Precision Measurement and Calibration

Temperature

Special Publication 300

Volume 2

United States Department of Commerce

National Bureau of Standards

UNITED STATES DEPARTMENT OF COMMERCE • C. R. Smith, *Secretary*
U.S. NATIONAL BUREAU OF STANDARDS • A. V. Astin, *Director*

Precision Measurement and Calibration

Selected NBS Papers on

Temperature

J. F. Swindells, Editor

A compilation of previously published papers by the staff of the National Bureau of Standards, including selected abstracts by NBS and non-NBS authors. Issued in several volumes, see page IV.

NBS Special Publication 300 — Volume 2

Issued August 1968

(Supersedes in part Handbook 77—Volume II)

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 - Price $4.75

Abstract

This volume is one of an extended series which brings together the previously published papers, monographs, abstracts, and bibliographies by NBS authors dealing with the precision measurement of specific physical quantities and the calibration of the related metrology equipment. The contents have been selected as being useful to the standards laboratories of the United States in tracing to NBS standards the accuracies of measurement needed for research work, factory production, or field evaluation.

Volume 2 contains reprints through June 1967 covering the general topics: Uncertainties, Temperature Scales, Resistance Thermometry, Thermoelectric Thermometry, Liquid-in-Glass Thermometry, Optical Pyrometry, and Spectroscopic Thermometry. A selected bibliography covering the period from January 1953 through December 1965 is included.

Key words: Acoustical thermometry, cerous magnesium nitrate thermometer, error analysis, liquid-in-glass thermometry, reprints, resistance thermometry, spectroscopic thermometry, standards, temperature scales, thermoelectric thermometry.

Foreword

In the 1950's the tremendous increase in industrial activity, particularly in the missile and satellite fields, led to an unprecedented demand for precision measurement, which, in turn, brought about the establishment of hundreds of new standards laboratories. To aid these laboratories in transmitting the accuracies of the national standards to the shops of industry, NBS in 1959 gathered together and reprinted a number of technical papers by members of its staff describing methods of precision measurements and the design and calibration of standards and instruments. These reprints, representing papers written over a period of several decades, were published as NBS Handbook 77, Precision Measurement and Calibration, in three volumes: Electricity and Electronics; Heat and Mechanics; Optics, Metrology, and Radiation.

Some of the papers in Handbook 77 are still useful, but new theoretical knowledge, improved materials, and increasingly complex experimental techniques have so advanced the art and science of measurement that a new compilation has become necessary. The present volume is part of a new reprint collection, designated NBS Special Publication 300, which has been planned to fill this need. Besides previously published papers by the NBS staff, the collection includes selected abstracts by both NBS and non-NBS authors. It is hoped that this new compilation of several volumes will serve both as a textbook and as a reference source for the many scientists and engineers who fill responsible positions in standards laboratories.

A. V. ASTIN, *Director.*

Preface

The general plan for this compilation has been reviewed by the Information Committee of the National Conference of Standards Laboratories. The plan calls for Special Publication 300 to be published in 12 volumes having the following titles and editors:

Statistical Concepts and Procedures, H. H. Ku
Frequency and Time, A. H. Morgan
Electricity—Low Frequency, F. L. Hermach and R. F. Dziuba
Electricity—Radio Frequency, A. J. Estin
Heat, D. C. Ginnings
Temperature, J. F. Swindells
Mechanics, R. L. Bloss
Dimensional Metrology—Length and Angle, H. K. Hammond, III
Radiometry and Photometry, H. K. Hammond, III
Colorimetry and Image Optics, H. K. Hammond, III
Spectrochemical Analysis, B. F. Scribner
Ionizing Radiation, E. H. Eisenhower

This division of subject matter has been chosen to assure knowledgeable selection of content rather than to attain uniform size. However, the larger volumes, of approximately 600 pages, will still be small enough for convenient handling in the laboratory. The compilation consists primarily of original papers by NBS authors which have been reprinted by photoreproduction, with occasional updating of graphs or numerical data when this has appeared desirable. In addition, some important publications by non-NBS authors, as well as publications by NBS authors that are too long to be included, are represented by abstracts or references.

Each volume has a subject index and author index, and within each volume, contents are grouped by subtopics to facilitate browsing. Many entries follow the recent Bureau practice of assigning several key words to each document. Each paper reproduced for the compilation is essentially complete as originally published, retaining its original page numbers. In addition, all pages have been numbered in regular sequence throughout each volume. Thus, each page carries the volume page number and the original page number, for example, 201–32. In the index, an entry is referred to a volume number, boldface, and a volume page number, for example, 2–201. A convenient list of SI (Système International) physical units and conversion factors is to be found inside the back cover.

The publications listed herein for which a price is indicated are available from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 (foreign postage, one-fourth additional). Many documents in the various NBS nonperiodical series are also available from the NBS Clearinghouse for Federal Scientific and Technical Information, Springfield, Va. 22151. Reprints from the NBS Journal of Research or from non-NBS journals may sometimes be obtained directly from an author.

Suggestions as to the selection of papers which should be included in future editions will be welcome. Current developments in measurement technology at NBS are covered in annual seminars held at either the Gaithersburg (Maryland) or the Boulder (Colorado) laboratories. These developments are summarized, along with a running list of publications by NBS authors, in the monthly NBS Technical News Bulletin.

H. L. Mason,
Coordinator for Measurement Services
NBS Institute for Basic Standards.

Editor's Note

With few exceptions, the papers are reprinted in this volume in unabridged form. Since the NBS Provisional Scale of 1955 has not been specifically described elsewhere in print, a paragraph explaining the Scale has been inserted preceding the Technical News Bulletin note on "Corrections for use in low-temperature platinum resistance thermometry".

Because the emphasis here is on measurement techniques, the actual tables have been deleted from the two papers, "Reference tables for the Pt–30 percent Rh versus Pt–6 percent Rh thermocouple", and "Reference tables for 40 percent iridium–60 percent rhodium versus iridium thermocouples". Reprints, complete with the tables, are available from the Heat Division, National Bureau of Standards.

It should be pointed out that in several of these papers "Certificates" are referred to, while under current NBS practice "Reports of Calibration" are issued rather than certificates. Also, in 1964 the NBS adopted the "International System of Units" for use by its staff, except where use of these units would obviously impair communication or would reduce the usefulness of a publication to the primary recipients. In this volume the units used by the authors have been left as originally published. The list of recommended units is given inside the back cover.

J. F. Swindells, *Editor.*

Contents

Expression of Uncertainties

Temperature Scales

Resistance Thermometry

Thermoelectric Thermometry

Liquid-in-Glass Thermometry

Optical Pyrometry

Spectroscopic Thermometry

Selected Bibliography January 1953 to December 1965

Expression of Uncertainties

Expression of the Uncertainties of Calibration

Churchill Eisenhart

Senior Research Fellow, National Bureau of Standards

AND

A Tabular Guide to Commonly Used Terms and Expression

H. H. Ku

Institute for Basic Standards
National Bureau of Standards

Synopsis

Final results and their respective uncertainties should be reported in sentence form whenever possible. The short-hand form "$a \pm b$" should be avoided in abstracts and summaries; and never used without explicit explanation of its connotation. If no explanation is given, many persons will take $\pm b$, to signify bounds to the inaccuracy of a. Others may assume that b is the "standard error," or the "probable error," of a, and hence the uncertainty of a is at least $\pm 3b$, or $\pm 4b$, respectively. Still others may take b to be an indication merely of the imprecision or dispersion of the individual measurements, that is, to be the "standard deviation," or the "average deviation," or the "probable error" of a SINGLE observation. Each of these interpretations reflects a practice of which instances can be found in current scientific literature.

The terms "standard deviation" and "standard error" should be reserved to denote the canonical values for the measurement process, based on considerable recent experience with the measurement process or processes involved. When there is insufficient recent experience, a value for the standard error (or standard deviation) must often of necessity be computed by recognized statistical procedures from the same measurements as the reported value itself. To avoid possible misunderstanding, in such cases, the term "computed standard error" ("computed standard deviation") should be used.

If the uncertainty in the accepted value of a national standard or of some fundamental constant of nature (e.g., in the volt as maintained at the National Bureau of Standards, or in the acceleration of gravity g on the Potsdam basis) is an important source of systematic error affecting the measurement of some other quantity of primary interest, the "accepted value" actually utilized should be given explicitly, and no allowance for possible systematic error from this source should be included ordinarily, in evaluating over-all bounds to the systematic error of the quantity of primary interest.

In quoting a reported value and its associated uncertainty from the literature, the interpretation of the uncertainty quoted should be stated if given by the author. If the interpretation is not known, a remark to this effect is in order.

No single form of expression for indicating the uncertainty of a reported value is universally satisfactory. Different forms of expression are called for, depending on the relative magnitudes of the imprecision and likely bias, and their relative importance in relation to the intended use of the reported value, as well as to other possible uses to which it may be put.

Four distinct cases need to be recognized: (1) both systematic error and imprecision negligible in relation to the requirements of the intended and likely uses of the result; (2) systematic error not negligible, but imprecision negligible; (3) neither systematic error nor imprecision negligible; and (4) systematic error negligible, but imprecision not negligible.

Since imprecision and systematic error are distinctly different components of inaccuracy, and are subject to different treatments and interpretations in usage, two numerics, respectively, expressing the imprecision and bounds to the systematic error of the reported result, should be used whenever both of these errors are factors requiring consideration. Specific recommendations with respect to each of the foregoing cases are given.

The annotated guide gives a comprehensive listing of commonly used expressions of imprecision, systematic error, and uncertainty associated with a reported value.

The companion papers of which the preceding is a synopsis, have been submitted to technical journals for publication and are to be reprinted in full in NBS Special Publication 300, Volume 1, Precision Measurement and Calibration—Statistical Concepts and Procedures. (For an earlier version of the first paper, see Chapter 23 of NBS Handbook 91, Experimental Statistics).*

---

*Available for $4.25 from the Superintendent of Documents, Government Printing Office, Washington, D.C. 20402.

Temperature Scales

Reprinted from TEMPERATURE--ITS MEASUREMENT AND CONTROL IN SCIENCE AND INDUSTRY, Vol. 3, Part 1
1962 Reinhold Publishing Corp., New York, N. Y.

6. The Thermodynamic Temperature Scale, Its Definition and Realization

C. M. HERZFELD

National Bureau of Standards, Washington, D. C.

REMARKS ON TEMPERATURE

Temperature is one of the primary quantities, along with length, time, and mass, but it is a different kind of concept than these. It is subtle, in some ways, and requires very precise definition. Several papers in this volume treat various aspects of the concept of temperature. Lindsay[1] treats the basic concept of temperature, as obtained in thermodynamics and statistical mechanics. The nature of non-equilibrium thermodynamics becomes important in non-equilibrium systems, and is discussed by Callen.[2] The approach to equilibrium can be worked out exactly in detail for certain simple systems, and Shuler[3] shows how instructive results can be obtained. Certain general considerations about temperature are presented by McNish.[4]

Two basic points must be made concerning the general concept of temperature:

(1) The thermodynamic concept of temperature is an idealization. It is based on considerations of reversible processes, and of equilibrium. But no real measurement is reversible, and no real system is completely in equilibrium. (There is always a heat leak somewhere.) The problem is, therefore, to make the departures from equilibrium slight. If this can be achieved, then statistical mechanics indicates that the results of thermodynamics are correct in the limit of small disturbances.

(2) For systems which are not wholly in thermodynamic equilibrium, but where the departures from it are slight, it is possible to assume the existence of "local thermodynamic equilibrium," i.e., that the material in each small region of space is in thermodynamic equilibrium with itself, and in a steady state with respect to changes involving neighboring regions of space. It is then possible to ascribe a temperature to this region, and the temperature will be a function of space and time.

These remarks may help to set this paper in a suitable context of general ideas. The aims of this paper are to give a general survey of the thermodynamic temperature scale and to discuss both its definition and its realization. The paper is not addressed to the specialist in temperature scales and is an elementary introduction to the more specialized papers which follow.

The matter of definition and realization of temperature scales is a matter wherein great care in analysis and experimentation is necessary. This review will attempt to deal with the principal ideas and methods and will omit discussions of experimental detail. For greater detail on a variety of matters the reader will be referred to other papers, some of them in these volumes.

Temperature scales can be devised in a variety of ways. In principle, nearly every property of a material which changes with temperature in a well defined way can serve as a thermometric substance, and the changes of this property could be used to define a temperature scale. Thus, for example, the expansion of mercury with temperature makes possible the mercury-in-glass thermometer, and has been the basis of a temperature scale. Let us denote temperature, as measured on such an arbitrary scale, by t. Some properties (and some materials) are better than others for the establishment of a scale. It is easy to see that the coefficient of thermal expansion of water would not provide a good thermometer around 4°C. Its temperature variation of density is such that answers obtained there would be quite confusing. The variety of thermometric systems (material and property) which are of practical use is enormous. But is is obvious that a temperature scale which is easily or fundamentally defined is desirable. In fact two such scales exist. One is relatively easily defined, it is the so-called International Practical Temperature Scale. It is discussed by Stimson.[5] The other scale is easily given a good theoretical foundation; it is the thermodynamic temperature scale. It is defined using the laws of thermodynamics and some additional arbitrary definitions (which should be held to the theoretical minimum of two definitions). It is a scale which is independent of the material used, or of the specific details of the experiment. In other words, it is a scale which is as near to a *true* scale as it is possible to come.

THE THERMODYNAMIC TEMPERATURE SCALE DEFINED

The basic definition of the Thermodynamic Temperature Scale is closely tied to the second law of thermodynamics. A simple, but rigorous definition can be given with the aid of the Carnot heat engine. While the use of Carnot cycles is perhaps never essential for thermodynamic derivations, it provides a good method for demonstration and explanation. For a discussion of the theory of Carnot cycles, see, for example, Zemansky.[6]

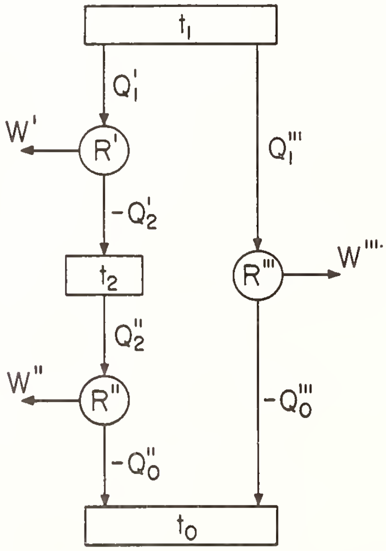


Fig. 1. Heat engines used for the classical definition of the thermodynamic temperature scale.

Table 1

Engine:	R'	R''	R'''
Work produced in surroundings:	W'	W''	W'''
Heat withdrawn from reservoir at t_1:	Q_1'	—	Q_1'''
Heat withdrawn from reservoir at t_2:	Q_2'	Q_2''	—
Heat withdrawn from reservoir at t_0:	—	Q_0''	Q_0'''

Consider[7] three Carnot heat engines R', R'', and R''', which are connected to three heat reservoirs, at temperatures t_1, t_2, and t_0. (These temperatures can be measured with any practical thermometer which has a monotonic behavior, i.e., one which does not produce the kind of ambiguity the water-in-glass thermometer does near 4°C.) Further, assume that $t_1 > t_2 > t_0$. Let the engines operate between the reservoirs as indicated in Fig. 1, and let the arrows give the directions of flow of heat. The relations of the various quantities are then given in Table 1. The Carnot engines can be run in a variety of ways. Let them operate in such a direction that Q_2', Q_0'', and Q_0''' are all negative. (This means that heat flows into the reservoirs at t_2 and t_0.) All other heat flows and all work produced will therefore be positive. It is obviously possible to adjust the engines in such a way that

$$Q_1' = Q_1''' \tag{1}$$

and

$$Q_2' = -Q_2'' \tag{2}$$

that is, equal amounts of heat flow into engines R' and R''' from t_1, and also, just as much heat is taken out of t_2 by R'' as is put into it by R'. Thus the reservoir t_2 does not change its state at all. The second law of thermodynamics requires that

$$W' + W'' = W''' \tag{3}$$

and

$$Q_0'' = Q_0''' \tag{4}$$

This is obvious if we consider R' and R'' as a single engine, operating between the same two reservoirs as R''', and withdrawing the same amount of heat from t_1.

The second law of thermodynamics tells us (among other things) that the efficiency of a Carnot heat engine is a function of the temperatures of the two heat reservoirs only. This also holds for the heats withdrawn from the reservoirs. Thus the following holds

$$\frac{Q_1'}{Q_2'} = f(t_1, t_2) \qquad (5)$$

with similar equations for Q_2''/Q_0'' and Q_1'''/Q_0'''. We may obtain a relation between $f(t_1, t_2)$, $f(t_2, t_0)$ and $f(t_1, t_0)$ by using Eq. (1), (2) and (4) in Eq. (5). This gives

$$f(t_1, t_2) = -\frac{f(t_1, t_0)}{f(t_2, t_0)} \qquad (6)$$

It is clear, however, that this last equation must be independent of t_0, since $f(t_1, t_2)$ cannot depend on t_0 in any way. Hence we may rewrite Eq. (6) as follows:

$$\frac{Q_1'}{Q_2'} = f(t_1, t_2) = -\frac{g(t_1)}{g(t_2)} \qquad (7)$$

Here the right equality expresses the fact that $f(t_1, t_2)$ does not depend on t_0, and the left equality restates Eq. (5). The great importance of Eq. (7) is this: The heat absorbed from the reservoir at temperature t_1 depends in the same way on temperature t_1, as the heat absorbed from the reservoir at temperature t_2 depends on t_2. In other words, the function $g(t)$ is a function which holds for any temperature. (Note that the temperature t was defined in terms of any arbitrary, but well-behaved, thermometer.) The fact that $f(t)$ is a universal function of temperature allows one to use Eq. (7) as a definition of a temperature scale. There are a variety of ways in which this might be done. We will come back to an examination of the alternatives below. The modern definition of the Kelvin Thermodynamic Temperature Scale is obtained by letting $g(t) = T$. Then

$$\frac{T_1}{T_2} = -\frac{Q_1'}{Q_2'} \qquad (8)$$

In other words, the ratio of the two temperatures of the heat reservoirs is defined as equal to the ratio of the heats absorbed from the two reservoirs. (The minus sign in Eq. (8) arises, of course, from the way the heats are defined, and from the fact that engine, R', actually delivers heat to the reservoir at the lower temperature.)

There are a number of thermodynamic consequences of this definition: (a) the state with $T = 0$ cannot be reached in a finite number of steps, (b) for reversible processes

$$\oint \frac{dQ}{T} = 0 \qquad (9)$$

when integrated around a closed path, and (c) the temperature T is independent of the working substance used in the thermometer.

We return now to a more careful examination of the definition of T. Consider a Carnot engine operating between temperatures t and $t - dt$ (as measured by any well-behaved thermometer). The efficiency of the engine, η, is defined as follows:

$$\eta = \frac{Q(t - dt) + Q(t)}{Q(t)} = \frac{Q(t - dt)}{Q(t)} + 1 \qquad (10)$$

and the Carnot function μ is defined as

$$\mu dt = \eta \qquad (11)$$

Because of Eq. (7), this can be written as

$$\mu dt = -\frac{g(t - dt)}{g(t)} + 1 = \frac{g(t) - g(t - dt)}{g(t)} \qquad (12)$$

But

$$\frac{dg(t)}{dt} = \frac{g(t) - g(t - dt)}{dt}$$

by definition of the derivative, and therefore,

$$\mu = \frac{dg(t)}{g(t)\, dt} = \frac{d \ln g(t)}{dt} \qquad (13)$$

There are now a number of options available. Kelvin originally suggested that μ be set equal to 1, or

$$\frac{d \ln g}{d\theta} = 1$$

Therefore,

$$g(\theta) = ae^{\theta} \qquad (14)$$

where θ is then on a thermodynamic scale. His later proposal, which is the basis of the Kelvin thermodynamic scale, was to set

$$\mu = \frac{1}{T} \qquad (15)$$

and thus

$$\frac{d \ln g}{dT} = \frac{1}{T}$$

and

$$g(T) = bT \tag{16}$$

The scale defined by Eq. (16) is the same as that defined by Eq. (8). The point of the present discussion is twofold. One, the arbitrariness of the choice of the function f is exhibited here more clearly. Two, it is obvious from Eq. (16) that only *one* constant needs to be fixed arbitrarily, in order to fix the scale.[8]

The choice of the magnitude of b is arbitrary. In fact it was determined in 1954[9] by *choosing* the temperature of the triple point of water to be 273.16 K exactly, on the thermodynamic scale of temperatures. It is obvious from the preceding, that this choice determines the scale completely, particularly by considering Eqs. (8) and (16). This point was made originally by Kelvin,[10] later by Mendeleef,[11] and in recent times by Giauque.[12]

Prior to 1954, the thermodynamic scale was defined by assigning the temperatures of the ice point of water (equilibrium of air-saturated water with ice) and the steam point of water, the temperatures 0° Celsius (thermodynamic) and 100° Celsius (thermodynamic) respectively. The position of the zero of the scale was then a matter for experimentation. Prior to 1954 there were fairly good *practical* reasons for so defining the scale. Progress in thermometry has outgrown these practical reasons,[13] and the new, more fundamental definition is clearly preferable on theoretical grounds. It is clear that in the new definition the interval between the ice and the steam point is a matter for experimental determination, and is almost certainly not exactly 100 degrees.

The definition of the thermodynamic temperature scale given in Eq. (8) lends itself particularly well to its realization by means of a gas thermometer. There is nothing unique or fundamental about this, however, and we shall see several examples of thermodynamic definitions and realizations of temperatures which have nothing to do with gas thermometry.

THE EQUALITY OF THE THERMODYNAMIC AND THE IDEAL GAS SCALES OF TEMPERATURES

The temperature scale based on an ideal (or perfect) gas is the same as that based on the considerations leading to Eq. (8), except for the arbitrary choice of the size of the degree, i.e., the choice of the single free constant in Eq. (16). It is this fact which makes gas thermometry so important. Furthermore, while an ideal gas is an abstract concept (to be discussed below) it can be approximated experimentally as closely as one needs to for the present purpose.

An ideal gas is defined by two properties:

(1) Boyle's law:

$$PV = f(t) \text{ only} \tag{17}$$

where P is the pressure, V the volume, and t the temperature, as measured on any thermometer.

(2) Joule's law: The temperature of an ideal gas which expands into a vacuum, i.e., without doing work, does not change during the expansion.

It is important to note that this is a definition of an *ideal* gas. No real gas satisfies all these requirements exactly under all conditions, but the definitions give a useful model[14] of an ideal gas.

In order to exhibit the identity of the thermodynamic and the ideal gas scale, we must digress briefly to consider thermometry in general. In all thermometry one has two systems to deal with, system A, the system whose temperature is required, and system B, the thermometer. One wishes to assign a numerical value t_A to the temperature of A, by measuring a property π of the system B. For example π may be a thermal emf of B, if B is a thermocouple, or π may be a pressure if B is a gas thermometer. The next step is this: A convention must be established which ascribes numerical values of temperature to two reference states of the thermometer B, say, t_1, and t_2. (In practice, these are fixed points on a temperature scale such as the triple point and the steam point of water. Then, when system B is in equilibrium with a system at either of these points, it has the temperatures t_1, and t_2 respectively.) Next, the property π must be measured for these two temperatures. Let it be π_1, and π_2, respectively. When system B is in equilibrium with system A at temperature t_A, then t_A is determined from

$$\frac{(t_A - t_1)}{(\pi_A - \pi_1)} = \frac{(t_2 - t_1)}{(\pi_2 - \pi_1)} \tag{18}$$

which can be written as

$$t_A = t_1 + \frac{(\pi_A - \pi_1)}{(\pi_2 - \pi_1)} (t_2 - t_1) \tag{19}$$

Two different thermometers must agree in the way in which they *order* the temperatures of system A. This means that if thermometer B ascribes the temperatures t_{A1} and t_{A2} to two states of system A (with $t_{A1} > t_{A2}$), and if a different thermometer C, ascribes the temperatures t'_{A1} and t'_{A2} to the same states of system A, then t'_{A1} must be $> t'_{A2}$ also. (It is this requirement which makes it impossible to use the density of water as the property π of a thermometer, near 4°C.)

We can now *define* a temperature scale based on the ideal gas having the properties enumerated above. Let us use the product PV as the property π of the ideal gas thermometer. Let us also set $t_1 = 0°$ and $t_2 = 273.16°$, the defining point of the thermodynamic scale. Then it follows from Eq. (19) that

$$t_A = \frac{[(PV)_A - (PV)_0]\,[t_2]}{(PV)_2 - (PV)_0} \tag{20}$$

We define the ideal gas temperature τ in the following way: Let

$$\frac{(PV)_t}{(PV)_{t_2}} = \frac{\tau}{\tau_2} \tag{21}$$

where t_2 is the defining fixed point. Then, for a particular τ

$$(PV)_\tau = \tau\frac{(PV)_2}{\tau_2} = K\tau \tag{22}$$

because $(PV)_2/\tau_2$ is some constant K, whose value is, of course, a matter for experimental determination.[15] Eq. (22) is, of course, "nothing but" the ideal gas law.

It remains, finally, to show that the thermodynamic temperature scale, as defined by Eq. (8) and (16) is identical with the ideal gas scale defined by Eq. (21) and (22). The proof of this identity is a straightforward thermodynamic matter. We consider first what are called the thermodynamic equations of state. They are

$$P = T\left(\frac{\partial P}{\partial T}\right)_V - \left(\frac{\partial E}{\partial V}\right)_T \tag{23}$$

$$V = T\left(\frac{\partial V}{\partial T}\right)_P + \left(\frac{\partial H}{\partial P}\right)_T \tag{24}$$

Here E is the internal energy, and H the enthalpy. The derivation of these equations can be found in any textbook on thermodynamics.[6]

The chief property of an ideal gas required here is property 2, namely, that its temperature is constant when the gas expands freely, i.e., does no work. This is equivalent to

$$\left(\frac{\partial E}{\partial V}\right)_T = 0 \tag{25}$$

and holds for any and all temperature scales. For an ideal gas, Eq. (23) becomes the following (by using (Eq. 25)):

$$P = T\left(\frac{\partial P}{\partial T}\right)_V \tag{26}$$

The same equation, using the ideal gas-temperature scale, is written

$$P = \tau\left(\frac{\partial P}{\partial \tau}\right)_V \tag{27}$$

For both scales, therefore, the pressure is proportional to the temperature, at constant volume. Combining the Eq. (26) and (27), one obtains

$$T = \tau\left(\frac{\partial P}{\partial \tau}\right)_V \Big/ \left(\frac{\partial P}{\partial T}\right)_V \tag{28}$$

The relation between the two scales is such that they differ at most by a constant factor. But since the size of the degree is a matter of choice, the two scales can be chosen to be identical. Derivation of this result was the basic goal of this section.

THE REALIZATION OF THE THERMODYNAMIC TEMPERATURE SCALE WITH GAS THERMOMETERS

The basic point in gas thermometry is to devise a method in which a real gas can be made to behave like an ideal gas, or, if this is not possible, to devise a method where the differences in behavior between the real and ideal gases are known and can be corrected to the required accuracy.

There are three broad classes of static gas thermometers possible. One may keep the volume of gas constant and measure the pressure as a function of temperature; this is called a "constant volume thermometer." Or, one may keep the pressure of the gas constant and measure the volume as a function of temperature; this is called a "constant pressure thermometer." Finally, one may keep the temperature of the gas bulb constant. Variations of these cases are, of course, possible. No details of the experimental arrangements will be given here; for these the reader is referred to the references.

In all methods the fact that the gas is not ideal must be taken into account. The behavior of real gases can be summed up by an equation of the state of the gas which differs from Eq. (22):

$$PV = nRT\left[1 + \frac{nB}{V} + \frac{n^2C}{V^2} + \cdots\right] \qquad (29)$$

Here R is the gas constant, which must be determined experimentally, and B and C are the second and third virial coefficients of the gas. These latter constants must be determined experimentally. They are a particular function of the temperature for each gas. The equation is written for n moles of gas. The non-ideal behavior of the gas can be taken into account if B and C are known over the relevant temperature range. If these are not known, then all experiments can be made as a function of pressure. Since V is constant, n decreases with the pressure. In the limit of very low pressures, the correction terms will have negligible effect.

Gas thermometers have been described by Beattie,[16] Moser[17] and by Moser, Otto, and Thomas.[18, 19] The most recent developments in gas thermometry are described in the present volume by Moessen and Aston,[20] by Barber[21] (low-temperature thermometry, 10–90°K), by Moser,[22] and Kirenkov[23] (high temperatures freezing point of gold, 1063°K), and by Guildner.[24]

Finally, it is interesting to mention briefly the principal dynamic method of gas thermometry, i.e., that based on the determination of the velocity of sound in a gas.

It is easy to show[25] that in an ideal gas, the velocity of sound, v_0, of very low frequency is given by

$$v_0^2 = \gamma_0 \frac{RT}{M} \qquad (30)$$

where γ_0 the ratio of the heat capacities at constant pressure and volume ($\gamma_0 = C_P/C_V$) appropriate for the low-frequency case, and M is the molecular weight for the gas. For a non-ideal gas, described by Eq. (29), (but neglecting the term proportional to C), one obtains for the velocity at any frequency:[26]

$$v^2 = v_0^2\left[1 + 2P\left(\frac{B}{RT} + \frac{1}{C_V{}^0}\frac{\partial B}{\partial T} + \frac{1}{2}\frac{RT}{C_P{}^0 C_V{}^0}\frac{\partial^2 B}{\partial T^2}\right)\right] \qquad (31)$$

Here $C_V{}^0$ and $C_P{}^0$ are the ideal gas-heat capacities. Thus, a measurement of the velocity of sound can provide one with a measurement of the thermodynamic temperature. Again one needs B as a function of temperature, or else the measurements must be made as a function of pressure, and extrapolated to low pressures. The method has been used successfully by Van Itterbeeck,[27] and a recent development in the technique is discussed by Plumb and co-workers[28] in this volume. One of the important aspects of this general approach lies in the fact that the method is completely different from that used in the static methods, and can thus help to eliminate systematic errors.

THE MAGNETIC THERMODYNAMIC TEMPERATURE SCALE AT VERY LOW TEMPERATURES

At temperatures which are so low that the vapor pressure of liquid helium is too low to measure accurately (this is below about 0.3°K, for He^3), it is necessary to find other ways to establish the thermodynamic temperature scale. This can be done using the magnetic properties of paramagnetic solids.

The general subject of paramagnetism of solids is vast and well beyond the scope of this paper. For an elementary introduction to it, and for further references, see Kittel.[29] The magnetic susceptibility χ of a paramagnetic substance depends on temperature, and thus provides one with a thermometric method. Eqs. (18) and (19) can be used for this purpose, where the property π is now taken as the magnetic susceptibility χ. For many substances χ depends on temperature in the following way:

$$\chi = \frac{C}{t + \Delta} + \alpha \qquad (32)$$

where C is a constant, often called the Curie constant, and Δ is another constant, the Weiss constant, both being characteristic of the solid. The temperature independent part of the susceptibility is given by α. This equation (the Curie-Weiss law) is satisfied for some substances in a useful temperature range. The equation can be interpreted theoretically in terms of the atomic structure of the constituents of the solid and their arrangement and interactions in the solid. It is, however, not usually possible to derive the values of C and Δ accurately from first principles, so that it would not in general be correct to call the temperature as determined from Eq. (32) a thermodynamic temperature.

A purely thermodynamic method exists, however. First of all, Eq. (32) is used to establish a "magnetic practical" temperature scale denoted T^*, by measuring χ for the thermometric substance. Using Eq. (32), one can then assign a temperature T^* for every value of χ for the substance. Next, one must determine (by measuring χ) how the temperature T^* rises when known amounts of heat Q are added to the thermometric substance. This yields a Q versus T^* curve. This curve must be obtained in the absence of any magnetic field H. Finally, we need a curve of entropy, S, versus T^* for zero magnetic field. This can be obtained in two steps. In step one, the dependence of S on H is determined at a temperature T_0 which is already known on the thermodynamic scale. Step two involves a series of isentropic demagnetizations (i.e., holding S constant) all starting at T_0, but at different values of H, and therefore ending at different temperatures T^*. This series of demagnetizations yields a relation between S and T^* at zero magnetic field (See Fig. 2).

All of these data are then combined to give T (thermodynamic) as a function of T^*:

$$T = \frac{dQ}{dS} = \frac{(\partial Q/\partial T^*)_{H=0}}{(\partial S/\partial T^*)_{H=0}} \tag{33}$$

Here the left equality follows from the definition of entropy, and the right equality from the (mathematical) properties of partial differentiation. It is clear that the experimental curves of Q versus T^*, and S versus T^*, allow one to calculate the partial derivatives. The relation of T and T^* follows directly because the partial derivatives are calculated for various values of T^*.

The experimental arrangements necessary for these processes are complicated. They are described by De Klerk and Steenland.[30] Recent developments are given in the present volume by Hudson.[31]

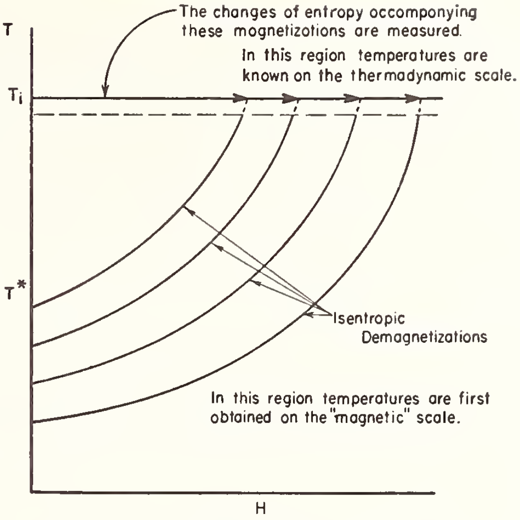


FIG. 2. The establishment of the relation between the entropy S and the magnetic temperature T^*.

THE THERMODYNAMIC TEMPERATURE SCALE FROM RADIATION MEASUREMENTS

At high temperatures, say above 1000°K, it becomes difficult to construct precision gas thermometers because the materials of construction become increasingly unreliable. Fortunately, it is a straightforward matter to define the thermodynamic temperature scale at high temperatures, and it is not too difficult to realize it experimentally.

The basic point involved in the definition of the thermodynamic temperature scale at high temperatures is this: If one has a body at a high temperature, and if the radiation emitted by the body is in thermodynamic equilibrium with the body, then various properties of the radiation are related directly to the thermodynamic temperature of that body.[32] Concretely, this problem is approached by assuming that the body has a cavity, and the radiation in the cavity is considered. If a long time has elapsed[33] during which the body was at temperature T, when the radiation will be in equilibrium with the body. In addition, it is convenient (though not at all necessary) to assume that the internal walls of the cavity are "black," i.e., that the emissivity of the walls is unity at all wavelengths. Such a cavity is called a blackbody. It is a straightforward matter to show that the total intensity of the radiation in the cavity, and its spectral distribution (i.e., intensity as a function of wavelength), depend only on the temperature of the body and in no way on the material of which the body is constructed. This is analogous to the situation found in the theory of the Carnot cycle, the efficiency of the Carnot engine depending only on the temperatures of the heat reservoirs, and not in any way on the properties of the working fluid. In both cases one could design an arrangement which would violate the second law of thermodynamics, if the properties of the cavity walls or of the working fluid affected the problem.

In this section we will only state the main results, and give references for their derivation.

The total intensity of radiation U (energy density per unit volume) in the space in equilibrium with radiation is given[34] by the Stefan-Boltzmann law:

$$U = \sigma T^4 \tag{34}$$

Here σ is a constant which depends (in a known way) on some fundamental constants of physics, which in turn must be determined from experiment.[35]

Another relation, which is more important from the point of view of thermometry, is the Planck radiation law. This gives the energy density as function of frequency and wavelength:

$$U(\nu, T) = \frac{2(kT)^3}{h^2 c^2} \frac{\alpha^3}{e^\alpha - 1} \tag{35}$$

where ν is the frequency of the radiation, T the thermodynamic temperature, k the Boltzmann factor, h Planck's constant, c the velocity of light in vacuum, and $\alpha = h\nu/kT$. Again the values of the constants must be obtained from experiment.[35]

The Planck radiation law was first obtained by Planck as an empirical equation to fit experimental data. Then it was derived by Planck on the basis of theory. He set out to calculate the entropy of radiation, in equilibrium with a solid at a given temperature, and then to let the entropy become a maximum, i.e., he calculated the most probable state of the radiation. Then he found that he could obtain the experimentally observed law only by assuming that the elementary oscillators are quantized.[36]

Eq. (35) is occasionally written in terms of the wavelength λ of the radiation:

$$U(\lambda, T) = \frac{c_1}{\lambda^5} [e^{c_2/\lambda T} - 1]^{-1} \tag{36}$$

Here c_1 and c_2 are the "first" and "second" radiation constants respectively:[35]

$$c_1 = hc^2 \tag{37}$$

and

$$c_2 = hc/k \tag{38}$$

It is clear that the way is open now for the establishment of a thermodynamic temperature scale: Whenever the radiation emitted by an object is in thermal equilibrium with it, Eq. (36) will be satisfied by the energy density of radiation. But $U(\lambda, T)$ can be measured by various radiation detecting devices.

In practice, the radiation is obtained in a cavity with a small opening, through which some of the radiation can escape. The opening must be so small that the radiation in the cavity is not disturbed measurably. Then the intensity of the radiation is measured, for example, with a pyrometer. The temperature of the body containing the cavity must be known initially on the thermodynamic temperature scale. Then the intensity of the radiation is fixed by (36), and a measurement of the intensity of the radiation will *calibrate* the measuring instrument. It is possible to calibrate the measuring instrument in this way at a variety of effective temperatures by "splitting" the intensity of the radiation by optical methods. The theory and practice of pyrometry is discussed by Kostkowski and Lee,[37] and certain new developments are discussed by many authors in this volume.[38]

Another radiation method for the determination of thermodynamic temperature is based on the statistical mechanical interpretation of thermodynamics.[39] This theory shows that for a system consisting of particles, each of the particles may have any amount of energy. At equilibrium, the sum of all energies of all particles must be equal to the total (macroscopic) energy of the system. The number of particles with a given energy is, however, a function of the temperature, if the whole system is in equilibrium. In fact, the ratio of numbers of particles n_1 and n_2, having energies E_1 and E_2 respectively, are given by

$$\frac{n_1}{n_2} = \frac{g_1}{g_2} e^{-(E_1 - E_2)/kT} \tag{39}$$

Here g_1 and g_2 are statistical weights, which depend on the detailed properties of the particles. Note that the population of particle states with given energy depends only on the energy and on the thermodynamic temperature. This enables one to measure T, if the energies and statistical weights are known, by measuring the populations of several states of different energy. This is accomplished most easily by spectroscopic methods, which are discussed by Penner,[40] Dieke,[41] and Broida.[42] In principle, this method can be used for temperatures of unlimited magnitudes. There exists a very serious limitation to this method, however, because of the requirement that the system to be measured be in thermodynamic equilibrium. This requirement is often not satisfied, and then the method yields temperatures which are not strictly thermodynamic. For a discussion of the problem see Herzfeld,[43] and some of the papers in this Volume.[44]

NEGATIVE THERMODYNAMIC TEMPERATURES

In recent years it has become possible to prepare physical systems which can best be described by assigning a negative thermodynamic temperature to them. These systems have a number of important properties in common, which will be described below, but no violation of thermodynamic principles is involved. The easiest way to understand such systems is by considering Eq. (39). Limiting ourselves to positive T for the moment, it is clear that, when $E_1 > E_2$, $n_1 < n_2$, i.e., the population of the state with higher energy is smaller than the population of the state with lower energy. Suppose now, that for some reason $n_1 > n_2$, and also that n_1 and n_2 satisfy Eq. (39) with T negative. It is in such a situation that it *may* become useful to consider negative absolute temperatures.

The conditions under which it is possible to ascribe rigorously to a system a negative absolute temperature, are these:

(1) The system must be fairly well isolated from its surroundings, but must come to internal equilibrium rapidly.

(2) The states of the system must be quantized.

(3) The system must have a highest state, in the same sense in which a system usually has a lowest state.

When these conditions are satisfied it may be possible to prepare the system in a thermodynamic state where the populations of the quantum states satisfy Eq. (39), but with T negative. Examples of such systems are the nuclear magnetic moments of the constituents of certain crystals.

It must be made clear that a system with T negative is *hotter* than a system with T infinite. This is easy to see: For $T = \infty$, all quantum states have equal populations. If, however, the higher states have larger populations than the lower states, the system must be *hotter* than it was when $T = \infty$. Naturally, such a system radiates energy.

The thermodynamic consequences of the existence of such systems has been discussed by Ramsay,[45, 46] Abragam and Proctor,[47] Coleman and Noll,[48] and others.

CONCLUSION

A temperature scale based on thermodynamics is conceptually straightforward. It can be extended by appeal to the statistical mechanical interpretation of thermodynamics, both to higher and lower temperatures, and to systems greatly differing from those contemplated in classical thermodynamics.

References

1. R. B. Lindsay, "Temperature Concept for Systems in Equilibrium," this volume.
2. H. B. Callen, "Nonequilibrium Thermodynamics," Fourth Symposium on Temperature.
3. K. E. Shuler, "Relaxation of Non-equilibrium Distributions," this volume.
4. A. G. McNish, "The Role of Temperature in Our Measurement System," this volume.
5. H. F. Stimson, "The Text Revision of the International Temperature Scale of 1948," this volume.
6. M. Zemansky, *Heat and Thermodynamics* (McGraw-Hill Book Company, Inc., New York, 1957).
7. The present discussion is based in part on lecture notes by J. A. Beattie, which this author has found particularly clear.
8. The scales defined by Eqs. (14) and (16) are related. In fact, $T = (a/b)\,e^{\theta}$, or $\theta = \ln T + \ln (b/a)$.
9. "Comptes Rendus des Séances," *Dixième Conférence Général Des Poids et Mesures,* 1954 (Gauthier-Villiars, Paris, 1955), p. 79.
10. J. P. Joule and W. Thomson, "On the Thermal Effects of Fluids in Motion," Phil. Trans. Roy. Soc., London, 144, Section IV, 351 (1854). See also, W. Thomson, "On an Absolute Thermometric Temperature Scale," Phil. Mag., 33, 313 (1848).
11. See W. Louguinine, Bull. Soc. Chim., Paris, 21, 302 (1874).
12. W. F. Giauque, "A Proposal to Redefine the Thermodynamic Temperature Scale," Nature, 143, 623 (1939).
13. H. T. Wensel, "Temperature," *Temperature, Its Measurement and Control in Science and Industry,* Vol. 1 (Reinhold Publishing Corporation, New York, 1941), p. 7 ff; and J. A. Hall, "The International Temperature Scale," *Temperature, Its Measurement and*

Control in Science and Industry, Vol. 2 (Reinhold Publishing Corporation, New York, 1955), p. 124 ff.

14. Note that this model of the ideal gas is a phenomenological one, i.e., is given *only* in terms of macroscopic variables which can be directly measured. Nothing is said in this model about atoms. This is typical of thermodynamical models.
15. Confusion is possible here unless care is taken. K must be determined *experimentally*, but under such conditions that the gas at hand satisfies the ideal gas laws stated earlier.
16. J. A. Beattie, "Gas Thermometry," *Temperature, Its Measurement and Control in Science and Industry*, Vol. 2 (Reinhold Publishing Corporation, New York, 1955), p. 63.
17. H. Moser, "High Temperature Gas Thermometry," *Temperature, Its Measurement and Control in Science and Industry*, Vol. 2 (Reinhold Publishing Corporation, New York, 1955), p. 103.
18. H. Moser, J. Otto, and W. Thomas, "High Temperature Gas Thermometry I," Z. Phys., **147**, 59 (1957).
19. H. Moser, J. Otto and W. Thomas, "High Temperature Gas Thermometry II," Z. Phys., **147**, 76 (1957).
20. G. W. Moessen and J. G. Aston, "The Pennsylvania State University Thermodynamic Temperature Scale below 90°K and the Normal Boiling Points of Oxygen and Normal Hydrogen on the Thermodynamic Scale," this volume.
21. C. R. Barber, "Helium Gas Thermometry at Low Temperatures," this volume.
22. H. Moser, "Review of Recent Determinations of Thermodynamic Temperatures of Fixed Points above 419°C," this volume.
23. I. I. Kirenkov *et al.*, "Measurements of Thermodynamic Temperatures by Means of a Gas Thermometer," this volume.
24. L. A. Guildner, "A National Bureau of Standards Gas Thermometer," this volume.
25. K. F. Herzfeld and T. Litovitz, "Absorption and Dispersion of Ultrasonic Waves" (Academic Press, New York, 1959), Chap. 4.
26. If the term proportional to C in Eq. (29) needs to be taken into account, the expression for the velocity becomes much more complicated.
27. A. van Itterbeeck, *Progress in Low-Temperature Physics*, Vol. 1 (Interscience Publishers, Inc., New York, 1955), p. 355.
28. G. Cataland, M. H. Edlow and H. H. Plumb, "Determination of Absolute Temperature from Sound Velocity Measurements," this volume.
29. C. Kittel, *Introduction to Solid State Physics* (John Wiley & Sons, Inc., New York, 1956).
30. D. DeKlerk and M. J. Steenland, *Progress in Low Temperature Physics* (North-Holland Publishing Company, Amsterdam, 1955), Vol. I.
31. R. P. Hudson, "The Thermodynamic Temperature Scale below 1°K," this volume.
32. For a general and thorough discussion of the thermodynamics of radiation from a viewpoint which is particularly useful here, see M. Planck, *Theorie der Wärme* (Hirzel, Leipzig, 1930) Part III.
33. What is a "long" time depends on the case at hand. The argument is not, however, tautological: If the time has been "long enough," a state of equilibrium is reached, which can be recognized by the fact that the system does not change any longer.
34. M. Planck, *Theorie der Wärme* (Hirzel, Leipzig, 1930) Part III, p. 168.
35. For the latest estimate of the "best value" of σ and the other atomic constants needed here, see Reference 37.
36. M. Planck, *Theorie der Wärme* (Hirzel, Leipzig, 1930) Part III, p. 219 ff. This intimate historical connection between the old quantum theory and statistical thermodynamics is often overlooked.
37. H. J. Kostkowski and R. D. Lee, "Theory and Methods of Optical Pyrometry," this volume.
38. See, for example, the papers by Thorn and Lovejoy in this volume.
39. J. E. Mayer and M. G. Mayer, *Statistical Mechanics* (John Wiley & Sons, Inc., New York, 1940).
40. S. S. Penner, "Spectroscopic Methods of Temperature Measurement," this volume.
41. G. H. Dieke, "High Gas Temperatures," *Temperature, Its Measurement and Control in Science and Industry*, Vol. 2 (Reinhold Publishing Corporation, New York, 1955).
42. H. P. Broida, "Experimental Temperature Measurement in Flames and Hot Gases," *Temperature, Its Measurement and Control in Science and Industry*, Vol. 2. (Reinhold Publishing Corporation, New York, 1955).
43. C. M. Herzfeld, "Incomplete Equilibrium and Temperature Measurement," J. Wash. Acad. Sci., **46**, 269 (1956).
44. See particularly the papers by Kostkowski and Hattenburg, F. Rössler, E. A. McLean.
45. N. Ramsey, Phys. Rev. **103**, 20 (1956).
46. N. Ramsey, "Thermodynamics and Statistical Mechanics at Negative Absolute Temperatures," this volume.
47. A. Abragam and W. G. Proctor, Phys. Rev., **109**, 1441 (1958).
48. B. D. Coleman and W. Noll, Phys. Rev., **115**, 262 (1959).

UNITED STATES DEPARTMENT OF COMMERCE • Luther H. Hodges, *Secretary*
NATIONAL BUREAU OF STANDARDS • A. V. Astin, *Director*

International Practical Temperature Scale of 1948

Text Revision of 1960

H. F. Stimson

Reprinted from the Journal of Research of the National
Bureau of Standards—A. Physics and Chemistry, Vol. 65A,
No. 3, May–June 1961

National Bureau of Standards Monograph 37
Issued September 8, 1961

17-I

Contents

International Practical Temperature Scale of 1948

Text Revision of 1960

H. F. Stimson

(February 1, 1961)

The International Practical Temperature Scale of 1948 is a text revision of the International Temperature Scale of 1948, the numerical values of temperatures remaining the same. The adjective "Practical" was added to the name by the International Committee on Weights and Measures. The scale continues to be based upon six fixed and reproducible equilibrium temperatures to which values have been assigned, and upon the same interpolation formulas relating temperatures to the indications of specified measuring instruments. Some changes have been made in the text to make the scale more reproducible than its predecessor. The triple point of water, with the value 0.01 °C replaces the former ice point as a defining fixed point of the scale. It is also recommended that the zinc point, with the value 419.505 °C, be used instead of the sulfur point. The recommendations include new information that has become available since 1948.

An internationally accepted scale on which temperatures can be measured conveniently and accurately is necessary for science and industry. As early as 1911 the directors of the national laboratories of Germany, Great Britain, and the United States agreed to undertake the unification of the temperature scales in use in their respective countries. A practical scale, named the International Temperature Scale, was finally agreed upon, was recommended to the Seventh General Conference on Weights and Measures by its International Committee on Weights and Measures, and was adopted in 1927.[1]

The General Conference on Weights and Measures is the official international body now representing 36 nations that subscribe to the Treaty of the Meter. The General Conference normally meets every six years, and at those times may adopt recommendations submitted by the International Committee. The International Committee is the executive body elected by the General Conference. It consists of 18 scientists, only one from any one nation, and it normally meets every two years. The International Committee now has six advisory committees of specialists most of whom represent large national laboratories. The Advisory Committee on Thermometry was authorized in 1933 and first met in 1939.

In 1948 a revision of the International Temperature Scale was prepared by the Advisory Committee and proposed to the International Committee. The International Committee recommended this revision to the Ninth General Conference which adopted it.[2] At this time the General Conference also adopted the designation of degree Celsius in place of degree Centigrade or Centesimal.[3] The revised scale was designed to conform as nearly as practicable to the thermodynamic scale as then known, while incorporating certain refinements, based on experience, to make the scale more uniform and reproducible than its predecessor. In the revision there were only three changes which affected values of temperatures on the scale. One was to increase the value assigned to the silver point by 0.3 degree, merely to make the scale more uniform. Another was to specify Planck's radiation formula instead of Wien's formula so the scale would be consistent with the thermodynamic scale above the gold point. The third was to increase the value for the second radiation constant to bring it nearer to the value derived from atomic constants.

In 1954 the Advisory Committee proposed a resolution redefining the Kelvin thermodynamic scale by assigning a value to the triple point of water. This kind of definition was what Kelvin, in 1854, had said "must be adopted ultimately." This resolution was recommended by the International Committee and adopted by the Tenth General Conference.[4] As soon as this resolution had been adopted it was pointed out that it would be necessary to revise the introduction of the text of the International Temperature Scale of 1948 to conform with the action just taken.

In preparing a tentative proposal for a new text of the introduction it soon became evident that the other three parts of the text would also profit by a revision. For example, the triple point of water could now be made one of the defining fixed points of the scale and thus become the one defining fixed point common to both the international and the Kelvin scales. The Recommendations could include new information that had become available since 1948. At the higher temperatures some new determinations of differences between the international and thermodynamic scales could be included.

---

[1] Comptes Rendus de la Septième Conférence Générale des Poids et Mesures, p. 94 (1927).

[2] Comptes Rendus de la Neuvième Conférence Générale des Poids et Mesures, p. 89 (1948).

[3] Comptes Rendus de la Neuvième Conférence Générale des Poids et Mesures, p. 64 (1948).

[4] Comptes Rendus de la Dixième Conférence Générale des Poids et Measures, p. 79 (1954).

The values reported for these differences, however, were still not certain enough to warrant a change of the scale itself. The new text, therefore, does not change the value of any temperature on the 1948 scale by as much as the experimental error of measurement.

In 1958 the tenative proposal was discussed in detail at sessions of the Advisory Committee in June, and many suggested changes were agreed upon. It was proposed to the International Committee in October. Minor corrections were made during the next two years, and in 1960 the International Committee gave the scale its new name. The International Committee recommended this text revision to the Eleventh General Conference and it was adopted in October 1960.

A translation of the official text [5] follows.

1. Introduction

The Kelvin thermodynamic scale, on which temperatures are designated as °K and denoted by the symbol T, is recognized as the fundamental scale to which all temperature measurements should ultimately be referable. The magnitude of the degree Kelvin is now defined by the decision (Tenth General Conference on Weights and Measures, 1954, Resolution 3) fixing the thermodynamic temperature of the triple point of water at exactly 273.16 °K.

The experimental difficulties inherent in the measurement of temperature on the thermodynamic scale led to the adoption in 1927, by the Seventh General Conference on Weights and Measures, of a practical scale called the "International Temperature Scale". This scale was intended to be conveniently and accurately reproducible and to agree as closely as practicable with the thermodynamic scale.

The International Temperature Scale was revised in 1948 to make it conform with the state of the knowledge then available.

In May 1960 the International Committee on Weights and Measures approved the new name, "International Practical Temperature Scale of 1948", for the scale presented in this document. Inasmuch as the numerical values of temperature on this scale are the same as in 1948, this scale is not a revision of the scale of 1948 but merely a revision of its text.

2. Definition of the International Practical Temperature Scale of 1948

Temperatures on the International Practical Temperature Scale of 1948 are expressed in degrees Celsius, designated by °C or °C (Int. 1948), and are denoted here by the symbol t or t_{int}.

The International Practical Temperature Scale is based on six reproducible temperatures (defining fixed points), to which numerical values are assigned, and on formulas establishing the relation between temperature and the indications of instruments calibrated by means of values assigned to the six defining fixed points. These fixed points are defined by specified equilibrium states, each of which, except for the triple point of water, is under a pressure of 101 325 newtons/meter^2 (1 standard atmosphere).

The fixed points of the scale and the exact numerical values assigned to them are given in table 1.

TABLE 1. *Defining fixed points*

Exact values assigned. The pressure is 1 standard atmosphere, except for the triple point of water.

	Temperature °C (Int. 1948)
Temperature of equilibrium between liquid oxygen and its vapor (oxygen point)	−182. 97
Temperature of equilibrium between ice, liquid water, and water vapor (triple point of water)	+0. 01
Temperature of equilibrium between liquid water and its vapor (steam point)	100
Temperature of equilibrium between liquid sulfur and its vapor (sulfur point)	444. 6*
Temperature of equilibrium between solid silver and liquid silver (silver point)	960. 8
Temperature of equilibrium between solid gold and liquid gold (gold point)	1063

*In place of the sulfur point, it is recommended to use the temperature of equilibrium between solid zinc and liquid zinc (zinc point) with the value 419.505 °C (Int. 1948). The zinc point is more reproducible than the sulfur point and the value which is assigned to it has been so chosen that it use leads to the same values of temperature on the International Practical Temperature Scale as does the use of the sulfur point.

The procedures for interpolation lead to a division of the scale into four parts.

a. From 0 °C to 630.5 °C (antimony point) the temperature t is defined by the formula

$$R_t = R_0(1 + At + Bt^2),$$

where R_t is the resistance at temperature t of the platinum wire resistor of a standard resistance thermometer, and R_0 is the resistance at 0 °C. The constants R_0, A, and B are to be determined from the values of R_t at the triple point of water, at the steam point, and at the sulfur point (or the zinc point). The platinum wire of a standard resistance thermometer shall be annealed and its purity shall be such that R_{100}/R_0 is not less than 1.3920.

b. From the oxygen point to 0 °C, the temperature t is defined by the formula

$$R_t = R_0\,[1 + At + Bt^2 + C(t - t_{100})t^3],$$

where R_0, A, and B are determined in the same manner as in *a* above, the constant C is to be determined from the value of R_t at the oxygen point, and $t_{100} = 100$ °C.

c. From 630.5 °C to the gold point the temperature t is defined by the formula

$$E = a + bt + ct^2,$$

where E is the electromotive force of a standard thermocouple of platinum and platinum-rhodium alloy, when one of the junctions is at 0 °C and the other at the temperature t. The constants a, b, and c are to be determined from the values of E at 630.5 °C, at the silver point, and at the gold point. The value of the electromotive force at 630.5 °C is to be determined by measuring this temperature with a standard resistance thermometer.

---

[5] Comptes Rendus de la Onzième Conférence Générale des Poids et Mesures (1960).

The wires of the standard thermocouple shall be annealed and the purity of the platinum wire shall be such that the ratio R_{100}/R_0 is not less than 1.3920. The platinum-rhodium wire shall consist nominally of 90 percent platinum and 10 percent rhodium by weight. When one junction of the thermocouple is at 0 °C and the other is successively at 630.5 °C, the silver point, and the gold point, the completed thermocouple shall have electromotive forces such that

$$E_{\mathrm{Au}}=10\,300\ \mu\mathrm{v}\pm 50\ \mu\mathrm{v}$$

$$E_{\mathrm{Au}}-E_{\mathrm{Ag}}=1183\ \mu\mathrm{v}+0.158\ (E_{\mathrm{Au}}-10\,300\ \mu\mathrm{v})\pm 4\ \mu\mathrm{v}$$

$$E_{\mathrm{Au}}-E_{630.5}=4766\ \mu\mathrm{v}+0.631\ (E_{\mathrm{Au}}-10\,300\ \mu\mathrm{v})\pm 8\ \mu\mathrm{v}.$$

d. Above the gold point the temperature t is defined by the formula

$$\frac{J_t}{J_{\mathrm{Au}}}=\frac{\exp\left[\dfrac{C_2}{\lambda(t_{\mathrm{Au}}+T_0)}\right]-1}{\exp\left[\dfrac{C_2}{\lambda(t+T_0)}\right]-1},$$

where J_t and J_{Au} are the radiant energies per unit wavelength interval at wavelength λ, emitted per unit time per unit solid angle per unit area of a blackbody at the temperature t and the gold point respectively, C_2 is the second radiation constant with the value $C_2=0.014\,38$ meter-degrees, λ is in meters, and $T_0=273.15$ degrees.

3. Recommendations

The following recommendations are advisory rather than mandatory. The recommended apparatus, methods, and procedures represent good practice at the present time, but there is no intention of retarding the development and use of improvements and refinements. Experience has shown these recommendations to be in the interest of uniformity and reproducibility in the realization of the International Practical Temperature Scale defined in Section 2.

3.1. Standard Resistance Thermometer

A standard resistance thermometer should be so designed and constructed that the wire of the platinum resistor is as nearly strainfree as practicable and will remain so during continued use. The platinum wire should be drawn from a fused ingot, not from forged sponge.

Standard resistance thermometers have been made of wire with diameters between 0.05 and 0.5 mm, at least a short portion of each lead adjacent to the resistor also being of platinum. The completed resistor of the thermometer should be annealed in air at a temperature higher than the highest temperature at which it is to be used, but in no case below 450 °C. There is reason to believe, furthermore, that better stability is obtained when the tube protecting the completed resistor is filled with gas containing some oxygen.

Useful criteria which serve as safeguards against inferior construction of the completed thermometer and against errors in the calibrations at the fixed points are that the value of the constant B is $(-0.5857\pm 0.0010)\times 10^{-6}/\mathrm{deg}^2$ and that the value of the constant C is $(-4.35\pm 0.05)\times 10^{-12}/\mathrm{deg}^4$. Another useful criterion of the adequacy of the annealing and of the reliability of the thermometer is the constancy of its resistance at some reference temperature. For example the resistance of a thermometer at the triple point of water should not change by as much as the equivalent of 0.001 deg when the thermometer is subjected to temperature cycles such as are necessary for its calibration.

3.2. Standard Thermocouple

Standard thermocouples have been made of wires having a diameter between 0.35 and 0.65 mm.

Before calibration the wires of the thermocouple should be carefully annealed to ensure the constancy of the electromotive forces during use. For this it is necessary to heat the platinum wire to a temperature of at least 1100 °C and the platinum-rhodium wire to 1450 °C. If the annealing is done before the wires are mounted in their insulators, the completed thermocouple should be heated again to a temperature of at least 1100 °C, until the electromotive force is stable and local inhomogeneities caused by strains have disappeared. When the thermocouple has been annealed sufficiently, its indications should not vary with a change in the temperature gradient along the wire; they should not vary, for example, with the depth of immersion in an enclosure at uniform temperature.

The electromotive force of the thermocouple at 630.5 °C should be determined from measurements at some uniform and constant temperature between 630.3 and 630.7 °C.

3.3. Pressure

In practice, pressures are determined with a mercury column. Pure mercury may be taken as having a mean density at 20 °C of 13 545.87 kg/m^3 in a mercury column balancing one atmosphere. In the practical determination of the standard atmosphere the International Committee on Weights and Measures recommends that the value of local gravity be expressed in the Potsdam system until it sanctions the use of another system.

In the following sections on the oxygen point, the steam point, and the sulfur point the formulas for the equilibrium temperatures t_p are given as polynomials in powers of (p/p_0-1), where p is the equilibrium pressure and p_0 is one standard atmosphere. The limits of accuracy are also given for stated ranges of pressure. In practice, the errors caused by using these formulas are less than the errors caused by the instability of systems open to the atmosphere. Greater stability and increased accuracy can be realized in closed systems held at a constant pressure which is maintained within a few parts in a thousand of one atmosphere. Only the first power terms of (p/p_0-1) in the polynomials are then needed.

3.4. Zero Point of the Scale and Triple Point of Water

a. Zero Point of the Scale

The zero point of the International Practical Temperature Scale is defined as being the temperature exactly 0.01 deg below the triple point of water. Calculations show that the temperature of the former "ice point", defined as the temperature of equilibrium between ice and air-saturated water under a pressure of one standard atmosphere, is 0 °C within 0.0001 deg.

It is difficult, however, to obtain the ice point directly with an accuracy better than ±0.001 deg; but when this accuracy suffices, the temperature 0 °C may be be realized by the use of a mixture of finely divided ice and water saturated with air at 0 °C in a well insulated container such as a Dewar flask. The equilibrium temperature t corresponding to an ambient atmosphere pressure p and at a depth h below the surface of the water, may be calculated by the formula

$$t = 0.01\ (1 - p/p_o)\ ^\circ\mathrm{C} - (0.7 \times 10^{-6}\ \mathrm{deg/mm})h.$$

b. Triple Point of Water

The temperature of the triple point of water has been realized in sealed glass cells which contain only water of high purity; these cells have axial re-entrant wells for thermometers. In such cells the triple-point temperature is realized wherever ice is in equilibrium with a liquid-vapor surface. At a depth of h below the liquid-vapor surface the equilibrium temperature between ice and liquid water is given by the formula

$$t = 0.01\ ^\circ\mathrm{C} - (0.7 \times 10^{-6}\ \mathrm{deg/mm})h.$$

The recommended method of preparing a triple-point cell for use is first to freeze a thick mantle of ice around the well by cooling from within, and then to melt enough of this mantle, also from within, to produce a new water-ice interface close to the well. After these cells have been prepared for use, the temperatures measured in the wells have been found to rise by amounts ranging from 0.0001 to 0.0005 deg before becoming stable after from 1 to 3 days. This initial change can probably be explained either by the increase in the dimensions of the crystals of ice or by the slow release of strains in the crystals. A cell prepared in this manner and kept in an ice bath is capable of maintaining a temperature which is constant within about 0.0001 deg for several months. When cells from different sources have been compared under these conditions, no differences greater than 0.0002 deg have been reported.

Water from most natural sources (normal water) contains about 0.0148 mole percent deuterium, 0.20 mole percent O^{18}, and 0.04 mole percent O^{17}. Variations from this norm as large as 0.0015 mole percent have been found in the deuterium content of natural waters. An increase of 0.001 mole percent in the deuterium content of water corresponds to an increase of 0.000 04 deg in the triple-point temperature. Waters from rivers that rise to the leeward of mountain ranges or at the base of permanent glaciers may contain less than the normal amount of deuterium, whereas waters from the surface of large lakes may contain more than the normal amount.

