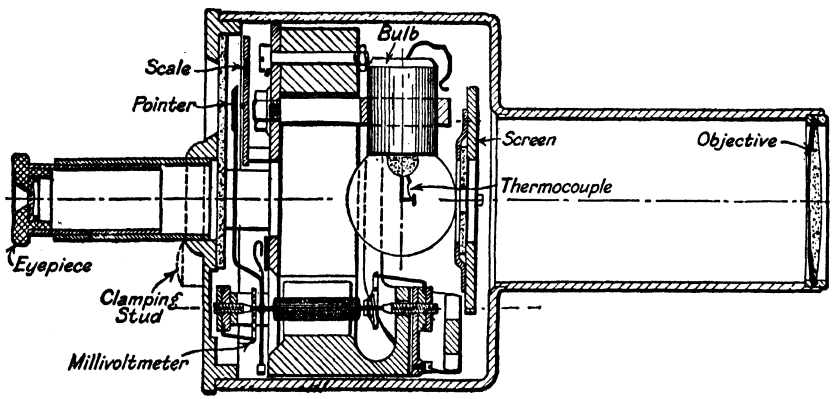


FIG. 67.—Longitudinal section of Pyro total radiation pyrometer. (*Pyrometer Instrument Co.*)

temperatures and the indicating scale empirically marked directly in degrees.

Photoelectric Pyrometers.—The photoelectric effect, originally discovered by Millikan, can be employed to measure radiation intensities. Surfaces coated with various alkaline metals emit electrons when exposed to radiation. By enclosing the active surface in a vacuum and introducing an additional electrode charged positively, the electrons will be attracted, giving rise to a feeble electric current. This photoelectric current may be applied to the grid of an amplifying tube whose output may be read on a meter.

An arrangement of this equipment, as used by W. R. King[1] at the General Electric Company, is shown in Fig. 68. The indication of the meter for a given amount

[1] W. R. King, *Gen. Elec. Rev.*, **39**, 526 (1936).

of energy varies with the wave length of the radiation. The over-all sensitivity, as observed by King, is shown in Fig. 69. The loss in sensitivity at wave lengths

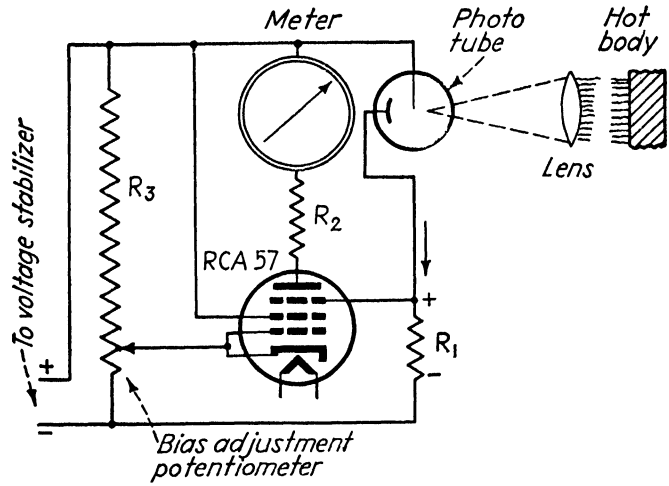


FIG. 68.—Circuit for photoelectric pyrometer.

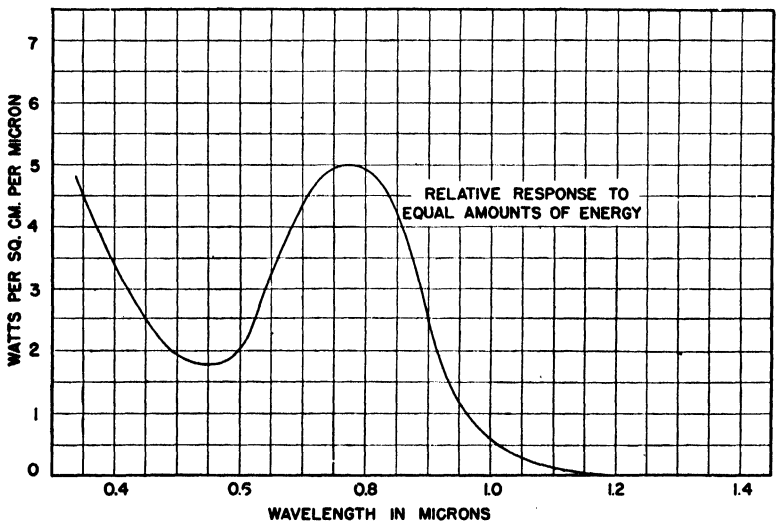


FIG. 69.—Sensitivity of the phototube with change in wave length.

above 0.9 micron may be due to the absorption of the material in the path of the radiation.

It is found empirically that the temperature of the source is approximately proportional to the logarithm of the indication of the meter. Thus, although the

sensitivity of the photocell may change by as much as 10 per cent, the error in temperature is very small for such a change.

Other Radiation Pyrometers.—Radiation pyrometers with specific characteristics have been adapted to particular problems. In the field of biophysics, it is significant to be able to measure the temperature of the human skin. It has been shown that in the infrared region the skin radiates as a black body. At the Russell Sage Foundation,[1] a sensitive radiometer has been devised capable of comparing the surface temperature of the skin with that of a standard source with an accuracy of 0.01°C. This makes use of a silvered conical receiver with a multiple thermojunction, as described by Pfund,[2] at the receiving apex. The electromotive force is balanced with the fall in potential across part of a potentiometer resistance carrying a preadjusted current. The resistance can then be calibrated directly in terms of temperature.

It is not difficult to recognize the advantages that would be associated with a reliable radiometric device capable of accurately indicating the temperatures only slightly above the usual temperature of the surroundings. The ordinary radiation pyrometer becomes insensitive below about 500°C. A black surface at 200°C. radiates about 0.25 watt per square centimeter with the maximum energy at about 6 microns. If this radiation is reflected by crystalline surfaces, certain definite wave lengths are completely reflected, and the remaining radiation may be largely absorbed. By two or more such reflections in succession, only narrow wave-length bands known as "Reststrahlen" remain. A pyrometer making use of the "Reststrahlen" from surfaces of crystalline quartz was described by J. Strong.[3] His

[1] J. D. Hardy and C. I. Soderstrom, *Rev. Sci. Instruments*, **8**, 419 (1937).
[2] *Loc. cit.*
[3] J. Strong, *Rev. Sci. Inst.*, **29**, 520 (1939).

device using five reflections was capable of measuring temperature between −100°C. and +100°C., with an accuracy of .1°C. The energy reflected by the quartz lies principally in two wave-length bands at 9 and 19 microns, respectively. In this wave-length region, surfaces reflect only a negligible amount of energy, so

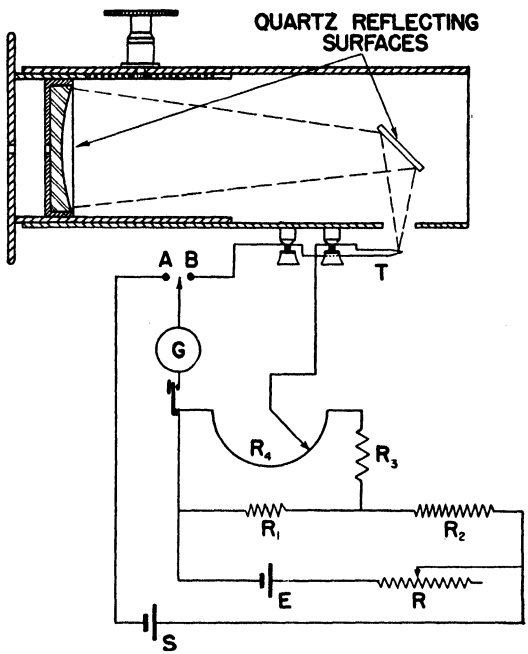


FIG. 70.—Radiation pyrometer with quartz reflectors.

there is no error due to reflection. A modification of this device employing only two surfaces, as used in this laboratory,[1] is shown in Fig. 70. The radiation is focused upon a sensitive vacuum thermocouple through a window of potassium iodide. The electrical circuit, as shown in the figure, employs a standard cell to adjust the current through the potentiometer resistance to the proper value. A high-sensitivity galvanometer is used in balancing the potentiometer.

[1] J. M. Cork, "Temperature Measurement," p. 321, Reinhold Publishing Corporation, 1941.

Experiment 1

Object: To calibrate a total radiation pyrometer and obtain its scale law.

Focus the pyrometer upon some high-temperature source of known value. This may be a furnace containing a crucible of some substance whose melting point is known or a broad metal strip heated by an electric current. The temperature of the strip may be obtained by a calibrated thermojunction, a calibrated optical pyrometer, or the melting point of a small particle attached to the strip. The metal strip should be placed in an enclosure to ensure black-body conditions. The diameter of the heated area should be not less than about one-sixth of the distance to the pyrometer opening. Why?

Féry Radiation Pyrometer.—Making use of the Stefan-Boltzmann law, the scale law for the Féry total radiation pyrometer is shown to be

$$\log (\text{e.m.f.}) = A + B \log T \tag{5}$$

where A and B are constants.

Observe the e.m.f. developed in the pyrometer for several known temperatures, keeping the end of the pyrometer tube completely open. Taking any two of these, calculate A and B. Now solve for some of the other temperatures from the e.m.f. readings. Do the calculated and observed values of T agree? Suggest possibilities for disagreement. Show the observed and calculated values graphically, using log (e.m.f.), and log T as coordinates. Explain the focusing device of the Féry instrument, and state the importance of correct focus. Repeat some of the readings with the pyrometer opening half closed and three-fourths closed. Calculate the e.m.f. that should be obtained for these last readings.

Thwing Total Radiation Pyrometer.—How does the scale law of the Thwing pyrometer differ from that of the Féry pyrometer. Obtain results as outlined in previous paragraph, and check results similarly.

Observe the effect of absorbing media by interposing a glass plate between the pyrometer and high-temperature source. Explain why the effect is so much more noticeable than with the optical pyrometer.

Study the effect of distance by placing the pyrometer successively at increasing distances from the fixed-temperature source. Explain results with a figure.

Would a heated platinum strip give the same apparent temperature in the open as when enclosed? Why?

Experiment 2

Object: To evaluate the fundamental constant in the Stefan-Boltzmann law and to check the fourth-power rule.

A blackened metal sphere may be fitted with an internal electric heating element and suspended in an evacuated enclosure. An arrangement of this sort is shown in Fig. 71. Power P is supplied to the element at some definite known value and the absolute temperature T of the surface of the sphere observed for the condition of equi-

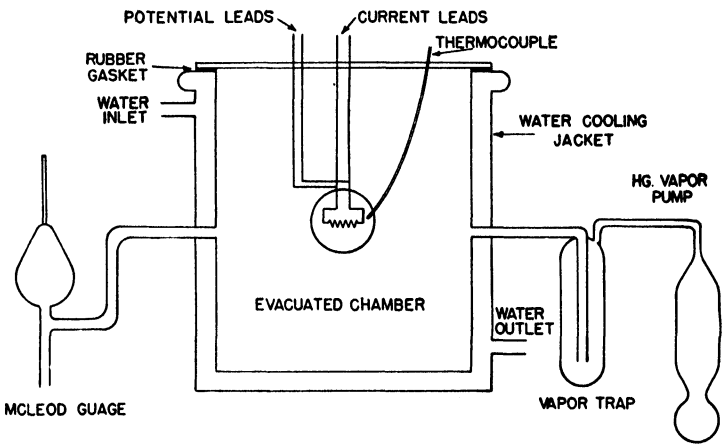


Fig. 71.—Apparatus to determine the constant σ in the Stefan-Boltzmann law.

librium. The temperature T_0 of the enclosure is maintained at a constant value by circulating water. In the condition of equilibrium, the total power P being supplied is also being radiated from the surface of known area A. Hence the Stefan-Boltzmann constant σ is from Eq. 1, page 149, given as

$$\sigma = \frac{P}{A(T^4 - T_0^4)} \tag{6}$$

The chamber may be evacuated by a rotary oil pump in series with a mercury-vapor pump. The pressure can be measured by a McLeod gauge. A rubber gasket suffices for the vacuum joint at the cover of the container. Assuming that the surface radiates as a black body, the measurements of the various quantities can be made with an accuracy sufficient to give a very precise value for the fundamental constant.

The power applied to the heating element may now be set at another value and the new temperature of equilibrium observed. This may be repeated for several temperatures. If these data be

plotted on a $\log T - \log P$ plot, then a straight line of slope 4 might be expected as a locus for the points if the Stefan-Boltzmann law is obeyed. What would be the effect of imperfect evacuation upon the results in each case? What uncertainty usually enters into the determination of the Stefan-Boltzmann constant by other methods? What are the fundamental dimensions of this quantity?

Problems

1. In a Féry total-radiation pyrometer, e.m.f. values of 0.5 and 2.5 millivolts are developed at temperatures of 1135°C. and 1765°C., respectively. What temperatures should correspond to 2 and 3.5 millivolts, respectively?

2. Using the Stefan-Boltzmann law, compare the relative power supply to a furnace to maintain temperatures of 1500 and 2500°C.

3. The normal radiation intensity of the sun at the earth is 1.94 calories per square centimeter per minute. What does this mean for the radiation per square centimeter per minute at the surface of the sun, assuming it to be a black-body radiator? Calculate its temperature.

$$W = \sigma A(T_1^4 - T_2^4)$$

$\sigma = 5.735 \times 10^{-12}$ when W is joules per second.

4. To what temperature would the blackened spherical bulb of a thermometer rise if exposed to the radiation of the sun when the temperature of its surroundings is 25°C.?

5. What daily temperature range might be expected on the equator of the moon? The length of the day on the moon is 28 days.

6. What should be the ratio of the open to the total area in a radiation pyrometer when sighted upon melting palladium 1553°C., in order that the same reading is obtained as when used with the total space open with melting gold 1063°C.?

7. A radiation pyrometer, when sighted upon a molten metal surface, indicates a temperature of 1040°C., and a standard thermocouple gives the temperature as 1150°C. What is the emissivity of the surface?

8. A certain coating of dust upon the conical mirror of a Thwing radiation pyrometer reduces its coefficient of reflection to 95 per cent (for all wave lengths) of the value for which the pyrometer was calibrated. Thus, when the pyrometer reads 1500°C., what is the true temperature?

CHAPTER VII

TEMPERATURE RECORDERS AND CONTROLLING DEVICES

In both the laboratory and the plant, many operations require continuous and permanent records of temperature. In careful experimental work, it is often very helpful to operate a recorder in conjunction with other more sensitive instruments being used to make temperature measurements. In this way, a constant check can be maintained, since any large variance between the two instruments would be immediately evident and the cause investigated. The applications of recorders in plant work are numerous, because any operation or series of operations is made more efficient by the use of permanent records of past performance. In furnace work, it is thus possible to have ready information regarding the work of different shifts, rates of heating and cooling, time at heat, variations while at heat, comparison of fuels, and continuity of operation. In some of the large plants maintaining heat-treating departments, the number of recorders runs into the hundreds.

One of the greatest benefits accompanying the use of pyrometers is the improved control of furnace temperatures. Several methods of control have been used, but the present tendency is distinctly in the direction of automatic control by instruments which may or may not also record temperatures.

TEMPERATURE RECORDERS

Types of Pyrometers Which Can Be Made Recording. All pyrometers can be made at least semirecording, but

the ones that lend themselves most easily to automatic recording are the fluid thermometers, bimetallic strip thermometers, thermoelectric pyrometers, resistance thermometers, and radiation pyrometers.

Fluid Thermometers.—The constant-volume gas thermometer is easily made recording by connecting a registering manometer with the bulb of the thermometer (see Fig. 6). The calibration of this type of recorder is difficult and inaccurate. There are, however, several

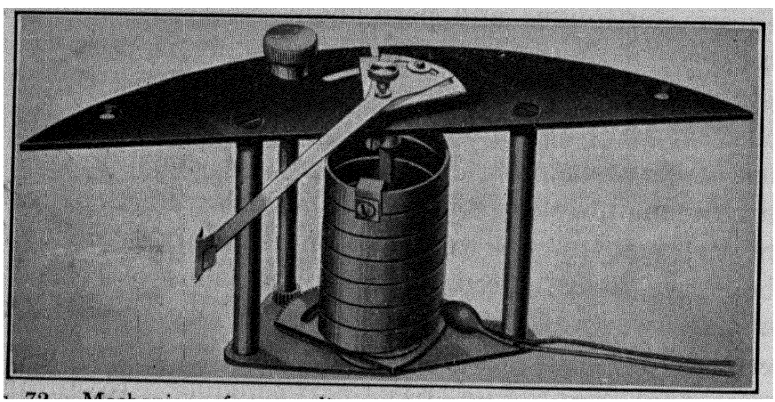


FIG. 72.—Mechanism of a recording pressure thermometer. (*Brown Instrument Co.*)

commercial fluid-thermometer recorders that are being used successfully. The record is made by means of a pressure indicator that carries an inked stylus. The stylus rests against a sheet of paper that moves in either a linear or circular direction. This paper is usually actuated by a clock. As the temperature varies, the indicator carrying the stylus moves back and forth over the sheet, leaving a line that is a record of the variation of temperature with time. Figure 72 represents the indicator mechanism in one of these instruments. As the pressure in the bulb increases, the hollow helical spring opens out, causing the indicator arm to move through a fairly long arc. Figure 73 represents the complete assembly of the recorder, with the stylus drawing a curve on the paper. Figure 74 represents the

bulb of such a recorder installed in a pipe line. This bulb contains the noncompressible fluid, the expansion of which causes the movement of the recorder needle.

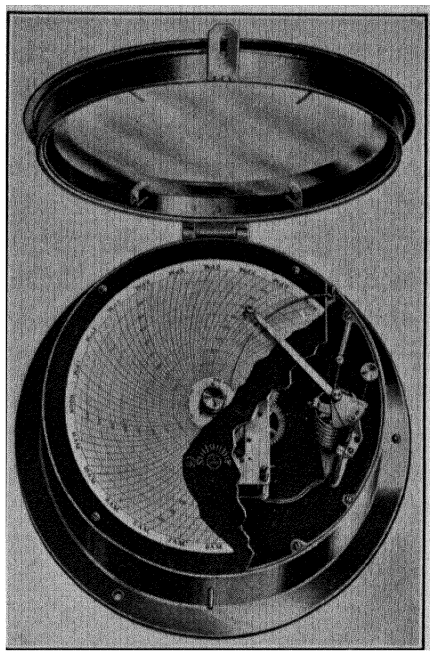


FIG. 73.—Recording pressure thermometer. (*Brown Instrument Co.*)

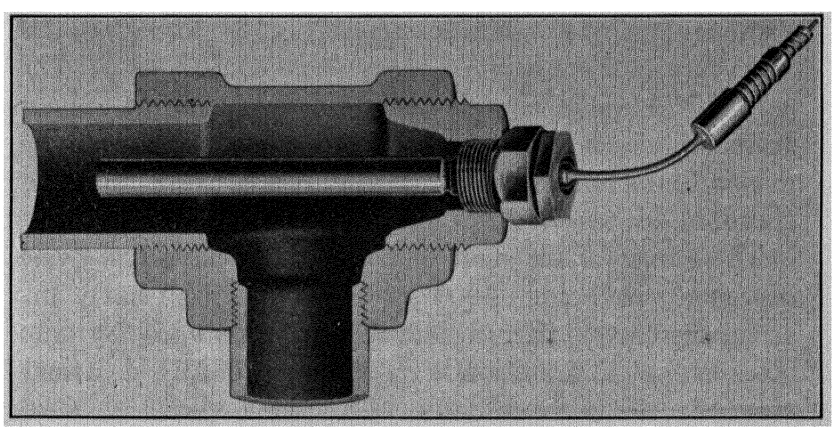


FIG. 74.—Bulb of a pressure thermometer installed in a pipe line. (*Brown Instrument Co.*)

The Bimetallic Strip Thermometer.—A type of thermometer, first used, probably, by L. Breguet, makes

use of the dissimilar expansion of two metals. Strips of the two elements are riveted or fused together along their common broad surface. As the temperature increases, the metal with the larger coefficient of expansion enlarges more than the other, so that if the strip was originally straight it will assume a circular form, or, if circular at the lower temperature, the radius of curvature will alter. This change in radius may result in a relatively large lateral motion for a relatively small change in temperature. Bimetallic strips of invar and bronze, for which the difference in coefficient of expansion $(\alpha_2 - \alpha_1)$ is about $0.000018°C.^{-1}$, as well as other pairs of metals, are widely used in industrial operations.

If L is the original length of a straight element and t the effective thickness, *i.e.*, one-half $t_1 + t_2$, and R is the final radius of curvature for a change in temperature ΔT, then, approximately,

$$R = \frac{t}{(\alpha_2 - \alpha_1)\Delta T} \tag{1}$$

Similarly, the lateral displacement S of one end of the strip, if the other is fixed as shown in Fig. 75, is

$$S = \frac{L^2(\alpha_2 - \alpha_1)\Delta T}{2t} \tag{2}$$

In recorders, the free end may carry a stylus that moves over a temperature chart rotating at a constant angular speed.

The range of all such instruments as have just been described is below 1200°F. Such devices have an advantage over thermoelectric and resistance pyrometers in that their action is independent of any electrical circuits.

Thermoelectric Recorders.—As discussed in Chap. III, two types of indicators are used in thermoelectric pyrometry, the millivoltmeter and the potentiometer. It follows that there are two corresponding types of

recorders. Each type of recorder is subject to the same limitations as the indicating instrument from which it was developed.

The records made by these instruments are time-temperature curves and in the millivoltmeter type of recorder are made by periodically impressing some sort of mark upon a paper that is traveling in either a linear

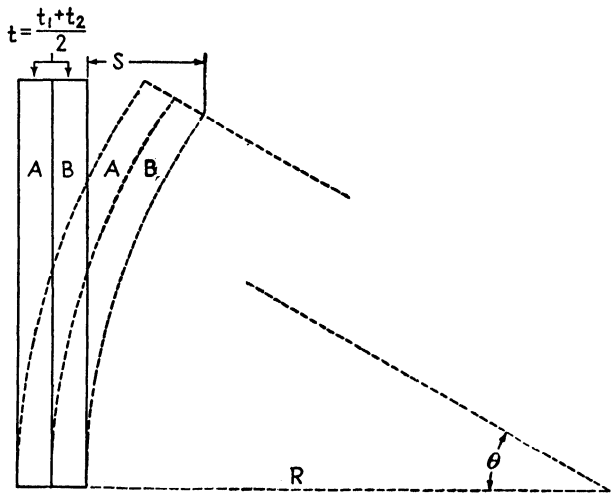


FIG. 75.—Lateral displacement of bimetallic strip on heating.

or circular direction. The potentiometer type of recorder may draw a continuous curve. If a circular record is made, the time between renewals of the paper is shorter than when a continuous roll chart is used. Circular record sheets are usually replaced every 24 hours; a roll chart will last much longer. The record for each day may be torn off and filed, if desired.

The Millivoltmeter Recorder.—Figure 76 illustrates in a simple manner the fundamental operations of this type of recorder. *P* is the record paper that is caused to pass gradually forward or downward under the galvanometer needle *N*. *N* carries some sort of stylus. *B* is a depresser or chopper bar that, at stated intervals, is caused to move against the needle *N*, carrying it into contact with the paper. In some cases, the stylus

carries ink and thus leaves a dot upon the paper directly. In other cases, the stylus merely causes a contact between the paper and an inked ribbon or thread. A series of dots that are so close together as to give the appearance of a continuous curve is thus formed. The operation is necessarily intermittent, since the needle must be given an opportunity to swing freely to its proper indicating positions. The chopper bar is actuated in some cases by clockwork; in other cases, by an electric motor or an

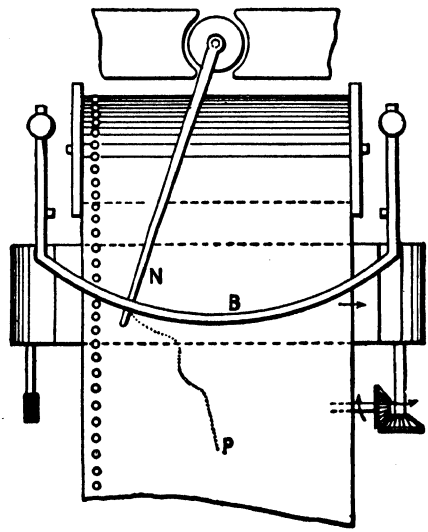


FIG. 76.—Millivoltmeter recorder with roll chart.

electromagnet. In any event, the mechanism must work in such a manner that no damage is done to the galvanometer coil mounting. This means that the construction must be somewhat more rugged than in portable indicators. Usually the resistance of a recorder is a little less than that of an indicator of the same type, and the magnetic flux is increased by using stronger magnets.

It is possible to produce more than one record on the same recorder. This is accomplished by introducing an automatic commutating switch into the instrument. By this means, several thermocouples may be con-

nected in succession to the recorder. As each couple in turn is connected to the instrument, the needle swings to its new position and leaves a dot or dash. It is rather difficult sometimes to distinguish similarly formed records, and in order to eliminate this, several features have been introduced. In some instruments, different colored ribbons or threads are used, each one being brought into position by the movement of the commutating switch. Thus, each record is made in a different color. Another scheme is to vary the time of contact of the stylus with the paper. By this means, several combinations of dots and dashes may be secured.

Figure 77 represents an instrument that makes a circular record. Although this particular instrument is no longer available, it represents the general idea of the operation of such devices. The hours of the day are upon the margin of the paper. The galvanometer needle and chopper bar are suspended in front of the paper. The paper has a smoked surface, and the stylus coming in contact with it leaves a series of white dots. After the removal of the chart from the instrument, the sheet is dipped in a fixing solution that renders the record permanent. Figure 78 is a close-up view of the recording point of a roll-chart type of recorder. The chopper bar, inked ribbon, and galvanometer needle are clearly shown. Arrow indicates index for timing the chart properly. Figure 79 is an assembled view of the recorder mechanism. The instrument is operated by either a hand-wound clock or a synchronous electric clock.

The Potentiometer Recorder.—Readings on a null-point potentiometer are taken by balancing the unknown source of e.m.f. against a portion of a known e.m.f. In a manually operated potentiometer, the observer moves the contact back and forth until the galvanometer shows no deflection, indicating an exact balance between the two e.m.fs. If such an instrument is to be made automatically recording, it is evident that the departure

of the galvanometer from the position of balance must be made to actuate a mechanism that will move the contact point closer to the position of balance.