The isotopic composition at the water-ice interfaces in the triple-point cells depends also on the natural differences in the proportions of the oxygen isotopes, on the process of distilling water. and on the procedure of freezing. The effects of these different isotopic compositions on the temperatures realized in triple-point cells are probably sufficiently small to be neglected.

3.5. Oxygen Point

The temperature of equilibrium between liquid oxygen and its vapor is usually realized by the static method. The platinum resistor of a standard thermometer and the liquid oxygen in its container are brought to the same temperature in a metal block placed in a suitable cryostat. The metal block is usually immersed in a well-stirred bath of liquid oxygen open to the atmosphere, but greater stability has been obtained by enclosing the metal block inside an evacuated envelope maintained at a uniform temperature near the oxygen point. The oxygen vapor pressure is transmitted through a tube leading out to a manometer. The entire length of this tube should be at temperatures above the saturation temperature of the oxygen.

Criteria that the equilibrium temperature has been realized are that the observed temperature, corrected to constant pressure at the free surface of the oxygen, is independent of: Small variations in the depth of immersion of the thermometer in the metal block, the ratio of the volume of the liquid oxygen to the volume of the vapor, and small variations in the temperature of the envelope.

The equilibrium temperature t_p corresponding to a pressure p at the surface of the liquid oxygen may be found to an accuracy of a few thousandths of a degree over the range from $p = 660$ mm to $p = 860$ mm of mercury by means of the formula

$$t_p = [-182.97 + 9.530(p/p_o - 1) \\ -3.72(p/p_o - 1)^2 + 2.2(p/p_o - 1)^3]\ ^\circ\mathrm{C}.$$

3.6. Steam Point

The temperature of equilibrium between liquid water and its vapor is usually realized by the dynamic method with the thermometer placed within the saturated vapor. Open systems were formerly used for the realization of the steam point but for precise calibration it is preferable to use a closed system in which a boiler and a manometer are connected to a manostat filled with air or, preferably, helium.

The boiler should be constructed so as to avoid all contamination of the vapor. The thermometer should be shielded against radiation from bodies that are at temperatures different from the saturation temperature.

The criteria that the equilibrium temperature has been realized are that the observed temperature, corrected to a constant pressure, is independent of: The water used, the elapsed time, the variations in the heat input to the liquid water, and the depth of immersion of the thermometer.

The equilibrium temperature t_p, corresponding to a pressure p, may be found to within 0.001 deg over the range between $p=660$ mm and $p=860$ mm of mercury by means of the formula

$$t_p=[100+28.012(p/p_0-1) -11.64(p/p_0-1)^2+7.1(p/p_0-1)^3]\,^{\circ}\mathrm{C}.$$

A change in the proportion of deuterium in water produces about one third as much change at the boiling-point temperature as that produced at the triple point, and in the same direction.

3.7. Sulfur Point

The temperature of equilibrium between liquid sulfur and its vapor is usually realized by the dynamic method in an aluminum boiler similar in shape to that used for the steam point except that extra shielding against radiation and larger spaces for free circulation of the vapor are needed.

The addition of 0.1 percent of arsenic and then of 0.1 percent of selenium to sulfur has been reported to raise the normal boiling point by 0.02 deg and then by 0.07 deg. These elements are common in sulfur from volcanic sources. Commercial sulfur contains organic impurities which slowly decompose and leave carbon when the sulfur is boiled. Carbon itself probably has no observable effect on the boiling point of sulfur, but it is preferable to remove the organic matter and carbon.

The criteria that the sulfur point has been realized are similar to those for the realization of the steam point, except that it may take many hours to reach a constant temperature.

The equilibrium temperature t_p, corresponding to a pressure p, may be found to an accuracy of about 0.001 deg in the range between $p=660$ mm and $p=800$ mm of mercury by means of the formula

$$t_p=[444.6+69.010(p/p_0-1)-27.48(p/p_0-1)^2 +19.14(p/p_0-1)^3]\,^{\circ}\mathrm{C}.$$

3.8. Zinc Point

Highly reproducible temperatures, closely related to those which give the temperature of the liquidus curve of an alloy, have been realized as plateau temperatures on slow-rate freezing curves of high purity (99.999 weight percent) zinc.

The zinc is usually melted and frozen in high purity artificial graphite (99.999 weight percent) crucibles with axial thermometer wells, in simple block furnaces. The crucibles should be about 5 cm in diameter and deep enough to eliminate the effects of heat conduction along the thermometer leads.

When cooling has been started and solid has begun to form on the crucible wall, the thermometer should be removed, cooled to the room temperature, and then reinserted in its well to induce a thin mantle of solid zinc on the outside of the well. Another technique, which has been used, is to remove the thermometer when the temperature indicated by it is 0.01 deg below the freezing point, and to insert a silica rod for about 30 sec; the thermometer is then replaced in its well. The plateau temperature is that of equilibrium between the liquid zinc and the solid zinc of the mantle while freezing is progressing slowly inward from the outside of the crucible. The melts are best made in an inert atmosphere to inhibit oxidation of the graphite and zinc, yet there has been no evidence of the plateau temperatures being affected by zinc oxide in the melt even after prolonged heating in air. The plateau temperatures have been found to increase 0.0043 deg per atmosphere.

A criterion of adequate purity of a sample is that its melting range is not greater than about 0.001 deg. Samples of zinc of this high purity, originating in different countries, have given plateau temperatures which were practically identical (within 0.0002 deg). Samples with melting ranges of about 0.01 deg yielded plateau temperatures that were low by from 0.0004 deg to 0.0016 deg.

3.9. Silver and Gold Points

The temperature of equilibrium between solid and liquid silver or between solid and liquid gold has been realized in covered crucibles either of high purity artificial graphite, or ceramic, or vitreous silica. The dimensions of the crucibles should be such as to allow for the considerable expansion of these metals on melting and the crucibles should be deep enough to eliminate the effects of heat conduction along the thermocouple wires. Silver must be protected from oxygen while molten.

The crucible and its contents should be brought to a uniform temperature a few degrees above the melting point of the metal and then allowed to cool slowly. A thermocouple, mounted in a protecting tube of porcelain or other suitable material, with insulators separating the two wires, is immersed in the molten metal which is then allowed to freeze.

Criteria that the equilibrium temperature has been realized are: That the electromotive force of the thermocouple is independent of small changes in the depth of immersion during successive freezings, and that the electromotive force remains essentially constant for a period of at least 5 min during a single freezing.

For the range of the scale above 1063 °C, where the Planck radiation formula is used, the gold-point crucible should be modified to have a blackbody cavity at the temperature of the freezing gold.

4. Supplementary Information

4.1. Resistance—Temperature Formulas

The interpolation formula for the range 0 to 630.5 °C as given in the definition of the scale (sec. 2, *a*),

$$R_t=R_0(1+At+Bt^2),$$

may be written in the Callendar form

$$t=\frac{1}{\alpha}\left(\frac{R_t}{R_0}-1\right)+\delta\left(\frac{t}{t_{100}}-1\right)\frac{t}{t_{100}}$$

where

$$\alpha=\frac{1}{t_{100}}\left(\frac{R_{100}}{R_0}-1\right), \text{ and } t_{100}=100\ ^\circ C.$$

The relations between the coefficients are

$$A=\alpha\left(1+\frac{\delta}{t_{100}}\right), \qquad \alpha=A+Bt_{100},$$

$$B=-\frac{\alpha\delta}{t_{100}^2}, \qquad \delta=-\frac{Bt_{100}^2}{A+Bt_{100}}.$$

The interpolation formula for the range 0°C to the oxygen point as given in the definition of the scale (sec. 2b),

$$R_t=R_0[1+At+Bt^2+C(t-t_{100})t^3],$$

may be written in the Callendar-Van Dusen form

$$t=\left[\frac{1}{\alpha}\left(\frac{R_t}{R_0}-1\right)+\delta\left(\frac{t}{t_{100}}-1\right)\frac{t}{t_{100}}\right.$$
$$\left.+\beta\left(\frac{t}{t_{100}}-1\right)\left(\frac{t}{t_{100}}\right)^3\right]{}^\circ C.$$

The relations connecting A, B and α, δ are the same as those given above and the other relations are

$$C=-\frac{\alpha\beta}{t_{100}^4}, \qquad \beta=-\frac{Ct_{100}^4}{A+Bt_{100}}.$$

4.2. Secondary Reference Points

In addition to the defining fixed points of the scale, given in table 1, certain other points may be useful for reference purposes. Some of these and their corresponding reported temperatures on the International Practical Temperature Scale of 1948 are given in table 2. Except for the triple points, each temperature is for a system in equilibrium under a pressure of 1 standard atmosphere. The formulas for the variation of temperature with pressure are intended for use over the range of pressures from p=680 mm to p=780 mm of mercury.

TABLE 2. *Secondary reference points*

Under a pressure of 1 standard atmosphere, except for the triple points.

	Temperature °C (Int. 1948)
Temperature of equilibrium between solid carbon dioxide and its vapor	−78.5
$t_p=[-78.5 \text{ to } +12.12(p/p_o-1)-6.4(p/p_o-1)^2]$°C	
Temperature of equilibrium between solid mercury and liquid mercury	−38.87
Temperature of equilibrium between ice and air-saturated water	0.000
Temperature of triple point of phenoxybenzene (diphenyl-ether)	26.88
Temperature of transition of sodium sulphate decahydrate	32.38
Temperature of triple point of benzoic acid	122.36
Temperature of equilibrium between solid indium and liquid indium	156.61
Temperature of equilibrium between liquid naphthalene and its vapor	218.0
$t_p[=218.0+44.4(p/p_o-1)-19(p/p_o-1)^2]$°C	
Temperature of equilibrium between solid tin and liquid tin	231.91
Temperature of equilibrium between liquid benzophenone and its vapor	305.9
$t_p+[305.9+48.8(p/p_o-1)-21(p/p_o-1)^2]$°C	
Temperature of equilibrium between solid cadmium and liquid cadmium	321.03
Temperature of equilibrium between solid lead and liquid lead	327.3
Temperature of equilibrium between liquid mercury and its vapor	356.58
$t_p=[356.58+55.552(p/p_o-1)-23.03(p/p_o-1)^2+14.0(p/p_o-1)^3]$°C	
Temperature of equilibrium between solid aluminum and liquid aluminum	660.1
Temperature of equilibrium between solid copper and liquid copper (in a reducing atmosphere)	1083
Temperature of equilibrium between solid nickel and liquid nickel	1453
Temperature of equilibrium between solid cobalt and liquid cobalt	1492
Temperature of equilibrium between solid palladium and liquid palladium	1552
Temperature of equilibrium between solid platinum and liquid platinum	1769
Temperature of equilibrium between solid rhodium and liquid rhodium	1960
Temperature of equilibrium between solid iridium and liquid iridium	2443
Temperature of melting tungsten	3380

4.3. Relation Between the International Practical Temperature Scale and the Thermodynamic Scale

When the International Temperature Scale was adopted in 1927 it was in as close accord with the thermodynamic scale as was practicable with the knowledge then available. It was recognized, however, that further research would increase our knowledge of the actual differences between values of temperature on the two scales. When it is desired to know the value of a temperature on the thermodynamic scale, the usual procedure is to obtain the value on the International Practical Temperature Scale and then to convert it to the thermodynamic scale by adding the appropriate difference between the scales. These differences, however, have to be determined by experiment. They are difficult to determine accurately because they are small compared with their Kelvin temperature. Some of these differences obtained in various parts of the scale are given below in order to show the present state of our information about the agreement of the two scales.

On account of the uncertainties in these differences it seems preferable not to modify the values of temperature on the International Practical Temperature Scale now but to further improve our knowledge of the differences between the scales. When it is desired, it will be possible to improve the means of determining temperatures on the International Practical Temperature Scale without changing significantly the values of temperature. This procedure will avoid the confusion which would result from too frequent changes in values of temperature.

In the range from 0 °C to the sulfur point, intercomparisons of two nitrogen gas thermometers with standard resistance thermometers were reported in 1939 from The Massachusetts Institute of Technology. The differences found between the thermodynamic Celsius temperature t_{th} (definition of 1954) and the temperature t_{int} (1948 scale) have been formulated as follows:

$$t_{th}-t_{int}=\frac{t}{t_{100}}\left[-0.0060+\left(\frac{t}{t_{100}}-1\right)\right.$$
$$\left.(0.041\,06-7.363\times10^{-5}\,\text{deg}^{-1}t)\right]\text{deg}.$$

This relation gives 99.994 °C (therm.) for the steam point and 444.70 °C (therm.) for the sulfur point. The results obtained with the two gas thermometers differed by 0.005 deg at the steam point and 0.05 deg at the sulfur point. In 1958 the Physikalisch-Technische Bundesanstalt reported the value 444.66 °C (therm.) for the sulfur point.

In the range from the oxygen point to 0 °C, investigations at the Physikalisch-Technische Reichsanstalt, reported in 1932, and at the University of Leiden, reported in 1935, give a set of values which indicate that the differences $t_{th}-t_{int}$ have a maximum of about +0.04 deg at about −80 °C. Below −100 °C some of the reported differences have opposite signs. These differences are of the order of magnitude of the possible uncertainties in the gas thermometer measurements. For the oxygen point, the results published since 1927 by four laboratories have been recalculated on the basis of the value $T_0=273.15$ °K (adopted in 1954). These values are 90.191 °K from the Physikalisch-Technische Reichsanstalt (1932), 90.17 °K from the Tohoku University, Sendai, Japan (1935), 90.160 °K from the University of Leiden (1940), and 90.150 °K from the Pennsylvania State University (1953). The average of these four results is 90.168 °K or −182.982 °C (therm.).

The International Practical Temperature Scale is not defined below the oxygen point.

In the neighborhood of 1000 °C new determinations of the thermodynamic temperature of the silver point and gold point have been made in recent years in Germany and Japan. At the Physikalisch-Technische Bundesanstalt (1958) 962.16 °C (therm.) was obtained for the silver point and 1064.76 °C (therm.) for the gold point. At the Tokyo Institute of Technology (1958), the values 961.20 °C (therm.) and 1063.73 °C (therm.) were obtained for these points; these last two values being little different from those reported by the same laboratory in 1956, namely 961.28 °C (therm.) and 1063.69 °C (therm.)

In the range above the gold point the Planck radiation formula is used. The Planck formula is consistent with the thermodynamic scale and hence it would give true values of Kelvin temperature if the correct values were known for the Kelvin temperature of the gold point and for the second radiation constant C_2.

An analysis of variance of data on atomic constants by The California Institute of Technology, published in 1955, gave the value 0.014 388 8 meter-degree for C_2. A similar analysis from The Johns Hopkins University, published in 1957, gave the value 0.014 388 6 meter-degree for C_2.

The international practical Kelvin temperatures are obtained by adding the value of $T_0=273.15$ deg to the international practical Celsius temperatures, defined above. Values of the thermodynamic Celsius temperatures are obtained by subtracting T_0 from the thermodynamic Kelvin temperatures. Table 3 gives the recommended designations; the arrows point from the defined temperatures to the temperatures derived by changing the origin.

Table 3.

	International Practical Scales	
Celsius		Absolute
International Practical Temperature	Names ⟶	International Practical Kelvin Temperature
t_{int}	Symbols	$T_{int}=t_{int}+T_0$
°C (Int. 1948) degrees Celsius international practical 1948	Designations	°K (Int. 1948) degrees Kelvin international practical 1948
	Thermodynamic Scales	
Celsius		Absolute
Thermodynamic Celsius Temperature	Names ⟵	Thermodynamic Kelvin Temperature
$t=T-T_0$	Symbols	T
°C (therm.) degrees Celsius thermodynamic	Designations	°K degrees Kelvin

($T_0=273.15$ deg)

Note. For the international practical temperature, the subscript "int" after t may be omitted if there is no possibility of confusion.

NOTE IN PROOF - It is expected that a new International Practical Temperature Scale will come in to use in 1969. This new scale may deviate considerably from the International Scale defined herein. It probably will extend downward to 14 K.

PREPRINT INSTRUMENT SOCIETY of AMERICA
20th Annual ISA Conference and Exhibit • October 4-7, 1965, Los Angeles
Preprint Number 14.3-1-65

The Realization and Use
Of The
International Practical Temperature Scale of 1948

John P. Evans
National Bureau of Standards
Washington, D. C.

ABSTRACT

This paper describes the International Practical Temperature Scale of 1948, the methods and accuracy with which it is realized, and the current efforts being made to improve the scale. Methods of transferring the scale to temperature measuring instruments are also discussed.

Key words: Fixed-point, freezing point, international, practical, pyrometer, scale, standard, temperature, thermocouple, thermometer, and triple-point.

DESCRIPTION OF THE SCALE

It is recognized that all temperature measurements should be ultimately referrable to the Thermodynamic Kelvin Temperature Scale.[1] This scale, based on the second law of thermodynamics, can be realized only with considerable difficulty, and few laboratories are equipped to make the necessary measurements. There are other methods of determining temperatures more precisely and conveniently, however. In 1927 the Seventh General Conference on Weights and Measures adopted the International Temperature Scale based on some of these methods. The scale was revised in 1948, and at that time the designation "degree Celsius" (rather than degree Centigrade) was agreed upon. In 1960 a few changes were made in the text of the scale, but these changes did not alter values of temperature expressed on the scale. The word "practical" was inserted in the name, and the scale is now called the International Practical Temperature Scale of 1948.[2] In this paper the abbreviation IPTS will sometimes be used in reference to the scale.

The definition of the IPTS is given in the appendix to this paper. The scale is based on six reproducible temperatures called "defining fixed points." The numerical values assigned to these defining fixed points were originally chosen to make the scale conform as closely as practicable to the thermodynamic scale. While the sulfur point is listed as one of the six defining fixed points, the zinc point is recommended instead, since it has been shown to be more reproducible than the sulfur point, and its use leads to the same values of temperature on the IPTS[3].

Temperatures other than the defining fixed points are derived from the indications of specified standard instruments calibrated at the defining fixed points. The definition of the IPTS therefore includes formulas giving the relation between temperature and the indications of the standard interpolating instruments. To complete the definition, essential physical characteristics of the standard instruments are specified. Above the gold point, temperatures are derived from the ratio of spectral radiances of two blackbodies, one at the gold point, by means of the Planck radiation formula. Though the IPTS does not specify how or at what wavelength the ratio is to be determined, this is usually done with an optical pyrometer operating in the red region of the visible spectrum.

The official text (adopted by the Eleventh General Conference on Weights and Measures) of the International Practical Temperature Scale of 1948 includes a section on recommendations and a section of supplementary information. The recommendations are given in the interest of uniformity and reproducibility in realizing temperature on the scale. For further details, the reader is referred to reference 2 which is a translation of the official text (French).

REALIZATION OF THE SCALE

In order to realize the IPTS it is necessary to establish the six defining fixed points and to develop the equipment required to calibrate interpolating instruments at these points. The equipment and procedures have been well described in the literature so that only a brief outline of the general problem need be given here.[4-6]

The triple point of water is realized in sealed glass cells containing water from which impurities and dissolved gases have been removed. A mantle of ice is frozen on the re-entrant thermometer well, after which the ice adjacent to the well is melted to produce a thin layer of very pure water. After the ice in the mantle has aged a day or so, this ice-water interface establishes a temperature which is highly reproducible from cell to cell and which can be maintained for long

---

Superior numbers refer to similarly numbered references at the end of this paper.

periods of time if the cell is properly stored in an ice bath.

The oxygen, steam, and sulfur points are boiling points; consequently the equilibrium temperature is strongly dependent on pressure. A change in pressure of 10^{-2} torr corresponds to temperature changes of about 0.0001 deg at the oxygen point, 0.0003 deg at the steam point, and 0.001 deg at the sulfur point. It is therefore evident that the pressure in the baths used to maintain these fixed points must be very carefully determined. The oxygen point may be realized in an apparatus which utilizes the equilibrium temperature of liquid and gaseous oxygen at a pressure of one atmosphere, while the steam and sulfur points are usually achieved as condensation points in apparatus in which the water and sulfur, respectively, are actively boiled.

The gold, silver, and zinc points are realized as freezing points. A sample of pure metal is first melted in a high purity graphite crucible of appropriate size and shape. Freezing of the metal is then established, and the constant temperature observed is taken as the freezing point. The crucibles used for calibrating resistance thermometers and thermocouples are equipped with thermometer wells, while the crucibles used to establish the scale above the gold point contain a graphite blackbody cavity. The emittance of this blackbody should be at least 0.999.

With the defining fixed points established, the next step in realizing the IPTS is to calibrate the interpolating instruments at these points. Here the problem is to first bring the instrument to a stable physical condition, then to place the temperature-sensitive part of the instrument in thermal equilibrium with the defining fixed point, and finally to determine the instrument indication with sufficient precision.

Standard resistance thermometers and standard thermocouples must be well annealed before calibration, and during testing they must be properly protected from chemical contamination and physical harm. At the defining fixed points, they must be sufficiently well immersed to eliminate any significant stem losses by conduction and radiation. This applies also to the reference junctions of a standard thermocouple which are maintained at 0 °C in an ice bath. Instruments that can determine thermometer resistance and thermocouple emf with adequate precision have been developed, but there are many precautions to be observed. For example, one must account for the self-heating of a resistance thermometer by its measuring current, and in the case of thermocouples, one must maintain a precise voltage reference and carefully guard against the intrusion of spurious emfs in the measuring circuitry.

Above the gold point the IPTS is usually realized with an optical pyrometer. The calibration of an optical pyrometer consists of determining the relation between current through the filament of a reference lamp in the pyrometer and the temperature of a blackbody to which the lamp filament is matched in brightness. The calibration procedure is lengthy and far too involved to describe here in detail. An excellent account of the theories that are applied and the techniques used is given in reference 4.

ACCURACY OF REALIZING THE SCALE

Before attempting to assess the accuracy with which the IPTS can be realized, let us first consider some of the factors affecting reproducibility of the defining fixed points and the precision of the interpolating instruments. Fixed-point reproducibility has to do with differences in equilibrium temperatures achieved from time to time in a particular laboratory because of slight variations in the purity of the materials, in fixed-point apparatus, and in techniques. Precision of interpolating instruments, on the other hand, is concerned with how well a particular instrument is able to repeat its indication at a given temperature.

The triple point of water is especially important since it is the single point common to both the practical and the thermodynamic temperature scales. However, the equilibrium temperature of a freshly prepared ice mantle may increase slowly from 0.0001 to 0.0005 deg over a period of several days before becoming stable.[2] This increase is thought to be caused by release of strain in the ice or by a change in the size of the ice crystals. Radiation transmitted through the ice and water in the cell and surrounding ice bath can measurably alter the temperature of a resistance thermometer in the cell.[17] This can be eliminated by covering the cell and bath. Finally, the equilibrium temperature is a function of the depth below the liquid-vapor interface so that a depth correction must be applied. Under the best conditions, cells from different sources have been shown to produce equilibrium temperatures which are constant for long periods of time and agree within 0.0002 deg.

As pointed out earlier, the boiling points are strongly dependent on pressure. It is quite difficult to determine precisely the pressure in that part of the apparatus where the thermometer is located. Impurities in the boiling-point material can cause errors, as can radiative transfer of heat between the thermometer and parts of the apparatus at temperatures different from the equilibrium temperature. In the case of sulfur, it has been observed that when boiling is first started after a period of rest, the equilibrium temperature at one atmosphere will decrease for several days. The reason for this is not fully understood. For these and other reasons, the boiling points are somewhat less reproducible than the triple point.

The metal freezing points, on the other hand, are not significantly affected by usual changes in atmospheric pressure, though the hydrostatic pressure of the liquid metal does have a measurable effect on the equilibrium temperature and must be taken into account. The main requirements for achieving reproducible freezing points are to start with very pure metal, to keep the metal pure during use, and to freeze the metal very slowly and uniformly. Under these conditions samples of high purity zinc from different sources have been shown to have the same freezing point within 0.0002 deg.[7] There are no reasons to expect that silver and gold would differ appreciably in behavior from zinc, and in fact there is experimental evidence to show that the gold point is reproducible within at least 0.002 deg (see below). Silver must be protected from oxygen since a small amount of oxygen dissolved in the silver will depress its freezing point significantly.

The reproducibilities of the defining fixed points are summarized in column 3 of Table 1. The numbers given represent the maximum difference which should be observed in the fixed points in a particular laboratory from time to time and from sample to sample when materials of the highest available purity are used to establish the fixed points.[7]

Column 4 of Table 1 gives an estimate of the precision (really imprecision), associated with interpolating instruments and measuring equipment. The numbers were estimated by examining the instrumental precision achieved in various laboratories. For the most part these uncertainties are influenced by the stability of the instruments themselves.[7]

Platinum resistance thermometers are very stable instruments if they are made of pure platinum wire which is kept strain-free, and if they are protected from chemical contamination and from physical and thermal shock. To achieve the high precision of which they are capable it is essential they always be used in a well annealed condition. Standard thermocouples are also relatively stable instruments if they are well annealed, used in clean oxidizing atmospheres, and are protected from chemical and physical contamination. The largest uncertainty in thermocouples arises from emf's which are generated in regions of slight inhomogenities in the thermocouple wires as they pass through temperature gradients. Optical pyrometer precision is

Table 1
Estimates of Imprecisions in Realizing the IPTS

Temperature 1	Interpolating Instrument 2	Reproducibility (spread) of Fixed Point 3	Instrumental Imprecision 4	Interlaboratory Imprecision 5	Differences $t_{th} - t_{int}$ 6
Oxygen point	Resistance Thermometer	0.001 deg	±0.004 deg	±0.02 deg	−0.01 deg
Triple point		.0002	.0002	.0002	--
Steam point		.0005	.0002	.0005	-0.001_5
Zinc point		.0003	.0002	.001	+0.074
Sulfur point		.0015	.0002	.002	+0.076
630.5 °C		--	.001	.02	+0.17
630.5 °C	Thermocouple		.1	.2	
Silver point		.002 (est)	.1	.2	+1.13
Gold point		.002 (est)	.1	.2	+1.41
Gold point	Optical Pyrometer		.3	.4	
2000 °C		--	1.0	2.0	
4000 °C		--	3.0	10.0	

largely determined by the stability of the reference lamp characteristics and by the ability to achieve brightness matches. The latter is especially significant in visual optical pyrometry where the matching detector is an observer's eye.

In order to arrive at how accurately the IPTS can be realized, one might circulate "perfect" transfer standards among all laboratories in which attempts have been made to realize the IPTS. The standard deviation of the average temperatures determined for the transfer standards in each laboratory could then be considered a measure of the accuracy of realizing the scale.[4,8] The figures in column 5 of Table 1 are estimates of such standard deviations, and they are based on a limited number of interchanges of interpolating instruments and transfer standards between several national standards laboratories.

Also of interest is the difference between the practical and thermodynamic temperature scales. The differences given in column 6 of Table 1 are taken from a table prepared by the Advisory Committee on Thermometry* at the Seventh Session in 1964. This table was based on the best assessed information available to the committee at that time. In the table t_{int} is the value of temperature on the IPTS and t_{th} + 273.15 deg is the value of the same temperature on the Thermodynamic Kelvin Temperature Scale.

TRANSFER OF THE SCALE TO OTHER INSTRUMENTS

To be widely useful the IPTS must be transferred from the standard instruments to other temperature measuring devices. This is customarily done by directly comparing standard resistance thermometers, standard thermocouples, and standard optical pyrometers with the instrument to be calibrated over the temperature range to be used.

In the range -183 to +500 °C comparison calibrations may be made by inserting thermometers or thermocouples to be tested, together with a standard resistance thermometer, in stirred liquid baths of appropriate design.[9] Solid metal baths maintained at a uniform temperature are also useful. At higher temperatures, thermocouples are more conveniently compared with a standard thermocouple by fusing the measuring junctions of the test and standard thermocouples together. The emf's of the thermocouples are then measured simultaneously as the temperature of the common junction is changed.[6,10]

Above the gold point optical pyrometers are compared with a standard instrument by sighting both the test and standard on the same radiating source. If the radiating source is not a blackbody, a correction must be applied to compensate for the difference in mean effective wavelengths at which the two instruments operate. Thermocouples are compared with optical pyrometers at high temperatures by bringing a thermocouple to thermal equilibrium with blackbody radiation, the temperature of which is determined with a calibrated optical pyrometer.

The IPTS may also be transferred to other instruments and other laboratories by means of "transfer standards", such as calibrated tungsten ribbon-filament lamps and thermometric fixed points. Examples of thermometric fixed points are the freezing points of pure metals and eutectic alloys, and the freezing and boiling points of other pure inorganic and organic materials. The ice point (0 °C) is particularly easy to achieve with considerable precision in the laboratory, and the steam point may be approximated closely in open hypsometers. Tungsten ribbon-filament lamps, which provide continuously adjustable sources of radiation, are useful transfer standards above the gold point. They are calibrated by determining the relation between current through the filament and the brightness temperature at a particular wavelength when viewed under specified conditions.

Any well equipped laboratory may realize the IPTS directly as described above, and then transfer the scale to other instruments or transfer standards. If this is carefully done, an interchange of standard interpolating instruments with other laboratories should show that the realizations of the scale agree within the limits given in Table 1. However, because of the complexity of such procedures, it is usually not practical for most laboratories to maintain temperature standards in this manner. For this reason, and so that there may be a common source for the realization of the IPTS in this country, the National Bureau of Standards offers a series of calibration services by which the IPTS, as it is realized at NBS, may be transferred to other laboratories.[11] NBS also maintains and distributes a supply of metal samples, the freezing points of which have been determined on the IPTS, and a supply of thermometric cells which establish reference temperatures by means of the freezing behavior of purified organic compounds.[12]

METAL FREEZING POINTS

This decade has seen the advent of a new era in the use of pure metal freezing points as precise thermometric fixed points, brought about by the increasing commercial availability of extremely pure metals and by a series of careful researches on these metals. As a result, metal freezing points are now among the most useful of the fixed points. They are relatively easy to realize with simple equipment, they are highly reproducible and durable, and they are not strongly dependent on pressure.

Outstanding among recent investigations of metal freezing points is the work of McLaren at the National Research Council in Canada.[13] He has shown the freezing points of a number of metals, which are realized as the plateau temper-

---

*The Advisory Committee on Thermometry is one of the six advisory committees of the International Committee on Weights and Measures. See reference 3.

atures on slow-rate freezing curves, to be nearly as reproducible as any temperature on the IPTS if the metals are sufficiently pure. McLaren has already reported the results of his investigations of indium, tin, cadmium, lead, and zinc, and at the present (early 1965) he is working with antimony. A preliminary report indicates that the antimony point is comparable to the other points (contrary to what was thought earlier - see ref. 3), but its temperature on the IPTS still needs to be determined with precision.[14] McLaren has developed techniques for inducing a freezing condition in a metal sample to establish an isothermal liquid-solid interface surrounding the temperature-sensitive part of a thermometer. This shields the thermometer from temperature fluctuations of the heating equipment, and permits freezing to progress very slowly and uniformly. McLaren has also devised a method of thermal analysis, based on alloy melting range, which allows one to discriminate between samples of pure metal so that the purest may be chosen as the thermometric standard. This method also affords a simple means of self-checking the continued integrity of the standard.

A recent investigation of the mercury freezing point by Dengler has shown this point to be highly reproducible and easy to achieve.[15] Mercury of very high purity is apparently readily available from a number of sources. An effort is now being made to determine the temperature of the mercury point on the IPTS. McAllen, working at the National Research Council in Canada, is currently studying the characteristics of the copper-silver eutectic point. If this point proves tractable, it will fill an important gap between the antimony point and the silver point. The aluminum point is also in this temperature range and it should be investigated thoroughly.

Definitive investigations of the gold and silver points, comparable to those which have been made at the lower temperatures, have had to await the development of more sophisticated instrumentation and technique. A few preliminary experiments have been made at NBS and more are being planned. In one test, the freezing points of two samples of pure gold (impurity concentrations of the order 1 - 10 ppm) were determined with a high temperature platinum resistance thermometer of special design. They were found to differ between freezings and between samples by less than 0.002 deg, though melting range curves obtained with the same thermometer revealed that one sample was definitely of higher purity than the other.

Above 1063 °C, the copper point has been substituted for the gold point in some laboratories for thermocouple and optical pyrometer calibrations. The palladium and platinum points have also been used, in a melting disk method, to establish calibration curves for high temperature thermocouples.[16] These points all need to be redetermined with the precise photoelectric pyrometers now being developed.[20]

Table 2 presents a selected list of metal freezing points covering a large portion of the IPTS. The temperatures given are believed by the author to be the best available at the present time. When current investigations are completed, these metal freezing points, together with the triple point of water, will provide many laboratories a simple basis for approximating the IPTS very closely from -50 to 1063 °C, probably within the accuracy of the scale itself. Several manufacturers are developing or have already marketed freezing point equipment to do this.

Table 2
Selected Metal Freezing Points

Metal	Reported Freezing Point °C, Int. 1948	Reference
Mercury	-38.86	15
Indium	156.611	13
Tin	231.913	13
Cadmium	321.032	13
Lead	327.426	13
Zinc	419.505	Defined
Antimony	630.55 (est)	*
Alumium	660.1	2
Copper-Silver Eutectic	778.3	20
Silver	960.8	Defined
Gold	1063	Defined
Copper	1083	2
Palladium	1552	2
Platinum	1769	2

*Tentative value based on preliminary measurements at NBS.

IMPROVEMENT OF THE SCALE

The figures in Table 1 show that some parts of the IPTS would benefit from changes based on information already available. Obviously, use of the zinc point instead of the sulfur point makes the part of the scale covered by the standard resistance thermometer more reproducible. Similarly, substitution of the tin point for the steam point would improve the upper part of the range, though at the expense of a slight degradation of the scale below 100 °C.[7]

Recent findings also lead to improved resistance thermometry. For example, McLaren reports that serious thermometer errors can occur at the higher temperatures because of "radiation piping" up the stems of quartz tube thermometers.[17] This error may be as much as 0.1 degree at the antimony point. By coating the thermometer with a substance which breaks up the total internal reflections, this source of error can be eliminated and an increase in thermometer precision achieved. Studies of the annealing behavior and low temperature characteristics of platinum resistance thermometers point the way to improved manufacture which ought to further enhance thermometer stability.[18,19]

There are some difficulties with the scale in the region of the oxygen point, and there appears to be a definite need for extending the scale to lower temperatures. In recent years the existing provisional low temperature scales maintained in the various national standards laboratories have been compared. From the results of these comparisons, the Advisory Committee on Thermometry in 1964 derived a platinum resistance thermometer interpolation table. It is expected that these efforts, together with recent investigations of low temperature fixed points, will lead eventually to extending the practical temperature scale to the boiling point of equilibrium hydrogen (about -253 °C or 20 °K).[20]

Considerable improvement can be achieved in the range 630.5 to 1063 °C, where precision of the standard thermocouple seriously limits realization of the scale, by replacing the thermocouple with a platinum resistance thermometer as interpolating instrument. It has been shown that with the very pure platinum wire and insulating and protecting materials available today, highly stable thermometers can be made.[21-24] Thermometers have been built and tested which, when heated for hundreds of hours at temperatures above 1000 °C, have changed by less than the equivalent of 0.05 deg at the gold point. Thus, the way is open to defining a practical temperature scale all the way from the hydrogen point to the gold point by platinum resistance thermometry.

Above the gold point, the fundamental limitations imposed on the scale by visual optical pyrometry are being overcome with photoelectric pyrometers. Such instruments have increased the sensitivity and precision of optical pyrometry by nearly an order of magnitude.[20]

Finally, the results of gas thermometer determinations of the defining fixed points will, in the near future, permit meaningful changes to be made in the numbers assigned to these points.[20] This will bring the practical temperature scale into closer agreement with the thermodynamic scale. One can therefore look to the adoption of a significantly improved international practical temperature scale at the next General Conference on Weights and Measures in 1968.

SUMMARY

In summary, we have seen that the International Practical Temperature Scale of 1948 is a well defined scale that can be realized with high precision and accuracy. Information is available which can lead to an even better practical scale in the near future. It has also been pointed out that the freezing points of pure metals provide a simple and precise means of transferring and maintaining the scale in a laboratory. The use of these metal freezing-point standards is highly recommended to all who are interested in precise temperature measurements.

REFERENCES

1. Comptes Rendus de la Dixième Conférence Générale des Poids et Mesures, p. 79 (1954).
2. H. F. Stimson, "International Practical Temperature Scale of 1948, text revision of 1960", NBS Monograph 37, (1961).
3. H. F. Stimson, "Text revision of the International Temperature Scale of 1948", Temperature, Its Measurement and Control in Science and Industry, Vol. 3, (Reinhold Publishing Corp., New York, N. Y., 1962).
4. H. J. Kostkowski and R. D. Lee, "Theory and methods of optical pyrometry", NBS Monograph 41, (1962).
5. H. F. Stimson, "Precision resistance thermometry and fixed points", Temperature, Its Measurement and Control in Science and Industry, Vol. 2, (Reinhold Publishing Corp., New York, N. Y., 1955).
6. W. F. Roeser and S. T. Lonberger, "Methods of testing thermocouples and thermocouple materials", NBS Circular 590 (1958).
7. H. Preston-Thomas, "The replacement of fixed points on a temperature scale", Temperature, Its Measurement and Control in Science and Industry, Vol. 3, (Reinhold Publishing Corp., New York, N. Y., 1962).
8. H. J. Kostkowski, "The accuracy and precision of measuring temperature above 1000 °K," Proceedings of an International Symposium on High Temperature Technology, (McGraw-Hill Book Co., New York, N. Y., 1960).
9. J. F. Swindells, "Calibration of liquid-in-glass thermometers", NBS Monograph 90 (1965).
10. T. M. Dauphinee, "An apparatus for the comparison of thermocouples", Can. J. Phys., **33**, 275 (1955).
11. The Federal Register, Title 15, Chapter II, Subchapter A, "Test fee schedules". Copies of part 203, Heat, may be obtained from the Temperature Section, IBS, National Bureau of Standards, Washington, D. C. 20234.
12. NBS Miscellaneous Publication M241, "Standard materials", (1962).
13. E. H. McLaren, "The freezing points of high purity metals as precision temperature standards", Temperature, Its Measurement and Control in Science and Industry, Vol. 3, (Reinhold Publishing Corp., New York, N. Y., 1962).
14. E. H. McLaren and E. G. Murdock, "Preliminary investigations at the freezing point of high purity antimony", Document No. 17, Comité Consultatif de Thermométrie, Seventh Session (1964).
15. C. O. Dengler, "A new mercury freezing point cell", Proceedings ISA, Vol. 17, Part 1, Paper No. 19.4.62 (1962).
16. W. Obrowski and W. Prinz, "Newly determined reference table for the thermocouple combination Pt-30% Rh—Pt-6% Rh", Archiv f. Eisenhüttenwesen, **33**, (1962).
17. E. H. McLaren and E. G. Murdock, "Radiation effects in precision resistance thermometry",

Document No. 18, Comité Consultatif de Thermométrie, Seventh Session (1964).

18. R. J. Berry, "The stability of platinum resistance thermometers at temperatures up to 630 °C", Temperature, Its Measurement and Control in Science and Industry, Vol. 3, (Reinhold Publishing Corp., New York, N. Y., 1962).
19. D. R. Lovejoy, "A surface layer model for the total resisitivity of thermometric-grade platinum wire", Can. J. Phys., 42, 2264 (1964).
20. See several appropriate papers in Temperature, Its Measurement and Control in Science and Industry, Vol. 3, Part 1, (Reinhold Publishing Corp., New York, N. Y., 1962).
21. J. P. Evans and G. W. Burns, "A study of the stability of high temperature platinum resistance thermometers", Temperature, Its Measurement and Control in Science and Industry, Vol. 3, (Reinhold Publishing Corp., New York, N. Y., 1962).
22. S. Nakaya and H. Uchiyama, "High temperature thermometry with platinum resistance thermometers—II", Document No. 16, Comité Consultatif de Thermométrie, Seventh Session (1964).
23. F. Z. Alieva, "New platinum resistance thermometer for precision measurements of high temperatures", Izmeritel'naya Teckhnika, No. 6, p. 21, June 1964.
24. D. A. Toenshoff, "Bird cage resistance thermometer", Engelhard Industries, Inc., Technical Bulletin, 5, 1927, (1965).

APPENDIX

Temperatures on the International Practical Temperature Scale of 1948 are expressed in degrees Celsius, designated °C or °C (Int. 1948), and are denoted here by the symbol t or t_{int}.

The International Practical Temperature Scale is based on six reproducible temperatures (defining fixed points), to which numerical values are assigned, and on formulas establishing the relation between temperature and the indications of instruments calibrated by means of values assigned to the six defining fixed points. These fixed points are defined by specified equilibrium states, each of which, except for the triple point of water, is under a pressure of 101 325 newtons/meter^2 (1 standard atmosphere).

The fixed points of the scale and the exact numerical values assigned to them are given in table 1.

TABLE 1. *Defining fixed points*

Exact values assigned. The pressure is 1 standard atmosphere, except for the triple point of water.

	Temperature °C (Int. 1948)
Temperature of equilibrium between liquid oxygen and its vapor (oxygen point)	−182.97
Temperature of equilibrium between ice, liquid water, and water vapor (triple point of water)	+0.01
Temperature of equilibrium between liquid water and its vapor (steam point)	100
Temperature of equilibrium between liquid sulfur and its vapor (sulfur point)	444.6*
Temperature of equilibrium between solid silver and liquid silver (silver point)	960.8
Temperature of equilibrium between solid gold and liquid gold (gold point)	1063

*In place of the sulfur point, it is recommended to use the temperature of equilibrium between solid zinc and liquid zinc (zinc point) with the value 419.505 °C (Int. 1948). The zinc point is more reproducible than the sulfur point and the value which is assigned to it has been so chosen that its use leads to the same values of temperature on the International Practical Temperature Scale as does the use of the sulfur point.

The procedures for interpolation lead to a division of the scale into four parts.

a. From 0 °C to 630.5 °C (antimony point) the temperature t is defined by the formula

$$R_t = R_0(1 + At + Bt^2),$$

where R_t is the resistance at temperature t of the platinum wire resistor of a standard resistance thermometer, and R_0 is the resistance at 0 °C. The constants R_0, A, and B are to be determined from the values of R_t at the triple point of water, at the steam point, and at the sulfur point (or the zinc point). The platinum wire of a standard resistance thermometer shall be annealed and its purity shall be such that R_{100}/R_0 is not less than 1.3920.

b. From the oxygen point to 0 °C, the temperature t is defined by the formula

$$R_t = R_0\,[1 + At + Bt^2 + C(t - t_{100})t^3],$$

where R_0, A, and B are determined in the same manner as in *a* above, the constant C is to be determined from the value of R_t at the oxygen point, and $t_{100} = 100$ °C.

c. From 630.5 °C to the gold point the temperature t is defined by the formula

$$E = a + bt + ct^2,$$

where E is the electromotive force of a standard thermocouple of platinum and platinum-rhodium alloy, when one of the junctions is at 0 °C and the other at the temperature t. The constants a, b, and c are to be determined from the values of E at 630.5 °C, at the silver point, and at the gold point. The value of the electromotive force at 630.5 °C is to be determined by measuring this temperature with a standard resistance thermometer.

The wires of the standard thermocouple shall be annealed and the purity of the platinum wire shall be such that the ratio R_{100}/R_0 is not less than 1.3920. The platinum-rhodium wire shall consist nominally of 90 percent platinum and 10 percent rhodium by weight. When one junction of the thermocouple is at 0 °C and the other is successively at 630.5 °C, the silver point, and the gold point, the completed thermocouple shall have electromotive forces such that

$$E_{Au} = 10\,300\ \mu v \pm 50\ \mu v$$

$$E_{Au} - E_{Ag} = 1183\ \mu v + 0.158\ (E_{Au} - 10\,300\ \mu v) \pm 4\ \mu v$$

$$E_{Au} - E_{630.5} = 4766\ \mu v + 0.631\ (E_{Au} - 10\,300\ \mu v) \pm 8\ \mu v.$$

d. Above the gold point the temperature t is defined by the formula

$$\frac{J_t}{J_{Au}} = \frac{\exp\left[\dfrac{C_2}{\lambda(t_{Au} + T_0)}\right] - 1}{\exp\left[\dfrac{C_2}{\lambda(t + T_0)}\right] - 1},$$

where J_t and J_{Au} are the radiant energies per unit wavelength interval at wavelength λ, emitted per unit time per unit solid angle per unit area of a blackbody at the temperature t and the gold point respectively, C_2 is the second radiation constant with the value $C_2 = 0.014\,38$ meter-degrees, λ is in meters, and $T_0 = 273.15$ degrees.

NOTE IN PROOF - It is expected that a new International Practical Temperature Scale will come in to use in 1969. This new scale may deviate considerably from the International Scale defined herein. It probably will extend downward to 14 K.

U. S. DEPARTMENT OF COMMERCE NATIONAL BUREAU OF STANDARDS

RESEARCH PAPER RP1188

Part of Journal of Research of the National Bureau of Standards, Volume 22, March 1939

ESTABLISHMENT OF A TEMPERATURE SCALE FOR THE CALIBRATION OF THERMOMETERS BETWEEN 14° AND 83° K

By Harold J. Hoge and Ferdinand G. Brickwedde

ABSTRACT

Seven resistance thermometers (six Pt; one 90Pt:10Rh alloy) have been calibrated on the thermodynamic scale by comparison with a helium gas thermometer. The boiling point of oxygen was taken to be 90.19° K, and computations were made in such a way as to secure continuity between the International Temperature Scale and the scale being established. On the latter scale the triple point of normal hydrogen was found to be 13.96° K and the boiling point 20.39° K. Tables have been prepared by means of which temperatures corresponding to observed resistances may be obtained by linear interpolation.

CONTENTS

I. INTRODUCTION

There are in the United States at the present time 13 laboratories equipped or being equipped to produce liquid hydrogen, liquid helium, or both, and the number is growing steadily. Many of the investigations being carried on in these laboratories require the precise measurement of temperatures in the region below 83° K (−190° C), and the National Bureau of Standards has received a number of requests for calibrations in this temperature range. The International Temperature Scale [1] defines no standard procedure for the measurement of temperatures below −190° C, and as a consequence it has been customary for cryogenic laboratories to calibrate their temperature-measuring instruments by direct comparison with a gas thermometer. The difficulties inherent in gas thermometry make it highly desirable that some simpler procedure be found, which may be used in all investigations where the measurement of temperature is not itself the primary object. Since from 660° C down to −190° C the International Temperature Scale is based on the resistance of platinum, a desirable solution of the problem would be to extend the useful range of the platinum resistance thermometer to lower temperatures. The

---

[1] George K. Burgess, BS J. Research 1, 635 (1928) RP22.

provisional temperature scale described in this paper represents such an extension. Apparatus is now being set up to make this scale available to other laboratories by the calibration of thermometers which may be submitted for test. The purpose of this paper is to describe the establishment of this scale, which is to serve (1) as the basis for calibrations made by the National Bureau of Standards between 14° and 83° K and (2) as the scale to be used by this Bureau in reporting the results of its own investigations.

Since the National Bureau of Standards, in common with other standardizing laboratories, makes all calibrations above −190° C on the International Temperature Scale, it is important that the scale extending to lower temperatures should join smoothly with it at its lowest point. This continuity can be obtained by using the oxygen point as the primary fixed point in determining the constant of the gas thermometer, rather than the ice point, which is the more usual procedure, and by assigning to it the same temperature on both scales. The scale described in this paper is based on seven resistance thermometers (six Pt; one 90Pt:10Rh alloy) whose resistances have been determined as a function of temperature by comparison with the gas thermometer.

The resistances of these thermometers will be checked from time to time at the triple point and boiling point of hydrogen, at the boiling point of oxygen, and at the ice point. It is planned in subsequent investigations to determine a number of other fixed points on the scale described. With a sufficient number of such points established, the maintenance of the scale will not be dependent on the preservation of the seven original thermometers.

It is hoped that the scale will be found to be in agreement with the thermodynamic scale to within ±0.02°. When a program for thermometry was laid out it was considered advisable to establish first a provisional scale of reasonable accuracy without waiting for the construction of more elaborate apparatus with which somewhat greater accuracy might have been attained. The continuation of this program includes, however, the construction of a new and more accurate gas thermometer with which not only to improve the present provisional scale but also to determine fixed points throughout the region below the ice point.

II. APPARATUS

There was available the low temperature adiabatic calorimeter used by Southard [2] and his collaborators in their calorimetric investigations. This calorimeter had been used by Southard and Milner [3] as a cryostat for the gas thermometer with which they calibrated their resistance thermometers. After some changes, designed to improve its accuracy, this apparatus was used in the present work.

The thermometer bulb and cryostat are shown schematically in figure 1. Surrounding the heavy cylindrical copper bulb was a thermal shield with independent heaters in top, side, and bottom, and outside the shield in turn was a vacuum-tight brass container. Outside this container was a dewar flask which was filled with liquid hydrogen (in some cases with liquid air). This dewar flask was entirely enclosed by a metal jacket (not shown). By reducing the

---

[2] J. C. Southard and F. G. Brickwedde, J. Am. Chem. Soc. **55**, 4378 (1933).
[3] J. C. Southard and R. T. Milner, J. Am. Chem .Soc. **55**, 4384 (1933).

pressure inside this jacket with a vacuum pump, temperatures down to 55° K could be obtained with liquid air and temperatures down to 10.5° with (solid) hydrogen. The metal jacket was always surrounded by liquid air before filling the inner dewar with liquid hydrogen.

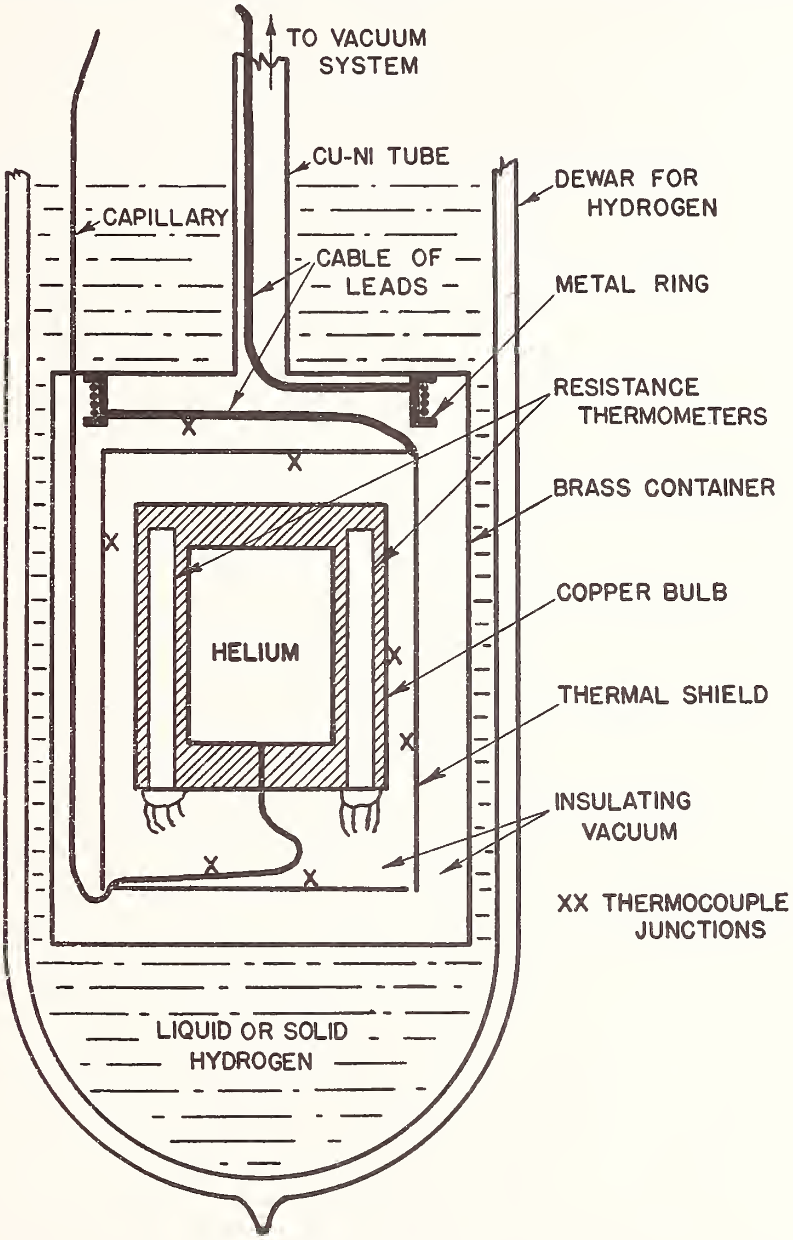


Figure 1.—*Thermometer bulb and cryostat.*

The copper-nickel capillary led to a mercury manometer where the pressures were read on a glass mirror scale. The end of the capillary passed through a turned-brass plug which was waxed into the short arm of the manometer. On the bottom of this plug was a sharp point to which the mercury was adjusted by means of a leveling reservoir before each reading. The long arm of the manometer was connected to a vacuum system and the mercury columns were thermally protected by light aluminum shields. Thermocouple junctions were placed at 10-cm intervals along the portion of the capillary extending from the brass container to the region at room temperature. The reference junction for these thermoelements was in melting ice. Six differential thermocouples (marked × in fig. 1), having a common junction on the bulb itself, indicated any temperature differences between the bulb and the points marked ×. It was necessary to furnish separate heaters both for the cable of leads and for the capillary. The input to the various heating circuits was regulated to keep the indications of the differential thermocouples as near zero as possible. Under these conditions the bulb could be kept at constant temperature as long as desired.

All of the resistance thermometers used were of the four-lead coiled-helix type wound on mica crosses, as described by Meyers,[4] but were sealed into cylindrical platinum cases (5 by 50 mm), filled with helium to promote rapid attainment of thermal equilibrium. The leads were brought out through a glass seal at the end of each case. Two resistance thermometers are shown in place in figure 1. Low-melting solder was used to insure good thermal contact between the thermometer cases and the copper block. All of the thermometers had been repeatedly annealed at approximately 500° C until heating to the sulfur point (444.6° C) did not change their ice-point resistances by more than the equivalent of 0.001°. No great difficulty was experienced in making thermometers which fulfilled this requirement. However, the 7 thermometers chosen were the best of a group of 12, not all of which satisfied the condition just laid down. The ice points of the seven thermometers have been checked several times during the progress of the investigation, some of them over a period of nearly 3 years, and no significant trend has been detected. The constants of the thermometers used are given in table 4, page 362.

The leads from the thermometers were wrapped several times around the bulb and shellacked down, so as to minimize heat leaks to the thermometers. The leads passed from the bulb to a groove in the radiation shield, passed several times around it, and emerged from the top of the shield, where all the leads were collected into a cable and wound with a heater. After making several turns around a metal ring, the cable passed up through the central copper-nickel tube and emerged from the vacuum system through a wax joint at room temperature. The purpose of the metal ring, which was soldered to the top of the brass container, was to cool the leads to the temperature of the refrigerating bath. The central copper-nickel tube led to a vacuum system into which helium could be admitted whenever the gas thermometer was to be brought rapidly to the temperature of the bath. This vacuum system was entirely independent of the one to which the manometer was connected.

---

[4] C. H. Meyers, BS J. Research 9, 807 (1932) RP 508.

Resistances were measured on a thermostated Wheatstone bridge of the type designed by Mueller.[5] The thermocouples on the capillary were read with a potentiometer; those on the temperature-controlling system were arranged for direct connection to a galvanometer.

III. THEORY

A real gas, confined in a volume which is strictly constant and at uniform temperature throughout, exerts a pressure which is a single-valued function of the temperature. This pressure may be used to define a scale of temperatures according to the equation

$$p=cT_g, \qquad (V \text{ const}), \qquad (1)$$

where the subscript g indicates that the scale depends on the kind of gas and on its density, and does not necessarily agree with the thermodynamic scale. The constant c is fixed by the condition that T_g increase by 100° in passing from the ice point to the steam point.

To realize a definite gas scale of temperatures it is necessary to take into account the fact that no actual gas thermometer quite fulfills the conditions laid down above. The volume always changes somewhat with changing temperature and pressure, and there is always some gas in the capillary and other pressure-transmitting volume[6] that is not in general at the same temperature as the gas in the thermometer bulb. These facts make it necessary to work with the product pV in place of the single variable p of eq 1. Referring to unit mass of gas, consider the equation

$$pv=aT_g \qquad (2)$$

For any given value of v this may be made identical with eq 1 by making $a/v=c$, so that there are exactly 100° between the ice and steam points. If a is kept fixed while v is allowed to vary, the T_g corresponding to a given thermal state is no longer uniquely defined by eq 2, but may range over a narrow band of values whose width is proportional to the deviation of the gas from Boyle's law. Evidently the ice-to-steam interval will in general be 100° only for one particular gas density. Let a be so chosen that the particular density for which this occurs is the same as the density[7] of the gas in the bulb of a constant-volume gas thermometer. Then, if the total volume of the gas thermometer is V and the mass of gas contained is m, we have

$$pV=maT_g \qquad (3)$$

if the entire thermometer is at uniform temperature. If it is not at uniform temperature, imagine it subdivided into smaller volumes, each of which may be considered to be at uniform temperature. For the gas in each we may write

$$pV_i=m_iaT_{gi}, \qquad (4)$$

---

[5] E. F. Mueller, J. Research NBS. (Publication pending.)

[6] Other expressions used for this volume are "obnoxious volume", "noxious volume", "dead space", "nuisance volume", "unheated space", "schädlicher Raum", and "espace nuisible". The expression "pressure-transmitting volume" was adopted as being more descriptive of the actual function of this part of the apparatus.

[7] This density will change slightly as the thermometer bulb expands and as the temperature of the pressure-transmitting volume changes. Within the experimental error, however, a constant value of a may be used, since the density variations are small,

and summing over all the volumes

$$p\sum_i \frac{V_i}{T_{gi}} = a\sum_i m_i = A = \text{constant}.$$

Separating out and dropping subscripts on the important term which refers to the gas-thermometer bulb,

$$p\left\{\frac{V}{T_g} + \sum_i{}' \frac{V_i}{T_{gi}}\right\} = A, \tag{5}$$

the prime indicating that one of the terms has been taken outside the summation. Variations in the bulb volume may be taken into account by writing

$$\begin{aligned} V &= V_0(1+\alpha T+\beta T^2+ \; . \; . \; . \; . \; +\gamma p+\epsilon p^2+ \; . \; . \; . \; .) \\ &= V_0[1+f(T,p)], \end{aligned}$$

the constants being determined by preliminary investigations. Substituting this expression in eq 5 and multiplying by T_g/V_0, we obtain

$$p\left\{1+f(T,p)+\frac{T_g}{V_0}\sum_i{}' \frac{V_i}{T_{gi}}\right\} = \frac{A}{V_0}T_g$$

and putting $V_0/A = C$,

$$T_g = C\left\{1+f(T,p)+\frac{T_g}{V_0}\sum_i{}' \frac{V_i}{T_{gi}}\right\}p. \tag{6}$$

From this equation, T_g may readily be found by successive approximations since only the first term in the braces is large. In the calculations it is generally permissible to use T_g for T in finding the change in bulb volume with temperature. The change in bulb volume with pressure is in many cases negligible. The pressure-transmitting volumes, V_i, must be found by actual measurement, but their change with temperature and pressure may ordinarily be neglected. The temperatures T_{gi} which should be assigned to the transmitting volumes are really defined by eq 4. However, they are ordinarily measured with thermometers or thermocouples calibrated to give temperatures in approximate agreement with the thermodynamic scale. With data on the deviation of the gas from Boyle's law one may calculate how the value of T_{gi} corresponding to a given thermal state will vary as the gas density is changed. For most gases this variation is small, seldom more than a few hundredths of a degree throughout the range of densities likely to occur in a gas-thermometer system. Hence, since the T_{gi}'s occur only in small correction terms, it is generally permissible to replace them directly with the thermometer and thermocouple indications of T.

Experimental determination of the constant C requires in principle that p be measured at both the ice and steam points. In many instances it is better to determine C from measurements made at a single point, employing the results of earlier investigations to insure the preservation of the 100° ice-to-steam interval. With the apparatus used in the present work, for example, determination of C at the oxygen point rather than at the ice and steam points permitted the helium density to be increased by a factor of 373/90, with a proportional increase in sensitivity. It is worth-while to emphasize that when C is determined without measuring the ice-to-steam interval, the gas-scale temperature, T_g, rather than the thermodynamic temperature, T, of the calibration point must be inserted in eq 6.

To obtain centigrade gas-scale temperatures from temperatures on the corresponding absolute gas scale, the temperature of the ice point on the latter scale must be subtracted,

$$t_g = T_g - T_{g0}.$$

Since many investigators employ the pressure coefficient β and compute temperatures directly on a centigrade gas scale it should be pointed out that in eq 1

$$c = \beta p_0$$

IV. REDUCTION TO THE THERMODYNAMIC SCALE

The most common method of reducing gas-scale temperatures to the thermodynamic scale is based on the assumption that when a gas is used at lower and lower densities, the corresponding gas scale approaches the thermodynamic. Data for helium which permit this extrapolation to zero density have been obtained both at the Reichsanstalt and at Leiden for the temperature range in which we are interested, and tables of corrections [8], [9] based on these data have been published. These corrections are for a centigrade gas scale and are consequently zero at the ice and steam points. To permit a more direct comparison of the results of the two laboratories, the corrections which they would obtain for the absolute scale of the same gas were computed. The Kelvin and Celsius thermodynamic scales satisfy the relation $T = T_0 + t$, while two corresponding gas scales satisfy the relation $T_g = T_{g0} + t_g$. Hence

$$T - T_g = (T_0 - T_{g0}) + (t - t_g). \tag{7}$$

The published tables referred to give values of $t - t_g$.

From the Reichsanstalt data we have computed $T - T_g$ directly, following the procedure of Henning[10] on page 174. In place of his equation for $t - t_v$ ($t - t_g$ in our notation) the corresponding equation

$$T - T_g = -\frac{T}{A_0}\left[(B_t - B_0) - \frac{T_0 + 100}{100}(B_{100} - B_0)\right] p_0$$

was used, where A_0, B_t, etc., are taken from equations of isotherms of the form

$$\frac{(pV)_t}{(pV)_s} = A_t + B_t p + C_t p^2 \; . \; . \; . \; . \; .$$

The B values used were computed from the equation used by Henning.[11] The value found for $T_0 - T_{g0}$ was $-0.021°$. As a check,

---

[8] F. Henning, Z.ges. Kälte-Ind. **37**, 169 (1930).

[9] W. H. Keesom and W. Tuyn, Leiden Commun. Supp. No. 78, table on p. 49. (Reprinted from Travaux et Mémoires du Bureau International des Poids et Mesures **20** (1936).)

[10] Footnote 8.

[11] F. Henning, Z. ges. Kälte-Ind. **37**, 169 (1930); the entire set of constants is given by J. Otto, Hand. Exp. Physik **8**, part 2, 191 (1929).

$t-t_g$ was computed from eq 7, using this value, and the values found were identical with those of the Reichsanstalt table.

Keesom and Tuyn plotted the corrections computed from several sets of isotherm data, and based their table on a smooth curve drawn through these points. In the heading of their table it is stated that their corrections are based on a value of -0.361×10^{-6} for $\alpha_A-\alpha_{nHe}$ ($=\gamma-\beta$ in our notation).