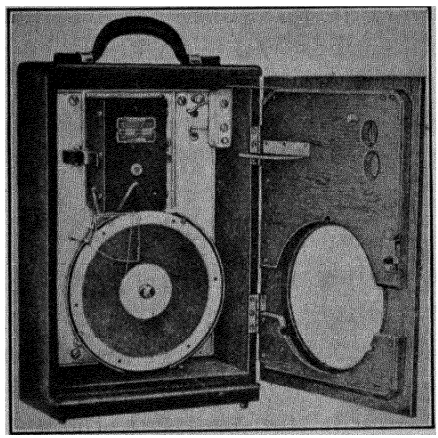


FIG. 77.—Millivoltmeter recorder with circular chart. (*The Bristol Co.*)

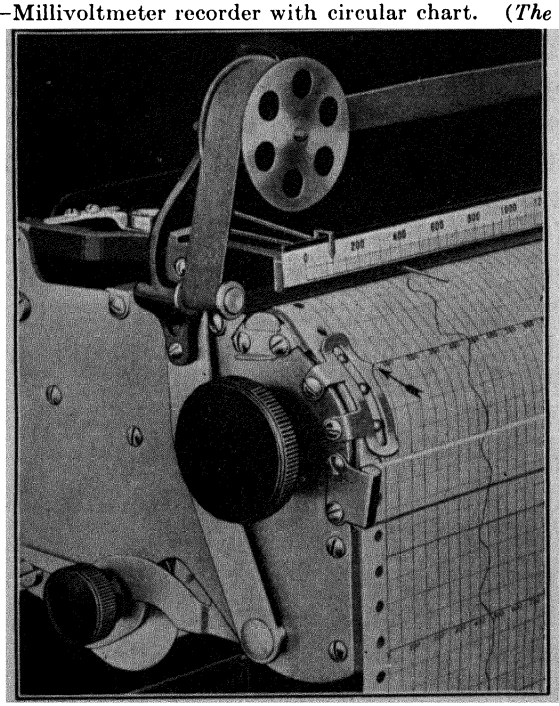


FIG. 78.—Recording point of a roll chart millivoltmeter recorder. (*Brown Instrument Co.*)

Figure 80 represents the wiring in the measuring circuit of a potentiometer recorder. It is of the split-circuit

type, as is evident from the diagram. The checking of the main battery current against the standard cell is accomplished by closing contact H and adjusting rheostat R. This may be done manually or auto-

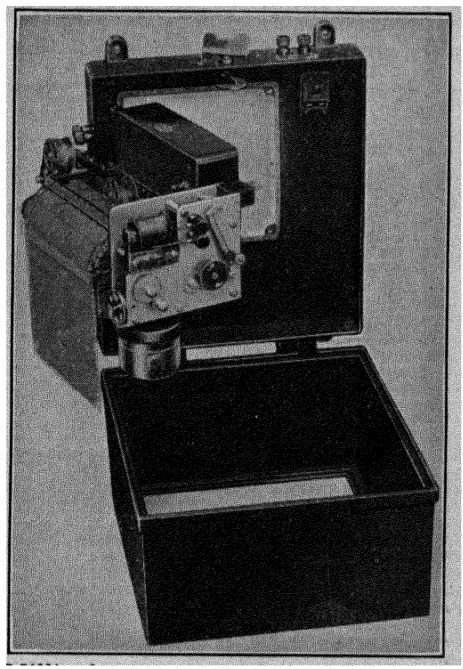


FIG. 79.—Millivoltmeter recorder. (*Brown Instrument Co.*)

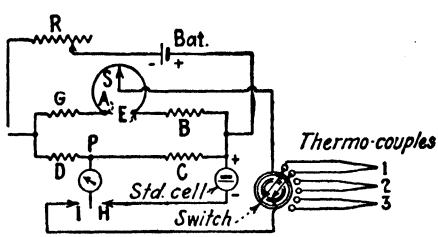


FIG. 80.—Measuring circuit of a potentiometer recorder. (*Leeds and Northrup Co.*)

matically, as will be brought out later. The deviations of the galvanometer from its zero position cause the contact S to move to such a position that the galvanometer will be balanced. The movements of point S are translated into a linear movement of an inked stylus across a roll of paper that is moving in a direction perpendicular to that of the stylus.

Figure 81 is the front view of such a recorder in operation. The panel at the left inside the case carries a push switch (at bottom of panel) and the rheostat for manually checking against the standard cell. This check should be made at least once a day when the instrument is in continuous operation. In the center is

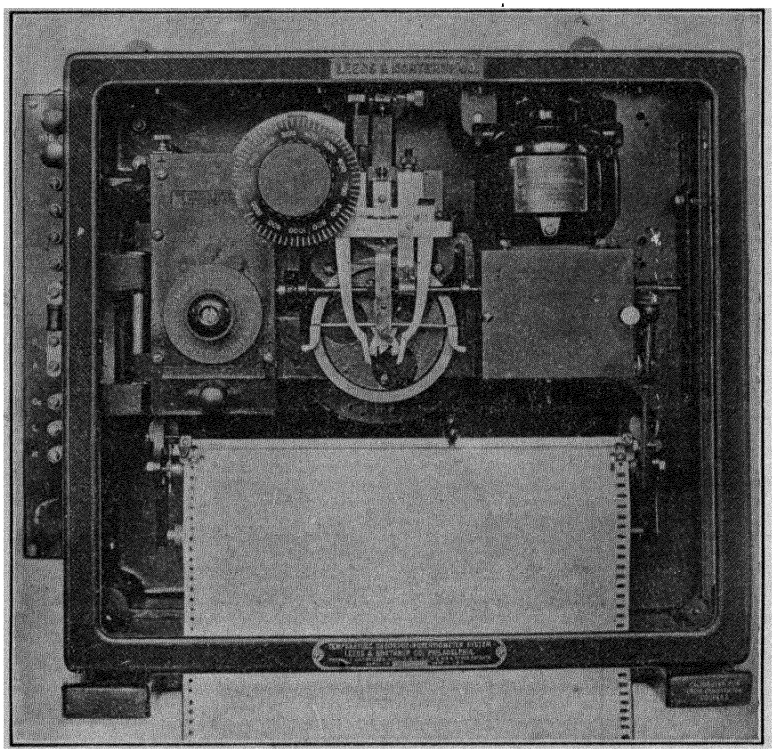


FIG. 81.—Potentiometer recorder—Front view. (*Leeds and Northrup Co.*)

found the balancing mechanism, and at the right is the small electric motor with speed governor that operates the balancing mechanism. At the bottom of the case is the chart upon which the record is made. The chart is gradually unrolled at a constant speed by means of a gear train from the motor shaft, thus causing a line to be drawn by the inked stylus whose point is resting on the paper.

The operation of the balancing mechanism will be described in detail. Disk 1 in Fig. 82 is mounted on the

same shaft as the disk that carries the slide wire AE in Fig. 80. This disk with slide-wire and its contact are shown in Fig. 83, which is a diagrammatic view from the rear of the instrument. Around this slide-wire disk passes a violin string to which the pen carriage is fastened. The position of the violin string and the manner in which it causes the pen carriage to move back

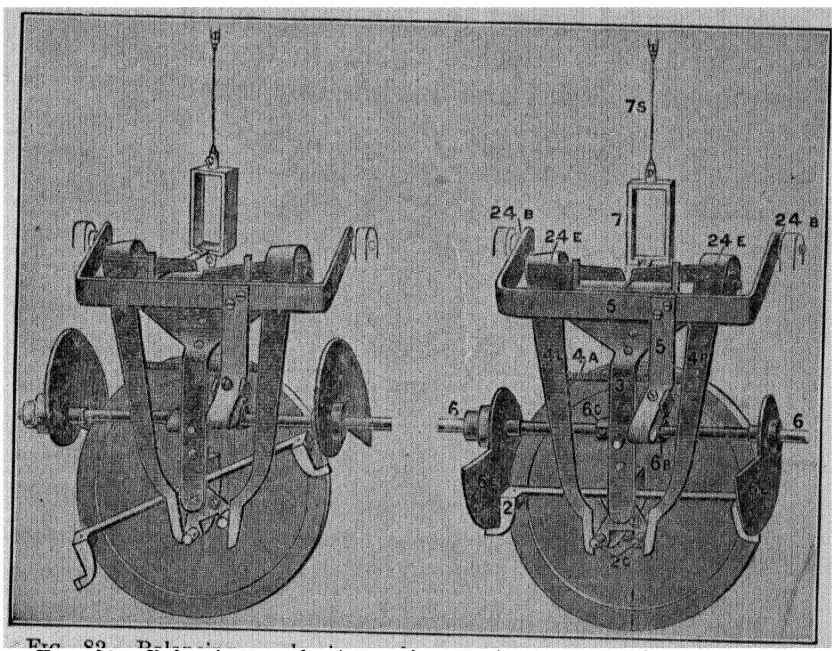


FIG. 82.—Balancing mechanisms of potentiometer recorder. (*Leeds and Northrup Co.*)

and forth are evident from Fig. 83. Any movement, therefore, of disk 1 on the front of the instrument will cause the slide-wire disk to move. This, in turn, will change the position of the contact and the pen. Referring to Fig. 82, it is seen that the galvanometer swings in a slot over rocker arm 5 and under the right-angle levers $4L$ and $4R$. When the galvanometer is balanced at the mid-point of its arc, the needle is directly under the open space between the ends of the right-angle bars $4L$ and $4R$, which are pivoted at $24E$. In this position, the rocker arm 5, in rising, will lift the point of the

needle into this open space, and no change in the position of the other parts will occur.

Shaft 6 carrying cams 6*E* is driven by the motor and rotates in such a direction that cams 6*E* are always tending to bring bar 2 to a horizontal position. Bar 2 carries at each end on the inner side a cork pad that rests tightly against the outer rim of disk 1, unless pushed forward against the tension of spring 3 by cam 6*C*. Spring 3 is attached rigidly to the frame of the instrument. Rocker arm 5 is lifted by cam 6*B*.

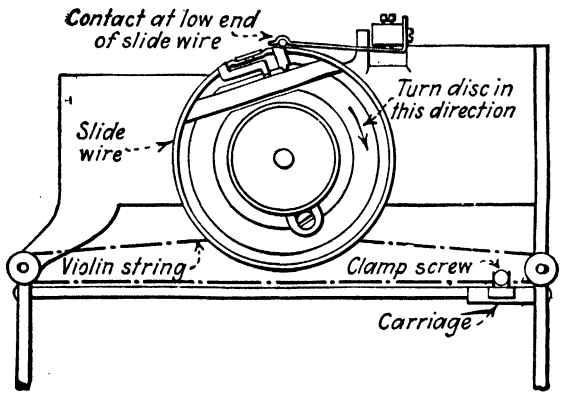


FIG. 83.—Slide wire disk with contact. Potentiometer recorder. (*Leeds and Northrup Co.*)

The movements in the mechanism caused by a swing to the left of the galvanometer needle will now be considered in order. A swing to the right causes the same movements, only in the opposite phase. Rocker arm 5, lifted by cam 6*B*, lifts the needle against the right-angle arm 4*L*. The lower arm of 4*L* is thus moved to the right, carrying lug 2*C* with it. Lug 2*C* is fastened securely to bar 2, the whole assembly being free to turn about an axis above the contact point of 4*L* with 2*C*. This contact was made while bar 2*C* was out of contact with disk 1. The whole mechanism is now in the position shown at the left in Fig. 82. Cam 6*C* now moves down, allowing the cork contacts of bar 2 to rest against disk 1. Cams 6*E* come around and force bar 2 back to

the horizontal position. Bar 2 being in close contact with disk 1 is turned in a clockwise direction. This moves the sliding contact on the back of the instrument nearer the position of balance. The operation is repeated until the galvanometer needle is not deflected but merely lifted into the space between arms $4L$ and $4R$. The pen has then been moved to the point on the chart that indicates the correct temperature or millivoltage.

The amount of rotation given to arm 2 and disk 1 depends on the extent of the galvanometer deflection, since the needle approaches the fulcrum of the lever as the deflection increases. Ordinarily, the rebalancing steps of the recorder pen vary by uniform gradations from $\frac{1}{50}$ to $\frac{3}{4}$ inch. Thus, large variations may be followed rapidly and small ones accurately. The rotation of the shaft 6 takes about 2 seconds, which gives ample time for the galvanometer to assume its new position after being released by rocker arm 5. The full scale of the instrument may be varied from 10 to 80 millivolts by the use of suitable shunts. If temperature alone is indicated on the scale, the calibration is made according to the temperature-e.m.f. relation of the particular thermocouple to be used.

In some cases, the standard cell check is made automatically. It is then necessary to place on the main shaft a disk that carries resistance R in Fig. 80. At stated intervals, a commutating switch breaks the contact s at points S and H and closes those at points R and I. Movements of disk 1 (Fig. 82) then result in varying the resistance in the battery circuit until the standard cell is correctly balanced.

The instrument can be made to record the temperatures indicated by more than one couple by introducing a commutating switch and a mechanism for depressing and lifting the print wheel from the paper. The commutating switch connects each couple with the

instrument for a period of time, long enough for the print-wheel carriage to be brought to its proper position and a record made. The print wheel revolves in synchronism with the commutating switch so that when it is

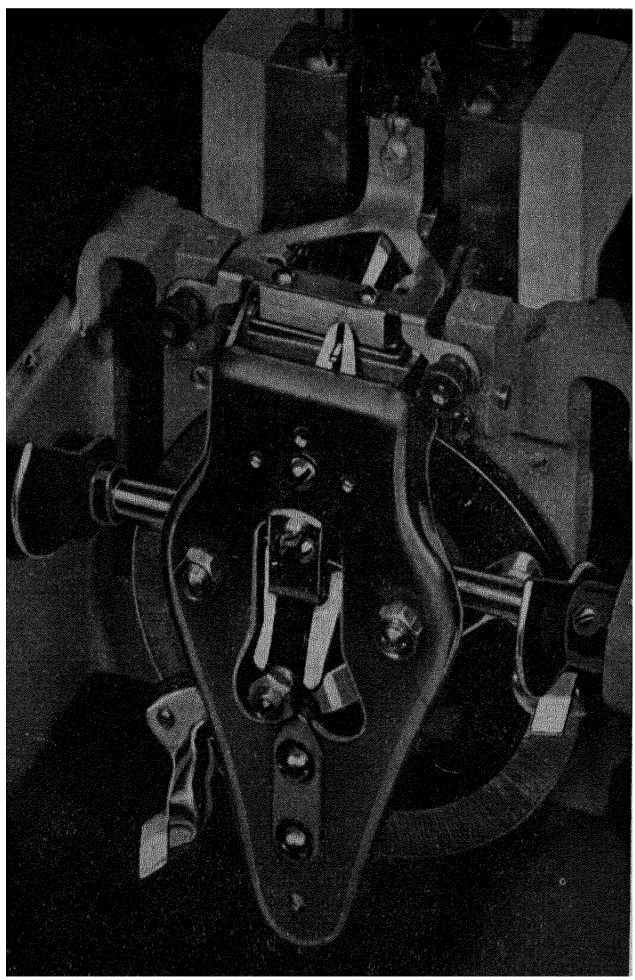


FIG. 84.—Balancing mechanism in Micromax recorder. (*Leeds and Northrup Co.*)

depressed the record on the paper consists of the number of the thermocouple and a large dot. The line of dots thus formed is the record of the variations of that particular thermocouple. The print wheel and the commutating

switch are actuated by a gear train from the motor. The print wheel is inked by a pad that is constantly in contact with it. This pad must be saturated with ink every few days.

Recently the mechanism that has just been discussed has been redesigned. Since many thousands of the older type of recorder are still in daily use, it seemed desirable to retain the foregoing discription of it.

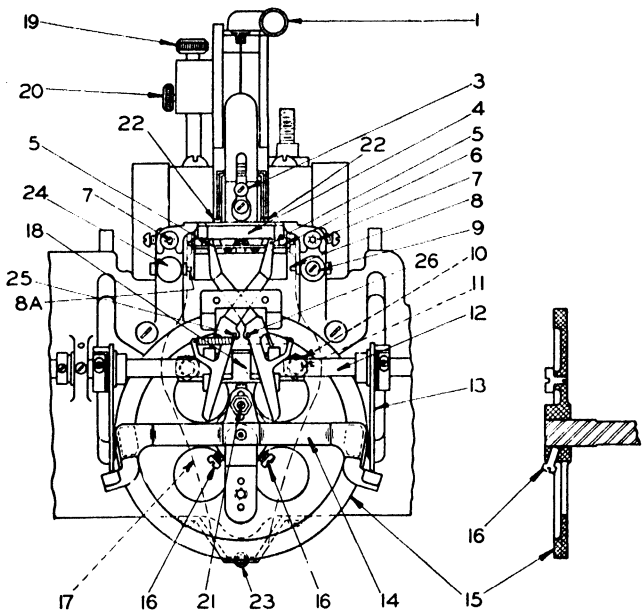


FIG. 85.—Diagram of balancing mechanism of Micromax recorder. (*Leeds and Northrup Co.*)

The newer mechanism termed "Micromax," now used by Leeds and Northrup Company for their recording instruments, is illustrated by Figs. 84 and 85. Comparison with the older mechanism indicates that the principle of operation of the two is very similar, the main difference being that there is no dead space through which the galvanometer pointer must swing in the redesigned instruments before the mechanism operates.

Figure 84 is a photograph showing the actual appearance of the new mechanism. Figure 85 shows the same

thing, with the head 17 designated with dotted lines to show the operating cams and levers. The following description refers to the numbers in Fig. 85.

The balancing mechanism completes a single cycle of operation in approximately 2 seconds. All power is obtained from a motor-driven camshaft 12. The cycle begins with cam 13 mounted on shaft 12 in the position shown and revolving into the page. At this point, the bottom of the head 17, which is pivoted at 8 and 8*A*, is held slightly forward by cam 18, mounted on shaft 12, pushing on fiber-bearing surface 11, mounted on head 17, with a duplicate bearing shown on the left. In this position, arm 14 is free to rotate about its pivot point, which is located just below pin 21. The positioning levers 5 that are pivoted at 25 and 26 are held by cam 18 in the position shown. Clamping spring 6, in the position shown allows the galvanometer pointer to swing freely in the space between spring 6 and clamping bar 4, which is held rigidly in position by screws 7 and 3.

Camshaft 12 and cams 13 and 18 rotate from the starting position, and cam 18 lifts the clamping spring 6 so as to clamp the galvanometer pointer, in its deflected or undeflected position, tightly against bar 4. Cam 18 then releases the positioning levers 5, which are pulled together by the springs shown just below pivot points 25 and 26 and which extend from the arm of one lever, as shown, to the similar arm on the other lever. The positioning levers then close on the galvanometer pointer and at the same time on pin 21. If the galvanometer pointer is in the undeflected or zero position, no force is exerted by lever 5 on pin 21, and there is no tendency to rotate arm 14 about its pivot point. If, however, the galvanometer pointer is deflected either to the right or left, a horizontal force is exerted on pin 21, causing rotation of arm 14, an amount proportional to the amount of galvanometer deflection. Thus, if the poten-

tiometer or bridge is far off balance, a larger corrective action is made than if only a slight unbalance exists.

As shaft 12 and its associated cams continue to rotate, cam 18 spreads the positioning levers 5, releases galvanometer pointer clamping spring 6, and then releases head 17. This action leaves arm 14 in either its horizontal or deflected position and permits spring 23 to pull the head 17 and arm 14 toward clutch disk 15 until the corks shown by dotted lines on arm 14 are in friction contact with clutch disk 15.

Cams 13 continue to rotate and restore arm 14 to its horizontal position if it has been deflected, at the same time turning the clutch disk 15 and the balancing slide-wire that are mounted on a common shaft in a direction to rebalance the bridge or potentiometer. If the instrument had been originally balanced, *i.e.*, with no galvanometer deflection, there would have been no repositioning action, since arm 14 would already have been at its horizontal position. This action completes the cycle, and a new one begins again by continued rotation of the camshaft.

Figure 84 shows the galvanometer in a deflected position and the clutch arm rotated from its horizontal position. At this point in the cycle, the mechanism has just positioned the clutch arm and will next spread the positioning levers as described above.

Photoelectrically Controlled Recorders.—Photoelectric cells have now been generally adopted in the technique of stabilizing an electric current or potential. Similarly, a temperature recorder and controller designed[1] and manufactured by the C. J. Tagliabue Mfg. Co. makes use of a photoelectric cell to effect the balance of the potentiometer. In this instrument, as in all potentiometers, the galvanometer is the primary controlling element. In this case, however, a beam of light

[1] C. O. Fairchild and V. L. Parsegian, *Rev. Sci. Instruments*, **9**, 422 (1938).

reflected from a mirror on the galvanometer takes the place of a metal pointer. The beam of light from the galvanometer, in moving on and off the plate of a photoelectric tube, operates relays. The relays, in turn, control a reversing motor that drives the moving contact of the potentiometer toward the balance point.

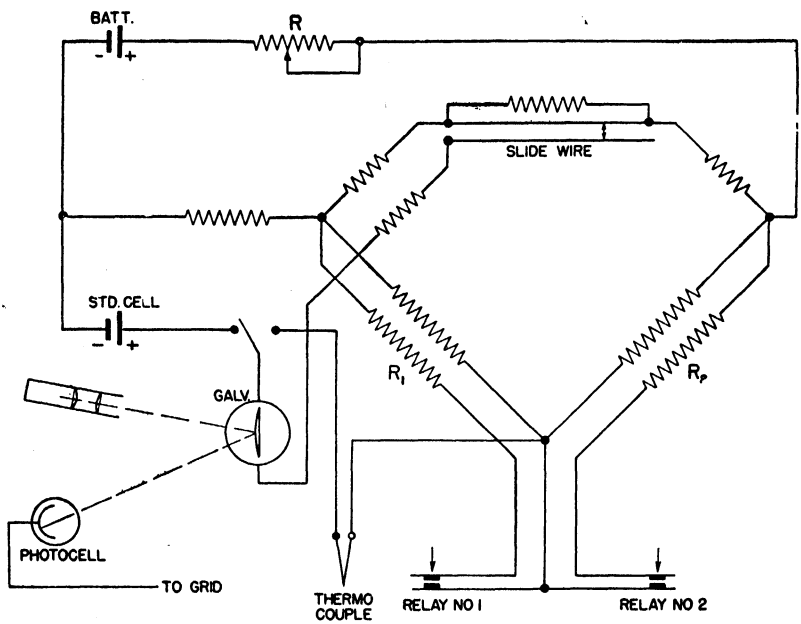


FIG. 86.—Potentiometer with photoelectric control. (*C. O. Fairchild and V. L. Parsegian.*)

A schematic arrangement of the potentiometer circuit is shown in Fig. 86. The two relays shown are designated as No. 1 and No. 2 and are connected in series in the plate circuit of a three-electrode vacuum tube. Relay 2 actuates on a higher value of current than relay 1. The output of the photoelectric cell is applied to the control grid of the vacuum tube and thus determines the plate current through the relays. The two relays, together with a reversing motor, constitute the balancing power circuit. When both relays are closed, the reversing motor carries the moving contact of the potentiometer downscale, and when both relays are

open, the contact travels upscale. With relay 1 closed and relay 2 open, the motor and contact stand still. The relays thus operate to bring the moving contact accurately to the correct balance point.

The photoelectric circuit consists of a transformer, a phototube, amplifier tube, lamp, the coils of the relays, and certain resistors and capacitances. The last items are required to smooth the half-wave current from the amplifying tube and also to control the operating speeds of the relays. The circuit is so designed that relay 1 can close quickly and relay 2 cannot, and so that relay 2 can open quickly and relay 1 cannot. Thus, when the light beam suddenly swings onto the photocell, relay 1 will quickly close, but relay 2 remains open while the galvanometer stops swinging and the reversing motor stops. Similarly, when the light beam swings suddenly off the photocell, relay 2 opens promptly, but relay 1 does not. It follows that such a circuit can trap the light beam half on and half off the photocell, *i.e.*, split by the "controlling edge" of the screen. In order to permit rapid travel of the moving contact and high sensitivity of the galvanometer, the generated-back e.m.f. of the moving galvanometer is canceled by special connections in the potentiometer. The speed of action of the relays, reversing motor, and galvanometer are such that the moving contact can traverse the full-scale range in 45 seconds and stop accurately within a few hundredths of 1 per cent of the 10-inch scale. Exact balance is then obtained in a few small steps.

Recorders for Resistance Thermometers.—There are two types of recorders for use with resistance thermometers, one employing the balanced and the other the unbalanced Wheatstone-bridge method of measuring resistance (see Chap. IV, Resistance Thermometers). Figure 87 represents the wiring diagram of a recorder using the unbalanced Wheatstone-bridge principle. Switch K' is first placed in the position shown

on the diagram. The rheostat *Rh* is then adjusted until the galvanometer needle is brought to some arbitrary point. Switch *K'* is then swung over to the position indicated by the arrow. In this position, the resistance element *X'* is connected to the bridge with a three-wire-lead compensation arrangement. The galvanometer in the unbalanced bridge then swings to a point representing the temperature in terms of resistance. Any varia-

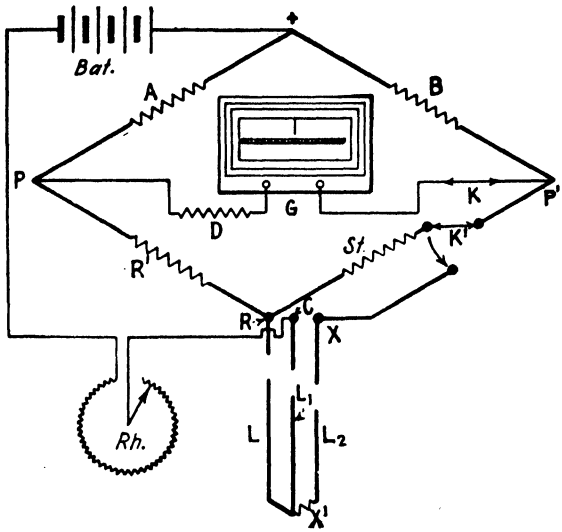


FIG. 87.—Wiring diagram of resistance thermometer recorder using the unbalanced Wheatstone bridge. (*Brown Instrument Co.*)

tion in temperature will be indicated by a movement of the galvanometer. It is possible to construct the instrument in such a manner that the galvanometer will cover any desired range up to about 1000°F. The adjustment of the current described above is made every day or two.

From what has been said in the preceding paragraph, it is evident that the temperature is indicated by a galvanometer needle in precisely the same manner as in the millivoltmeter used with a thermocouple. It is, therefore, possible to record the temperature with the same type of instrument used in thermoelectric recorders of the millivoltmeter type, the principle and operation

of which have been described earlier in the present chapter.

Figure 88 represents the wiring diagram of a recorder using the balanced Wheatstone bridge for measuring resistance. As may be seen, this circuit involves the use of a double slide-wire. All the moving contacts are in the galvanometer or battery circuits and, therefore, cannot affect the accuracy of the measurement. The two slide-wires S and S_1 and the contacts V and V_1 are placed side by side in the instrument. V and V_1, therefore, are made to move simultaneously. The two slide-wires are electrically so proportioned that at all points the resistance A_1V_1 is equal to resistance VV_1, thus keeping the ratio arms of the bridge at unity. As the contacts V and V_1 move, however, the resistance VB varies, and, since VV_1 always equals A_1V_1, the bridge will be balanced when $VC_1 = C_1A_1$, or when the variable resistance VC_1 equals the resistance in the thermometer bulb T. The proper proportioning of lead wires has been previously discussed. By properly calibrating the slide wire S, which makes up the variable section of the resistance VB, the setting will read in terms of temperature at T instead of ohms.