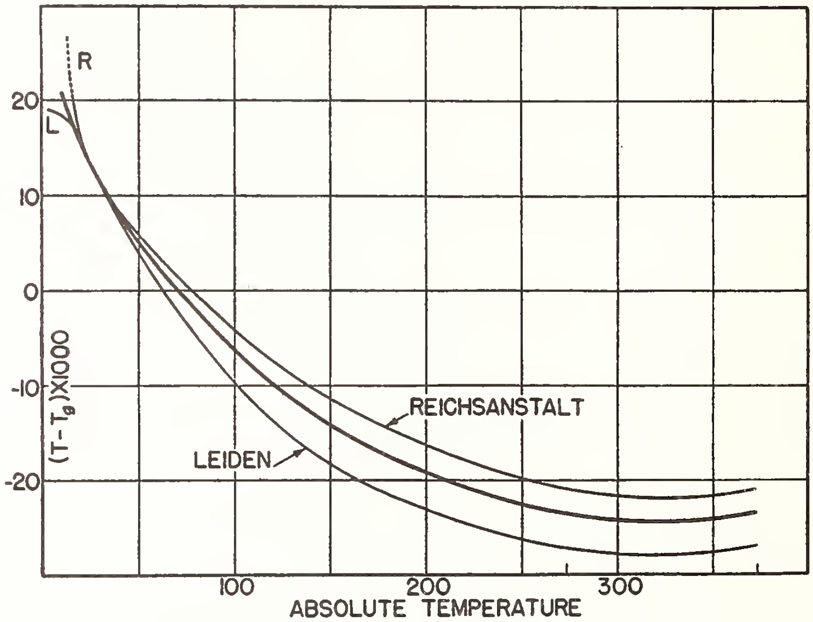


FIGURE 2.—*Corrections for reducing to the thermodynamic scale, computed from data of the Kamerlingh Onnes Laboratory at Leiden and the Physikalisch-Technische Reichsanstalt.*

The heavy line represents corrections adopted for use in this paper.

Since $T_0=1/\gamma$ and $T_{g0}=1/\beta$, we have

$$(T_0-T_{g0})=1/\gamma-1/\beta=\frac{\beta-\gamma}{\beta\gamma}\doteq T_0^2(\beta-\gamma).$$

Substituting their value for $\beta-\gamma$, we find $T_0-T_{g0}=-0.027°$. This quantity was used with eq 7 to compute $T-T_g$ from the Leiden table.

In table 1 the original values of the two laboratories are reproduced, together with the derived values of $T-T_g$. In figure 2 the corrections $T-T_g$ have been plotted against the absolute temperature. The heavy line on this graph is a weighted mean of the two sets, and represents the corrections adopted for use in the present work. The numerical values are given in table 2. Since the computed ice point pressure of our thermometer was 2.46 m Hg, the corrections actually used were 2.46 times those given in the table.

Table 1.—*Deviation of the constant-volume helium gas scale ($p_0=1$ m Hg) from the thermodynamic scale, according to the Kamerlingh Onnes Laboratory at Leiden and the Physikalisch-Technische Reichsanstalt*

t	$T=t+$ 273.16	$t-t_g$		$T-T_g$	
		L[a]	PTR[b]	L	PTR
100	37.16	0.000	0.000	−0.027	−0.021
50	323.16	−.001	(−.001)	−.028	−.022
0	273.16	.000	.000	−.027	−.021
−50	223.16	.002	.003	−.025	−.018
−100	173.16	.006	.007	−.021	−.014
−150	123.16	.013	.013	−.014	−.008
−180	93.16	.019	-------	−.008	-------
−183	90.16	-------	.019	-------	−.002
−200	73.16	.024	.022	−.003	.001
−220	53.16	.030	(.026)	.003	.005
−240	33.16	.037	(.031)	.010	.010
−250	23.16	.041	.035	.014	.014
−260	13.16	.045	(.045)	.018	.024
−270	3.16	.046	-------	.019	-------

[a] W. H. Keesom and W. Tuyn, Leiden Commun. Supp. No. 78, table on p. 49 (Reprinted from Travaux et Mémoires du Bureau International des Poids et Mesures 20 (1936).

[b] F. Henning, Z. ges. Kälte-Ind. 37, 169 (1930). Values in parentheses were computed by the authors from Henning's formula.

Table 2.—*Deviations used in this paper for correcting from the helium gas scale (T_g) to the thermodynamic (T)*

[For $p_0=1$ m Hg.]

T	$T-T_g$	T	$T-T_g$	T	$T-T_g$	T	T_g
10	+0.021	60	+0.002	120	−0.010	220	−0.021
15	+.018	65	+.001	130	−.012	230	−.021
20	+.016	70	+.000	140	−.013	240	−.022
25	+.013	75	−.001	150	−.014	250	−.022
30	+.011	80	−.002	160	−.015	260	−.023
35	+0.009	85	−0.003	170	−0.016	273.16	−0.023
40	+.008	90	−.004	180	−.017	373.16	−.023
45	+.006	95	−.005	190	−.018	----------	----------
50	+.005	100	−.006	200	−.019	----------	----------
55	+.004	110	−.008	210	−.020	----------	----------

V. PROCEDURE AND CALCULATIONS

The thermometer was filled to approximately atmospheric pressure at liquid-air temperature. The gas was admitted through the manometer after evacuating the system for several days. During the filling the helium was purified by slow passage over charcoal cooled by liquid air and through a cotton-filled tube immersed in liquid hydrogen. Mercury was brought up into the manometer and the manometer tube evacuated. The cryostat was filled with liquid hydrogen and the bulb cooled to the temperature of the hydrogen bath. Measurements were then made at intervals of a few degrees, one operator being required to control the bulb temperature, a second to measure resistances, and a third to observe the pressure. Pressure readings were alternated with resistance-thermometer readings, and the temperature computed from the mean observed pressure. Two thermometers on the mercury column and the thermocouples on the capillary were also read at each temperature. Readings at the very lowest temperatures were obtained with helium in the space surrounding the bulb.

The pressure readings were corrected for capillarity and reduced to mm Hg at 0° C and standard gravity. Values of R and of $w(=R/R_0)$ for each thermometer were computed. Thermal expansion of the copper thermometer bulb was calculated from the data of Keesom, Van Agt, and Jansen.[12] The equation $V=V_0(0.991171+3.267\times10^{-6}T+1.064\times10^{-7}T^2)$ was found to fit these data satisfactorily below 90° K.[13] A rough calculation showed that pressure changes should have a negligible effect on the volume of the bulb.

The temperatures of the pressure-transmitting volumes were deduced from the thermocouple and thermometer readings. The transmitting volumes were determined by substituting for the gas-thermometer bulb a calibrated glass tube sealed to the capillary and arranged to be filled with mercury to any desired height. After admitting a small amount of gas to the system its volume was varied by changing the height of the mercury in the glass tube. The effect of volume change on the pressure was noted, and the transmitting volume computed from Boyle's law. This process was repeated after cutting off all except a small section of the capillary. Volumes found were 0.180 cm³ for the space where the capillary joined the manometer, and 0.000942 cm³/cm length for the capillary. The length of the capillary was 146.7 cm, making the total transmitting volume[14] 0.318 cm³, or 1.6 percent of the volume of the thermometer bulb, which was 19.69 cm³. In calculating the quantity

$$\sum_i{}' \frac{V_i}{T_{gi}},$$

a linear change in temperature between one thermocouple and the next was assumed. The section of the capillary between the bulb and the first thermocouple was wound with a heater extending about half its length, by means of which the flow of heat away from the bulb was prevented. A parabolic temperature distribution in the heated section and a linear distribution beyond it were assumed.

To determine the gas-thermometer constant, C, of eq 6 several observations in the neighborhood of the oxygen point were made at the end of each run. All of the thermometers used were intercompared before the final calculations were made, and all had had their oxygen-point resistances determined on the International Temperature Scale. By utilizing the results of the intercomparisons, the error in the oxygen-point resistance assigned to any particular thermometer was considerably reduced. From resistance measurements, the temperatures of all experimental points above 86° K were computed on the International Temperature Scale, on which the boiling point of oxygen is −182.97° C. These were converted to absolute thermodynamic temperatures by using the value of 273.16° K for the thermodynamic temperature of the ice point. Each value of T thus found was converted to the corresponding T_g on the gas

---

[12] W. H. Keesom, F. P. G. A. J. van Agt, and Miss A. F. J. Jansen, Leiden Commun. 182a (1926).

[13] Southard and Milner (J. Am. Chem. Soc. 55, 4384 (1933)) used a different equation based on these same data. Dr. Southard has informed us that an error was made in the derivation of their equation.

[14] Earlier estimates of the transmitting volume based on filling a section of the capillary with water and weighing, and computing the volume at the manometer from dimensions gave somewhat smaller values. The possibility that this might be the case was brought to our attention by J. A. Beattie of the Massachusetts Institute of Technology, who also suggested the method finally adopted.

scale by use of table 2 and substituted in eq 6 to determine C. Determined in this way the constant C is presumably the same as would have been obtained by making actual measurements at the ice and steam points. On one occasion during an interruption of measurements the thermometer bulb was kept at liquid-air temperature for more than a month. In this interval the gas in the thermometer was lost at the rate of about 11 parts in 10^6 per day. During a single run such a loss would be entirely negligible, but for each run the value of C was independently determined. Having found C, temperatures were computed from eq 6 and corrected from the gas scale to the thermodynamic by means of table 2. The corrected temperatures and the corresponding resistance values are given in table 3.

Table 3.—*Experimental data: p is corrected pressure ($=T_0/C$ in eq 6); T is temperature corrected from the gas scale to the thermodynamic, $w=R/R_0$*

Point Number	p	T	w_{L6}	w_{L11}	w_{M1}
	mm Hg	° *K*			
55	96.16	10.754	0.00 2890	0.00 2952	----------
18	97.38	10.833	2899	2963	0.55 3710
49	97.68	10.923	2911	2975	----------
50	100.73	11.262	2963	3026	----------
56	101.01	11.293	2968	3034	----------
51	104.91	11.726	0.00 3045	0.00 3110	----------
52	111.65	12.475	3183	3250	----------
66	125.48	14.013	3554	3624	----------
53	125.50	14.015	3561	3630	----------
67	128.47	14.344	3654	3726	----------
54	132.18	14.756	0.00 3786	0.00 3860	----------
68	133.44	14.897	3833	3907	----------
69	142.69	15.925	4215	4296	----------
70	153.39	17.115	4751	4827	----------
57	162.07	18.080	5257	----------	----------
19	165.07	18.317	0.00 5392	----------	----------
58	178.10	19.862	6413	----------	----------
20	182.01	20.191	6656	----------	----------
11	183.90	20.399	6820	0.00 6917	0.55 5783
71	189.77	21.159	7443	7545	----------
59	195.82	21.832	0.00 8048	0.00 8154	----------
21	207.46	23.004	9199	9311	----------
29	209.63	23.246	9452	----------	----------
72	235.19	26.209	0.01 3173	.01 3306	----------
12	245.95	27.261	.01 4731	.01 4870	0.56 0052
22	255.39	28.305	0.01 6464	----------	----------
30	259.35	28.742	.01 7196	0.01 7350	0.56 1343
13	300.49	33.293	.02 6275	----------	----------
60	310.12	34.540	.02 9302	.02 9482	----------
31	315.83	34.990	.03 0330	----------	----------
23	341.45	37.825	0.03 7719	0.03 7918	.57 1665
14	350.92	38.873	.04 0656	.04 0859	.57 3094
32	360.42	39.925	.04 3731	----------	----------
73	384.41	42.804	.05 2674	.05 2894	----------
33	409.93	45.401	.06 1177	.06 1400	.58 2912
24	422.69	46.813	0.06 6058	----------	----------
34	444.94	49.274	.07 4875	----------	----------
25	492.10	54.494	.09 4634	0.09 4875	.59 8528
15	499.15	55.274	.09 7631	----------	----------
35	501.94	55.582	.09 8819	----------	----------
36	545.03	60.349	0.11 7946	0.11 8188	.60 9276
3	552.65	61.192	.12 1407	----------	----------
26	575.85	63.759	.13 2076	----------	----------
A	585.30	64.757	.13 6290	----------	----------
61	589.95	65.666	.14 0019	.14 0268	----------
4	595.93	65.982	0.14 1363	----------	----------
37	623.18	68.997	.15 4157	----------	----------
B	625.85	69.242	.15 5179	----------	----------
5	634.51	70.251	.15 9402	----------	----------
16	640.70	70.936	.16 2422	----------	----------
42	642.17	71.442	0.16 4606	----------	----------
C	663.56	73.413	.17 2996	----------	----------
27	668.81	74.047	.17 5691	----------	----------
6	690.46	76.443	.18 5968	----------	----------
D	703.23	77.799	.19 1822	----------	----------

Table 3.—*Experimental data: p is corrected pressure ($=T_0/C$ in eq 6); T is temperature corrected from the gas scale to the thermodynamic, $w=R/R_0$*—Continued

Point Number	p	T	w_{L6}	w_{L11}	w_{M1}
	mm Hg	° K			
38	708. 31	78. 418	0. 19 4514	0. 19 4754	0. 64 4313
7	713. 11	78. 949	. 19 6776	----------	----------
65	711. 44	79. 182	. 19 7745	. 19 7988	----------
E	740. 89	81. 963	. 20 9845	----------	----------
8	751. 93	83. 245	. 21 5384	----------	----------
I	764. 94	84. 623	0. 22 1438	----------	----------
44	761. 59	84. 722	. 22 1820	----------	----------
46	766. 03	85. 216	. 22 3866	----------	----------
F	778. 92	86. 169	. 22 8058	----------	----------
1	785. 20	86. 927	. 23 1366	0. 23 1608	0. 66 1101
J	791. 41	87. 549	0. 23 4078	----------	----------
9	791. 14	87. 584	. 23 4294	----------	----------
17	802. 95	88. 891	. 23 9819	0. 24 0049	----------
62	804. 91	89. 581	. 24 2940	. 24 3173	----------
74	809. 30	90. 069	. 24 4956	. 24 5187	----------
40	814. 46	90. 165	0. 24 5425	0. 24 5658	0. 66 7512
10	815. 08	90. 233	. 24 5762	----------	----------
41	815. 33	90. 261	. 24 5943	. 24 6176	. 66 7748
47	812. 68	90. 403	. 24 6420	. 24 6651	----------
G	817. 59	90. 445	. 24 6544	----------	----------
63	813. 70	90. 559	0. 24 7128	0. 24 7358	----------
28	818. 48	90. 610	. 24 7330	. 24 7560	----------
48	816. 44	90. 821	. 24 8287	. 24 8518	----------
2	823. 01	91. 111	. 24 9465	. 24 9696	0. 66 9351
64	820. 82	91. 350	. 25 0600	. 25 0831	----------
45	821. 56	91. 390	0. 25 0793	0. 25 1025	----------
39	825. 77	91. 416	. 25 0772	. 25 1004	0. 66 9946

VI. DATA AND RESULTS

The constants of the seven resistance thermometers are given in table 4. All except two had previously received complete calibrations on the International Temperature Scale. The constants δ and β are those appearing in the modification of Callendar's equation proposed by Van Dusen [15]

$$t=\frac{1}{\alpha}(w-1)+\delta\left(\frac{t}{100}-1\right)\frac{t}{100}+\beta\left(\frac{t}{100}-1\right)\left(\frac{t}{100}\right)^3,$$

which is equivalent to the International Temperature Scale equation and somewhat easier to use.

Table 4.—*Constants of the seven calibrated resistance thermometers*

Thermometer	Material	R_0	δ	β	R/R_0 at various fixed points				
					n-H_2, triple (13.96° K)	n-H_2, nbp (20.39° K)	O_2, nbp (90.19° K)	Steam (373.16° K)	Sulfur (717.76° K)
		Ohms							
L3	Pt	29. 11355	1. 4951	0. 11294	0.00 3665	0.00 6993	0.24 6325	1.39 1177	2.64 9570
L5	Pt	23. 10284	1. 4974	. 11142	3669	6990	6114	1316	2.65 0018
L6	Pt	28. 83022	----------	----------	3543	6811	5540	----------	----------
L9	Pt	27. 54587	1. 4963	. 10840	3607	6901	5780	1607	1312
L10	Pt	24. 93025	1. 4945	. 11235	3628	6935	5936	1406	0568
L11	Pt	27. 52747	1. 4952	. 10895	3613	6909	5771	1604	1364
M1	90Pt: 10Rh	59. 47388	----------	----------	----------	----------	----------	----------	----------

---

[15] M. S. Van Dusen, J. Am. Chem. Soc. 47, 326 (1925).

Of the seven resistance thermometers, three (*L6*, *L11*, *M1*) were compared directly with the gas thermometer, and the data given in table 3 obtained. After this the capillary was removed and thermometers *L3*, *L5*, *L9*, and *L10* placed with *L6* in the copper thermometer bulb, which now served as a comparison block. Resistance readings on all the thermometers were then made at 1- or 2-degree intervals throughout the range 10° to 90° K, without making use of the apparatus as a gas thermometer.

No satisfactory simple formula connecting the resistance of platinum and the temperature in this range has yet been proposed. The formula of Henning and Otto [16] based on the sum of two Debye functions can be used, but since it does not avoid the use of a tabulated function it was decided to construct directly a table which gave the resistance-temperature relation for one of the thermometers used (*L6*), and to use this table for the other thermometers by tabulating the deviations of each from this table. A previously published table [17] was taken as a starting point and values of $w(=R/R_0)$ corresponding to the observed temperatures computed from it. These were subtracted from the observed values of W_{L6} and the quantities $(W_{L6}-W_{table})$ plotted. A deviation curve was drawn and used to improve the original table. This process was repeated several times until a table was obtained from which the deviations were random. This table was next smoothed by Spencer's method.[18] The smoothed values are given in table 5, page 364. In figure 3 the deviations of the observed values from this smoothed table are plotted. The curved lines in this graph correspond to ±0.01° and allow the scattering to be estimated in degrees. They also show how very rapidly dw/dT falls off below 25° K. It is this rapid decrease which makes it more convenient to plot Δw, which approaches zero, than ΔT, which becomes large. However, the actual scattering is chiefly due to errors in the determination of T rather than w.

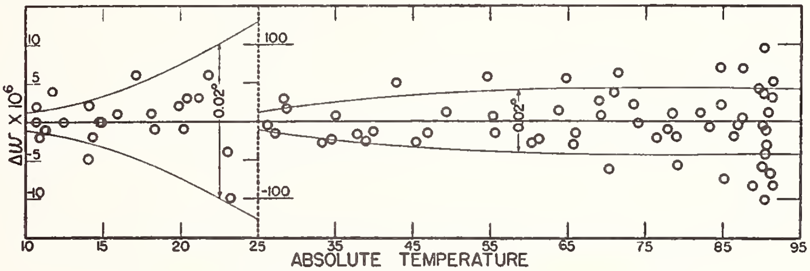


Figure 3.—*Scattering of the experimental points.*

Zero deviation represents agreement with table 5.

---

[16] F. Henning and J. Otto, Phys. Z. 37, 601 (1936) and earlier papers.

[17] J. C. Southard and R. T. Milner, J. Am. Chem. Soc. 55, 4384 (1933).

[18] E. T. Whittaker and G. Robinson, The Calculus of Observations, 2d ed. p. 290 (Blackie and Son, Ltd., London and Glasgow, 1929).

TABLE 5.—*Smoothed temperature-resistance table for platinum, based on thermometer L6*

[$w=R/R_0$. Differences are for use in Bessel's interpolation formula. Example: $w_{55.800}=10^{-6}\left[96552+0.8\times 3931+\frac{0.8(0.8-1)}{4}\times 75\right]=0.099694$]

T	*w*			*T*	*w*			*T*	*w*		
10	0.002789			39	0.041046			67	0.145672		
		135	59			2921	186			4230	25
11	2924			40	.043967			68	.149902		
		166	73			3011	176			4242	22
12	3090			41	.046978			69	.154144		
		208	91			3097	169			3252	20
13	3298			42	.050075			70	.158396		
		257	105			3180	162			4262	18
14	3555			43	.053255			71	.162658		
		313	119			3259	154			4270	16
15	3868			44	.056514			72	.166928		
		376	132			3334	147			4278	16
16	4244			45	.059848			73	.171206		
		445	146			3406	141			4286	14
17	4689			46	.063254			74	.175492		
		522	160			3475	133			4292	14
18	5211			47	.066729			75	.179784		
		605	175			3539	125			4300	13
19	5816			48	.070268			76	.184084		
		697	187			3600	118			4305	11
20	6513			49	.073868			77	.188389		
		792	197			3657	112			4311	12
21	7305			50	.077525			78	.192700		
		894	208			3712	104			4317	10
22	8199			51	.081237			79	.197017		
		1000	219			3761	97			4321	10
23	9199			52	.084998			80	.201338		
		1113	227			3809	91			4327	9
24	0.010312			53	.088807			81	.205665		
		1227	231			3852	84			4330	--
25	.011539			54	.092659			82	.209995		
		1344	235			3893	79			4334	--
26	.012883			55	.096552			83	.214329		
		1462	239			3931	75			4337	--
27	.014345			56	.100483			84	.218666		
		1583	241			3968	70			4339	--
28	.015928			57	.104451			85	.223005		
		1703	240			4001	66			4342	--
29	.017631			58	.108452			86	.227347		
		1823	241			4034	63			4344	--
30	.019454			59	.112486			87	.231691		
		1944	240			4064	58			4344	--
31	.021398			60	.116550			88	.236035		
		2063	237			4092	55			4342	--
32	.023461			61	.120642			89	.240377		
		2181	234			4119	51			4339	--
33	.025642			62	.124761			90	.244716		
		2297	228			4143	46			4336	--
34	.027939			63	.128904			91	.249052		
		2409	222			4165	42			4333	--
35	.030348			64	.133069			92	.253385		
		2519	217			4185	36			4330	--
36	.032867			65	.137254			93	.257715		
		2626	209			4201	32			4327	--
37	.035493			66	.141455			94	.262042		
		2728	199			4217	29			4323	--
38	.038221							95	.266365		
		2825	193								

Spencer's method of smoothing does not yield values at the extreme ends of the table. At the upper end of the table the International Temperature Scale supplied the missing values. At the lower end use was made of the equation $R=A+BT^2+CT^5$ proposed by Landau and Pomerantschusk [19] and also by Baber.[20] These authors point out that the term in T^2 should be important in metals such as platinum, which have incomplete inner shells of electrons. This equation fits the experimental data for thermometer *L6* very well up to 15° K, but above this temperature the deviations rapidly become large. Values of the constants found for thermometer *L6* were

$$A=0.067238$$
$$B=1.04350\times10^{-4}$$
$$C=2.74577\times10^{-8}.$$

With this set of constants the T^5 term is negligible below about 5° K and reaches 90 percent of the T^2 term at 15° K. The range in which the equation was used (10° to 15° K) is too small to provide a thorough test, although it does represent a change of 50 percent in absolute temperature. However, it was considered sufficiently good to be used to extend the table down to the lowest temperature measured.

The results of the intercomparison of the various resistance thermometers are shown in figure 4, where the differences $\Delta w_i=w_i-w_{L6}$ have been plotted against the absolute temperature (the index i refers to any one of the calibrated platinum thermometers). From the original large-scale graphs, values of Δw_i were read off at every degree. These values, taken with table 5, are equivalent to a separate table for each platinum thermometer, all agreeing among themselves to within the accuracy of the resistance measurement. Since, except at the lowest temperatures, the precision of the resistance thermometry was of the order of ten times the precision of the gas thermometry, the additional step of intercomparison introduced little additional error. Tables of Δw_i have not been included, since they are useful only in conjunction with a particular group of thermometers.

The 90Pt:10Rh thermometer *M1* cannot be used with table 5. Figure 5 shows the temperature dependence of the resistance of *M1*, after subtracting a constant resistance of 32.5 ohms. The lower curve represents the resistance of the pure platinum thermometer *L6*. It can be seen that the addition of 10 percent of rhodium corresponds roughly to the addition of a constant resistance of 32.5 ohms to a thermometer such as *L6*. Matthiessen's rule, which may be stated in the form "resistance due to impurity is independent of temperature" is seen to hold even when the amount of rhodium "impurity" is as large as 10 percent.

In resistance thermometry the most common problem is that of computing a temperature from a measured resistance. With table 5 this requires inverse interpolation, which is more difficult than direct interpolation. In addition, linear interpolation is insufficiently accurate in this table below 80° K, according to the usual rule that second differences should not exceed 4. Accordingly, table 6, page 366, was made up, the values being found from table 5 by quadratic interpolation. Entries in this table are so closely spaced that linear interpolation introduces no error greater than 0.0005° above 19° K and no error greater than the equivalent of ½ unit in the last figure of w below this temperature.

---

[19] L. Landau and I. Pomerantschusk, Phys. Z. Sowjetunion 10, 649 (1936).
[20] W. G. Baber, Proc. Roy. Soc. (London) [A] 158, 383 (1937).

TABLE 6.—*Resistance-temperature table arranged for linear interpolation. Based on platinum thermometer L6*

[Linear interpolation yields temperatures correct to the nearest 0.001° above 19° K, and correct to the equivalent of the nearest unit in the last figure of w below this temperature. $w=R/R_0$]

W	T	$\frac{\Delta T}{\Delta w}$
0. 002800	10. 090	7780
2850	10. 479	7160
2900	10. 837	6700
2950	11. 172	6260
3000	11. 485	5860
3050	11. 778	5520
3100	12. 054	5160
3150	12. 312	4880
3200	12. 556	4640
3250	12. 788	4420
3300	13. 009	4220
3350	13. 220	4040
3400	13. 422	3880
3450	13. 616	3720
3500	13. 802	3600
3550	13. 982	3480
3600	14. 156	3360
3650	14. 324	3260
3700	14. 487	3160
3750	14. 645	3060
3800	14. 798	2980
3850	14. 947	2900
3900	15. 092	2840
3950	15. 234	2740
4000	15. 371	2700
4050	15. 506	2620
4100	15. 637	2580
4150	15. 766	2500
4200	15. 891	

W	T	$\frac{\Delta T}{\Delta w}$
0. 004200	15. 891	2440
4300	16. 135	2350
4400	16. 370	2250

W	T	$\frac{\Delta T}{\Delta w}$
0. 004500	16. 595	2170
4600	16. 812	2110
4700	17. 023	2030
4800	17. 226	1970
4900	17. 423	1910
5000	17. 614	1860
5100	17. 800	1800
5200	17. 980	1770
5300	18. 157	1710
5400	18. 328	1680
5500	18. 496	1630
5600	18. 659	1600
5700	18. 819	1560
5800	18. 975	1530
5900	19. 128	1490
6000	19. 277	1470
6100	19. 424	1430
6200	19. 567	1410
6300	19. 708	1390
6400	19. 847	1350
6500	19. 982	1340
6600	20. 116	1320
6700	20. 248	1290
6800	20. 377	1270
6900	20. 504	1250
7000	20. 629	1240
7100	20. 753	1210
7200	20. 874	1200
7300	20. 994	1180
7400	21. 112	1160
7500	21. 228	1150
7600	21. 343	1130
7700	21. 456	1120

W	T	$\frac{\Delta T}{\Delta w}$
0. 007800	21. 568	1100
7900	21. 678	1090
8000	21. 787	1080
8100	21. 895	1060
8200	22. 001	1050
8300	22. 106	1040
8400	22. 210	1030
8500	22. 313	1010
8600	22. 414	1010
8700	22. 515	990
8800	22. 614	980
8900	22. 712	970
9000	22. 809	

W	T	$\frac{\Delta T}{\Delta w}$
0. 009000	22. 809	960
9200	23. 001	935
9400	23. 188	920
9600	23. 372	905
9800	23. 553	885
0. 010000	23. 730	870
. 010200	23. 904	855
. 010400	24. 075	840
. 010600	24. 243	830
. 010800	24. 409	815
. 011000	24. 572	805
. 011200	24. 733	790
. 011400	24. 891	780
. 011600	25. 047	770
. 011800	25. 201	760
. 012000	25. 353	750
. 012200	25. 503	740
. 012400	25 651	730
. 012600	25. 797	720

Table 6.—*Resistance-temperature table arranged for linear interpolation. Based on platinum thermometer L6*—Continued

W	T	$\frac{\Delta T}{\Delta w}$
0. 012800	25. 941	710
. 013000	26. 083	705
. 013200	26. 224	695
. 013400	26. 363	690
. 013600	26. 501	680
. 013800	26. 637	670
. 014000	26. 771	

W	T	$\frac{\Delta T}{\Delta w}$
0. 014000	26. 771	663
. 014300	26. 970	653
. 014600	27. 166	643
. 014900	27. 359	637
. 015200	27. 550	623
. 015500	27. 737	617
. 015800	27. 922	607
. 016100	28. 104	600
. 016400	28. 284	593
. 016700	28. 462	587
. 017000	28. 638	577
. 017300	28. 811	570
. 017600	28. 982	567
. 017900	29. 152	557
. 018200	29. 319	553
. 018500	29. 485	547
. 018800	29. 649	540
. 019100	29. 811	533
. 019400	29. 971	530
. 019700	30. 130	523
. 020000	30. 287	

W	T	$\frac{\Delta T}{\Delta w}$
0. 020000	30. 287	518
. 020500	30. 546	508
. 021000	30. 800	502
. 021500	31. 051	494

W	T	$\frac{\Delta T}{\Delta w}$
0. 022000	31. 298	486
. 022500	31. 541	480
. 023000	31. 781	474
. 023500	32. 018	468
. 024000	32. 252	462
. 024500	32. 483	456
. 025000	32. 711	452
. 025500	32. 937	444
. 026000	33. 159	440
. 026500	33. 379	436
. 027000	33. 597	432
. 027500	33. 813	426
. 028000	34. 026	422
. 028500	34. 237	418
. 029000	34. 446	414
. 029500	34. 653	410
. 030000	34. 858	408
. 030500	35. 062	402
. 031000	35. 263	400
. 031500	35. 463	396
. 032000	35. 661	392
. 032500	35. 857	390
. 033000	36. 052	386
. 033500	36. 245	382
. 034000	36. 436	380
. 034500	36. 626	378
. 035000	36. 815	376
. 035500	37. 003	372
. 036000	37. 189	368
. 036500	37. 373	368
. 037000	37. 557	364
. 037500	37. 739	362
. 038000	37. 920	360
. 038500	38. 100	358

W	T	$\frac{\Delta T}{\Delta w}$
0. 039000	38. 279	356
. 039500	38. 457	354
. 040000	38. 634	

W	T	$\frac{\Delta T}{\Delta w}$
0. 040000	38. 634	350
. 041000	38. 984	346
. 042000	39. 330	342
. 043000	39. 672	339
. 044000	40. 011	335
. 045000	40. 346	332
. 046000	40. 678	329
. 047000	41. 007	326
. 048000	41. 333	323
. 049000	41. 656	320
. 050000	41. 976	318
. 051000	42. 294	314
. 052000	42. 608	313
. 053000	42. 921	310
. 054000	43. 231	307
. 055000	43. 538	306
. 056000	43. 844	303
. 057000	44. 147	301
. 058000	44. 448	300
. 059000	44. 748	297
. 060000	45. 045	296
. 061000	45. 341	293
. 062000	45. 634	292
. 063000	45. 926	290
. 064000	46. 216	289
. 065000	46. 505	287
. 066000	46. 792	285
. 067000	47. 077	284
. 068000	47. 361	283
. 069000	47. 644	281

TABLE 6.—*Resistance-temperature table arranged for linear interpolation. Based on platinum thermometer L6*—Continued

W	*T*	$\frac{\Delta T}{\Delta w}$	*W*	*T*	$\frac{\Delta T}{\Delta w}$	*W*	*T*	$\frac{\Delta T}{\Delta w}$
0.070000	47.925	280	0.104000	56.887	250.5	0.150000	68.023	235.8
.071000	48.205	278	.106000	57.388	249.5	.155000	69.202	235.0
.072000	48.483	277	.108000	57.887	249.0	.160000	70.377	234.4
.073000	48.760	276	.110000	58.385	247.5	.165000	71.549	233.8
.074000	49.036	275	.112000	58.880	246.5	.170000	72.718	233.4
.075000	49.311	274	.114000	59.373	246.0	.175000	73.885	233.0
.076000	49.585	272	.116000	59.865	245.0	.180000	75.050	232.6
.077000	49.857	272	.118000	60.355	244.5	.185000	76.213	232.2
.078000	50.129	270	.120000	60.844	243.0	.190000	77.374	231.8
.079000	50.399	269	.122000	61.330	243.0	.195000	78.533	231.4
.080000	50.668		.124000	61.816	242.0	.200000	79.690	231.2
0.080000	50.668	268.0	.126000	62.300	241.0	.205000	80.846	231.0
.082000	51.204	266.0	.128000	62.782	241.0	.210000	82.001	230.8
.084000	51.736	264.0	.130000	63.264	240.0	.215000	83.155	230.4
.086000	52.264	262.5	.132000	63.744	239.5	.220000	84.307	230.4
.088000	52.789	261.0	.134000	64.223	239.0	.225000	85.459	230.4
.090000	53.311	259.5	.136000	64.701	238.5	.230000	86.611	230.2
.092000	53.830	258.0	.138000	65.178	238.0	.235000	87.762	230.2
.094000	54.346	256.5	.140000	65.654	237.5	.240000	88.913	230.4
.096000	54.859	255.0	.142000	66.129	237.5	.245000	90.065	230.8
.098000	55.369	254.5	.144000	66.604	237.0	.250000	91.219	230.8
.100000	55.878	252.5	.146000	67.078	236.5	.255000	92.373	231.0
.102000	56.383	252.0	.148000	67.551	236.0	.260000	93.528	231.2
			.150000	68.023		.265000	94.684	

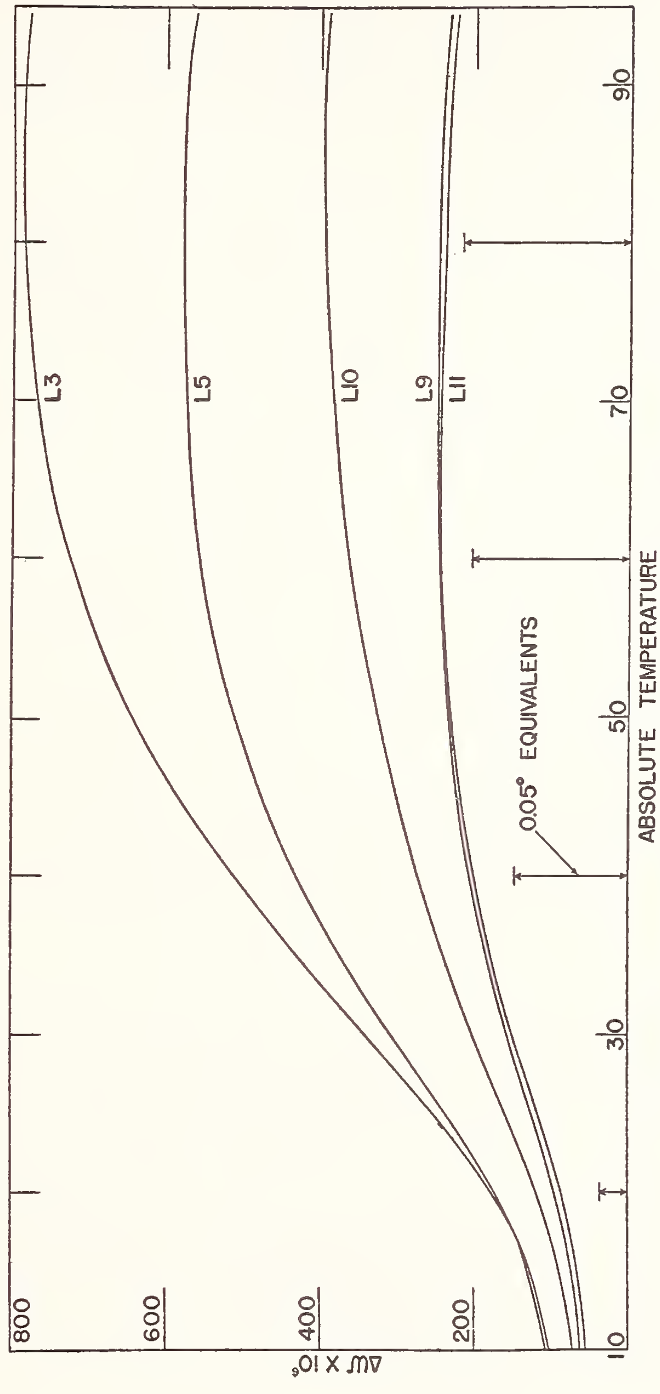


Figure 4.—*Comparison of the six calibrated platinum resistance thermometers.*

$\Delta w_i = w_i - w_{L8}$ and $w = R/R_0$.

After the calibration and intercomparison had been completed, resistance thermometer *L3* was installed in a calorimetric apparatus in which the vapor pressure of hydrogen could be measured, and in which the triple point could be located calorimetrically. Values found for the resistance of *L3* at the triple point and boiling point of normal hydrogen are given in table 4. The resistances of the other thermometers at these fixed points were found by adding the appropriate values of Δw_t, as determined by the intercomparisons. The temperatures corresponding to these resistances are

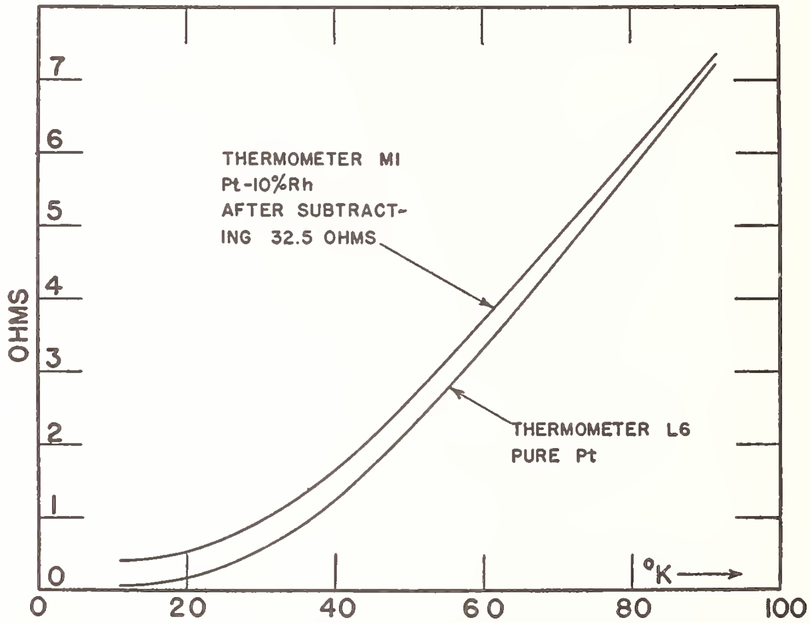


FIGURE 5.—*Temperature dependence of the resistance of pure platinum compared with that of an alloy containing 10 percent of rhodium.*

triple point—13.96° K
boiling point—20.39° K.

The most recent of the previously reported values for these fixed points are 13.96° K by Henning and Otto [21] for the triple point, and −252.754° C (20.37_6° K) by Keesom, Bijl, and Van der Horst,[22] and 20.38° K by Heuse and Otto [23] for the boiling point. A summary of work on low-temperature fixed points has been given by Henning and Otto.[24]

Three years prior to obtaining the above values, thermometer *L6* had been used in an apparatus for determining the vapor pressure of hydrogen, and its resistance at the boiling point of normal hydrogen

---

[21] F. Henning and J. Otto, Phys. Z. **37**, 601 (1936); **37**, 633 (1936).

[22] W. H. Keesom, A. Bijl, and H. van der Horst, Leiden Commun. 217a (1931). The pressure coefficient used by these authors was 0.0036609, whence $T_{g0}=273.157$ or using the Leiden value of $T_g - T_{g0}$ in table 1, $T_0=273.13$. With this value of T_0 the boiling point is 20.37_6° K rather than 20.336, the value given in Henning and Otto's summary.

[23] W. Heuse and J. Otto, Ann. Physik **9**, 486 (1931).

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

had been determined. The temperature computed from this resistance agreed within slightly less than 0.01° with that given above. This was considered satisfactory, in view of the fact that the two determinations were made with entirely different apparatus and with different resistance thermometers.

VII. ESTIMATION OF ERRORS

Pressure.—Uncertainty in the pressure measurements is responsible for a large part of the scattering of the data. The height of the mercury column could be read on the calibrated glass scale to about 0.1 mm, which is equivalent to about 0.01°. The uncertainty in the temperature of the column was reduced by surrounding it with light aluminum shields, leaving only the two menisci exposed. Even so, it was found necessary on some occasions to circulate the air in the room to keep the top and bottom of the column at the same temperature. Meniscus corrections were made, although the menisci were so regular that they could for the most part have been omitted. Thermal transpiration might be expected to set up a pressure gradient in the capillary. R. B. Scott of this Bureau investigated the effect for helium. His results (unpublished) are in substantial agreement with the theory,[25] and indicate that the pressure at the two ends of the gas-thermometer capillary could not have differed by more than 0.003 mm even under the most unfavorable conditions.

Pressure-transmitting volume.—Errors in the corrections for the pressure-transmitting volume may be due either to errors in the volume ratios V_i/V_0 or to errors in the determination of the temperatures T_i. The temperatures obtained from thermocouple readings were computed from the equation, $\text{emf}=a+bT^2+cT^3+dT^4$, proposed by Ahlberg and Lundberg,[26] the constants being determined by calibration at the boiling and triple points of hydrogen and in liquid air at normal and reduced pressure. Of the V_i the most uncertain was the volume where the capillary joined the manometer. This volume was subject to fluctuation, not only because of the difficulty of setting the mercury meniscus exactly on the tip of the pointer, but also because of variations in meniscus height. In the 11-mm manometer tube used, a change in meniscus height from 1.4 to 1.6 mm would increase the transmitting volume by 14 mm^3 according to data in the International Critical Tables. In our work variations in meniscus height were actually more serious in their effect on the transmitting volume than in their effect on the pressure.

Thermal expansion of bulb.—The change in volume of the copper bulb from 11° K to 90° K calculated from eq 3 is about 0.11 percent. An error of even 4 percent in the mean expansion coefficient over this range would give rise to a maximum error in temperature of only slightly over 0.001°.

Thermometer constant C.—By obtaining the thermometer constant in the particular manner described in the section on procedure and calculations, continuity with the International Temperature Scale is secured. The value 90.19° K accepted for the oxygen point in determining C may be in error either because of uncertainty in the value −182.97° C assigned to the oxygen point on the International Tem-

---

[25] M. Knudsen, Ann. Physik 83, 797 (1927).
[26] J. E. Ahlberg and W. O. Lundberg, J. Am. Chem. Soc. 57, 2722 (1935).

perature Scale or because of uncertainty in the value 273.16° K used for the ice point. Since the error introduced in this way is proportional to the temperature, it will in any case be very small at the lower end of the scale.

Since *C* is inversely proportional to the mass of gas in the thermometer, any loss of gas from the system or change in the effective mass by adsorption will cause error unless corrected for. The loss by diffusion during a single run was entirely negligible. An estimate of the thickness of the layer of gas which would have to be adsorbed to produce appreciable error led us to conclude that this effect was probably negligible.

Reduction to the thermodynamic scale.—The corrections used to reduce to the thermodynamic scale were taken from the results of other investigators. The error introduced is probably small at the higher temperatures but may be rather important below the boiling point of hydrogen.

VIII. COMPARISON WITH PREVIOUS WORK

Comparison of the temperature scales set up by different laboratories is chiefly a matter of comparing the values assigned to fixed points. However, some additional information may be obtained by combining the data of the different laboratories to obtain graphs similar to figure 4. This is of course only possible when the resistance thermometers are of the same material. Figure 6 is such a graph, utilizing recent results from Leiden [27] and the Reichsanstalt.[28] [29] Taking table 5 as a standard, $\Delta w_t = w_t - w_{table}$ has been plotted against the absolute temperature. It will be seen that the deviations are much larger than those found by intercomparison of our own thermometers. This is probably due chiefly to greater differences in the samples of platinum. However, the deviation curves are not as smooth as those of our own thermometers, and this lack of smoothness is probably associated with

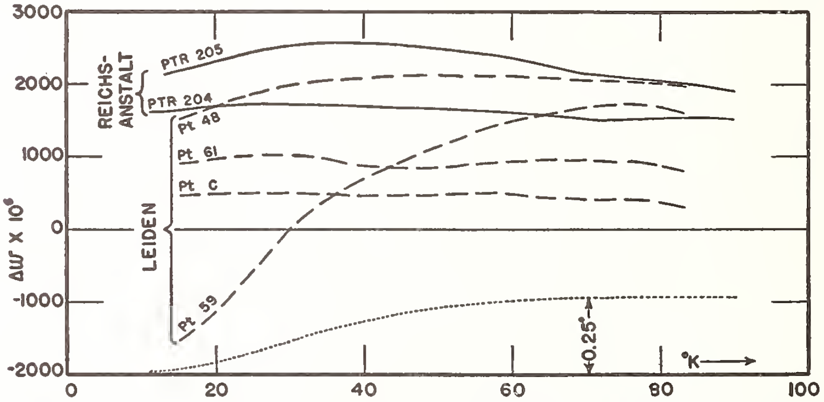


FIGURE 6.—*Comparison of thermometers calibrated by other laboratories with thermometer L6.*

$\Delta w_t = w_t - w_{table}$ and $w = R/R_0$.

---

[27] W. H. Keesom and A. Bijl, Physica 3, 418 (1936). (Leiden Commun. 242b).

[28] F. Henning and J. Otto, Phys. Z. 37, 601 (1936);

[29] F. Henning and J. Otto, Actes 6 ème congr. int. froid (Buenos Aires) 2b, 257 (pub. 1935).

differences in gas thermometry. It should be emphasized that the choice of a standard table was arbitrary and that if the table of another laboratory were chosen the deviations of our thermometers would show a corresponding lack of smoothness. The 11 thermometers for which Δw_t is plotted in figures 4 and 6 represent platinum from at least three different sources. Such a sampling is too limited to allow any general conclusions to be drawn. However, it is of interest to point out certain characteristics of these 11 thermometers. Since resistance thermometers are supposedly constructed only of platinum of high purity, it is to be expected that their curves of w versus T will be very similar in form. All such curves have a common point at 0° C, and it is evident that if their slopes at this temperature are very nearly equal, values of Δw_t will be small for a considerable distance to either side of 0° C. At low temperatures, however, values of Δw_t may become large, even though the curves may still be nearly parallel. Several of the deviation curves of figures 4 and 6 illustrate this type of behavior. Between 60° and 90° K, for example, the curves of figure 4 are all parallel to the T-axis to within the equivalent of about 0.01°. In figure 6 all the curves except one are approximately parallel to the T-axis. The exception is the Leiden thermometer Pt 59, for which the platinum was prepared[30] by decomposition of $PtCOCl_2$.

The authors acknowledge the assistance of D. O. Burger, who made the resistance thermometers. Their thanks are also due to C. S. Cragoe, to whom they are indebted for valuable discussions.

WASHINGTON, December 20, 1938.

---

[30] W. H. Keesom and A. Bijl, Physica 3, 418 (1936) (Leiden Commun. 242b).

National Bureau of Standards Provisional Scale of 1955

In 1954 the Tenth General Conference on Weights and Measures defined the Thermodynamic Kelvin Scale by assigning a value of 273.16 °K to the triple point of water. On the Kelvin Scale the temperature of the ice point then became 273.15 °K instead of 273.16 °K as had been used by Hoge and Brickwedde*. About the same time, Hoge and Brickwedde, in light of more recent determinations of the boiling point of normal hydrogen, came to the conclusion that their value of this temperature was about 0.01 °K too high. As a consequence of these two circumstances the National Bureau of Standards decided to reduce the values of temperature on the Hoge and Brickwedde scale by 0.01 °K throughout. This adjusted scale was named the National Bureau of Standards Provisional Scale of 1955 and is still maintained as a reference scale for calibrations in the range 12 to 90.18 °K.

---

*H. J. Hoge and F. G. Brickwedde, Establishment of a temperature scale for the calibration of thermometers between 14° and 83 °K, J. Res. NBS, 22, 351 (1939) RP1188.

CORRECTIONS[1]

for use in low-temperature platinum resistance thermometry

STEM-TYPE PLATINUM resistance thermometers (prt's) usually are calibrated by the Bureau at the oxygen, triple, steam, and sulfur points. Thermometers so calibrated are then often used by other laboratories as references against which similar prt's are calibrated. Because of the potential risks involved in the use of liquid oxygen, many laboratories prefer to substitute a bath of liquid nitrogen, which has a temperature about 13 deg C lower, for their calibrations. Herein lies a difficulty.

The interpolation formula relating resistance to temperature on the International Practical Temperature Scale holds good only above the normal boiling point of oxygen (90.18 °K). Below this point, the IPTS is undefined and temperatures calculated with the IPTS formula are higher than the actual temperature being measured. Therefore, the NBS–55 scale is used from the oxygen point down to 10 °K. This scale is realized over its entire range solely with small capsule-type prt's. At the nitrogen point the value calculated with the IPTS formula will differ from the value on the NBS–55 scale by about 0.08 deg.

Platinum thermometers intended for use only *at the oxygen point and above* but which are calibrated by being compared at the nitrogen point with a standard prt calibrated only on the IPTS need not have this difference applied to their readings. This is because they are calibrated against a thermometer of similar material which has essentially the same behavior up through the oxygen point. However, if such thermometers are to be used below the oxygen point, down to about 50 °K, a table of corrections, such as that at right, should be consulted to bring the temperature within close agreement to NBS–55. Below 50 °K the characteristics of prt's differ sufficiently to make corrections for individual thermometers necessary.

Corrections to computed temperature on NBS–55 scale [a]

Temperature as computed using IPTS formula [b]	Correction to computed temp. to give values on NBS–55 scale [c]	Temperature as computed using IPTS formula [b]	Correction to computed temp. to give values on NBS–55 scale [c]
°K		*°K*	
90	−0.0000	70	−0.273
89	.0003	69	.311
88	.0008	68	.353
87	.0018	67	.399
86	.0036	66	.449
85	.0065	65	.505
84	.0107	64	.566
83	.0164	63	.634
82	.0236	62	.710
81	.0323	61	.794
80	.0428	60	.887
79	.0553	59	.990
78	.0698	58	1.103
77	.0865	57	1.229
76	.1054	56	1.367
75	.1266	55	1.519
74	.1503	54	1.688
73	.1766	53	1.874
72	.2055	52	2.080
71	.2376	51	2.309

[a] A similar table, based on experience at the National Research Council of Canada, has been prepared by R. L. Lovejoy.

[b] Degrees K are obtained from °C by adding 273.15.

[c] These values are based on measurements of thermometers which were manufactured in the United States and which meet the requirements and recommendations of the text of the IPTS. The corrections are not expected to be in error by more than 0.01 °C at the lowest temperature given when applied to temperatures determined with such thermometers.

[1] *June 1963 NBS Technical News Bulletin*

Offprint from „Metrologia“
Journal International de Métrologie scientifique — International Journal of scientific Metrology
Internationale Zeitschrift für wissenschaftliche Metrologie. Vol. 2, No. 4, October 1966, Pages 127—139

Springer-Verlag, Berlin · Heidelberg · New York

Acoustical Thermometer and the National Bureau of Standards Provisional Temperature Scale 2—20 (1965)

HARMON PLUMB and GEORGE CATALAND

Institute for Basic Standards: National Bureau of Standards, Washington, D.C., U.S.A.

Received May 24, 1966

Abstract

An acoustical thermometer has been developed at the National Bureau of Standards to determine values of temperature that approximate the Thermodynamic Temperature Scale. The instrument, called an ultrasonic interferometer in acoustical literature, has been used to determine isotherms of the speed of sound in helium gas as a function of pressure. Each isotherm has been extrapolated to zero pressure to approximate the condition of an ideal gas; from the resulting intercepts, values of temperature were calculated.

The instrument and its operation are described and the data isotherms, which have been determined at approximately every degree from 2° – 20 °K, are listed. The isotherm data have been treated both graphically and by electronic computer analysis (by the method of least squares) to yield values of temperature that are the basis for a new temperature scale — NBS Provisional Scale 2 – 20 (1965). When the scale is compared with other existing scales, T_{58} and NBS (1955), in regions of overlap, the agreement with NBS (1955) is excellent but noticable departures from T_{58} – the helium-4 vapor pressure scale – are indicated.

Ten years ago the National Bureau of Standards recognized the necessity of undertaking primary and secondary thermometry investigations in the temperature range below 20 °K. This was in response to the need for a basic scale and attendant calibrations between 4 °K and 20 °K as expressed by both engineering and basic research groups. At approximately the same time temperature scales in the He^4 vapor pressure range (2° to 5 °K) were being discussed with the resulting emergence of the 1958 He^4 Scale of Temperatures (the T^{58} scale) [1]. Provisional scales maintained by platinum resistors were in existence; they covered the temperature range from 20 °K down to about 11 °K and left an obvious gap from 5° to 11 °K. Of considerable importance also were reports [2] on the existence of germanium resistors that possessed adequate sensitivities and reproducibilities (of resistance-temperature calibrations) for use as practical secondary thermometers at low temperatures. Thus, there existed a convenient means for "retaining" a primary thermometry scale that could later be communicated to the scientific and engineering public.

At that time, as now, serious discrepancies existed in the absolute temperature determinations by various investigators in both the 2° to 5 °K and 10° to 20 °K temperature ranges. Consequently, we decided to undertake a primary thermometry program that would cover the entire range 2° to 20 °K for two principal reasons. (1) To establish a temperature scale in the uncharted region 5° to 10 °K. (2) To provide absolute temperature values that might aid in resolving discrepancies between existing scales from 2° to 5 °K and 10° to 20 °K. Actually, the second item is mandatory both in establishing the smoothness of adjoining temperature scales, and as an aid in assessing the accuracy of a newly derived temperature scale.

Two methods have been customarily employed for determining values of absolute temperature below 20 °K; pressure-volume isotherm determinations with extrapolations to zero pressure [3, 4], to simulate an ideal gas; and gas thermometry, in which thermometric measurements of a real gas are corrected to give reference to an ideal gas. Each of these methods presents certain serious experimental difficulties and requires the application of specific corrections that have been ably presented in the literature on low temperature thermometry [3 to 11]. But temperature measurements by these two methods have produced values of temperature that are less consistent than might be expected. We felt that some of the existing discrepancies might be inherent in either the instruments or their operational techniques, and therefore decided to embark upon a completely different experimental approach to primary low temperature thermometry.

The experimental determination of isotherms from measurements of the speed of sound in helium gas as a function of pressure seemed to present an approach that would be at least competitive with the more conventional thermometry. Furthermore, it completely avoided the corrections that must be applied to gas thermometry and pressure-volume isotherms determinations.

The concept of deriving values of absolute temperature from speed-of-sound measurements is not of recent origin. Lord Rayleigh recognized the possibility of such an experiment in 1878 [12] in observations on a communication from A. M. MAYER [13]. More recent manifestations of interest appear in the contemporary literature — for example, in a paper by HEDRICH and PARDUE [14], and a chapter by VAN ITTERBEEK [15]. VAN ITTERBEEK and KEESOM [16], de Laet [17], and Brodsky et al. [18] have investigated the feasibility of attaining the required accuracy, with varying degrees of success.

It is pertinent to introduce here a theoretical discussion which will demonstrate that values of temperature on the absolute thermodynamic scale can be approximated from the experimentally determined quantities, sound-speed and pressure, in helium gas*.

Theory: Speed of Sound in a Gas, and Absolute Temperature

When sound is propagated through a gas, if the frequency of the sound is not too high relative to the mean collision frequency of the gas molecules, the propagation is nearly adiabatic, and speed of sound [15, 20] is

$$W = \sqrt{E/\varrho} = \sqrt{\frac{-v^2}{M}\left(\frac{\partial p}{\partial v}\right)_S} = \sqrt{-\frac{C_p v^2}{C_v M}\left(\frac{\partial p}{\partial v}\right)_T} \qquad (1)$$

where ϱ is the density of the medium and E is the adiabatic-bulk modulus defined by the relation

$$E = -v\left(\frac{\partial p}{\partial v}\right)_S = -\frac{C_p}{C_v}v\left(\frac{\partial p}{\partial v}\right)_T . \qquad (2)$$

The symbols v and p refer to the volume and pressure of the medium, and the partial derivative is at constant entropy or temperature, as indicated; C_p and C_v are specific heats at constant pressure and volume, respectively. If the conducting medium were an ideal gas, its equation of state would be expressed by

$$pv = RT \qquad (3)$$

and there would result

$$\left(\frac{\partial p}{\partial v}\right)_T = -\frac{RT}{v^2} . \qquad (4)$$

Additionally the ratio of specific heats would be that of an ideal gas,

$$\left(\frac{C_p}{C_v}\right)_{\text{ideal gas}} = \frac{5}{3}$$

(if the gas is assumed to be monatomic), and Eq. (1) becomes

$$W_0^2 = \frac{5\,RT}{3\,M} . \qquad (5)$$

Equation 5 indicates the simple relationship between the absolute thermodynamic temperature T and the speed of sound in an ideal gas W_0. (The gas constant R and the molecular weight M are considered to be accurately known constants.)

In actuality an ideal gas does not exist, so Eq. (5) must be modified for application to real gases. Of the two gases, He^3 and He^4, which can be used for sound measurements at temperatures between 2° and 20 °K, He^4 has been selected for experimental measurements. Its equation of state can be assumed to be represented by the empirical relationship [21]

$$pv = RT\left(1 + \frac{B}{v} + \frac{C}{v^2} + \dots\right) \qquad (6)$$

where B and C are functions of the temperature called the second and third virial coefficients, respectively. If the quantity $\left(\frac{\partial p}{\partial v}\right)_T$ is evaluated from Eq. (6) and the ratio C_p/C_v is evaluated for the real gas, Eq. (1) can be written

$$W^2 = \left(\frac{C_p}{C_v}\right)_{\text{ideal}} \frac{RT}{M}(1 + \alpha p + \beta p^2 + \dots) \qquad (7)$$

where

$$\alpha = \frac{1}{RT}\left[2\,B + \frac{4\,T}{3}\frac{\mathrm{d}B}{\mathrm{d}T} + (4/15)\,T^2\frac{\mathrm{d}^2B}{\mathrm{d}T^2}\right] . \qquad (8)$$

β is a term that includes higher orders of the virial coefficients B and C. From Eqs. (5) and (7) we obtain

$$W^2 = W_0^2(1 + \alpha p + \beta p^2 + \dots) . \qquad (9)$$

It is now apparent that, if one determines an isotherm of W^2 as a function of pressure, the intercept W_0^2 of the extrapolated isotherm readily affords a means of calculating the isotherm temperature on the absolute scale.

In the foregoing relationships we note that precise volume or changes in volumes, conservation of thermometric fluid, nonideal representations of the gas, and "dead" spaces are extraneous considerations. And since the pressure measurement is a second-order quantity [in Eq. (9) αp is small as compared with 1 and the pressure terms of higher order are even less significant], the precision with which it must be determined is less stringent than in the case of gas thermometry; thus for practical purposes, the need for thermolecular-pressure corrections is entirely eliminated.

In order to obtain values for the speed of sound as a function of pressure, one must determine the wavelength and frequency. Several methods are possible, but our work is based upon the creation of standing waves in helium gas by means of an apparatus with a fixed frequency and a variable path. Other investigators, in attempting a similar type of thermometry (that is, thermometry based on the creation of standing waves in helium gas), have employed apparatus in which the path length for the sound is fixed and the frequency is variable [16 to 18]. We readily acknowledge that other methods may be as feasible as the method we have used.

The instrument we have used is called, in the field of acoustics, an ultrasonic interferometer, but because of its particular application we generally refer to our model as an acoustical thermometer*.

Qualitative Method

A method (often illustrated by Kundt's tube) for measuring the speed of sound in a gas is shown schematically in Fig. 1. In Fig. 1, Q is a quartz crystal energized, by an outside circuit, at its resonance frequency f. The voltage across Q is continuously monitored. Energy radiating from the crystal is transmitted through helium gas; after reflection from the plane surface R, the energy again traverses the gas and returns to the source crystal. The impedance at the electrical terminals of Q, and therefore also the magnitude of the voltage (the input current is held constant), depends on the length of the gas column. If the electrical circuit is properly designed, the magnitude of the voltage at Q peaks sharply for certain distances be-

---

* We are omitting a general discussion on the Thermodynamic Temperature Scale and Methods of realizing it since the subject has been most ably discussed by J. de Boer [19] in a recent issue of this journal.

* Pierce [22], Hubbard [23] and Loomis are to be credited with the early development and use of the ultrasonic interferometer. The articles of Stewart and Stewart [24] and Del Grosso [25], pertaining to measurements on gases and liquids at room temperature, have been particularly informative and helpful. A most pertinent and informative chapter on the "Transmission of Sound Waves in Gases at Very Low Pressures" by Greenspan [26] has recently been published and in part applies to the instrument used in our investigation.

tween R and Q; each of these distance values differs from the next by a half-wavelength.

One measures the displacement of R through n half-wavelengths, which are visually observable on the voltmeter; the displacement divided by $n/2$ yields the wavelength of sound in helium gas. Since the resonance frequency f of the quartz crystal is continuously measured, the experimental value for the speed of sound in helium gas may be readily calculated from $W = \lambda f$. This value of W is, of course, the phase speed corresponding to whatever mode exists in the tube of gas. It is supposed that this mode is sufficiently like the plane wave mode to allow identification of W, for our purpose, as the free-space value. The mode may not be pure but, if this is the case, its components are spaced so closely that the interferometer does not resolve them.

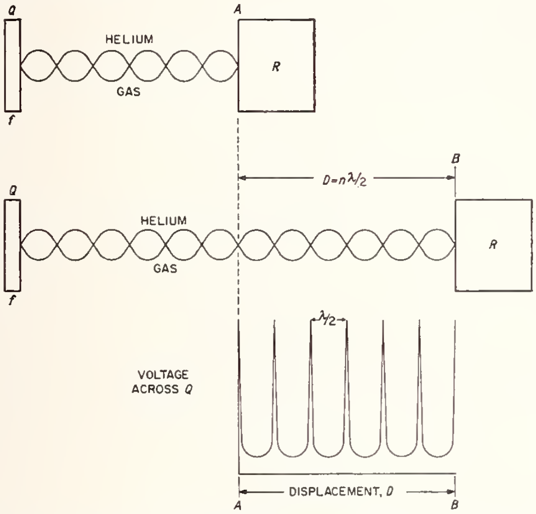


Fig. 1. Schematic representation of the basic method for measuring the speed of sound in a gas

Experimental Instrument

The most important requirement in the design of an ultrasonic interferometer concerns the mounting-relationship between the crystal source and the reflecting surface. It is essential that plane parallelism exist between these surfaces, regardless of the displacement of one surface with respect to the other. Our instrument is so constructed that plane parallelism is maintained to within three light fringes, even though the reflection surface is either displaced by 2 centimeters from the crystal source or completely rotated. This parallelism was maintained at room temperature, and because of the design a comparable result is expected at operational temperatures (20 °K and below).

Another requirement pertains to the purity of the gas being investigated. Because measurements are being made at low temperatures, nearly all the possible impurities are frozen out. Nevertheless, to maintain an operationally clean system and also to exclude the few gases which might be contaminating, the entire enclosed gas system was made vacuum-tight. Additionally, the entire system was repeatedly flushed with He^4 gas during routine preparations and operations. Outgassing at a temperature that is high compared with ambient conditions is, for our apparatus, impractical and seems unnecessary since, as mentioned, nearly all the possible contaminants are frozen out at temperatures below 20 °K.

One of the most difficult design problems is associated with the measurement of the relevant displacement of the reflecting surface relative to the crystal surface. The difficulty arises from the possible expansions and contractions of material in existing extreme temperature gradients — which are not necessarily constant. The design must not only provide for actuation of the reflecting surface but must also permit accurate measurement of the translational motion.

Another requirement concerns the need for making precise measurements of electrical resistance. If the ultrasonic interferometer is to serve as a primary thermometer, we must be able to calibrate secondary thermometers against the scale of temperature that is established. Germanium resistors can be used as secondary thermometers, but their use presents certain measurement problems: the occurrence of stray joule heating at radio-frequencies [43]; the problem of making resistance measurements at low power levels; and the difficulty of attaining thermal equilibrium.

Certainly not least among the design requirements is the necessity of accurately maintaining the essential components at any desired temperature between 2° and 20 °K for long periods. Considerations of primary and secondary thermometry are paramount, for it is hoped that the instrument will be at least competitive with the best existing techniques of low-temperature thermometry.

Construction Details

During experimentation, the lower portion (Fig. 2) of the apparatus is maintained in a liquid helium bath; the upper portion (Fig. 3), which is necessary for effecting and measuring displacements of the reflecting piston A, is at room temperature.

Copper piston A is capable of being translated smoothly, without seizing, within the copper cylinder B. The quartz crystal ($f = 1$ M Hz) is seated against the lower surface of the cylinder B; the lower assembly D not only maintains the crystal in position but also accommodates the electrical lead which energizes the crystal. The piston's upper end is connected to a fused quartz rod by a ball joint designed to permit reasonably simple assembly and a degree of self-adjustment during thermal expansion or contraction and to constrain the piston to follow axial displacements of the fused quartz rod. The rod extends upward about 1.2 m to enter ambient conditions above the indicated neoprene O ring vacuum seal (Fig. 3). At its upper end the rod is smaller in diameter than it is throughout the rest of its length, and at the point where this change in diameter occurs it is secured to a plate, P, that is constrained to move in translation only along the axis of the quartz rod. Fixed pins which pass through holes drilled in the plate prevent rotation of the plate. The motion of the handoperated driving mechanism is limited to rotation about the axis of the quartz rod. Plate P is threaded into the driving mechanism, hence a rotation of the driving mechanism produces a translation of plate P along the axis of the quartz rod. Because the quartz rod and the piston undergo the same translation, the position of the reflecting surface (Fig. 2) with respect to the quartz crystal is controlled by manual turning of the driving mechanism.

The thermometric gas He^4 is contained within cylinder B, assembly D, copper piece C, and the Invar and quartz tubings which lead to the base plate L (Figs. 2 and 3). From the base plate there is gas communication through a side arm to a manifold that affords connection with a manometer, a large gas-ballast volume, and gas evacuating or filling systems. This arrangement permits vacuum leak detection, gas filling, and pressure control and measurement.

Since the entire assembly of Fig. 2 is maintained in liquid helium during experimental measurements, a large temperature gradient exists along the fused quartz tubing — from 4 °K at the top of the vacuum can to 300 °K several centimeters below the base plate. Fluctuations in the gradient could have a critical effect on the displacement measurement from which the speed of sound is calculated. Precautions have been taken to minimize the changes in the thermal gradient; more important, fused quartz was selected for the tubing because of its relatively small coefficient of expansion.

The temperature of the helium gas between piston A and the quartz crystal is of paramount importance; it must be controllable so that it can be maintained for long periods at any selected temperature in the range of interest, 2° to 20 °K. This is best accomplished by controlling the temperature of C, A, B, and D, which are in intimate contact with the thermometric gas. When the apparatus is in operation there should be no discernible temperature difference for these components, and their temperature should exceed that of the surrounding liquid helium bath. In order to achieve the best temperature control and also maintain a reasonable rate of evaporation for the surrounding liquid helium, the controlled components should be thermally isolated from the helium bath. Complete isolation is both impractical and undesirable*; hence thermal losses to the bath must be controlled to minimize undesired thermal gradients. Accordingly, the instrument design is such that there is a heat flow from C toward the vacuum-can cover, which is exposed to the helium bath temperature. A vacuum is maintained in the can, which surrounds C, B, and D; a radiation shield surrounding B and D is thermally coupled to C; secondary-thermometer electrical leads are thermally anchored to C; and the heater coil for supplying power to maintain C, B, A, and D at the desired temperature is wound on C, as shown in Fig. 2. Small secondary thermometers (germanium resistors imbedded in the outer wall of cylinder B) and the acoustical-wave generating system supply heat to the system (A, B, C, and D) and therefore could conceivably establish an undesired gradient. However, experimental variation of the power applied to these small heating sources has not revealed any such gradients. In effect, the components below C are "dead-ended" thermally, so that, for all practical purposes, the imbedded secondary thermometers are in thermal equilibrium with the excited helium gas.

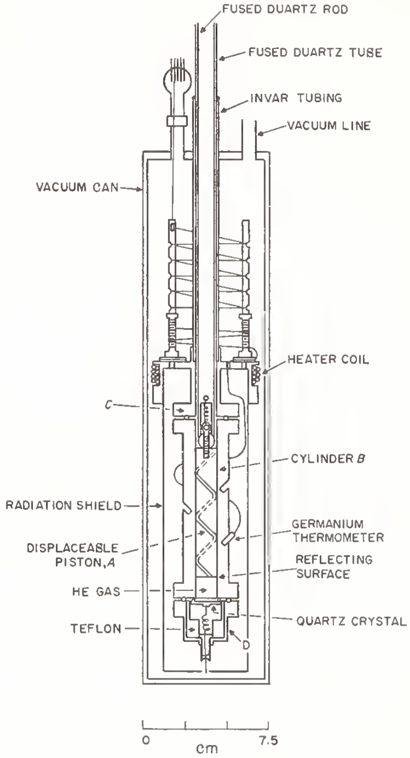


Fig. 2. Acoustical-thermometer components which are maintained at low temperature during the experiment

Precautions were taken to avoid thermal oscillations [27] of the helium gas in the annular space between the quartz tube and the rod. But another serious problem was encountered. When the temperature-controlled section was maintained at a temperature which exceeded the bath temperature by several degrees, convection currents were set up in the gas that occupies the annular volume between the thin-walled Invar tubing and the quartz rod. The convection cycle transmitted heat in an erratic manner from component C to the region of the vacuum-can cover. This necessitated a larger heat input to the heater coil and resulted in the loss of temperature stability for the chamber components. The difficulty was overcome by introducing nylon material, formed into a spiral, to fill the annular volume; the spiral broke up the convection path but permitted the necessary pressure communication between the helium gas chamber and the manometer and ballast volume.

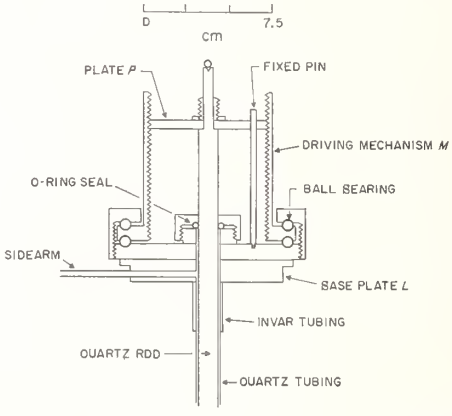


Fig. 3. Mechanism for driving the accoustical-thermometer piston

In measuring piston displacements it is assumed that the upper end of the quartz rod (Fig. 3) undergoes the same translation as the piston's reflecting surface. This is correct within the limits of our measurement error. Actually, with the lower assembly in thermal equilibrium at 10 °K, if the displacement is 1 cm upward and thermal equilibrium is again attained, the end of the quartz rod will have been displaced by approximately 1 cm. The departure from this 1-cm measurement will be the change in length of a centimeter of fused quartz when its temperature is raised from 10 °K to room temperature. A report by Gibbons [28] indicates that this correction might be less than a micron, which is approximately the accuracy of our measurements.

A stainless steel ball is seated on the upper end of the quartz rod (Fig. 3), and above it a calibrated micrometer head is mounted. The micrometer head mounting and base plate L are both referenced to a rigid plane. All components of the length-measuring system, which are in both the room-temperature and the low-temperature parts of the apparatus, are made of either Invar or fused quartz to minimize errors caused by temperature flucations. An electrical system is used to indicate when the micrometerhead barrel makes contact with the stainless steel ball. Quite obviously, the micrometer is never operating under a load, since the piston activation is effected by the driving mechanism.

In Fig. 2, one of four germanium resistors is shown mounted in the cylinder wall. Three of the resistors are used to indicate the temperature stability of the thermally controlled apparatus. Since they are also calibrated against the acoustically determined absolute temperatures, they "retain" the temperature scale and can be used as secondary thermometers

---

* There must be a physical or material approach to the system for both wavelength and pressure determinations. Complete thermal isolation is also impossible because continuous application of a low current to the quartz crystal and germanium resistors would slowly increase the temperature of the thermometric gas and its surroundings. The rise in temperature would be perceptible, since the heat capacity of materials at low temperatures is extremely small.

in future calibrations. The fourth resistor serves as a temperature sensor. It connects with outside controls that automatically regulate the heater-coil power to achieve necessary temperature control of various components.

Experimental Operation

After precautionary flushings with helium gas, the acoustical-thermometer gas space (which includes the ballast volume, the manometer, and the manifold) is filled to a pressure slightly below atmospheric pressure. A small amount of helium exchange gas is admitted to the vacuum can, and the low-temperature portion of the apparatus is cooled by means of liquid nitrogen. After 4 h, a liquid-helium transfer is initiated. When the transfer has been completed, the pressure of the helium bath is placed under manostatic control and maintained above ambient pressures.

When the bath has become stabilized and the electrical circuits have been monitored, the temperature desired for measurements is approached. The resistance of the germanium sensor is dialed on the Wheatstone bridge, and the temperature regulator assumes control of the system. For a number of possible reasons a slight loss of control can occur, but this can be offset by infrequent manual corrections to the Wheatstone bridge setting, made in accordance with the temperature indicated by the germanium secondary thermometers. In this manner the interferometer temperature is easily controllable to ± 0.002 °K for hours. After an operating temperature has been achieved, the pressure of the thermometric helium gas is gradually increased or reduced to a desired value. Next, the quartz crystal is energized at its resonance frequency* and its voltage is monitored. When the piston is advanced at a uniform rate toward the quartz crystal, the voltage rises to a sharp maximum each time a standing wave exists in the gas.

The Invar spindle (*M* of Fig. 3) is then turned to raise the piston to a point where its lower reflecting-surface is about 1.7 cm above the opposing quartz-crystal face, and a standing wave exists in the gas. Since this operation is accompanied by a flow of gas into the volume between the quartz crystal and the reflecting surface (Fig. 2), the temperature will change and the experimenter must wait several minutes until it returns to the temperature control point. Then by means of the micrometer head the position of the stainless steel ball that is atop the quartz rod is determined. At least two independent readings are made at each measured resonance point: after the initial reading the micrometer contact-surface is raised, the piston is intentionally slightly displaced, the piston position for resonance is redetermined, and another micrometer reading is made. Following this, the piston is moved toward the crystal through a definite number of resonance points (an interval of 40 half-wavelengths is often used); this downward motion is terminated at a resonance point. The micrometer head is then advanced downward to determine the new position of the stainless steel ball. The piston is caused to approach the quartz crystal in incremental steps, and other micrometer measurements of the position of the ball are made. From these measurements an average wavelength may be calculated and, consequently, the speed of sound through the gas also, since the resonance frequency of the quartz crystal is known from continuous measurements. The gas pressure is also systematically observed and recorded during this procedure, so a value for average pressure is obtained. The values for speed and corresponding pressure determine one point on an isotherm. To obtain an additional point, the pressure is changed, in general a slightly different frequency is ascertained (the resonance frequency of the quartz crystal varies slightly with the pressure of the surrounding gas), and the measurement proceeds as described above.

Typical Isotherm Point

Tab. 1 contains data that are typical measurements for determining one point of an isotherm and apply to the highest point of the 20.051 °K isotherm (Fig. 4). With reference to Tab. 1, before the micrometer readings were taken at $n\lambda$, temperature control of the acoustical thermometer was indicated by the measured resistance value (column 4). The gas pressure was read and the piston's position, for helium gas resonance, was twice located and measured with the micrometer head. Next, the piston was advanced 20 λ toward the quartz crystal and, after the accompanying slight perturbation in temperature, several minutes were required for reestablishing temperature control of the acoustical thermometer. — This was indicated by values of resistance for the monitoring germanium thermometers. — New readings were taken at $(n-20)\lambda$. The procedure was repeated at intervals of 20 λ until the piston's reflecting surface had passed through a total of 60 λ; at this point the reflecting surface and quartz crystal were separated by about 1 mm.

Table 1. *Measurement Data for a point on the 20.0 °K Isotherm*

Displacement[a] Interval (wavelengths)	Micrometer[b] Readings (mm)	Pressure[c] (Atmospheres)	Resistance[d] (ohms)	Mean Micrometer Reading (mm)	20 λ Interval (mm)
$n\lambda$	25.0683	1.2032	62.023		
	25.0683[e]			25.0683	
					5.3173
$(n-20)\lambda$	19.7510	1.2034	62.019		
	19.7510[e]			19.7510	
					5.3169
$(n-40)\lambda$	14.4341	1.2035	62.020		
	14.4341[e]			14.4341	
					5.3170
$((n-60)\lambda$	9.1171	1.2037	62.019		
	9.1171[e]		62.017	9.1171	

p(ave) = 1.2035 (Atmospheres) λ(ave) = .26585 (mm)
frequency = 994,956 hertz
$W = \lambda(\text{ave}) \times f = 264.51$ (m/s)
$W^2 = 69{,}966$ (m/s)^2

[a] Displacement of the reflecting piston toward the quartz crystal.

[b] The micrometer head is actually calibrated in inches; its least count is (0.00001 inches) 0.00025 mm.

[c] The pressure reading has been converted to atmospheres for this table.

[d] Resistance of monitoring germanium resistor (one of two); its temperature coefficient of resistance is approximately − 0.007 (ohms/m deg) at 20 °K.

[e] The second value indicates a redetermination of the reflecting piston's position after a second establishment of gas resonance.

We have recorded, in column 2, positions of the piston's reflecting surface relative to the quartz crystal — i. e., two readings for each position. The coincidence of the pairs of readings at each location is fortuitous since measurements that differ by ± 0.0003 mm are sometimes observed but still considered satisfactory. Column 5 contains readings that are the average of those listed in column 2 and differences between the average readings of column 5 are recorded in column 6.

The constancy of the measured 20 λ intervals is apparent and is typical of most of our measurements (including those in which 10 λ was the measuring interval). Whenever the measured interval has systematically varied, as the quartz crystal is approached, we

---

* The tuning of a quartz crystal circuit for an acoustical interferometer is discussed by J. L. and E. S. Stewart [24].

have been able to associate it with the malfunctioning of the acoustical thermometer.

It is apparent that the pressure (column 3) is systematically increasing as the piston approaches the quartz crystal. This result is expected since the advancing piston displaces the high density helium gas of the resonating chamber thereby decreasing the helium gas volume*. In this instance the observed pressure variation is of slight importance for it is much less than the experimental error of reproducing points on an isotherm. — From the slope of the isotherm in Fig. 4 we have calculated that a pressure indeterminancy of 0.008 atmospheres is equivalent to a temperature indeterminancy of 0.001 °K. Thus the pressure variation of column 3 is equivalent to approximately 0.00007 °K, which is negligible in our measurements. At the lowest temperatures, where the isotherms have much larger slopes (at 2.3 °K, 0.0004 atmospheres is equivalent to 0.001 °K in temperature), the measurements are conducted at sufficiently low gas pressures that pressure variations are not detected during the piston's travel.

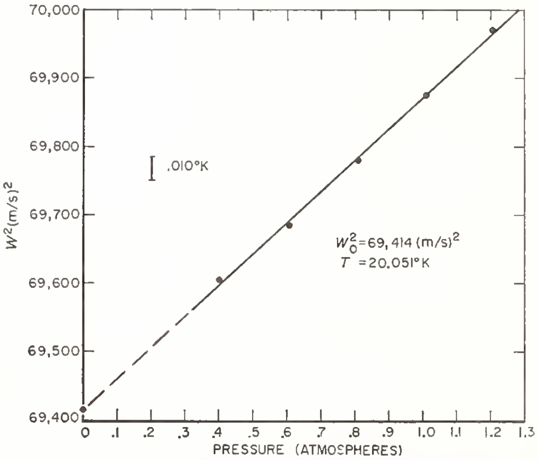


Fig. 4. 20.051 °K Isotherm. The square of the speed of sound in helium gas as a function of the pressure. The dotted portion of the curve represents the isotherm's extrapolation to W_0^2 at zero pressure

Pressures are measured to an accuracy of 0.050 mm (0.00007 atmospheres) which, in temperature equivalence, is considerably better than the observed experimental reproducibility of the isotherms.

Column 4 indicates the constancy of the acoustical thermometer's temperature during the series of measurements. Since the germanium resistor's temperature coefficient of resistance is about − 0.007 ohms/m deg, it is apparent that the instrument temperature was constant within one millidegree at the times of acoustical measurements.

An average wavelength, based upon the 60 wavelength interval, has been computed and multiplied by the resonance frequency of the quartz crystal to yield values of W and W^2. The computed W^2, 69,966 (m/s)^2 is not the same as the value of W^2, 69,971 (m/s)^2 listed in Tab. 2 for the highest pressure point of the 20.0 °K isotherm. The difference is easily explained. Because all of the points for an isotherm were not measured at exactly the temperature (indicated by the monitoring germanium resistors), minor corrections were applied to obtain a common reference temperature. Such corrections have been incorporated, where appropriate, in the W^2's listed in Table 2; the corrections never were greater than a temperature equivalent of three millidegrees.

Definition of Isotherms

The isotherm data are listed in Tab. 2. While the actual measurements yielded W (speed in m/s) and p (pressure in atmospheres), W^2 and p are listed in Tab. 2 since, in accordance with Eq. (7), temperatures are explicitly related to W^2. The data for individual isotherms have been subjected to both graphic and computer analysis and, except for the lowest isotherms, the best representations appear to be afforded by a straight line. Fig. 4 is typical of the isotherms above 7 °K and demonstrates the adequacy of representing these isotherms by a linear relationship.

Applicable to the least squares fitting in the computer analysis, Δ of Tab. 2 indicates the difference between an isotherm data point and the computer-fitted function evaluated at the pressure of the data point. σ is the standard deviation in the least squares fitting of the isotherm. Relevant to assessing Δ and σ, a variation in W^2 of 3.5 is equivalent to a temperature variation of 0.001 °K. From this it is apparent that the scatter of data points from the isotherm functional representation is generally within ± 0.002 °K; this is supported by the indicated spread of data as portrayed in Fig. 4. — Except for the isotherms below 7 °K, there are only five instances where the ± 0.002 °K band is exceeded; at pressures of 1.0070 atmospheres at 14.0 °K, .3680 and 1.4153 atmospheres at 12.0 °K, and .1326 and .3680 atmospheres at 7.0 °K. — We interpret this as signifying that the reproducibility of isotherm data points is generally within 0.002 °K. Consequently, systematic departures (which are noticeably in excess of 0.002 °K) from a liner representation signify the need of including higher order pressure terms (Eq. 7) for adequate representation of an isotherm. This is clearly the case in Fig. 5 and is even suggested in Fig. 6. The observed departure of an isotherm from linearity is not unexpected, particularly at low temperatures and relatively high pressures. The βp^2 term of equation 7 includes the second and third virial coefficients, as well as their derivatives, and since these coefficients are relatively large and rapidly changing with decreased temperature, their effect on the speed of sound should become apparent under the above-mentioned conditions.

Two procedures for representing the lower temperature isotherms are apparent from viewing Fig. 5. (a) Either the higher pressure data (data that deviate from a linear relationship by more than 0.002 °K) can be neglected, or (b) higher order pressure terms can be included to represent more effectively all of the data. Admittedly, the use of (a) will result in some degree of inaccuracy when the isotherm is extrapolated to zero pressure for obtaining a value of W_0^2 and subsequently calculating T. However, procedure (b) has disadvantages also: there exists no *a priori* approach to predict the significance of particular higher order pressure

---

* If a large ballast volume (a 50 l volume located at ambient temperatures) were not employed the pressure variation would present a serious problem because the speed of sound is naturally dependent on the gas pressure.

Table 2. *Experimental Data for Isotherms Measured by the Acoustical Thermometer*

T	W^2	P	Δ[a]	σ[b]
20.0 °K	69,604	.4024	7.2	
	69,684	.6052	−6.0	
	69,779	.8081	−4.9	
	69,875	1.0074	−1.1	
	69,971	1.2035	4.8	6.7
18.9 °K	65,734	.4020	−3.8	
	65,821	.6034	0.2	
	65,910	.8086	4.1	
	65,995	1.0108	5.8	
	66,075	1.2325	−6.2	5.9
18.0 °K	62,503	.4017	6.3	
	62,569	.6024	−3.7	
	62,643	.8072	−7.1	
	62,725	1.0067	0.0	
	62,805	1.2067	4.5	6.4
17.0 °K	58.869	.4018	0.6	
	58,930	.6051	−0.8	
	58,993	.8102	−1.6	
	59,058	1.0061	3.2	
	59,111	1.1936	−1.4	2.3
16.0 °K	55,659	.4008	6.3	
	55,650	.4030	−2.7	
	55,698	.6065	−2.3	
	55,745	.8096	−3.6	
	55,794	1.0065	−0.6	
	55,841	1.1950	2.9	4.3
15.0 °K	51,952	.3354	−1.2	
	51,989	.5356	3.5	
	52,016	.7377	−2.1	
	52,049	.9420	−1.6	
	52,084	1.1419	1.4	2.7
14.6 °K	50,753	.3356	6.0	
	50,765	.5040	−4.8	
	50,787	.6630	−3.4	
	50,866	1.2120	2.2	6.1
14.0 °K	48,672	.4020	7.3	
	48,678	.6030	−2.9	
	48,695	.8042	−2.5	
	48,702	1.0070	−12.4	
	48,738	1.2060	7.6	
	48,741	1.3832	−4.2	
	48,753	1.3899	7.2	8.3
13.0 °K	44,858	.4019	5.8	
	44,841	.6040	−3.7	
	44,836	.8090	−0.4	
	44,822	1.0076	−6.2	
	44,819	1.2961	−0.9	
	44,817	1.3960	5.4	5.4
12.0 °K	41,550	.3680	14.8	
	41,507	.5330	−0.5	
	41,475	.7070	−2.8	
	41,424	1.0050	−3.3	
	41,392	1.2103	−0.3	
	41,371	1.4153	12.9	5.4
10.9 °K	37,678	.2005	7.9	
	37,614	.3730	2.6	
	37,599	.4018	−2.8	
	37.535	.5745	−8.5	
	37,467	.7770	−8.2	
	37,467	.8066	2.1	
	37,407	.9777	−0.6	
	37,346	1.1650	1.3	
	37,346	1.1778	5.7	6.0
9.9 °K	34,121	.2040	4.2	
	34,062	.3149	4.1	
	34,011	.4030	−0.7	
	33,895	.6061	−8.3	
	33,790	.8067	−6.7	
	33,694	1.00003	0.6	
	33,606	1.1770	6.8	6.2
9.0 °K	30,980	.2017	5.0	
	30,818	.4076	−3.0	
	30,665	.6068	−6.9	
	30,524	.8096	2.8	
	30,380	1.0005	2.2	5.6
8.1 °K	27,792	.1343	5.1	
	27,642	.2680	−4.4	
	27,466	.4380	−2.0	
	27,287	.6090	−2.3	
	27,120	.7740	3.5	4.8
7.0 °K	23,988	.1326	9.5	
	23,770	.2680	−10.1	
	23,532	.4370	−1.8	
	23,287	.6040	−2.5	
	23,069	.7580	4.9	8.7
6.1 °K	*20.756*	*.1011*	−18.6	
	20,768	.1028	−3.5	
	20,712	.1338	0.2	
	20,589	.2008	8.0	
	20,578	.2013	−2.8	
	20,572	.2036	−3.8	
	20,553	.2162	2.0	
	20,398	.30003	8.7	
	20,380	.3022	−5.1	
	20,186	.4004	−8.3	
	20,190	.4014	−2.7	
	20,187	.4080	7.2	
	19,822	(.5853)	−14.0	
	19,790	(.6030)	−11.5	
	19,421	(.7850)	−26.7	6.1
5.0 °K	*17.208*	*0.0644*	−12.5	
	17.135	.0988	6.2	
	17,033	.1340	−2.0	
	16,943	.1676	2.2	
	16,866	.1978	1.2	9.6
4.2 °K	*14,461*	*0.0322*	−9.5	
	14,444	*.0328*	−21.6	
	14,407	.0501	4.0	
	14,391	.0507	−1.9	
	14,342	.06638	−2.2	
	14,344	.0668	−0.7	
	14,287	.0801	.6	
	14,223	.0997	−1.6	
	14,216	.10211	−.1	
	14,225	.10271	10.7	
	14,145	.1204	2.8	
	14,042	.1505	−0.7	
	13,975	.1674	1.2	
	13,874	.1986	3.8	
	13,867	.1976	−5.9	
	13,855	.2017	−3.7	
	13,746	(.2357)		
	13,481	(.3024)		
	13,646	(.2555)		
	13,160	(.3805)		3.1
3.2 °K	*10.951*	*0.03048*	−5.3	
	10,909.4	.04007	3.7	
	10,849.7	.0501	−3.0	
	10,815.2	.0568	−3.3	
	10,768.0	.0668	3.4	
	10,675.8	.08366	.2	
	10,597	.0989	1.9	
	10,585.1	.1003	−2.6	
	10,403.0	(.1340)		
	10,210.9	(.1672)		
	9,995.0	(.2036)		3.7
2.8 °K	*9,612.5*	*0.01601*	−8.4	
	9,612.3	.0233	3.5	
	9,535.1	.03011	−0.6	
	9,495.4	.03666	−.7	
	9,455.8	.04333	−.1	6.2

Table 2 (continued)

T	W^2	P	Δ[a]	σ[b]
	7,919.4	*0.0135*	−12.4	
	7,915.3	.01541	− 1.1	
	7,886.5	.02005	− 7.6	
	7,837.2	.0251	− 1.0	
2.3 °K	7,837.4	.0251	− 1.2	
	7,874.8	.02076	1.6	
	7,795.5	.02966	− 5.9	
	7,799.0	.02991	− 0.4	
	7,733.77	.03837	2.7	6.9

W^2 – *(meters/sec)*^{2}; p – *atmospheres*

[a] The columns under Δ contain the difference between the experimental W^2 at the indicated pressures and the W^2 of linear function determined by the computer least squares fitting.

[b] σ is the standard deviation in the least squares fitting of an isotherm.

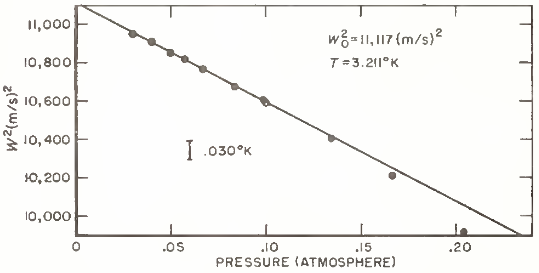


Fig. 5. 3.211 °K Isotherm — W^2 as a function of pressure

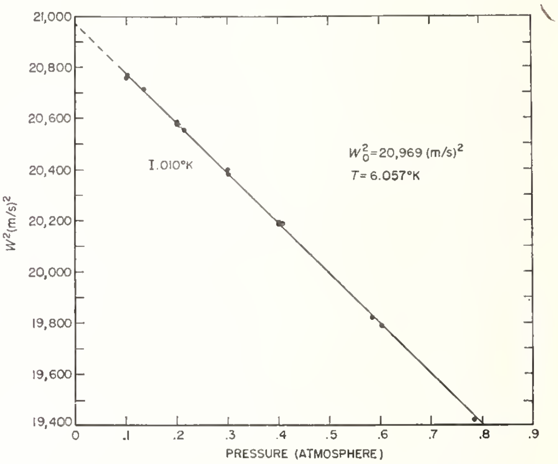


Fig. 6. 6.057 °K Isotherm— W^2 as a function of pressure

terms since the analytical representation of higher order virial coefficients is unknown. Additionally, we feel that our isotherm data do not extend to sufficiently high pressures to yield meaningful higher order analysis*. Therefore we have selected procedure (a) as the more suitable method for representing our present data.

We have naturally attempted to obtain isotherm data points at the lowest possible pressures to minimize errors that result from extrapolating an isotherm to zero pressure. For the isotherms below 7 °K it is apparent that the data points at the lowest pressure may be less significant than other data points; this is borne out by the relatively large values of Δ for the lowest pressure points at 2.3°, 4.2°, 5.0° and 6.0 °K. The inaccuracy of these points is caused by a lack of resolution resulting from the high attenuation of sound energy in the thermometric gas. Because of this inaccuracy, the data (Tab. 2) in italics received 1/4 weighting in the least squares fitting. For the 3.2°, 4.2° and 6.0 °K isotherms, the data in parentheses were neglected in fitting the isotherms to a linear function; other isotherms did not contain comparable "high pressure" data that warranted comparable treatment. The remainder of the data were assigned a weighting of unity.

Although linear representations of isotherms have appeared to be appropriate (within the limitations previously presented), the computer fitting was extended to functions that included higher order pressure terms. This resulted in an improvement in the statistical certainty of the first coefficient [W_0^2 of Eq. (9) from which values of isotherm temperatures are calculated] in two cases: for one isotherm, 9.9 °K,

Table 3. *Intercepts* [W_0^2 *(meters/sec)*^{2}] *and Temperatures* [T *°K*] *derived from isotherm extrapolations*

T °K	$W^2_{0\,\mathrm{graph}}$	$W^2_{0\,\mathrm{comp}}$(linear)	$\Delta W^2_{0\,\mathrm{comp}}$	T_{graph}	T_{comp}(linear)	ΔT_{comp}
20.0	69,414	69,411	9.1	20.051	20.051	.003
18.9	65,567	65,571	7.7	18.939	18.941	.002
18.0	62,350	62,344	8.6	18.010	18.009	.002
17.0	58,748	58,745	3.1	16.970	16.969	.001
16.0	55,552	55,559	4.7	16.047	16.048	.001
15.0	51,904	51,899	3.4	14.993	14.992	.001
14.6	50,704	50,702	7.0	14.646	14.646	.002
14.0	48,632	48,632	9.1	14.048	14.048	.003
13.0	44,871	44,869	6.3	12.961	12.961	.002
12.0	41,598	41,597	7.7	12.016	12.016	.002
10.9	37,740	37,738	4.8	10.901	10.901	.001
9.9	34,228	34,226	5.1	9.887	9.886	.001
9.0	31,130	31,125	5.9	8.992	8.991	.002
8.1	27,926	27,928	4.6	8.067	8.067	.001
7.0	24,170	24,172	8.6	6.982	6.982	.002
6.1	20,971	20,971	5.0	6.057	6.057	.001
5.0	17,393	17,392	9.6	5.024	5.024	.002
4.2	14,580	14,583	3.1	4.211	4.212	.001
3.2	11,123	11,117	3.2	3.213	3.211	.001
2.8	9,723	9,718	6.2	2.808	2.807	.002
2.3	8,038	8,041	6.9	2.322	2.323	.002

---

* In a previous paper [29] we have reported the results of fitting the entire 3.2° and 4.2 °K isotherm data to functions that included quadratic and cubic terms.

by the inclusion of a quadratic term; and for another, 14.6 °K, by the inclusion of both quadratic and cubic terms. These results are considered fortuitous and therefore no significance is ascribed to the isolated instances.

In summary, because of the limited nature of the isotherm data points, we have felt that the best interpretation of the data is effected by restricting, where necessary, the range of data to sufficiently low pressures so that, within the limits of isotherm reproducibilities (0.002 °K), they can be represented by a linear relationship.

Isotherm Intercepts and Derived Temperatures

The isotherm intercepts (W_0^2 at $p = 0$) have been evaluated, both graphically and analytically, and are listed in Tab. 3. For each isotherm, W_0^2 comp is the first term or constant in the equation

$$W^2 = W_0^2 + W_0^2 \alpha p \tag{9a}$$

and the adjacent $\varDelta W^2_{0\mathrm{comp}}$ is the individual term's uncertainty as calculated in the least squares fitting. From the relationship for the speed of sound in an ideal gas,

$$W_0^2 = \left(\frac{C_p}{C_v}\right)_{p=0} \cdot \frac{R_M T}{M_{\mathrm{He}}} \tag{5}$$

the absolute temperatures T were readily calculated. These are listed in columns 5 and 6 for the graphical and computer analyses, respectively. The $\varDelta T$'s of column 7, the temperature equivalents of the $\varDelta W^2_{0\mathrm{comp}}$, indicate the statistical temperature inaccuracies that have resulted from the least squares fitting and the isotherm extrapolation to zero pressure; $\varDelta T_{\mathrm{comp}}$ is not the estimated accuracy in realizing a value of absolute thermodynamic temperature.

Discussion

NBS Provisional Temperature Scale 2—20 (1965)

During the isotherm measurements, at least two germanium thermometers were in thermal contact with the helium-4 gas that served as the thermometric fluid. — More specifically, they were embedded in the wall of cylinder *B* (Fig. 2), which in part bounds the helium gas. — Since the germanium thermometers' resistances were systematically measured in monitoring the isothermal stability of the acoustical thermometer, we possessed a temperature calibration of the germanium thermometers when the isotherm measurements were concluded and evaluated. Afterwards, additional germanium thermometers were calibrated by comparison with the original group so that we now posses six that are referenced to the acoustically determined isotherms and maintain the scale NBS P 2 – 20 (1965)*. The scale consists of resistance values (for the individual thermometers) associated with values of temperature that closely approximate the original isotherm temperatures.

Comparison of NBS P 2—20 (1965) with NBS (1955)

While we do not wish to state a figure for the accuracy of our scale (with respect to the Thermodynamic Temperature Scale), we are able to make comparisons with other scales in regions of overlap. One such is the NBS (1955)*, which is maintained by a group of platinum resistors.

Two germanium resistors were calibrated in the region 11° to 20 °K on the NBS (1955) temperature scale by J. L. Riddle and his associates. The resistors are identified as No. 4 and D in accordance with previous designations [31]**. Resistor No. 4 was calibrated at four temperatures against NBS (1955) about a year previous to its insertion in the acoustical thermometer. After the insertion, the acoustical thermometer was controlled at a temperature that reproduced No. 4's calibrated resistance value [NBS (1955)] and subsequently an isotherm was determined to obtain the relevant sonic temperature. This procedure was repeated for the other three calibration points.

Resistor D was calibrated in a different manner. After we had determined our isotherm temperatures between 10° and 20 °K, resistor *D* of reference [31] was submitted to the NBS platinum resistance thermometer calibration group for calibration against the NBS (1955) temperature scale. By diligent effort on their part, the thermometer *D* was calibrated against NBS (1955) at temperatures that were generally within 0.020 °K of the acoustically determined isotherm temperatures. Within a period of several days resistor *D* was then installed in the acoustical thermometer and calibrated against resistors *A* and *B* at temperatures that approximated the original isotherm temperatures (indicated by the measured resistance values of both *A* and *B*). — The germanium resistors *A* and *B* of reference [31] have been continously employed as monitoring resistors in the acoustical thermometer and therefore have been calibrated against every determined isotherm.

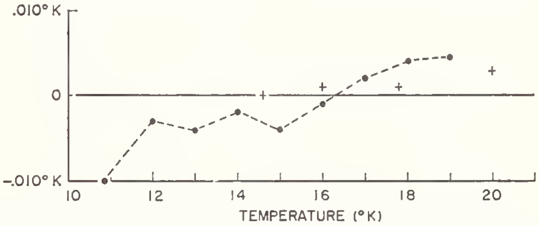


Fig. 7. A comparison between the acoustically derived temperature scale [NBS Provisional Scale 2—20 (1965)] and the NBS (1955) temperature scale. The difference in values of the two scales [NBS P 2—20 (1965) minus NBS (1955)], as indicated by two germanium resistors, is plotted as a function of the Kelvin temperature

From the dual calibrations of resistors No. 4 and *D*, we have been able to compare values on the temperature scale (1955) with values of temperature derived

---

* Some of the comparison calibrations were performed with the resistors positioned in the acoustical thermometer, but more recent calibrations have been made in a comparison calibrator [30] that has been designed for more routine calibration procedures.

* The present National Bureau of Standards temperature scale in the region 10.5 °K and above is maintained on platinum resistors, is designated as "NBS (1955)," and is defined as being 0.01 °K lower than the scale given in the following; H. J. Hoge, and F. G. Brickwedde, "The Establishment of a Temperature Scale for the Calibration of Thermometers between 14° and 83 °K" [9].

** Reference [31] reports the thermal histories of a group of germanium resistors; 4.2 °K resistance-temperature calibrations (against T_{58} [1]) were periodically performed between thermal cyclings of the resistors from room temperature to 4.2 °K. Resistor No. 4's 4.2 °K calibration was constant within a temperature equivalent of 0.0003 °K during 11 thermal cycles; *D*'s calibration was constant within 0.0005 °K during 86 cycles. Thus it is expected that later calibrations of these resistors are reliable.

from the acoustical thermometer. This is depicted in Fig. 7 and it appears that the deviation of our values from those of the NBS (1955) scale is, in general, within the limits of accuracy (from ± 0.01 °K to ± 0.02 °K) stated for that scale. The lowest point, at 11 °K (a difference of − 0.01 °K), may indicate an actual deviation between the two scales. It is unfortunate that it has not been convenient to effect a comparison between the two scales at 10 °K.

In a recent issue of Metrologia, M. P. Orlova et al. have reported [32] the comparison of four temperature scales covering the range 10° to 90 °K*. Through NBS (1955), the NPL scale can be compared with the present work in the range of overlap (10.9° to 20 °K). While it may be fortuitous, the two scales are remarkably similar in detailed deviations from NBS (1955); the differences are sufficiently small that any discussion of them would be of little significance at present.

Comparison of NBS P 2—20 (1965) with T_{58}

In the temperature range, 2° to 5 °K, values of temperature derived from the acoustical thermometer have been compared with the helium-4 vapor pressure scale, T_{58} [1]. Since we have not incorporated a helium vapor pressure thermometer into the acoustical thermometer assembly, helium-4 vapor pressures have not been measured in conjunction with our isotherm determinations. Rather, germanium thermometers have been calibrated against both the T_{58} scale and the acoustical thermometer to afford the desired scale comparisons.

Calibrations against the helium vapor pressure scale have been performed in a manner that was consistent with vapor pressure measuring techniques that we have previously described [33]. The resistors were contained in "constant temperature" bath of liquid helium and helium-4 vapor pressures were measured by immersed vapor pressure thermometers that were partially vacuum-jacketed; that is, the thermometer tubing was thermally insulated from the bath's colder surface to avoid the effects of "cold spots" [33, 34]. This technique has proven to be very consistent and reliable when applied to helium-4 vapor pressure as evidenced by investigations that have been conducted in our laboratory during the last five years.

The comparison of our values of isotherm temperatures with T_{58} is shown in Fig. 8. Additionally, there are indicated values of temperature (relative to T_{58}) that have resulted from other primary thermometry investigations in which the values of absolute temperature were associated with a corresponding helium-4 vapor pressure. Since the comparison of absolute thermometry values is afforded through the medium of helium-4 vapor pressure determinations, it should be emphasized that possible errors in both values of absolute temperature and vapor pressure measurements are germane to the comparisons of different thermometry investigations as represented in Fig. 8. While we are unable to assess the validity of the represented results it is obvious that serious discrepancies (of the order of 0.010 °K) exist not only between the results of different investigators but also in the consistency of temperature values reported by an individual investigator. If one believes that the scale, T_{58}, is smooth with respect to possible departures from the thermodynamic temperature scale, the plot suggests that perhaps the acoustical thermometer data are the most self-consistent of any temperature measurements that have been made below 5 °K.

In a previous paper [29] we have included the results of some gas thermometry determinations in the comparison of temperature values below 5 °K. Their inclusion does not appear to aid in assessing the departures of either individual temperature values or T_{58} from the thermodynamic scale. We concur with van Dijk's statement [35] that below 4.0 °K "the results obtained from measurements on isotherms are more accurate than those obtained from gas thermometry data". Most of the gas thermometry results are dependent upon the realization of an assumed 'gas filling' temperature, i. e., the normal boiling point of liquid helium-4. If the temperature or its realization are erroneous, there result additional indeterminancies which are reflected in the gas thermometer measurements. One must acknowledge, however, values of temperature associated with gas thermometry at and above 4.2 °K.

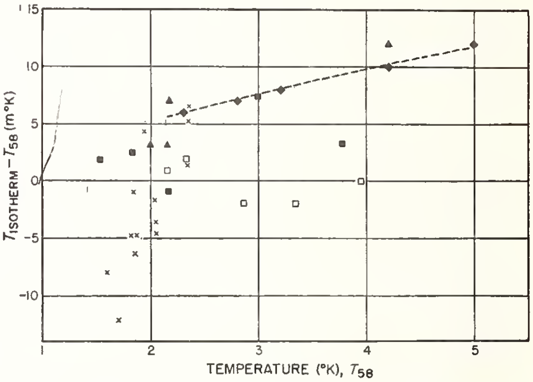


Fig. 8. A comparison, with values of the T_{58} scale, of temperature values derived from pressure-volume isotherm measurements and acoustical-thermometer measurements. × Kistemaker [3] isotherms (1946); □ Keller [4] helium-4 isotherms (1955); ■ Keller [4] helium-3 isotherm (1955); ▲ Preliminary results [39] velocity of sound in helium-4 gas, acoustical thermometer (1962); ♦ Present work, isotherms determined by the NBS acoustical thermometer. Except for our data points, Fig. 8 is taken from van Dijk [35]

In 1937 Schmidt and Keesom [5] recommended a value of 4.216 °K as the normal boiling point of liquid helium-4-based upon 20.381 °K as the boiling point of liquid hydrogen. Their actual measurements yielded three of temperature 4.215°, 4.215° and 4.222 °K but higher weightings were assigned to the 4.215 °K value so that 4.216 °K emerged as their recommended value of temperature. This becomes 4.215 °K, which is the normal boiling point of liquid helium-4 in T_{58}, if the boiling point of normal hydrogen is changed to 20.378 °K.

Berman and Swenson [7] confirmed the Schmidt and Keesom boiling point within 0.002 °K using a gas thermometer that was referenced to the normal

---

* Each of four laboratories (PRMI, NBS, NPL and Pennsylvania State University) submitted two platinum resistors that had been calibrated on the individual laboratory's temperature scale. The thermometers were measured at both NPL and PRMI thereby producing the above-mentioned comparison.

boiling point of what was assumed to be normal hydrogen. However their continued gas thermometer measurements, between 4.1° and 5.2 °K exhibit inconsistencies of about ± 0.005 °K with respect to T_{58}; this is evidenced in Fig. 1 of reference [35].

More recent gas thermometry at 4 °K, reported by D. L. Martin [11], resulted in values of temperature that exceeded temperatures derived from helium vapor pressure measurements and T_{58} by 0.003 °K. This result was based upon the use of Keesom [36] virial coefficients. Martin also reported that if he employed the Kilpatrick, Keller and Hammel [37] virial coefficients, instead of the Keesom virials "the average temperatures obtained at 4°K from the gas thermometer are increased by about 0.005 °K." (The gas thermometer was calibrated at 20 °K against a vapor pressure thermometer that contained normal liquid hydrogen).

An additional investigation of the helium boiling point has been reported by M. P. Orlova and D. N. Astrov*. In establishing a temperature scale from 4.2° to 20 °K they employed a helium gas thermometer, without dead space, as a primary instrument. Gas fillings were made at $T_{H_2} = 20.384$ °K, the "natural composition" liquid hydrogen boiling point. In correcting for the non-ideality of the helium gas, they selected values of the second virial coefficient from Kilpatrick, Keller and Hammel** and the third virial coefficients defined by Keesom [36]. The resulting mean value for the normal boiling point of liquid helium was 4.214 ± 0.005 °K. Also of interest is their remark that, if they used values of second virial coefficients as defined by Keesom [36] in calculating temperatures, the resultant values of thermodynamic temperature would be higher than those resulting from use of the Kilpatrick, Keller and Hammel** second virials.

Finnemore et al. [42] have reported helium gas thermometry which was referenced to a filling temperature at 4.2 °K. They report the following: "If we assume that helium-4 has a saturated vapor pressure of 760.00 torr at 4.215 °K, then we measure the temperature of equilibrium hydrogen at a saturated vapor pressure of 760.00 torr to be 20.253 ± 0.03 °K." — "As an additional check on thermometry we have measured the vapor pressure of helium-4 from 4.2 to 5.0 °K and confirm the work of Berman and Swenson [7] (and hence the T_{58} scale [1]) to ± 0.003 °K." Virial coefficients from Kilpatrick, Keller and Hammel [37] were used to correct for the nonideality of helium-4 gas. In a private communication they informed us that the converse of the first quotation is probably applicable; namely, if the gas thermometer were referenced to 20.253 °K, an uncertainty of ± 0.006 °K might be encountered in the determination of the liquid helium normal boiling point.

Phillips* has furnished us with information concerning the results of his low temperature gas thermometry investigation. The thermometer was referenced to a filling temperature (approximately 20.4 °K) that was measured on the platinum thermometer scale, NBS (1955). In addition to other measurements, he has determined three values of temperature near 4 °K which, on comparison through helium-4 vapor pressure measurements, appear to reproduce values of temperature on T_{58} within 0.001 °K The accuracy is estimated to be that caused by uncertainties of the virial coefficients plus 0.002 °K.

Additionally, the following results of gas thermometry have been conveyed to us in a private communication** from D. W. Osborne, H. E. Flotow and F. Schreiner of the Argonne National Laboratory.

"In the calibration of our germanium resistance thermometers against a gas thermometer and against the vapor pressure of liquid ^{4}He we obtained the following values for the normal boiling point of liquid ^{4}He.

Normal Boiling Point of ^{4}He

Series	T_{MR5} (°K)	T_K (°K)
May 1963	4.215_3	4.207_5
Oct. 1963	4.214_7	4.206_5
Average	4.215_0	4.206_9

T_{MR5} is the temperature calculated with the aid of the second virial coefficients calculated by Kilpatrick, Keller and Hammel [37], from their potential energy curve MR5. T_k is the temperature calculated with the aid of the second virial coefficients given in Table 2.14 of Keesom's book [21]. The number of moles of ^{4}He in the gas thermometer was determined near the boiling point of normal H_2, which was taken to be 20.384 °K. The gas thermometer pressure at this temperature was approximately 632 mm Hg in the May 1963 series and 646 mm Hg in the other series. The pressures were read to 0.01 mm Hg, which corresponds to 0.0003 °K, but we estimate that the precision of each temperature (probable error) is about 0.002 °K."

"Since our T_{MR5} value for the boiling point of ^{4}He agrees with the value on the T_{58} scale we adopted the MR5 second virial coefficients for all our gas thermometer calculations, which extended from 4 to 25 °K. This gives us a temperature scale that merges smoothly into the T_{58} scale."

The preceding gas thermometry discussion appears to indicate that the normal boiling point of liquid helium-4, as determined by gas thermometry, may be indeterminate by as much as 5 or 6 millidegrees. It is quite evident that at least some of the thermometry is dependent upon the selection of virial coefficients for helium-4 gas. Also, a principal cause for the indeterminancy may well be attributed to the inability to realize a normal boiling point for liquid hydrogen as a thermometer reference temperature.

---

* This paper is Document No. 9, "Thermodynamic Temperature Scale for the 4.2 – 20 °K Temperature Range," which was presented to the Comité Consultatif de Thermométrie, 7e Session (1964). It is available on request to M. P. Orlova of the Physicotechnical and Radiotechnical Measurements Institute, USSR.

** The reference of the above-mentioned PRMI document appears to indicate that the second virial coefficients are those listed by Kilpatrick, Keller, Hammel, and Metropolis; Phys. Rev. **94**, 1103 (1954). These virials are not identical with those of reference [37].

* Professor Norman Phillips (University of California, Berkeley) has kindly supplied this information in a private communication. It is expected that a more complete account of the investigation will be published by Professor Phillips in the near future.

** Dr. D. W. Osborne has kindly provided this information and it is expected that a more complete account of the investigation will be published in the near future.

Discussion of the Temperatures Associated with NBS P 2—20 (1965)

We have shown that our values of temperature appear to agree, within 0.012 °K, with two widely recognized scales (T_{58} and NBS [1955]) in temperature regions where the scales overlap. Since the experimental operation of the acoustical thermometer does not seem to change in the range 2° to 20 °K, there is no reason to suppose that values of temperature between 5 °K and 10 °K are inferior to those measured in the exterior temperature ranges.

We feel that our values of temperature are within the stated experimental accuracy of both NBS (1955) from 12° to 20 °K and the NPL [10, 38] scale from 10.8° to 20 °K. Since the acoustical thermometer represents a completely different approach to thermometry in this temperature range, we expect that the coincidence of the three scales between 12° and 20 °K indicates the achievement of a reasonable approximation to the Thermodynamic Temperature Scale. If the three scales do indicate such an accomplishment it is difficult to understand the departures of our values of sonic temperatures from T_{58}. While our isotherms in the helium range are remarkably consistent, in indicating temperature values that smoothly deviate from T_{58}, we feel that it is necessary to determine additional isotherms, which are defined by as many points as is practicable. Sufficient curvature is exhibited by isotherms below 7 °K to persuade us that our present data should be extended to higher pressures and subsequently analyzed with the inclusion of higher order pressure terms [Eq. (7)].

It is possible that T_{58} may deviate noticeably from the thermodynamic temperature scale, but we feel that assessment of this should be deferred until additional absolute temperature data is available. Since gas thermometry at low temperatures is sensitive to the selection of virial coefficients, it is necessary that the virials be determined to the best possible accuracy. We are hopeful that, when we have completed our measurements, we will be able to make a significant contribution in defining the helium-4 virials below 20 °K.

Conclusion

As has been indicated previously in this paper, we expect to continue the determination of isotherms below 20 °K. The measurements will result in a greater number of points for defining an isotherm, extend the isotherms to higher pressure, and include the use of helium-3 gas so that isotherms below 2.3 °K can be more easily defined. We shall probably also determine isotherms that are interspersed between those defined in this paper. Special efforts will be exerted toward the determination of virial coefficients for both helium-3 and helium-4 gases.

Calibrations of germanium secondary thermometers have been performed for nearly a year and a half against the scale NBS P 2 – 20 (1965). The results, which aid in identifying the characteristics of germanium resistors, are in the process of being reported. The availability of reproducible calibrated germanium thermometers is already affording comparisons between the low temperature thermometry endeavors of different investigators that will undoubtedly lead to an international low temperature scale.

Acknowledgements. Since the development of the acoustical thermometer has spanned a period of 10 years, the authors are indebted to many who have periodically provided stimulation and encouragement.

Dr. F. G. Brickwedde's concern was instrumental in initiating the investigation and we gratefully acknowledge the stimulating contacts with and interest of Dr. R. P. Hudson, Dr. E. Ambler, Dr. C. M. Herzfeld, Mr. M. Greenspan, Dr. H. F. Stimson, Dean R. B. Lindsay and Prof. C. F. Squire.

The talents and suggestions of Mr. R. Chidester and Mr. J. Hettenhouser, who constructed essential components of the acoustical thermometer, merit special recognition; Mr. M. Edlow and Mr. W. Osten aided in conducting the measurements.

And finally we wish to express our thanks for the support of the administrative direction of the National Bureau of Standards.

Appendix

Possible Inherent Errors of the Acoustical Interferometer

Our instrument employs an x-cut quartz crystal, operating at its resonance frequency (1 Mhz), and it is assumed that the crystal acts as a plane wave radiator. Actually, the crystal surface can be expected to contain several radiating areas that differ in amplitude and phase of vibration since the thickness vibration of the quartz is coupled to various transverse modes. If the modes match the radially resonant condition of the helium gas (within the interferometer chamber), they will be propagated as Rayleigh modes, with phase velocities and attenuations that differ from those of the assumed plane wave. The detection of such nonuniform radiation is discussed by J. L. and E. S. Stewart [24] with appropriate reference to other specific investigations. Krasnooshkin [39], in discussing the "corrugated" waves in a cylindrical wave guide, has analyzed a wave's various natural modes of vibration in a cylinder of several wave lengths diameter. He predicts that because of the same non-plane wave form, relative errors in the experimentally measured wave lengths for different media should be proportional to the square of wave length. Earlier experimental measurements by Bell [40] and the Stewarts have appeared to confirm the prediction; and more recent results [41] are in general agreement.

To determine this type of systematic error for an acoustical interferometer, it is suggested that a calibration of a given crystal and interferometer chamber be performed. This would be accomplished by experimentally determining the wave length of sound λ_x for several gaseous media and comparing observed wavelengths with known or accepted values of wavelength λ_k. For the different gases one would plot

$$\frac{\lambda_x - \lambda_k}{\lambda_k}$$

as a function of λ_k^2 and thus obtain a correction $\lambda_x - \lambda_k$ that would be applicable for some λ_x.

The Stewarts [24] for an interferometer operated at 2 MHz observed an apparent increase in wave length $\frac{\Delta\lambda}{\lambda}$ equal to .005 for helium gas at room temperature [$\lambda^2 = 0.25\ (\mathrm{mm})^2$]; Blythe et al. [41] operating at 83 and 152 kHz observed an increase in $\frac{\Delta\lambda}{\lambda}$ of .03 and .01 respectively (helium gas at 30 °C, λ^2 equal to approximately 50 and 150 mm²).

For our operating temperatures, i. e., below 20 °K, the number of gases that can be used for such a calibration are limited. Helium-3 and helium-4 can be used throughout the entire temperature range but investigations with hydrogen gas would be limited to the higher temperatures only since its highest operating pressure is limited by the liquidvapor condensation curve. Thus far we have employed helium-4 gas only in our acoustical interferometer, since the introduction of helium-3 gas will undoubtedly result in a gas contamination of the apparatus. When the measurement program for helium-4 gas is completed, helium-3 and hydrogen gases will be employed as fluids to ascertain the possible importance of "an acoustical interferometer correction" for our instrument.

It is quite possible that the "correction", which might apply to our instrument, is less than other experimental errors or reproducibilities (i. e., errors in temperature control, resistance determination or linear displacement measurements). Indeed, if the coincidence of our values of temperature with values of the NPL and NBS (1955) Temperature Scales between 14 and 20 °K is interpreted to indicate a good approximation of the Thermodynamic Temperature Scale, this in itself signifies the comparative inapplicability of an "interferometer correction" for our instrument.

If one assumes that the scales NPL and NBS (1955) are good approximations to the Thermodynamic Temperature Scale in the region 12° to 20 °K, then one can calculate — by using these assumed temperatures — the speed of sound in an ideal gas. Since our experimental measurements yield a value that is, for all practical purposes, identical, one can assume that the interferometer is "calibrated" by measurements in this temperature range and that the effect of transverse resonances in our ultrasonic interferometer is negligible — within a temperature equivalence of a few millidegrees.

To investigate further the possibility of an operational error in our acoustical interferometer, we have conducted isotherm measurements with the quartz crystal driven at a higher harmonic (3 MHz). At this frequency we have measured points on the 5.0°, 6.1° and 7.0 °K isotherms. These points lie within the reproducibilities of the isotherms that were determined from the general measurements in which the quartz crystal was operated at 1 MHz – no systematic departures between the data derived from the 3 and 1 MHz investigations were observed. When we attempted to duplicate two isotherms at higher temperatures (9 °K and 16 °K) we encountered difficulties (at 3 MHz) which were apparently caused by spurious resonance frequencies of the quartz crystal coupling into the main resonance frequency at which the quartz crystal was being driven.

It has also been observed [40, 41], when waves of different phase velocities are being propagated in an acoustical interferometer, that the measured positions of maximum acoustical impedance are not separated by a constant amount; interference effects result in irregular values for the incremental displacement measurements as the reflecting surface systematically approaches the radiating quartz crystal. While we have observed this effect in the past, with quartz crystals that we have rejected, the present instrument has not exhibited such irregularities. This also probably indicates that, in our existing apparatus, the effects of the Krachnooshkin "corrugated" waves are sufficiently small that they cannot be resolved and do not significantly affect our measurements.

References: [1] Brickwedde, F. G., H. van Dijk, M. Durieux, J. R. Clement , and J. K. Logan: Research Natl Bur. Standards **64A**, (Phys. and Chem.) No. 1, 1 (1960). — [2] Geballe, T. H., F. J. Morin, and J. P. Maita: Conférence de physique de basses températures, Paris (September (1955), Paper 98; Kunzler, J. E., T. H. Geballe, and G. W. Hull: Rev. Sci. Instr. 28, 96 (1957), presented at the Eleventh Calorimetry Conference, Baltimore, Maryland (September 14, 1956). — [3] Kistemaker, J., and W. H. Keesom: Leiden Commun. No. 269b; Physica's-Grav. **12**, 227 (1964). [4] Keller, W. E.: Phys. Rev. **97**, 1 (1955); 98, 1571 (1955); **100**, 1790 (1955). — [5] Schmidt, G., and W. H. Keesom: Leiden Commun. No. 250b; Physica's Grav. **4**, 963 (1937). — [6] Kistemaker, J.: Leiden Commun. No. 269c; Physica's Grav. **12**, 272 (1946). — [7] Berman, R., and C. A. Swenson: Phys. Rev. **95**, 311 (1954). — [8] Moessen, G. W., J. G. Aston, and R. G. Ascah: In Temperature, its Measurement and control in science and industry. Herzfeld, C. M.: Ed., **3**; Brickwedde, F. G.: Ed., Pt. 1, p. 90; Barber, C. R.: p. 103; Borovik-Romanov, A. C., P. G. Strelkov, M. P. Orlova, and D. N. Astrov: p. 113. New York: Reinhold Publishing Corp. 1962. — [9] Hoge, H. J., and F. G. Brickwedde: J. Research Natl. Bur. Standards **22**, 351 (1939). — [10] Barber, C. R.: Brit. J. Appl. Phys. **13**, 235 (1962). — [11] Martin, D. L.: Phys. Rev. **141**, 576 (1966). — [12] Rayleigh, J. W.: Theory of sound, Vol. 2, p. 30. New York: Dover. New ed. 1945. — [13] Mayer, A. M.: Phil. Mag. **45**, 18 (1873). — [14] Hedrich, A. L., and D. R. Pardue: Temperature, its measurement and control in science and industry. Wolfe, H. C. ed. Vol. 2, p. 383. New York: Reinhold 1955. — [15] van Itterbeek, A.: Progress Low Temp. Phys. I, 355, North Holl. Publ. Co. 1955. — [16] van Itterbeek, A. and W. H. Keesom: Leiden Commun. 209c (1931); Keesom, W. H., and A. van Itterbeek: Leiden Commun. 213b (1931); Konikl. Akad. Wetenschap. Amsterdam **34**, 204 (1931). — [17] De Laet, J.: Verhandel. Koninkl. Acad. Belg. Kl. Wetenschap. **66**, 3 (1960). — [18] Brodsky, A. D., V. P. Kremlevsky, and A. V. Savattev: In Compt. Rend. Comité Intern. Poids Mesures, Comité Consultat. Thermométrie, 6ᵉ Session (1962), annexe 27. — [19] de Boer, J.: Metrologia **1**, 158 (1955). — [20] Bergman, L.: Der Ultraschall, S. 501. Stuttgart: Hirzel 1954. — [21] Keesom, W. H.: Helium, p. 30, Amsterdam: 1942. — [22] Pierce, G. W.: Proc. Am. Acad. Arts. Sci. **60**, 271 (1925). — [23] Hubbard, J. C., and A. L. Loomis: Phil. Mag. **5**, 1177 (1928); Hubbard, J. C.: Phys. Rev. **41**, 523 (1923), **38**, 1011 (1931). — [24] Stewart, J. L.: Rev. Sci. Instr. **17**, 59 (1946); Stewart, J. L., and E. S. Stewart: J. Acoust. Soc. Am. **24**, 22 (1952). — [25] Del Grosso, V. A., E. J. Smura, and P. F. Fougere: Naval Res. Lab. Rep. **1954**, 4439. — [26] Greenspan, M.: Physical Acoustics, ed. 2A, p. 1. New York: Academic Press Inc. 1965. — [27] Taconis, K. W., J. J. Beenakker, A. O. C. Nier, and L. T. Aldrich: Physica **15**, 733 (1949); Kramers, H. A.: Physica **15**, 971 (1949). — [28] Gibbons, D. F.: J. Phys. Chem. Solids **11**, 246 (1959). — [29] Cataland, G., and H. Plumb: J. Research Natl. Bur. Standards **69A**, 531 (1965). — [30] Cataland, G., and H. H. Plumb: J. Research Natl. Bur. Standards **70A**, 243 (1966). — [31] Edlow, M. H., and H. H. Plumb: J. Research Natl. Bur. Standards **70C**, No 4(1966). — [32] Orlova, M. P., D. I. Sharevskaya, D. N. Astrov, I. G. Krutikova, C. R. Barber, and J. G. Hayes: Metrologia **2**, 6 (1966). — [33] Cataland, G., M. H. Edlow, and H. H. Plumb: Temperature, its measurement and control in science and industry. Herzfeld, C. M.: Ed., **3**; Brickwedde, F. G.: Ed., Pt. **1**, p. 413. New York: Rheinhold Publishing Corp. 1962; Edlow, M. H., and H. H. Plumb: J. Research Natl. Bur. Standards (1966). — [34] Durieux, M.: Thesis, University of Leiden, 1960. — [35] van Dijk, H.: Progress in Cryogenics, p. 130. London: Heywood 1960. — [36] Keesom, W. H.: Helium, p. 49 Amsterdam-London-New York-Princeton: Elsevier 1942. — [37] Kilpatrick, J. E., W. E. Keller, and E. F. Hammel: Phys. Rev. **97**, 9 (1955). — [38] Barber, C. R.: Acta Imeko 2, 415 (1964). — [39] Krasnooshkin, P. E.: Phys. Rev. **65**, 190 (1944). — [40] Bell, J. F. W.: Proc. Phys. Soc. (London) B **63**, 958 (1950). — [41] Blythe, A. R., T. L. Cottrell, and M. A. Day: Acustica **16**, 118 (1965/66). — [42] Finnemore, D. K., D. L. Johnson, J. E. Ostenson, F. H. Spedding, and B. J. Beaudry: Phys. Rev. **137**, A550 (1965). — [43] Ambler, E., and H. Plumb: Rev. Sci. Instr. **31**, 656 (1960).

UNITED STATES DEPARTMENT OF COMMERCE • Frederick H. Mueller, *Secretary*
NATIONAL BUREAU OF STANDARDS • A. V. Astin, *Director*

The "1958 He^4 Scale of Temperatures"

Part 1. Introduction

F. G. Brickwedde

Part 2. Tables for the 1958 Temperature Scale

H. van Dijk, M. Durieux, J. R. Clement, and J. K. Logan

Reprinted from the Journal of Research of the National
Bureau of Standards—A. Physics and Chemistry, Vol. 64A,
No. 1, January–February 1960.

National Bureau of Standards Monograph 10

Issued June 17, 1960

70-I

Contents

The "1958 He^4 Scale of Temperatures"

Part 1. Introduction

F. G. Brickwedde [1]

Part 2. Tables for the 1958 Temperature Scale

H. van Dijk,[2] M. Durieux,[2] J. R. Clement,[3] and J. K. Logan [3]

(Revision: May 1, 1959)

The generally used practical scale of temperatures between 1° and 5.2° K is the He^4 vapor pressure scale based on an accepted vapor pressure equation or table. In Sèvres (near Paris), October 1958, the International Committee on Weights and Measures recommended for international use the "1958 He^4 Scale" based on a vapor pressure table arrived at through international cooperation and agreement. This table resulted from a consideration of all reliable He^4 vapor pressure data obtained using gas thermometers, and paramagnetic susceptibility and carbon resistor thermometers. The theoretical vapor pressure equation from statistical thermodynamics was used with thermodynamic data on liquid He^4 and the vapor equation of state to insure satisfactory agreement of the vapor pressure table with reliable thermodynamic data.

Part 1. Introduction

The International Committee on Weights and Measures at a meeting in Sèvres (near Paris), France, September 29 to October 3, 1958, approved the "1958 He^4 Vapor Pressure Scale of Temperatures" as an international standard for thermometry from 1° to 5.2° K. This was the culmination of several years of intensive research and cooperation on the helium vapor pressure scale at the Kamerlingh Onnes Laboratory in Leiden, Holland, and the U.S. Naval Research Laboratory in Washington.