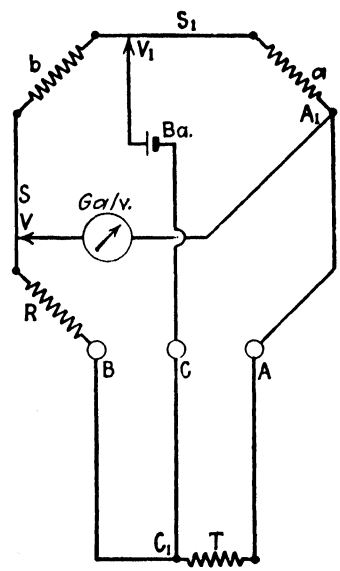


FIG. 88.—Wiring diagram of resistance thermometer recorder using the balanced Wheatstone bridge. (*Leeds and Northrup Co.*)

This kind of measuring circuit can be made recording by the use of an instrument similar to the potentiometer recorder already discussed in this chapter. Slide-wires S and S_1 are mounted side by side on the disk at the rear end of the main shaft (see Fig. 84). The departure of the galvanometer from its balanced

position will then cause the balancing mechanism to turn the disk until a point of balance is obtained. The chart is usually calibrated in terms of temperature and may be made to cover any desired range up to about 1000°F.

Radiation Pyrometers.—Since the readings of total radiation pyrometers are made in terms of e.m.f. developed by sensitive thermocouples, permanent records may be made by the use of either millivoltmeter or potentiometer recorders. The only variation will be in the temperature-e.m.f. relationship, and this is merely a matter of proper calibration.

CONTROLLING DEVICES

The control of furnace temperatures, as herein considered, involves the heating and cooling of the furnace between two points, the interval between which is determined by the requirements of the process. In some cases, it is essential that temperature be held as nearly as possible at a single point. Where this is necessary, the range of variation may be as small as 2 or 3°C. In other cases, a variation of 25°C. may be allowed. In any event, control is secured by alternately increasing or decreasing the amount of heat being supplied to the furnace. It is sometimes accomplished by completely shutting off and turning on the source of heat. In research laboratories, closer control is sometimes required. This is secured by increasing the sensitivity of the controlling device rather than by changing the principle of operation.

Controlling devices naturally fall into two classes: that in which a signal is given the furnace operator and that in which the controlling device automatically makes the adjustments of valves or switches that are required to hold the furnace in a given temperature range. The first class has two divisions, one wherein the signal is given manually to the furnace operator

by a central-station observer and one wherein the signal is given automatically.

Signaling. *Manual Signaling.*—Figure 89 illustrates the central-station equipment for a manually operated signaling system. The indicating instrument—in this case, a potentiometer—is connected to a large number of thermocouples through a selector switchboard. Each thermocouple circuit is equipped with a push-button

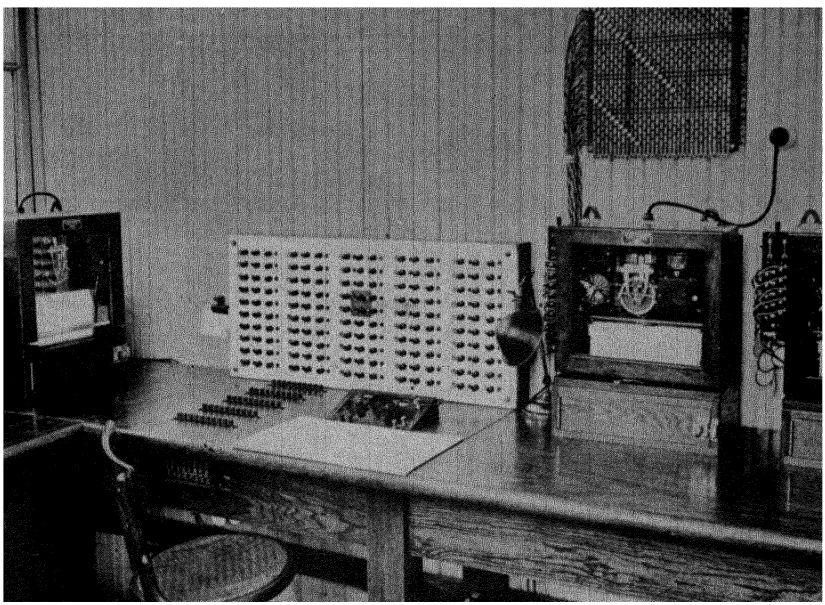


FIG. 89.—Equipment for manual signaling. (*Leeds and Northrup Co.*)

switch on the board, and at regular intervals the central-station operator closes the switches and reads the temperatures indicated. He then, by means of a signaling system, advises the furnace operator of the condition of the furnace. This signal is usually given by means of colored lights, although telephones and pneumatic tubes are sometimes used. An annunciator is occasionally used to enable the furnace operator to advise the station operator that he desires a reading made. Manual signaling has been almost entirely supplanted by automatic signaling and automatic control.

Automatic Signaling.—An automatic signaling system eliminates the central-station operator but not necessarily the central station, since there are advantages in locating all the signaling instruments in one group. Both the millivoltmeter and the potentiometer types of instruments may be made to operate a bank of signal lights automatically.

Figure 90 represents an automatic signaling pyrometer of the millivoltmeter type. Red, white, and blue lights

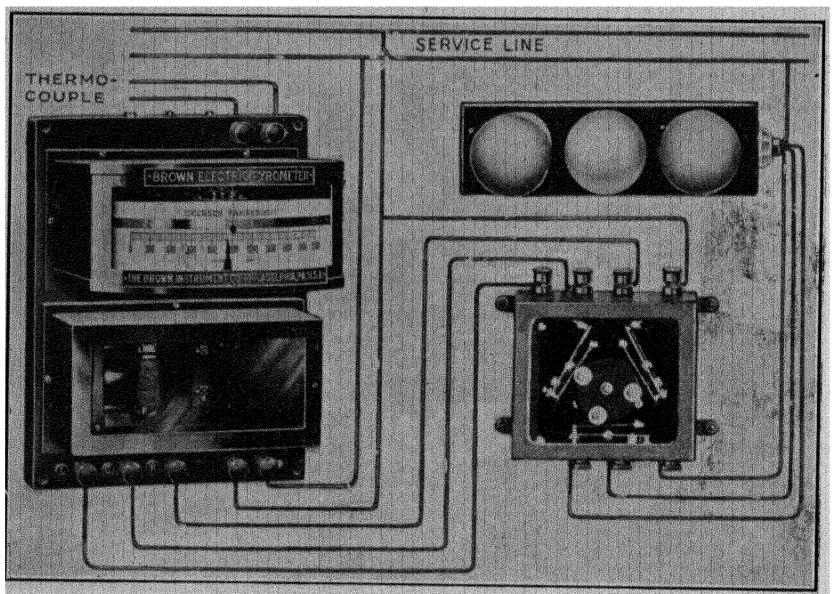


FIG. 90.—Automatic signaling pyrometer. (*Brown Instrument Co.*)

are used. Mounted on an arm that is free to swing across the scale are two sets of platinum contacts that determine the signaling range. This arm is placed in such a position that the point midway between the two sets of contacts is at the desired temperature. As in the case of the recorder, this instrument is equipped with a depressor or chopper bar. At short intervals, this depressor bar pushes down the galvanometer needle. As long as the needle remains nearly at the correct temperature, the white light is on. If the temperature rises or falls slightly, the needle will swing over that

corresponding set of platinum contacts. When it is next depressed, the two points of the contact will be pushed together and thereby close a relay circuit that causes an electromagnetic switch to disconnect the white light and turn on the red or blue light. The range over which the white light burns is, in this instrument, about 20°F., although it may be changed to meet other requirements.

Figure 91 represents the circuits in a signaling potentiometer recorder with deviation meter. The deviation indicator shows in degrees centigrade or Fahrenheit the exact departure of the furnace from the desired temperature. The deviation indicator, as well as the signal lights, are operated by an external circuit, preferably a 110-volt alternating current. The deviation indicator is a Wheatstone bridge, the deviations being given by the deflections of the galvanometer. The disks carrying the slide-wire of this Wheatstone bridge and the contacts for the signal lights all are mounted on the main shaft of the recorder and may be loosened and set for any desired signaling range. As the temperature varies, the balancing mechanism of the recorder rotates the disks, which results in connecting the proper light and causing the deviation indicator to move to the right or left through the unbalancing of the Wheatstone-bridge circuit.

Automatic Temperature Control.—The construction of instruments for automatic temperature control is very similar to that of the signaling instruments. In the latter case, the relays actuate lighting circuits; in the former, the secondary circuit contains devices for changing the position of valves or switches that control the heating units of the furnace. It is probably safe to assert that at the present time nearly all new commercial installations employ automatic temperature control.

Millivoltmeter Control.—Figure 92 is a sectional view showing the construction of a millivoltmeter controller

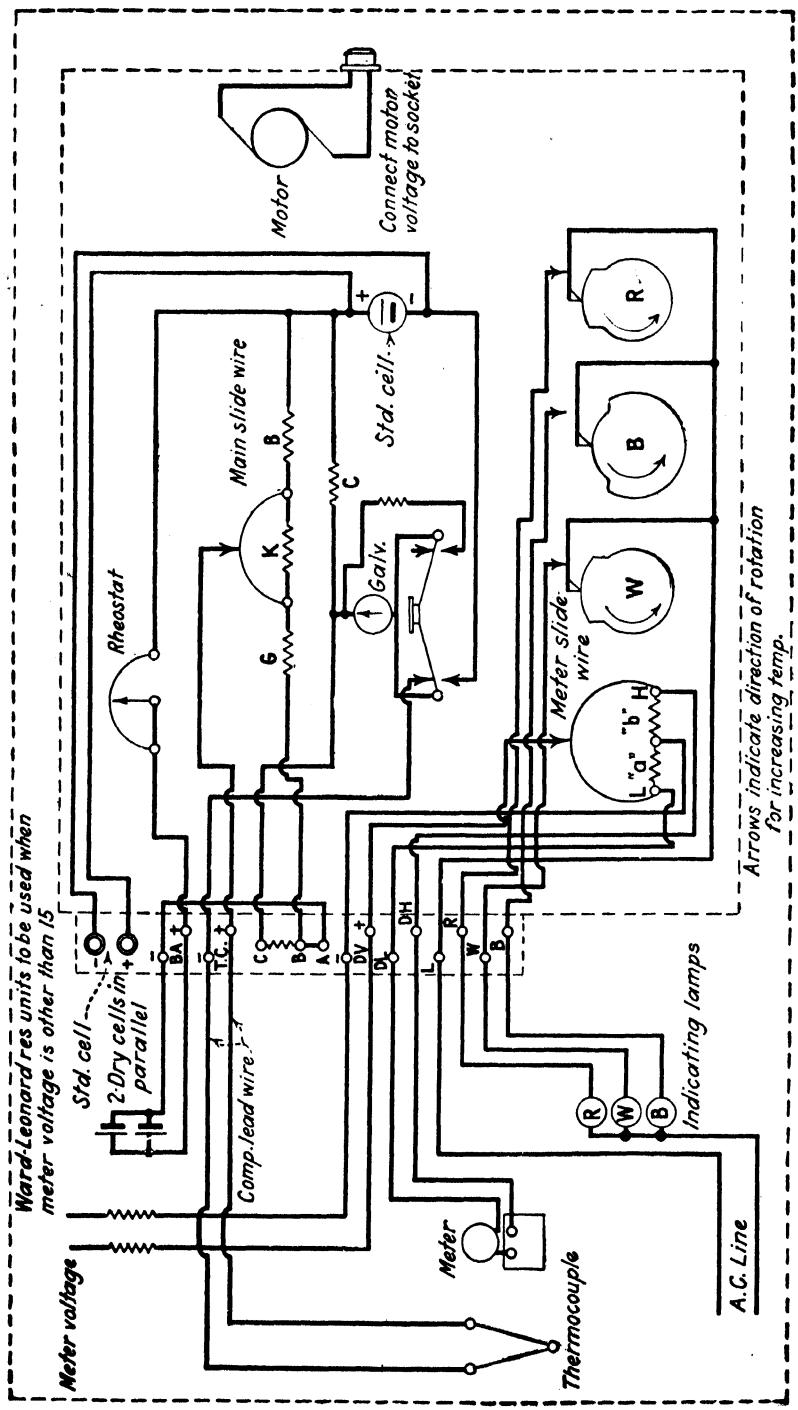


FIG. 91.—Circuits in a signaling potentiometer recorder with deviation meter. (*Leeds and Northrup Co.*)

that is featured by the Brown Instrument Company. In common with most controllers, it may be used with the simple "on-and-off" type of control or with what might be termed the "positioning" type of control. In the first type, the heat source is shut off completely when the temperature of the furnace rises above the control value and is turned on as the furnace drops below this value. In the second type of control, the flow of heat

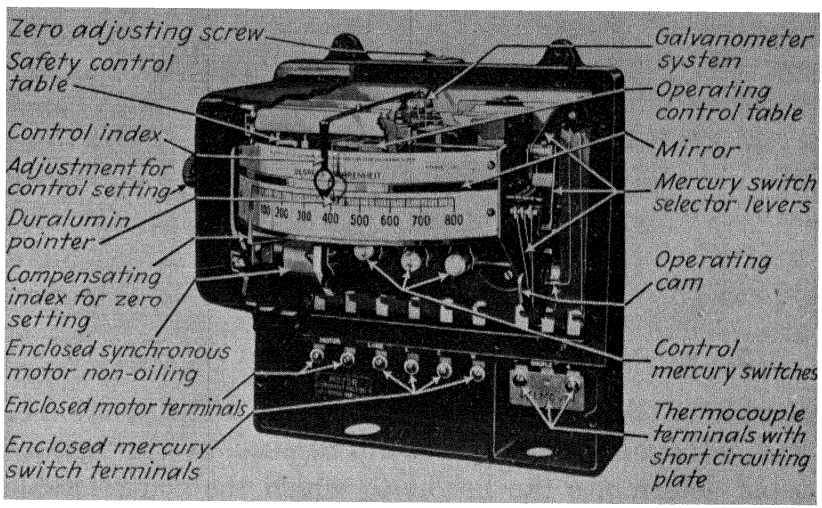


FIG. 92.—Millivoltmeter type of controller. (*Brown Instrument Co.*)

to the furnace is not completely shut off at any time but is adjusted to high or low values as required by the furnace in order to hold it at the desired temperature. The Brown controller may be equipped with one, two, or three tilting mercury switches, one if the "on-and-off" type of control is to be used and either two or three for the other type of control.

The instrument contains a control table to which is attached the control index. This index is a long pointer, the end of which is bent down in front of the temperature scale. By means of a knob on the side of the instrument, the index can be moved to the temperature at which it is desired to maintain the furnace.

A motor-driven cam periodically raises the control table, which, in turn, raises the galvanometer needle against

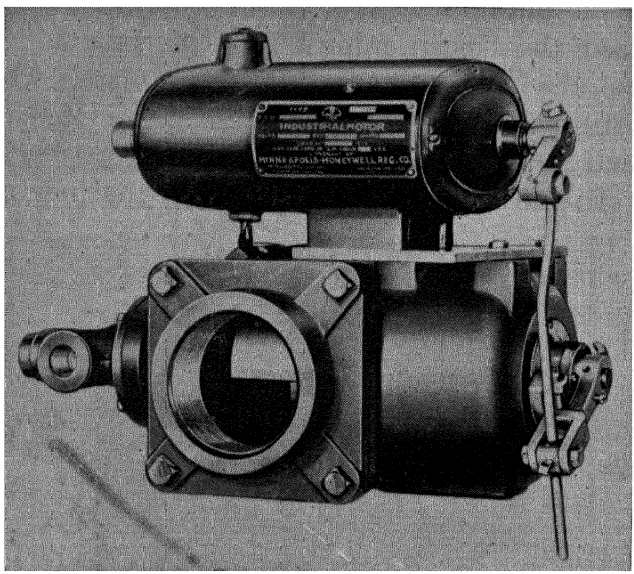


FIG. 93.—Motor operated orifice valve. (*Prowx Instrument Co.*)

the top of the frame of the instrument. The position of the galvanometer needle with respect to the control table determines the height to which the control table can be raised. The height to which the control table is raised positions a secondary pointer that causes a selector lever to release one of three control levers. These control levers tilt the mercury switches, which, in turn, actuate the device for varying the heat input to the furnace.

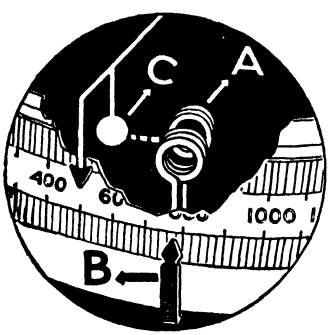


FIG. 94.—Coils and pointer of radio controller. (*Wheelco Instrument Co.*)

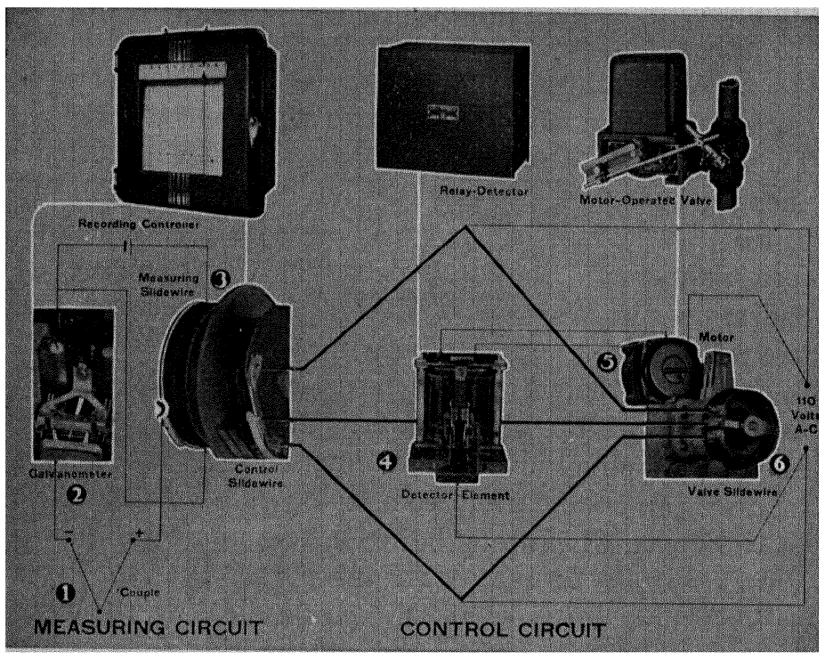
Figure 93 shows a view of an orifice valve that is operated by a small electric motor. Such a valve may be used with any type of controller. It regulates the flow of air, gas, or oil to the furnace. By suitable settings of the cranks and connecting rod the degree of

opening of the valve may be varied over a wide range. The operation of the motor is regulated by mercury switches or other contact devices in the controller, as mentioned in the preceding paragraph.

The Wheelco Controller.—A temperature controller of unique design, shown in Fig. 94, has been developed by the Wheelco Instrument Company. In this device, an index pointer B_1, when set at the desired temperature, carries with it an inductance of two small coils marked A. These coils are in the grid circuit of a three-electrode vacuum tube and are slightly off resonance with the tuned plate circuit of the tube. Now, as the temperature approaches the desired value, the needle of a deflection meter carries a disk of metal between the two coils. The presence of this metal lowers the natural frequency of the grid circuit, bringing it more nearly in resonance with the plate circuit. The increased pickup in the grid circuit because of resonance is sufficient to increase the plate current so as to operate a relay in the plate circuit, which may be made to actuate the power supply to the furnace. The needle of the deflecting meter thus rides free, at all times indicating the temperature, and only an imperceptible motion is necessary to operate the controller.

Potentiometer Control.—Instruments using the potentiometer principle are well adapted to automatic temperature control. It is necessary only to allow the condition of unbalance to actuate valves or switches that control the power input to the furnace. Figure 95 is a composition cut showing the control principle that is used in connection with the Leeds and Northrup Micromax pyrometer. The caption of the cut is of assistance in understanding the sequence of operations. The measuring slide-wire and the control slide-wire are both mounted on the same shaft. When the thermocouple in the furnace registers a slight rise or fall in the furnace temperature, the measuring slide-wire

will be moved to restore balance in the potentiometer. Simultaneously, the control slide-wire will be moved, producing a condition of unbalance in the control circuit which causes relay 4 to close. This energizes reversible motor 5, which will move the fuel value in a proper



❶ Demand changes, causing unbalance in measuring circuit. ❷ Galvanometer deflects to engage Micromax Balancing Mechanism. ❸ Mechanism turns both sidewires as a unit—restoring balance in measuring circuit; causing unbalance in control circuit. ❹ Relay closes, energizing the motor drive. ❺ Motor moves input valve. ❻ Sidewire turns with valve to restore balance in control circuit.

FIG. 95.—Composition view of various parts in a system of a gas- or oil-fired furnace. (*Leeds and Northrup Co.*)

manner to increase or decrease the fuel input to the furnace. Coincidentally with the movement of the valve, slide-wire 6 is moved in a direction that restores the balance in the control circuit, thus completing the cycle.

The valve movement can be adjusted so that the valve will operate over ranges up to fully open and fully closed positions. Of course, the same device can be used to

control electric furnaces by opening and closing switches in the power line or operating electrical equipment that will vary the power input to the furnace. This, in some cases, gives better temperature control than the "open-and-closed" system.

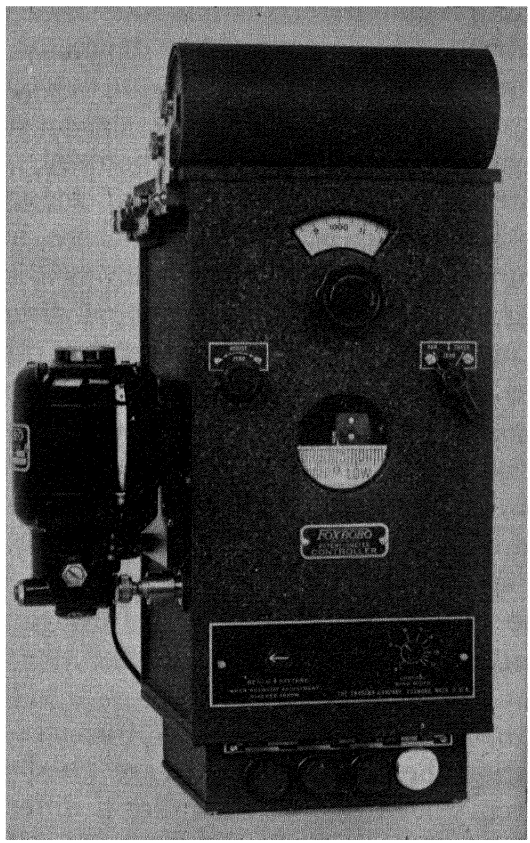


FIG. 96.—Potentiometer controller with stationary contact. (*Foxboro Company.*)

Figure 96 is a controller with a potentiometer circuit featured by the Foxboro Company. In this instrument, the sliding contact is set at the desired temperature by means of the large dial at the upper end of the panel. The galvanometer (whose pointer is seen through the window in center of the panel) indicates departures from the temperature for which the main dial is set.

On the horizontal portion of the pointer, which is immediately above the scale, there is a small rectangular block that regulates the distance through which the depressor bar oscillates. The depressor bar is seen at the right of the galvanometer pointer.

When the galvanometer pointer moves to the "low" side, it obstructs the descent of the depressor, but when on the "high" side, the depressor can descend through its full stroke. This variation in depressor position selects the action of the control mechanism.

For controlling electric furnaces of maximum load not over 65 amperes at 110 volts, these instruments may be equipped with a tilting mercury switch, to which the heating elements may be connected directly. The switch is mounted in a compartment at the bottom of the case. The instrument shown in Fig. 96 is so equipped. An arm carried by the depressor acts as a selective stop to permit or prevent the tilting of the mercury switch by the mechanism, according to the position of the pointer. When the pointer is on the low side, the switch is closed, permitting current to flow to the heating elements of the furnace, and when the pointer moves to the high side, the switch is tilted to the open position.

For controlling gas- or oil-fired furnaces or electric furnaces whose heat requirements are greater than the tilting mercury switches can handle, a different device is used. Fastened to the depressor bar are three control circuit brushes, the upper two or the lower two of which are wiped by contact studs that are mounted on a revolving spindle. The rating of these control circuit brushes is high enough to operate the usual type of motor-operated fuel valves, electric contactor solenoids, and similar control apparatus. When contact is made on the "low" side, the depressor bar does not drop through its complete arc, and contact is made between the lower two control circuit brushes, and the supply of heat

to the furnace is increased. As the temperature rises slightly, the galvanometer moves toward the "high" side, the depressor ball falls to such a position that the upper two of the control circuit brushes are connected, and the supply of heat to the furnace is decreased. An interrupter switch is included in the instrument to prevent the make and break of the current from actually occurring at the point where the brushes and revolving studs make contact.

For throttling control, the depressor bar presses the pointer against a slide-wire, making a contact on the slide-wire at a point determined by the position of the pointer. This slide-wire, together with one located in the valve operating unit, is a part of a Wheatstone-bridge circuit. When the contact created by the pointer is at a position that causes an unbalance of the circuit, a sensitive relay is closed in such a direction as to energize the valve motor. The valve motor not only moves the valve to vary the flow of heat to the furnace but also moves the contact on its slide-wire until balance is restored. The sensitive relay then opens the motor circuit to stop the motor.

These controllers are constructed in such a manner that several of them can be connected in series and driven by a single motor. The minimum range of control is about 2.5°F.

Experiment 1

The Recording Millivoltmeter

a. Observe the instrument in operation until the purpose and relation of all parts are clear. Sufficient notes should be taken to pass satisfactorily an oral quiz on the mechanical operation of the instrument and the location of the various parts of the electrical circuits, both measuring and auxiliary.

b. Calibration.—Using a battery box or some other means of obtaining a variable e.m.f., check readings at regular points on the scales (if more than one) against a potentiometer. Construct a correction curve for each scale. If there are errors in the readings,

state possible reasons for their occurrence and what might be done to correct them.

Experiment 2

The Recording Potentiometer

a. Same as Experiment 1.

b. Calibration.—In calibrating one potentiometer against another, it is unnecessary to employ an external source of e.m.f. Why? In checking the scales of a recording potentiometer, therefore, it is necessary only to connect the corresponding terminals of the two instruments. A portable potentiometer is sufficiently accurate for checking. Short-circuit the galvanometer on the recorder, and turn the balancing mechanism to such a position that the clutch is released. This allows the main shaft to be rotated freely to any position. By thus rotating the shaft, set the pen indicator at various points on the scale, and check against the portable instrument. Prepare a correction curve for each scale, and give possible reasons for any errors found.

Experiment 3

The Recording Resistance Thermometer

a. Same as Experiment 1.

b. Using an oil bath that can be heated over a range of several hundred degrees Fahrenheit, check the readings of the recorder against a standard thermocouple or fluid thermometer that is tightly attached to the resistance-thermometer bulb. Be sure the bulb is properly immersed. Prepare a correction curve, and give possible reasons for any errors found.

Experiment 4

High-temperature Control

Using a recorder with control attachment, assemble an apparatus for automatic control of either a small electric resistance or gas-fired laboratory furnace. Make a drawing of the setup, and write a brief description of its operation.