The vapor pressure of liquid He^4 has for a long time been used as a standard for thermometry between 1° and 5.2° K. The first measurements of thermodynamic temperatures in the liquid He^4 range were made with constant volume gas thermometers filled with He^4. Simultaneous measurements of the vapor pressure of liquid helium in temperature equilibrium with the gas thermometer established a vapor pressure-temperature relation which then was used as the basis for determining thermodynamic temperatures from vapor pressure measurements. With these vapor pressure-gas thermometer measurements there were measurements of He^4 vapor pressures made simultaneously with measurements of the He^4 isotherms from which temperatures were obtained by extrapolating the isotherms to zero density ($N/V \rightarrow 0$) in accordance with the virial equation of state:

$$p\,V/N = RT\,[1 + B\,(N/V) + C\,(N/V)^2 + \ldots] \quad (1)$$

After the latent and specific heats of liquid He^4 had been measured, the experimental vapor pressure-temperature relation was improved through the use of the theoretical vapor pressure (P) equation:

$$\ln P = i_0 - \frac{L_0}{RT} + \frac{5}{2} \ln T - \frac{1}{RT} \int_0^T S_l\,dT + \frac{1}{RT} \int_0^P V_l dP + \epsilon \quad (2)$$

where

$$i_0 \equiv \ln\,(2\pi m)^{3/2} k^{5/2}/h^3 \quad (3)$$

and

$$\epsilon \equiv \ln\,(PV/NRT) - 2B\,(N/V) - (3/2)\,C\,(N/V)^2. \quad (4)$$

L_0 is the heat of vaporization of liquid He^4 at 0° K, S_l and V_l are the molar entropy and volume of liquid He^4, m is the mass of a He^4 atom, B and C are the virial coefficients in eq (1), and the other symbols have their usual meaning. Both theoretically calculated and directly measured vapor pressures were considered in arriving at the 1958 He^4 Temperature Scale.

Equation (2) presupposes that the thermodynamic properties entering the equation have been measured on the thermodynamic scale, otherwise the use of this equation for the calculation of P is not valid. In practice, however, these properties are measured on an empirical scale that only approximates the thermodynamic scale. In general this empirical scale has been a He^4 vapor pressure scale based on gas thermometer measurements.

---

[1] Consultant to NBS. Permanent address College of Chemistry and Physics, Pennsylvania State University, University Park, Pa.

[2] Kamerlingh Onnes Laboratory, Leiden, Netherlands.

[3] U.S. Naval Research Laboratory, Washington, D.C.

As T is lowered, the fourth, fifth, and sixth terms in eq (2) become smaller and less important relative to the first three terms. At 1.5° K, the inclusion or exclusion of the sum of the fourth, fifth, and sixth terms in eq (2) affects the temperature calculated from a given value of P by only 0.0005 deg. It may be said then, that below 1.5° K, the vapor pressure of He^4 is in effect really determined, within the present accuracy of the vapor pressure measurement, by a single empirical constant, the heat of vaporization of liquid He^4 at 0° K. At present, L_0 for He^4 is normally calculated from vapor pressure data obtained with a gas thermometer. The magnitude of the last three terms in eq (2) increases rather rapidly with rising T, and above the λ-point (2.172° K) the accuracy of the evaluation of these terms is a very important consideration.

In Amsterdam in 1948, on the occasion of a General Assembly of the International Union of Physics, a small group of low temperature physicists, meeting informally, agreed to use and recommend for temperature measurements between 1° and 5.2° K, a table of vapor pressures of He^4, then in use in Leiden, which came to be known as the "1948 Scale" [1].[4] This scale has sometimes been referred to as the "1949 Scale". From 1° to 1.6° K, the "1948 Scale" was based on vapor pressures calculated by Bleaney and Simon [2] using eq (2). From 1.6° to 5.2° K, the scale was based on measured vapor pressures and temperatures determined with gas thermometers. From 1.6° to 4.2° K, it was based primarily on the vapor pressure measurements of Schmidt and Keesom [3].

Even in 1948, when the "1948 Scale" was agreed to, there was evidence in the measurements and calculations of Kistemaker [4] that the "1948 Scale" deviated significantly from the thermodynamic scale. However, it was thought at the time that, on general principles, indicated changes in an existing scale should be made only after these changes had been confirmed. With improvements in the precision and accuracy of physical measurements at low temperatures, irregularities appeared in the temperature variation of physical properties between 1° and 5° K that were in the main reproducible in different substances and properties and were, therefore, attributable to errors in the "1948 Scale" [5]. Stimulated by these results which corroborated Kistemaker's work, the investigations of the He^4 vapor pressure scale were undertaken that culminated in the "1958 He^4 Scale."

Paramagnetic susceptibility and carbon resistor thermometers were later employed in investigations of the He^4 vapor pressure-temperature relation [6]. These thermometers were used for the interpolation of temperatures between calibration points (temperatures) using an assumed relation connecting temperature and paramagnetic susceptibility or carbon resistance for the calculation of the temperatures. For suitably chosen paramagnetic salts, the Curie-Weiss Law was assumed to hold:

$$\chi=\frac{C}{T+\Delta} \qquad (5)$$

where χ is the magnetic susceptibility and C and Δ are empirical constants. Measurements at two temperatures would suffice to determine these two empirical constants if the measurement were really of χ or a quantity directly proportional to χ. However, a calibration of the paramagnetic thermometer at a third calibration temperature is necessary because the arbitrariness in the size and arrangement of the paramagnetic salt samples and the induction coils that surround the salt sample for the susceptibility measurement make the measurement a linear function of χ. Interpolation equations for carbon resistor thermometers are not as simple as eq (5) and do not have a theoretical basis. Hence, vapor pressure data obtained with carbon resistor thermometers are of more limited usefulness for the determination of the He^4 vapor pressure-temperature relation. Clement used carbon thermometer data to examine the derivative $d\ (\ln P)/\ d\ (1/T)$, [7].

Important use has been made of He^4 vapor pressure measurements made with magnetic susceptibility and carbon resistor thermometers in arriving at the "1958 He^4 Scale." These vapor pressure measurements were considered along with those made with gas thermometers and vapor pressures calculated using eq (2). Temperature measurements with magnetic and carbon resistor thermometers are much simpler to make than measurements with gas thermometers, and hence vapor pressure data obtained with magnetic and carbon resistor thermometers are more numerous. Also, the measurements made with these secondary thermometers are more precise (to be distinguished from accurate) which makes them especially useful for interpolation between the gas thermometer data.

There are, accordingly, three practical methods for determining the He^4 vapor pressure-temperature relation: (1) By use of the direct vapor pressure measurements made with gas thermometers, (2) through the use of eq (2) with some vapor pressure-gas thermometer data, and (3) through the use of vapor pressure measurements with secondary thermometers which have been calibrated using some gas thermometer data. If all the pertinent experimental data were accurate and all temperatures were on the thermodynamic scale, these three methods would yield results in good agreement with each other, and any one might be relied upon for the construction of the He^4 vapor pressure-temperature table defining the scale. Because of experimental errors, however, the vapor pressures obtained by the different methods differ when carried to the limit of the sensitivity of the measurements. For He^4 between 1° and 4.5° K, different choices of the methods and different selections of the experimental data used, weighting factors and corrections to the published data yield scales all within about 4 millidegrees of each other. The

---

[4] Figures in brackets indicate the literature references on page 4.

primary evidence for this is that 4 millidegrees is the maximum difference between the L55 Scale [8] obtained by method (2) and the 55E Scale [9] obtained by method (3). This then is a measure of the range (total spread) of uncertainty at present in the He^4 vapor pressure scale of temperatures between 1° and 4.5° K.

All published He^4 vapor pressure measurements, and thermodynamic data needed for eq (2) were independently studied and correlated by H. van Dijk and M. Durieux at the Kamerlingh Onnes Laboratory in Leiden [8] and by J. R. Clement and J. K. Logan at the U.S. Naval Research Laboratory in Washington [9]. As far as possible, the experimental data of the original investigators were recalculated on the basis of later knowledge of the temperature scale, fundamental constants, and the properties of He^4. In some cases, limitations were imposed on these recalculations by the incomplete reporting of the experimental data by the original investigator.

After working independently, Van Dijk and Clement cooperated to compromise their differences. They met first in Leiden, August 1955 and later in Washington, summer of 1957. From January 22 to March 14, 1958, Logan worked at Leiden, and later represented Clement at a conference in Leiden, June 1958, at which agreement was reached on the "1958 He^4 Scale." This cooperation was an important factor in the improvement of the scale.

Where the differences between the values obtained by handling the experimental data differently are largest (4 millidegrees), the "1958 Scale" falls between the extremes. At other places it is close to the mean of these values and at no place does it deviate by more than 2 millidegrees from the mean. The estimated uncertainty of the "1958 He^4 Scale" is accordingly ±2 millidegrees between 1° and 4.5° K. At higher temperatures, the estimated uncertainty is larger.

Now that the International Committee on Weights and Measures has recommended the "1958 He^4 Scale" as an international standard it is presumed that henceforth the International Committee on Weights and Measures will take the initiative in improving the scale when changes are needed. Before the International Committee on Weights and Measures assumed responsibility for the He^4 vapor pressure scale, the Commission on Very Low Temperature Physics in the International Union of Pure and Applied Physics concerned itself with the scale. This began with the informal meeting in Amsterdam in 1948 that resulted in the "1948 Scale." At the Low Temperature Conferences sponsored by the Commission on Very Low Temperature Physics of the International Union of Physics at Paris in 1955, and at Madison, Wisconsin, in 1957, sessions were held at which the He^4 vapor pressure scale of temperatures was discussed.

The National Bureau of Standards sponsored meetings, for discussion of the helium vapor pressure scale of temperatures, held at the NBS during the spring meetings of the American Physical Society in Washington, 1955 and 1957. Also, the NBS encouraged cooperation in reaching national and international agreement on the scale. It initiated or promoted the meetings for discussion of the differences between the L55 and 55E Scales proposed respectively by Van Dijk and Durieux, and by Clement. These were the meetings held August 26 and 27, 1955 in Leiden (before the Low Temperature Conference in Paris) [10], July 30, 31, and August 1, 1957 in Washington (before the Low Temperature Conference in Madison) [11], and June 13, 14, and 16, 1958 in Leiden (before the meeting of the Advisory Committee on Thermometry of the International Committee on Weights and Measures in Sèvres) [12]. Also, the National Bureau of Standards promoted the arrangement which sent Dr. Logan of the U.S. Naval Research Laboratory to work in the Kamerlingh Onnes Laboratory from January 22, to March 14, 1958.

The Scale agreed upon at Leiden, June 13 to 16, 1958 was presented to the Advisory Committee on Thermometry of the International Committee on Weights and Measures at its meeting in Sèvres, June 20 and 21, 1958. The recommendation of the Advisory Committee to the International Committee was as follows [12]:

> "Le Comité Consultatif de Thermométrie,
>
> "ayant reconnu la nécessité d'établir dans le domaine des très basses températures une échelle de température unique,
>
> "ayant constaté l'accord général des spécialistes dans ce domaine de la physique,
>
> "recommande pour l'usage général l'"Echelle ^4He 1958," basée sur la tension de vapeur de l'hélium, comme définie par la table annexée.
>
> "Les valeur des températures dans cette échelle sont désignées par le symbole T_{58}."

The table of He^4 vapor pressures that was sent to the International Committee with this recommendation was the table distributed at the Kamerlingh Onnes Conference on Low Temperature Physics at Leiden, June 23 to 28, 1958. It was published in the Proceedings of the Kamerlingh Onnes Conference [13].

On the recommendation of its Advisory Committee on Thermometry, the International Committee on Weights and Measures approved the "1958 He^4 Scale of Temperatures" at its meeting at Sèvres, September 29 to October 3, 1958.

The table adopted by the International Committee on Weights and Measures was a table of vapor pressures at hundredth degree intervals. This table was expanded by Clement and Logan making table I of this paper with millidegree entries. Table I was inverted to give tables II and III which express T as a function of vapor pressures. Auxiliary tables were added including a table of the differences between the 1958 Scale and other earlier used scales. Linear interpolation is valid for all tables except at the lower temperature end of table IV.

The assistance at Leiden of H. ter Harmsel and C. van Rijn, students of Dr. H. van Dijk at the Kamerlingh Onnes Laboratory, with the computations for the defining and auxiliary tables is gratefully acknowledged.

Various members of the Cryogenics Branch of the Naval Research Laboratory at Washington assisted with numerous calculations which contributed toward the development of the present scale. This assistance, especially that of Dr. R. T. Swim, is gratefully acknowledged.

References

[1] H. van Dijk and D. Shoenberg, Nature **164,** 151 (1949); Procès-Verbaux du Comité Consultatif de Thermométrie auprès du Comité International des Poids et Mesures, session de 1952, p. T151 (Gauthier-Villars, Paris, France).

[2] B. Bleaney and F. Simon, Trans. Faraday Soc. **35,** 1205 (1939).

[3] G. Schmidt and W. H. Keesom, Leiden Comm. 250b and c, Physica **4,** 963 and 971 (1937).

[4] J. Kistemaker and W. H. Keesom, Leiden Comm. 269b and c, Physica **12,** 227 and 272 (1946); J. Kistemaker, Leiden Comm. Suppl. 95a, Physica **12,** 281 (1946).

[5] See: H. van Dijk, Proc. Intern. Conf. Physics Very Low Temp., Mass. Inst. Technol., p. 118 (1949); R. D. Worley, M. W. Zemansky, and H. A. Boorse, Phys. Rev. **93,** 45 (1954); R. A. Erickson and L. D. Roberts, Phys. Rev. **93,** 957 (1954); J. R. Clement, Phys. Rev. **93,** 1420 (1954); R. Berman and C. A. Swenson, Phys. Rev. **95,** 311 (1954); W. E. Keller, Phys. Rev. **97,** 1 (1955), **98,** 1571 (1955), and **100,** 1790 (1955); H. van Dijk, Temperature, its measurement and control **2,** p. 199 (Reinhold Publishing Corp., New York, N. Y., 1955) and Leiden Comm. Suppl. 112c; W. S. Corak, M. P. Garfunkel, C. B. Satterthwaite, and A. Wexler, Phys. Rev. **98,** 1699 (1955); J. R. Clement, J. K. Logan, and J. Gaffney, Phys. Rev. **100,** 743 (1955); E. Ambler and R. P. Hudson, J. Research NBS **56,** 99 (1956) RP2654, and **57,** 23 (1956) RP2689.

[6] H. van Dijk, Proc. Intern. Conf. Physics Very Low Temp., Mass. Inst. Technol., p. 118 (1949); R. A. Erickson and L. D. Roberts, Phys. Rev. **93,** 957 (1954); H. van Dijk, Temperature, its measurement and control **2,** p. 199 (Reinhold Publishing Corp., New York, N.Y., 1955) and Leiden Comm. Suppl. 112c; E. Ambler and R. P. Hudson, J. Research NBS **56,** 99 (1956) RP2654 and **57,** 23 (1956) RP2689; H. van Dijk and M. Durieux, Progress in low temperature physics, vol. II, chap. XIV (North-Holland Publishing Co., Amsterdam, Netherlands, 1957).

[7] J. R. Clement, Low temperature physics and chemistry, Proc. Fifth Intern. Conf., p. 187 (Univ. Wis. Press, Madison, Wis., 1958).

[8] H. van Dijk and M. Durieux, Proc. Conf. Physics Low Temp., Paris, 1955, p. 595 (Annexe 1955–3, Suppl. au bulletin de l'Institut Intern. du Froid, Paris); Progress in low temperature physics, vol. II, chap. XIV (North-Holland Publishing Co., Amsterdam, Netherlands, 1957); and Leiden Comm. Suppl. 113c, Physica **24,** 1 (1958).

[9] J. R. Clement, J. K. Logan, and J. Gaffney, Proc. Conf. Physics Low Temp., Paris, 1955, p. 601 (Annexe 1955–3, Suppl. au bulletin de l'Institut Intern. du Froid, Paris); Phys. Rev. **100,** 743 (1955); U.S. Naval Research Rept. 4542 (Wash., May 1955); Liquid helium vapor pressure-temperature scale, rept. compiled by J. R. Clement, distributed at the Baton Rouge, La. Conf. Low Temp. Physics and Chem. (Dec. 1955); J. R. Clement, Low temperature physics and chemistry, Proc. Fifth Intern. Conf., p. 187 (Univ. Wis. Press, Madison, Wis., 1958).

[10] F. G. Brickwedde, Report on the conference agreement on the helium vapor pressure scale of temperatures, Proc. Conf. Physics Low Temp., Paris, 1955, p. 608 (Annexe 1955–3, Suppl. au bulletin de L'Institut Intern. du Froid, Paris).

[11] See F. G. Brickwedde, Physics Today **11,** 23 (1958).

[12] F. G. Brickwedde, Physica **24,** Suppl. p. S 128 (1958).

[13] H. van Dijk, M. Durieux, J. R. Clement, and J. K. Logan, Physica **24,** Suppl., S 129 (1958); H. van Dijk and M. Durieux, Leiden Comm. Suppl. 115a, Physica **24,** 920 (1958); Procès-Verbaux des Séances du Comité International des Poids et Mesures—2^{e} Serie, tome 26–A, Annexe T22 in the Procès-Verbaux des Séances, 5^{e} Session (1958) du Comité Consultatif de Thermométrie.

Part 2. Tables for the 1958 Temperature Scale

H. van Dijk, M. Durieux, J. R. Clement, and J. K. Logan

1. Introduction

The tables which follow are these:

TABLE I. *Vapor pressure of* He^4 *(1958 Scale) in microns (*10^{-3} *mm) mercury at 0° C and standard gravity (980.665 cm/sec*^{2}*).* This table is an expanded version, with pressure values at millidegree intervals, of the table which defines the vapor pressure on the 1958 scale at 10-millidegree intervals.

TABLE II. *1958* He^4 *vapor pressure-temperature scale,* T *in °K as a function of* P *in millimeters mercury at 0° C and standard gravity.* This table is an inversion of table I for appropriate ranges of pressures and pressure intervals. Since this table contains differences between successive entries, it furnishes a convenient means for converting a measured vapor pressure to a temperature within 0.1 millidegree.

TABLE III. *1958* He^4 *vapor pressure-temperature scale,* T *in °K as a function of* P *in centimeters mercury at 0° C and standard gravity.* This table is an extension of table II for pressures greater than 80 cm mercury. It is numbered independently because the pressure unit is centimeters mercury rather than millimeters mercury.

TABLE IV. *Temperature derivative in millimeters* Hg/°*K for the 1958* He^4 *Scale.* This table gives values of the first derivative, dP/dT, to four significant digits. These values are smoother and more precise than values obtained directly from table I by simple difference calculation, and they represent true derivatives of the scale defined by table I.

TABLE V. *Auxiliary table for making hydrostatic head correction.* This table gives, as a function of pressure, values of the ratio between the density of liquid He I and the density of mercury at 0° C.

TABLE VI. *Deviations of earlier scales from the 1958 scale.* The definitions of earlier scales used for obtaining the values in this table are explicitly given in explanatory notes which accompany it.

TABLE VII. *Auxiliary table for making corrections for the density of mercury at temperatures other than*

0° C. This table gives values of the ratio between the density of mercury at temperatures between 10° and 39° C and the density at 0° C. Following this table is an equation useful for making another correction which in precise work must be applied to the observed height of a mercury column. This equation gives an empirical relation between the acceleration due to gravity and the local latitude and altitude. If the local value of this acceleration is unknown, the equation will yield a value sufficiently accurate for the purpose of manometry.

2. Constants Used in the Computation of the Scale

Certain constants are necessary for computing a vapor pressure-temperature scale. The values of these constants adopted for the computation of the 1958 scale are tabulated below. The significance of the L_0 value may be found in Part 1, Introduction by F. G. Brickwedde. These constants are: $i_0=12.2440$ cgs units; $L_0=59.62$ j/mole; $R=8.31662$ j/mole·deg; density of mercury at 0° $C=13.5951$ g/cm^3; standard gravity$=980.665$ cm/sec^2; pressure at the λ-point$=37.80$ mm mercury at 0° C and standard gravity.

3. Fixed Points on the Scale

The boiling point is at 4.2150° K for $P=760.00$ mm mercury at 0° C and standard gravity (or 1013250 dynes/cm^2). The λ-point is at 2.1720° K for P as noted above. The critical point, if the critical pressure is taken to be 1718 mm mercury (Kamerlingh Onnes, Leiden Comm. 124b) at 0° C and standard gravity, is at 5.1994° K.

4. Comments on Determining Temperature by Measuring Vapor Pressure

Two techniques are commonly used for determining a temperature by measuring the vapor pressure of liquid He^4. In one, the pressure at some point above a bath of liquid helium is measured. In this case, standard practice has been to add to the measured pressure, when above the λ-point pressure, an amount equal to the pressure exerted by the column of helium between the point where the pressure is measured and the point in the bath occupied by the object whose temperature is desired. Below the λ-point, no correction of the observed pressure is ordinarily made, although the pressure drop in the gas due to pumping may become significant at low pressures. In the other technique, the pressure over a small amount of helium condensed in a "vapor pressure bulb" is measured. Since this "bulb" is normally placed close to the point in the bath occupied by the object whose temperature is desired, correction of the observed pressure is usually considered unnecessary above, as well as below, the λ-point. Numerous arrangements have been used for the pressure-transmitting line from the "bulb" to the manometer, but no standard practice seems to prevail. In any such apparatus, thermomolecular pressure differences between the cold "bulb" and the warm manometer arise at sufficiently low pressures.

It is generally known that various adaptations of these two techniques yield slightly different pressures and therefore slightly different temperatures, especially above the λ-point. Although these temperatures usually differ by no more than 0.01° K, special attention to technique seems required when precision exceeding 0.01° K is desired. Two conditions necessary to any satisfactory technique for determining the temperature of an object by measuring the vapor pressure of a liquid seem obvious. First, there must be thermal equilibrium between the object and the liquid. Second, the pressure at which the liquid is in equilibrium with its saturated vapor must somehow be determined. In the case of He^4 there is one criterion which, if satisfied, probably assures that these conditions are met. Differences between the thermal properties of He^4 above and below the λ-point are so large that, if the calibration of a secondary thermometer yields a continuous curve through the λ-point, the technique by which the calibration was obtained is probably satisfactory.

Table I. *Vapor pressure of* He^4 *(1958 scale) in microns* (10^{-3} *mm) mercury at 0° C and standard gravity (980.665 cm/sec^2)*

T°K	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
0.50	0.016342	0.016901	0.017476	0.018069	0.018680	0.019309	0.019956	0.020623	0.021310	0.022017
.51	.022745	.023494	.024265	.025058	.025875	.026714	.027578	.028467	.029381	.030321
.52	.031287	.032280	.033301	.034351	.035431	.036541	.037681	.038852	.040055	.041291
.53	.042561	.043865	.045205	.046581	.047993	.049443	.050932	.052461	.054030	.055640
.54	.057292	.058987	.060727	.062512	.064343	.066221	.068147	.070123	.072149	.074226
.55	.076356	.078540	.080779	.083074	.085426	.087836	.090306	.092837	.095431	.098088
.56	.10081	.10360	.10646	.10938	.11237	.11544	.11858	.12179	.12508	.12845
.57	.13190	.13543	.13904	.14274	.14652	.15039	.15435	.15840	.16254	.16678
.58	.17112	.17555	.18008	.18471	.18945	.19430	.19926	.20433	.20951	.21480
.59	.22021	.22574	.23139	.23716	.24306	.24908	.25524	.26153	.26795	.27451

Table I. *Vapor pressure of* He⁴ *(1958 scale) in microns* $(10^{-3}$ *mm) mercury at 0° C and standard gravity* $(980.665\ cm/sec^2)$—Con.

T°K	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
0.60	0.28121	0.28805	0.29504	0.30218	0.30947	0.31691	0.32450	0.33225	0.34017	0.34825
.61	.35649	.36490	.37349	.38225	.39120	.40032	.40963	.41912	.42881	.43869
.62	.44877	.45905	.46953	.48023	.49113	.50225	.51358	.52514	.53692	.54894
.63	.56118	.57366	.58638	.59935	.61256	.62603	.63975	.65374	.66799	.68250
.64	.69729	.71236	.72771	.74334	.75926	.77548	.79200	.80882	.82595	.84340
.65	.86116	.87925	.89766	.91641	.93550	.95493	.97471	.99484	1.0153	1.0362
.66	1.0574	1.0790	1.1010	1.1233	1.1461	1.1692	1.1928	1.2167	1.2411	1.2659
.67	1.2911	1.3168	1.3429	1.3694	1.3964	1.4238	1.4518	1.4802	1.5090	1.5384
.68	1.5682	1.5985	1.6293	1.6607	1.6925	1.7249	1.7578	1.7913	1.8253	1.8598
.69	1.8949	1.9306	1.9669	2.0037	2.0412	2.0792	2.1179	2.1571	2.1970	2.2375
.70	2.2787	2.3205	2.3629	2.4061	2.4499	2.4944	2.5395	2.5853	2.6319	2.6792
.71	2.7272	2.7760	2.8255	2.8757	2.9267	2.9785	3.0311	3.0845	3.1386	3.1936
.72	3.2494	3.3060	3.3635	3.4218	3.4810	3.5411	3.6021	3.6639	3.7266	3.7903
.73	3.8549	3.9204	3.9869	4.0544	4.1228	4.1922	4.2626	4.3340	4.4064	4.4798
.74	4.5543	4.6298	4.7064	4.7841	4.8629	4.9428	5.0238	5.1059	5.1891	5.2735
.75	5.3591	5.4459	5.5338	5.6230	5.7134	5.8050	5.8978	5.9919	6.0873	6.1840
.76	6.2820	6.3813	6.4819	6.5839	6.6872	6.7919	6.8980	7.0055	7.1144	7.2247
.77	7.3365	7.4498	7.5645	7.6807	7.7985	7.9178	8.0386	8.1610	8.2849	8.4104
.78	8.5376	8.6664	8.7968	8.9289	9.0627	9.1981	9.3352	9.4741	9.6147	9.7571
.79	9.9013	10.047	10.195	10.345	10.496	10.650	10.805	10.962	11.121	11.282
.80	11.445	11.610	11.777	11.946	12.117	12.290	12.465	12.642	12.822	13.003
.81	13.187	13.373	13.561	13.751	13.944	14.138	14.335	14.535	14.737	14.941
.82	15.147	15.356	15.567	15.781	15.997	16.216	16.437	16.661	16.887	17.116
.83	17.348	17.582	17.819	18.058	18.300	18.545	18.793	19.043	19.296	19.552
.84	19.811	20.073	20.337	20.605	20.875	21.149	21.425	21.704	21.987	22.272
.85	22.561	22.853	23.148	23.446	23.747	24.052	24.360	24.671	24.985	25.303
.86	25.624	25.948	26.276	26.608	26.943	27.281	27.623	27.969	28.318	28.671
.87	29.027	29.387	29.751	30.119	30.490	30.865	31.245	31.628	32.014	32.405
.88	32.800	33.199	33.602	34.009	34.420	34.835	35.254	35.678	36.106	36.538
.89	36.974	37.415	37.860	38.309	38.763	39.221	39.684	40.151	40.623	41.100
.90	41.581	42.067	42.557	43.053	43.553	44.058	44.568	45.082	45.602	46.126
.91	46.656	47.191	47.730	48.275	48.825	49.380	49.940	50.505	51.076	51.652
.92	52.234	52.821	53.414	54.012	54.615	55.224	55.839	56.459	57.085	57.717
.93	58.355	58.999	59.648	60.303	60.964	61.632	62.305	62.984	63.670	64.361
.94	65.059	65.763	66.473	67.190	67.913	68.642	69.378	70.120	70.869	71.624
.95	72.386	73.155	73.930	74.713	75.502	76.298	77.101	77.910	78.727	79.551
.96	80.382	81.220	82.066	82.918	83.778	84.645	85.520	86.402	87.291	88.188
.97	89.093	90.005	90.925	91.853	92.789	93.732	94.683	95.642	96.609	97.584
.98	98.567	99.558	100.557	101.565	102.581	103.605	104.638	105.679	106.728	107.786
.99	108.853	109.928	111.012	112.104	113.205	114.315	115.434	116.562	117.699	118.845
1.00	120.000	121.165	122.339	123.523	124.716	125.918	127.129	128.350	129.580	130.820
1.01	132.070	133.330	134.600	135.880	137.169	138.468	139.778	141.097	142.427	143.766
1.02	145.116	146.477	147.848	149.230	150.622	152.025	153.438	154.862	156.297	157.742
1.03	159.198	160.666	162.145	163.634	165.135	166.647	168.170	169.704	171.250	172.806
1.04	174.375	175.956	177.548	179.152	180.768	182.395	184.035	185.686	187.349	189.024
1.05	190.711	192.412	194.124	195.849	197.587	199.336	201.098	202.874	204.661	206.461
1.06	208.274	210.101	211.941	213.794	215.660	217.538	219.431	221.335	223.255	225.187
1.07	227.132	229.092	231.065	233.052	235.053	237.068	239.096	241.138	243.195	245.265
1.08	247.350	249.450	251.565	253.694	255.838	257.995	260.168	262.355	264.557	266.774
1.09	269.006	271.254	273.516	275.794	278.087	280.396	282.719	285.058	287.413	289.783
1.10	292.169	294.572	296.991	299.426	301.877	304.344	306.828	309.327	311.843	314.375
1.11	316.923	319.489	322.072	324.671	327.287	329.920	332.570	335.237	337.921	340.622
1.12	343.341	346.079	348.834	351.606	354.397	357.205	360.030	362.874	365.735	368.614
1.13	371.512	374.429	377.364	380.318	383.290	386.280	389.290	392.317	395.364	398.430
1.14	401.514	404.619	407.744	410.887	414.050	417.232	420.434	423.655	426.896	430.156
1.15	433.437	436.739	440.060	443.402	446.764	450.146	453.549	456.972	460.416	463.880
1.16	467.365	470.873	474.402	477.951	481.522	485.114	488.728	492.363	496.019	499.697
1.17	503.396	507.118	510.863	514.630	518.418	522.229	526.062	529.917	533.794	537.694
1.18	541.617	545.564	549.535	553.528	557.544	561.583	565.645	569.731	573.840	577.972
1.19	582.129	586.310	590.515	594.744	598.998	603.275	607.576	611.901	616.251	620.626
1.20	625.025	629.450	633.901	638.377	642.877	647.403	651.954	656.530	661.131	665.758
1.21	670.411	675.091	679.797	684.529	689.287	694.071	698.881	703.717	708.580	713.470
1.22	718.386	723.331	728.303	733.301	738.327	743.380	748.461	753.569	758.704	763.866
1.23	769.057	774.277	779.525	784.801	790.105	795.437	800.798	806.187	811.605	817.052
1.24	822.527	828.033	833.569	839.135	844.730	850.353	856.006	861.689	867.402	873.144
1.25	878.916	884.720	890.555	896.420	902.315	908.241	914.197	920.184	926.202	932.250
1.26	938.330	944.442	950.585	956.759	962.965	969.203	975.473	981.774	988.107	994.472
1.27	1000.87	1007.30	1013.77	1020.27	1026.80	1033.36	1039.95	1046.58	1053.24	1059.94
1.28	1066.67	1073.44	1080.24	1087.07	1093.93	1100.83	1107.77	1114.74	1121.74	1128.78
1.29	1135.85	1142.96	1150.10	1157.28	1164.49	1171.74	1179.02	1186.34	1193.69	1201.08

TABLE I. *Vapor pressure of* He^4 *(1958 scale) in micron* (10^{-3} *mm) mercury at 0° C and standard gravity* (980.665 cm/sec^2)—Con.

T°K	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
1.30	1208.51	1215.98	1223.48	1231.02	1238.59	1246.20	1253.85	1261.54	1269.26	1277.02
1.31	1284.81	1292.64	1300.51	1308.42	1316.37	1324.35	1332.37	1340.43	1348.53	1356.66
1.32	1364.83	1373.04	1381.30	1389.59	1397.92	1406.29	1414.70	1423.15	1431.64	1440.16
1.33	1448.73	1457.34	1465.98	1474.67	1483.40	1492.17	1500.97	1509.82	1518.71	1527.64
1.34	1536.61	1545.62	1554.68	1563.78	1572.91	1582.09	1591.31	1600.57	1609.88	1619.23
1.35	1628.62	1638.06	1647.54	1657.06	1666.62	1676.23	1685.88	1695.57	1705.31	1715.09
1.36	1724.91	1734.78	1744.69	1754.65	1764.65	1774.69	1784.78	1794.91	1805.09	1815.31
1.37	1825.58	1835.90	1846.26	1856.66	1867.11	1877.61	1888.16	1898.75	1909.38	1920.06
1.38	1930.79	1941.57	1952.39	1963.26	1974.18	1985.14	1996.15	2007.21	2018.32	2029.47
1.39	2040.67	2051.92	2063.22	2074.57	2085.96	2097.40	2108.89	2120.43	2132.02	2143.66
1.40	2155.35	2167.09	2178.88	2190.72	2202.61	2214.54	2226.53	2238.57	2250.66	2262.80
1.41	2274.99	2287.23	2299.52	2311.87	2324.27	2336.72	2349.22	2361.77	2374.37	2387.02
1.42	2399.73	2412.49	2425.30	2438.17	2451.09	2464.06	2477.09	2490.17	2503.30	2516.48
1.43	2529.72	2543.01	2556.36	2569.76	2583.21	2596.72	2610.29	2623.91	2637.58	2651.31
1.44	2665.09	2678.93	2692.82	2706.77	2720.78	2734.84	2748.96	2763.13	2777.36	2791.65
1.45	2805.99	2820.39	2834.85	2849.37	2863.95	2878.58	2893.27	2908.02	2922.82	2937.68
1.46	2952.60	2967.58	2982.62	2997.72	3012.88	3028.09	3043.36	3058.69	3074.08	3089.53
1.47	3105.04	3120.61	3136.24	3151.94	3167.69	3183.50	3199.37	3215.30	3231.30	3247.36
1.48	3263.48	3279.66	3295.90	3312.20	3328.57	3345.00	3361.49	3378.04	3394.65	3411.33
1.49	3428.07	3444.87	3461.74	3478.67	3495.66	3512.72	3529.84	3547.03	3564.28	3581.59
1.50	3598.97	3616.41	3633.92	3651.49	3669.13	3686.83	3704.60	3722.43	3740.33	3758.29
1.51	3776.32	3794.42	3812.59	3830.82	3849.12	3867.49	3885.92	3904.42	3922.99	3941.62
1.52	3960.32	3979.09	3997.93	4016.83	4035.80	4054.84	4073.95	4093.12	4112.37	4131.69
1.53	4151.07	4170.52	4190.05	4209.65	4229.32	4249.06	4268.87	4288.74	4308.68	4328.70
1.54	4348.79	4368.95	4389.17	4409.47	4429.84	4450.28	4470.80	4491.39	4512.05	4532.78
1.55	4553.58	4574.46	4595.41	4616.44	4637.54	4658.71	4679.96	4701.28	4722.67	4744.14
1.56	4765.68	4787.29	4808.98	4830.74	4852.58	4874.49	4896.48	4918.54	4940.68	4962.89
1.57	4985.18	5007.54	5029.98	5052.50	5075.09	5097.76	5120.51	5143.33	5166.23	5189.21
1.58	5212.26	5235.39	5258.60	5281.89	5305.26	5328.71	5352.23	5375.83	5399.51	5423.27
1.59	5447.11	5471.03	5495.02	5519.10	5543.26	5567.49	5591.81	5616.21	5640.68	5665.24
1.60	5689.88	5714.60	5739.40	5764.28	5789.25	5814.30	5839.42	5864.63	5889.92	5915.30
1.61	5940.76	5966.30	5991.92	6017.62	6043.41	6069.28	6095.24	6121.28	6147.40	6173.61
1.62	6199.90	6226.27	6252.72	6279.26	6305.88	6332.59	6359.39	6386.27	6413.23	6440.28
1.63	6467.42	6494.64	6521.95	6549.35	6576.84	6604.41	6632.07	6659.81	6687.64	6715.56
1.64	6743.57	6771.66	6799.84	6828.11	6856.47	6884.91	6913.44	6942.07	6970.78	6999.58
1.65	7028.47	7057.45	7086.52	7115.67	7144.92	7174.26	7203.69	7233.21	7262.82	7292.52
1.66	7322.31	7352.19	7382.15	7412.21	7442.36	7472.60	7502.94	7533.37	7563.89	7594.50
1.67	7625.21	7656.01	7686.90	7717.88	7748.96	7780.13	7811.40	7842.76	7874.21	7905.76
1.68	7937.40	7969.13	8000.96	8032.88	8064.90	8097.01	8129.22	8161.53	8193.93	8226.43
1.69	8259.02	8291.70	8324.48	8357.36	8390.33	8423.40	8456.57	8489.84	8523.20	8556.66
1.70	8590.22	8623.87	8657.62	8691.47	8725.42	8759.47	8793.62	8827.86	8862.20	8896.64
1.71	8931.18	8965.82	9000.56	9035.40	9070.33	9105.36	9140.50	9175.74	9211.08	9246.52
1.72	9282.06	9317.70	9353.44	9389.28	9425.22	9461.26	9497.41	9533.66	9570.01	9606.46
1.73	9643.02	9679.68	9716.45	9753.32	9790.29	9827.36	9864.54	9901.82	9939.21	9976.70
1.74	10014.3	10052.0	10089.8	10127.7	10165.7	10203.8	10242.0	10280.3	10318.7	10357.3
1.75	10395.9	10434.6	10473.4	10512.4	10551.5	10590.7	10630.0	10669.4	10708.9	10748.5
1.76	10788.2	10828.0	10867.9	10907.9	10948.0	10988.3	11028.7	11069.2	11109.7	11150.4
1.77	11191.2	11232.1	11273.1	11314.2	11355.4	11396.7	11438.1	11479.7	11521.4	11563.2
1.78	11605.1	11647.1	11689.2	11731.4	11773.7	11816.1	11858.7	11901.4	11944.2	11987.1
1.79	12030.1	12073.2	12116.4	12159.7	12203.1	12246.6	12290.3	12334.1	12378.0	12422.0
1.80	12466.1	12510.3	12554.7	12599.2	12643.8	12688.5	12733.3	12778.2	12823.2	12868.4
1.81	12913.7	12959.1	13004.6	13050.2	13095.9	13141.8	13187.8	13233.9	13280.1	13326.4
1.82	13372.8	13419.3	13466.0	13512.8	13559.7	13606.7	13653.8	13701.1	13748.5	13796.0
1.83	13843.6	13891.3	13939.1	13987.1	14035.2	14083.4	14131.7	14180.1	14228.6	14277.3
1.84	14326.1	14375.0	14424.0	14473.2	14522.5	14571.9	14621.4	14671.0	14720.8	14770.7
1.85	14820.7	14870.8	14921.0	14971.4	15021.9	15072.5	15123.2	15174.0	15225.0	15276.1
1.86	15327.3	15378.6	15430.1	15481.7	15533.4	15585.2	15637.2	15689.3	15741.5	15793.8
1.87	15846.3	15898.9	15951.6	16004.4	16057.3	16110.4	16163.6	16216.9	16270.4	16324.0
1.88	16377.7	16431.5	16485.5	16539.6	16593.8	16648.1	16702.6	16757.2	16811.9	16866.7
1.89	16921.7	16976.8	17032.0	17087.3	17142.8	17198.4	17254.1	17309.9	17365.9	17422.0
1.90	17478.2	17534.6	17591.1	17647.7	17704.5	17761.4	17818.4	17875.5	17932.8	17990.2
1.91	18047.7	18105.4	18163.2	18221.1	18279.1	18337.3	18395.6	18454.0	18512.6	18571.3
1.92	18630.1	18689.0	18748.1	18807.3	18866.7	18926.2	18985.8	19045.5	19105.4	19165.4
1.93	19225.5	19285.8	19346.2	19406.7	19467.4	19528.2	19589.1	19650.1	19711.3	19772.6
1.94	19834.1	19895.7	19957.4	20019.2	20081.2	20143.3	20205.6	20268.0	20330.5	20393.1
1.95	20455.9	20518.8	20581.9	20645.1	20708.4	20771.8	20835.4	20899.1	20963.0	21027.0
1.96	21091.1	21155.4	21219.8	21284.3	21348.9	21413.7	21478.6	21543.7	21608.9	21674.2
1.97	21739.7	21805.3	21871.1	21937.0	22003.0	22069.2	22135.5	22201.9	22268.5	22335.2
1.98	22402.0	22469.0	22536.1	22603.3	22670.7	22738.2	22805.9	22873.7	22941.6	23009.7
1.99	23077.9	23146.2	23214.7	23283.3	23352.1	23421.0	23490.0	23559.1	23628.4	23697.8

TABLE I. *Vapor pressure of* He^4 *(1958 scale) in microns* (10^{-3} *mm) mercury at 0° C and standard gravity (980.665 cm/sec*^{2}*)*—Con.

T°K	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
2.00	23767.4	23837.1	23907.0	23977.0	24047.2	24117.5	24187.9	24258.4	24329.1	24399.9
2.01	24470.9	24542.0	24613.2	24684.6	24756.1	24827.8	24899.6	24971.5	25043.6	25115.8
2.02	25188.1	25260.6	25333.2	25406.0	25478.9	25551.9	25625.1	25698.4	25771.9	25845.5
2.03	25919.2	25993.1	26067.1	26141.3	26215.6	26290.0	26364.6	26439.3	26514.1	26589.1
2.04	26664.2	26739.5	26814.9	26890.5	26966.2	27042.0	27118.0	27194.1	27270.4	27346.8
2.05	27423.3	27500.0	27576.8	27653.8	27730.9	27808.1	27885.4	27962.9	28040.6	28118.4
2.06	28196.3	28274.4	28352.6	28430.9	28509.4	28588.0	28666.8	28745.7	28824.7	28903.9
2.07	28983.2	29062.7	29142.3	29222.1	29302.0	29382.0	29462.2	29542.5	29622.9	29703.5
2.08	29784.2	29865.1	29946.1	30027.2	30108.5	30189.9	30271.5	30353.2	30435.0	30517.0
2.09	30599.1	30681.4	30763.8	30846.4	30929.1	31011.9	31094.9	31178.0	31261.2	31344.6
2.10	31428.1	31511.8	31595.6	31679.6	31763.7	31847.9	31932.3	32016.8	32101.4	32186.2
2.11	32271.1	32356.2	32441.4	32526.8	32612.3	32697.9	32783.6	32869.5	32955.5	33041.7
2.12	33128.0	33214.5	33301.1	33387.8	33474.6	33561.6	33648.7	33736.0	33823.4	33910.9
2.13	33998.6	34086.4	34174.4	34262.5	34350.7	34439.0	34527.5	34616.1	34704.9	34793.8
2.14	34882.8	34971.9	35061.2	35150.6	35240.2	35329.9	35419.7	35509.7	35599.8	35690.0
2.15	35780.3	35870.7	35961.3	36052.0	36142.9	36233.9	36325.0	36416.3	36507.7	36599.2
2.16	36690.9	36782.7	36874.6	36966.6	37058.8	37151.1	37243.5	37336.0	37428.6	37521.4
2.17	37614.3	37707.4	37800.6	37893.9	37987.3	38080.8	38174.4	38268.1	38362.0	38456.0
2.18	38550.2	38644.5	38739.0	38833.6	38928.4	39023.3	39118.4	39213.6	39309.0	39404.6
2.19	39500.3	39596.2	39692.2	39788.3	39884.6	39981.0	40077.6	40174.4	40271.3	40368.4
2.20	40465.6	40563.0	40660.5	40758.2	40856.0	40954 0	41052.2	41150.6	41249.1	41347.8
2.21	41446.6	41545.6	41644.7	41744.0	41843 4	41943.0	42042.8	42142.7	42242.8	42343.1
2.22	42443.5	42544.1	42644.8	42745.7	42846.8	42948.0	43049.4	43150.9	43252.6	43354.5
2.23	43456.5	43558.7	43661.0	43763.5	43866.2	43969.0	44072.0	44175.2	44278.5	44382.0
2.24	44485.7	44589.5	44693.5	44797.6	44901.9	45006.4	45111.0	45215.8	45320.8	45426.0
2.25	45531.3	45636.8	45742.4	45848.2	45954.1	46060.2	46166.5	46273.0	46379.7	46486.5
2.26	46593.5	46700.6	46807.9	46915.4	47023.0	47130.8	47238.8	47347.0	47455.3	47563.8
2.27	47672.5	47781.3	47890.3	47999.5	48108.9	48218.4	48328.1	48438.0	48548.0	48658.2
2.28	48768.6	48879.2	48989.9	49100.8	49211.8	49323.0	49434.4	49546.0	49657.8	49769.7
2.29	49881.8	49994.1	50106.5	50219.1	50331.9	50444.9	50558.0	50671.3	50784.8	50898.5
2.30	51012.3	51126.3	51240.5	51354.8	51469.3	51584.0	51698.9	51814.0	51929.2	52044.6
2.31	52160.2	52276.0	52391.9	52508.0	52624.3	52740.8	52857.4	52974.2	53091.2	53208.4
2.32	53325.8	53443.3	53561.0	53678.9	53797.0	53915.3	54033.7	54152.3	54271.1	54390.1
2.33	54509.2	54628.5	54748.0	54867.7	54987.6	55107.6	55227.8	55348.2	55468.8	55589.6
2.34	55710.5	55831.6	55952.9	56074.4	56196.1	56318.0	56440.0	56562.2	56684.6	56807.2
2.35	56930.0	57053.0	57176.1	57299.4	57422.9	57546.6	57670.5	57794.6	57918.8	58043.2
2.36	58167.8	58292.6	58417.5	58542.6	58668.0	58793.5	58919.2	59045.0	59171.1	59297.4
2.37	59423.8	59550.5	59677.3	59804.3	59931.5	60058.9	60186.5	60314.3	60442.3	60570.5
2.38	60698.8	60827.3	60955.9	61084.7	61213.8	61343.1	61472.5	61602.1	61731.9	61861.9
2.39	61992.0	62122.4	62253.0	62383.7	62514.6	62645.8	62777.1	62908.6	63040.3	63172.2
2.40	63304.3	63436.5	63569.0	63701.6	63834.4	63967.4	64100.5	64233.9	64367.5	64501.2
2.41	64635.2	64769.4	64903.7	65038.2	65173.0	65307.9	65443.0	65578.3	65713.8	65849.5
2.42	65985.4	66121.5	66257.7	66394.2	66530.8	66667.7	66804.7	66941.9	67079.4	67217.0
2.43	67354.8	67492.8	67631.0	67769.4	67907.9	68046.7	68185.7	68324.8	68464.2	68603.7
2.44	68743.5	68883.5	69023.6	69164.0	69304.5	69445.3	69586.2	69727.4	69868.7	70010.3
2.45	70152.0	70294.0	70436.1	70578.4	70721.0	70863.7	71006.6	71149.7	71293.0	71436.5
2.46	71580.2	71724.1	71868.2	72012.5	72157.0	72301.6	72446.5	72591.6	72736.9	72882.4
2.47	73028.1	73174.0	73320.1	73466.4	73612.8	73759.5	73906.4	74053.5	74200.8	74348.3
2.48	74496.0	74643.9	74792.0	74940.3	75088.8	75237.6	75386.5	75535.6	75685.0	75834.5
2.49	75984.2	76134.2	76284.3	76434.7	76585.3	76736.1	76887.1	77038.3	77189.7	77341.3
2.50	77493.1	77645.1	77797.3	77949.7	78102.3	78255.1	78408.1	78561.3	78714.7	78868.4
2.51	79022.2	79176.3	79330.5	79485.0	79639.7	79794.6	79949.7	80105.0	80260.5	80416.3
2.52	80572.2	80728.3	80884.7	81041.2	81198.0	81354.9	81512.1	81669.5	81827.1	81984.9
2.53	82142.9	82301.1	82459.6	82618.2	82777.1	82936.1	83095.4	83254.9	83414.6	83574.5
2.54	83734.6	83894.9	84055.4	84216.2	84377.1	84538.3	84699.6	84861.2	85023.0	85185.0
2.55	85347.2	85509.6	85672.3	85835.2	85998.2	86161.5	86325.0	86488.7	86652.7	86816.8
2.56	86981.2	87145.8	87310.6	87475.6	87640.8	87806.3	87971.9	88137.8	88303.9	88470.2
2.57	88636.7	88803.4	88970.4	89137.6	89304.9	89472.5	89640.3	89808.4	89976.7	90145.1
2.58	90313.8	90482.7	90651.8	90821.2	90990.8	91160.5	91330.5	91500.7	91671.1	91841.8
2.59	92012.6	92183.7	92355.0	92526.6	92698.3	92870.3	93042.5	93214.9	93387.5	93560.3
2.60	93733.4	93906.7	94080.2	94253.9	94427.8	94602.0	94776.3	94950.9	95125.7	95300.8
2.61	95476.0	95651.5	95827.2	96003.1	96179.3	96355.6	96532.2	96709.0	96886.1	97063.3
2.62	97240.8	97418.5	97596.5	97774.7	97953.1	98131.7	98310.6	98489.6	98668.9	98848.5
2.63	99028.2	99208.2	99388.4	99568.8	99749.4	99930.3	100111	100293	100474	100656
2.64	100838	101020	101202	101385	101568	101751	101934	102117	102301	102485
2.65	102669	102854	103038	103223	103409	103594	103780	103966	104152	104338
2.66	104525	104712	104899	105086	105273	105461	105649	105837	106026	106214
2.67	106403	106592	106781	106971	107161	107351	107541	107731	107922	108113
2.68	108304	108495	108687	108879	109071	109263	109456	109648	109841	110035
2.69	110228	110422	110616	110810	111004	111199	111393	111588	111784	111979

Table .I *Vapor pressure of* He^4 (*1958 scale*) *in microns* (10^{-3} *mm*) *mercury at 0° C and standard gravity* (*980.665* cm/sec^2)—Con.

T°K	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
2.70	112175	112371	112567	112764	112960	113157	113354	113552	113749	113947
2.71	114145	114343	114542	114741	114940	115139	115339	115538	115738	115939
2.72	116139	116340	116541	116742	116943	117145	117346	117548	117751	117953
2.73	118156	118359	118562	118766	118970	119174	119378	119583	119788	119993
2.74	120198	120403	120609	120815	121021	121228	121434	121641	121848	122055
2.75	122263	122471	122679	122887	123096	123305	123514	123723	123933	124143
2.76	124353	124563	124773	124984	125195	125406	125617	125829	126041	126253
2.77	126465	126678	126891	127104	127317	127531	127745	127959	128173	128388
2.78	128603	128818	129033	129249	129465	129681	129897	130114	130331	130548
2.79	130765	130983	131200	131419	131637	131855	132074	132293	132513	132732
2.80	132952	133172	133392	133613	133834	134055	134276	134498	134720	134942
2.81	135164	135387	135609	135832	136056	136279	136503	136727	136952	137176
2.82	137401	137626	137851	138077	138303	138529	138755	138982	139209	139436
2.83	139663	139890	140118	140346	140574	140803	141032	141261	141490	141719
2.84	141949	142179	142409	142640	142870	143101	143333	143564	143796	144028
2.85	144260	144493	144725	144958	145192	145425	145659	145893	146128	146362
2.86	146597	146832	147068	147304	147540	147776	148012	148249	148486	148723
2.87	148961	149199	149437	149675	149913	150152	150391	150630	150869	151109
2.88	151349	151589	151830	152070	152312	152553	152794	153036	153278	153520
2.89	153763	154006	154249	154493	154736	154980	155224	155469	155714	155959
2.90	156204	156450	156695	156941	157188	157434	157681	157928	158176	158423
2.91	158671	158919	159168	159416	159665	159914	160164	160413	160663	160914
2.92	161164	161415	161666	161917	162169	162421	162673	162925	163178	163431
2.93	163684	163937	164191	164445	164699	164954	165208	165463	165719	165974
2.94	166230	166486	166742	166999	167256	167513	167770	168028	168285	168544
2.95	168802	169061	169320	169579	169839	170099	170359	170619	170880	171141
2.96	171402	171663	171925	172187	172449	172712	172974	173237	173501	173764
2.97	174028	174292	174557	174821	175086	175352	175617	175883	176149	176415
2.98	176682	176949	177216	177484	177752	178020	178288	178557	178825	179095
2.99	179364	179634	179904	180174	180444	180715	180986	181257	181529	181801
3.00	182073	182345	182618	182891	183164	183438	183712	183986	184260	184535
3.01	184810	185085	185361	185636	185912	186189	186465	186742	187019	187296
3.02	187574	187852	188130	188409	188687	188967	189246	189525	189805	190086
3.03	190366	190647	190928	191209	191491	191773	192055	192338	192621	192904
3.04	193187	193471	193755	194039	194324	194608	194894	195179	195465	195751
3.05	196037	196323	196610	196897	197184	197472	197760	198048	198336	198625
3.06	198914	199203	199492	199783	200073	200363	200654	200945	201237	201528
3.07	201820	202112	202405	202697	202991	203284	203578	203871	204166	204460
3.08	204755	205050	205346	205641	205937	206233	206530	206827	207124	207421
3.09	207719	208017	208315	208614	208912	209221	209511	209810	210110	210411
3.10	210711	211012	211313	211614	211916	212218	212520	212823	213125	213429
3.11	213732	214036	214340	214644	214949	215254	215559	215865	216171	216477
3.12	216783	217090	217397	217704	218012	218320	218628	218937	219246	219555
3.13	219864	220174	220484	220794	221105	221416	221727	222039	222350	222663
3.14	222975	223288	223601	223914	224227	224541	224855	225170	225485	225800
3.15	226115	226431	226747	227063	227379	227696	228013	228331	228649	228967
3.16	229285	229604	229922	230242	230561	230881	231201	231521	231842	232163
3.17	232484	232806	233128	233450	233772	234095	234418	234742	235066	235390
3.18	235714	236039	236364	236689	237014	237340	237666	237993	238320	238647
3.19	238974	239302	239630	239958	240287	240616	240946	241275	241605	241935
3.20	242266	242597	242928	243259	243591	243923	244255	244588	244920	245254
3.21	245587	245920	246255	246589	246924	247259	247595	247930	248266	248602
3.22	248939	249276	249613	249951	250289	250627	250965	251304	251643	251982
3.23	252322	252662	253002	253343	253684	254025	254367	254709	255051	255393
3.24	255736	256079	256423	256767	257111	257455	257800	258145	258490	258836
3.25	259182	259528	259875	260222	260569	260916	261264	261612	261960	262309
3.26	262658	263007	263357	263707	264057	264408	264759	265110	265462	265814
3.27	266166	266519	266871	267225	267578	267932	268286	268641	268995	269351
3.28	269706	270062	270418	270774	271131	271488	271845	272203	272561	272919
3.29	273278	273637	273996	274355	274715	275075	275435	275796	276157	276518
3.30	276880	277242	277605	277967	278331	278694	279058	279422	279786	280151
3.31	280516	280881	281247	281613	281979	282346	282712	283080	283447	283815
3.32	284183	284552	284920	285290	285659	286029	286399	286770	287140	287512
3.33	287883	288255	288627	288999	289372	289745	290118	290492	290866	291240
3.34	291615	291990	292365	292741	293117	293493	293870	294247	294624	295002
3.35	295380	295758	296137	296516	296895	297275	297655	298035	298416	298797
3.36	299178	299560	299941	300324	300706	301089	301472	301856	302239	302624
3.37	303008	303393	303778	304163	304549	304935	305322	305709	306096	306483
3.38	306871	307259	307648	308037	308426	308815	309205	309595	309986	310377
3.39	310768	311159	311551	311943	312335	312728	313121	313515	313908	314302

Table I. *Vapor pressure of* He⁴ *(1958 scale) in microns (10^{-3} mm) mercury at 0° C and standard gravity (980.665 cm/sec²)*—Con.

T°K	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
3.40	314697	315092	315487	315882	316278	316674	317070	317467	317864	318261
3.41	318659	319057	319455	319854	320253	320652	321052	321452	321852	322253
3.42	322654	323055	323457	323859	324262	324665	325068	325471	325875	326279
3.43	326684	327089	327493	327899	328305	328711	329118	329525	329932	330339
3.44	330747	331155	331564	331973	332382	332792	333202	333612	334023	334434
3.45	334845	335257	335668	336081	336493	336906	337319	337733	338147	338561
3.46	338976	339391	339806	340222	340638	341054	341471	341888	342305	342723
3.47	343141	343559	343978	344397	344817	345237	345657	346077	346498	346919
3.48	347341	347763	348185	348608	349030	349454	349877	350301	350725	351150
3.49	351575	352000	352426	352852	353278	353705	354132	354560	354987	355416
3.50	355844	356273	356702	357131	357561	357991	358422	358852	359284	359715
3.51	360147	360579	361012	361445	361878	362312	362746	363180	363615	364050
3.52	364485	364921	365357	365794	366231	366668	367106	367544	367982	368421
3.53	368860	369299	369739	370179	370619	371060	371501	371943	372384	372826
3.54	373269	373712	374155	374599	375043	375487	375932	376377	376822	377268
3.55	377714	378160	378607	379054	379502	379950	380398	380846	381295	381744
3.56	382194	382644	383094	383545	383996	384447	384899	385351	385804	386257
3.57	386710	387164	387617	388072	388526	388982	389437	389893	390349	390805
3.58	391262	391719	392177	392634	393092	393551	394010	394469	394929	395389
3.59	395849	396310	396770	397232	397693	398155	398618	399081	399544	400007
3.60	400471	400935	401400	401865	402330	402796	403262	403728	404195	404662
3.61	405130	405598	406066	406535	407004	407473	407943	408413	408883	409354
3.62	409825	410296	410768	411240	411713	412186	412659	413133	413607	414081
3.63	414556	415031	415507	415983	416459	416935	417412	417890	418367	418846
3.64	419324	419803	420282	420761	421241	421721	422202	422683	423164	423646
3.65	424128	424610	425093	425576	426060	426543	427028	427512	427997	428482
3.66	428968	429454	429941	430427	430915	431402	431890	432379	432867	433356
3.67	433846	434336	434826	435316	435807	436298	436790	437282	437774	438267
3.68	438760	439254	439748	440242	440737	441232	441727	442223	442719	443216
3.69	443713	444210	444708	445206	445704	446203	446702	447201	447701	448201
3.70	448702	449203	449704	450206	450708	451211	451714	452217	452721	453225
3.71	453729	454234	454739	455244	455750	456257	456763	457270	457778	458286
3.72	458794	459303	459812	460321	460831	461341	461851	462362	462873	463385
3.73	463897	464409	464922	465435	465949	466463	466977	467492	468007	468522
3.74	469038	469554	470071	470588	471105	471623	472141	472660	473179	473698
3.75	474218	474738	475258	475779	476300	476822	477344	477866	478389	478912
3.76	479435	479959	480483	481008	481538	482058	482584	483110	483637	484164
3.77	484691	485219	485747	486275	486804	487333	487863	488393	488923	489454
3.78	489985	490516	491048	491580	492113	492646	493180	493713	494247	494782
3.79	495317	495852	496388	496924	497461	497998	498535	499073	499611	500149
3.80	500688	501227	501767	502307	502847	503388	503929	504471	505013	505555
3.81	506098	506641	507185	507729	508273	508818	509363	509908	510454	511000
3.82	511547	512094	512642	513190	513738	514287	514836	515385	515935	516485
3.83	517036	517587	518139	518690	519243	519795	520348	520901	521455	522009
3.84	522564	523119	523674	524230	524786	525343	525900	526457	527015	527573
3.85	528132	528691	529250	529810	530370	530930	531491	532053	532614	533176
3.86	533739	534302	534865	535429	535993	536558	537123	537688	538254	538820
3.87	539387	539954	540521	541089	541657	542226	542795	543364	543934	544504
3.88	545075	545646	546218	546790	547362	547935	548508	549082	549656	550230
3.89	550805	551380	551956	552531	553108	553684	554262	554839	555417	555995
3.90	556574	557153	557732	558312	558893	559473	560054	560636	561218	561800
3.91	562383	562966	563550	564133	564718	565303	565889	566474	567060	567647
3.92	568234	568821	569409	569997	570586	571175	571764	572354	572944	573535
3.93	574126	574717	575309	575902	576494	577087	577681	578275	578869	579464
3.94	580059	580655	581251	581847	582444	583041	583639	584237	584836	585435
3.95	586034	586634	587234	587835	588436	589037	589639	590241	590844	591447
3.96	592051	592655	593259	593864	594470	595075	595681	596288	596895	597502
3.97	598110	598718	599327	599936	600545	601155	601765	602376	602987	603598
3.98	604210	604822	605435	606048	606662	607276	607890	608505	609120	609736
3.99	610352	610969	611586	612203	612821	613439	614058	614677	615297	615917
4.00	616537	617158	617779	618401	619023	619645	620268	620891	621515	622139
4.01	622764	623389	624014	624640	625266	625893	626520	627148	627776	628404
4.02	629033	629662	630292	630922	631553	632184	632815	633447	634079	634712
4.03	635345	635979	636613	637247	637882	638517	639153	639789	640426	641063
4.04	641700	642338	642976	643615	644254	644894	645534	646174	646815	647457
4.05	648099	648741	649384	650027	650671	651315	651959	652604	653249	653895
4.06	654541	655188	655836	656482	657130	657778	658427	659076	659726	660376
4.07	661026	661677	662328	662980	663632	664284	664938	665591	666245	666899
4.08	667554	668209	668865	669521	670177	670834	671491	672149	672807	673466
4.09	674125	674784	675444	676105	676766	677427	678089	678751	679413	680076

TABLE I. *Vapor pressure of* He^4 *(1958 scale) in microns* (10^{-3} *mm) mercury at 0° C and standard gravity* (980.665 *cm/sec*^{2})—Con.

T°K	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
4.10	680740	681404	682068	682733	683398	684064	684730	685397	686064	686731
4.11	687399	688067	688736	689405	690075	690745	691416	692087	692759	693431
4.12	694103	694776	695449	696123	696797	697471	698146	698822	699498	700174
4.13	700851	701528	702206	702884	703562	704241	704921	705601	706281	706962
4.14	707643	708325	709007	709689	710372	711055	711739	712423	713108	713793
4.15	714479	715165	715852	716538	717226	717914	718602	719291	719980	720670
4.16	721360	722050	722741	723433	724124	724817	725500	726203	726896	727590
4.17	728285	728980	729675	730371	731067	731764	732461	733159	733857	734556
4.18	735255	735954	736654	737354	738055	738756	739458	740160	740863	741566
4.19	742269	742973	743677	744382	745087	745793	746499	747205	747912	748620
4.20	749328	750036	750745	751454	752164	752874	753584	754295	755007	755719
4.21	756431	757144	757857	758571	759285	759999	760714	761430	762146	762862
4.22	763579	764296	765014	765732	766451	767170	767889	768609	769330	770051
4.23	770772	771494	772216	772938	773662	774385	775109	775834	776559	777284
4.24	778010	778736	779463	780190	780918	781646	782375	783104	783833	784563
4.25	785294	786025	786756	787488	788220	788953	789686	790419	791153	791888
4.26	792623	793358	794094	794831	795568	796305	797043	797781	798520	799259
4.27	799999	800739	801480	802221	802962	803705	804447	805190	805934	806678
4.28	807422	808167	808912	809658	810405	811152	811899	812647	813395	814144
4.29	814893	815643	816393	817143	817894	818646	819398	820151	820904	821657
4.30	822411	823166	823921	824676	825432	826188	826945	827703	828461	829219
4.31	829978	830737	831497	832257	833018	833779	834541	835303	836065	836828
4.32	837592	838356	839121	839886	840651	841417	842184	842951	843718	844486
4.33	845255	846024	846793	847563	848334	849104	849876	850648	851420	852193
4.34	852966	853740	854514	855289	856064	856839	857616	858392	859169	859947
4.35	860725	861504	862283	863062	863842	864623	865404	866185	866967	867750
4.36	868533	869317	870101	870885	871670	872455	873241	874028	874815	875602
4.37	876390	877178	877967	878757	879546	880337	881128	881919	882711	883503
4.38	884296	885089	885883	886678	887472	888268	889064	889860	890657	891454
4.39	892252	893050	893849	894649	895448	896249	897050	897851	898653	899455
4.40	900258	901061	901865	902669	903474	904279	905085	905891	906698	907505
4.41	908313	909121	909930	910739	911549	912359	913170	913981	914793	915605
4.42	916418	917231	918045	918859	919674	920489	921305	922121	922938	923755
4.43	924573	925391	926210	927029	927849	928669	929490	930311	931133	931955
4.44	932778	933601	934425	935249	936074	936899	937725	938551	939378	940205
4.45	941033	941861	942690	943519	944349	945179	946010	946841	947673	948505
4.46	949338	950171	951005	951839	952674	953509	954345	955181	956018	956855
4.47	957693	958531	959370	960209	961049	961890	962730	963572	964414	965256
4.48	966099	966942	967786	968631	969476	970321	971167	972013	972860	973708
4.49	974556	975405	976254	977104	977954	978804	979656	980508	981360	982213
4.50	983066	983920	984774	985629	986485	987340	988197	989054	989911	990769
4.51	991628	992487	993346	994206	995066	995927	996788	997650	998513	999376
4.52	1000239	1001103	1001968	1002833	1003699	1004565	1005432	1006300	1007168	1008036
4.53	1008905	1009774	1010644	1011514	1012385	1013256	1014128	1015001	1015874	1016747
4.54	1017621	1018496	1019371	1020246	1021122	1021999	1022876	1023754	1024632	1025511
4.55	1026390	1027270	1028150	1029031	1029913	1030795	1031677	1032561	1033444	1034328
4.56	1035213	1036098	1036984	1037870	1038756	1039643	1040531	1041419	1042308	1043197
4.57	1044087	1044977	1045868	1046759	1047651	1048544	1049437	1050330	1051224	1052119
4.58	1053014	1053910	1054806	1055703	1056600	1057498	1058396	1059295	1060194	1061094
4.59	1061995	1062896	1063797	1064700	1065602	1066505	1067409	1068313	1069218	1070123
4.60	1071029	1071935	1072842	1073749	1074656	1075565	1076474	1077383	1078293	1079203
4.61	1080114	1081026	1081938	1082850	1083763	1084677	1085591	1086506	1087422	1088338
4.62	1089254	1090171	1091089	1092007	1092925	1093845	1094764	1095685	1096606	1097527
4.63	1098449	1099372	1100295	1101218	1102142	1103067	1103992	1104918	1105845	1106772
4.64	1107699	1108627	1109555	1110484	1111414	1112344	1113274	1114205	1115137	1116069
4.65	1117002	1117935	1118869	1119803	1120738	1121674	1122610	1123546	1124483	1125421
4.65	1126359	1127298	1128237	1129177	1130118	1131059	1132000	1132942	1133885	1134828
4.67	1135772	1136716	1137661	1138606	1139552	1140499	1141446	1142393	1143341	1144290
4.68	1145239	1146189	1147139	1148090	1149041	1149993	1150945	1151899	1152852	1153806
4.69	1154761	1155716	1156672	1157629	1158585	1159543	1160501	1161460	1162419	1163379
4.70	1164339	1165300	1166261	1167223	1168186	1169149	1170112	1171076	1172041	1173006
4.71	1173972	1174938	1175905	1176873	1177841	1178810	1179779	1180749	1181719	1182690
4.72	1183662	1184634	1185606	1186580	1187553	1188527	1189502	1190478	1191453	1192430
4.73	1193407	1194385	1195363	1196342	1197321	1198301	1199281	1200262	1201244	1202226
4.74	1203209	1204192	1205176	1206160	1207145	1208130	1209116	1210103	1211090	1212078
4.75	1213066	1214055	1215044	1216035	1217025	1218016	1219008	1220001	1220993	1221987
4.76	1222981	1223976	1224971	1225967	1226964	1227961	1228959	1229957	1230956	1231955
4.77	1232955	1233955	1234956	1235957	1236959	1237962	1238965	1239969	1240973	1241978
4.78	1242983	1243989	1244996	1246003	1247011	1248019	1249028	1250037	1251047	1252058
4.79	1253069	1254081	1255093	1256106	1257119	1258133	1259148	1260163	1261179	1262195

TABLE I. *Vapor pressure of* He^4 *(1958 scale) in microns (10^{-3} mm) mercury at 0° C and standard gravity (980.665 cm/sec^2)*—Con.

T°K	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
4.80	1263212	1264230	1265248	1266266	1267286	1268306	1269326	1270347	1271369	1272391
4.81	1273414	1274437	1275461	1276486	1277511	1278536	1279562	1280589	1281616	1282644
4.82	1283673	1284702	1285732	1286762	1287793	1288825	1289857	1290889	1291923	1292957
4.83	1293991	1295026	1296062	1297098	1298134	1299172	1300210	1301248	1302287	1303327
4.84	1304367	1305408	1306449	1307491	1308534	1309577	1310621	1311665	1312710	1313756
4.85	1314802	1315849	1316896	1317944	1318993	1320042	1321092	1322142	1323193	1324245
4.86	1325297	1326350	1327403	1328457	1329511	1330566	1331622	1332678	1333735	1334792
4.87	1335850	1336908	1337968	1339027	1340088	1341148	1342210	1343272	1344335	1345398
4.88	1346462	1347527	1348592	1349658	1350724	1351791	1352859	1353927	1354996	1356066
4.89	1357136	1358207	1359278	1360350	1361422	1362495	1363569	1364643	1365718	1366794
4.90	1367870	1368947	1370024	1371101	1372180	1373258	1374338	1375418	1376499	1377580
4.91	1378662	1379745	1380828	1381912	1382996	1384081	1385167	1386253	1387340	1388428
4.92	1389516	1390605	1391694	1392783	1393874	1394965	1396056	1397149	1398241	1399335
4.93	1400429	1401524	1402619	1403715	1404812	1405909	1407007	1408105	1409204	1410304
4.94	1411404	1412505	1413606	1414708	1415810	1416913	1418017	1419121	1420226	1421332
4.95	1422438	1423545	1424652	1425760	1426869	1427978	1429088	1430198	1431309	1432421
4.96	1433533	1434646	1435760	1436874	1437988	1439104	1440220	1441336	1442454	1443572
4.97	1444690	1445809	1446929	1448050	1449171	1450293	1451415	1452538	1453662	1454786
4.98	1455911	1457036	1458162	1459288	1460415	1461543	1462671	1463800	1464930	1466060
4.99	1467191	1468323	1469455	1470588	1471721	1472855	1473990	1475125	1476261	1477398
5.00	1478535	1479673	1480811	1481950	1483089	1484230	1485370	1486512	1487654	1488797
5.01	1489940	1491084	1492229	1493374	1494520	1495667	1496814	1497962	1499110	1500259
5.02	1501409	1502559	1503710	1504862	1506014	1507167	1508320	1509474	1510629	1511784
5.03	1512940	1514097	1515254	1516412	1517570	1518730	1519889	1521050	1522211	1523373
5.04	1524535	1525698	1526861	1528025	1529190	1530356	1531522	1532688	1533856	1535023
5.05	1536192	1537361	1538531	1539701	1540872	1542044	1543216	1544389	1545563	1546737
5.06	1547912	1549088	1550264	1551441	1552619	1553797	1554976	1556155	1557336	1558516
5.07	1559698	1560880	1562062	1563246	1564429	1565614	1566799	1567985	1569171	1570358
5.08	1571546	1572734	1573923	1575113	1576303	1577494	1578685	1579878	1581070	1582264
5.09	1583458	1584653	1585849	1587045	1588242	1589439	1590638	1591836	1593036	1594236
5.10	1595437	1596638	1597841	1599043	1600247	1601451	1602656	1603861	1605067	1606274
5.11	1607481	1608689	1609897	1611107	1612316	1613527	1614738	1615950	1617162	1618375
5.12	1619589	1620803	1622018	1623234	1624450	1625667	1626884	1628102	1629321	1630541
5.13	1631761	1632982	1634204	1635426	1636649	1637872	1639096	1640321	1641547	1642773
5.14	1644000	1645228	1646456	1647685	1648914	1650144	1651375	1652606	1653839	1655071
5.15	1656305	1657539	1658773	1660008	1661244	1662481	1663718	1664956	1666194	1667433
5.16	1668673	1669913	1671155	1672396	1673639	1674882	1676126	1677370	1678616	1679862
5.17	1681108	1682355	1683603	1684852	1686102	1687352	1688602	1689854	1691106	1692359
5.18	1693612	1694866	1696120	1697375	1698631	1699888	1701145	1702403	1703661	1704920
5.19	1706180	1707441	1708702	1709964	1711228	1712490	1713754	1715019	1716284	1717550
5.20	1718817	1720084	1721352	1722621	1723891	1725161	1726431	1727703	1728975	1730248
5.21	1731521	1732795	1734069	1735345	1736620	1737897	1739174	1740452	1741731	1743010
5.22	1744290	----------	----------	----------	----------	----------	----------	----------	----------	----------

TABLE II. *1958* He^4 *vapor pressure-temperature scale,* T *in ° K as a function of* P *in millimeters mercury at 0° C and standard gravity, 980.665 cm/sec^2*

P	0		1		2		3		4		5		6		7		8		9	
0.01	0.7907	65	7972	61	8033	57	8090	53	8143	50	8193	47	8240	45	8285	43	8328	40	8368	39
.02	.8407	38	8445	35	8480	35	8515	33	8548	32	8580	32	8612	30	8642	29	8671	28	8699	28
.03	.8727	27	8754	26	8780	25	8805	25	8830	24	8854	24	8878	23	8901	22	8923	22	8945	22
.04	.8967	21	8988	21	9009	20	9029	20	9049	19	9068	20	9088	18	9106	19	9125	18	9143	18
.05	.9161	18	9179	17	9196	17	9213	17	9230	16	9246	17	9263	16	9279	15	9294	16	9310	15
.06	.9325	15	9340	15	9355	15	9370	15	9385	14	9399	14	9413	14	9427	14	9441	14	9455	13
.07	.9468	14	9482	13	9495	13	9508	13	9521	13	9534	12	9546	13	9559	12	9571	12	9583	12
.08	.9595	12	9607	12	9619	12	9631	12	9643	11	9654	11	9665	12	9677	11	9688	11	9699	11
.09	.9710	11	9721	11	9732	10	9742	11	9753	10	9763	11	9774	10	9784	10	9794	10	9804	10
.10	.9814	10	9824	10	9834	10	9844	10	9854	9	9863	10	9873	10	9883	9	9892	9	9901	10
.11	.9911	9	9920	9	9929	9	9938	9	9947	9	9956	9	9965	9	9974	9	9983	8	9991	9
.12	1.0000	9	0009	8	0017	9	0026	8	0034	8	0042	9	0051	8	0059	8	0067	8	0075	8
.13	1.0083	8	0091	8	0099	8	0107	8	0115	8	0123	8	0131	8	0139	7	0146	8	0154	8
.14	1.0162	7	0169	8	0177	7	0184	8	0192	7	0199	7	0206	8	0214	7	0221	7	0228	8
.15	1.0236	7	0243	7	0250	7	0257	7	0264	7	0271	7	0278	7	0285	7	0292	7	0299	6
.16	1.0305	7	0312	7	0319	7	0326	6	0332	7	0339	7	0346	6	0352	7	0359	6	0365	7
.17	1.0372	6	0378	7	0385	6	0391	7	0398	6	0404	6	0410	7	0417	6	0423	6	0429	6
.18	1.0435	6	0441	7	0448	6	0454	6	0460	6	0466	6	0472	6	0478	6	0484	6	0490	6
.19	1.0496	6	0502	6	0508	5	0513	6	0519	6	0525	6	0531	6	0537	5	0542	6	0548	6

TABLE II. *1958* He^4 *vapor pressure-temperature scale,* T *in* °K *as a function of* P *in millimeters mercury at 0° C and standard gravity, 980.665 cm/sec*^{2}—Continued

P	0		1		2		3		4		5		6		7		8		9	
0.2	1.0554	55	0609	54	0663	52	0715	49	0764	49	0813	46	0859	45	0904	44	0948	43	0991	41
.3	1.1032	41	1073	39	1112	38	1150	38	1188	36	1224	36	1260	35	1295	34	1329	33	1362	33
.4	1.1395	32	1427	32	1459	31	1490	30	1520	30	1550	29	1579	29	1608	28	1636	27	1663	28
.5	1.1691	27	1718	26	1744	26	1770	26	1796	25	1821	25	1846	25	1871	24	1895	24	1919	23
.6	1.1942	24	1966	23	1989	22	2011	23	2034	22	2056	22	2078	21	2099	21	2120	21	2141	21
.7	1.2162	21	2183	20	2203	20	2223	20	2243	20	2263	20	2283	19	2302	19	2321	19	2340	19
.8	1.2359	18	2377	18	2395	19	2414	18	2432	17	2449	18	2467	18	2485	17	2502	17	2519	17
.9	1.2536	17	2553	17	2570	16	2586	17	2603	16	2619	16	2635	16	2651	16	2667	16	2683	16
1.0	1.2699	15	2714	16	2730	15	2745	15	2760	15	2775	15	2790	15	2805	15	2820	14	2834	15
1.1	1.2849	14	2863	15	2878	14	2892	14	2906	14	2920	14	2934	14	2948	13	2961	14	2975	14
1.2	1.2989	13	3002	13	3015	14	3029	13	3042	13	3055	13	3068	13	3081	13	3094	13	3107	12
1.3	1.3119	13	3132	13	3145	12	3157	12	3169	13	3182	12	3194	12	3206	12	3218	12	3230	12
1.4	1.3242	12	3254	12	3266	12	3278	12	3290	11	3301	12	3313	12	3325	11	3336	12	3348	11
1.5	1.3359	11	3370	11	3381	12	3393	11	3404	11	3415	11	3426	11	3437	11	3448	11	3459	10
1.6	1.3469	11	3480	11	3491	10	3501	11	3512	11	3523	10	3533	11	3544	10	3554	10	3564	11
1.7	1.3575	10	3585	10	3595	10	3605	10	3615	10	3625	10	3635	10	3645	10	3655	10	3665	10
1.8	1.3675	10	3685	10	3695	9	3704	10	3714	10	3724	9	3733	10	3743	9	3752	10	3762	9
1.9	1.3771	9	3780	10	3790	9	3799	10	3809	9	3818	9	3827	9	3836	9	3845	9	3854	9
2	1.3863	89	3952	86	4038	82	4120	80	4200	77	4277	75	4352	73	4425	71	4496	69	4565	67
3	1.4632	65	4697	63	4760	63	4823	60	4883	60	4943	58	5001	56	5057	56	5113	55	5168	53
4	1.5221	53	5274	51	5325	51	5376	49	5425	49	5474	48	5522	47	5569	47	5616	46	5662	45
5	1.5707	44	5751	44	5795	43	5838	42	5880	42	5922	41	5963	41	6004	40	6044	40	6084	39
6	1.6123	39	6162	38	6200	38	6238	37	6275	37	6312	36	6348	36	6384	36	6420	35	6455	35
7	1.6490	35	6525	34	6559	34	6593	33	6626	33	6659	33	6692	32	6724	32	6756	32	6788	32
8	1.6820	31	6851	31	6882	31	6913	30	6943	30	6973	30	7003	30	7033	29	7062	29	7091	29
9	1.7120	28	7148	29	7177	28	7205	28	7233	28	7261	27	7288	28	7316	27	7343	27	7370	26
10	1.7396	27	7423	26	7449	26	7475	26	7501	26	7527	25	7552	26	7578	25	7603	25	7628	25
11	1.7653	25	7678	24	7702	25	7727	24	7751	24	7775	24	7799	24	7823	23	7846	24	7870	23
12	1.7893	23	7916	23	7939	23	7962	23	7985	23	8008	22	8030	23	8053	22	8075	22	8097	22
13	1.8119	22	8141	22	8163	21	8184	22	8206	21	8227	22	8249	21	8270	21	8291	21	8312	21
14	1.8333	20	8353	21	8374	21	8395	20	8415	20	8435	21	8456	20	8476	20	8496	20	8516	20
15	1.8536	19	8555	20	8575	20	8595	19	8614	20	8634	19	8653	19	8672	19	8691	19	8710	19
16	1.8729	19	8748	19	8767	18	8785	19	8804	19	8823	18	8841	19	8860	18	8878	18	8896	18
17	1.8914	18	8932	18	8950	18	8968	18	8986	18	9004	18	9022	17	9039	18	9057	17	9074	18
18	1.9092	17	9109	17	9126	18	9144	17	9161	17	9178	17	9195	17	9212	17	9229	17	9246	16
19	1.9262	17	9279	17	9296	16	9312	17	9329	16	9345	17	9362	16	9378	16	9394	17	9411	16
20	1.9427	16	9443	16	9459	16	9475	16	9491	16	9507	16	9523	16	9539	15	9554	16	9570	16
21	1.9586	16	9602	15	9617	15	9632	16	9648	15	9663	16	9679	15	9694	15	9709	15	9724	16
22	1.9740	15	9755	15	9770	15	9785	15	9800	15	9815	15	9830	14	9844	15	9859	15	9874	15
23	1.9889	14	9903	15	9918	14	9932	15	9947	14	9961	15	9976	14	9990	15	0005	14	0019	14
24	2.0033	15	0048	14	0062	14	0076	14	0090	14	0104	14	0118	14	0132	14	0146	14	0160	14
25	2.0174	14	0188	14	0202	13	0215	14	0229	14	0243	14	0257	13	0270	14	0284	13	0297	14
26	2.0311	13	0324	14	0338	13	0351	14	0365	13	0378	13	0391	14	0405	13	0418	13	0431	13
27	2.0444	14	0458	13	0471	13	0484	13	0497	13	0510	13	0523	13	0536	13	0549	13	0562	13
28	2.0575	13	0588	12	0600	13	0613	13	0626	13	0639	13	0652	12	0664	13	0677	13	0690	12
29	2.0702	13	0715	12	0727	13	0740	12	0752	13	0765	12	0777	13	0790	12	0802	12	0814	13
30	2.0827	12	0839	12	0851	12	0863	13	0876	12	0888	12	0900	12	0912	12	0924	12	0936	13
31	2.0949	12	0961	12	0973	12	0985	12	0997	12	1009	12	1021	11	1032	12	1044	12	1056	12
32	2.1068	12	1080	12	1092	11	1103	12	1115	12	1127	12	1139	11	1150	12	1162	12	1174	11
33	2.1185	12	1197	11	1208	12	1220	11	1231	12	1243	11	1254	12	1266	11	1277	12	1289	11
34	2.1300	12	1312	11	1323	11	1334	12	1346	11	1357	11	1368	11	1379	12	1391	11	1402	11
35	2.1413	11	1424	12	1436	11	1447	11	1458	11	1469	11	1480	11	1491	11	1502	11	1513	11
36	2.1524	11	1535	11	1546	11	1557	11	1568	11	1579	11	1590	11	1601	11	1612	11	1623	11
37	2.1634	10	1644	11	1655	11	1666	11	1677	11	1688	10	1698	11	1709	11	1720	11	1731	10
38	2.1741	11	1752	11	1763	10	1773	11	1784	11	1795	10	1805	11	1816	10	1826	11	1837	11
39	2.1848	10	1858	11	1869	11	1880	10	1890	10	1900	10	1910	11	1921	10	1931	11	1942	10
40	2.1952	10	1962	11	1973	10	1983	10	1993	11	2004	10	2014	10	2024	10	2034	10	2044	11
41	2.2055	10	2065	10	2075	10	2085	10	2095	10	2105	10	2115	11	2126	10	2136	10	2146	10
42	2.2156	10	2166	10	2176	10	2186	10	2196	10	2206	10	2216	9	2225	10	2235	10	2245	10
43	2.2255	10	2265	10	2275	10	2285	9	2294	10	2304	10	2314	10	2324	10	2334	9	2343	10
44	2.2353	10	2363	9	2372	10	2382	10	2392	9	2401	10	2411	10	2421	9	2430	10	2440	10
45	2.2450	9	2459	9	2468	10	2478	10	2488	10	2498	9	2507	9	2516	9	2525	10	2535	9
46	2.2544	10	2554	9	2563	10	2573	9	2582	9	2591	10	2601	9	2610	9	2619	10	2629	9
47	2.2638	9	2647	9	2656	10	2666	9	2675	9	2684	9	2693	10	2703	9	2712	9	2721	9
48	2.2730	9	2739	9	2748	9	2757	10	2767	9	2776	9	2785	9	2794	9	2803	9	2812	9
49	2.2821	9	2830	9	2839	9	2848	9	2857	9	2866	9	2875	9	2884	9	2893	9	2902	9
50	2.2911	88	2999	87	3086	86	3172	85	3257	84	3341	83	3424	82	3506	81	3587	79	3666	79
60	2.3745	78	3823	78	3901	76	3977	75	4052	75	4127	74	4201	73	4274	73	4347	71	4418	71
70	2.4489	71	4560	69	4629	69	4698	68	4766	68	4834	67	4901	66	4967	66	5033	66	5099	64
80	2.5163	64	5227	64	5291	63	5354	63	5417	62	5479	61	5540	61	5601	61	5662	60	5722	59
90	2.5781	60	5841	58	5899	59	5958	57	6015	58	6073	57	6130	56	6186	57	6243	55	6298	56

TABLE II. *1958 He⁴ vapor pressure-temperature scale,* T *in °K as a function of* P *in millimeters mercury at 0° C and standard gravity, 980.665 cm/sec²*—Continued

P	0		1		2		3		4		5		6		7		8		9	
100	2.6354	55	6409	55	6464	54	6518	54	6572	53	6625	54	6679	53	6732	52	6784	52	6836	52
110	2.6888	52	6940	51	6991	51	7042	51	7093	50	7143	50	7193	50	7243	49	7292	49	7341	49
120	2.7390	49	7439	48	7487	48	7535	48	7583	48	7631	47	7678	47	7725	47	7772	46	7818	47
130	2.7865	46	7911	46	7957	45	8002	46	8048	45	8093	45	8138	44	8182	45	8227	44	8271	44
140	2.8315	44	8459	43	8402	44	8446	43	8489	43	8532	43	8575	42	8617	42	8659	43	8702	42
150	2.8744	41	8785	42	8827	42	8869	41	8910	41	8951	41	8992	40	9032	41	9073	40	9113	40
160	2.9153	40	9193	40	9233	40	9273	39	9312	40	9352	39	9391	39	9430	39	9469	39	9508	38
170	2.9546	39	9585	38	9623	38	9661	38	9699	38	9737	37	9774	38	9812	38	9850	36	9886	38
180	2.9924	37	9961	36	9997	37	0034	37	0071	36	0107	36	0143	36	0179	36	0215	36	0251	36
190	3.0287	36	0323	35	0358	35	0393	36	0429	35	0464	35	0499	35	0534	34	0568	35	0603	34
200	3.0637	35	0672	34	0706	34	0740	34	0774	34	0808	34	0842	34	0876	33	0909	34	0943	33
210	3.0976	34	1010	33	1043	33	1076	33	1109	33	1142	32	1174	33	1207	33	1240	32	1272	32
220	3.1304	33	1337	32	1369	32	1401	32	1433	32	1465	31	1496	32	1528	32	1560	31	1591	31
230	3.1622	32	1654	31	1685	31	1716	31	1747	31	1778	31	1809	31	1840	30	1870	31	1901	30
240	3.1931	31	1962	30	1992	30	2022	30	2052	30	2082	30	2112	30	2142	30	2172	30	2202	29
250	3.2231	30	2261	30	2291	29	2320	29	2349	30	2379	29	2408	29	2437	29	2466	29	2495	29
260	3.2524	28	2552	29	2581	29	2610	28	2638	29	2667	28	2695	29	2724	28	2752	28	2780	28
270	3.2808	28	2836	28	2864	28	2892	28	2920	28	2948	28	2976	27	3003	28	3031	27	3058	28
280	3.3086	27	3113	28	3141	27	3168	27	3195	27	3222	27	3249	27	3276	27	3303	27	3330	27
290	3.3357	27	3384	26	3410	27	3437	26	3463	27	3490	26	3516	27	3543	26	3569	26	3595	27
300	3.3622	26	3648	26	3674	26	3700	26	3726	26	3752	26	3778	25	3803	26	3829	26	3855	25
310	3.3880	26	3906	25	3931	26	3957	25	3982	26	4008	25	4033	25	4058	25	4083	26	4109	25
320	3.4134	25	4159	25	4184	25	4209	24	4233	25	4258	25	4283	25	4308	24	4332	25	4357	25
330	3.4382	24	4406	25	4431	24	4455	24	4479	25	4504	24	4528	24	4552	24	4576	25	4601	24
340	3.4625	24	4649	24	4673	24	4697	24	4721	23	4744	24	4768	24	4792	24	4816	23	4839	24
350	3.4863	23	4886	24	4910	23	4933	24	4957	23	4980	24	5004	23	5027	23	5050	23	5073	24
360	3.5097	23	5120	23	5143	23	5166	23	5189	23	5212	23	5235	23	5258	22	5280	23	5303	23
370	3.5326	23	5349	22	5371	23	5394	23	5417	22	5439	23	5462	22	5484	22	5506	23	5529	22
380	3.5551	22	5573	23	5596	22	5618	22	5640	22	5662	22	5684	22	5706	22	5728	22	5750	22
390	3.5772	22	5794	22	5816	22	5838	22	5860	21	5881	22	5903	22	5925	22	5947	21	5968	22
400	3.5990	21	6011	22	6033	21	6054	22	6076	21	6097	22	6119	21	6140	21	6161	21	6182	22
410	3.6204	21	6225	21	6246	21	6267	21	6288	21	6309	21	6330	21	6351	21	6372	21	6393	21
420	3.6414	21	6435	21	6456	21	6477	20	6497	21	6518	21	6539	20	6559	21	6580	21	6601	20
430	3.6621	21	6642	20	6662	21	6683	20	6703	21	6724	20	6744	20	6764	21	6785	20	6805	20
440	3.6825	20	6845	21	6866	20	6886	20	6906	20	6926	20	6946	20	6966	20	6986	20	7006	20
450	3.7026	20	7046	20	7066	20	7086	19	7105	20	7125	20	7145	20	7165	19	7184	20	7204	20
460	3.7224	19	7243	20	7263	19	7282	20	7302	20	7322	19	7341	19	7360	20	7380	19	7399	20
470	3.7419	19	7438	19	7457	20	7477	19	7496	19	7515	19	7534	19	7553	20	7573	19	7592	19
480	3.7611	19	7630	19	7649	19	7668	19	7687	19	7706	19	7725	19	7744	19	7763	18	7781	19
490	3.7800	19	7819	19	7838	19	7857	18	7875	19	7894	19	7913	18	7931	19	7950	19	7969	18
500	3.7987	19	8006	18	8024	19	8043	18	8061	19	8080	18	8098	19	8117	18	8135	18	8153	19
510	3.8172	18	8190	18	8208	19	8227	18	8245	18	8263	18	8281	18	8299	18	8317	19	8336	18
520	3.8354	18	8372	18	8390	18	8408	18	8426	18	8444	18	8462	18	8480	18	8498	18	8516	17
530	3.8533	18	8551	18	8569	18	8587	18	8605	17	8622	18	8640	18	8658	18	8676	17	8693	18
540	3.8711	17	8728	18	8746	18	8764	17	8781	18	8799	17	8816	18	8834	17	8851	18	8869	17
550	3.8886	17	8903	18	8921	17	8938	17	8955	18	8973	17	8990	17	9007	18	9025	17	9042	17
560	3.9059	17	9076	17	9093	18	9111	17	9128	17	9145	17	9162	17	9179	17	9196	17	9213	17
570	3.9230	17	9247	17	9264	17	9281	17	9298	17	9315	17	9332	17	9349	16	9365	17	9382	17
580	3.9399	17	9416	17	9433	16	9449	17	9466	17	9483	16	9499	17	9516	17	9533	16	9549	17
590	3.9566	17	9583	16	9599	17	9616	16	9632	17	9649	16	9665	17	9682	16	9698	17	9715	16
600	3.9731	16	9747	17	9764	16	9780	17	9797	16	9813	16	9829	17	9846	16	9862	16	9878	16
610	3.9894	17	9911	16	9927	16	9943	16	9959	16	9975	16	9991	16	0007	17	0024	16	0040	16
620	4.0056	16	0072	16	0088	16	0104	16	0120	16	0136	16	0152	16	0168	16	0184	15	0199	16
630	4.0215	16	0231	16	0247	16	0263	16	0279	16	0295	15	0310	16	0326	16	0342	16	0358	15
640	4.0373	16	0389	16	0405	15	0420	16	0436	16	0452	15	0467	16	0483	15	0498	16	0514	16
650	4.0530	15	0545	16	0561	15	0576	16	0592	15	0607	16	0623	15	0638	15	0653	16	0669	15
660	4.0684	16	0700	15	0715	15	0730	16	0746	15	0761	15	0776	16	0792	15	0807	15	0822	15
670	4.0837	16	0853	15	0868	15	0883	15	0898	15	0913	15	0928	16	0944	15	0959	15	0974	15
680	4.0989	15	1004	15	1019	15	1034	15	1049	15	1064	15	1079	15	1094	15	1109	15	1124	15
690	4.1139	15	1154	15	1169	15	1184	14	1198	15	1213	15	1228	15	1243	15	1258	15	1273	14
700	4.1287	15	1302	15	1317	15	1332	14	1346	15	1361	15	1376	15	1391	14	1405	15	1420	15
710	4.1435	14	1449	15	1464	14	1478	15	1493	15	1508	14	1522	15	1537	14	1551	15	1566	14
720	4.1580	15	1595	14	1609	15	1624	14	1638	15	1653	14	1667	14	1681	15	1696	14	1710	15
730	4.1725	14	1739	14	1753	15	1768	14	1782	14	1796	15	1811	14	1825	14	1839	14	1853	15
740	4.1868	14	1882	14	1896	14	1910	15	1925	14	1939	14	1953	14	1967	14	1981	14	1995	14
750	4.2009	15	2024	14	2038	14	2052	14	2066	14	2080	14	2094	14	2108	14	2122	14	2136	14
760	4.2150	14	2164	14	2178	14	2192	14	2206	14	2220	14	2234	14	2248	14	2262	13	2275	14
770	4.2289	14	2303	14	2317	14	2331	14	2345	14	2358	14	2372	14	2386	14	2400	14	2414	13
780	4.2427	14	2441	14	2455	14	2469	13	2482	13	2496	14	2510	13	2523	14	2537	14	2551	13
790	4.2564	14	2578	14	2592	13	2605	14	2619	13	2632	14	2646	13	2659	14	2673	13	2686	14

TABLE III. *1958* He^4 *vapor pressure-temperature scale,* T *in ° K as a function of* P *in centimeters mercury at 0° C and standard gravity, 980.665 cm/sec*^{2}

P	0		1		2		3		4		5		6		7		8		9	
80	4. 2700	135	2835	133	2968	132	3100	131	3231	131	3362	129	3491	128	3619	127	3746	126	3872	125
90	4. 3997	124	4121	123	4244	122	4366	122	4488	120	4608	120	4728	118	4846	118	4964	117	5081	116
100	4. 5197	116	5313	114	5427	114	5541	113	5654	112	5766	112	5878	111	5989	110	6099	109	6208	109
110	4. 6317	108	6425	107	6532	107	6639	106	6745	105	6850	105	6955	104	7059	103	7162	103	7265	102
120	4. 7367	102	7469	101	7570	100	7670	100	7770	100	7870	98	7968	99	8067	97	8164	97	8261	97
130	4. 8358	96	8454	96	8550	95	8645	94	8739	94	8833	94	8927	93	9020	92	9112	92	9204	92
140	4. 9296	91	9387	91	9478	90	9568	90	9658	89	9747	89	9836	89	9925	88	0013	88	0101	87
150	5. 0188	87	0275	86	0361	86	0447	86	0533	85	0618	85	0703	84	0787	84	0871	84	0955	83
160	5. 1038	83	1121	82	1203	83	1286	81	1367	82	1449	81	1530	81	1611	80	1691	80	1771	80
170	5. 1851	79	1930	79	2009	79	2088	78	2166	78										

TABLE IV. *Temperature derivative,* dP/dT, *in millimeters* Hg/° *K for the 1958* He^4 *vapor pressure-temperature scale,* P *in millimeters mercury at 0° C and standard gravity, 980.665 cm/sec*^{2}

T	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0. 5	0. 0005503	0. 0007383	0. 0009799	0. 001287	0. 001674	0. 002157	0. 002755	0. 003489	0. 004384	0. 005468
. 6	. 006772	. 008329	. 01018	. 01236	. 01493	. 01792	. 02141	. 02544	. 03008	. 03540
. 7	. 04148	. 04838	. 05622	. 06506	. 07501	. 08617	. 09863	. 1125	. 1280	. 1451
. 8	. 1640	. 1848	. 2077	. 2328	. 2602	. 2902	. 3228	. 3583	. 3968	. 4385
. 9	. 4835	. 5320	. 5843	. 6406	. 7008	. 7654	. 8346	. 9084	. 9871	1. 071
1. 0	1. 160	1. 255	1. 355	1. 462	1. 575	1. 694	1. 820	1. 953	2. 093	2. 240
1. 1	2. 395	2. 557	2. 728	2. 907	3. 095	3. 291	3. 496	3. 711	3. 935	4. 169
1. 2	4. 412	4. 666	4. 930	5. 205	5. 491	5. 788	6. 096	6. 416	6. 747	7. 090
1. 3	7. 445	7. 813	8. 194	8. 587	8. 993	9. 413	9. 846	10. 29	10. 75	11. 23
1. 4	11. 72	12. 22	12. 73	13. 26	13. 81	14. 37	14. 95	15. 54	16. 15	16. 77
1. 5	17. 41	18. 06	18. 73	19. 42	20. 12	20. 84	21. 58	22. 33	23. 10	23. 88
1. 6	24. 68	25. 50	26. 33	27. 18	28. 05	28. 94	29. 84	30. 76	31. 69	32. 64
1. 7	33. 61	34. 59	35. 59	36. 61	37. 64	38. 69	39. 76	40. 84	41. 94	43. 05
1. 8	44. 18	45. 33	46. 49	47. 67	48. 86	50. 06	51. 28	52. 52	53. 77	55. 03
1. 9	56. 30	57. 59	58. 89	60. 20	61. 52	62. 85	64. 19	65. 54	66. 91	68. 28
2. 0	69. 65	71. 03	72. 42	73. 81	75. 20	76. 60	77. 99	79. 39	80. 79	82. 20
2. 1	83. 60	85. 00	86. 38	87. 74	89. 09	90. 41	91. 71	92. 96	94. 28	95. 77
2. 2	97. 31	98. 88	100. 5	102. 1	103. 7	105. 4	107. 1	108. 8	110. 5	112. 2
2. 3	113. 9	115. 7	117. 5	119. 2	121. 0	122. 9	124. 7	126. 5	128. 4	130. 3
2. 4	132. 1	134. 1	136. 0	137. 9	139. 9	141. 8	143. 8	145. 8	147. 8	149. 8
2. 5	151. 9	153. 9	156. 0	158. 1	160. 2	162. 3	164. 5	166. 6	168. 8	171. 0
2. 6	173. 2	175. 4	177. 6	179. 8	182. 0	184. 3	186. 6	188. 8	191. 2	193. 5
2. 7	195. 9	198. 2	200. 6	202. 9	205. 3	207. 7	210. 1	212. 5	215. 0	217. 4
2. 8	219. 9	222. 4	224. 9	227. 4	230. 0	232. 4	235. 0	237. 6	240. 1	242. 7
2. 9	245. 4	248. 0	250. 6	253. 3	256. 0	258. 6	261. 3	264. 1	266. 8	269. 5
3. 0	272. 3	275. 1	277. 9	280. 7	283. 5	286. 3	289. 2	292. 0	294. 9	297. 8
3. 1	300. 7	303. 7	306. 6	309. 5	312. 5	315. 5	318. 5	321. 5	324. 5	327. 6
3. 2	330. 6	333. 7	336. 8	339. 9	343. 0	346. 1	349. 3	352. 4	355. 6	358. 7
3. 3	361. 9	365. 1	368. 4	371. 6	374. 8	378. 1	381. 4	384. 7	388. 0	391. 3
3. 4	394. 6	398. 0	401. 3	404. 7	408. 1	411. 5	414. 9	418. 3	421. 7	425. 2
3. 5	428. 7	432. 1	435. 6	439. 1	442. 7	446. 2	449. 7	453. 3	456. 9	460. 5
3. 6	464. 1	467. 7	471. 3	474. 9	478. 6	482. 3	486. 0	489. 7	493. 4	497. 2
3. 7	500. 9	504. 6	508. 4	512. 2	516. 0	519. 8	523. 6	527. 5	531. 3	535. 2
3. 8	539. 1	543. 0	546. 9	550. 8	554. 8	558. 8	562. 8	566. 8	570. 8	574. 9
3. 9	578. 9	583. 0	587. 1	591. 2	595. 4	599. 5	603. 7	607. 9	612. 1	616. 3
4. 0	620. 6	624. 8	629. 1	633. 3	637. 6	642. 0	646. 3	650. 6	655. 0	659. 4
4. 1	663. 7	668. 1	672. 6	677. 0	681. 4	685. 9	690. 3	694. 8	699. 2	703. 7
4. 2	708. 1	712. 6	717. 1	721. 6	726. 1	730. 7	735. 3	740. 0	744. 7	749. 4
4. 3	754. 1	758. 9	763. 7	768. 6	773. 4	778. 3	783. 2	788. 1	793. 0	797. 9
4. 4	802. 9	807. 9	812. 9	817. 9	822. 9	828. 0	833. 1	838. 1	843. 2	848. 4
4. 5	853. 5	858. 7	863. 9	869. 1	874. 3	879. 5	884. 8	890. 1	895. 3	900. 7
4. 6	906. 0	911. 4	916. 7	922. 1	927. 6	933. 0	938. 5	943. 9	949. 4	955. 0
4. 7	960. 5	966. 1	971. 7	977. 3	982. 9	988. 6	994. 4	1000	1006	1011
4. 8	1017	1023	1029	1035	1041	1046	1052	1058	1064	1070
4. 9	1076	1082	1088	1094	1100	1107	1113	1119	1125	1131
5. 0	1137	1144	1150	1156	1163	1169	1175	1182	1188	1195
5. 1	1201	1207	1214	1221	1227	1234	1240	1247	1254	1260
5. 2	1267	1274	1280							

TABLE V. *Auxiliary table for use in making hydrostatic head correction*

Table gives values of the ratio between the density of liquid He I at its saturated vapor pressure and the density of mercury at 0° C. (*P* in centimeters mercury at 0° C and standard gravity, 980.665 cm/sec^2.) The density of mercury has been taken as 13.5951 g/cm^3. If densities of liquid He I constitute critical data in an analysis, examination of the original literature is recommended.

P	0		1		2		3		4		5		6		7		8		9	
0	0.01								0754	37	0717	35	0682	33	0649	30	0619	29	0590	29
10	.010561	27	0534	26	0508	26	0482	25	0457	24	0433	24	0409	23	0386	23	0363	23	0340	23
20	.010317	22	0295	22	0273	22	0251	21	0230	21	0209	21	0188	21	0167	21	0146	20	0126	21
30	.010105	20	0085	20	0065	20	0045	20	0025	20	0005	20	9985	20	9965	19	9946	20	9926	19
40	.009907	20	9887	20	9867	19	9848	20	9828	19	9809	20	9789	19	9770	20	9750	19	9731	20
50	.009711	19	9692	19	9673	20	9653	19	9634	20	9614	20	9594	20	9574	19	9555	19	9536	20
60	.009516	20	9496	19	9477	19	9458	20	9438	19	9419	20	9399	19	9380	20	9360	20	9340	19
70	.009321	20	9301	19	9282	19	9263	20	9243	19	9224	19	9205	19	9186	19	9167	20	9147	19
80	.009128	19	9109	19	9090	20	9070	19	9051	20	9031	19	9012	20	8992	20	8972	20	8952	20
90	.008932	19	8913	20	8893	20	8873	20	8853	20	8833	21	8812	20	8792	21	8771	20	8751	21
100	.008730	21	8709	22	8687	21	8666	22	8644	21	8623	21	8602	22	8580	22	8558	22	8536	23
110	.008513	23	8490	22	8468	23	8445	23	8422	24	8398	23	8375	24	8351	24	8327	25	8302	24
120	.008278	24	8254	24	8230	25	8205	26	8179	26	8153	26	8127	27	8100	26	8074	27	8047	28
130	.008019	28	7991	28	7963	28	7935	29	7906	29	7877	29	7848	30	7818	31	7787	32	7755	32
140	.007723	33	7690	32	7658	33	7625	34	7591	36	7555	36	7519	37	7482	38	7444	39	7405	41
150	.007364	42	7322	43	7279	44	7235	46	7189	48	7141	49	7092	51	7041	53	6988	56	6932	59
160	.006873	61	6812	64	6748	68	6680	73	6607	79	6528	87	6441	103	6338	130	6208	154	6054	190
170	.005864	229	5635	287	5348															

TABLE VI. *Deviations of earlier scales from the 1958 scale,*[a] $T_n - T_{58}$ *in millidegrees*

T_n \ *n*	L55	55E	48	BS	37	32	29	24
° *K*								
0.7	−1.1	+1.0	+0.4	+0.3	--------	−18.4	−2.7	−2.1
.8	−1.2	+1.1	+.5	+.3	--------	−20.4	−10.3	−2.3
.9	−1.3	+1.2	+.6	+.4	−31.9	−22.1	−17.3	−2.4
1.0	−1.5	+1.3	+.3	+.4	−26.8	−23.5	−23.5	−2.6
1.1	−1.6	+1.4	−.2	+.4	−21.5	−24.7	−28.5	−2.7
1.2	−1.7	+1.5	+.4	+.5	−15.2	−25.4	−32.1	−2.8
1.3	−1.8	+1.5	+.3	+.6	−8.1	−25.7	−34.1	−3.0
1.4	−1.9	+1.6	+1.0	+.8	−2.3	−25.5	−34.5	−3.2
1.5	−2.0	+1.6	+1.3	+1.2	+1.1	−24.7	−33.2	−3.5
1.6	−2.1	+1.5	+2.9	+1.8	+2.6	−23.2	−30.3	+0.2
1.7	−2.1	+1.4	+3.8	+2.6	+3.2	−21.0	−25.9	+33.0
1.8	−2.2	+1.1	+3.9	+3.4	+3.5	−18.0	−20.2	+58.6
1.9	−2.2	+0.8	+5.1	+4.1	+4.2	−14.2	−13.3	+78.5
2.0	−2.2	+.6	+6.0	+4.6	+5.6	−9.7	−5.6	+93.6
2.1	−2.2	+.6	+8.4	+5.1	+7.1	−4.5	+2.5	+104.5
2.2	−2.2	+.8	+9.4	--------	+9.3	+8.2	+8.2	+111.2
2.3	−2.1	+.5	+8.5	--------	+8.2	+7.0	+7.0	+113.3
2.4	−2.0	0	+7.0	--------	+6.9	+5.4	+5.4	+111.2
2.5	−1.9	−.4	+5.6	--------	+5.5	+3.8	+3.8	+106.8
2.6	−1.8	−.7	+5.0	--------	+4.4	+2.1	+2.1	+100.7
2.7	−1.5	−.9	+4.5	--------	+3.6	+0.6	+0.6	+93.4
2.8	−1.3	−1.1	+3.6	--------	+3.4	−.9	−.9	+85.2
2.9	−0.9	−1.1	+4.7	--------	+3.6	−2.2	−2.2	+76.3
° *K*								
3.0	−.6	−1.1	+5.6	--------	+4.2	−3.5	−3.5	+66.8
3.1	−.2	−1.1	+6.0	--------	+5.3	−4.5	−4.5	+57.2
3.2	+.2	−0.9	+8.0	--------	+6.7	−5.2	−5.2	+47.7
3.3	+.7	−.7	+8.6	--------	+7.9	−5.7	−5.7	+38.4
3.4	+1.3	−.5	+8.7	--------	+8.7	−5.9	−5.9	+29.4
3.5	+1.9	−.3	+8.8	--------	+8.9	−5.8	−5.8	+21.0
3.6	+2.5	−.1	+8.7	--------	+9.0	−5.5	−5.5	+13.2
3.7	+2.9	0	+8.6	--------	+8.6	−4.8	−4.8	+6.2
3.8	+3.2	0	+7.7	--------	+7.5	−3.9	−3.9	−0.1
3.9	+3.2	−.1	+6.6	--------	+6.3	−2.6	−2.6	−5.4
4.0	+3.0	−.2	+5.0	--------	+4.7	−0.9	−0.9	−9.6
4.1	+2.4	−.3	+2.6	--------	+2.8	+1.2	+1.2	−12.7
4.2	+1.2	−.6	+0.5	--------	+1.1	+3.7	+3.7	−14.6
4.3	0	−1.0	−.4	--------	−0.5	+6.6	+6.6	−15.3
4.4	−.9	−1.4	+.9	--------	--------	+10.0	+10.0	−14.6
4.5	−1.5	−1.9	+3.8	--------	--------	+14.0	+14.0	−12.4
4.6	−1.7	−2.3	+7.7	--------	--------	+18.5	+18.5	−8.8
4.7	−1.5	−2.8	+11.9	--------	--------	+23.6	+23.6	−3.7
4.8	−0.9	−3.2	+15.8	--------	--------	+29.3	+29.3	+3.0
4.9	+.2	−3.7	+18.6	--------	--------	+35.7	+35.7	+11.1
5.0	+1.7	−4.1	+19.0	--------	--------	+42.6	+42.6	+20.8
5.1	+3.7	−4.5	+15.8	--------	--------	--------	--------	+32.1
5.2	+6.3	−5.0	+6.5	--------	--------	--------	--------	+45.0

[a] Explanatory notes concerning table of deviations of earlier scales from the 1958 scale:

T_{24}: Defined by equation on p. 33 of Leiden Comm. No. 147b (Kamerlingh Onnes and Weber) and by last equation on p. 23 of Leiden Comm. Suppl. No. 49 (Verschaffelt). These equations yield equal pressures at about 1.59° K. Therefore, values up through 1.5° K were derived from Verschaffelt's equation and those above from that of Kamerlingh Onnes and Weber.

T_{29}: Defined by eq (6) on p. 36 of Leiden Comm. No. 202c (Keesom, Weber, and Schmidt). These equations give equal pressures at 2.1765° K. The authors state in the last paragraph of the communication, p. 37, that the first of the equations fits reasonably well the data of Comm. No. 147b up to 5° K. Therefore, deviations up to 5.0° K have been included in the table.

T_{32}: Defined by the first of eq (6) on p. 36 of Leiden Comm. No. 202c (Keesom, Weber, and Schmidt) and by the equation on p. 8 of Leiden Comm. No. 219a (Keesom). T_{32} and T_{29} are thus identical above the lambda point. These two equations are discontinuous by about 0.008° at 2.190° K and this fact was noted by Keesom (Leiden Comm. Suppl. 71d).

T_{37}: Defined by T_{32} together with curves in figure 1 of Leiden Comm. No. 250c (Schmidt and Keesom). Differences between T_{37} and T_{32} were determined directly from figure 1 with sufficient precision to determine differences between T_{58} and T_{37} to 0.1 millidegree.

T_{BS}: Defined by eq (9) and curve of figure 4, p. 1212 of Trans. Faraday Soc. **35** (Bleaney and Simon, 1939). Part, or all, of this scale is sometimes referred to as T_{39}. In order to obtain differences between this scale and T_{58}, pressures were calculated from the equation and curve with sufficient precision to yield differences to 0.1 millidegree.

(*Continued on page 17*)

T_{48}: Defined by tables I and II on pages T153 to T159 and by second equation on p. T152 of Procès-Verbaux des séances du Comité International des Poids et Mesures **23B**, T151 (1952). Values given in the table were obtained in the following ways. First, values of the difference between this scale and the 1958 scale were calculated at every 0.01° interval between 0.95° and 4.25° K from data of table II on pp. T158 and T159. The tabulated values from 1.0° through 4.2° K were then obtained by averaging the calculated differences between $T-0.05°$ and $T+0.05°$, with weights of ½ assigned to the values at $T-0.05°$ and $T+0.05°$ and unit weights to all values at intermediate temperatures. For example, the tabulated value at 2.0° K is actually 1/20 of the sum of the differences at 1.95° and 2.05° plus 1/10 of the sum of the differences at 1.96°, 1.97°, 1.98°, 1.99°, 2.00°, 2.01°, 2.02°, 2.03°, and 2.04° K. The tabulated values at 0.7°, 0.8°, and 0.9° K were obtained by calculating the pressure corresponding to each 0.01° interval between 0.65° and 0.95° K from the data on p. T153 of table I and averaging the results in the manner just described. At 4.3° K and above, the tabulated values were obtained directly from the equation given on p. T152. Tables and equation have been published also by C. F. Squire, *Low temperature physics*, pp. 229 to 233 and p. 26 (McGraw-Hill Book Co., Inc., New York, N.Y., 1953).

T_{55E}: Defined by the unnumbered equations on p. 188, *Low temperature physics and chemistry* (Clement), Proc. Fifth Intern. Conf. (Univ. of Wisconsin Press, Madison, Wis., 1958). Values of vapor pressure in millimeters mercury at 20° C were calculated by the computer at the U.S. Naval Research Laboratory (the NAREC) and values in millimeters mercury at 0° C were calculated by the computer at Los Alamos Scientific Laboratory (the MANIAC). The MANIAC calculation was used for obtaining the values in the table.

T_{L55}: Defined by table VII on p. 461, *Progress in low temperature physics* (Van Dijk and Durieux), (North-Holland Publishing Co., Amsterdam, Netherlands, 1957). Values below 0.9° K were obtained from the tables mentioned in section 23 of the reference. Table VII mentioned above is the same as table V published in Physica **24,** 1 (1958) and in Leiden Comm. Suppl. 113c.

TABLE VII. *Auxiliary table for use in making corrections for density of mercury at temperatures other than 0° C*[a]

Table gives values of the ratio between the density of mercury at the indicated temperature (° C) and that at 0° C.

t° C	0	1	2	3	4	5	6	7	8	9
10	0.99818	800	782	764	746	728	710	692	674	655
20	.99637	619	601	583	565	547	529	511	493	475
30	.99457	439	421	403	385	367	349	331	313	295

[a] Smithsonian Physical Tables, Ninth Revised Ed., edited by W. E. Forsythe, p. 153 (The Smithsonian Inst., Washington, D.C., 1954).

Equation for Computing Local Acceleration Due to Gravity[1, 2]

Most frequently the vapor pressure is measured as a distance between two mercury levels. After corrections for capillarity and for the temperature of the mercury and the scale have been applied, the height, h, has to be reduced to standard gravity. The reduced height, h_0, can be computed from $h_0=hg/980.665$. If the local value of g is unknown, it may be computed with sufficient accuracy for correcting the height of a mercury column from

$$g=980.632-2.586\cos 2\phi+0.003\cos 4\phi$$
$$-0.0003086\,H$$

where ϕ is the local latitude and H the local altitude in meters. The unit of g is cm/sec².

---

[1] Procès-Verbaux des séances du Comité International des Poids et Mesures **22,** pp. 96 to 98, 114 to 118, 129 to 134 (1950).

[2] G. D. Garland, pp. 221, 222, Karl Jung, p. 564, Handbuch der Physik edited by J. Bartels **47,** (Springer-Verlag, Berlin, 1956).

JOURNAL OF RESEARCH of the National Bureau of Standards—A. Physics and Chemistry
Vol. 68A, No. 6, November–December 1964

The 1962 He^3 Scale of Temperatures
IV. Tables[1, 2]

R. H. Sherman, S. G. Sydoriak, and T. R. Roberts

Los Alamos Scientific Laboratory, University of California
Los Alamos, N. Mex.

(June 16, 1964)

The detailed tables of the 1962 He^3 Scale of Temperatures are presented. The vapor pressure of He^3 is tabulated in steps of 1 millidegree from 0.2 to 3.324 °K, the critical temperature. A table giving temperature, to 0.1 millidegree, as a function of pressure is included, as well as the temperature derivative of the vapor pressure.

1. Introduction

It is the purpose of this paper to present the detailed tables which comprise the 1962 He^3 Scale of Temperatures. The reader is referred to the other publications in this series for discussions of the apparatus and input vapor pressure data [45, 46];[3] the derivation of the scale [6, 66]; and the evaluation of the scale with gas isotherm and other data [7, 10].

2. Description of the Tables

In tables 1a and 1b, He^3 vapor pressures are given as a function of the temperature, designated as T_{62}. Tables 1a and 1b contain entries every millidegree from 0.2 to 3.324 °K, the critical temperature. The pressure, in millimeters of mercury at 0 °C, and standard gravity (980.665 cm/sec.^{2}), is given by the following equation, which defines the 1962 He^3 Scale:

$$\begin{aligned}\ln P_3 = & -2.49174/T + 4.80386 - 0.286001\,T \\ & + 0.198608T^2 - 0.0502237T^3 + 0.00505486T^4 \\ & + 2.24846 \ln T \qquad 0.2 < T < 3.324\ \text{°K}. \qquad (1)\end{aligned}$$

Tables 2a and 2b are inverted tables giving the temperature as a function of the vapor pressure of He^3. The entries were evaluated by solving eq (1) implicitly by a process of successive iterations. The convergence criterion was set at 0.01 mdeg after which the entries were rounded to the nearest 0.1 mdeg (a 5 was always rounded up). Thus tables 1 and 2 should never show more than a 0.1 mdeg deviation from one another.

Table 3, giving values of the derivative dP_3/dT_{62} at intervals of 0.01 deg from 0.2 to 3.33 °K, was computed analytically from eq (1) and its first temperature derivative, i.e.,

$$\frac{dP}{dT} = P\,\frac{d \ln P}{dT}. \qquad (2)$$

Certain portions of parts I, II, and III of this series might be particularly useful to users of these tables. For example, a shortened version of tables 1a and 1b appears as table 5 of Part II.

Deviations of the 1962 He^3 Scale from various previous He^3 temperature scales are given in table 6 of Part II.

A compliation of thermodynamic properties of He^3 consistent with the 1962 He^3 Scale is given in table 4 of Part III.

General remarks concerning various needed corrections to a vapor-pressure measurement are given in the section of Part I entitled "Pressure Measurement." Figure 4 of Part I depicts a convenient procedure for making the important thermal transpiration correction. Additional remarks on this latter correction factor are given in section 5 of Part III.

---

[1] Work performed under the auspices of the United States Atomic Energy Commission.

[2] These tables are the same as those issued as Los Alamos Scientific Laboratory Report LAMS-2701 (July, 1962).

[3] Figures in brackets indicate the literature references at the end of this paper.

Table 1a. *Vapor pressure of He³ (1962 Scale) in microns (10^{-3} mm) of mercury at 0 °C and standard gravity, 980.665 cm/sec²*

T_{62}, °K	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
0.200	0.0121	0.0130	0.0140	0.0150	0.0161	0.0173	0.0185	0.0199	0.0213	0.0228
.210	.0244	.0260	.0278	.0297	.0317	.0338	.0360	.6384	.0409	.0435
.220	.0463	.0492	.0523	.0555	.0590	.0626	.0664	.0703	.0745	.0789
.230	.0835	.0884	.0935	.0988	.1044	.1103	.1165	.1229	.1296	.1367
.240	.1441	.1518	.1599	.1683	.1772	.1864	.1960	.2060	.2165	.2274
.250	.2388	.2506	.2630	.2759	.2893	.3032	.3178	.3329	.3486	.3649
.260	.3819	.3995	.4179	.4369	.4566	.4771	.4984	.5205	.5434	.5671
.270	.5917	.6172	.6436	.6710	.6993	.7286	.7589	.7903	.8228	.8564
.280	.8911	.9270	.9642	1.0025	1.0421	1.0830	1.1253	1.1689	1.2139	1.2603
.290	1.3082	1.3576	1.4086	1.4612	1.5153	1.5712	1.6287	1.6880	1.7490	1.8119
.300	1.877	1.943	2.012	2.082	2.155	2.230	2.307	2.386	2.467	2.550
.310	2.636	2.724	2.815	2.908	3.004	3.102	3.203	3.306	3.413	3.522
.320	3.633	3.748	3.866	3.987	4.111	4.237	4.368	4.501	4.638	4.778
.330	4.921	5.069	5.219	5.373	5.531	5.693	5.859	6.028	6.202	6.379
.340	6.561	6.747	6.937	7.131	7.330	7.533	7.741	7.954	8.171	8.393
.350	8.619	8.851	9.088	9.330	9.577	9.829	10.087	10.350	10.619	10.893
.360	11.173	11.459	11.750	12.048	12.351	12.661	12.977	13.299	13.628	13.963
.370	14.304	14.653	15.008	15.370	15.739	16.115	16.498	16.889	17.287	17.692
.380	18.105	18.525	18.954	19.390	19.834	20.286	20.747	21.216	21.693	22.179
.390	22.673	23.176	23.688	24.209	24.739	25.278	25.826	26.384	26.952	27.529
.400	28.115	28.712	29.319	29.935	30.562	31.200	31.847	32.506	33.175	33.855
.410	34.546	35.248	35.961	36.686	37.422	38.169	38.929	39.700	40.483	41.278
.420	42.086	42.906	43.738	44.583	45.441	46.312	47.196	48.093	49.003	49.927
.430	50.864	51.815	52.780	53.759	54.753	55.760	56.782	57.818	58.870	59.936
.440	61.017	62.113	63.225	64.352	65.494	66.653	67.827	69.017	70.224	71.447
.450	72.686	73.942	75.215	76.505	77.812	79.136	80.478	81.837	83.214	84.609
.460	86.022	87.453	88.902	90.370	91.857	93.362	94.887	96.431	97.994	99.576
.470	101.179	102.801	104.443	106.105	107.787	109.490	111.214	112.959	114.724	116.511
.480	118.319	120.148	121.999	123.872	125.768	127.685	129.624	131.586	133.571	135.579
.490	137.610	139.664	141.741	143.842	145.967	148.115	150.288	152.485	154.707	156.953
.500	159.224	161.520	163.841	166.188	168.560	170.958	173.381	175.831	178.308	180.810
.510	183.339	185.896	188.479	191.089	193.727	196.392	199.085	201.806	204.556	207.333
.520	210.139	212.974	215.838	218.731	221.653	224.604	227.586	230.597	233.638	236.709
.530	239.811	242.943	246.107	249.301	252.526	255.783	259.072	262.392	265.745	269.129
.540	272.546	275.995	279.478	282.993	286.541	290.123	293.739	297.388	301.071	304.788
.550	308.540	312.326	316.147	320.003	323.895	327.821	331.784	335.782	339.816	343.886
.560	347.992	352.136	356.316	360.533	364.787	369.079	373.408	377.775	382.181	386.624
.570	391.106	395.627	400.187	404.785	409.423	414.100	418.818	423.575	428.372	433.209
.580	438.087	443.006	447.966	452.967	458.009	463.093	468.219	473.387	478.597	483.850
.590	489.145	494.483	499.864	505.288	510.756	516.268	521.824	527.423	533.068	538.756
.600	544.490	550.268	556.092	561.961	567.876	573.837	579.844	585.897	591.997	598.143
.610	604.337	610.577	616.865	623.201	629.584	636.016	642.496	649.024	655.601	662.227
.620	668.902	675.626	682.400	689.224	696.097	703.021	709.996	717.021	724.097	731.224
.630	738.402	745.633	752.914	760.248	767.634	775.073	782.564	790.108	797.705	805.355
.640	813.059	820.817	828.629	836.495	844.416	852.391	860.421	868.506	876.646	884.842
.650	893.094	901.402	909.766	918.186	926.663	935.197	943.789	952.437	961.143	969.907
.660	978.729	987.609	996.548	1005.545	1014.601	1023.717	1032.891	1042.126	1051.420	1060.774
.670	1070.189	1079.664	1089.199	1098.796	1108.454	1118.173	1127.954	1137.796	1147.701	1157.668
.680	1167.698	1177.790	1187.946	1198.164	1208.446	1218.792	1229.202	1239.675	1250.213	1260.816
.690	1271.483	1282.216	1293.013	1303.877	1314.805	1325.800	1336.861	1347.989	1359.183	1370.443
.700	1381.771	1393.167	1404.629	1416.160	1427.758	1439.425	1451.160	1462.964	1474.836	1486.778
.710	1498.789	1510.870	1523.021	1535.241	1547.532	1559.894	1572.326	1584.829	1597.403	1610.048
.720	1622.766	1635.555	1648.416	1661.350	1674.356	1687.434	1700.586	1713.811	1727.110	1740.482
.730	1753.928	1767.449	1781.043	1794.713	1808.457	1822.276	1836.171	1850.141	1864.186	1878.308
.740	1892.506	1906.780	1921.132	1935.559	1950.065	1964.647	1979.307	1994.045	2008.861	2023.755
.750	2038.728	2053.779	2068.909	2084.119	2099.408	2114.776	2130.225	2145.753	2161.362	2177.051
.760	2192.821	2208.673	2224.605	2240.619	2256.715	2272.892	2289.152	2305.494	2321.919	2338.426
.770	2355.017	2371.691	2388.448	2405.289	2422.215	2439.224	2456.318	2473.496	2490.760	2508.108
.780	2525.542	2543.061	2560.667	2578.358	2596.136	2614.000	2631.951	2649.988	2668.113	2686.326
.790	2704.626	2723.014	2741.490	2760.054	2778.707	2797.448	2816.279	2835.199	2854.208	2873.307
.800	2892.496	2911.775	2931.145	2950.605	2970.156	2989.798	3009.531	3029.356	3049.272	3069.280
.810	3089.381	3109.574	3129.860	3150.239	3170.710	3191.275	3211.934	3232.686	3253.533	3274.474
.820	3295.508	3316.638	3337.863	3359.183	3380.598	3402.109	3423.716	3445.419	3467.217	3489.113
.830	3511.105	3533.194	3555.381	3577.665	3600.046	3622.525	3645.103	3667.779	3690.553	3713.426
.840	3736.398	3759.469	3782.640	3805.910	3829.281	3852.751	3876.322	3899.993	3923.765	3947.639
.850	3971.613	3995.689	4019.866	4044.146	4068.528	4093.012	4117.598	4142.288	4167.080	4191.976
.860	4216.976	4242.079	4267.286	4292.597	4318.012	4343.533	4369.158	4394.888	4420.723	4446.664
.870	4472.711	4498.864	4525.123	4551.488	4577.960	4604.539	4631.225	4658.018	4684.919	4711.928
.880	4739.044	4766.269	4793.602	4821.044	4848.595	4876.255	4904.024	4931.903	4959.891	4987.990
.890	5016.198	5044.517	5072.947	5101.488	5130.140	5158.903	5187.778	5216.764	5245.863	5275.073
.900	5304.397	5333.832	5363.381	5393.043	5422.818	5452.707	5482.709	5512.826	5543.057	5573.402
.910	5603.862	5634.436	5665.126	5695.931	5726.852	5757.889	5789.041	5820.310	5851.695	5883.196
.920	5914.815	5946.551	5978.404	6010.374	6642.463	6074.669	6106.994	6139.436	6171.998	6204.679
.930	6287.478	6270.397	6303.435	6336.593	6369.871	6403.269	6436.788	6470.427	6504.187	6538.068
.940	6572.071	6606.195	6640.440	6674.808	6709.297	6743.909	6778.644	6813.502	6848.482	6883.586
.950	6918.813	6954.164	6989.639	7025.238	7060.961	7096.809	7132.781	7168.879	7205.101	7241.450
.960	7277.923	7314.523	7351.249	7388.101	7425.079	7462.185	7499.417	7536.776	7574.263	7611.878
.970	7649.620	7687.490	7725.489	7763.616	7801.872	7840.256	7878.770	7917.413	7956.186	7995.088
.980	8034.121	8073.283	8112.576	8152.000	8191.554	8231.240	8271.057	8311.005	8351.085	8391.297
.990	8431.641	8472.118	8512.727	8553.469	8594.343	8635.352	8676.493	8717.768	8759.177	8800.720

Table 1b. *Vapor pressure of* He^3 *(1962 Scale) in millimeters of mercury at 0 °C and standard gravity, 980.665 cm/sec*^{2}

T_{62}, °K	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
1.000	8.842	8.884	8.926	8.968	9.010	9.053	9.095	9.138	9.181	9.224
1.010	9.267	9.310	9.353	9.397	9.440	9.484	9.528	9.572	9.616	9.660
1.020	9.704	9.749	9.794	9.839	9.884	9.929	9.974	10.019	10.065	10.110
1.030	10.156	10.202	10.248	10.294	10.341	10.387	10.434	10.481	10.528	10.575
1.040	10.622	10.669	10.717	10.765	10.812	10.860	10.908	10.957	11.005	11.054
1.050	11.102	11.151	11.200	11.249	11.298	11.348	11.397	11.447	11.497	11.547
1.060	11.597	11.647	11.698	11.748	11.799	11.850	11.901	11.952	12.003	12.055
1.070	12.106	12.158	12.210	12.262	12.314	12.367	12.419	12.472	12.525	12.577
1.080	12.631	12.684	12.737	12.791	12.845	12.898	12.952	13.007	13.061	13.115
1.090	13.170	13.225	13.280	13.335	13.390	13.446	13.501	13.557	13.613	13.669
1.100	13.725	13.781	13.838	13.894	13.951	14.008	14.065	14.123	14.180	14.238
1.110	14.295	14.353	14.411	14.469	14.528	14.586	14.645	14.704	14.763	14.822
1.120	14.881	14.941	15.001	15.060	15.120	15.180	15.241	15.301	15.362	15.423
1.130	15.484	15.545	15.606	15.667	15.729	15.791	15.853	15.915	15.977	16.039
1.140	16.102	16.165	16.227	16.291	16.354	16.417	16.481	16.544	16.608	16.672
1.150	16.737	16.801	16.865	16.930	16.995	17.060	17.125	17.191	17.256	17.322
1.160	17.388	17.454	17.520	17.586	17.653	17.720	17.787	17.854	17.921	17.988
1.170	18.056	18.124	18.192	18.260	18.328	18.396	18.465	18.534	18.603	18.672
1.180	18.741	18.810	18.880	18.950	19.020	19.090	19.160	19.231	19.301	19.372
1.190	19.443	19.514	19.586	19.657	19.729	19.801	19.873	19.945	20.018	20.090
1.200	20.163	20.236	20.309	20.382	20.456	20.529	20.603	20.677	20.751	20.826
1.210	20.900	20.975	21.050	21.125	21.200	21.275	21.351	21.427	21.503	21.579
1.220	21.655	21.732	21.808	21.885	21.962	22.039	22.117	22.194	22.272	22.350
1.230	22.428	22.507	22.585	22.664	22.743	22.822	22.901	22.980	23.060	23.140
1.240	23.220	23.300	23.380	23.460	23.541	23.622	23.703	23.784	23.866	23.947
1.250	24.029	24.111	24.193	24.276	24.358	24.441	24.524	24.607	24.690	24.774
1.260	24.857	24.941	25.025	25.110	25.194	25.279	25.363	25.448	25.534	25.619
1.270	25.704	25.790	25.876	25.962	26.049	26.135	26.222	26.309	26.396	26.483
1.280	26.571	26.658	26.746	26.834	26.922	27.011	27.099	27.188	27.277	27.366
1.290	27.456	27.545	27.635	27.725	27.815	27.906	27.996	28.087	28.178	28.269
1.300	28.360	28.452	28.544	28.636	28.728	28.820	28.913	29.005	29.098	29.191
1.310	29.285	29.378	29.472	29.566	29.660	29.754	29.849	29.943	30.038	30.133
1.320	30.229	30.324	30.420	30.516	30.612	30.708	30.805	30.901	30.998	31.095
1.330	31.193	31.290	31.388	31.486	31.584	31.682	31.781	31.879	31.978	32.077
1.340	32.177	32.276	32.376	32.476	32.576	32.676	32.777	32.878	32.979	33.080
1.350	33.181	33.283	33.385	33.486	33.589	33.691	33.794	33.897	34.000	34.103
1.360	34.206	34.310	34.414	34.518	34.622	34.726	34.831	34.936	35.041	35.146
1.370	35.252	35.358	35.464	35.570	35.676	35.783	35.889	35.996	36.104	36.211
1.380	36.319	36.427	36.535	36.643	36.751	36.860	36.969	37.078	37.187	37.297
1.390	37.407	37.516	37.627	37.737	37.848	37.958	38.069	38.181	38.292	38.404
1.400	38.516	38.628	38.740	38.853	38.965	39.078	39.191	39.305	39.418	39.532
1.410	39.646	39.761	39.875	39.990	40.105	40.220	40.335	40.451	40.566	40.682
1.420	40.799	40.915	41.032	41.149	41.266	41.383	41.501	41.618	41.736	41.855
1.430	41.973	42.092	42.210	42.330	42.449	42.568	42.688	42.808	42.928	43.049
1.440	43.169	43.290	43.411	43.533	43.654	43.776	43.898	44.020	44.142	44.265
1.450	44.388	44.511	44.634	44.758	44.882	45.006	45.130	45.254	45.379	45.504
1.460	45.629	45.754	45.880	46.006	46.132	46.258	46.385	46.511	46.638	46.765
1.470	46.893	47.020	47.148	47.276	47.405	47.533	47.662	47.791	47.920	48.050
1.480	48.179	48.309	48.439	48.570	48.700	48.831	48.962	49.094	49.225	49.357
1.490	49.489	49.621	49.754	49.886	50.019	50.152	50.286	50.419	50.553	50.687
1.500	50.822	50.956	51.091	51.226	51.361	51.497	51.633	51.769	51.905	52.041
1.510	52.178	52.315	52.452	52.589	52.727	52.865	53.003	53.141	53.280	53.419
1.520	53.558	53.697	53.837	53.976	54.116	54.257	54.397	54.538	54.679	54.820
1.530	54.961	55.103	55.245	55.387	55.529	55.672	55.815	55.958	56.101	56.245
1.540	56.389	56.533	56.677	56.822	56.967	57.112	57.257	57.402	57.548	57.694
1.550	57.840	57.987	58.134	58.281	58.428	58.575	58.723	58.871	59.019	59.168
1.560	59.316	59.465	59.615	59.764	59.914	60.064	60.214	60.364	60.515	60.666
1.570	60.817	60.968	61.120	61.272	61.424	61.576	61.729	61.882	62.035	62.189
1.580	62.342	62.496	62.650	62.805	62.959	63.114	63.269	63.425	63.580	63.736
1.590	63.892	64.049	64.205	64.362	64.519	64.677	64.834	64.992	65.150	65.309
1.600	65.467	65.626	65.785	65.945	66.105	66.264	66.425	66.585	66.746	66.907
1.610	67.068	67.229	67.391	67.553	67.715	67.878	68.040	68.203	68.366	68.530
1.620	68.694	68.858	69.022	69.186	69.351	69.516	69.682	69.847	70.013	70.179
1.630	70.345	70.512	70.679	70.846	71.013	71.181	71.348	71.517	71.685	71.854
1.640	72.022	72.192	72.361	72.531	72.701	72.871	73.041	73.212	73.383	73.554
1.650	73.726	73.897	74.070	74.242	74.414	74.587	74.760	74.934	75.107	75.281
1.660	75.455	75.630	75.804	75.979	76.154	76.330	76.505	76.681	76.858	77.034
1.670	77.211	77.388	77.565	77.743	77.921	78.099	78.277	78.456	78.635	78.814
1.680	78.993	79.173	79.353	79.533	79.714	79.894	80.075	80.257	80.438	80.620
1.690	80.802	80.985	81.167	81.350	81.533	81.717	81.901	82.085	82.269	82.453
1.700	82.638	82.823	83.009	83.194	83.380	83.566	83.753	83.939	84.126	84.314
1.710	84.501	84.689	84.877	85.065	85.254	85.443	85.632	85.821	86.011	86.201
1.720	86.391	86.582	86.773	86.964	87.155	87.347	87.539	87.731	87.923	88.116
1.730	88.309	88.502	88.696	88.890	89.084	89.278	89.473	89.668	89.863	90.059
1.740	90.254	90.450	90.647	90.843	91.040	91.238	91.435	91.633	91.831	92.029
1.750	92.228	92.426	92.626	92.825	93.025	93.225	93.425	93.625	93.826	94.027
1.760	94.229	94.430	94.632	94.834	95.037	95.240	95.443	95.646	95.850	96.054
1.770	96.258	96.462	96.667	96.872	97.077	97.283	97.489	97.695	97.902	98.108
1.780	98.315	98.523	98.730	98.938	99.146	99.355	99.564	99.773	99.982	100.192
1.790	100.402	100.612	100.822	101.033	101.244	101.455	101.667	101.879	102.091	102.304

TABLE 1b. *Vapor pressure of He^3 (1962 Scale) in millimeters of mercury at 0 °C and standard gravity, 980.665 cm/sec^2*—Con.