If an automatically controlled gas, oil, or electric furnace is not available in the laboratory, it is frequently possible to visit a near-by plant that operates one. Study the operation of the control apparatus, and prepare a drawing that shows the relative positions of all electrical and mechanical parts of the equipment. Write a brief description of its operation, indicating the type of controller, the types of valves or switches used, and the range of control. Suggest any improvements that might be applicable to the installation.

CHAPTER VIII

TRANSITION POINTS AND THERMAL ANALYSIS

All substances may exist in three different physical states—liquid, solid, and gaseous. Provided that suitable means of supplying or removing heat are available, the pressure remaining at a suitable value, it is possible to cause substances to pass from one state to another. The temperatures at which such changes take place are termed "transition points." While the change in state is taking place, the temperature may remain stationary, or nearly so, as long as the two phases of the substance are present.

Molecular or atomic rearrangements may take place in a substance while it remains in a single physical state, thus giving different phases of the substance. Examples are the allotropic changes in phosphorus and carbon, the change from eutectoid to solid solution in steel, or from one solid solution to another in some nonferrous alloys. Many minerals exhibit transitions of one kind or another. The temperatures at which these changes in phase occur may also be called transition or transformation points.

All substances exhibit various physical and constitutional changes as they pass through a transition point. One phenomenon, however, is always present, namely, the absorption or evolution of heat. The different phases of a substance have different energy contents, but those stable at higher temperatures have greater energy contents than those stable at lower temperatures. This is in accord with the proposition that all natural processes take place in such a way that the potential energy of the system approaches a minimum. It

follows, therefore, that when a higher temperature phase passes to a lower, there will be an evolution of heat, and vice versa. The heat evolved as unit mass of a vapor changes to a liquid is called the latent heat of vaporization, and as unit mass of liquid changes to a solid, the latent heat of fusion.

It is this evolution or absorption of heat that maintains the temperature of the radiating mass nearly stationary while the change is taking place.

The determination of transition points is clearly a problem in temperature measurement. Boiling and melting points can be observed directly with a thermometer or pyrometer when both phases are present and in equilibrium. In many cases, particularly where changes are taking place without change of physical state, it is necessary to locate the transition points by means of cooling curves. Some transitions do not take place sharply at certain temperatures but extend over certain ranges of temperature.

Importance of Transition-point Determinations.—The determination of transition points has become such an important phase in the study of the constitution of substances, particularly alloys, that it has been dignified by the name of "thermal analysis." It is scarcely necessary to point out the importance of knowing the boiling and melting points of elementary substances and compounds. They form two of the most important groups of constants that the physical sciences use. The equilibrium diagrams that are so useful in metallurgy, as well as in other sciences, are maps of melting-points, boiling points, and constitutional variations, as shown by determining the location of the transition points in a series of alloys or complex compounds.

The occurrence of transition points in solid substances, particularly alloys, makes possible, in some cases, a variation of physical properties of the substance through heat treatment. Different phases of the same system

often show very marked variations in strength, hardness, corrosion resistance, etc. If an alloy is suddenly cooled or, as it is usually stated, quenched, from above a transition point, the tendency is to retain to a large degree that phase present at the temperature from which

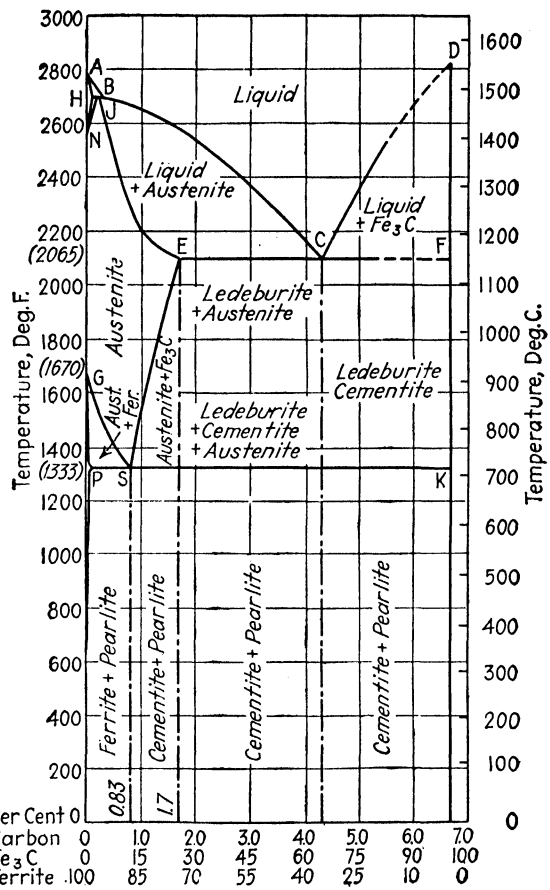


FIG. 97.—Equilibrium diagram of the iron-carbon system. (*A. H. White, "Engineering Materials."*)

it was cooled. In many cases, this phase is a solid solution, and it is through the partial or complete decomposition of these solid solutions under well-controlled conditions that the striking variations in physical properties are brought about. Steel, which is an iron-carbon alloy, furnishes the best example of this. Figure 97 is the equilibrium diagram of the iron, iron-carbide

system. All types of carbon steels occur to the left of point *E* on this diagram. The carbon content of steels is usually less than 1.5 per cent.

All steels, while cooling from the molten condition, pass through the area *AGSE*. While in this area, they are composed completely of a solid solution of carbon in gamma iron. This solid solution is called austenite. Steels containing less than 0.6 per cent carbon exist for a brief period during solidification as the delta solution, as shown in the upper left-hand corner of the diagram. Upon further slow cooling, each steel at some point crosses the broken line *GSE*. In the case of those which cross the portion *GS*, it is found that free alpha iron, called also alpha ferrite, is separating out. Alpha and gamma iron are allotropic forms of this metal; so it is clear that the transition point whose locus is *GS* is largely concerned with an allotropic change. Those steels which cross portion *SE* precipitate iron carbide, usually called cementite. The crossing of the line *PSK* is attended by a complete change of the remaining solid solution, austenite, to a eutectoid mixture of alpha ferrite and cementite which is called pearlite. In the final analysis, therefore, all slowly cooled carbon steels are an aggregate of alpha ferrite and cementite.

If a steel is heated to some point just above the line *GSE* and cooled very rapidly, the changes noted on slow cooling do not have time to occur completely. This results in the formation of constituents that can be considered only as intermediate steps in the change of the austenite to an aggregate of alpha ferrite and cementite. These intermediate products are the well-known martensite, troostite, and sorbite. Since their properties are markedly different from the normal aggregate of alpha ferrite and cementite and since they will retain these properties indefinitely, they are of very great importance to the steel treater. Their retention makes possible the widely varying combinations of hard-

ness, tensile strength, and ductility that are demanded in the industrial utilization of steel.

The importance to steel treaters of a knowledge of the position of the above-mentioned transition or critical points is evident, particularly since the points do not always occur at the same temperature but show a certain hysteresis depending upon the rate of cooling or heating. The introduction of alloying elements also changes their position, some elements lowering and other elements raising the critical ranges.

A somewhat similar situation exists in bronzes carrying from 13 to 28 per cent tin, since it is possible to increase their strength by quenching from above a certain transition point.

Alloys whose properties are improved by the solution effect or by age hardening are another important group in which the location of transition points must be accurately known. All these alloys exist as solid solutions in some range of temperature and exhibit decreases in solubility as the temperature drops. It is important to know the point above which all these alloys exist as unsaturated solid solutions. Thermal analysis furnishes one of the useful means of determining these points.

HEATING AND COOLING CURVES

Simple Time-temperature Curves.—If a substance is heated or cooled over a particular range and at a fairly constant rate, it is possible to take temperature readings at stated time intervals and plot a time-temperature curve that represents the rate of heating or cooling. If the temperature remains nearly constant at any time during the heating or cooling, there will be a sharp change in the slope of the curve, and a portion of the curve will be nearly parallel to the time axis. Figure 98 represents this condition. *BC* is that portion of the curve where the temperature remained constant. Such curves are typical of melting-point determinations and sharply

defined constitutional changes. The halt in the cooling curve occurs because the evolution of heat on cooling through the transition point is sufficient to supply that radiated by the body, so that the temperature of the system remains constant for a definite interval. A similar time-temperature curve is obtained if heat is added at a uniform rate.

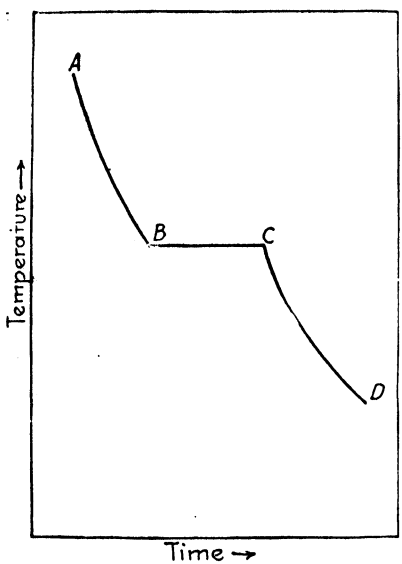


FIG. 98.—Cooling curve of a pure substance or a eutectic. (*Jeffries and Archer, "The Science of Metals."*)

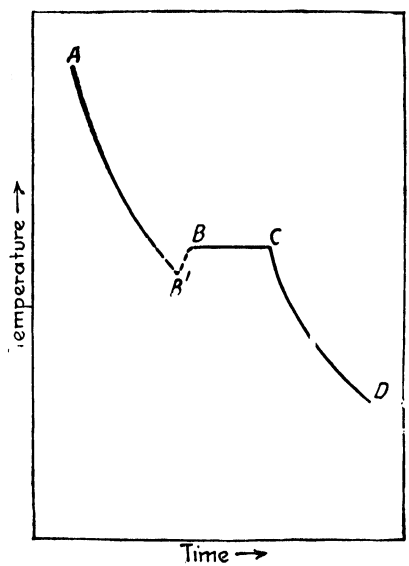


FIG. 99.—Cooling curve exhibiting supercooling. (*Jeffries and Archer, "The Science of Metals"*).

In an actual determination, the points *B* and *C* will not be as sharply defined as shown in the figure, and the flat portion of the curve may be very small. In some cases, there may be a definite slope over the whole portion *BC*. In determining melting points, the heating curves show more slope than the cooling curves, and for this reason cooling curves are more generally employed.

Some molten metals—antimony, for instance—show a tendency to cool below the freezing point before solidification begins. This phenomenon, known as supercooling or surfusion, is illustrated in Fig. 99.

If two metals are completely soluble in each other in all proportions in the liquid state, but nearly insoluble in the solid state, one proportion of the two retains the liquid solubility to a lower temperature than any other proportion. This is called the eutectic alloy. When this alloy reaches the lowest temperature at which it is possible to retain liquid solubility, it tends to transform into a physical mixture of the two metals. Since a certain degree of mutual solubility always exists, the physical mixture will actually consist of two solid solutions. All such binary alloys tend, on cooling, to expel from solution the constituent that is present in excess of eutectic proportions, thereby allowing the remaining portion of the alloy to remain in liquid solution as long as possible.

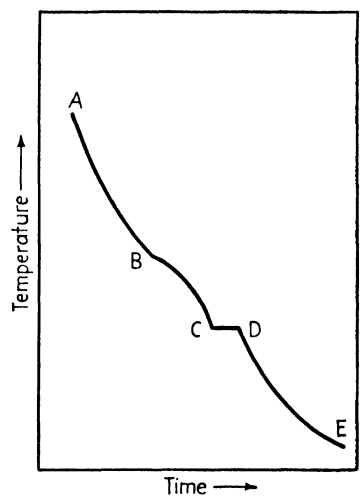


FIG. 100.—Cooling curve of a binary alloy consisting of an excess constituent and a eutectic.

The cooling curve of a pure eutectic has the same form as the curve of a pure metal (Fig. 98). If the alloy consists of a eutectic and an excess constituent, the cooling curve assumes the form shown in Fig. 100. The sloping portion *BC* represents the solidification of the excess constituent and the portion *CD* the solidification of the eutectic. In this case, the solidification of the alloy takes place over a temperature range represented by the vertical distance between *B* and *D*. The convexity of portion *BC* is due to the presence of two tendencies. The separation of the excess constituent tends to produce a halt in the curve, and the removal of the excess constituent from the liquid bath tends to lower the average melting point of the bath. The resultant of these two is the bulge in the curve.

Figure 101 is the cooling curve of a binary alloy, the component metals of which are completely and mutually soluble in the liquid and solid states. Here, again, solidification takes place over a range *BC*. The convexity of the portion *BC* is due to two tendencies. The metal with the higher melting point tends to solidify first, which would cause a halt in the curve. Since the metal with the lower melting point is soluble in the other, a small portion of the former is dissolved in the first crystals that are formed. The net result is the removal from the liquid of a greater amount of the metal with the higher melting point than that with the lower melting point. The average freezing point of the residual liquid is therefore lowered.

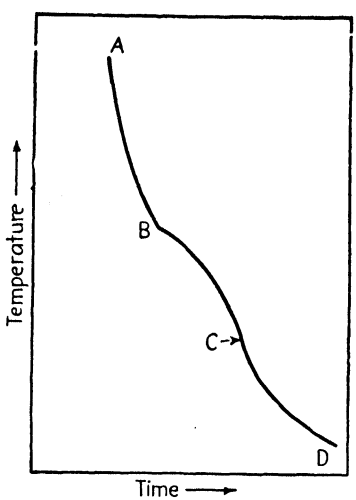


FIG. 101.—Cooling curve of a completely soluble binary alloy.

The evolution of heat at some transition points is so slight that it would scarcely be noted on a simple time-temperature curve. In order to make such transition points more prominent, the *inverse-rate* curve, the *differential* curve, or the *derived differential* curve may be used.

The Inverse-rate Curve.—The data for this curve are obtained by observing the time required for a specimen to fall through a predetermined temperature interval. This temperature interval may be anything up to 10°C., depending on the accuracy required. The curve is obtained by plotting the time as an absolute value against the lower temperature of each temperature interval. For instance, if it takes a specimen 20 seconds to drop from 560 to 558°C., the 20-second time interval is plotted against 558°C. The next 2°C. drop may

require 30 seconds, which is plotted against 556°C. Merica[1] has suggested a simple means of determining these time intervals through the use of two stop watches. One is stopped and the other started at the end of each time interval. During each time interval, it is thus possible to record the length of the preceding interval.

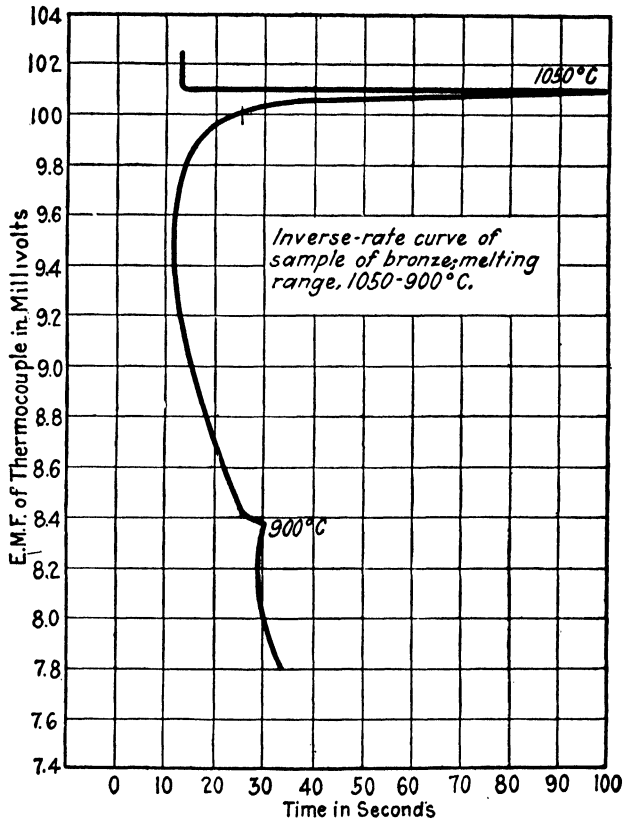


FIG. 102.—Inverse-rate curve.

Figure 102 is the inverse-rate curve of a bronze during solidification.

The Differential Curve.—This curve is obtained by observing the difference in temperature between the material under observation and a so-called neutral body while the two are slowly heated or cooled. The neutral body must have no transition points in the same tempera-

[1] P. D. Merica, *U. S. Bur. Standards, Sci. Paper* 336.

ture range. It is, of course, necessary that the two bodies be in very intimate contact during the operation. The arrangement of the system is illustrated in Fig. 103. Two thermocouples are employed, one a differential couple with an insulated junction in each material and the other a carefully calibrated couple to indicate the temperature of the specimen under observation. By using a sensitive galvanometer with the differential couple, very small thermal variations may be detected. If the specific heats of the two materials are not widely different and the samples are in close contact, variations in the rate of heating or cooling make negligible errors. If there is a steady large deflection of the galvanometer, it may be convenient to reduce this to zero by a variable counter e.m.f. obtained by means of a battery and slide wire. The curve is obtained by plotting the temperature difference between the sample and the neutral body against the temperature of the sample.

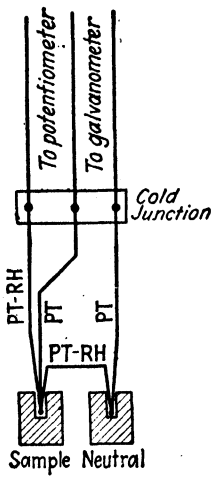


FIG. 103.—Diagram of arrangement for obtaining differential or derived differential curves. (*U. S. Bur. Standards*, T. P. 170.)

The Derived Differential Curve.—The apparatus required to obtain this curve is the same as for the differential curve. The only difference lies in the method of reporting and plotting the data. This method bears the same relationship to the differential curve as the inverse-rate curve bears to the simple time-temperature curve. For each predetermined temperature interval, say 2°C., the difference in the readings of the galvanometer is noted. In plotting a cooling curve, this difference is plotted against the upper point of each temperature interval. In plotting a heating curve, on the other hand, it is plotted against the lower point of the interval. From a mathematical standpoint, this

curve is the first derived curve of the differential curve with respect to the temperature. The advantage in its use lies in the fact that the transition points are more easily located. This is evident from Fig. 104, which represents the transition points in a piece of pure iron, as determined by both methods.

Nearly all types of thermometers and pyrometers can be used in thermal analyses, depending upon the

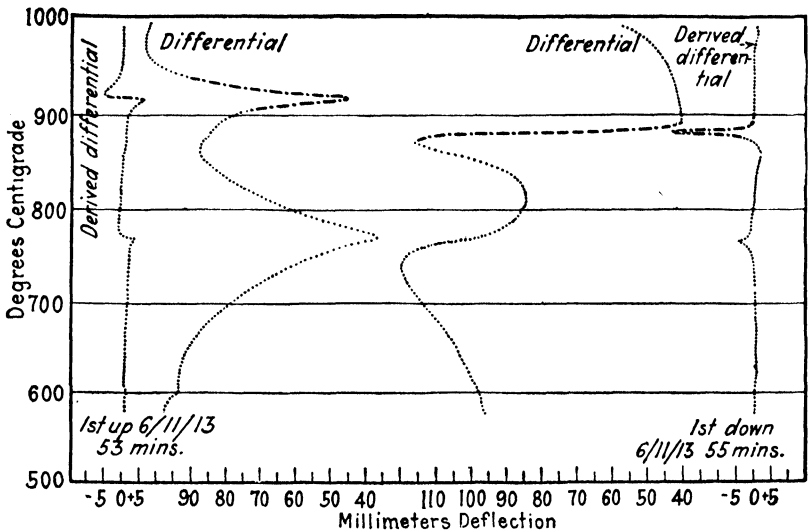


FIG. 104.—Differential and derived differential curves for a sample of pure iron. (*U. S. Bur. Standards*, T. P. 170.)

temperature range, nature of the material under test, and other special conditions. Most high-temperature work is done with thermocouples or optical pyrometers.

Melting-point Determinations.—The design of melting-point apparatus and the technique of operation are largely controlled by the properties of the material under investigation and the temperature of melting.

Figure 105 represents a melting-point furnace for precision work with metals and alloys melting below 1100°C., as used at the U. S. Bureau of Standards. The metal *G* lies in graphite crucible *H*, which, in turn, rests in porcelain crucible *F*. Pyrometer tube *A* extends

through the cover of the crucible down into the metal. The graphite crucible is entirely surrounded by powdered graphite *E*. A layer of powdered graphite is shown covering the surface of the metal, but this should not be added until the metal is molten. The assembly of

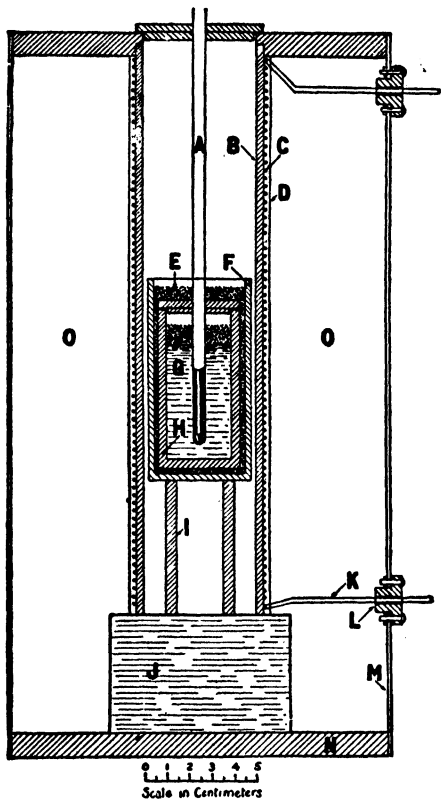


FIG. 105.—Electric furnace for melting-point determinations. (*U. S. Bur. Standards*, T. P. 170.)

crucibles is supported by alundum tube *I*, which, together with alundum heater tube *B*, rests on a nonconducting fire brick *J*. The heater tube *B* is wound with a suitable number of turns of No. 14 chromel *A* wire, with lead-in terminals of No. 10 chromel *A* wire. The furnace shell *M* is made of sheet iron, and the ends are closed with impregnated asbestos boards *N*. The annular space *O* is filled with silocel powder or some suitable insulating material. The lead-in wires are insulated

from the furnace by asbestos board or steatite bushings. The furnace is connected in series with a rheostat and operates on a 110-volt line.

Care should be taken that the thermocouple is immersed to a proper depth in the metal. This condition is indicated when slight variations in depth do not show any temperature variations. The pyrometer tube may be left in the metal until it cools a few degrees below the melting point, but if it cannot then be easily removed, the metal should be immediately remelted. The cooling rate should be about 2°C. per minute from 10°C. above the melting point.

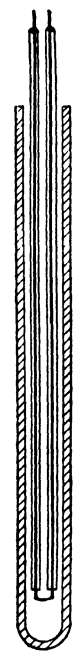


FIG. 106.—Apparatus for wire method. (*U. S. Bur. Standards*, T. P. 170.)

Figure 106 shows the apparatus for melting-point determinations by the so-called wire method. This method is applicable when noble metals are being studied or when only a small amount of metal is available and it is ductile enough to be drawn into a short section of wire. The thermocouple is cut apart at the hot junction, and a short section of the wire is fused between the cut-apart wires of the couple. Solder should not be used. The temperature of the furnace is slowly increased as the melting point is approached, and a halt in the fusing temperature is noted shortly before the circuit is broken by the melting of the fused-in wire section. The temperature corresponding to the e.m.f. of the point at which the halt occurred is the desired melting point.

The use of thermocouples is attended with considerable difficulty when making melting-point determinations above 1400°C. The use of optical pyrometers is desirable, and above 1550°C is necessary. Figure 107 shows a device that may be used for melting points above 1400°C. and below 1750°C. The outer tube is

made of sillimanite and is the unit that is inserted into the furnace. The crucible inside this tube is fitted with a cover having two holes through it in the positions shown. The center hole is for observing the progress of melting while the pyrometer is sighted through the other hole. The pyrometer should be rigidly mounted and sighted upon the convex surface of the meniscus of the metal, which gives suitable black-body conditions. A halt in the varying temperature readings will be observed when the melting point is reached.

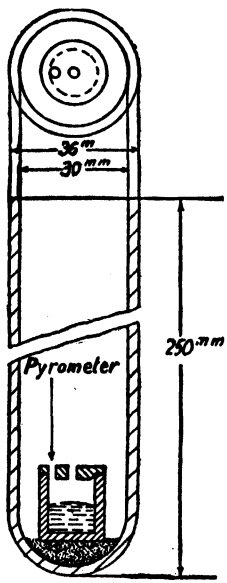


FIG. 107.—Apparatus for melting points of metals and alloys with optical pyrometer. (*U. S. Bur. Standards*, T. P. 170.)

Acheson graphite crucibles can be used for most metals with the exception of iron and nickel. For these metals, crucibles of magnesia, alumina, or mixtures of the two may be used. Porcelain crucibles may be used for many of the metals, but there is danger that these may crack when the metal melts or freezes. Anything containing silica cannot be used in contact with aluminum. When thermocouples are used, similar precautions as to the types of protecting tubes must be observed.

Figure 108 shows an apparatus that may be used for making melting-point determinations on inorganic salts and silicates. A sillimanite protection tube *A* is joined to a platinum sleeve *B*, into which tightly fits platinum crucible *C*, containing the charge. The noble-metal couple carefully centered is inserted with no protection tube. Heating and cooling curves are then made in the usual manner.

Transition Points in Solid Substances.—These determinations are best made by the use of thermocouples whose e.m.fs. are read by precision or semiprecision

potentiometers. The hot junction of the couple should, if possible, be buried within the mass of the solid substance. In the case of many metals, this may be done by drilling a small hole into the metal and peaning the hot junction into the hole. The solid with thermocouple attached is then placed in an electric furnace whose temperature can be varied fairly rapidly over the desired range. By using this type of setup, either simple time-temperature curves or inverse-rate curves can be plotted. In the case of the differential method, it is necessary to have in addition to the instrument giving the absolute temperature of the solid under investigation, another device to read the temperature difference between the solid and the neutral body. Some special instruments have been designed to determine transition points, such as the critical ranges in steel.



FIG. 108.—Silicate melting point apparatus. (*U. S. Bur. Standards*, T. P. 170.)

Leeds and Northrup Apparatus.—This apparatus uses the differential method. The neutral body is a cylinder of nickel drilled in such a way that the sample under investigation can be inserted until its end is nearly flush with the end of the neutral body. The sample has in the end that is inserted in the furnace a No. 10 hole ½ inch in length. The differential couple and the couple for measuring the temperature of the sample are threaded through a four-hole porcelain tube. This tube carrying the couples is inserted through the open end of the nickel cylinder to such a distance that the hot junction of the temperature-measuring couple is within the sample and the differential couple has one junction in the sample and the other farther back, where it is wholly surrounded by the nickel. This whole assembly is placed in a cylindrical electric resistance furnace, the temperature of which can be rapidly

raised or lowered. Cold-junction errors are automatically compensated.