T_{62}, °K	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
1.800	102.516	102.729	102.943	103.156	103.370	103.585	103.799	104.014	104.229	104.444
1.810	104.660	104.876	105.092	105.309	105.526	105.743	105.960	106.178	106.396	106.614
1.820	106.833	107.052	107.271	107.490	107.710	107.930	108.150	108.371	108.592	108.813
1.830	109.035	109.256	109.479	109.701	109.924	110.147	110.370	110.593	110.817	111.042
1.840	111.266	111.491	111.716	111.941	112.167	112.393	112.619	112.846	113.072	113.300
1.850	113.527	113.755	113.983	114.211	114.440	114.669	114.898	115.127	115.357	115.587
1.860	115.818	116.048	116.279	116.511	116.742	116.974	117.206	117.439	117.672	117.905
1.870	118.138	118.372	118.606	118.840	119.075	119.310	119.545	119.781	120.016	120.253
1.880	120.489	120.726	120.963	121.200	121.438	121.676	121.914	122.153	122.391	122.631
1.890	122.870	123.110	123.350	123.590	123.831	124.072	124.313	124.555	124.797	125.039
1.900	125.282	125.525	125.768	126.011	126.255	126.499	126.743	126.988	127.233	127.478
1.910	127.724	127.970	128.216	128.463	128.709	128.957	129.204	129.452	129.700	129.948
1.920	130.197	130.446	130.695	130.945	131.195	131.445	131.696	131.946	132.198	132.449
1.930	132.701	132.953	133.205	133.458	133.711	133.965	134.218	134.472	134.727	134.981
1.940	135.236	135.491	135.747	136.003	136.259	136.515	136.772	137.029	137.287	137.545
1.950	137.803	138.061	138.320	138.579	138.838	139.098	139.358	139.618	139.879	140.140
1.960	140.401	140.662	140.924	141.186	141.449	141.712	141.975	142.238	142.502	142.766
1.970	143.031	143.295	143.560	143.826	144.091	144.357	144.624	144.890	145.157	145.425
1.980	145.692	145.960	146.228	146.497	146.766	147.035	147.305	147.575	147.845	148.115
1.990	148.386	148.657	148.929	149.200	149.473	149.745	150.018	150.291	150.564	150.838
2.000	151.112	151.386	151.661	151.936	152.212	152.487	152.763	153.040	153.316	153.593
2.010	153.870	154.148	154.426	154.704	154.983	155.262	155.541	155.821	156.101	156.381
2.020	156.661	156.942	157.224	157.505	157.787	158.069	158.352	158.635	158.918	159.201
2.030	159.485	159.769	160.054	160.339	160.624	160.910	161.195	161.482	161.768	162.055
2.040	162.342	162.629	162.917	163.205	163.494	163.783	164.072	164.361	164.651	164.941
2.050	165.232	165.523	165.814	166.105	166.397	166.689	166.982	167.275	167.568	167.861
2.060	168.155	168.449	168.744	169.038	169.334	169.629	169.925	170.221	170.518	170.814
2.070	171.112	171.409	171.707	172.005	172.304	172.602	172.902	173.201	173.501	173.801
2.080	174.102	174.403	174.704	175.005	175.307	175.610	175.912	176.215	176.518	176.822
2.090	177.126	177.430	177.735	178.040	178.345	178.651	178.957	179.263	179.570	179.877
2.100	180.184	180.492	180.800	181.108	181.417	181.726	182.035	182.345	182.655	182.965
2.110	183.276	183.587	183.899	184.211	184.523	184.835	185.148	185.461	185.775	186.089
2.120	186.403	186.717	187.032	187.348	187.663	187.979	188.295	188.612	188.929	189.246
2.130	189.564	189.882	190.200	190.519	190.838	191.158	191.477	191.797	192.118	192.439
2.140	192.760	193.081	193.403	193.725	194.048	194.371	194.694	195.018	195.342	195.666
2.150	195.990	196.315	196.641	196.967	197.293	197.619	197.946	198.273	198.600	198.928
2.160	199.256	199.585	199.914	200.243	200.572	200.902	201.233	201.563	201.891	202.226
2.170	202.557	202.889	203.222	203.554	203.888	204.221	204.555	204.889	205.223	205.558
2.180	205.894	206.229	206.565	206.901	207.238	207.575	207.913	208.250	208.588	208.927
2.190	209.266	209.605	209.944	210.284	210.624	210.965	211.306	211.647	211.989	212.331
2.200	212.673	213.016	213.359	213.703	214.046	214.391	214.735	215.080	215.425	215.771
2.210	216.117	216.463	216.810	217.157	217.505	217.852	218.201	218.549	218.898	219.247
2.220	219.597	219.947	220.297	220.648	220.999	221.350	221.702	222.054	222.407	222.760
2.230	223.113	223.467	223.821	224.175	224.530	224.885	225.240	225.596	225.952	226.309
2.240	226.665	227.023	227.380	227.738	228.097	228.455	228.815	229.174	229.534	229.894
2.250	230.255	230.616	230.977	231.339	231.701	232.063	232.426	232.789	233.153	233.516
2.260	233.881	234.245	234.610	234.976	235.342	235.708	236.074	236.441	236.808	237.176
2.270	237.544	237.912	238.281	238.650	239.019	239.389	239.759	240.130	240.501	240.872
2.280	241.244	241.616	241.989	242.361	242.735	243.108	243.482	243.856	244.231	244.606
2.290	244.982	245.357	245.734	246.110	246.487	246.864	247.242	247.620	247.999	248.378
2.300	248.757	249.136	249.516	249.897	250.277	250.658	251.040	251.422	251.804	252.187
2.310	252.570	252.953	253.337	253.721	254.105	254.490	254.876	255.261	255.647	256.034
2.320	256.420	256.808	257.195	257.583	257.971	258.360	258.749	259.139	259.528	259.919
2.330	260.309	260.700	261.092	261.483	261.876	262.268	262.661	263.054	263.448	263.842
2.340	264.236	264.631	265.026	265.422	265.818	266.214	266.611	267.008	267.406	267.804
2.350	268.202	268.601	269.000	269.399	269.799	270.199	270.600	271.001	271.402	271.804
2.360	272.206	272.609	273.012	273.415	273.819	274.223	274.627	275.032	275.437	275.843
2.370	276.249	276.656	277.062	277.470	277.877	278.285	278.694	279.103	279.512	279.921
2.380	280.331	280.742	281.152	281.563	281.975	282.387	282.799	283.212	283.625	284.039
2.390	284.452	284.867	285.281	285.696	286.112	286.528	286.944	287.361	287.778	288.195
2.400	288.613	289.031	289.450	289.869	290.288	290.708	291.128	291.549	291.970	292.391
2.410	292.813	293.235	293.658	294.081	294.504	294.928	295.352	295.777	296.202	296.627
2.420	297.053	297.479	297.906	298.333	298.760	299.188	299.616	300.045	300.474	300.903
2.430	301.333	301.763	302.194	302.625	303.056	303.488	303.920	304.353	304.786	305.219
2.440	305.653	306.087	306.522	306.957	307.392	307.828	308.264	308.701	309.138	309.575
2.450	310.013	310.451	310.890	311.329	311.768	312.208	312.648	313.089	313.530	313.972
2.460	314.414	314.856	315.299	315.742	316.185	316.629	317.074	317.518	317.963	318.409
2.470	318.855	319.301	319.748	320.195	320.643	321.091	321.539	321.988	322.438	322.887
2.480	323.337	323.788	324.239	324.690	325.142	325.594	326.046	326.499	326.953	327.406
2.490	327.861	328.315	328.770	329.226	329.681	330.138	330.594	331.051	331.509	331.967
2.500	332.425	332.884	333.343	333.803	334.263	334.723	335.184	335.645	336.107	336.569
2.510	337.031	337.494	337.957	338.421	338.885	339.350	339.815	340.280	340.746	341.212
2.520	341.679	342.146	342.613	343.081	343.550	344.018	344.487	344.957	345.427	345.897
2.530	346.368	346.840	347.311	347.783	348.256	348.729	349.202	349.676	350.150	350.625
2.540	351.100	351.575	352.051	352.527	353.004	353.481	353.959	354.437	354.915	355.394
2.550	355.874	356.353	356.833	357.314	357.795	358.276	358.758	359.240	359.723	360.206
2.560	360.690	361.174	361.658	362.143	362.628	363.114	363.600	364.086	364.573	365.061
2.570	365.549	366.037	366.526	367.015	367.504	367.994	368.484	368.975	369.466	369.958
2.580	370.450	370.943	371.436	371.929	372.423	372.917	373.412	373.907	374.403	374.899
2.590	375.395	375.892	376.389	376.887	377.385	377.884	378.383	378.882	379.382	379.882

Table 1b. *Vapor pressure of* He^3 *(1962 Scale) in millimeters of mercury at 0 °C and standard gravity, 980.665 cm/sec²*—Con.

T_{62}, °K	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
2.600	380.383	380.884	381.386	381.888	382.390	382.893	383.396	383.900	384.404	384.909
2.610	385.414	385.920	386.426	386.932	387.439	387.946	388.454	388.962	389.471	389.980
2.620	390.489	390.999	391.510	392.020	392.532	393.043	393.555	394.068	394.581	395.094
2.630	395.608	396.122	396.637	397.152	397.668	398.184	398.701	399.218	399.735	400.253
2.640	400.771	401.290	401.809	402.329	402.849	403.369	403.890	404.412	404.933	405.456
2.650	405.978	406.502	407.025	407.549	408.074	408.599	409.124	409.650	410.176	410.703
2.660	411.230	411.758	412.286	412.814	413.343	413.873	414.403	414.933	415.464	415.995
2.670	416.526	417.059	417.591	418.124	418.658	419.192	419.726	420.261	420.796	421.332
2.680	421.868	422.404	422.942	423.479	424.017	424.555	425.094	425.634	426.173	426.714
2.690	427.254	427.795	428.337	428.879	429.422	429.965	430.508	431.052	431.596	432.141
2.700	432.686	433.232	433.778	434.325	434.872	435.419	435.967	436.516	437.064	437.614
2.710	438.164	438.714	439.265	439.816	440.367	440.919	441.472	442.025	442.578	443.132
2.720	443.687	444.242	444.797	445.353	445.909	446.466	447.023	447.580	448.138	448.697
2.730	449.256	449.816	450.375	450.936	451.497	452.058	452.620	453.182	453.745	454.308
2.740	454.872	455.436	456.000	456.565	457.131	457.697	458.263	458.830	459.379	459.965
2.750	460.534	461.102	461.671	462.241	462.811	463.382	463.953	464.525	465.097	465.669
2.760	466.242	466.816	467.390	467.964	468.539	469.114	469.690	470.266	470.843	471.420
2.770	471.998	472.576	473.155	473.734	474.313	474.893	475.474	476.055	476.636	477.218
2.780	477.801	478.384	478.967	479.551	480.135	480.720	481.305	481.891	482.477	483.064
2.790	483.651	484.239	484.827	485.415	486.004	486.594	487.184	487.774	488.365	488.957
2.800	489.549	490.141	490.734	491.327	491.921	492.516	493.110	493.706	494.302	494.898
2.810	495.495	496.092	496.689	497.288	497.886	498.486	499.085	499.685	500.286	500.887
2.820	501.488	502.091	502.693	503.296	503.900	504.504	505.108	505.713	506.318	506.924
2.830	507.531	508.138	508.745	509.353	509.961	510.570	511.180	511.789	512.400	513.010
2.840	513.622	514.234	514.846	515.459	516.072	516.686	517.300	517.915	518.530	519.145
2.850	519.762	520.378	520.996	521.613	522.231	522.850	523.469	524.089	524.709	525.330
2.860	525.951	526.572	527.194	527.817	528.440	529.064	529.688	530.312	530.937	531.563
2.870	532.189	532.816	533.443	534.070	534.698	535.327	535.956	536.585	537.216	537.846
2.880	538.477	539.109	539.741	540.373	541.006	541.640	542.274	542.909	543.544	544.179
2.890	544.815	545.452	546.089	546.726	547.364	548.003	548.642	549.282	549.922	550.562
2.900	551.203	551.845	552.487	553.130	553.773	554.416	555.061	555.705	556.350	556.996
2.910	557.642	558.289	558.936	559.584	560.232	560.880	561.530	562.179	562.830	563.480
2.920	564.131	564.783	565.435	566.088	566.742	567.395	568.050	568.704	569.360	570.016
2.930	570.672	571.329	571.986	572.644	573.302	573.961	574.621	575.281	575.941	576.602
2.940	577.264	577.926	578.588	579.251	579.915	580.579	581.243	581.909	582.574	583.240
2.950	583.907	584.574	585.242	585.910	586.579	587.248	587.918	588.588	589.259	589.930
2.960	590.602	591.275	591.947	592.621	593.295	593.969	594.644	595.320	595.996	596.672
2.970	597.349	598.027	598.705	599.384	600.063	600.743	601.423	602.104	602.785	603.467
2.980	604.149	604.832	605.515	606.199	606.884	607.569	608.254	608.940	609.627	610,314
2.990	611.002	611.690	612.379	613.068	613.758	614.448	615.139	615.830	616.522	617.214
3.000	617.907	618.601	619.295	619.989	620.684	621.380	622.076	622.773	623.470	624.168
3.010	624.866	625.565	626.264	626.964	627.665	628.366	629.067	629.769	630.472	631.175
3.020	631.879	632.583	633.288	633.993	634.699	635.405	636.112	636.820	637.528	638.236
3.030	638.945	639.655	640.365	641.076	641.787	642.499	643.211	643.924	644.638	645.351
3.040	646.066	646.781	647.497	648.213	648.930	649.647	650.365	651.083	651.802	652.521
3.050	653.241	653.962	654.683	655.405	656.127	656.850	657.573	658.297	659.021	659.746
3.060	660.472	661.198	661.924	662.652	663.379	664.108	664.836	665.566	666.296	667.026
3,070	667.757	668.489	669.221	669.954	670.687	671.421	672.155	672.890	673.626	674.362
3,080	675.098	675,836	676,573	677.312	678.051	678.790	679.530	680.271	681.012	681.753
3.090	682.496	683.238	683.982	684.726	685.470	686.215	686.961	687.707	688.454	689.201
3.100	689.949	690.697	691.446	692.196	692.946	693.697	694.448	695.200	695.952	696.705
3.110	697.459	698.213	698.968	699.723	700.479	701.235	701.992	702.750	703.508	704.267
3.120	705.026	705.786	706.546	707.307	708.069	708.831	709.594	710.357	711.121	711.885
3.130	712.650	713.416	714.182	714.949	715.716	716.484	717.252	718.021	718.791	719.561
3.140	720.332	721.104	721.875	722.648	723.421	724.195	724.969	725.744	726.520	727.296
3.150	728.072	728.849	729.627	730.406	731.184	731.964	732.744	733.525	734.306	735.088
3.160	735.871	736.654	737.437	738.222	739.006	739.792	740.578	741.364	742.152	742.939
3.170	743.728	744.517	745.306	746.097	746.887	747.679	748.471	749.263	750.056	750.850
3.180	751.644	752.439	753.235	754.031	754.828	755.625	756.423	757.221	758.020	758.820
3.190	759.620	760.421	761.223	762.025	762.828	763.631	764.435	765.239	766.044	766.850
3.200	767.656	768.463	769.271	770.079	770.888	771.697	772.507	773.317	774.129	774.940
3.210	775.753	776.566	777.379	778.193	779.008	779.824	780.640	781.456	782.274	783.091
3.220	783.910	784.729	785.549	786.369	787.190	788.011	788.833	789.656	790.480	791.304
3.230	792.138	792.953	793.779	794.606	795.433	796.260	797.089	797.918	798.747	799.577
3.240	800.408	801.240	802.072	802.904	803.738	804.571	805.406	806.241	807.077	807.913
3.250	808.750	809.588	810.426	811.265	812.104	812.945	813.785	814.627	815.469	816.311
3.260	817.155	817.999	818.843	819.688	820.534	821.380	822.228	823.075	823.923	824.772
3.270	825.622	826.472	827.323	828.175	829.027	829.879	830.733	831.587	832.442	833.297
3.280	834.153	835.009	835.867	836.724	837.583	838.442	839.302	840.162	841.023	841.885
3.290	842.747	843.610	844.474	845.388	846.203	847.069	847.935	848.802	849.669	850.537
3.300	851.406	852.276	853.146	854.016	854.888	855.760	856.632	857.506	858.380	859.254
3.310	860.130	861.006	861.882	862.759	863.637	864.516	865.395	866.275	867.155	868.037
3.320	868.918	869.801	870.684	871.568	872.452	873.337				

TABLE 2a. T_{62} He^3 *temperatures in °K as a function of vapor pressure,* P, *in microns (10^{-3} mm) of mercury at 0 °C and standard gravity, 980.665 cm/sec²*

P	0	1	2	3	4	5	6	7	8	9
0.01	0.1974 13	1987 12	1999 11	2010 10	2020 10	2030 9	2039 9	2048 8	2056 7	2063 8
.02	.2071 7	2078 7	2085 6	2091 7	2098 6	2104 6	2110 5	2115 6	2121 5	2126 5
.03	.2131 6	2137 4	2141 5	2146 5	2151 4	2155 5	2160 4	2164 4	2168 4	2172 4
.04	.2176 4	2180 4	2184 4	2188 4	2192 3	2195 4	2199 3	2202 4	2206 3	2209 4
.05	.2213 3	2216 3	2219 3	2222 3	2225 3	2228 3	2231 3	2234 3	2237 3	2240 3
.06	.2243 3	2246 2	2248 3	2251 3	2254 3	2257 2	2259 3	2262 2	2264 3	2267 2
.07	.2269 3	2272 2	2274 2	2276 3	2279 2	2281 2	2283 3	2286 2	2288 2	2290 2
.08	.2292 3	2295 2	2297 2	2299 2	2301 2	2303 2	2305 2	2307 2	2309 2	2311 2
.09	.2313 2	2315 2	2317 2	2319 2	2321 2	2323 2	2325 2	2327 1	2328 2	2330 2
.10	.2332 18	2350 16	2366 15	2381 14	2395 13	2408 12	2420 12	2432 11	2443 11	2454 10
.20	.2464 10	2474 9	2483 9	2492 9	2501 8	2509 9	2518 8	2526 7	2533 8	2541 7
.30	.2548 7	2555 7	2562 6	2568 7	2575 6	2581 6	2587 6	2593 6	2599 6	2605 5
.40	.2610 6	2616 5	2621 5	2626 6	2632 5	2637 5	2642 5	2647 4	2651 5	2656 5
.50	.2661 4	2665 5	2670 4	2674 5	2679 4	2683 4	2687 4	2691 4	2695 4	2699 4
.60	.2703 4	2707 4	2711 4	2715 4	2719 3	2722 4	2726 4	2730 3	2733 4	2737 3
.70	.2740 4	2744 3	2747 3	2750 4	2754 3	2757 3	2760 4	2764 3	2767 3	2770 3
.80	.2773 3	2776 3	2779 3	2782 3	2785 3	2788 3	2791 3	2794 3	2797 3	2800 3
.90	.2803 2	2805 3	2808 3	2811 3	2814 2	2816 3	2819 3	2822 2	2824 3	2827 2
1	.2829 25	2854 23	2877 21	2898 20	2918 19	2937 18	2955 17	2972 16	2988 16	3004 14
2	.3018 14	3032 14	3046 13	3059 13	3072 12	3084 12	3096 11	3107 11	3118 11	3129 11
3	.3140 10	3150 10	3160 9	3169 10	3179 9	3188 9	3197 9	3206 8	3214 9	3223 8
4	.3231 8	3239 8	3247 8	3255 7	3262 8	3270 7	3277 7	3284 8	3292 7	3299 6
5	.3305 7	3312 7	3319 6	3325 7	3332 6	3338 6	3344 6	3350 6	3356 6	3362 6
6	.3368 6	3374 6	3380 6	3386 5	3391 6	3397 5	3402 6	3408 5	3413 5	3418 5
7	.3423 5	3428 6	3434 5	3439 4	3443 5	3448 5	3453 5	3458 5	3463 5	3468 4
8	.3472 5	3477 4	3481 5	3486 4	3490 5	3495 4	3499 5	3504 4	3508 4	3512 4
9	.3516 5	3521 4	3525 4	3529 4	3533 4	3537 4	3541 4	3545 4	3549 4	3553 4
10	.3557 37	3594 34	3628 33	3661 30	3691 29	3720 27	3747 26	3773 24	3797 24	3821 23
20	.3844 21	3865 21	3886 21	3907 19	3926 19	3945 18	3963 18	3981 17	3998 17	4015 16
30	.4031 16	4047 15	4062 15	4077 15	4092 15	4107 14	4121 13	4134 14	4148 13	4161 13
40	.4174 13	4187 12	4199 12	4211 12	4223 12	4235 11	4246 12	4258 11	4269 11	4280 11
50	.4291 10	4301 11	4312 10	4322 10	4332 10	4342 10	4352 10	4362 10	4372 9	4381 10
60	.4391 9	4400 9	4409 9	4418 9	4427 9	4436 8	4444 9	4453 8	4461 9	4470 8
70	.4478 8	4486 9	4495 8	4503 7	4510 8	4518 8	4526 8	4534 7	4541 8	4549 7
80	.4556 8	4564 7	4571 7	4578 8	4586 7	4593 7	4600 7	4607 7	4614 7	4621 7
90	.4628 6	4634 7	4641 7	4648 6	4654 7	4661 6	4667 7	4674 6	4680 6	4686 7

TABLE 2b. T_{62} He^3 *temperatures in °K as a function of vapor pressure,* P, *in millimeters of mercury at 0 °C and standard gravity, 980.665 cm/sec²*

P	0	1	2	3	4	5	6	7	8	9
0.1	0.4693 60	4753 56	4809 53	4862 50	4912 47	4959 44	5003 43	5046 41	5087 39	5126 37
.2	.5163 37	5200 34	5234 34	5268 33	5301 31	5332 31	5363 30	5393 29	5422 28	5450 27
.3	.5477 27	5504 26	5530 26	5556 24	5580 25	5605 24	5629 23	5652 23	5675 23	5698 22
.4	.5720 21	5741 22	5763 20	5783 21	5804 20	5824 20	5844 19	5863 20	5883 19	5902 18
.5	.5920 19	5939 18	5957 18	5975 17	5992 18	6010 17	6027 17	6044 16	6060 17	6077 16
.6	.6093 16	6109 16	6125 16	6141 15	6156 16	6172 15	6187 15	6202 14	6216 15	6231 15
.7	.6246 14	6260 14	6274 14	6288 14	6302 14	6316 14	6330 13	6343 14	6357 13	6370 13
.8	.6383 13	6396 13	6409 13	6422 12	6434 13	6447 12	6459 13	6472 12	6484 12	6496 12
.9	.6508 12	6520 12	6532 12	6544 12	6556 11	6567 12	6579 11	6590 11	6601 12	6613 11
1.0	.6624 11	6635 11	6646 11	6657 11	6668 10	6678 11	6689 11	6700 10	6710 11	6721 10
1.1	.6731 11	6742 10	6752 10	6762 10	6772 10	6782 10	6792 10	6802 10	6812 10	6822 10
1.2	.6832 10	6842 9	6851 10	6861 9	6870 10	6880 9	6889 10	6899 9	6908 9	6917 9
1.3	.6926 10	6936 9	6945 9	6954 9	6963 9	6972 9	6981 9	6990 8	6998 9	7007 9
1.4	.7016 9	7025 8	7033 9	7042 9	7051 8	7059 9	7068 8	7076 8	7084 9	7093 8
1.5	.7101 8	7109 9	7118 8	7126 8	7134 8	7142 8	7150 8	7158 8	7166 8	7174 8
1.6	.7182 8	7190 8	7198 8	7206 7	7213 8	7221 8	7229 8	7237 7	7244 8	7252 8
1.7	.7260 7	7267 8	7275 7	7282 8	7290 7	7297 8	7305 7	7312 7	7319 8	7327 7
1.8	.7334 7	7341 7	7348 8	7356 7	7363 7	7370 7	7377 7	7384 7	7391 7	7398 7
1.9	.7405 7	7412 7	7419 7	7426 7	7433 7	7440 7	7447 7	7454 6	7460 7	7467 7
2.0	.7474 7	7481 7	7488 6	7494 7	7501 7	7508 6	7514 7	7521 6	7527 7	7534 6
2.1	.7540 7	7547 6	7553 7	7560 6	7566 7	7573 6	7579 7	7586 6	7592 6	7598 7
2.2	.7605 6	7611 6	7617 6	7623 7	7630 6	7636 6	7642 6	7648 6	7654 7	7661 6
2.3	.7667 6	7673 6	7679 6	7685 6	7691 6	7697 6	7703 6	7709 6	7715 6	7721 6
2.4	.7727 6	7733 6	7739 6	7745 5	7750 6	7756 6	7762 6	7768 6	7774 6	7780 5
2.5	.7785 6	7791 6	7797 6	7803 5	7808 6	7814 6	7820 5	7825 6	7831 6	7837 5
2.6	.7842 6	7848 5	7853 6	7859 5	7864 6	7870 6	7876 5	7881 6	7887 5	7892 5
2.7	.7897 6	7903 5	7908 6	7914 5	7919 6	7925 5	7930 5	7935 6	7941 5	7946 5
2.8	.7951 6	7957 5	7962 5	7967 6	7973 5	7978 5	7983 5	7988 6	7994 5	7999 5
2.9	.8004 5	8009 5	8014 5	8019 6	8025 5	8030 5	8035 5	8040 5	8045 5	8050 5

TABLE 2b. T_{62} He^3 *temperatures in °K as a function of vapor pressure,* P, *in millimeters of mercury at 0 °C and standard gravity 980.665 cm/sec*^{2}—Continued

P	0		1		2		3		4		5		6		7		8		9	
3	0. 8055	50	8105	49	8154	48	8202	47	8249	46	8295	45	8340	44	8384	43	8427	43	8470	42
4	. 8512	41	8553	40	8593	40	8633	39	8672	38	8710	38	8748	38	8786	36	8822	37	8859	35
5	. 8894	36	8930	34	8964	35	8999	33	9032	34	9066	33	9099	32	9131	33	9164	31	9195	32
6	. 9227	31	9258	31	9289	30	9319	30	9349	30	9379	29	9408	29	9437	29	9466	29	9495	28
7	. 9523	28	9551	28	9579	27	9606	27	9633	27	9660	27	9687	26	9713	27	9740	26	9766	25
8	. 9791	26	9817	25	9842	25	9867	25	9892	25	9917	24	9941	25	9966	24	9990	24	0014	24
9	1. 0038	23	0061	24	0085	23	0108	23	0131	23	0154	22	0176	23	0199	22	0221	23	0244	22
10	1. 0266	22	0288	22	0310	21	0331	22	0353	21	0374	21	0395	21	0416	21	0437	21	0458	21
11	1. 0479	21	0500	20	0520	20	0540	21	0561	20	0581	20	0601	19	0620	20	0640	20	0660	19
12	1. 0679	20	0699	19	0718	19	0737	19	0756	19	0775	19	0794	19	0813	19	0832	18	0850	19
13	1. 0869	18	0887	18	0905	19	0924	18	0942	18	0960	18	0978	18	0996	17	1013	18	1031	18
14	1. 1049	17	1066	17	1083	18	1101	17	1118	17	1135	17	1152	17	1169	17	1186	17	1203	17
15	1. 1220	17	1237	16	1253	17	1270	16	1286	17	1303	16	1319	16	1335	17	1352	16	1368	16
16	1. 1384	16	1400	16	1416	16	1432	15	1447	16	1463	16	1479	15	1494	16	1510	15	1525	16
17	1. 1541	15	1556	15	1571	16	1587	15	1602	15	1617	15	1632	15	1647	15	1662	15	1677	15
18	1. 1692	15	1707	14	1721	15	1736	15	1751	14	1765	15	1780	14	1794	15	1809	14	1823	14
19	1. 1837	14	1851	15	1866	14	1880	14	1894	14	1908	14	1922	14	1936	14	1950	14	1964	14
20	1. 1978	13	1991	14	2005	14	2019	13	2032	14	2046	14	2060	13	2073	14	2087	13	2100	13
21	1. 2113	14	2127	13	2140	13	2153	13	2166	14	2180	13	2193	13	2206	13	2219	13	2232	13
22	1. 2245	13	2258	13	2271	13	2284	12	2296	13	2309	13	2322	13	2335	12	2347	13	2360	13
23	1. 2373	12	2385	13	2398	12	2410	13	2423	12	2435	12	2447	13	2460	12	2472	12	2484	12
24	1. 2496	13	2509	12	2521	12	2533	12	2545	12	2557	12	2569	12	2581	12	2593	12	2605	12
25	1. 2617	12	2629	12	2641	12	2653	11	2664	12	2676	12	2688	12	2700	11	2711	12	2723	11
26	1. 2734	12	2746	12	2758	11	2769	12	2781	11	2792	11	2803	12	2815	11	2826	12	2838	11
27	1. 2849	11	2860	11	2871	12	2883	11	2894	11	2905	11	2916	11	2927	11	2938	11	2949	11
28	1. 2960	11	2971	11	2982	11	2993	11	3004	11	3015	11	3026	11	3037	11	3048	11	3059	10
29	1. 3069	11	3080	11	3091	11	3102	10	3112	11	3123	11	3134	10	3144	11	3155	10	3165	11
30	1. 3176	11	3187	10	3197	10	3207	11	3218	10	3228	11	3239	10	3249	11	3260	10	3270	10
31	1. 3280	10	3290	11	3301	10	3311	10	3321	10	3331	11	3342	10	3352	10	3362	10	3372	10
32	1. 3382	10	3392	10	3402	10	3412	10	3422	10	3432	10	3442	10	3452	10	3462	10	3472	10
33	1. 3482	10	3492	10	3502	10	3512	10	3522	9	3531	10	3541	10	3551	10	3561	9	3570	10
34	1. 3580	10	3590	9	3599	10	3609	10	3619	9	3628	10	3638	9	3647	10	3657	10	3667	9
35	1. 3676	10	3686	9	3695	10	3705	9	3714	9	3723	10	3733	9	3742	10	3752	9	3761	9
36	1. 3770	10	3780	9	3789	9	3798	10	3808	9	3817	9	3826	9	3835	9	3844	10	3854	9
37	1. 3863	9	3872	9	3881	9	3890	9	3899	10	3909	9	3918	9	3927	9	3936	9	3945	9
38	1. 3954	9	3963	9	3972	9	3981	9	3990	9	3999	9	4008	8	4016	9	4025	9	4034	9
39	1. 4043	9	4052	9	4061	9	4070	8	4078	9	4087	9	4096	9	4105	8	4113	9	4122	9
40	1. 4131	9	4140	8	4148	9	4157	9	4166	8	4174	9	4183	9	4192	8	4200	9	4209	8
41	1. 4217	9	4226	8	4234	9	4243	8	4251	9	4260	8	4268	9	4277	8	4285	9	4294	8
42	1. 4302	9	4311	8	4319	9	4328	8	4336	8	4344	9	4353	8	4361	8	4369	9	4378	8
43	1. 4386	8	4394	9	4403	8	4411	8	4419	8	4427	9	4436	8	4444	8	4452	8	4460	8
44	1. 4468	9	4477	8	4485	8	4493	8	4501	8	4509	8	4517	8	4525	8	4533	8	4541	9
45	1. 4550	8	4558	8	4566	8	4574	8	4582	8	4590	8	4598	8	4606	8	4614	8	4622	8
46	1. 4630	7	4637	8	4645	8	4653	8	4661	8	4669	8	4677	8	4685	8	4693	8	4701	7
47	1. 4708	8	4716	8	4724	8	4732	8	4740	7	4747	8	4755	8	4763	8	4771	7	4778	8
48	1. 4786	8	4794	8	4802	7	4809	8	4817	8	4825	7	4832	8	4840	8	4848	7	4855	8
49	1. 4863	7	4870	8	4878	8	4886	7	4893	8	4901	7	4908	8	4916	8	4924	7	4931	8
50	1. 4939	74	5013	74	5087	73	5160	72	5232	71	5303	70	5373	69	5442	69	5511	68	5579	67
60	1. 5646	66	5712	66	5778	65	5843	64	5907	64	5971	62	6033	63	6096	62	6158	61	6219	60
70	1. 6279	60	6339	60	6399	59	6458	58	6516	58	6574	57	6631	57	6688	56	6744	56	6800	56
80	1. 6856	55	6911	54	6965	55	7020	53	7073	54	7127	52	7179	53	7232	52	7284	52	7336	51
90	1. 7387	51	7438	51	7489	50	7539	50	7589	49	7638	49	7687	49	7736	49	7785	48	7833	48
100	1. 7881	47	7928	48	7976	47	8023	46	8069	47	8116	46	8162	46	8208	45	8253	45	8298	45
110	1. 8343	45	8388	45	8433	44	8477	44	8521	43	8564	44	8608	43	8651	43	8694	43	8737	42
120	1. 8779	43	8822	42	8864	41	8905	42	8947	41	8988	42	9030	41	9071	40	9111	41	9152	40
130	1. 9192	40	9232	40	9272	40	9312	39	9351	40	9391	39	9430	39	9469	39	9508	38	9546	39
140	1. 9585	38	9623	38	9661	38	9699	38	9737	37	9774	38	9812	37	9849	37	9886	37	9923	36
150	1. 9959	37	9996	36	0032	37	0069	36	0105	36	0141	35	0176	36	0212	36	0248	35	0283	35
160	2. 0318	35	0353	35	0388	35	0423	35	0458	34	0492	34	0526	35	0561	34	0595	34	0629	34
170	2. 0663	33	0696	34	0730	33	0763	34	0797	33	0830	33	0863	33	0896	33	0929	32	0961	33
180	2. 0994	33	1027	32	1059	32	1091	32	1123	32	1155	32	1187	32	1219	32	1251	31	1282	32
190	2. 1314	31	1345	31	1376	32	1408	31	1439	30	1469	31	1500	31	1531	31	1562	30	1592	31
200	2. 1623	30	1653	30	1683	30	1713	30	1743	30	1773	30	1803	30	1833	30	1863	29	1892	30
210	2. 1922	29	1951	29	1980	30	2010	29	2039	29	2068	29	2097	29	2126	28	2154	29	2183	29
220	2. 2212	28	2240	28	2268	29	2297	28	2325	28	2353	28	2381	28	2409	28	2437	28	2465	28
230	2. 2493	28	2521	27	2548	28	2576	27	2603	28	2631	27	2658	27	2685	27	2712	28	2740	27
240	2. 2767	26	2793	27	2820	27	2847	27	2874	27	2901	26	2927	27	2954	26	2980	26	3006	27
250	2. 3033	26	3059	26	3085	26	3111	26	3137	26	3163	26	3189	26	3215	26	3241	25	3266	26
260	2. 3292	26	3318	25	3343	26	3369	25	3394	25	3419	26	3445	25	3470	25	3495	25	3520	25
270	2. 3545	25	3570	25	3595	25	3620	25	3645	24	3669	25	3694	24	3718	25	3743	25	3768	24
280	2. 3792	24	3816	25	3841	24	3865	24	3889	24	3913	24	3937	24	3961	24	3985	24	4009	24
290	2. 4033	24	4057	24	4081	23	4104	24	4128	24	4152	23	4175	24	4199	23	4222	24	4246	23
300	2. 4269	23	4292	24	4316	23	4339	23	4362	23	4385	23	4408	23	4431	23	4454	23	4477	23
310	2. 4500	23	4523	22	4545	23	4568	23	4591	22	4613	23	4636	22	4658	23	4681	22	4703	23
320	2. 4726	22	4748	22	4770	23	4793	22	4815	22	4837	22	4859	22	4881	22	4903	22	4925	22
330	2. 4947	22	4969	22	4991	22	5013	21	5034	22	5056	22	5078	21	5099	22	5121	22	5143	21
340	2. 5164	21	5185	22	5207	21	5228	22	5250	21	5271	21	5292	21	5313	22	5335	21	5356	21

TABLE 2b. T$_{62}$ He^3 *temperatures in °K as a function of vapor pressure,* P, *in millimeters of mercury at 0 °C and standard gravity, 980.665 cm/sec^2*—Continued

P	0	1	2	3	4	5	6	7	8	9
350	2.5377 21	5398 21	5419 21	5440 21	5461 21	5482 21	5503 21	5524 20	5544 21	5565 21
360	2.5586 20	5606 21	5627 21	5648 20	5668 21	5689 20	5709 21	5730 20	5750 21	5771 20
370	2.5791 20	5811 20	5831 21	5852 20	5872 20	5892 20	5912 20	5932 20	5952 20	5972 20
380	2.5992 20	6012 20	6032 20	6052 20	6072 20	6092 20	6112 19	6131 20	6151 20	6171 19
390	2.6190 20	6210 20	6230 19	6249 20	6269 19	6288 20	6308 19	6327 19	6346 20	6366 19
400	2.6385 19	6404 20	6424 19	6443 19	6462 19	6481 19	6500 20	6520 19	6539 19	6558 19
410	2.6577 19	6596 19	6615 19	6634 18	6652 19	6671 19	6690 19	6709 19	6728 18	6746 19
420	2.6765 19	6784 18	6802 19	6821 19	6840 18	6858 19	6877 18	6895 19	6914 18	6932 19
430	2.6951 18	6969 18	6987 19	7006 18	7024 18	7042 19	7061 18	7079 18	7097 18	7115 18
440	2.7133 18	7151 19	7170 18	7188 18	7206 18	7224 18	7242 18	7260 18	7278 17	7295 18
450	2.7313 18	7331 18	7349 18	7367 18	7385 17	7402 18	7420 18	7438 17	7455 18	7473 18
460	2.7491 17	7508 18	7526 17	7543 18	7561 17	7578 18	7596 17	7613 18	7631 17	7648 17
470	2.7665 18	7683 17	7700 17	7717 18	7735 17	7752 17	7769 17	7786 17	7803 18	7821 17
480	2.7838 17	7855 17	7872 17	7889 17	7906 17	7923 17	7940 17	7957 17	7974 17	7991 17
490	2.8008 17	8025 16	8041 17	8058 17	8075 17	8092 16	8108 17	8125 17	8142 17	8159 16
500	2.8175 17	8192 17	8209 16	8225 17	8242 16	8258 17	8275 16	8291 17	8308 16	8324 17
510	2.8341 16	8357 16	8373 17	8390 16	8406 17	8423 16	8439 16	8455 16	8471 17	8488 16
520	2.8504 16	8520 16	8536 16	8552 17	8569 16	8585 16	8601 16	8617 16	8633 16	8649 16
530	2.8665 16	8681 16	8697 16	8713 16	8729 16	8745 16	8761 16	8777 15	8792 16	8808 16
540	2.8824 16	8840 16	8856 15	8871 16	8887 16	8903 16	8919 15	8934 16	8950 16	8966 15
550	2.8981 16	8997 15	9012 16	9028 16	9044 15	9059 16	9075 15	9090 16	9106 15	9121 15
560	2.9136 16	9152 15	9167 16	9183 15	9198 15	9213 16	9229 15	9244 15	9259 16	9275 15
570	2.9290 15	9305 15	9320 15	9335 16	9531 15	9366 15	9381 15	9396 15	9411 15	9426 15
580	2.9441 15	9456 15	9471 15	9486 15	9501 15	9516 15	9531 15	9546 15	9561 15	9576 15
590	2.9591 15	9606 15	9621 15	9636 14	9650 15	9665 15	9680 15	9695 15	9710 14	9724 15
600	2.9739 15	9754 15	9769 14	9783 15	9798 14	9812 15	9827 15	9842 14	9856 15	9871 14
610	2.9885 15	9900 15	9915 14	9929 15	9944 14	9958 14	9972 15	9987 14	0001 15	0016 14
620	3.0030 15	0045 14	0059 14	0073 15	0088 14	0102 14	0116 15	0131 14	0145 14	0159 14
630	3.0173 15	0188 14	0202 14	0216 14	0230 14	0244 14	0258 15	0273 14	0287 14	0301 14
640	3.0315 14	0329 14	0343 14	0357 14	0371 14	0385 14	0399 14	0413 14	0427 14	0441 14
650	3.0455 14	0469 14	0483 14	0497 14	0511 13	0524 14	0538 14	0552 14	0566 14	0580 14
660	3.0594 13	0607 14	0621 14	0635 14	0649 13	0662 14	0676 14	0690 13	0703 14	0717 14
670	3.0731 13	0744 14	0758 14	0772 13	0785 14	0799 13	0812 14	0826 13	0839 14	0853 13
680	3.0866 14	0880 13	0893 14	0907 13	0920 14	0934 13	0947 14	0961 13	0974 13	0987 14
690	3.1001 13	1014 13	1027 14	1041 13	1054 13	1067 14	1081 13	1094 13	1107 13	1120 14
700	3.1134 13	1147 13	1160 13	1173 14	1187 13	1200 13	1213 13	1226 13	1239 13	1252 13
710	3.1265 13	1278 14	1292 13	1305 13	1318 13	1331 13	1344 13	1357 13	1370 13	1383 13
720	3.1396 13	1409 13	1422 13	1435 13	1448 12	1460 13	1473 13	1486 13	1499 13	1512 13
730	3.1525 13	1538 12	1550 13	1563 13	1576 13	1589 13	1602 12	1614 13	1627 13	1640 13
740	3.1653 12	1665 13	1678 13	1691 12	1703 13	1716 13	1729 12	1741 13	1754 13	1767 12
750	3.1779 13	1792 12	1804 13	1817 13	1830 12	1842 13	1855 12	1867 13	1880 12	1892 13
760	3.1905 12	1917 13	1930 12	1942 13	1955 12	1967 12	1979 13	1992 12	2004 13	2017 12
770	3.2029 12	2041 13	2054 12	2066 12	2078 13	2091 12	2103 12	2115 13	2128 12	2140 12
780	3.2152 12	2164 13	2177 12	2189 12	2201 12	2213 13	2226 12	2238 12	2250 12	2262 12
790	3.2274 12	2286 12	2298 13	2311 12	2323 12	2335 12	2347 12	2359 12	2371 12	2383 12
800	3.2395 12	2407 12	2419 12	2431 12	2443 12	2455 12	2467 12	2479 12	2491 12	2503 12
810	3.2515 12	2527 12	2539 12	2551 12	2563 11	2574 12	2586 12	2598 12	2610 12	2622 12
820	3.2634 12	2646 11	2657 12	2669 12	2681 12	2693 11	2704 12	2716 12	2728 12	2740 11
830	3.2751 12	2763 12	2775 12	2787 11	2798 12	2810 12	2822 11	2833 12	2845 12	2857 11
840	3.2868 12	2880 11	2891 12	2903 12	2915 11	2926 12	2938 11	2949 12	2961 11	2972 12
850	3.2984 11	2995 12	3007 11	3018 12	3030 11	3041 12	3053 11	3064 12	3076 11	3087 12
860	3.3099 11	3110 11	3121 12	3133 11	3144 12	3156 11	3167 11	3178 12	3190 11	3201 11
870	3.3212 12	3224 11	3235 11	3246						

The correction for He^4 impurity is mentioned briefly in Part I and in more detail in section 3 of Part III. In figure 7 of Part III several correction curves are given which may be used to adjust an uncorrected temperature for the effect of the He^4 impurity content in the liquid. In this connection the experimenter is cautioned that, due to fractionation between vapor and liquid, the actual concentration of He^4 in the liquid probably will be greater than the average concentration of the total gas in the vapor-pressure system by an amount depending on the volume of the vapor space and the experimental technique. For example, if most of the gas is first condensed at very low temperature into the vapor-pressure bulb and then most of that liquid subsequently is evaporated into the vapor space, a large fraction of the He^4 will remain in the liquid state and a corresponding high value of the impurity correction will be needed. Such considerations may become particularly important if temperature is being measured as the vapor pressure of a bath of He^3. Tables of equilibrium vapor/liquid concentration ratios, if unavoidably needed, are given in references [38] and [74]. The best technique, of course, is to use only very high purity He^3. As explained in section 3 of Part III, steps have been undertaken to make He^3 of very high purity available for thermometry.

Remarks concerning the possibility and detection of errors due to gas oscillations are given at the end of Part I.

Table 3. *The temperature derivative,* dP_3/dT_{62}, *in millimeters of mercury per degree Kelvin, for the 1962* He^3 *Scale of Temperatures*

T_{62}, °K	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.20	0.001	0.002	0.003	0.005	0.008	0.012	0.017	0.025	0.035	0.049
.30	.066	.087	.113	.145	.184	.229	.283	.345	.417	.499
.40	.592	.696	.814	.944	1.089	1.248	1.422	1.612	1.819	2.042
.50	2.283	2.543	2.820	3.117	3.433	3.769	4.125	4.501	4.898	5.317
.60	5.756	6.217	6.700	7.204	7.731	8.280	8.851	9.445	10.061	10.700
.70	11.362	12.046	12.753	13.483	14.236	15.012	15.811	16.632	17.477	18.344
.80	19.234	20.147	21.082	22.041	23.022	24.025	25.051	26.100	27.171	28.264
.90	29.379	30.517	31.677	32.859	34.063	35.289	36.537	37.806	39.097	40.410
1.00	41.745	43.100	44.478	45.876	47.296	48.737	50.199	51.682	53.186	54.711
1.10	56.257	57.823	59.410	61 018	62.646	64.295	65.964	67.653	69.363	71.093
1.20	72.843	74.613	76.403	78.213	80.043	81.893	83.763	85.652	87.561	89.490
1.30	91.438	93.406	95.394	97.400	99.427	101.472	103.537	105.621	107.724	109.847
1.40	111.988	114.149	116.329	118.528	120.745	122.982	125.237	127.512	129.805	132.117
1.50	134.447	136.796	139.164	141.551	143.956	146.380	148.822	151.283	153.762	156.260
1.60	158.776	161.311	163.863	166.435	169.024	171.632	174.257	176.902	179.564	182.244
1.70	184.943	187.659	190.394	193.147	195.918	198.706	201.513	204.338	207.181	210.041
1.80	212.920	215.816	218.730	221.662	224.612	227.579	230.565	233.568	236.589	239.627
1.90	242.684	245.758	248.849	251.959	255.086	258.230	261.393	264.573	267.770	270.985
2.00	274.218	277.468	280.736	284.022	287.325	290.646	293.984	297.340	300.713	304.104
2.10	307.513	310.939	314.383	317.844	321.323	324.820	328.334	331.866	335.416	338.983
2.20	342.568	346.171	349.792	353.430	357.086	360.760	364.451	368.161	371.889	375.634
2.30	379.398	383.179	386.979	390.796	394.632	398.486	402.359	406.250	410.159	414.086
2.40	418.032	421.997	425.980	429.982	434.003	438.042	442.101	446.178	450.275	454.391
2.50	458.526	462.680	466.854	471.048	475.261	479.495	483.748	488.021	492.314	496.628
2.60	500.962	505.317	509.692	514.088	518.505	522.944	527.404	531.885	536.388	540.912
2.70	545.459	550.028	554.619	559.233	563.870	568.530	573.212	577.919	582.649	587.402
2.80	592.180	596.982	601.809	606.661	611.537	616.440	621.367	626.321	631.301	636.307
2.90	641.340	646.401	651.488	656.604	661.747	666.919	672.120	677.349	682.609	687.898
3.00	693.217	698.567	703.948	709.360	714.804	720.281	725.790	731.332	736.908	742.517
3.10	748.162	753.841	759.556	765.306	771.093	776.918	782.779	788.679	794.617	800.595
3.20	806.612	812.670	818.768	824.909	831.091	837.316	843.585	849.898	856.255	862.658
3.30	869.108	875.604	882.148	888.740	----------	----------	----------	----------	----------	----------

The fit of the 1962 He^3 Scale to the intercomparison He^3 and He^4 vapor-pressure data of Part I and to the 1958 He^4 Scale is given in table 1 and figure 1 of Part II and is discussed in detail in subsection 1.1 of Part III. The fit of the 1962 He^3 Scale to Keller's isotherms is given in figure 2 of Part II and is discussed in detail in subsection 1.5 of Part III.

The 1962 He^3 Scale of Temperatures has been given status similar to that of the 1958 He^4 Scale of Temperatures by the International Committee on Weights and Measures [68, 69]. The pertinent portion of the minutes of that committee's Advisory Committee on Thermometry [67] is given in section 4 of Part III.

References*

[1] S. G. Sydoriak, T. R. Roberts, and R. H. Sherman, Proc. 7th Intern. Conf. Low Temperature Physics, ed. G. M. Graham and A. C. Hollis-Hallett (Univ. of Toronto Press, Toronto, 1961), ch. 30, p. 717.

[2] F. G. Brickwedde, H. van Dijk, M. Durieux, J. R. Clement, and J. K. Logan, J. Res. NBS **64A** (Phys. & Chem.), 1 (1960).

[3] D. F. Brewer, A. K. Sreedhar, H. C. Kramers, and J. G. Daunt, Phys. Rev. **115,** 836 (1959).

[4] B. Weinstock, B. M. Abraham, and D. W. Osborne, Nuovo Cimento Suppl. **9,** 310 (1958).

[5] B. M. Abraham, D. W. Osborne, and B. Weinstock, Phys. Rev. **80,** 366 (1950).

[6] S. G. Sydoriak, T. R. Roberts, and R. H. Sherman, Paper II of this series.

[7] T. R. Roberts, R. H. Sherman, and S. G. Sydoriak, Paper III of this series.

[8] R. H. Sherman, S. G. Sydoriak, and T. R. Roberts, Paper IV of this series. See also Los Alamos Scientific Lab. Rept. LAMS 2701 (July 1962).

[9] S. G. Sydoriak and T. R. Roberts, Phys. Rev. **106,** 175 (1957).

[10] T. R. Roberts, S. G. Sydoriak, and R. H. Sherman, Proc. 4th Symp. Temperature, Its Measurement and Control in Science and Industry, ed. C. M. Herzfeld (Reinhold Publ. Corp., New York, 1962), Vol. 3, pt. 1, p. 75.

[11] W. E. Keller, Phys. Rev. **97,** 1 (1955); **100,** 1790 (1955).

[12] W. E. Keller, Phys. Rev. **98,** 1571 (1955).

[13] F. E. Hoare and J. E. Zimmerman, Rev. Sci. Instr. **30,** 184 (1959); R. T. Swim, Advances in Cryogenic Engineering, ed. K. D. Timmerhaus (Plenum Press, Inc., New York, 1960), Vol. 5, pp. 498–504.

[14] H. H. Plumb, Proc. 10th Intern. Congr. Refrigeration, Copenhagen, 1959, ed. M. Jul and A. M. S. Jul (Pergamon Press, Paris, 1960), Vol. 1, pp. 184–187.

[15] M. Durieux, Thermometry at Liquid Helium and Liquid Hydrogen Temperatures, Thesis, Leiden Univ. (16 Mar. 1960).

[16] F. G. Brickwedde, Report on the Conference Agreement on the Helium Vapor-Pressure Scale of Temperatures, Conf. Physique des Basses Temperatures, Paris, 2–8 Septembre 1955, pp. 608–610.

[17] B. Bleaney and F. Simon, Trans. Faraday Soc. **35,** 1205 (1939).

[18] B. Bleaney and R. A. Hull, Proc. Roy. Soc. (London) **178A,** 74 (1941).

[19] J. de Boer and E. G. D. Cohen, Physica **17,** 993 (1951).

[20] E. W. Becker and R. Misenta, Phys. Rev. **93,** 244 (1954).

[21] E. W. Becker, R. Misenta, and F. Schmeissner, Z. Physik **137,** 126 (1954).

[22] K. Mendelssohn and G. K. White, Proc. Phys. Soc. (London) **A63,** 1328 (1950).

---

*This list of references applies to papers I, II, III, and IV of this series. For completeness and convenience, it is reproduced in its entirety at the end of each paper.

[23] R. Bowers and K. Mendelssohn, Nature **163,** 870 (1949); Proc. Phys. Soc. (London) **A63,** 1318 (1950).

[24] K. W. Taconis, Progress in Low Temperature Physics, ed. C. J. Gorter (North Holland Publ. Co., Amsterdam, The Netherlands, 1961), Vol. 3, p. 154.

[25] H. van Dijk and M. Durieux, Physica **24,** 1 (1958).

[26] S. G. Sydoriak and H. S. Sommers, Jr., Rev. Sci. Instr. **22,** 915 (1951).

[27] P. Kapitza, J. Phys. (U.S.S.R.) **4,** 181 (1941).

[28] H. A. Fairbank and J. Wilks, Proc. Roy. Soc. (London) **A231,** 545 (1955).

[29] L. J. Challis, K. Dransfeld, and J. Wilks, Proc. Roy. Soc. (London) **A260,** 31 (1961).

[30] Kuang Wey-Yen, Zh. Experim. i Teor. Fiz. (U.S.S.R.) **42,** 921 (1962); Soviet Phys. JETP (English Transl.) **15,** 635 (1962).

[31] I.M. Khalatnikov, Zh. Experim. i Teor. Fiz. (U.S.S.R.) **22,** 687 (1952).

[32] S. G. Sydoriak and T. R. Roberts, Phys. Rev. **118.** 901 (1960).

[33] R. L. Mills, E.R. Grilly, and S. G. Sydoriak, Ann. Phys. **12,** 41 (1961).

[34] W. Cawood and H. S. Patterson, Trans. Faraday Soc. **29,** 522 (1933).

[35] J. Kistemaker, Leiden Commun. **268d** (1944); Physica **11,** 277 (1944–1946); B. E. Blaisdell, J. Math. Phys. **19,** 186 (1940).

[36] W. G. Brombacher, D. P. Johnson, and J. L. Cross, Mercury Barometers and Manometers, NBS Mono. 8 (U.S. Govt. Printing Office, Washington, 1960).

[37] T. R. Roberts and S. G. Sydoriak, Phys. Rev. **102,** 304 (1956).

[38] B. N. Esel'son and N. G. Berezniak, Zh. Experim. i Teor. Fiz. (U.S.S.R.) **30,** 628 (1956); Soviet Phys. JETP (English Transl.) **3,** 568 (1956).

[39] S. G. Sydoriak, E. R. Grilly, and E. F. Hammel, Phys. Rev. **75,** 303 (1949).

[40] V. P. Peshkov, Zh. Experim. i Teor. Fiz. (U.S.S.R.) **33,** 833 (1957); Soviet Phys. JETP (English Transl.) **4,** 645 (1958).

[41] H. van Dijk and D. Shoenberg, Nature **164,** 151 (1949).

[42] T. C. Chen and F. London, Phys. Rev. **89,** 1038 (1953).

[43] W. E. Keller, Nature **178,** 883 (1956); J. R. Clement, Low Temperature Physics and Chemistry (Univ. of Wisconsin Press, Madison, 1958), p. 187 (Proc. 5th Intern. Conf. Low Temperature Physics and Chemistry, Madison, Wis., 1957).

[44] L. Goldstein, Phys. Rev. **96,** 1455 (1954); Phys. Rev. **102,** 1205 (1956).

[45] R. H. Sherman, T. R. Roberts, and S. G. Sydoriak, Supplement au Bulletin de l'Institut International du Froid, Annexe 1961–5, p. 125 (Proc. Meeting of Commission I of the International Institute of Refrigeration, London, 1961).

[46] S. G. Sydoriak and R. H. Sherman, Paper I of this series.

[47] W. E. Deming, Statistical Adjustment of Data (John Wiley & Sons, New York, 1943).

[48] T. R. Roberts, S. G. Sydoriak, and R. H. Sherman, see ref. [45], p. 115.

[49] E. R. Grilly and E. F. Hammel, Progress in Low Temperature Physics III (1961), pp. 113–152.

[50] E. C. Kerr and R. D. Taylor, Proc. 7th Intern. Conf. Low Temperature Physics, ch. 24, pp. 605–608, ed. G. M. Graham and A. C. Hollis-Hallett (Univ. of Toronto Press, Toronto, 1961).