Figure 109 is a diagram of the apparatus by means of which the differential curve is drawn. The measurement of the temperature of the sample is made by means

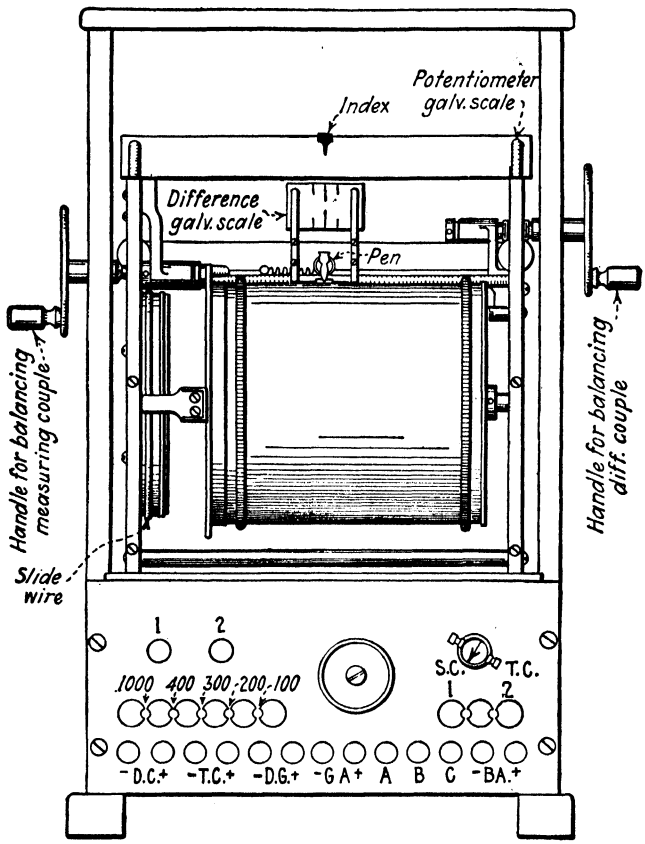


FIG. 109.—Leeds and Northrup apparatus for thermal analysis. (*Leeds and Northrup Co.*)

of a simple null-point potentiometer, the slide-wire of which encircles the drum. The galvanometer is suspended about 1 meter back of the instrument, and a ray of light from a lamp fastened to the back of the instrument is reflected from the galvanometer mirror to the upper frosted scale, as indicated. The paper upon which the curve is drawn fits around the cylindrical surface of the drum, just covering it. This paper is graduated in

millivolts and temperature and must be placed on the drum in such a way that its lowest millivoltage figure coincides with the corresponding figure on the drum. The paper is held on the drum by two helical springs that encircle the drum. The circuit having been checked against the standard cell, the temperature of the sample is obtained by revolving the drum by means of the crank on the left side of the instrument box, until the beam from the galvanometer is brought to the point marked "index." As the temperature of the sample increases, this balance is maintained by slowly turning the drum.

If the pen carriage remains stationary as the temperature of the sample increases, a straight line will be drawn on the paper as the drum revolves. The pen carriage, however, may be moved back and forth along the drum surface by the crank on the right side of the instrument. These lateral movements indicate the difference in temperature between the neutral body and the sample as will be shown.

The lead-wires from the differential couple are connected to a second galvanometer, which is suspended beside the potentiometer galvanometer. The beam from this galvanometer is directed upon the frosted scale that is fastened to the pen carriage. As long as there is no difference in temperature between the sample and the neutral body, the beam from the differential galvanometer will remain stationary. As soon as a transition point is reached, however, the rates of heating or cooling of the sample and the neutral body cease to be the same, and a small temperature difference appears. This causes the beam from the differential galvanometer to move either to the right or the left. In order, then, to keep the beam in the same position, on the differential galvanometer scale, it is necessary to move the pen carriage a corresponding distance. The curve being drawn on the drum then shows a break at the temperature at which the transition point occurs.

In series with the differential galvanometer is a variable resistance that makes it possible to decrease the sensitivity of the galvanometer. Otherwise the beam may swing outside of the instrument in case the transition point is accompanied by the evolution or absorption of a large amount of heat. On the other hand, the sensitivity of this apparatus is not great enough to locate transition points if the evolution of heat is small. The curve can be replotted as a derived differential curve, thus bringing out more clearly points that may be doubtful.

The Heat Treatment of Steel.—It has been pointed out that the mechanical properties of steel may be varied by heat treatment. To harden steel, it is necessary to quench it from above the critical point. The location of this critical point must be known for every steel. Two methods have been devised for indicating by attendant physical phenomena that steel parts being heat-treated have actually passed through the critical range.

The Hump Method.—This method, devised by Leeds and Northrup, makes use of the fact that as heat is added at the transition point no change in temperature occurs. The steel is placed in a specially designed electric furnace in such a way that it is in close proximity to and surrounds the thermocouple. The e.m.f. of the thermocouple is indicated on a specially designed potentiometer recorder. As the furnace heats up, the temperature indicated on the recorder increases at a uniform rate. As the critical point is reached, the steel absorbs a large amount of heat without increase of temperature. This produces a "hump" in the heating curve and indicates to the operator that the steel has been heated to the critical point. As soon as the rate of heating becomes constant again, it is time to remove the steel from the furnace and quench it. The distance past the hump to which it is necessary to carry the charge is dependent upon

the size and shape of the charge. A certain amount of experience is necessary for successful operation.

The Dilatometric Method.—It has been observed that as steel is heated through its critical range a contraction in volume occurs, as well as an absorption of heat. If, therefore, while the steel is being heated, it is placed in rigid contact with an indicator such as an Ames dial, it will be noted that the metal expands at a uniform rate until the critical range is reached. While passing through the critical range, the dial will remain stationary or may even indicate a contraction. After the range is passed, the dial again indicates a uniform expansion. With some experience, it is possible to determine the best time to quench the steel after the point of contraction has been passed.

The Curie Transition Temperature.—It is not uncommon in materials that are ferromagnetic for an abrupt change in magnetic properties to accompany the transition in phase. Ferromagnetic substances are characterized by exhibiting a large magnetization that is not proportional to the magnetizing force but that reaches a saturated value in relatively weak fields. Above a certain critical temperature, known as the Curie point, these substances become paramagnetic. In this condition, the magnetization is directly proportional to the magnetizing force. The ratio of the magnetization to the magnetizing force, called the magnetic susceptibility, was found by Curie[1] and by Weiss[2] to vary inversely with the absolute temperature of the material.

If pure iron is heated through the temperature range around 900°C., it changes abruptly from the alpha ferromagnetic body-centered cubic structure to the gamma paramagnetic face-centered cubic structure. Thus, an observation of the abrupt change in magnetic properties can be made the criterion of the change in phase. Many

[1] P. Curie, *Jour. phys.* **4**, 197, 263 (1895).
[2] P. Weiss, *Jour. phys.*, **6**, 667 (1907).

experimental procedures have been employed to detect these discontinuities in the magnetic properties and thereby the transition points. Figure 110 is an arrange-

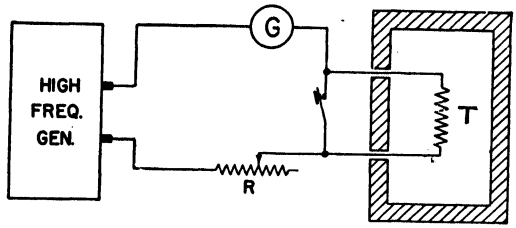


FIG. 110.—Apparatus to determine the Curie temperature of a specimen.

ment[1] in which the high-frequency resistance of the specimen T is observed as the temperature is varied. The resistance is measured by substituting for the conductor T an increase in the calibrated resistance R to give the same current in the galvanometer. The high-

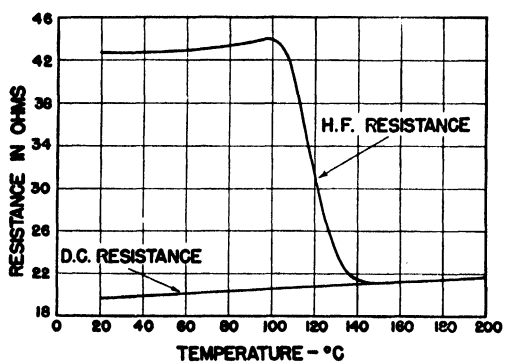


FIG. 111.—Variation of high-frequency resistance of an Fe-Cr-Ni alloy with temperature.

frequency resistance is a function of the depth of penetration of the current in the conductor. This, in turn, depends upon the permeability μ of the material that changes abruptly at the Curie point. The results obtained for an Fe-Cr-Ni alloy are shown in Fig. 111.

EXPERIMENT 1

Melting Point of Zinc

Using a furnace similar to the one shown in Fig. 105, determine the melting and the freezing points of a sample of pure zinc. If the

[1] J. M. Bryant and J. S. Webb, *Rev. Sci. Inst.* **10**, 47 (1939).

crucible contains a mass of solid metal, close the heating circuit until the metal is molten. Cover the surface with graphite powder, insert the thermocouple tube, and start the determination. If a charge of small pieces of solid metal is being melted, the procedure is the same. Best results will be obtained by starting to cool from a point about 10°C. above the melting point. The rate of cooling should be about 2°C. per minute. As soon as the metal is solid, turn on the heating current, and obtain the data for a melting-point curve.

a. Plot simple time-temperature curves of the freezing and melting point, taking temperature readings every 20 seconds with some type of potentiometer.

b. Repeat the determination, plotting inverse-rate curves for the freezing and melting points. The data for these curves are obtained by determining the time interval in seconds for each 2°C. fall or rise of temperature.

Experiment 2

The Transition Points of Iron and Steel

Make determinations of the critical points (on both heating and cooling) of the following samples, plotting inverse-rate curves:

a. Pure iron

b. 0.85 per cent carbon steel

c. 3.5 per cent nickel steel with 0.2 per cent carbon

Carry out these determinations by the method described on page 216. What point on the inverse-rate curves should be taken as the location of the critical range?

Experiment 3

Phase Diagram

Determine by means of cooling curves the phase diagram representing approximately the lead-antimony system. Assuming the melting points of the two pure elements known, make cooling curves from about 450°C. for alloys containing: (*a*) 8 per cent antimony, 92 per cent lead, (*b*) 50 per cent antimony, 50 per cent lead. From these data sketch the phase diagram showing the percentage composition and melting point for the eutectic.

CHAPTER IX

REFRACTORY MATERIALS USED IN PYROMETRY

Since the subject of pyrometry deals almost exclusively with the measurement of high temperatures, it is greatly concerned with the properties of refractory materials. Fluid and resistance thermometers require bulbs that will not be affected in the temperature ranges over which they operate. Thermocouples require protecting tubes that will not fuse, contaminate the wires, or react chemically with the surrounding medium. There is also the question of crucibles and furnace materials for the calibration of pyrometers. It is from these viewpoints that the subject of refractory materials will be dealt with in the present chapter.

Fluid-thermometer Bulbs.—Nearly all mercurial thermometers employ glass containers, although some manufacturers have used fused quartz as containers for the mercury, especially when the upper range is high. The results obtained with quartz thermometer bulbs have not been of such a quality as to warrant their extensive use at low temperatures, although it is imperative to use them at temperatures as high as 750°C. At this temperature, hard glass softens. The limit for the ordinary mercury in glass thermometers is about 550°C. In certain types of industrial thermometers, the bulb is enclosed in a metal tube to furnish protection from bending or swelling. Any metal melting above 600°C. may be used for this purpose, depending upon the type of service. There is, of course, considerable lag in the readings of such instruments, although this may be greatly reduced by filling the space between the bulb and the metal protecting tube with a conducting medium. Mer-

cury is used below 200°C. and heavy oils in the higher range. Pressure thermometers generally use metal bulbs. Here again the metal must be chosen that is best suited to conditions. It must not react with the material, the temperature of which is being taken, or with the fluid contained within it.

Resistance-thermometer Bulbs.—As has been brought out in the discussion of resistance thermometers, coils of platinum or nickel wire are used as resistor units. Iridium, palladium, and rhodium have been suggested as resistor materials but are not used to any appreciable extent. The resistor wire is wound around plates or tubes of such materials as mica, steatite, or quartz. The coil thus mounted is placed within a tube of glazed porcelain, which, in turn, is protected by an outer tube of either iron or nickel. Other metals may be used as necessary. Since the range of resistance thermometers is rather low, the refractory aspect of the mounting is not of as much importance as in the case of thermocouples. It is very essential, however, that the mounting be impervious to any material into which the bulb may be introduced.

Protection of Thermocouple Elements.—The mountings of thermocouples are made with two ideas in mind: (1) The two elements of the couple must be insulated from each other, and (2) they must be protected from the possible effects of the medium into which the couple is introduced. The usual mounting consists of two parts, an inner tube with longitudinal holes through which the couple wires may be threaded and an outer or protection tube proper into which the longitudinally bored tube carrying the wires is inserted. In the case of base-metal thermocouples, using wire of large diameter, the outer tube is sometimes omitted. The insulating tubes, however, must always be used. These insulating tubes must be made of refractory materials that will not fuse at any temperature to which the couple may be heated.

Platinum, platinum-rhodium couples are particularly sensitive to reducing conditions. If exposed to the action of carbon monoxide for any length of time, a carbide of platinum is formed, and the wires become very brittle and soon fracture. Although not so susceptible to oxidizing conditions, it is very necessary that they never be used without adequate protection tubes. Iron-constantan couples are very sensitive to oxidizing conditions, particularly the iron element, and must, therefore, be kept in a neutral or slightly reducing atmosphere. The same is true of copper-constantan couples if used at temperatures above 300°C. In the lower ranges, they need no protection unless they are inserted in a medium that reacts with the metals.

It is sometimes necessary to use a secondary tube surrounding the primary gastight protecting tube. The secondary tube is used to give added strength to the assembly, to protect the outer glazed surface of the primary tube from abrasion or fluxing action, and to prevent bending of the primary tube due to softening at high temperatures. Secondary tubes are made of metals or unglazed refractory materials.

An ideal primary protecting tube should fulfill as nearly as possible the following conditions:

1. Low porosity. Many tubes become very porous to furnace gases at high temperatures. Furnace gases usually attack the couple.
2. Low volatility. Certain metal tubes are undesirable at high temperatures because the metal distills upon the couple, thus altering its calibration.
3. Ability to withstand high temperature.
4. Ability to withstand sudden changes in temperature.
5. Ability to withstand mechanical shocks and strains.
6. High rigidity or viscosity. Protecting tubes frequently deform and exhibit the phenomenon of plastic flow at high temperatures.

7. Thermal conductivity. High thermal conductivity is frequently desirable when rapidly changing temperatures are measured. Usually, however, low thermal conductivity is desired so that the flow of heat along the tubes is as small as possible.

8. Ability to resist corrosion from molten metals or furnace gases. No protecting tube has been developed that fulfills all these conditions perfectly, but a good many have been developed that give excellent service for special purposes.

Table I gives in a condensed form information regarding types of refractory materials as applied to thermocouple protecting tubes.

Crucibles.—In making thermal analyses of molten metals or alloys and primary calibrations of thermocouples, the type of crucible to be employed is an important consideration. Two requirements of such a crucible are self-evident. They must not fuse or soften over the temperature range required, and they must not react in any way with the molten metal that they contain. For metals melting below 600°C. (1112°F.), ordinary porcelain crucibles can be used, but there is always danger that they may crack, and the shapes in which they are made are not always well adapted for use in muffle furnaces. Graphite is probably the best all-round material to use for such crucibles. It is possible to obtain bars of graphite and machine out crucibles of any desired dimensions. Graphite, of course, deteriorates in strongly oxidizing conditions and should not be used with any metals that react with it, such as iron, nickel, and platinum.

The oxides of thorium, magnesium, zirconium, and beryllium appear to possess excellent refractory properties at high temperatures and in most cases show negligible reactions with any of the metals with high melting points. At the U. S. Bureau of Standards, crucibles of zirconium oxide bonded with clay are regularly used

TABLE I

Material	Chemical constitution	Applications	Temperature range	Advantages and limitations
Iron and steel	Alloys of iron and carbon	Primary tubes	Up to 850°C.	Oxidize easily. Are inexpensive and quite satisfactory for base-metal couples
Calorized iron	Wrought iron with surface coating of aluminum	Primary and secondary tubes	Up to 850°C.	Resists oxidation better than uncoated iron or steel
Duriron	High-silicon cast iron	Primary and secondary tubes	Up to 900°C.	May fracture with sudden temperature changes. Excellent protection against acid fumes
Fused quartz	SiO_2	Insulating, primary and secondary tubes	Up to 1050°C.	Should not be used with noble-metal or chromel-alumel couples. Resists oxidation. Practically impervious except to reducing gases. Low temperature coefficient. Resists acid fumes
Chromel, nichrome	Alloys of nickel and chromium	Primary and secondary tubes	Up to 1100°C.	High mechanical strength. Low porosity. Good resistance to oxidation. Are more expensive than iron and steel, but life is longer. Must be used in cast condition
Chromon	Alloy of iron, 75 per cent, and chromium, 25 per cent	Primary and secondary tubes	Up to 1000°C.	May be used for short periods to protect thermocouples from the action of molten brass and bronze
Alundum	Fused Al_2O_3 with clay binder	Insulating, primary and secondary tubes. Especially good for secondary tubes	Up to 1400°C.	Is somewhat porous. May be glazed, but glaze lowers fusion point. Very good for use with noble-metal thermocouples
Nickel	Nickel	Primary and secondary tubes	Up to 1400°C.	Resists oxidizing conditions
Porcelain: Marquardt, usalite, and impervite.	Very pure clays	Insulating and primary tubes	Up to 1500°C.	Must be glazed to be impervious to gases. Excellent for noble-metal couples. Less pure porcelain tubes may be used up to 1200°C. Porcelain tubes must not be subjected to sudden temperature changes

TABLE I.—(*Continued*)

Material	Chemical constitution	Applications	Temperature range	Advantages and limitations
Carborundum.....	SiC	Secondary tubes	Up to 1500°C.	High mechanical strength. Should not be used at high temperatures as a protecting tube for unvitrified glazed porcelain. Upper end of tube should have ready access to air
Corundite.....	Emery with clay binder	Secondary tubes	Up to 1500°C.	
Fire clay.....	Al_2O_3-SiO_2	Insulating and secondary tubes	1400°C.-1750°C. depending on purity of clay	Secondary protection tubes in kilns, glass, and steel furnaces. Insulating tubes for base-metal thermocouples
Sillimanite (mullite)....	Al_2O_3·SiO_2	Primary tubes	Up to 1800°C.	One of the best materials for high-temperature service
Zirconium oxide, or Baddeleyite.	ZrO_2	.....	Up to 2700°C.	Has not been widely applied to pyrometric service as yet. An excellent refractory
Graphite.....	Carbon	Secondary tubes	Up to 3000°C.	May be used in molten metals. Noble-metal couples must be protected from its action

for melting platinum and platinum-rhodium alloys. The temperature of the metal may be over 1770°C. (3218°F.), and the crucibles show no sign of softening. The same bureau reports that magnesium oxide crucibles may be used at temperatures several hundred degrees above 1800°C. (3272°F.) provided they are not in contact with carbon. Beryllium oxide shows less tendency than magnesium oxide to be reduced by carbon at 2000°C. (3632°F.). Crucibles of fused thorium oxide have been used to melt a platinum-iridium alloy at 2200°C. (3992°F.), and this oxide may stand a temperature of 2500°C. (4532°F.) without softening. Any-

one interested in the use of these oxides for the preparation of crucibles should refer to *Research Paper* 327 by Swanger and Caldwell of the U. S. Bureau of Standards.

For the ordinary calibration of thermocouples by comparison with a standard couple, tubular electric furnaces are most desirable. Alundum tubes are easily obtained and very satisfactory for this service. They are available in a variety of lengths and diameters.

APPENDIX

I. TEMPERATURES BELOW 1°K.

One of the most active and fruitful fields of thermal research at the present time is in the temperature range close to the absolute zero. It was suggested by Debye in 1926 and practically demonstrated by Giaque and MacDougall[2] in 1933 that temperatures very near the absolute zero might be attained by utilizing the magnetic behavior of certain substances. To magnetize a substance, an amount of work proportional to the product of the magnetization and the field strength must be done. If the substance were thermally insulated, this process would result in a rise in temperature. Conversely, if the paramagnetic substance, while magnetized, were cooled to a temperature around 1°K. and thermally insulated and then demagnetized, the temperature would be correspondingly reduced. The effect is particularly striking with those substances that obey the Curie law (page 220) in this temperature range. A record low temperature of 0.0034°K. was obtained in 1935 by deHaas and Wiersma[3] by demagnetizing adiabatically chrome-potassium alum from a starting field of 24,075 oersteds at a temperature of 1.29°K.

Figure 112 illustrates schematically the arrangement that might be employed both to produce and to measure the very low temperature. Helium gas at very low temperatures is an excellent conductor of heat. Hence, by surrounding the specimen with helium gas, the specimen is isothermally connected to the boiling helium cryostat. On pumping off the helium, the specimen is thermally insulated.

The method of estimating the temperature attained, as used at the University of Leiden, depends upon a weighing operation. The specimen is placed in a region where the magnetic field is small and nonhomogeneous. The small paramagnetic body then experiences a force that is directly proportional to (1) the magnetic susceptibility χ (2) the field strength H, and (3) the rate of variation of the field with distance dH/dx. Now, by knowing the values of the field and its rate of variation, the magnetic susceptibility can be evaluated. If Curie's law be assumed valid, the susceptibility leads directly to

[1] P. Debye, *Ann. Physik*, **81,** 1154 (1926).

[2] W. F. Giaque and D. P. MacDougall, *Phys. Rev.*, **43,** 768 (1933).

[3] W. J. deHaas and E. C. Wiersma, *Physica*, **2,** 335 (1935).

the absolute temperature. Many investigations have been carried out to interpret these Curie temperatures in terms of the thermo-

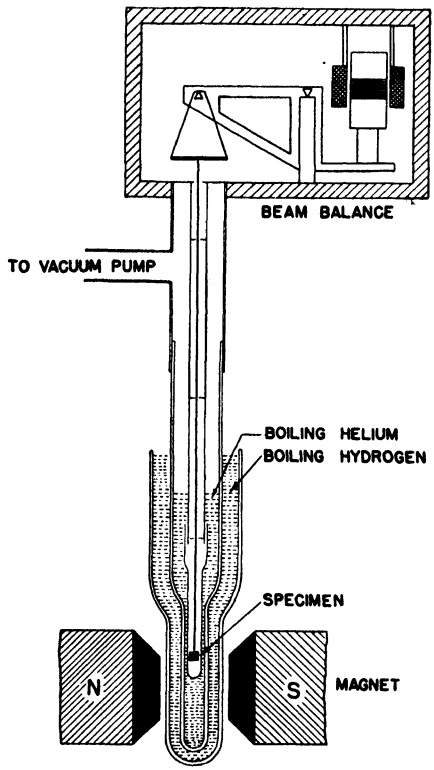


FIG. 112.—Apparatus for producing and measuring very low temperatures.

dynamic temperature scale. The corrections are, in many cases, not large.

TABLE I.—BOILING POINTS ARRANGED IN NUMERICAL ORDER
(Many of these may be used in standardization of pyrometers)

Helium	− 268.94°C.
Hydrogen	− 258.78°C.
Nitrogen	− 195.81°C.
Oxygen	− 182.97°C.
Carbon dioxide (CO_2)	− 78.5°C.
Ammonia (NH_3)	− 33.4°C.
Carbon disulphide	+ 46.3°C.
Carbon tetrachloride	76.8°C.
Water	100.0°C.
Naphthalene	217.9°C.
Mercury	356.9°C.
Sulphur	444.60°C.
Selenium	688°C.
Cadmium	767°C.
Zinc	907°C.
Magnesium	1115°C.
Bismuth	1450°C.
Lead	1620°C.
Aluminum	1800°C.
Manganese	1900°C.
Silver	1950°C.
Tin	2260°C.
Copper	2300°C.
Gold	2600°C. ?
Nickel	2900°C. ?
Molybdenum	3700°C. ?

TABLE II.—MELTING POINTS ARRANGED IN NUMERICAL ORDER
(Many of these may be used in standardization of pyrometers)

Helium	Below − 272.2°C.
Hydrogen	− 259.1°C.
Oxygen	− 218.8°C.
Nitrogen	− 209.8°C.
Chlorine	− 101.6°C.
Mercury	− 38.8°C.
Water	0.0
Naphthalene	80.1°C.
Cupric nitrate ($Cu(NO_3)_2 3H_2O$)	114.5°C.
Tin	231.8°C.
Bismuth	271.3°C.
Cadmium	320.9°C.
Lead	327.5°C.
Zinc	419.4°C.
Lead chloride ($PbCl_2$)	501.0°C.
Antimony	630.5°C.
Magnesium	651°C.
Aluminum	660.0°C.
Calcium chloride (anhydrous) ($CaCl_2$)	772.0°C.
Sodium chloride (NaCl)	801.0°C.
Silver	960.5°C.
Gold	1063.0°C.
Copper	1083°C.
Lead sulphide (PbS)	1114°C.
Barium fluoride (BaF_2)	1280°C.
Calcium fluoride (CaF_2)	1360°C.
Nickel	1455°C.
Iron	1539°C.
Palladium	1554.4°C.
Platinum	1773.5°C.
Molybdenum	2625°C.
Tantalum	3000°C.
Tungsten	3410°C.
Carbon	3700°C.

TABLE III.—MELTING POINTS OF SOME REFRACTORY MATERIALS

Coal ash	1100–1500°C.
Fire clay	1400–1750°C.
Silica	1700–1750°C.
Bauxite	1600–1800°C.
Kaolin	1740°C.
Chromite	1990–2180°C.
Alundum	2050°C.
Magnesia	2150–2800°C.
Zirconium oxide	2700°C.
Carborundum	Above 2700°C.
Graphite	Above 3000°C.

TABLE IV.—TEMPERATURE COEFFICIENTS OF VOLUME EXPANSION

Air	0–100°C.	0.0036728
Mercury	0–100°C.	0.00018138
Glass (soft)	0–100°C.	0.000025
Quartz (fused)	0–100°C.	0.000001638
Platinum	20°C.	0.0000267
Water	5–10°C.	0.0000053
	10–20°C.	0.0000150
	20–40°C.	0.0000362
	40–60°C.	0.0000458
	60–80°C.	0.0000587

Table V.—Temperature Conversion Table

C.°	0	10	20	30	40	50	60	70	80	90
	F	F	F	F	F	F	F	F	F	F
−200	−328	−346	−364	−382	−400	−418	−436	−454		
−100	−148	−166	−184	−202	−220	−238	−256	−274	−292	−310
−0	+32	+14	−4	−22	−40	−58	−76	−94	−112	−130
0	32	50	68	86	104	122	140	158	176	194
100	212	230	248	266	284	302	320	338	356	374
200	392	410	428	446	464	482	500	518	536	554
300	572	590	608	626	644	662	680	698	716	734
400	752	770	788	806	824	842	860	878	896	914
500	932	950	968	986	1004	1022	1040	1058	1076	1094
600	1112	1130	1148	1166	1184	1202	1220	1238	1256	1274
700	1292	1310	1328	1346	1364	1382	1400	1418	1436	1454
800	1472	1490	1508	1526	1544	1562	1580	1598	1616	1634
900	1652	1670	1688	1706	1724	1742	1760	1778	1796	1814
1000	1832	1850	1868	1886	1904	1922	1940	1958	1976	1994
1100	2012	2030	2048	2066	2084	2102	2120	2138	2156	2174
1200	2192	2210	2228	2246	2264	2282	2300	2318	2336	2354
1300	2372	2390	2408	2426	2444	2462	2480	2498	2516	2534
1400	2552	2570	2588	2606	2624	2642	2660	2678	2696	2714
1500	2732	2750	2768	2786	2804	2822	2840	2858	2876	2894
1600	2912	2930	2948	2966	2984	3002	3020	3038	3056	3074
1700	3092	3110	3128	3146	3164	3182	3200	3218	3236	3254
1800	3272	3290	3308	3326	3344	3362	3380	3398	3416	3434
1900	3452	3470	3488	3506	3524	3542	3560	3578	3596	3614
2000	3632	3650	3668	3686	3704	3722	3740	3758	3776	3794
2100	3812	3830	3848	3866	3884	3902	3920	3938	3956	3974
2200	3992	4010	4028	4046	4064	4082	4100	4118	4136	4154
2300	4172	4190	4208	4226	4244	4262	4280	4298	4316	4334
2400	4352	4370	4388	4406	4424	4442	4460	4478	4496	4514
2500	4532	4550	4568	4586	4604	4622	4640	4658	4676	4694
2600	4712	4730	4748	4766	4784	4802	4820	4838	4856	4874
2700	4892	4910	4928	4946	4964	4982	5000	5018	5036	5054
2800	5072	5090	5108	5126	5144	5162	5180	5198	5216	5234
2900	5252	5270	5288	5306	5324	5342	5360	5378	5396	5414
3000	5432	5450	5468	5486	5504	5522	5540	5558	5576	5594
3100	5612	5630	5648	5666	5684	5702	5720	5738	5756	5774
3200	5792	5810	5828	5846	5864	5882	5900	5918	5936	5954
3300	5972	5990	6008	6026	6044	6062	6080	6098	6161	6134
3400	6152	6170	6188	6206	6224	6242	6260	6278	6296	6314
3500	6332	6350	6368	6386	6404	6422	6440	6458	6476	6494
3600	6512	6530	6548	6566	6584	6602	6620	6638	6656	6674
3700	6692	6710	6728	6746	6764	6782	6800	6818	6836	6854
3800	6872	6890	6908	6926	6944	6962	6980	6998	7016	7034
3900	7052	7070	7088	7106	7124	7142	7160	7178	7196	7214
C.°	0	10	20	30	40	50	60	70	80	90

Interpolation Columns

C.°	F.°
1	1.8
2	3.6
3	5.4
4	7.2
5	9.0
6	10.8
7	12.6
8	14.4
9	16.2
10	18.0

F.°	C.°
1	.56
2	1.11
3	1.67
4	2.22
5	2.78
6	3.33
7	3.89
8	4.44
9	5.00
10	5.56
11	6.11
12	6.67
13	7.22
14	7.78
15	8.33
16	8.89
17	9.44
18	10.00

STANDARD TABLES FOR THE CONVERSION OF ELECTROMOTIVE FORCE OF THERMOCOUPLES TO TEMPERATURE

(Tables VI–XVII were selected from the conversion tables of Leeds and Northrup Co., through whose courtesy they are used)

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TABLE VI.—IRON VS. CONSTANTAN
(Degrees Fahrenheit;

°F.	0°	100°	200°	300°	400°	500°
	Millivolts					
0	.....	1.96	4.92	7.95	11.02	14.09
5	.....	2.11	5.07	8.10	11.18	14.24
10	.....	2.26	5.22	8.26	11.32	14.40
15	.....	2.40	5.37	8.41	11.48	14.55
20	.....	2.55	5.53	8.56	11.63	14.70
25	.....	2.70	5.68	8.72	11.79	14.86
30	.....	2.85	5.83	8.87	11.94	15.01
35	0.088	3.00	5.98	9.02	12.09	15.16
40	0.228	3.14	6.13	9.18	12.25	15.32
45	0.378	3.29	6.28	9.33	12.40	15.47
50	0.518	3.44	6.44	9.48	12.55	15.62
55	0.658	3.59	6.58	9.64	12.71	15.78
60	0.808	3.74	6.74	9.79	12.86	15.93
65	0.948	3.88	6.89	9.94	13.02	16.08
70	1.10	4.03	7.04	10.10	13.17	16.24
75	1.24	4.18	7.19	10.25	13.32	16.39
80	1.38	4.33	7.34	10.40	13.48	16.55
85	1.53	4.48	7.50	10.55	13.63	16.70
90	1.67	4.62	7.65	10.71	13.78	16.85
95	1.82	4.77	7.80	10.86	13.94	17.01
100	1.96	4.92	7.95	11.02	14.09	17.16
Millivolts per °F.	0.0288	0.0296	0.0303	0.0307	0.0307	0.0307

°F.	600°	700°	800°	900°	1000°	1100°
	Millivolts					
0	17.16	20.23	23.31	26.41	29.54	32.74
5	17.31	20.38	23.46	26.57	29.70	32.90
10	17.47	20.54	23.62	26.72	29.86	33.07
15	17.62	20.69	23.77	26.88	30.02	33.23
20	17.77	20.85	23.93	27.04	30.18	33.40
25	17.93	21.00	24.08	27.19	30.34	33.56
30	18.08	21.15	24.24	27.35	30.50	33.73
35	18.23	21.31	24.39	27.50	30.66	33.89
40	18.39	21.46	24.55	27.66	30.82	34.06
45	18.54	21.62	24.70	27.82	30.98	34.22
50	18.69	21.77	24.86	27.97	31.14	34.39
55	18.85	21.92	25.01	28.13	31.30	34.55
60	19.00	22.08	25.17	28.29	31.46	34.72
65	19.15	22.23	25.32	28.44	31.62	34.88
70	19.31	22.39	25.48	28.60	31.78	35.05
75	19.46	22.54	25.63	28.76	31.94	35.21
80	19.62	22.69	25.79	28.91	32.10	35.38
85	19.77	22.85	25.94	29.07	32.26	35.54
90	19.92	23.00	26.10	29.23	32.42	35.71
95	20.08	23.16	26.25	29.38	32.58	35.87
100	20.23	23.31	26.41	29.54	32.74	36.04
Millivolt per °F.	0.0307	0.0308	0.0310	0.0313	0.0320	0.033

THERMOCOUPLE
reference junction 32°F.)

°F.	1200°	1300°	1400°	1500°	1600°
	Millivolts				
0	36.04	39.46	42.96	46.48	50.00
5	36.21	39.64	43.14	46.66	50.18
10	36.38	39.81	43.31	46.83	50.35
15	36.55	39.98	43.49	47.01	50.53
20	36.72	40.16	43.66	47.18	50.70
25	36.89	40.34	43.84	47.36	50.88
30	37.07	40.51	44.02	47.54	51.06
35	37.24	40.68	44.19	47.71	51.23
40	37.41	40.86	44.37	47.89	51.41
45	37.58	41.03	44.54	48.06	51.58
50	37.75	41.21	44.72	48.24	51.76
55	37.92	41.38	44.90	48.42	51.94
60	38.09	41.56	45.07	48.59	52.11
65	38.26	41.73	45.25	48.77	52.29
70	38.43	41.91	45.42	48.94	52.46
75	38.60	42.08	45.60	49.12	52.64
80	38.78	42.26	45.78	49.30	52.82
85	38.95	42.43	45.95	49.47	52.99
90	39.12	42.61	46.13	49.65	53.17
95	39.29	42.78	46.30	49.82	53.34
100	39.46	42.96	46.48	50.00	53.52
Millivolts per °F.	0.0342	0.0350	0.0352	0.0352	0.0352

°F.	1700°	1800°	1900°	2000°	2100°
	Millivolts				
0	53.52	57.04	60.56	64.08	67.60
5	53.70	57.22	60.74	64.26	67.78
10	53.87	57.39	60.91	64.43	67.95
15	54.05	57.57	61.09	64.61	68.13
20	54.22	57.74	61.26	64.78	68.30
25	54.40	57.92	61.44	64.96	68.48
30	54.58	58.10	61.62	65.14	68.66
35	54.75	58.27	61.79	65.31	68.83
40	54.93	58.45	61.97	65.49	69.01
45	55.10	58.62	62.14	65.66	69.18
50	55.28	58.80	62.32	65.84	69.36
55	55.46	58.98	62.50	66.02	69.54
60	55.63	59.15	62.67	66.19	69.71
65	55.81	59.33	62.85	66.37	69.89
70	55.98	59.50	63.02	66.54	70.06
75	56.16	59.68	63.20	66.72	70.24
80	56.34	59.86	63.38	66.90	70.42
85	56.51	60.03	63.55	67.07	70.59
90	56.69	60.21	63.73	67.25	70.77
95	56.86	60.38	63.90	67.42	70.94
100	57.04	60.56	64.08	67.60	71.12
Millivolts per °F.	0.0352	0.0352	0.0352	0.0352	0.0352

TABLE VII.—IRON VS. CONSTANTAN
(Degrees centigrade;

°C.	0°	100°	200°	300°	400°	500°
	Millivolts					
0	0.0	5.28	10.78	16.30	21.82	27.39
2	0.10	5.39	10.89	16.41	21.93	27.50
4	0.21	5.50	11.00	16.52	22.04	27.62
6	0.31	5.61	11.11	16.63	22.15	27.73
8	0.42	5.72	11.22	16.74	22.26	27.84
10	0.52	5.83	11.33	16.85	22.37	27.96
12	0.62	5.94	11.44	16.96	22.48	28.08
14	0.73	6.05	11.55	17.07	22.59	28.19
16	0.83	6.16	11.66	17.18	22.70	28.31
18	0.94	6.27	11.77	17.29	22.81	28.42
20	1.04	6.38	11.88	17.40	22.92	28.53
22	1.14	6.49	11.99	17.51	23.03	28.65
24	1.25	6.60	12.10	17.62	23.14	28.76
26	1.35	6.70	12.22	17.74	23.26	28.88
28	1.46	6.81	12.33	17.85	23.37	28.99
30	1.56	6.92	12.44	17.96	23.48	29.11
32	1.66	7.03	12.55	18.07	23.59	29.22
34	1.77	7.14	12.66	18.18	23.70	29.33
36	1.87	7.25	12.77	18.29	23.81	29.45
38	1.98	7.36	12.88	18.40	23.92	29.56
40	2.08	7.47	12.99	18.51	24.03	29.68
42	2.18	7.58	13.10	18.62	24.14	29.79
44	2.29	7.69	13.21	18.73	24.25	29.91
46	2.39	7.80	13.32	18.84	24.36	30.02
48	2.50	7.91	13.43	18.95	24.47	30.14
50	2.60	8.02	13.54	19.06	24.58	30.25
52	2.71	8.13	13.65	19.17	24.69	30.37
54	2.81	8.24	13.76	19.28	24.80	30.48
56	2.92	8.35	13.87	19.39	24.92	30.60
58	3.03	8.46	13.98	19.50	25.03	30.71
60	3.14	8.57	14.09	19.61	25.14	30.83
62	3.24	8.68	14.20	19.72	25.25	30.95
64	3.35	8.79	14.31	19.83	25.37	31.06
66	3.46	8.90	14.42	19.94	25.48	31.18
68	3.56	9.01	14.53	20.05	25.59	31.30
70	3.67	9.12	14.64	20.16	25.70	31.41
72	3.78	9.23	14.75	20.27	25.82	31.53
74	3.89	9.34	14.86	20.38	25.93	31.65
76	3.99	9.45	14.98	20.49	26.04	31.76
78	4.10	9.57	15.09	20.61	26.15	31.88
80	4.21	9.68	15.20	20.72	26.27	32.00
82	4.31	9.79	15.31	20.83	26.38	32.11
84	4.42	9.90	15.42	20.94	26.49	32.23
86	4.53	10.01	15.53	21.05	26.60	32.35
88	4.64	10.12	15.64	21.16	26.72	32.46
90	4.74	10.23	15.75	21.27	26.83	32.58
92	4.85	10.34	15.86	21.38	26.94	32.69
94	4.96	10.45	15.97	21.49	27.05	32.81
96	5.06	10.56	16.08	21.60	27.17	32.93
98	5.17	10.67	16.19	21.71	27.28	33.04
100	5.28	10.78	16.30	21.82	27.39	33.16
Millivolts per °C.	0.0528	0.055	0.0552	0.0552	0.0557	0.0577

THERMOCOUPLE
reference junction 0°C.)

°C.	600°	700°	800°	900°	1000°
	Millivolts				
0	33.16	39.19	45.48	51.82	58.16
2	33.28	39.32	45.61	51.95	58.29
4	33.40	39.44	45.73	52.07	58.41
6	33.52	39.57	45.86	52.20	58.54
8	33.64	39.69	45.99	52.33	58.67
10	33.75	39.82	46.11	52.45	58.79
12	33.87	39.94	46.24	52.58	58.92
14	33.99	40.07	46.37	52.71	59.05
16	34.11	40.19	46.49	52.83	59.17
18	34.23	40.32	46.62	52.96	59.30
20	34.35	40.44	46.75	53.09	59.43
22	34.47	40.57	46.87	53.21	59.55
24	34.59	40.69	47.00	53.34	59.68
26	34.70	40.82	47.13	53.47	59.81
28	34.82	40.94	47.26	53.60	59.94
30	34.94	41.07	47.38	53.72	60.06
32	35.06	41.19	47.51	53.85	60.19
34	35.18	41.32	47.64	53.98	60.32
36	35.30	41.44	47.76	54.10	60.44
38	35.42	41.57	47.89	54.23	60.57
40	35.54	41.69	48.02	54.36	60.70
42	35.65	41.82	48..4	54.48	60.82
44	35.77	41.94	48.27	54.61	60.95
46	35.89	42.07	48.40	54.74	61.08
48	36.01	42.19	48.52	54.86	61.20
50	36.13	42.32	48.65	54.99	61.33
52	36.25	42.45	48.78	55.12	61.46
54	36.37	42.57	48.90	55.24	61.58
56	36.50	42.70	49.03	55.37	61.71
58	36.62	42.83	49.16	55.50	61.84
60	36.74	42.95	49.28	55.62	61.96
62	36.86	43.08	49.41	55.75	62.09
64	36.99	43.20	49.54	55.88	62.22
66	37.11	43.33	49.66	56.00	62.34
68	37.23	43.46	49.79	56.13	62.47
70	37.35	43.58	49.92	56.26	62.60
72	37.48	43.71	50.04	56.38	62.72
74	37.60	43.84	50.17	56.51	62.85
76	37.72	43.96	50.30	56.64	62.98
78	37.84	44.09	50.43	56.77	63.10
80	37.97	44.22	50.55	56.89	63.23
82	38.09	44.34	50.68	57.02	63.36
84	38.21	44.47	50.80	57.16	63.49
86	38.33	44.60	50.92	57.27	63.61
88	38.46	44.72	51.06	57.40	63.74
90	38.58	44.85	51.19	57.53	63.87
92	38.70	44.97	51.31	57.65	63.99
94	38.82	45.10	51.44	57.78	64.12
96	38.94	45.23	51.57	57.91	64.25
98	39.07	45.35	51.69	58.03	64.37
100	39.19	45.48	51.82	58.16	64.50
Millivolts per °C.	0.0603	0.0629	0.0634	0.0634	0.0634

TABLE VIII.—CHROMEL VS. ALUMEL
(Degrees Fahrenheit;

°F.	0°	100°	200°	300°	400°	500°	600°
	Millivolts						
0	−0.68	1.52	3.82	6.09	8.31	10.56	12.85
5	−0.58	1.63	3.93	6.20	8.42	10.67	12.96
10	−0.47	1.74	4.05	6.31	8.53	10.79	13.08
15	−0.37	1.85	4.16	6.42	8.64	10.90	13.19
20	−0.26	1.97	4.28	6.53	8.76	11.02	13.31
25	−0.15	2.08	4.39	6.64	8.87	11.13	13.43
30	−0.04	2.20	4.51	6.75	8.98	11.25	13.55
35	0.07	2.31	4.62	6.86	9.09	11.36	13.67
40	0.18	2.43	4.74	6.98	9.20	11.47	13.78
45	0.29	2.54	4.85	7.09	9.31	11.58	13.89
50	0.40	2.66	4.97	7.20	9.43	11.70	14.01
55	0.51	2.77	5.08	7.31	9.55	11.81	14.12
60	0.62	2.89	5.19	7.42	9.66	11.93	14.24
65	0.73	3.00	5.30	7.53	9.77	12.04	14.36
70	0.84	3.12	5.42	7.64	9.88	12.16	14.48
75	0.95	3.24	5.53	7.75	9.99	12.27	14.60
80	1.06	3.36	5.64	7.87	10.11	12.39	14.71
85	1.17	3.48	5.75	7.98	10.22	12.50	14.83
90	1.29	3.59	5.87	8.09	10.33	12.62	14.94
95	1.40	3.70	5.98	8.20	10.44	12.73	15.06
100	1.52	3.82	6.09	8.31	10.56	12.85	15.18
Millivolts per °F.	0.022	0.023	0.0227	0.0222	0.0225	0.0229	0.0233

°F.	700°	800°	900°	1000°	1100°	1200°	1300°
	Millivolts						
0	15.18	17.52	19.88	22.25	24.62	26.98	29.33
5	15.29	17.63	20.00	22.37	24.74	27.10	29.45
10	15.41	17.75	20.12	22.49	24.85	27.21	29.56
15	15.52	17.87	20.24	22.60	24.97	27.33	29.68
20	15.64	17.99	20.36	22.72	25.09	27.45	29.79
25	15.76	18.10	20.47	22.84	25.21	27.57	29.91
30	15.88	18.22	20.59	22.96	25.33	27.68	30.02
35	16.00	18.34	20.71	23.08	25.45	27.80	30.14
40	16.11	18.46	20.83	23.20	25.57	27.92	30.26
45	16.23	18.58	20.95	23.32	25.69	28.04	30.38
50	16.35	18.70	21.07	23.43	25.80	28.15	30.49
55	16.47	18.81	21.18	23.55	25.92	28.27	30.61
60	16.58	18.93	21.30	23.67	26.04	28.39	30.72
65	16.70	19.05	21.42	23.79	26.16	28.51	30.84
70	16.82	19.17	21.54	23.91	26.27	28.62	30.96
75	16.93	19.29	21.66	24.02	26.39	28.74	31.08
80	17.05	19.41	21.78	24.14	26.51	28.86	31.19
85	17.17	19.52	21.89	24.26	26.63	28.98	31.31
90	17.29	19.64	22.01	24.38	26.74	29.09	31.42
95	17.40	19.76	22.13	24.50	26.86	29.21	31.54
100	17.52	19.88	22.25	24.62	26.98	29.33	31.65
Millivolts per °F.	0.0234	0.0236	0.0237	0.0237	0.0236	0.0235	0.0232

THERMOCOUPLE
reference junction 32°F.)

°F.	1400°	1500°	1600°	1700°	1800°	1900°
	Millivolts					
0	31.65	33.94	36.20	38.43	40.62	42.77
5	31.77	34.06	36.31	38.54	40.73	42.88
10	31.88	34.17	36.42	38.65	40.83	42.98
15	32.00	34.29	36.54	38.76	40.94	43.09
20	32.11	34.40	36.65	38.87	41.05	43.20
25	32.23	34.51	36.76	38.98	41.16	43.31
30	32.34	34.62	36.87	39.09	41.27	43.41
35	32.46	34.74	36.99	39.20	41.38	43.52
40	32.57	34.85	37.10	39.31	41.48	43.62
45	32.69	34.97	37.21	39.42	41.59	43.73
50	32.80	35.08	37.32	39.53	41.70	43.83
55	32.92	35.19	37.43	39.64	41.81	43.94
60	33.03	35.30	37.54	39.75	41.91	44.04
65	33.15	35.42	37.65	39.86	42.02	44.15
70	33.26	35.53	37.76	39.96	42.13	44.26
75	33.38	35.64	37.88	40.07	42.24	44.37
80	33.49	35.75	37.99	40.18	42.34	44.47
85	33.60	35.87	38.10	40.29	42.45	44.58
90	33.71	35.98	38.21	40.40	42.56	44.68
95	33.83	36.09	38.32	40.51	42.67	44.79
100	33.94	36.20	38.43	40.62	42.77	44.89
Millivolts per °F.	0.0229	0.0226	0.0223	0.0219	0.0215	0.0212

°F.	2000°	2100°	2200°	2300°	2400°
	Millivolts				
0	44.89	46.97	49.01	51.00	52.95
5	45.00	47.08	49.11	51.10	53.05
10	45.10	47.18	49.21	51.20	53.14
15	45.20	47.28	49.31	51.30	53.24
20	45.31	47.38	49.41	51.39	53.33
25	45.41	47.49	49.51	51.49	53.43
30	45.52	47.59	49.61	51.59	53.52
35	45.62	47.69	49.71	51.69	53.62
40	45.73	47.79	49.81	51.78	53.71
45	45.83	47.89	49.91	51.88	53.81
50	45.93	47.99	50.01	51.98	53.90
55	46.04	48.10	50.11	52.08	54.00
60	46.14	48.20	50.21	52.17	54.09
65	46.25	48.30	50.31	52.27	54.19
70	46.35	48.40	50.41	52.37	54.28
75	46.46	48.51	50.51	52.47	54.38
80	46.56	48.61	50.61	52.56	54.47
85	46.66	48.71	50.71	52.66	54.57
90	46.76	48.81	50.80	52.75	54.66
95	46.87	48.91	50.90	52.85	54.76
100	46.97	49.01	51.00	52.95	54.85
Millivolts per °F.	0.0208	0.0204	0.0199	0.0195	0.0190

TABLE IX.—CHROMEL VS. ALUMEL
(Degrees centigrade;

°C.	0°	100°	200°	300°	400°	500°	600°
	Millivolts						
0	0	4.10	8.13	12.21	16.39	20.64	24.90
2	0.08	4.18	8.21	12.29	16.47	20.73	24.99
4	0.16	4.26	8.29	12.37	16.55	20.81	25.07
6	0.24	4.34	8.37	12.45	16.64	20.90	25.16
8	0.32	4.42	8.45	12.53	16.73	20.98	25.24
10	0.40	4.51	8.53	12.62	16.82	21.07	25.33
12	0.48	4.59	8.61	12.70	16.90	21.15	25.41
14	0.56	4.67	8.69	12.78	16.99	21.24	25.50
16	0.64	4.75	8.77	12.86	17.07	21.32	25.58
18	0.72	4.83	8.85	12.95	17.16	21.41	25.67
20	0.80	4.92	8.93	13.04	17.24	21.49	25.75
22	0.88	5.00	9.01	13.12	17.32	21.58	25.84
24	0.96	5.08	9.09	13.20	17.41	21.66	25.93
26	1.04	5.16	9.17	13.28	17.49	21.75	26.01
28	1.12	5.24	9.25	13.36	17.58	21.83	26.09
30	1.20	5.33	9.34	13.45	17.66	21.92	26.18
32	1.28	5.41	9.42	13.53	17.74	22.00	26.26
34	1.36	5.49	9.50	13.61	17.83	22.09	26.35
36	1.44	5.57	9.58	13.69	17.91	22.17	26.43
38	1.52	5.65	9.66	13.78	18.00	22.26	26.52
40	1.61	5.73	9.74	13.87	18.08	22.34	26.60
42	1.69	5.81	9.82	13.95	18.16	22.43	26.69
44	1.77	5.89	9.90	14.03	18.25	22.52	26.77
46	1.85	5.97	9.98	14.11	18.33	22.60	26.86
48	1.93	6.05	10.06	14.20	18.42	22.68	26.94
50	2.02	6.13	10.15	14.29	18.50	22.77	27.03
52	2.10	6.21	10.23	14.37	18.58	22.86	27.12
54	2.18	6.29	10.31	14.45	18.66	22.94	27.20
56	2.26	6.37	10.39	14.53	18.75	23.03	27.28
58	2.34	6.45	10.47	14.62	18.84	23.11	27.37
60	2.43	6.53	10.56	14.71	18.93	23.20	27.45
62	2.51	6.61	10.64	14.79	19.02	23.28	27.53
64	2.59	6.69	10.72	14.88	19.11	23.37	27.62
66	2.67	6.77	10.80	14.96	19.20	23.45	27.70
68	2.76	6.85	10.88	15.05	19.28	23.54	27.79
70	2.85	6.93	10.97	15.13	19.36	23.62	27.87
72	2.93	7.01	11.05	15.21	19.44	23.71	27.95
74	3.01	7.09	11.13	15.30	19.53	23.79	28.04
76	3.09	7.17	11.21	15.38	19.61	23.88	28.12
78	3.17	7.25	11.29	15.47	19.70	23.96	28.21
80	3.26	7.33	11.38	15.55	19.78	24.05	28.29
82	3.34	7.41	11.46	15.63	19.87	24.14	28.38
84	3.42	7.49	11.54	15.72	19.95	24.22	28.46
86	3.50	7.57	11.62	15.80	20.04	24.31	28.55
88	3.59	7.65	11.71	15.89	20.12	24.39	28.63
90	3.68	7.73	11.80	15.97	20.21	24.48	28.72
92	3.76	7.81	11.88	16.05	20.30	24.56	28.80
94	3.84	7.89	11.96	16.14	20.38	24.65	28.89
96	3.92	7.97	12.04	16.22	20.47	24.73	28.97
98	4.01	8.05	12.12	16.31	20.55	24.82	29.06
100	4.10	8.13	12.21	16.39	20.64	24.90	29.14
Millivolts per °C.	0.041	0.0403	0.0408	0.0418	0.0425	0.0426	0.0424

THERMOCOUPLE
reference junction 0°C.)

°C.	700°	800°	900°	1000°	1100°	1200°	1300°
	Millivolts						
0	29.14	33.31	37.36	41.31	45.14	48.85	52.41
2	29.22	33.39	37.44	41.39	45.22	48.93	52.48
4	29.31	33.47	37.52	41.47	45.29	49.00	52.55
6	29.39	33.55	37.60	41.55	45.37	49.07	52.62
8	29.48	33.63	37.68	41.63	45.44	49.14	52.69
10	29.56	33.71	37.76	41.70	45.52	49 21	52.75
12	29.64	33.79	37.84	41.78	45.59	49.29	52.82
14	29.73	33.87	37.92	41.86	45.67	49.36	52.89
16	29.81	33.95	38.00	41.94	45.74	49.43	52.96
18	29.90	34.03	38.08	42.01	45.82	49.50	53.03
20	29.98	34.12	38.16	42.08	45.89	49.57	53.10
22	30.06	34.20	38.24	42.16	45.97	49.65	53.17
24	30.15	34.28	38.32	42.24	46.04	49.73	53.24
26	30.23	34.36	38.40	42.32	46.12	49.80	53.31
28	30.32	34.44	38.48	42.40	46.19	49.87	53.38
30	30.40	34.53	38.56	42.47	46.27	49.94	53.45
32	30.48	34.61	38.64	42.55	46.35	50.01	53.52
34	30.57	34.69	38.72	42.62	46.43	50.08	53.59
36	30.65	34.77	38.80	42.70	46.50	50.15	53.66
38	30.74	34.85	38.88	42.78	46.57	50.22	53.73
40	30.82	34.94	38.96	42.86	46.64	50.29	53.79
42	30.90	35.02	39.04	42.94	46.71	50.37	53.86
44	30.98	35.10	39 12	43.02	46.79	50.44	53.93
46	31.06	35.18	39.20	43.10	46.86	50.51	54.00
48	31.14	35.26	39.28	43.17	46.94	50.58	54.07
50	31.23	35.35	39.35	43.24	47.01	50.65	54.13
52	31.31	35.43	39.43	43.32	47.08	50.72	54.20
54	31.40	35.51	39.51	43.39	47.16	50.79	54.27
56	31.48	35.59	39.59	43.47	47.23	50.86	54.34
58	31.57	35.67	39.67	43.54	47.31	50.93	54.41
60	31.65	35.75	39.75	43.62	47.38	51.00	54.47
62	31.73	35.83	39.83	43.70	47.45	51.08	54.54
64	31.82	35.91	39.91	43.77	47.53	51.15	54.61
66	31.90	35.99	39.99	43.85	47.60	51.22	54.68
68	31.99	36.07	40.07	43.92	47.68	51.29	54.75
70	32.07	36.16	40.14	44.00	47.75	51.36	54.81
72	32.15	36.24	40.22	44.08	47.82	51.43	54.88
74	32.23	36.32	40.30	44.15	47.90	51.50	54.95
76	32.31	36.40	40.38	44.23	47.97	51.57	55.02
78	32.39	36.48	40.46	44.30	48.05	51.64	55.09
80	32.48	36.56	40.53	44.38	48.12	51.71	55.15
82	32.56	36.64	40.61	44.46	48.20	51.78	55.22
84	32.65	36.72	40.69	44.53	48.27	51.85	55.29
86	32.73	36.80	40.77	44.61	48.34	51.92	55.36
88	32.82	36.88	40.85	44.68	48.41	51.99	55.42
90	32.90	36.96	40.92	44.76	48.48	52.06	55.48
92	32.98	37.04	41.00	44.84	48.56	52.13	55.55
94	33.06	37.12	41.08	44.91	48.64	52.20	55.62
96	33.14	37.20	41.16	44.99	48.71	52.27	55.69
98	33.22	37.28	41.24	45.06	48.78	52.34	55.75
100	33.31	37.36	41.31	45.14	48.85	52.41	55.81
Millivolts per °C.	0.0417	0.0405	0.0395	0.0383	0.0371	0.0356	0.0340

TABLE X.—PLATINUM VS. PLATINUM + (Degrees Fahrenheit;

°F.	0°	100°	200°	300°	400°	500°	600°	700°
	Millivolts							
0	−0.0920	0.221	0.595	1.016	1.473	1.956	2.457	2.975
5	−0.0778	0.239	0.615	1.038	1.497	1.980	2.482	3.001
10	−0.0636	0.257	0.635	1.060	1.521	2.005	2.508	3.028
15	−0.0494	0.274	0.655	1.082	1.544	2.030	2.534	3.054
20	−0.0351	0.292	0.676	1.105	1.568	2.055	2.560	3.081
25	−0.0207	0.310	0.696	1.127	1.592	2.080	2.585	3.107
30	−0.0060	0.328	0.717	1.150	1.616	2.105	2.611	3.133
35	+0.0090	0.346	0.737	1.173	1.640	2.130	2.637	3.159
40	0.0243	0.365	0.758	1.196	1.664	2.155	2.663	3.186
45	0.0398	0.383	0.779	1.218	1.688	2.180	2.689	3.212
50	0.0555	0.401	0.800	1.241	1.712	2.205	2.715	3.239
55	0.0714	0.420	0.821	1.264	1.736	2.230	2.741	3.266
60	0.0875	0.439	0.843	1.287	1.760	2.255	2.767	3.293
65	0.104	0.458	0.864	1.310	1.784	2.280	2.793	3.319
70	0.120	0.477	0.886	1.333	1.808	2.305	2.819	3.346
75	0.137	0.496	0.907	1.356	1.832	2.330	2.845	3.372
80	0.153	0.516	0.929	1.380	1.857	2.356	2.871	3.399
85	0.170	0.535	0.950	1.403	1.881	2.381	2.897	3.425
90	0.187	0.555	0.972	1.426	1.906	2.406	2.923	3.452
95	0.204	0.575	0.994	1.449	1.931	2.431	2.949	3.478
100	0.221	0.595	1.016	1.473	1.956	2.457	2.975	3.505
Millivolts per °F.	0.00313	0.00374	0.00421	0.00457	0.00483	0.00501	0.00518	0.00530

°F.	800°	900°	1000°	1100°	1200°	1300°	1400°	1500°
	Millivolts							
0	3.505	4.044	4.594	5.155	5.725	6.307	6.898	7.500
5	3.532	4.071	4.621	5.183	5.754	6.336	6.928	7.530
10	3.559	4.098	4.649	5.211	5.783	6.366	6.958	7.561
15	3.585	4.125	4.677	5.239	5.812	6.395	6.987	7.591
20	3.612	4.153	4.705	5.268	5.841	6.424	7.017	7.621
25	3.639	4.180	4.733	5.296	5.869	6.453	7.047	7.651
30	3.667	4.208	4.761	5.324	5.898	6.483	7.077	7.682
35	3.694	4.235	4.789	5.352	5.927	6.512	7.107	7.713
40	3.720	4.263	4.817	5.381	5.956	6.542	7.137	7.744
45	3.747	4.290	4.845	5.409	5.985	6.571	7.167	7.774
50	3.774	4.318	4.873	5.438	6.015	6.601	7.198	7.805
55	3.801	4.345	4.901	5.466	6.044	6.630	7.228	7.835
60	3.828	4.373	4.929	5.495	6.073	6.660	7.258	7.866
65	3.855	4.400	4.957	5.524	6.102	6.690	7.288	7.897
70	3.882	4.428	4.985	5.553	6.132	6.720	7.318	7.928
75	3.909	4.455	5.013	5.581	6.161	6.749	7.348	7.958
80	3.936	4.483	5.042	5.610	6.190	6.779	7.379	7.989
85	3.963	4.511	5.070	5.638	6.219	6.808	7.409	8.020
90	3.990	4.539	5.098	5.667	6.249	6.838	7.439	8.051
95	4.017	4.566	5.126	5.696	6.278	6.868	7.469	8.081
100	4.044	4.594	5.155	5.725	6.307	6.898	7.500	8.112
Millivolts per °F.	0.00539	0.00550	0.00561	0.00570	0.00582	0.00591	0.00602	0.00612

10 PER CENT RHODIUM THERMOCOUPLE
reference junction 32°F.)

°F.	1600°	1700°	1800°	1900°	2000°	2100°	2200°	2300°
	Millivolts							
0	8.112	8.734	9.365	10.007	10.657	11.316	11.977	12.642
5	8.143	8.765	9.397	10.039	10.690	11.349	12.010	12.675
10	8.174	8.796	9.429	10.071	10.723	11.382	12.043	12.708
15	8.205	8.827	9.461	10.103	10.756	11.415	12.076	12.741
20	8.236	8.859	9.493	10.136	10.789	11.448	12.110	12.775
25	8.267	8.890	9.525	10.168	10.822	11.481	12.143	12.808
30	8.298	8.922	9.557	10.201	10.855	11.514	12.177	12.841
35	8.329	8.953	9.589	10.233	10.887	11.547	12.210	12.874
40	8.360	8.985	9.621	10.266	10.920	11.580	12.243	12.907
45	8.391	9.016	9.653	10.298	10.953	11.613	12.276	12.941
50	8.422	9.048	9.685	10.331	10.986	11.646	12.310	12.974
55	8.453	9.079	0.717	10.363	11.019	11.679	12.343	13.007
60	8.484	9.111	9.749	10.396	11.052	11.712	12.376	13.040
65	8.515	9.143	9.781	10.428	11.085	11.745	12.409	13.074
70	8.546	9.175	9.813	10.461	11.118	11.778	12.442	13.107
75	8.577	9.206	9.845	10.493	11.151	11.811	12.475	13.140
80	8.609	9.238	9.877	10.526	11.184	11.844	12.509	13.173
85	8.640	9.270	9.909	10.558	11.217	11.877	12.542	13.206
90	8.671	9.302	9.942	10.591	11.250	11.911	12.575	13.239
95	8.702	9.333	9.974	10.624	11.283	11.944	12.608	13.272
100	8.734	9.365	10.007	10.657	11.316	11.977	12.642	13.305
Millivolts per °F.	0.06622	0.00631	0.00642	0.00650	0.00659	0.00661	0.00665	0.00663

°F.	2400°	2500°	2600°	2700°	2800°	2900°	3000°	3100°
	Millivolts							
0	13.305	13.968	14.629	15.288	15.943	16.596	17.247	17.892
5	13.339	14.001	14.662	15.321	15.976	16.629	17.279	17.925
10	13.372	14.034	14.695	15.353	16.009	16.661	17.311	17.957
15	13.405	14.067	14.728	15.386	16.042	16.694	17.344	17.989
20	13.438	14.100	14.761	15.418	16.074	16.726	17.376	18.021
25	13.472	14.133	14.794	15.451	16.107	16.759	17.408	
30	13.505	14.166	14.826	15.484	16.139	16.791	17.440	
35	13.538	14.200	14.859	15.517	16.172	16.824	17.473	
40	13.571	14.233	14.892	15.550	16.205	16.856	17.505	
45	13.604	14.266	14.925	15.583	16.238	16.889	17.538	
50	13.637	14.299	14.958	15.615	16.270	16.922	17.570	
55	13.670	14.332	14.991	15.648	16.303	16.955	17.602	
60	13.703	14.365	15.024	15.680	16.335	16.987	17.634	
65	13.737	14.398	15.057	15.713	16.368	17.020	17.667	
70	13.770	14.431	15.090	15.746	16.401	17.052	17.699	
75	13.803	14.464	15.123	15.779	16.434	17.085	17.731	
80	13.836	14.497	15.156	15.812	16.466	17.117	17.763	
85	13.869	14.530	15.189	15.845	16.499	17.150	17.796	
90	13.902	14.563	15.222	15.878	16.531	17.182	17.828	
95	13.935	14.596	15.255	15.911	16.564	17.215	17.860	
100	13.968	14.629	15.288	15.943	16.596	17.247	17.892	
Millivolts per °F.	0.00663	0.00661	0.00659	0.00655	0.00653	0.00651	0.00645	0.00645

TABLE XI.—PLATINUM VS. PLATINUM + (Degrees centigrade;

°C.	0°	100°	200°	300°	400°	500°	600°	700°	800°
	Millivolts								
0	0	0.643	1.436	2.316	3.251	4.219	5.222	6.260	7.330
2	0.011	0.658	1.453	2.334	3.270	4.239	5.243	6.281	7.352
4	0.023	0.672	1.470	2.352	3.289	4.258	5.263	6.302	7.374
6	0.034	0.687	1.487	2.370	3.308	4.278	5.284	6.323	7.396
8	0.046	0.702	1.504	2.388	3.327	4.298	5.304	6.344	7.417
10	0.057	0.717	1.521	2.406	3.346	4.318	5.325	6.365	7.439
12	0.068	0.732	1.538	2.425	3.365	4.337	5.345	6.387	7.461
14	0.080	0.747	1.555	2.443	3.384	4.357	5.366	6.408	7.483
16	0.091	0.762	1.572	2.462	3.403	4.377	5.386	6.429	7.505
18	0.103	0.777	1.589	2.480	3.422	4.397	5.407	6.450	7.527
20	0.114	0.792	1.606	2.498	3.441	4.417	5.427	6.471	7.548
22	0.126	0.807	1.623	2.517	3.461	4.436	5.448	6.493	7.570
24	0.138	0.822	1.641	2.536	3.480	4.456	5.469	6.514	7.592
26	0.150	0.838	1.658	2.554	3.499	4.476	5.489	6.535	7.614
28	0.162	0.853	1.675	2.573	3.519	4.496	5.510	6.556	7.636
30	0.174	0.869	1.692	2.591	3.538	4.516	5.530	6.578	7.658
32	0.186	0.884	1.710	2.610	3.557	4.536	5.551	6.599	7.680
34	0.198	0.899	1.727	2.628	3.577	4.556	5.571	6.620	7.702
36	0.211	0.915	1.744	2.647	3.596	4.576	5.592	6.642	7.724
38	0.223	0.931	1.762	2.665	3.615	4.596	5.613	6.663	7.746
40	0.235	0.946	1.779	2.684	3.634	4.616	5.633	6.684	7.768
42	0.248	0.962	1.797	2.703	3.653	4.636	5.654	6.706	7.790
44	0.260	0.977	1.814	2.721	3.673	4.656	5.675	6.727	7.812
46	0.273	0.993	1.832	2.740	3.692	4.676	5.696	6.748	7.834
48	0.286	1.009	1.850	2.759	3.711	4.696	5.717	6.769	7.856
50	0.299	1.025	1.867	2.778	3.731	4.716	5.737	6.790	7.878
52	0.312	1.041	1.885	2.796	3.750	4.736	5.758	6.812	7.900
54	0.325	1.057	1.902	2.815	3.770	4.756	5.779	6.834	7.922
56	0.338	1.073	1.920	2.834	3.789	4.776	5.800	6.855	7.944
58	0.351	1.089	1.938	2.852	3.808	4.796	5.821	6.877	7.966
60	0.365	1.105	1.956	2.871	3.828	4.817	5.841	6.898	7.989
62	0.378	1.121	1.973	2.890	3.847	4.837	5.862	6.920	8.011
64	0.391	1.137	1.991	2.909	2.867	4.857	5.883	6.941	8.033
66	0.405	1.154	2.009	2.928	3.886	4.877	5.904	6.963	8.055
68	0.418	1.170	2.027	2.947	3.906	4.897	5.925	6.984	8.077
70	0.432	1.186	2.045	2.965	3.925	4.918	5.945	7.005	8.100
72	0.445	1.203	2.063	2.984	3.945	4.938	5.966	7.027	8.122
74	0.459	1.219	2.081	3.003	3.964	4.958	5.987	7.049	8.144
76	0.473	1.236	2.099	3.022	3.984	4.978	6.008	7.070	8.166
78	0.487	1.252	2.117	3.041	4.003	4.998	6.029	7.092	8.188
80	0.500	1.269	2.134	3.060	4.023	5.019	6.050	7.113	8.211
82	0.514	1.285	2.152	3.079	4.042	5.039	6.071	7.135	8.233
84	0.528	1.302	2.170	3.098	4.062	5.059	6.092	7.157	8.255
86	0.542	1.318	2.189	3.117	4.081	5.080	6.113	7.179	8.277
88	0.557	1.335	2.207	3.136	4.101	5.100	6.134	7.200	8.300
90	0.571	1.352	2.225	3.155	4.121	5.120	6.155	7.222	8.322
92	0.585	1.368	2.243	3.174	4.140	5.141	6.176	7.244	8.344
94	0.600	1.385	2.261	3.193	4.160	5.161	6.197	7.265	8.367
96	0.614	1.402	2.279	3.212	4.180	5.182	6.218	7.287	8.389
98	0.629	1.419	2.297	3.232	4.200	5.202	6.239	7.309	8.411
100	0.643	1.436	2.316	3.251	4.219	5.222	6.260	7.330	8.434
Millivolts per °C.	0.00643	0.00793	0.00880	0.00935	0.00968	0.0100	0.0104	0.0107	0.0110

10 PER CENT RHODIUM THERMOCOUPLE
reference junction 0°C.)

°C.	900°	1000°	1100°	1200°	1300°	1400°	1500°	1600°	1700°
	Millivolts								
0	8.434	9.569	10.736	11.924	13.120	14.312	15.498	16.674	17.841
2	8.456	9.592	10.759	11.948	13.144	14.336	15.521	16.698	17.864
4	8.479	9.615	10.783	11.972	13.168	14.360	15.545	16.721	17.887
6	8.501	9.638	10.807	11.995	13.192	14.383	15.569	16.744	17.910
8	8.523	9.661	10.830	12.019	13.216	14.407	15.592	16.768	17.934
10	8.546	9.685	10.854	12.043	13.239	14.431	15.615	16.792	17.957
12	8.568	9.708	10.878	12.067	13.263	14.455	15.639	16.815	17.980
14	8.591	9.731	10.901	12.091	13.287	14.479	15.663	16.838	18.004
16	8.613	9.754	10.925	12.115	13.311	14.502	15.687	16.861	18.027
18	8.636	9.777	10.949	12.139	13.335	14.526	15.710	16.885	18.050
20	8.658	9.800	10.973	12.163	13.358	14.550	15.733	16.908	18.073
22	8.681	9.823	10.996	12.187	13.382	14.574	15.757	16.932	
24	8.703	9.846	11.020	12.211	13.406	14.597	15.781	16.955	
26	8.726	9.869	11.044	12.235	14.430	14.621	15.805	16.978	
28	8.748	9.893	11.067	12.259	13.454	14.645	15.828	17.002	
30	8.771	9.916	11.091	12.283	13.478	14.668	15.852	17.026	
32	8.794	9.939	11.115	12.307	13.502	14.692	15.875	17.049	
34	8.816	9.962	11.139	12.330	13.526	14.716	15.899	17.072	
36	8.839	9.985	11.162	12.354	13.550	14.740	15.923	17.095	
38	8.861	10.009	11.186	12.378	13.574	14.764	15.946	17.119	
40	8.884	10.033	11.209	12.402	13.598	14.787	15.969	17.142	
42	8.907	10.056	11.233	12.426	13.621	14.811	15.993	17.165	
44	8.929	10.079	11.257	12.450	13.645	14.835	16.017	17.189	
46	8.952	10.102	11.281	12.474	13.669	14.859	16.040	17.212	
48	8.975	10.125	11.305	12.498	13.693	14.882	16.064	17.235	
50	8.998	10.149	11.329	12.522	13.717	14.906	16.087	17.259	
52	9.020	10.172	11.352	12.546	13.741	14.930	16.111	17.282	
54	9.043	10.195	11.376	12.570	13.765	14.953	16.135	17.305	
56	9.066	10.219	11.400	12.594	13.788	14.977	16.158	17.329	
58	9.088	10.242	11.424	12.618	13.812	15.001	16.182	17.352	
60	9.111	10.266	11.448	12.642	13.836	15.024	16.205	17.376	
62	9.134	10.289	11.471	12.666	13.860	15.048	16.229	17.399	
64	9.157	10.313	11.495	12.690	13.884	15.072	16.252	17.422	
66	9.180	10.336	11.519	12.714	13.907	15.096	16.276	17.445	
68	9.202	10.359	11.543	12.738	13.931	15.119	16.299	17.468	
70	9.225	10.383	11.567	12.762	13.955	15.143	16.322	17.492	
72	9.248	10.406	11.590	12.785	13.979	15.167	16.346	17.515	
74	9.271	10.430	11.614	12.809	14.003	15.190	16.369	17.538	
76	9.294	10.453	11.638	12.833	14.026	15.214	16.393	17.562	
78	9.317	10.476	11.662	12.857	14.050	15.237	16.416	17.585	
80	9.340	10.500	11.686	12.881	14.074	15.261	16.440	17.608	
82	9.362	10.524	11.709	12.905	14.098	15.285	16.463	17.631	
84	9.385	10.547	11.733	12.929	14.122	15.308	16.487	17.655	
86	9.408	10.571	11.757	12.953	14.145	15.332	16.510	17.678	
88	9.431	10.594	11.781	12.977	14.169	15.356	16.533	17.701	
90	9.454	10.618	11.805	13.000	14.193	15.379	16.557	17.724	
92	9.477	10.641	11.828	13.024	14.217	15.403	16.580	17.748	
94	9.500	10.665	11.852	13.048	14.241	15.427	16.604	17.771	
96	9.523	10.689	11.876	13.072	14.264	15.450	16.627	17.794	
98	9.556	10.712	11.900	13.096	14.288	15.474	16.651	17.817	
100	9.569	10.736	11.924	13.120	14.312	15.498	16.674	17.841	
Millivolts per °C.	0.0114	0.0117	0.0119	0.0120	0.0119	0.0119	0.0118	0.0117	0.011e

TABLE XII.—PLATINUM VS. PLATINUM + (Degrees Fahrenheit;

°F.	0°	100°	200°	300°	400°	500°	600°	700°
	Millivolts							
0	−0.0890	0.220	0.596	1.030	1.504	2.012	2.546	3.102
5	−0.0756	0.237	0.617	1.052	1.528	2.038	2.574	3.131
10	−0.0621	0.255	0.637	1.075	1.553	2.064	2.601	3.159
15	−0.0484	0.272	0.658	1.098	1.578	2.090	2.629	3.187
20	−0.0346	0.290	0.679	1.121	1.603	2.117	2.656	3.216
25	−0.0205	0.308	0.700	1.144	1.628	2.143	2.684	3.244
30	−0.0060	0.326	0.721	1.168	1.653	2.169	2.711	3.272
35	+0.0090	0.344	0.742	1.191	1.678	2.196	2.739	3.301
40	0.0244	0.363	0.764	1.214	1.703	2.223	2.766	3.329
45	0.0399	0.381	0.785	1.238	1.728	2.249	2.794	3.358
50	0.0555	0.400	0.807	1.262	1.754	2.276	2.822	3.387
55	0.0712	0.419	0.829	1.285	1.779	2.303	2.850	3.415
60	0.0871	0.438	0.851	1.309	1.805	2.330	2.878	3.444
65	0.103	0.457	0.873	1.333	1.830	2.357	2.906	3.473
70	0.119	0.477	0.895	1.357	1.856	2.384	2.934	3.501
75	0.136	0.496	0.917	1.381	1.882	2.411	2.962	3.530
80	0.152	0.516	0.939	1.406	1.908	2.438	2.990	3.559
85	0.169	0.536	0.962	1.430	1.933	2.465	3.018	3.588
90	0.186	0.556	0.984	1.454	1.959	2.492	3.046	3.617
95	0.203	0.576	1.007	1.479	1.985	2.519	3.074	3.646
100	0.220	0.596	1.030	1.504	2.012	2.546	3.102	3.675
Millivolts per °F.	0.00131	0.00376	0.00434	0.00474	0.00508	0.00534	0.00556	0.00573

°F.	800°	900°	1000°	1100°	1200°	1300°	1400°	1500°
	Millivolts							
0	3.675	4.263	4.867	5.486	6.122	6.773	7.438	8.118
5	3.704	4.293	4.898	5.517	6.155	6.806	7.471	8.152
10	3.733	4.323	4.928	5.548	6.187	6.839	7.505	8.187
15	3.763	4.353	4.959	5.580	6.219	6.872	7.539	8.221
20	3.792	4.382	4.990	5.611	6.251	6.905	7.573	8.255
25	3.821	4.412	5.021	5.643	6.284	6.938	7.606	8.290
30	3.850	4.442	5.051	5.675	6.316	6.971	7.640	8.324
35	3.880	4.472	5.082	5.706	6.348	7.004	7.674	8.359
40	3.909	4.502	5.113	5.738	6.381	7.037	7.708	8.393
45	3.938	4.532	5.144	5.770	6.413	7.071	7.742	8.428
50	3.968	4.562	5.175	5.802	6.446	7.104	7.776	8.463
55	3.997	4.593	5.206	5.834	6.478	7.137	7.810	8.497
60	4.027	4.625	5.237	5.866	6.511	7.170	7.844	8.532
65	4.056	4.653	5.268	5.898	6.544	7.204	7.878	8.567
70	4.086	4.684	5.299	5.930	6.576	7.237	7.912	8.601
75	4.115	4.714	5.330	5.962	6.609	7.270	7.947	8.636
80	4.145	4.745	5.361	5.994	6.642	7.304	7.981	8.671
85	4.174	4.775	5.392	6.026	6.675	7.337	8.015	8.706
90	4.204	4.806	5.423	6.058	6.707	7.371	8.049	8.741
95	4.234	4.836	5.454	6.090	6.740	7.404	8.084	8.776
100	4.263	4.867	5.486	6.122	6.773	7.438	8.118	8.811
Millivolts per °F.	0.00588	0.00604	0.00619	0.00636	0.00651	0.00665	0.00680	0.00693

13 PER CENT RHODIUM THERMOCOUPLE
reference junction 32°F.)

°F.	1600°	1700°	1800°	1900°	2000°	2100°	2200°	2300°
	Millivolts							
0	8.811	9.518	10.237	10.970	11.720	12.478	13.242	14.010
5	8.846	9.553	10.274	11.008	11.758	12.516	13.280	14.048
10	8.881	9.589	10.310	11.045	11.796	12.554	13.319	14.087
15	8.916	9.625	10.346	11.082	11.834	12.592	13.357	14.125
20	8.951	9.661	10.383	11.119	11.871	12.630	13.396	14.164
25	8.986	9.696	10.419	11.157	11.909	12.668	13.434	14.202
30	9.021	9.732	10.455	11.194	11.947	12.707	13.472	14.240
35	9.056	9.768	10.492	11.231	11.985	12.745	13.511	14.279
40	9.092	9.804	10.528	11.269	12.023	12.783	13.549	14.317
45	9.127	9.840	10.565	11.306	12.061	12.821	13.588	14.355
50	9.162	9.876	10.602	11.344	12.098	12.859	13.626	14.394
55	9.198	9.912	10.638	11.381	12.136	12.898	13.664	14.432
60	9.233	9.948	10.675	11.419	12.174	12.936	13.703	14.470
65	9.269	9.984	10.712	11.457	12.212	12.974	13.741	14.509
70	9.304	10.020	10.749	11.494	12.250	13.012	13.780	14.547
75	9.340	10.056	10.786	11.532	12.288	13.051	13.818	14.585
80	9.375	10.092	10.822	11.569	12.326	13.089	13.856	14.624
85	9.411	10.129	10.859	11.607	12.364	13.127	13.895	14.662
90	9.446	10.165	10.896	11.645	12.402	13.165	13.923	14.700
95	9.482	10.201	10.933	11.683	12.440	13.204	13.972	14.739
100	9.518	10.237	10.970	11.720	12.478	13.242	14.010	14.777
Millivolts per °F.	0.00707	0.00719	0.00733	0.00750	0.00758	0.00764	0.00768	0.00767

°F.	2400°	2500°	2600°	2700°	2800°	2900°	3000°
	Millivolts						
0	14.777	15.543	16.309	17.073	17.833	18.588	19.342
5	14.815	15.581	16.347	17.111	17.871	18.626	19.379
10	14.854	15.619	16.385	17.149	17.909	18.663	19.417
15	14.892	15.658	16.423	17.187	17.947	18.701	19.455
20	14.930	15.696	16.462	17.225	17.985	18.739	19.492
25	14.969	15.734	16.500	17.263	18.022	18.777	19.530
30	15.007	15.773	16.538	17.302	18.060	18.814	19.567
35	15.045	15.811	16.576	17.340	18.098	18.852	19.605
40	15.084	15.849	16.614	17.378	18.136	18.890	19.642
45	15.122	15.887	16.653	17.416	18.173	18.927	19.680
50	15.160	15.926	16.691	17.454	18.211	18.965	19.717
55	15.198	15.964	16.729	17.492	18.249	19.003	19.755
60	15.237	16.002	16.767	17.530	18.286	19.040	19.793
65	15.275	16.041	16.805	17.568	18.324	19.078	19.830
70	15.313	16.079	16.844	17.606	18.362	19.116	19.868
75	15.352	16.117	16.882	17.643	18.400	19.154	19.905
80	15.390	16.156	16.920	17.682	18.437	19.191	19.943
85	15.428	16.194	16.958	17.720	18.475	19.229	19.980
90	15.466	16.232	16.996	17.758	18.513	19.267	20.018
95	15.505	16.270	17.035	17.795	18.550	19.304	20.055
100	15.543	16.309	17.073	17.833	18.588	19.342	20.093
Millivolts per °F.	0.00766	0.00766	0.00764	0.00760	0.00755	0.00755	0.00751

TABLE XIII.—PLATINUM VS. PLATINUM + (Degrees centigrade;

°C.	0°	100°	200°	300°	400°	500°	600°	700°	800°
	Millivolts								
0	0.000	0.646	1.464	2.394	3.398	4.454	5.561	6.720	7.927
2	0.011	0.661	1.482	2.414	3.419	4.476	5.583	6.743	7.951
4	0.022	0.676	1.500	2.433	3.439	4.497	5.606	6.767	7.976
6	0.033	0.691	1.518	2.453	3.460	4.519	5.629	6.791	8.000
8	0.044	0.706	1.536	2.472	3.480	4.540	5.652	6.815	8.025
10	0.056	0.721	1.553	2.492	3.501	4.562	5.675	6.839	8.049
12	0.067	0.736	1.570	2.512	3.521	4.583	5.698	6.862	8.073
14	0.079	0.752	1.588	2.531	3.542	4.605	5.721	6.886	8.098
16	0.090	0.767	1.606	2.551	3.563	4.627	5.744	6.910	8.123
18	0.102	0.783	1.624	2.570	3.584	4.649	5.767	6.934	8.148
20	0.113	0.798	1.642	2.590	3.605	4.671	5.790	6.958	8.173
22	0.125	0.813	1.660	2.609	3.626	4.693	5.813	6.981	8.198
24	0.137	0.829	1.678	2.629	3.647	4.715	5.836	7.005	8.222
26	0.149	0.845	1.696	2.649	3.668	4.737	5.859	7.029	8.247
28	0.161	0.861	1.714	2.669	3.689	4.759	5.882	7.053	8.271
30	0.173	0.877	1.733	2.689	3.711	4.781	5.905	7.077	8.296
32	0.185	0.893	1.851	2.709	3.732	4.803	5.928	7.100	8.321
34	0.197	0.909	1.770	2.729	3.753	4.825	5.951	7.124	8.346
36	0.209	0.925	1.788	2.749	3.774	4.847	5.974	7.148	8.371
38	0.221	0.941	1.807	2.769	3.795	4.869	5.997	7.172	8.396
40	0.234	0.957	1.825	2.789	3.816	4.891	6.020	7.196	8.421
42	0.247	0.973	1.844	2.809	3.837	4.913	6.043	7.220	8.446
44	0.259	0.990	1.862	2.829	3.858	4.935	6.066	7.244	8.471
46	0.272	1.006	1.881	2.849	3.879	4.957	6.089	7.268	8.496
48	0.284	1.023	1.899	2.869	3.900	4.979	6.112	7.292	8.521
50	0.297	1.039	1.918	2.889	3.921	5.002	6.135	7.317	8.546
52	0.310	1.055	1.937	2.909	3.942	5.024	6.158	7.341	8.571
54	0.324	1.072	1.955	2.929	3.963	5.046	6.181	7.365	8.596
56	0.337	1.088	1.974	2.949	3.984	5.068	6.204	7.389	8.621
58	0.351	1.105	1.992	2.969	4.005	5.090	6.227	7.413	8.646
60	0.364	1.121	2.011	2.990	4.027	5.113	6.251	7.438	8.671
62	0.377	1.138	2.030	3.010	4.048	5.135	6.274	7.462	8.696
64	0.391	1.154	2.049	3.030	4.069	5.157	6.298	7.487	8.721
66	0.404	1.171	2.068	3.050	4.090	5.179	6.321	7.511	8.746
68	0.418	1.187	2.087	3.070	4.111	5.201	6.345	7.536	8.771
70	0.431	1.204	2.106	3.091	4.133	5.224	6.368	7.560	8.796
72	0.444	1.221	2.125	3.111	4.154	5.246	6.391	7.584	8.821
74	0.458	1.238	2.144	3.132	4.175	5.269	6.415	7.609	8.847
76	0.472	1.255	2.163	3.152	4.196	5.291	6.438	7.633	8.872
78	0.486	1.272	2.182	3.173	4.217	5.314	6.462	7.658	8.898
80	0.500	1.290	2.201	3.193	4.239	5.336	6.485	7.682	8.923
82	0.514	1.307	2.220	3.213	4.260	5.358	6.508	7.706	8.948
84	0.529	1.324	2.239	3.234	4.282	5.381	6.532	7.731	8.973
86	0.543	1.341	2.258	3.254	4.303	5.403	6.555	7.755	8.998
88	0.558	1.358	2.277	3.275	4.325	5.426	6.579	7.780	9.023
90	0.572	1.376	2.297	3.295	4.346	5.448	6.602	7.804	9.049
92	0.587	1.394	2.316	3.316	4.368	5.471	6.626	7.829	9.075
94	0.602	1.411	2.336	3.336	4.389	5.493	6.649	7.853	9.100
96	0.617	1.429	2.355	3.357	4.411	5.516	6.673	7.878	9.126
98	0.632	1.446	2.375	3.377	4.432	5.538	6.696	7.902	9.151
100	0.646	1.464	2.394	3.398	4.454	5.561	6.720	7.927	9.177
Millivolts per °C.	0.00646	0.00818	0.00930	0.01004	0.01056	0.01107	0.01159	0.01207	0.01250

13 PER CENT RHODIUM THERMOCOUPLE
reference junction 0°C.)

°C.	900°	1000°	1100°	1200°	1300°	1400°	1500°	1600°
	Millivolts							
0	9.177	10.470	11.811	13.181	14.563	15.940	17.316	18.680
2	9.202	10.496	11.838	13.208	14.591	15.968	17.343	18.707
4	9.228	10.522	11.865	13.236	14.618	15.995	17.371	18.734
6	9.253	10.548	11.892	13.263	14.646	16.023	17.398	18.761
8	9.279	10.574	11.919	13.291	14.673	16.050	17.426	18.788
10	9.304	10.601	11.947	13.318	14.701	16.078	17.453	18.815
12	9.330	10.627	11.974	13.346	14.728	16.105	17.480	18.842
14	9.355	10.654	12.002	13.373	14.756	16.133	17.508	18.869
16	9.381	10.680	12.029	13.401	14.783	16.160	17.535	18.896
18	9.406	10.707	12.057	13.428	14.811	16.188	17.563	18.923
20	9.432	10.733	12.084	13.456	14.838	16.215	17.590	18.951
22	9.458	10.759	12.111	13.483	14.865	16.242	17.617	18.978
24	9.483	10.786	12.138	13.511	14.893	16.270	17.645	19.005
26	9.509	10.813	12.165	13.539	14.920	16.298	17.672	19.032
28	9.534	10.840	12.192	13.567	14.948	16.326	17.700	19.059
30	9.560	10.867	12.219	13.595	14.975	16.354	17.727	19.087
32	9.585	10.894	12.246	13.623	15.002	16.381	17.754	19.114
34	9.611	10.920	12.274	13.650	15.030	16.409	17.782	19.141
36	9.637	11.947	12.301	13.678	15.038	16.437	17.809	19.168
38	9.663	10.973	12.329	13.705	15.086	16.465	17.837	19.195
40	9.689	11.000	12.356	13.733	15.114	16.493	17.864	19.222
42	9.715	11.027	12.383	13.761	15.142	16.521	17.891	19.249
44	9.740	11.054	12.411	13.788	15.169	16.548	17.918	19.276
46	9.766	11.081	12.438	13.816	15.197	16.576	17.945	19.303
48	9.791	11.108	12.466	13.843	15.224	16.603	17.972	19.330
50	9.817	11.135	12.493	13.871	15.252	16.631	18.000	19.357
52	9.843	11.161	12.520	13.898	15.279	16.659	18.027	19.384
54	9.869	11.188	12.548	13.926	15.307	16.686	18.054	19.411
56	9.895	11.215	12.575	13.954	15.334	16.714	18.081	19.438
58	9.921	11.242	12.603	13.982	15.362	16.741	18.108	19.465
60	9.947	11.269	12.630	14.010	15.389	16.769	18.135	19.492
62	9.973	11.296	12.658	14.037	15.417	16.796	18.162	19.519
64	9.999	11.323	12.685	14.065	15.444	16.824	18.189	19.546
66	10.025	11.350	12.713	14.092	15.472	16.851	18.216	19.573
68	10.051	11.377	12.740	14.120	15.499	16.879	18.243	19.600
70	10.078	11.404	12.768	14.147	15.527	16.906	18.271	19.627
72	10.104	11.431	12.796	14.175	15.554	16.933	18.298	19.654
74	10.130	11.458	12.823	14.202	15.582	16.961	18.325	19.681
76	10.156	11.485	12.851	14.230	15.609	16.988	18.352	19.708
78	10.182	11.512	12.878	14.257	15.637	17.016	18.379	19.735
80	10.208	11.540	12.906	14.285	15.664	17.043	18.407	19.762
82	10.234	11.567	12.933	14.312	15.691	17.070	18.434	19.789
84	10.260	11.594	12.961	14.340	15.719	17.098	18.461	19.816
86	10.286	11.621	12.988	14.368	15.747	17.125	18.488	19.843
88	10.312	11.648	13.016	14.396	15.775	17.153	18.515	19.870
90	10.339	11.676	13.043	14.424	15.803	17.180	18.543	19.897
92	10.365	11.703	13.071	14.451	15.830	17.207	18.570	19.924
94	10.391	11.730	13.098	14.479	18.858	17.234	18.598	19.951
96	10.417	11.757	13.126	14.507	15.885	17.261	18.625	19.978
98	10.443	11.784	13.153	14.535	15.913	17.288	18.653	20.005
100	10.470	11.811	13.181	14.563	15.940	17.316	18.680	20.032
Millivolts per °C.	0.01293	0.01341	0.01370	0.01382	0.01377	0.01376	0.01364	0.01352

TABLE XIV.—COPPER VS. CONSTANTAN THERMOCOUPLE
(Degrees Fahrenheit; reference junction 32°F.)

°F.	Millivolts	°F.	Millivolts	°F.	Millivolts	°F.	Millivolts	°F.	Millivolts	°F.	Millivolts
0	−0.67	100	1.52	200	3.97	300	6.64	400	9.52	500	12.57
2	0.63	102	1.56	202	4.02	302	6.70	402	9.58	502	12.63
4	0.59	104	1.61	204	4.07	304	6.76	404	9.64	504	12.70
6	0.55	106	1.66	206	4.12	306	6.81	406	9.70	506	12.76
8	0.51	108	1.70	208	4.17	308	6.87	408	9.76	508	12.82
10	−0.46	110	1.75	210	4.22	310	6.92	410	9.82	510	12.89
12	0.42	112	1.80	212	4.28	312	6.98	412	9.88	512	12.95
14	0.38	114	1.84	214	4.33	314	7.04	414	9.94	514	13.01
16	0.34	116	1.89	216	4.38	316	7.09	416	10.00	516	13.07
18	0.30	118	1.94	218	4.43	318	7.15	418	10.06	518	13.14
20	−0.25	120	1.99	220	4.48	320	7.21	420	10.12	520	13.20
22	0.21	122	2.03	222	4.54	322	7.26	422	10.18	522	13.26
24	0.17	124	2.08	224	4.59	324	7.32	424	10.24	524	13.33
26	0.13	126	2.13	226	4.64	326	7.38	426	10.30	526	13.39
28	0.09	128	2.18	228	4.69	328	7.43	428	10.36	528	13.45
30	−0.04	130	2.23	230	4.75	330	7.49	430	10.42	530	13.52
32	0	132	2.27	232	4.80	332	7.55	432	10.48	532	13.58
34	+0.04	134	2.32	234	4.85	334	7.60	434	10.54	534	13.64
36	0.09	136	2.37	236	4.91	336	7.66	436	10.60	536	13.71
38	0.13	138	2.42	238	4.96	338	7.72	438	10.66	538	13.77
40	0.17	140	2.47	240	5.01	340	7.77	440	10.72	540	13.83
42	0.22	142	2.52	242	5.07	342	7.83	442	10.78	542	13.90
44	0.26	144	2.56	244	5.12	344	7.89	444	10.84	544	13.96
46	0.30	146	2.61	246	5.17	346	7.95	446	10.90	546	14.02
48	0.35	148	2.66	248	5.23	348	8.00	448	10.97	548	14.09
50	0.39	150	2.71	250	5.28	350	8.06	450	11.03	550	14.15
52	0.43	152	2.76	252	5.33	352	8.12	452	11.09	552	14.22
54	0.48	154	2.81	254	5.39	354	8.18	454	11.15	554	14.28
56	0.52	156	2.86	256	5.44	356	8.23	456	11.21	556	14.34
58	0.57	158	2.91	258	5.49	358	8.29	458	11.27	558	14.41
60	0.61	160	2.96	260	5.55	360	8.35	460	11.33	560	14.47
62	0.65	162	3.01	262	5.60	362	8.41	462	11.39	562	14.54
64	0.70	164	3.06	264	5.66	364	8.47	464	11.45	564	14.60
66	0.74	166	3.11	266	5.71	366	8.52	466	11.52	566	14.66
68	0.79	168	3.16	268	5.76	368	8.58	468	11.58	568	14.73
70	0.83	170	3.21	270	5.82	370	8.64	470	11.64	570	14.79
72	0.88	172	3.26	272	5.87	372	8.70	472	11.70	572	14.86
74	0.92	174	3.31	274	5.93	374	8.76	474	11.76	574	14.92
76	0.97	176	3.36	276	5.98	376	8.81	476	11.82	576	14.99
78	1.01	178	3.41	278	6.04	378	8.87	478	11.89	578	15.05
80	1.06	180	3.46	280	6.09	380	8.93	480	11.95	580	15.12
82	1.10	182	3.51	282	6.15	382	8.99	482	12.01	582	15.13
84	1.15	184	3.56	284	6.20	384	9.05	484	12.07	584	15.25
86	1.19	186	3.61	286	6.26	386	9.11	486	12.13	586	15.31
88	1.24	188	3.66	288	6.31	388	9.17	488	12.20	588	15.38
90	1.29	190	3.71	290	6.37	390	9.23	490	12.26	590	15.44
92	1.33	192	3.76	292	6.42	392	9.29	492	12.32	592	15.51
94	1.38	194	3.81	294	6.48	394	9.34	494	12.38	594	15.57
96	1.42	196	3.86	296	6.53	396	9.40	496	12.45	596	15.64
98	1.47	198	3.91	298	6.59	398	9.46	498	12.51	598	15.70
100	1.52	200	3.97	300	6.64	400	9.52	500	12.57	600	15.77
Millivolts per °F.	0.022	Millivolts per °F.	0.025	Millivolts per °F.	0.027	Millivolts per °F.	0.029	Millivolts per °F.	0.031	Millivolts per °F.	0.032

TABLE XV.—COPPER VS. CONSTANTAN THERMOCOUPLE
(Degrees centigrade; reference junction 0°C.)

°C.	Millivolts	°C.	Millivolts	°C.	Millivolts	°C.	Millivolts	°C.	Millivolts	°C.	Millivolts
0	0.00	50	2.03	100	4.28	150	6.70	200	9.29	250	12.01
1	0.04	51	2.08	101	4.32	151	6.75	201	9.34	251	12.07
2	0.08	52	2.12	102	4.37	152	6.80	202	9.39	252	12.12
3	0.12	53	2.16	103	4.42	153	6.85	203	9.44	253	12.18
4	0.16	54	2.21	104	4.46	154	6.90	204	9.50	254	12.23
5	0.19	55	2.25	105	4.51	155	6.95	205	9.55	255	12.29
6	0.23	56	2.29	106	4.56	156	7.00	206	9.60	256	12.35
7	0.27	57	2.34	107	4.61	157	7.05	207	9.66	257	12.40
8	0.31	58	2.38	108	4.65	158	7.10	208	9.71	258	12.46
9	0.35	59	2.42	109	4.70	159	7.15	209	9.77	259	12.51
10	0.39	60	2.47	110	4.75	160	7.21	210	9.82	260	12.57
11	0.43	61	2.51	111	4.79	161	7.26	211	9.87	261	12.63
12	0.47	62	2.56	112	4.84	162	7.31	212	9.93	262	12.68
13	0.51	63	2.60	113	4.89	163	7.36	213	9.98	263	12.74
14	0.55	64	2.64	114	4.94	164	7.41	214	10.04	264	12.80
15	0.59	65	2.69	115	4.99	165	7.46	215	10.09	265	12.85
16	0.63	66	2.73	116	5.03	166	7.51	216	10.14	266	12.91
17	0.67	67	2.78	117	5.08	167	7.56	217	10.20	267	12.97
18	0.71	68	2.82	118	5.13	168	7.61	218	10.25	268	13.02
19	0.75	69	2.86	119	5.18	169	7.66	219	10.31	269	13.08
20	0.79	70	2.91	120	5.23	170	7.72	220	10.36	270	13.14
21	0.83	71	2.95	121	5.27	171	7.77	221	10.41	271	13.19
22	0.87	72	3.00	122	5.32	172	7.82	222	10.47	272	13.25
23	0.91	73	3.04	123	5.37	173	7.87	223	10.52	273	13.31
24	0.95	74	3.09	124	5.42	174	7.92	224	10.58	274	13.36
25	0.99	75	3.13	125	5.47	175	7.97	225	10.63	275	13.42
26	1.03	76	3.18	126	5.51	176	8.03	226	10.69	276	13.48
27	1.07	77	3.22	127	5.56	177	8.08	227	10.74	277	13.54
28	1.11	78	3.27	128	5.61	178	8.13	228	10.80	278	13.59
29	1.15	79	3.31	129	5.66	179	8.18	229	10.85	279	13.65
30	1.19	80	3.36	130	5.71	180	8.23	230	10.91	280	13.71
31	1.24	81	3.40	131	5.76	181	8.29	231	10.96	281	13.76
32	1.28	82	3.45	132	5.81	182	8.34	232	11.02	282	13.82
33	1.32	83	3.49	133	5.86	182	8.39	233	11.07	283	13.88
34	1.36	84	3.54	134	5.91	184	8.44	234	11.13	284	13.93
35	1.40	85	3.58	135	5.96	185	8.49	235	11.18	285	13.99
36	1.44	86	3.63	136	6.00	186	8.55	236	11.24	286	14.05
37	1.48	87	3.67	137	6.05	187	8.60	237	11.29	287	14.11
38	1.53	88	3.72	138	6.10	188	8.65	238	11.35	288	14.16
39	1.57	89	3.77	139	6.15	189	8.70	239	11.40	289	14.22
40	1.61	90	3.81	140	6.20	190	8.76	240	11.46	290	14.28
41	1.65	91	3.86	141	6.25	191	8.81	241	11.51	291	14.34
42	1.69	92	3.90	142	6.30	192	8.86	242	11.57	292	14.40
43	1.74	93	3.95	143	6.35	193	8.91	243	11.62	293	14.45
44	1.78	94	4.00	144	6.40	194	8.97	244	11.68	294	14.51
45	1.82	95	4.04	145	6.45	195	9.02	245	11.73	295	14.57
46	1.86	96	4.09	146	6.50	196	9.07	246	11.79	296	14.63
47	1.91	97	4.14	147	6.55	197	9.13	247	11.84	297	14.69
48	1.95	98	4.18	148	6.60	198	9.18	248	11.90	298	14.74
49	1.99	99	4.23	149	6.65	199	9.23	249	11.95	299	14.80
50	2.03	100	4.28	150	6.70	200	9.29	250	12.01	300	14.86
Millivolts per °C.	0.041	Millivolts per °C.	0.045	Millivolts per °C.	0.048	Millivolts per °C.	0.052	Millivolts per °C.	0.054	Millivolts per °C.	0.057

TABLE XVI.—COPPER VS. CONSTANTAN THERMOCOUPLE
(Degrees Fahrenheit; below ice point, reference junction 32°F.)

°F.	Millivolts	°F.	Millivolts	°F.	Millivolts	°F.	Millivolts
.....	....	−300	5.28	−200	4.11	−100	2.56
.....	....	298	5.26	198	4.08	98	2.53
.....	....	296	5.24	196	4.05	96	2.49
.....	....	294	5.22	194	4.03	94	2.46
.....	....	292	5.20	192	4.00	92	2.42
.....	....	−290	5.18	−190	3.97	−90	2.39
.....	....	288	5.16	188	3.94	88	2.35
.....	....	286	5.14	186	3.91	86	2.32
.....	....	284	5.12	184	3.89	84	2.28
.....	....	282	5.10	182	3.86	82	2.24
.....	....	−280	5.08	−180	3.83	−80	2.21
.....	....	278	5.06	178	3.80	78	2.17
.....	....	276	5.04	176	3.77	76	2.14
.....	....	274	5.02	174	3.74	74	2.10
.....	....	272	4.99	172	3.71	72	2.06
.....	....	−270	4.97	−170	3.68	−70	2.03
.....	....	268	4.95	168	3.65	68	1.99
.....	....	266	4.93	166	3.62	66	1.95
.....	....	264	4.91	164	3.59	64	1.92
.....	....	262	4.88	162	3.56	62	1.88
.....	....	−260	4.86	−160	3.53	−60	1.84
.....	....	258	4.84	158	3.50	58	1.81
.....	....	256	4.81	156	3.47	56	1.77
.....	....	254	4.79	154	3.44	54	1.73
.....	....	252	4.77	152	3.41	52	1.69
.....	....	−250	4.74	−150	3.38	−50	1.66
.....	....	248	4.72	148	3.35	48	1.62
.....	....	246	4.70	146	3.32	46	1.58
.....	....	244	4.67	144	3.29	44	1.54
.....	....	242	4.65	142	3.25	42	1.50
.....	.....	−240	4.63	−140	3.22	−40	1.46
.....	....	238	4.60	138	3.19	38	1.43
.....	....	236	4.58	136	3.16	36	1.39
.....	....	234	4.55	134	3.13	34	1.35
.....	....	232	4.53	132	3.09	32	1.31
.....	....	−230	4.50	−130	3.06	−30	1.27
.....	....	228	4.48	128	3.03	28	1.23
−326	5.52	226	4.45	126	3.00	26	1.19
324	5.50	224	4.43	124	2.96	24	1.15
322	5.49	222	4.40	122	2.93	22	1.11
−320	5.47	−220	4.38	−120	2.90	−20	1.07
318	5.45	218	4.35	118	2.86	18	1.03
316	5.43	216	4.32	116	2.83	16	0.99
314	5.41	214	4.30	114	2.80	14	0.95
312	5.40	212	4.27	112	2.76	12	0.91
−310	5.38	−210	4.24	−110	2.73	−10	0.87
308	5.36	208	4.22	108	2.70	8	0.83
306	5.34	206	4.19	106	2.66	6	0.79
304	5.32	204	4.16	104	2.63	4	0.75
302	5.30	202	4.14	102	2.59	2	0.71
−300	5.28	−200	4.11	−100	2.56	0	0.67
Millivolts per °F.	0.009	Millivolts per °F.	0.012	Millivolts per °F.	0.016	Millivolts per °F.	0.019

TABLE XVII.—COPPER VS. CONSTANTAN THERMOCOUPLE
(Degrees centigrade; below ice point, reference junction 0°C.)

°C.	Millivolts	°C.	Millivolts	°C.	Millivolts	°C.	Millivolts
−200	5.54	−150	4.60	−100	3.35	−50	1.81
199	5.52	149	4.58	99	3.32	49	1.77
198	5.51	148	4.56	98	3.29	48	1.74
197	5.49	147	4.54	97	3.27	47	1.71
196	5.48	146	4.51	96	3.24	46	1.67
−195	5.46	−145	4.49	−95	3.21	−45	1.64
194	5.44	144	4.47	94	3.18	44	1.60
193	5.43	143	4.45	93	3.15	43	1.57
192	5.41	142	4.42	92	3.12	42	1.54
191	5.40	141	4.40	91	3.09	41	1.50
−190	5.38	−140	4.38	−90	3.06	−40	1.47
189	5.36	139	4.35	89	3.03	39	1.43
188	5.34	138	4.33	88	3.01	38	1.40
187	5.33	137	4.31	87	2.98	37	1.36
186	5.31	136	4.28	86	2.95	36	1.33
−185	5.29	−135	4.26	−85	2.92	−35	1.29
184	5.28	134	4.23	84	2.89	34	1.26
183	5.26	133	4.21	83	2.86	33	1.22
182	5.24	132	4.19	82	2.83	32	1.19
181	5.22	131	4.16	81	2.80	31	1.15
−180	5.20	−130	4.14	−80	2.77	−30	1.11
179	5.19	129	4.11	79	2.74	29	1.08
178	5.17	128	4.09	78	2.70	28	1.04
177	5.15	127	4.06	77	2.67	27	1.01
176	5.13	126	4.04	76	2.64	26	0.97
−175	5.11	−125	4.01	−75	2.61	−25	0.93
174	5.09	124	3.99	74	2.58	24	0.90
173	5.07	123	3.96	73	2.55	23	0.86
172	5.05	122	3.94	72	2.52	22	0.83
171	5.04	121	3.91	71	2.49	21	0.79
−170	5.02	−120	3.89	−70	2.46	−20	0.75
169	5.00	119	3.86	69	2.43	19	0.72
168	4.98	118	3.83	68	2.39	18	0.68
167	4.96	117	3.81	67	2.36	17	0.64
166	4.94	116	3.78	66	2.33	16	0.60
−165	4.92	−115	3.76	−65	2.30	−15	0.57
164	4.90	114	3.73	64	2.27	14	0.53
163	4.88	113	3.70	63	2.23	13	0.49
162	4.86	112	3.68	62	2.20	12	0.46
161	4.84	111	3.65	61	2.17	11	0.42
−160	4.82	−110	3.62	−60	2.14	−10	0.38
159	4.79	109	3.60	59	2.10	9	0.34
158	4.77	108	3.57	58	2.07	8	0.31
157	4.75	107	3.54	57	2.04	7	0.27
156	4.73	106	3.52	56	2.01	6	0.23
−155	4.71	−105	3.49	−55	1.97	−5	0.19
154	4.69	104	3.46	54	1.94	4	0.15
153	4.67	103	3.43	53	1.91	3	0.12
152	4.65	102	3.41	52	1.87	2	0.08
151	4.62	101	3.38	51	1.84	1	0.04
−150	4.60	−100	3.35	−50	1.81	0	0.00
Millivolts per °C.	0.019	Millivolts per °C.	0.025	Millivolts per °C.	0.031	Millivolts per °C.	0.036

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