[51] R. H. Sherman and F. J. Edeskuty, Ann. Phys. **9,** 522 (1960).

[52] T. R. Roberts, R. H. Sherman, S. G. Sydoriak, and F. G. Brickwedde, Progress in Low Temperature Physics IV, ch. 10 (North Holland Publ. Co., Amsterdam, The Netherlands, 1964), p. 480.

[53] A. M. Mood, Introduction to the Theory of Statistics, p. 299 (McGraw-Hill, New York, N.Y., 1950).

[54] M. Durieux, Procès-Verbaux du Comité Consultatif de Thermométrie auprès du Comité International des Poids et Mesures, 6^{e} Session, 1962 (Gauthier-Villars, Paris, France, 1964), p. 190.

[55] D. W. Osborne, private communication.

[56] R. Berman and C. F. Mate, Phil. Mag. **3,** 461 (1958).

[57] H. van Dijk, Progr. Cryog. **2,** p. 125 (Academic Press, Inc., New York, N.Y., 1962).

[58] G. Cataland and H. H. Plumb, Proc. 8th Intern. Conf. Low Temperature Physics, London, Sept. 16–22, 1962, ed R. O. Davies (Butterworths, Washington, D.C., 1963), pp. 439–40.

[59] E. C. Kerr, Phys. Rev. **96,** 551 (1954).

[60] E. C. Kerr and R. D. Taylor, Ann. Phys. **20,** 450 (1962).

[61] A. C. Anderson, G. L. Salinger, W. A. Steyert, and J. C. Wheatley, Phys. Rev. Letters **6,** 331 (1961); A. C. Anderson, W. Reese, and J. C. Wheatley, Phys. Rev. **130,** 495 (1963).

[62] M. Strongin, G. O. Zimmerman, and H. A. Fairbank, Phys. Rev. **128,** 1983 (1962).

[63] B. M. Abraham, D. W. Osborne, and B. Weinstock, Phys. Rev. **98,** 551 (1955).

[64] G. R. Grove and W. J. Haubach, Jr.; see ref. [58], p. 441. For further information, write Gaseous Isotope Sales, Monsanto Research Corporation, Mound Laboratory, Miamisburg, Ohio.

[65] D. O. Edwards and J. G. Daunt, Phys. Rev. **124,** 640 (1961).

[66] S. G. Sydoriak, T. R. Roberts, and R. H. Sherman; see ref. [58], pp. 437–8.

[67] J. A. Hall, Sixième Rapport du Comité Consultatif de Thermométrie au Comité International des Poids et Mesures; see ref. [54].

[68] H. F. Stimson, NBS Tech. News Bull. **47,** No. 2, 30 (Feb. 1963); Nature **197,** 1055 (1963).

[69] F. G. Brickwedde, Phys. Today **16,** 24 (1963).

[70] S. Weber, Commun. Kamerlingh Onnes Lab. Univ. Leiden Suppl. **71b** (1932), **264b** and **264d** (1936).

[71] S. Weber and G. Schmidt, Commun. Kamerlingh Onnes Lab. Univ. Leiden **264c** (1936).

[72] C. E. Chase, E. Maxwell, and W. M. Whitney, Physica **26,** 160 (1960); C. E. Chase, E. Maxwell, and W. E. Millett, Physica **27,** 1129 (1961).

[73] R. H. Moore and R. K. Zeigler, Trans. Am. Nuclear Soc. **1,** 128–9 (1958); The Solution of the General Least Squares Problem with Special Reference to High-Speed Computers, Los Alamos Scientific Lab. Rept. LA–2367 (Mar. 4, 1960).

[74] T. R. Roberts and B. K. Swartz, Proc. 2d Symp. Liquid and Solid Helium Three, ed. J. G. Daunt (Ohio State Univ. Press, Columbus, 1960), p. 163.

(Paper 68A6–304)

Physics Vol. 3, No. 2, pp. 95-113, 1967. Physics Publishing Co. Printed in Great Britain.

CEROUS MAGNESIUM NITRATE: A MAGNETIC TEMPERATURE SCALE 0.002–2°K

R.P. HUDSON and R.S. KAESER

National Bureau of Standards, Washington, D. C.

(*Received* 18 *July* 1966)

Abstract

Isentropic demagnetizations from known starting conditions yielded a determination of the entropy-magnetic susceptibility, or S-χ, *relation for single-crystal spheroids of the paramagnetic salt cerous magnesium nitrate, CMN. Enthalpy differences,* ΔQ, *between the low temperature end-points thus reached and an (arbitrary) reference temperature near 1°K (determined by gamma ray heating) yielded a corresponding* Q-S *curve, whence one obtained* S-T *and* χ-T *relations,* T *being the thermodynamic temperature. The salt exhibits a broad maximum in* χ *centered on* $S/R = 0.32$, *for which region the absolute temperature is determined to be* 0.001_5°K. *Our results disagree significantly with those of other workers (even* S-χ, *which is not subject to large experimental error) save for the observation that CMN obeys the Curie law at least down to 0.006°K.*

At high temperatures ($T > 0.006$°K), *all specimens show a heat capacity* $C/R = bT^{-2}$ *with* $b = 5.76 \times 10^{-6}$ deg^2. *Superimposed upon this is a small "anomaly" first appearing at approximately 0.015°K and reaching a maximum near 0.025°K. The attribution of such an effect to small concentrations of magnetic impurities cannot be reconciled with the results of chemical analysis. Other evidence, moreover, supports the idea of a non-magnetic origin for this anomaly.*

1. Introduction

SINCE first studied as a magnetic cooling and thermometric medium [1], the paramagnetic salt cerous magnesium nitrate, $2Ce(NO_3)_3 \cdot 3Mg(NO_3)_2 \cdot 24\ H_2O$ (hereinafter referred to as CMN), has stood pre-eminent as a working substance for the adiabatic demagnetization region [2]. Owing to the high magnetic dilution, the paramagnetic susceptibility follows the Curie Law down to approximately 0.006°K (highly convenient for thermometric indication) and can be used to produce temperatures a factor of at least two, and probably considerably more [3], lower. In the ground, $J = 5/2$, manifold the first excited doublet lies some 34 deg above the ground doublet [4] and the Curie Law behavior is exhibited through and beyond the liquid helium region [5,6].

As the applications of this salt multiplied and the question of reliability of the temperature scale provided by the first rough measurements aroused increasing interest, it became evident that new determinations were highly desirable. A series of these was undertaken [3], the first of which indicated that below the Curie Law region the absolute temperatures were considerably lower than suggested by the pioneer measurements and, furthermore, that the value of b in the "high" temperature approximation for the specific heat C, viz. $C/R = b/T^2$, was also much smaller than the published value.

Because the first experiments were carried out on a roughly ellipsoidally-shaped specimen and the above first check was made on a sphere, we next studied an ellipsoid and obtained [3] an entropy-temperature curve intermediate between the first two. The two new studies were reported in graphical form only, since we regarded them as preliminary, anticipating data of higher quality made on a new sphere with improvements in the apparatus and experimental procedures. The latter are the subject of this paper, which is being published now (a) because it is long overdue, (b) because other groups have recently reported [7,8] on a quite different approach to the determination of the CMN temperature scale with results tending to reinforce our preliminary findings, and (c) due to further enhanced interest in the scale with respect to recent important experiments, utilizing CMN, investigating the possible existence of a superfluid transition below 0.01°K in liquid He^3 [9].

2. Experimental Method

The approach adopted was the classical magnetic cooling and gamma-ray heating one [10] and, in detail, followed closely that described in earlier experiments by Ambler and Hudson [11] on a different paramagnetic salt. The CMN specimen was adiabatically demagnetized from known starting conditions of field, H_i, temperature, T_i, and hence entropy, S (calculated using the known g-value, 1.84 [12]) to a measured final susceptibility, χ, and hence magnetic temperature, $T\otimes$ (defined by $T\otimes = c/\chi$, where c is the Curie constant, 0.318 e.m.u./g ion). In this way a complete $S - T\otimes$ curve was obtained and combined with a heat content, $Q - T\otimes$ curve established via the "total-Q" gamma-ray heating method [1,11] to yield the $S - T$ and $T\otimes - T$ relations.

The maximum magnetic field available was 2.3 tesla (1 tesla = 10^4 gauss) and the lowest value employed was 0.176 tesla; even the latter, applied at a starting temperature of, typically, 1.13°K, produces a very low final temperature, viz. 0.035°K, wherefore weak-field demagnetizations were also performed from starting temperatures up to as high as 2.08°K in an attempt to span the higher reaches of the $S - T\otimes$ curve.

3. Apparatus

(a) Specimens and method of mounting.

The specimens were ground to the desired shape from large single crystals of CMN. The constituent cerous nitrate was the purest commercially available and the CMN was recrystallized several times before final growth was initiated. Upon analysis by "a general spectrochemical method" the identifiable impurities were reported [13] to be: calcium and copper - traces (indicating 10^{-6} to 10^{-5}); silicon and neodymium - very weak (indicating 10^{-5} to 10^{-4}).

Although the predominant Ce^{3+} tends to obscure other rare earth spectra, it was felt that the evidence was strongly in favor of all undesirable (magnetic) impurities being present in insignificant amounts, or at concentrations so small that the effects would be confined to a very small hfs entropy contribution above 0.05°K, readily identifiable if present and only necessitating at most a very small correction to the "initial entropy" (see 4 d(i) and (ii) below and Appendices).

The specimen was mounted within a glass vacuum case at the top of a 10.5 cm long low-thermally-conducting support, anchored at its lower end into the center of the ground-glass plug which sealed off the vacuum case. The spherical spcimens were either lashed with cotton thread to a small glass cup fixed to the top of a paper tube (actually a drinking "straw") or impaled by means of a vertical axial hole on the end of a drawn glass spill narrowed to a 2.5 cm long 0.084 cm o.d. section at the top; the ellipsoid was glued and tied to the slit and fanned-open ends of a paper tube.

The *c*-axis of the crystal coincides with the $g_=$ direction. In the plane perpendicular to this, two mutually perpendicular axes were marked, the one to be set vertically for the susceptibility measurement and the other in the direction of the field of the electromagnet. The marking was actually accomplished by drilling holes with a 0.064 cm drill; one of these was enlarged slightly and used to mount sphere I, as described above.

Owing to the marked anisotropy of CMN, a crystal will tend to line up with the magnetic field direction automatically. In assembling the apparatus visual alignment was used, good to probably ± 5°. This could be checked, and corrected if necessary, by generating a small field and measuring the susceptibility as the magnet was rotated over a few degrees. The demagnetization data were reproducible enough, too, to observe the effects of displacements of H from $g_\perp$ by 5°. Noting that cosine 5° is 0.9962, one sees that even a 5° error would reduce the effective field by only 0.4 per cent, but the above checks permitted a considerable improvement over this.

As the inside diameter of the vacuum case was only 30 mm it was necessary to be sure that the 25-mm diameter spherical specimens were centrally placed (sphere I was actually 27 mm dia.). This was confirmed by taking X-ray photographs after assembly but prior to mounting the dewars.

(b) Susceptibility measurement

The CMN specimen formed the core of a mutual inductance which could be measured by means of a Hartshorn bridge [14], normally operated at 267 H. The secondary, comprising a pick-up winding (1400 turns of 43 s.w.g. copper wire) plus symmetrically disposed bucking coils, was wound directly on the vacuum jacket; the primary, one layer of 30 s.w.g., was wound directly on to the tail section of the surrounding liquid helium dewar and immersed in the liquid nitrogen contained in the exterior dewar.

Calibration of the magnetic thermometer was carried out between 1.1 and 4.2°K, deriving the temperature from the vapor-pressure of the liquid helium with corrections for hydrostatic head in the He^4I region. The ensuing relationship between bridge turns, n, and temperature was the customary

$$n' = n - n_\infty = AT^{-1} \tag{1}$$

with A = 3 deg approximately and n_∞, the departure from exact bucking of mutual inductance, about 20. One bridge turn corresponds to 3.06 μH. With such an arrangement the maximum susceptibility encountered corresponded to $n \approx 900$, comfortably inside the n = 1111.1 range of the bridge. The minimum detectable bridge unbalance was 0.002 turn at 25 mA primary current (equivalent primary field ≈ 0.75 x 10^{-4} tesla) which corresponds to ± 0.01° at 4°K, ± 0.003° at 2°K, and 0.0008° at 1.1°K.

(c) Field and temperature controls

High stability of both magnetic field and temperature are required for accurate characterization of the (entropy) state of the CMN in an adiabatic demagnetization, while temperature control is of extreme importance during the calibration. The 100 kW electromagnet was excited by powers ranging from 50 W up to the maximum of the available 25 kW generator and adequate field stability was achieved by current stabilization, obtained by means of a shunt-tapping electronic servo-loop in the exciter circuit of the generator. The magnet current was stabilized against drift to $1:10^4$. The magnet was calibrated against the level-set control reading by means of a rotating-coil gaussmeter. This relatively crude instrument limited the accuracy of measurement of H to about ± 1/4 per cent for H greater than about 0.8 tesla. Below this, the non-reproducibility of the H vs. I characteristic due to remanence degraded the accuracy to about ± 0.002 tesla.

The helium vapor-pressure was measured, according to its magnitude, by a manometer or a McLeod gauge. A line tapped into the cryostat at its head led to a small mercury manometer in a photocell amplifier unit which in turn controlled a needle valve in the main pumping line. With this device, temperature drift was kept negligibly small. Magnetization temperatures usually ranged between the vapor pressure equivalents 0.3 and 0.6 mm Hg, the vacuum pump now operating via a fully-open 3-in. gate valve. During the magnetization period of some 6-8 min the McLeod reading might change by as much as 0.03 mm Hg at 0.4 mm, or $\Delta T = 0.01°$ at 1.14°K; usually the temperature drift was much less than this.

(d) Gamma-ray heating unit.

For heating the salt after cooling to low temperatures, the cryostat was swung out of the electromagnet. A massive lead pig located directly beneath contained a nominal 250 mCi Co^{60} source comprising 16 cobalt wires placed vertically and axially-symmetrically in a cylindrical brass container. This source could be raised from a remote position to the level of the salt in about 2 sec. Using this arrangement, a one-inch diameter CMN sphere could be heated at approximately 2000 ergs/min, which is about 50 times larger than the natural heat leak.

The gamma heating was not initiated instantaneously, of course. To investigate the detailed behavior we substituted a modified photomultiplier tube for the cryostat and fed the output signal to a chart recorder. From these observations we found that the elevation period was equivalent to about 0.2 sec of full gamma heating.

4. Results

(a) General

All three specimens studied showed the characteristic CMN behavior: dramatic cooling for even small entropy reduction (indicative of the very weak ion-ion interaction); the entropy varying as $(T^{\otimes})^{-2}$ down to about 0.006° [15] (but see 4 d(i) for anomalous features); practically constant susceptibility, or $T^{\otimes}$, for all entropies smaller than 0.38R; pseudo specific heat $C^{\otimes}$, $= dQ/dT^{\otimes}$, varying as $(T^{\otimes})^{-2}$ for magnetic temperatures greater than 0.006° (but see 4 d(ii) for anomalous behavior at "high" temperatures).

The latter property is indicated by the susceptibility decreasing linearly with time under constant heating, as follows from combining the relations $C(T^{\otimes})^2$ = const. and $\chi T^{\otimes}$ = const., first noted by Cooke and Hull [16]. Furthermore, as long as both $C^{\otimes}$ and S manifest an inverse square dependence on $T^{\otimes}$, the latter is identical with T, the absolute temperature (so long as $T^{\otimes}$ is meaningful, i.e. T is uniform throughout the specimen).

(b) Entropy-magnetic temperature, S-$T^{\otimes}$, relation

Within the limits of experimental error, the three different specimens gave identical S-$T^{\otimes}$ curves, as shown in Fig. 1 which is actually a plot of S-χ and is better suited to high χ (low $T^{\otimes}$) values.

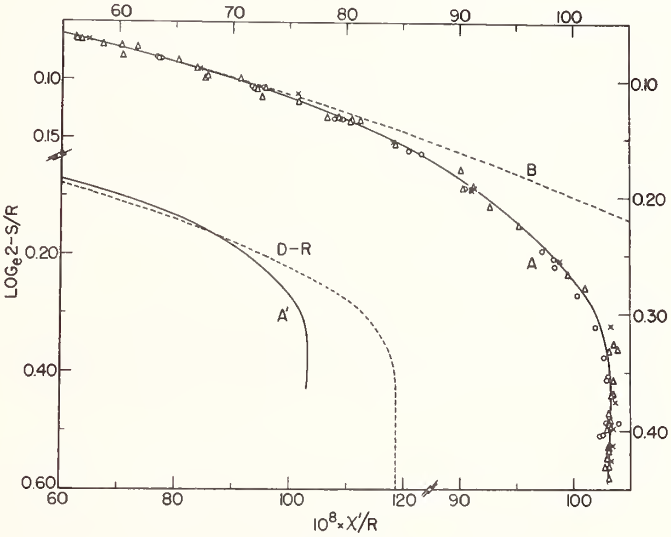


FIGURE 1

Entropy vs. susceptibility (per mole, divided by the gas constant). ○, ×, Δ, ——— data for sphere I, "ellipsoid", and sphere II, respectively. Curve A is a smooth line drawn through these points and curve B corresponds to ln 2 − $S/R = 2.88 \times 10^{-6}[T^{\otimes}]^{-2}$. Inset, comparison with results of Daniels and Robinson [1], curve D-R, curve A′ being a reproduction of curve A.

(The susceptibility of the ellipsoid was reduced to the case of a sphere by applying the appropriate shape-dependent demagnetizing correction, Δ, to the magnetic temperature, T^*, obtained from the formula $T^* = c/\chi$, since $T^{\otimes} = T^* + \Delta$ [17]. Using the latter and the relation $\ln 2 - S/R = \frac{1}{2}\, b\, (T^{\otimes})^{-2}$, one may obtain the value of Δ from the negative intercept on the abscissa axis of a plot of $(S/R)^{-1/2}$ vs. T^* [1]. The result was $\Delta = 1.75 \times 10^{-3}$ deg, and from the slope we calculated $b = 5.76 \times 10^{-6}$ deg^2.)

To obtain the value of b from the three sets of data, we plotted $\ln 2 - S/R$ vs. $(T^{\otimes})^{-2}$, as shown in Fig. 2.

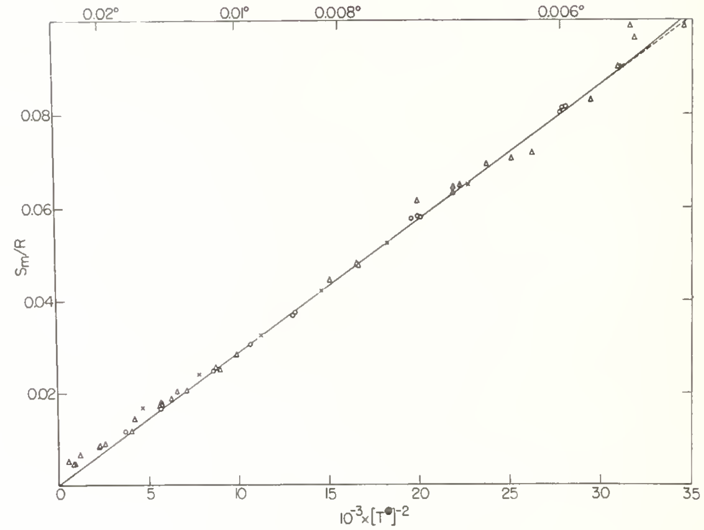


FIGURE 2

Entropy vs. reciprocal square of magnetic temperature. O, X, Δ——— data for sphere I, "ellipsoid", and sphere II, respectively. The straight line passes through the origin with a slope of 2.88×10^{-6}.

Two points need to be emphasized immediately, viz. the entropy, S, here is that of the spin system alone, calculated using $g = 1.84$ and the appropriate values of H and T; and, as is evident from Fig. 2, deviations from linearity occur at the high temperature end, $T^{\otimes} > 0.015°$. Deferring further discussion of these points until 4 d(i) below, we note that the straight line drawn through the mid-region points of Fig. 2 and through the origin has a slope of 2.88×10^{-6}, corresponding to $b = 5.76 \times 10^{-6}$ deg^2 as already found by the alternative procedure applied to the ellipsoid data (above). Again, one line represents the data for all specimens equally well.

(c) Heat content - susceptibility, Q-χ, relation

For a given entropy, the heat content was determined by measuring the time required to warm the specimen up from the low temperature reached upon adiabatic demagnetization to a reference temperature sufficiently high as to guarantee uniformity of temperature distribution. The latter should be indicated by the susceptibility vs. time curves being independent of total heating time. At very low temperatures the thermal diffusivity is not high enough to counter the inhomogeneity of the gamma ray heating and in that region the lower the initial entropy, the further the warm-up curve departs from the equilibrium or "master-Q" curve [11].

The bridge balance, n, changed from a maximum of about 900 turns (for the lowest entropies) to about 20 turns at bath temperature. For operational convenience, intermediate balance points were timed for 50 turn intervals above 80 which was the reference reading, corresponding to $T^{\otimes} \approx 0.05°$. Between 600 and 80, the n vs. t plot was linear for the spherical specimen I, indicating $C^{\otimes} \propto (T^{\otimes})^{-2}$ (see 4a above). For those demagnetizations which carried n initially beyond the linear region, however, the linear portions were not identical. The remainder of the curves could be used to establish the slope value, which is needed for calibrating the gamma source as a heater. In order to be certain that this slope was determined unambiguously, readings for sphere II were carried on down to n = 30 ($T^{\otimes} \simeq 0.25°$). As a result, a quite unexpected feature came to light, which is discussed in 4 d(ii) below.

In using the "total-Q" method, reliance is placed upon the heating rate being so fast that the background heating rate is relatively very small. Then errors due to the difficulty of making an accurate correction for the "drift" time prior to application of the gamma radiation, and those due to making the assumption that the "drift" is constant for the duration of the heating period, and from run to run, are minimized. In our case, the ratio of gamma heat to "drift" was about 50 : 1. Heating periods ranged from 50 to 110 sec while the "gamma equivalent" of the fore-period ranged from 1 to 3 sec. For all but the highest-field demagnetizations, the heating curve could be extrapolated back to the zero-time value of n for a satisfactory drift correction. For the rest, a pronounced initial curvature made the extrapolation somewhat suspect and a check was always made to see if the findings were consistent with the 50 : 1 ratio valid for the higher temperature points. One favorable circumstance is that for a given correction the percentage of total heating time is smallest for the most awkward points.

In Fig. 3 are shown some of the warm-up data for sphere II, where the heat content is plotted along the abscissa in seconds of heating time. If there were no inhomogeneity effect a unique,

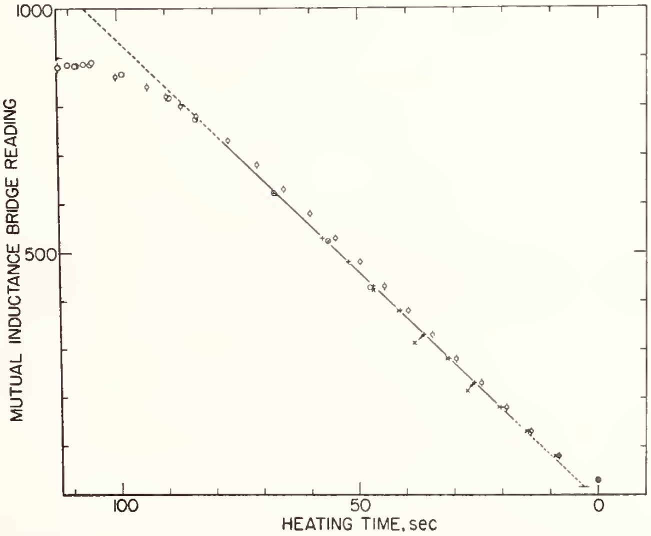


FIGURE 3

Representative data for sphere II of bridge turns ($n - n_{\infty}$) vs. time under constant heating. ⊗, x; ⊕, +; ——— initial (extrapolated) reading and subsequent readings for two separate "demagnetizations" within the linear region; ϕ, ϕ ; ——— similar for an extreme cooling; ○, ——— initial readings (only) for other warm-up curves; ⊛ , ——— universal end-point at 1°K. Drawn line represents linear portion of the "master-Q curve", corresponding to homogeneous heating of the crystal.

master-Q, curve would be obtained. We have plotted the extreme point for each entropy, together with sufficient of the intermediate points to illustrate their interpolating usefulness for the higher initial entropies and their deceptive nature otherwise. Note that between approximately 600 turns and 80 turns the n-t characteristic is quite linear.

From the original large-scale plot of Fig. 3 it may be seen that the warm-up curves for the lowest-entropy demagnetizations do not quite coincide with the master curve even at 80 turns on the bridge (63 actual turns, allowing for 17 turns residual coil unbalance). Although the spread in points is most probably very largely a manifestation of experimental scatter, we decided to choose 30 turns (13 "real turns" or ~ 0.25°K) for our reference point for heating time.

Referring back to 4(b) we know that $CT^2/R = 5.76 \times 10^{-6}$ deg^2; and from equation (1), differentiating w.r.t. time,

$$dn/dt = - AT^{-2}dT/dt. \tag{2}$$

Hence the heating rate is given by

$$\frac{d}{dt}(Q/R) = (C/R)\frac{dT}{dt} = -\frac{5.76 \times 10^{-6}}{A}\cdot\frac{dn}{dt} \tag{3}$$

and substituting $-dn/dt = 9.43$ turns/sec (from Fig. 3) and $A = 3.190$ deg, one finds

$$\frac{d}{dt}(Q/R) = 1.70 \times 10^{-5} \text{ deg sec}^{-1} \tag{4}$$

corresponding to 1830 ergs/min in the case of sphere II.

(d) Anomalous behavior at high temperatures

(i) Cooling. In deriving an S-$T^{\otimes}$ curve we calculate S for each point on the assumption that it is the same as it was at the commencement of the demagnetization. At that point the salt is at a high (approx. 1°K) temperature and, in general, the entropy, S_i, will be given by

$$S_i = R \ln 2 + S_l - S_m \tag{5}$$

where S_l is the entropy due to the lattice and $-S_m$ is the reduction in entropy due to the magnetic field.

A value for S_l is available from the work of Bailey [18], e.g. about $2 \times 10^{-4}R$ at 1°K, and is seen to be negligible for all except the smallest values of S_m [19]. In 0.176 tesla at 1.134°K, S_m and S_l are $4.6 \times 10^{-3}\ R$ and $2.8 \times 10^{-4}\ R$ respectively.

We thought it would be of interest to make an independent determination of S_l by keeping T_i considerably higher for some low-field demagnetizations, so that S_l could be comparable with S_m. The results were quite unexpected and indicated a breakdown of the validity of the isentropicity assumption, i.e. the lattice temperature now lags behind that of the electron spin system and the process is no longer thermodynamically reversible.

The effect is quite evident in Fig. 2 where the points towards the origin deviate from the straight line. Had we included the term S_l/R in calculating the entropy for Fig. 2, the anomalous points could have been lowered, it is true, but by a negligible amount for 1.1°K magnetizations. On the other hand, points for magnetizations at 2.1°K fall well *below* the line and indicate unexpectedly low temperatures, which is nonsense.

The fact that the best straight line through the data of Fig. 2 passes through the origin suggests, furthermore, that the lattice is not involved in the cooling process using *high* fields, i.e. the spins must cool immediately "out of the lattice's reach" and any ensuing manifestation of the lattice's relatively high temperatures would be indistinguishable from any other kind of heat leak. Accepting this line as "correct", one notes that the observed behavior approximates this more and more closely as T_f gets lower. By 0.015° all anomalous effects have disappeared, independently of the H_i and T_i values used to reach there. (The trend in the points as T_i is lowered is the important feature; the "origin" argument would only be conclusive if there were *no* experimental scatter. As we shall show later, the entropy correction due to impurities which possess hfs is negligible and the validity of the origin of Fig. 2 as a guide point for drawing the straight line is not compromised thereby.)

(ii) Heating. In Fig. 3 one may notice that the linear dependence of bridge turns upon time (for continuous gamma irradiation), which sets in as n falls below 600, is not maintained to the very highest temperatures. In fact, anomalous behavior which is barely discernible within the experimental scatter at 130 turns (0.03°) is very marked by 80 turns (0.05°). This slowing down of the rate of warming can only be explained, presumably, by the heat capacity rising above that due to the spins alone, which if falling as T^{-2}.

Figure 4 shows the high temperature portion of a gamma heating curve, the dotted line indicating the course the data would have taken for a normal T^{-2} specific heat. It must be

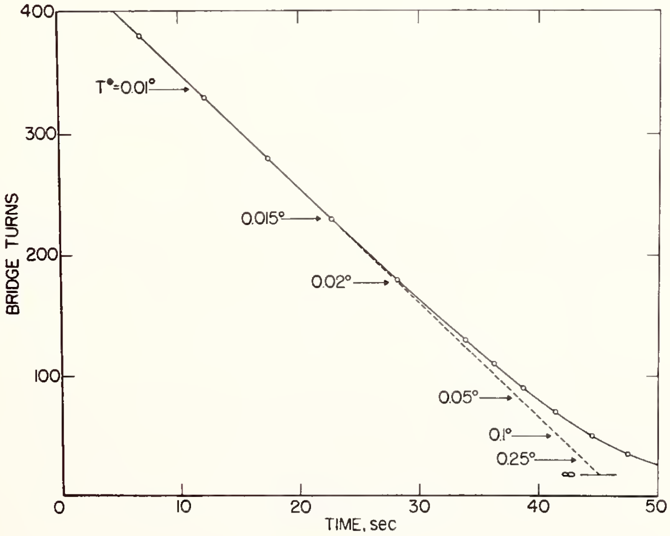


FIGURE 4

Bridge turns ($n - n_\infty$) vs. time for high temperature portion of a heating curve. The straight line corresponds to a T^{-2} dependence for the heat capacity and is identical with the straight line in Fig. 3.

emphasized that the anomalous, or excess, heat capacity is very small and is only made manifest by the extremely small heat capacity of CMN itself (see Appendix 3). The associated entropy amounts to roughly 0.0014 R, which is to be compared with R ln 2 or 0.6932 R for the total CMN spin entropy. (On the other hand, the spin system itself only gains 0.0128 R above 0.015°K.) The surprising fact is its appearance at so low a temperature as 0.015°K; lattice entropy is very decisively ruled out, if it is permissible to extrapolate the results of calorimetry obtained above 2°K [18] or to assume, at least, that the Debye characteristic temperature changes very little below 2°K.

The ready conclusion that the possible 10^{-4} concentration of Nd impurity explained all was easily shown to be erroneous and we resolved upon obtaining a quantitative determination of all the spectroscopically-indicated magnetic impurities. The results (Appendix 1) showed that the anomaly cannot be due to these impurities (their associated hfs entropy - see Appendix 2 - amounts to 10^{-4} R which has a negligible influence on Fig. 2) hence we must conclude - however surprised - that the anomaly is non-magnetic in origin. The concept of such a "ballast" is also consistent with the postulated non-isentropic nature of weak-field demagnetizations raised in the discussion of the features of Fig. 2, above.

(e) Absolute temperatures

Using the value of $\dot{Q}/R$ from equation (4), section 4(c), and the measured time to heat from the (extrapolated) initial low temperature point to the high reference temperature, values of Q/R were calculated. These were plotted against the corresponding entropy, S/R, values calculated for the initial H and T, as shown in Fig. 5.

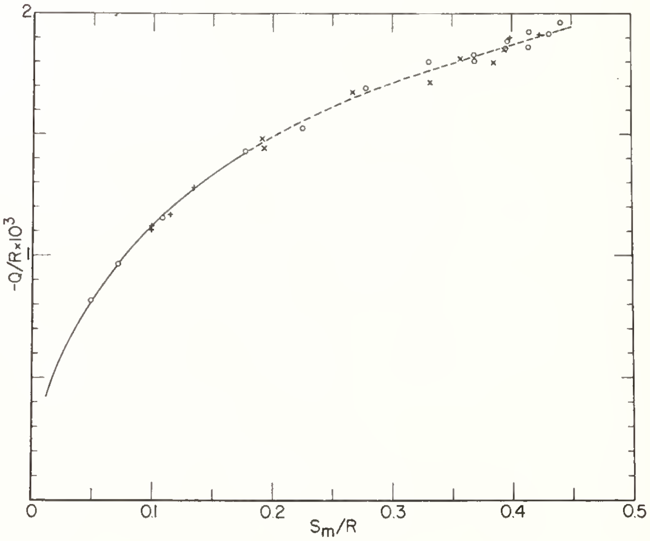


FIGURE 5

Heat content, Q/R, vs. entropy, S_m/R (= ln 2 - S/R).———, combination of linear portion of Fig. 3 and corresponding part of full line in Fig. 1.
----- least squares cubic equation fit to data points.

We made use only of the linear portion of the master Q-curve (Fig. 3) and the corresponding portion of the S-χ curve of Fig. 1. There results the portion of the curve $0.01 < S_m/R < 0.18$, and the individual demagnetization points are added there for completeness.

From 0.18 to the lowest entropies obtained we have plotted the individual points and fitted a curve through them and many points on the above mentioned curve. We used a computer "spline fit" [20] which determined "by least squares" two smoothly-joined cubic equations ($0.0144 < S_m/R < 0.1042$ and $0.1042 < S_m/R < 0.4312$) and yielded a r.m.s. deviation of 2.045×10^{-5} for Q/R over the whole region.

Absolute temperatures were obtained by differentiating the curve of Fig. 5, using the computed curve for the region $S_m/R > 0.18$. (For that region only the r.m.s. deviation is 2.603×10^{-5}.) The results are shown as a plot of entropy versus Kelvin temperature in Fig. 6. The

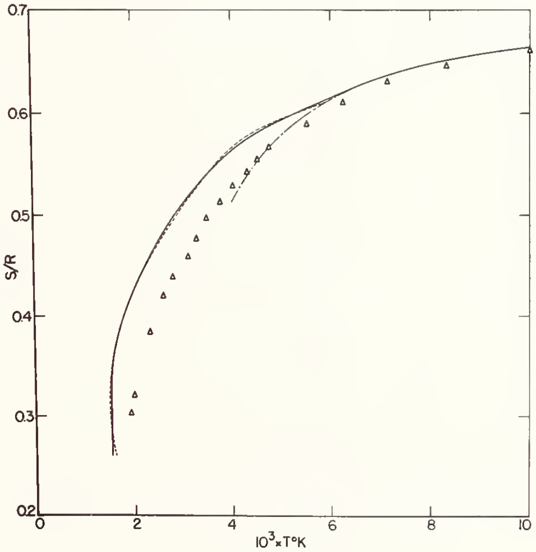


FIGURE 6

Entropy vs. Kelvin temperature. -----, from differentiation of curve in Fig. 5. ———, arbitrarily smoothed modification. — – — –, from equation: $\ln 2 - S/R = 2.88 \times 10^{-6}\ T^{-2}$.

chain-curve delineates the equation $\ln 2 - S/R = 2.88 \times 10^{-6},\ T^{-2}$ and the dashed curve the actual differentiation of Fig. 5. Having regard for the experimental uncertainties we deemed it appropriate to smooth out the curve by a relatively small redrawing (full line). The raw (dashed) curve curls back at the lowest entropies (which is not possible, physically) due to our inability to secure a curve for Fig. 5 without an inflexion point at low entropy. The substituted vertical portion is as satisfactory a representation of the data as any and, again, the possible additional error introduced thereby is negligible. The triangles included in Fig. 5 are from the data of Frankel, Shirley and Stone [8].

Table 1 summarizes our results with corresponding values of H/T, S/R, susceptibility,

TABLE I

10^{-3} x H/T (G deg^{-1})	$g\beta H/kT$	S/R	10^{8} x χ'/R (deg G^{-2})	$T^{\otimes}$ (m deg)	T (m deg)
2.0	0.2472	0.6856	19.60	19.49	19.49
2.5	0.3090	0.6814	24.45	15.63	15.63
3.0	0.3708	0.6763	29.27	13.06	13.06
3.5	0.4326	0.6703	34.04	11.23	11.23
4.0	0.4944	0.6635	38.77	9.86	9.86
4.5	0.5562	0.6559	43.45	8.80	8.80
5.0	0.6180	0.6476	48.05	7.95	7.95
5.5	0.6798	0.6386	52.61	7.26	7.26
6.0	0.7416	0.6289	57.09	6.69	6.69
6.5	0.8034	0.6185	61.49	6.21	6.18
7.0	0.8652	0.6077	65.71	5.81	5.66
7.5	0.9270	0.5963	69.73	5.48	5.14
8	0.9888	0.5844	73.55	5.19	4.65
9	1.1124	0.5595	80.38	4.75	3.90
10	1.2360	0.5333	86.25	4.43	3.37
11	1.3596	0.5063	90.86	4.20	2.93
12	1.4832	0.4788	94.70	4.03	2.56
13	1.6068	0.4512	97.89	3.90	2.25
15	1.8540	0.3965	102.41	3.73	1.78
17	2.1012	0.3444	103.76	3.68	1.54
19	2.3484	0.2960	103.77	3.68	1.53
21	2.5956	0.2521	103.52	3.69	(1.53)
23	2.8428	0.2131	-	-	(1.53)
25	3.0900	0.1790	-	-	(1.53)

magnetic and Kelvin temperatures. Values of χ'/R and $T^{\otimes}$ for given S/R were derived from curve A of Fig. 1 and the straight line of Fig. 2. (One should recall that our experience indicates that demagnetizations for $S/R > 0.67$, however, will not be isentropic.) Values of T greater than 0.0065°K were calculated from the relation $\ln 2 - S/R = 2.88 \times 10^{-6}\, T^{-2}$. Figures have been carried beyond the significant to facilitate faithful reproduction of the data, if desired.

Considering the case of a substance obeying Curie's law, $\chi = c/T$, the Curie constant c is given by

$$c = Ng^{2}\beta^{2}\, S(S + 1)/3k$$

for a total number of spins N; the other symbols have their usual meaning.

Thus the quantity c/R ($= g^{2}\beta^{2}/4k^{2}$ for $S = 1/2$) is a simple one involving only fundamental constants and the pertinent g-value. The susceptibility is frequently expressed, therefore, as χ/R ($= c/RT$) and may be calculated readily from relative susceptibility measurements, once the "thermometer" has been calibrated in a region where the T^{-1} dependence of χ obtains (equation (1)).

For CMN, $g_{\perp}$ (the appropriate g-value for these measurements) = 1.84 [12] and $c/R = 0.38_2$ deg^2 G^{-2}. The *susceptibility* values in Fig. 1 were actually computed using $c/R = 0.38$, but values read from the curve A have been adjusted to correspond to 0.38_2 before compilation of column 4 in Table 1.

5. Discussion

(a) Sources of error

The method of deriving values for the absolute temperature used in this paper, i.e. from a functional relationship between energy and entropy, relies upon one's ability to calibrate the gamma ray heat source, which in turn requires the salt to exhibit a quadratic dependence of entropy upon temperature in the high regions of the magnetic thermometer's application.

The current observations demonstrate, with rising temperature, the expected behavior between 0.006 and 0.015°K. At higher temperatures the effects of a small additional (anomalous) heat capacity become manifest but the evidence is strongly in favor of this being non-magnetic in origin (see Appendices). If this be so, then we can legitimately regard it as spurious for our purposes here, and rightfully adopt the procedures we have for obtaining corresponding Q-χ and S-χ relations valid for the spin system alone. (It is interesting to note that the highest temperature data shown (graphically) by Daniels and Robinson in their original paper [1] indicate a similar (but larger) anomalous heat capacity although their experimental scatter, it is true, leaves room for doubt.)

The commonest errors arise from uncertainties in the entropy (from H_i and T_i) and in the corresponding susceptibility (extrapolation of bridge reading to zero time); in the heating-time measurement, including the effect of "drift" alone, prior to applying the gamme ray source; in the assumption that the combination of drift heat and gamma heat is constant for all measurements; in fitting the respective straight lines to the data of Figs. 2 and 3; in deriving the Q-S curve from the data points and in differentiating this. It is the latter which introduces by far the greatest uncertainty and an appreciation of this combined with an inspection of the cource of the curve in Fig. 6 should convince one that derived temperatures between 3 and 5 m. deg are most sensitive to the combined errors in measurement and data processing.

Having due regard for all the above factors we believe that the random error may be cogently assessed at ± 0.3 m deg for all temperatures below 0.005°K, diminishing rapidly to possible ± 0.1 m deg at 0.006°K. Above 0.0065°K and up to 4°K, CMN should obey Curie's law exactly, as far as present measurement techniques can discern.

(b) Comparison with other work

The results reported here for our sphere II are in quite good accord with our previous, preliminary findings for sphere I and the "ellipsoid". They agree with the latter extremely closely down to 0.003°K, below which they fall generally between the two earlier sets.

The measurements for sphere I are suspect because of the increased inhomogeneity of the heating for this large crystal. The high temperature reference point for the timing of the heating period was chosen too low, and insufficient data were taken in the (now known to be very significant) region of 0.02°K and above. Furthermore, the withdrawal of the cryostat from the magnet introduced some vibrational heating, leading to increased errors and scatter in the data.

The ellipsoid data were not taken primarily to obtain absolute temperatures and the data points are really too few for derived quantities to give rise to high confidence. Nevertheless the agreement between them and our current results is quite good.

We wish to emphasize, however, that we do *not* consider that evidence exists for a shape-dependent S-T relation. Our sphere and "ellipsoid" data agree within the experimental uncertainties which are, of course, quite large.

The experiments of Frankel, Shirley and Stone [8] using gamma-ray anisotropy as a thermometric parameter showed very close agreement between results obtained for specimens of different shape. This approach should be very well suited to obtaining reliable data at the lowest temperatures, and where our method deteriorates. In the temperature region 0.0015-0.007°K (Fig. 6) our temperatures are approximately 0.0005 deg lower with a maximum separation of about 0.0007 deg in the region 0.003-0.0045°K.

Above 0.007°K Frankel *et al.* and we agree that $T = T^{\otimes}$; our S-T plots however lead to quite different estimates of T, given the entropy. This arises from our finding that $\ln 2 - S/R = 2.88 \times 10^{-6}\, T^{-2}$ while they accept $\ln 2 - S/R = 3.2 \times 10^{-6}\, T^{-2}$ as reported by Daniels and Robinson [1]. Actually they fitted their data to a theoretical curve above 0.006°K to derive a value for their quantity B, a hyperfine coupling parameter, and using only the fact that $T = T^{\otimes}$. Then this value for B was fed into the nuclear data obtained at very low temperatures to obtain estimates of the latter. Thus the elicitation of B is seen to be of crucial importance in this method.

Between 0.006 and 0.0032°K the temperatures (at equivalent entropies) of reference [8] are slightly higher than those of reference [1]. (Below 0.0032°K the reverse situation sets in and the divergence increases rapidly.) This indication that the latter scale is quite good for representing the nuclear orientation data lends support to the corresponding S-T relation. In addition, Frankel *et al.* state that "our T^{*}" ($T^{\otimes}$?) "versus $(H/T)_i$ data agree well with those of Daniels and Robinson and were very reproducible using different crystals". The agreement is clearly depicted in a graphical presentation of the pertinent data [21].

This good agreement and the discrepancy with our data are puzzling. Figure 1 shows clearly that our S-$T^{\otimes}$ results are very consistent between specimens of different shapes but quite different from those of Daniels and Robinson. And secondly one would expect the latter to become particular and unrepresentative of CMN in general for $\ln 2 - S/R > 0.2$, or $T < 0.0033$°K, since the demagnetization correction is large in this region and would not be valid for a roughly rounded rectangular block as was actually used [22] by Daniels and Robinson.

Considering the probable error involved in extracting from the data a value for the slope of the line in Fig. 1, the difference between 2.88×10^{-6} and 3.2×10^{-6} is, in the context, enormous and presently inexplicable. While the oft-made assertion concerning the unique value of CMN in producing millidegree temperatures and in obeying Curie's law down to approximately 0.006°K remains valid, it is evident that much further study will be required to yield a full understanding of the low temperature properties of this substance.

(c) Limitations of the CMN thermometer

The present investigations relate to the properties of spheroidal-shape single crystals of CMN. This substance is, of course, highly anisotropic and hence the results, particularly at the lowest temperatures, cannot be expected to apply to irregularly shaped crystals or aggregates of crystallites. This may be the reason for the marked discrepancy at the lowest temperatures between our conclusions and those of Abel, Anderson, Black and Wheatley [26], who concluded, using the properties of He^3 as a temperature reference, that for powdered CMN $T^* = T$ to the lowest temperatures ($\sim$0.003°K).

The thermometric parameter being χ (or $T^{\otimes}$), the salt diminishes in usefulness in the region where χ becomes an insensitive function of S/R. Inspection of Fig. 1 shows that the sensitivity diminishes rapidly for $\log_e 2 - S/R > 0.28$, i.e. for $T < 0.0019$°K (from Fig. 6). In the liquid helium region, the thermometer is insensitive because of the smallness of χ and, further, the highly advantageous feature of Curie law behavior disappears at an accelerating rate as T rises above, say, 5°K and the effect of energy doublets lying well above the ground state becomes significant [5,6]. Thus one may conclude that the $\chi - T$, or $T^{\otimes} - T$, relation for the $g_{\perp}$ direction in spheroidal-shape single crystal specimens of CMN is a useful temperature scale for the range 0.002-2°K.

References

1. J.M. DANIELS and F.N.H. ROBINSON, *Phil. Mag.* 44, 630 (1953).

2. R.P. HUDSON, in *Temperature – Its Measurement and Control in Science and Industry*, Vol. 3, Part 1, p.51. Reinhold, New York (1962).

3. R.P. HUDSON, R.S. KAESER and H.E. RADFORD, *Proceedings of the 7th International Conference on Low Temperature Physics*, p.45. University of Toronto, Canada (1960).

4. C.B.P. FINN, R. ORBACH and W.P. WOLF, *Proc. Phys. Soc.* A77, 261 (1961); for a summary of different determinations of this splitting see reference [18].

5. R.P. HUDSON and W.R. HOSLER, *Phys. Rev.* 122, 1417 (1961).

6. M.J.M. LEASK, R. ORBACH, M.J.D. POWELL and W.P. WOLF, *Proc. R. Soc.* A272, 371 (1963).

7. F. CARBONI and R.C. SAPP, *Ann. Phys.* 33, 77 (1965).

8. R.B. FRANKEL, D.A. SHIRLEY and N.J. STONE, *Phys. Rev.* 140, A1020 (1965); 143, 334 (1966).

9. V.P. PESHKOV, *Z. eksp. teor. Fiz.* 48, 997 (1965); W.R. ABEL, A.C. ANDERSON, W.C. BLACK and J.C. WHEATLEY, *Phys. Rev. Letters* 16, 273 (1966).

10. N. KURTI and F. SIMON, *Proc. R. Soc.* A149, 161 (1935).

11. E. AMBLER and R.P. HUDSON, *J. Chem. Phys.* 27, 378 (1957).

12. A.H. COOKE, H.J. DUFFUS and W.P. WOLF, *Phil. Mag.* 44, 623 (1953).

13. This analysis was conducted in the Spectrochemistry Section, National Bureau of Standards.

14. D. de KLERK and R.P. HUDSON, *J. Res. Natl Bur. Std.* 53, 173 (1954).

15. We differentiate between temperatures on the thermodynamic, or Kelvin, scale and on the "magnetic scale" by including and omitting the symbol *K*, respectively.

16. A.H. COOKE and R.A. HULL, *Proc. R. Soc.* A181, 83 (1942).

17. N. KURTI and F. SIMON, *Phil. Mag.* 26, 849 (1938).

18. C.A. BAILEY, *Proc. Phys. Soc.* 83, 369 (1964).

19. We consider a mole to contain 1 g ion of Ce^{3+}, not two as indicated by the molecular formula and encountered in calorimetry papers.

20. We are indebted to Mrs. CARLA MESSINA for making this program, a private communication from Professor JOHN RICE, Purdue University, available to us.

21. R.B. FRANKEL, Thesis, University of California (unpublished).

22. J.M. DANIELS, private communication.

23. The analysis was carried out by Mrs. M.M. DARR and T.C. RAINS, Analytical Chemistry Division, National Bureau of Standards.

24. Values for b_n (hfs term in heat capacity "tail", $C_n/R = b_nT^{-2}$) were taken from A.H. COOKE and H.J. DUFFUS, *Proc. R. Soc.* A229, 407 (1955); A.H. COOKE, H. MEYER and W.P. WOLF, *Proc. R. Soc.* A237, 395 (1956).

25. The calorimetric measurements were made by J.H. COLWELL to whom the authors are indebted for permission to include his results here.

26. W.R. ABEL, A.C. ANDERSON, W.C. BLACK and J.C. WHEATLEY, *Physics* 1, 337 (1965).

APPENDIX 1

Quantitative analysis [23]

The 3 : 1 "ellipsoid" specimen was destructively tested. By atomic absorption spectrophotometry and comparison with standard solutions the Cu content was determined to be 1 ± 0.3 μg/g.

Cerium was separated from other rare earths by oxidation with AgO and extraction by di(2-ethylhexyl) phosphoric acid in carbon tetrachloride. The rare earth fraction was precipitated with gallium as a carrier, ignited at 1000°C, and the Ga_2O_3 fraction subjected to spectrochemical examination using synthetic reference standards. Radioactive tracers were employed to cross-check the separation procedure; $Eu^{152,154}$ showed greater than 99 per cent recovery in the Ga_2O_3 and Pr^{144} was not extracted with the cerium.

The results, quoted in mass fraction of the CMN, were:

Dy	not detected ($< 10^{-6}$)
Gd	not detected ($< 10^{-6}$)
La	$< 5 \times 10^{-6}$
Lu	$< 10^{-6}$
Nd	3×10^{-5}
Pr	$< 5 \times 10^{-6}$
Sm	$< 5 \times 10^{-6}$
Tb	not detected ($< 5 \times 10^{-6}$)
Y	not detected ($< 10^{-6}$)
Yb	$< 10^{-6}$

APPENDIX 2

Effect of Impurities

From the foregoing Section we see that we need only consider the effects of Pr, Nd, and Sm. These will contribute to the entropy via their hfs; abundances and relevant spins are 100%, 5/2; 20%, 7/2; and 29%, 7/2 respectively. As the mass fraction of the Ce^{3+} itself is approximately 0.18, the effective concentrations, relative to their contributing additional entropy, are: $< 3 \times 10^{-5}$, 1.7×10^{-4} and $< 3 \times 10^{-5}$ respectively.

Thus for the contributions to S/R we calculate:

Pr: (less than) $1 \times 3 \times 10^{-5} \times \ln 6 = < 5.4 \times 10^{-5}$

Nd: $0.20 \times 1.7 \times 10^{-4} \times \ln 8 = 7.1 \times 10^{-5}$

Sm: (less than) $0.29 \times 3 \times 10^{-5} \times \ln 8 = < 1.8 = 10^{-5}$

and, in total, $< 1.4 \times 10^{-4}$.

Failure to include such a contribution to the entropies calculated for the points in Figure 1 would obviously not modify the derived value for the slope of 2.88×10^{-6}

These impurities would, however, add a contribution to the b-value (heat capacity coefficient of T^{-2}) in the liquid helium region [24]. This appears in the expression for the entropy as $b/2$; we found [3] 3.15×10^{-6} instead of the figure 2.88×10^{-6} but the impurity contribution of 0.15×10^{-6} (mostly due to Pr) accounts for only one half of the difference. The rest can readily be accounted for by imprecision in the paramagnetic relaxation determination.

APPENDIX 3

Anomalous heat capacity

Referring to Fig. 4, for any given value of n' (or $T^{\otimes}$) the slope of the curve and the slope of the "ideal" straight line are in inverse ratio to that of the total heat capacity and the dipole-dipole heat capacity $5.76 \times 10^{-6}\ T^{-2}$. The total heat capacity may therefore be derived.

Again a spline fit was used to place a "least squares" curve through the points (actually we fitted to $500 - n' = n''$), two cubic equations giving an excellent fit with a r.m.s. deviation in n'' of 1.5356. The curve was differentiated algebraically and the computation made of total heat capacity, then the anomalous fraction by subtraction.

The results are shown in Fig. 7. We emphasize that the numerical values diminish in validity

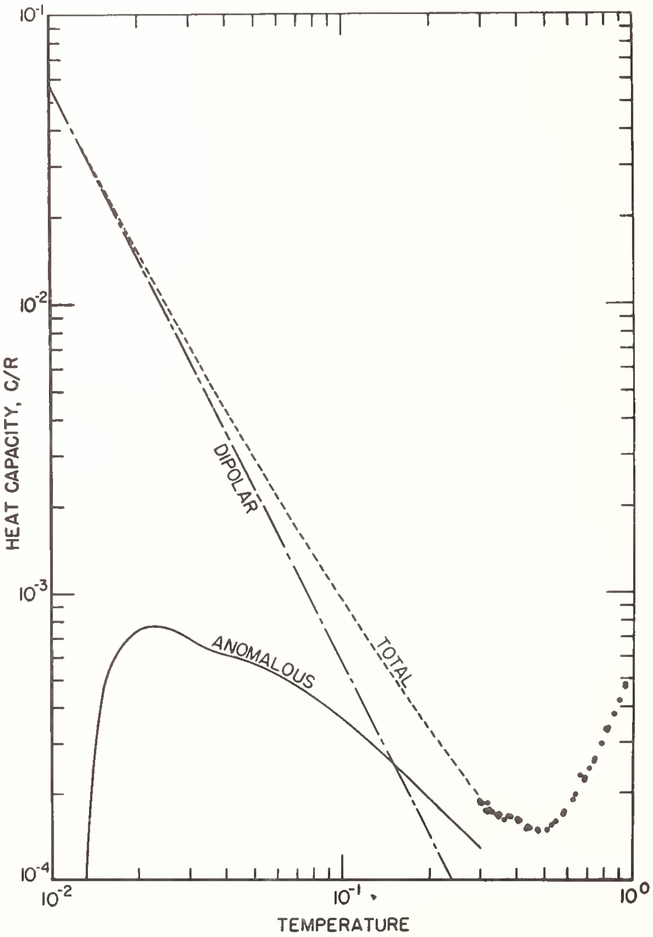


FIGURE 7

Heat capacity vs. temperature. Curve labelled "dipolar" is $5.76 \times 10^{-6}\ T^{-2}$. Points in lower right-hand corner due to Colwell [25].

at the temperature extremes: at the low end because we are taking the small difference between two large quantities, and at the high end because the primary experimental data are too sparse to determine the curve accurately. The general features of Fig. 7 are significant, however, and these show a peak in the anomaly around 0.02°K, and a high temperature "tail" which varies as T^{-1} and in the region of 0.3°K is much greater than the dipolar contribution. Also plotted are the results of conventional calorimetric determinations of the total heat capacity of a large single crystal of CMN [25] which appear to agree remarkably well with our derived data (though the measurements only meet, i.e. do not overlap).

These latter data cannot be represented by a combination of two terms varying respectively as T^{-2} and T^3. They suggest notable departures from T^3 below 1°K and in the region where any magnetic contribution would be negligible. (The measurements when carried to still higher temperatures agree well with the findings of Bailey [18] for the region above 2°K.)

The entropy associated with the anomaly curve of Fig. 7 is $1.4 \times 10^{-3}\, R$ approximately, or ten times as large as that arising from the hfs of the impurities (Appendix 2). On the other hand, it is still a very small quantity. In magnitude and temperature range it is highly suggestive of a magnetic impurity, but we have shown that this cannot be substantiated; a non-magnetic source, and in poor thermal contact with the spin system, is more likely. It is manifest in all our specimens but their varying shape, size, and mounting rule out the possibility of its arising from surface coating or mechanical support. It would be interesting to conduct low temperature heat capacity measurements on the (very pure) lanthanum double nitrate, and we plan to do this in the near future.

Resistance Thermometry

9. PRECISION RESISTANCE THERMOMETRY AND FIXED POINTS

H. F. Stimson

National Bureau of Standards

Introduction

The definition of the International Temperature Scale[1] gives the interpolation formulas relating temperature to the resistance of a standard resistance thermometer. The standard resistance thermometer and formula together provide the means for determining an unknown temperature relative to the ice point temperature from a determination of the ratio of two resistances of the thermometer, one at the unknown temperature and the other at the ice point. Precision resistance thermometry with a standard resistance thermometer, therefore, depends upon the precision and accuracy with which these ratios can be determined.

The standard resistance thermometer is calibrated at the ice, steam, and sulfur points for determinations of temperatures from the ice point to 630°C, and further calibrated at the oxygen point for determinations of temperatures between the oxygen and ice points. The accuracy of resistance thermometry depends fundamentally upon the accuracy with which the fixed-point temperatures can be realized. Precision resistance thermometry therefore requires not only precision measurements of resistances but also accurate realizations of the fixed points when the standard resistance thermometers are being calibrated.

The paper, "Precision Resistance Thermometry," at the temperature symposium held in New York in 1939, was contributed by E. F. Mueller.[2] He mentioned the beginning of precision resistance thermometry in 1887, when Callendar's paper on resistance thermometry was published. He then described the procedures of precision resistance thermometry that were the best practice a half century later. The present paper describes some of the techniques which have been developed in the 15 years since Mueller's paper was written.

At the time of the earlier symposium there had been some studies at the Massachusetts Institute of Technology[3, 11] on the reproducibility of the steam, sulfur and ice points which are the fixed points for the first resistance-thermometry part of the International Temperature Scale. Recognizing the importance of this work, the National Bureau of Standards began in 1942 to develop apparatus and techniques to improve the accuracy of the realization of all four fixed points which are the basis of both of the resistance-thermometry parts of the scale. The aim was to make the accuracy of realization of these fixed points comparable with the precision of measurement.

Recent Developments in Technique for Precision Determinations of Thermometer Resistances

Measurements of the resistances of platinum resistance thermometers are made with a small electric current flowing in the coils of the thermometers. This small current heats the platinum and raises its temperature above that of the surroundings. The amount which the temperature of the platinum is raised depends upon the construction of the platinum thermometer and often on the environment of the thermometer. For thermometry of the highest precision the effects of this heating must be taken into account.

When the surface of the protecting envelope of the thermometer is in direct contact with a substance which absorbs the heat of the measuring current, the platinum is heated only the amount of the temperature drop to the outside of the envelope itself. This condition might exist when the thermometer is directly in an ice bath or a stirred liquid bath. See Fig. 1. There are times, however, when this heat flows beyond the outside surface of the protecting envelope before it is absorbed. At these times there is a further temperature drop outside the envelope. This condition exists, for example, when the thermometer is being calibrated in a triple point cell (described later). See Fig. 2. In this instance there is a temperature drop from the envelope to the inside wall of the triple-point-cell well through the fluid in the well, usually water. There is a further drop in temperature through the glass of the well to the outside of the well and then another small drop through the film of water outside the well before the heat reaches the water-ice surface where the fixed point temperature is maintained by the liquid-solid equilibrium.

Sometimes the temperature drop from the outside of the thermometer envelope to the temperature of interest may be made smaller by the use of liquids or solids which improve the thermal contact. In the triple point cell, for example, it is convenient to use water in the well of the cell. Water is a much better thermal conductor than air but a free fitting metal bushing occupying most of the space in the water outside the thermometer coil helps a good deal more. In the triple point cell, when 2 milliamperes are

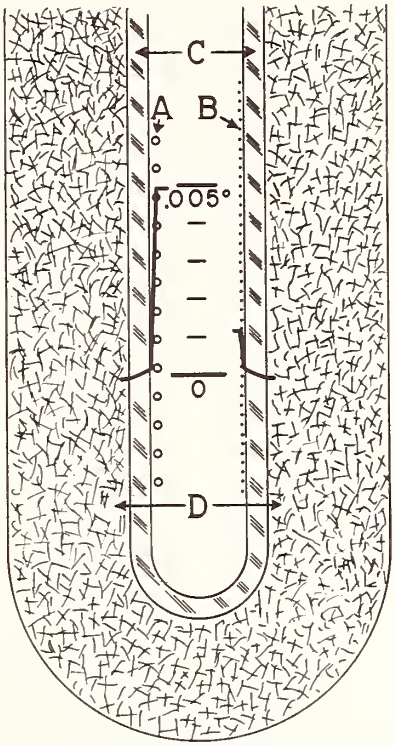


Fig. 1. Thermometers in ice bath. Temperature distribution from axis of thermometer with 2 milliamperes current. A. Platinum coils of coiled filament thermometer; only alternate coils are indicated. B. Platinum of single layer helix thermometer; alternate turns indicated. C. Pyrex thermometer envelope. D. Ice bath.

flowing in the thermometer coils, an aluminum bushing has reduced the temperature drop outside the thermometer envelope from about 0.0008°C to about 0.0002°C. In the benzoic acid cell[4] at about 122.36°C one can not use water, so bushings are of great help. See Fig. 3. In the benzoic acid cells especially, it is wise not to use a bushing much longer than the coils because the upper parts of the cells cool much sooner than the lower parts. Glycerine or oil has been used in the wells of benzoic acid cells to improve the thermal contact, but care must be taken lest these conducting fluids undergo a chemical reaction when they are at these temperatures and thus produce an independent source of energy to cause an erroneous determination of temperature. Obviously a thicker film of a given conducting medium will maintain a greater temperature difference across it.

Inasmuch as the platinum is heated by the measuring current it is necessary to wait till a sufficiently steady state of heat flow is established so that the resistance of the thermometer is constant enough for precision measure-

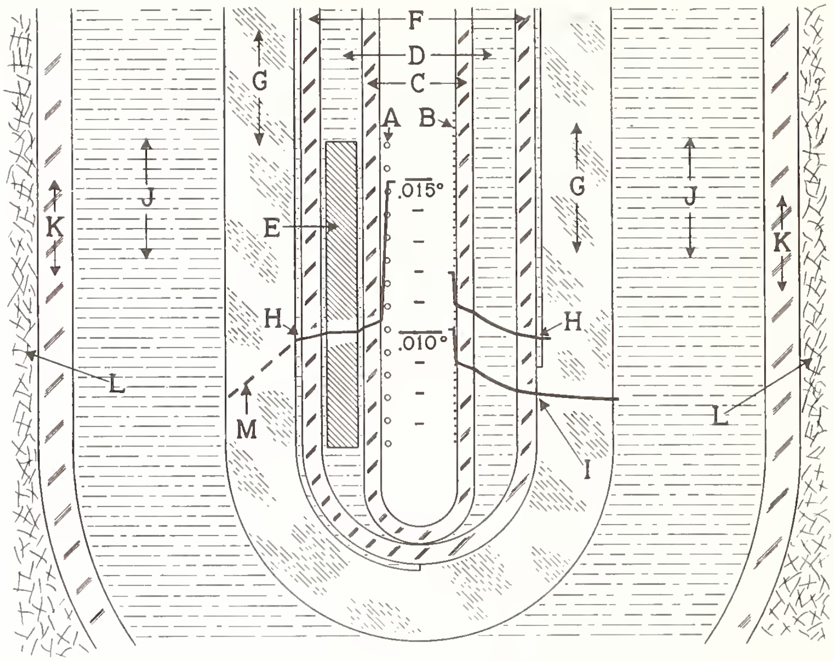


Fig. 2. Thermometers in triple point cell. Temperature distribution from axis of thermometer with 2 milliamperes current. A. Coiled filament. B. Single layer. C. Pyrex thermometer envelope. D. Water. E. Metal bushing. F. Pyrex thermometer well. G. Ice mantle. H. Inner melting. I. No inner melting. J. Water in cell. K. Cell wall. L. Outside ice bath. M. Temperature gradient through mantle.

ments. The time that it is necessary to wait depends upon the temperature rise of the platinum and the various heat capacities and thermal conductivities of the parts of the thermometer and the surroundings that intervene between the platinum and the substance whose temperature is being measured. The approach of the thermometer resistance to the steady state value, therefore, is not a simple exponential function of time. For precision measurements it is necessary to have a continuous current flowing in the thermometer coil and to wait till the resistance of the coil has reached its final value within the desired precision of measurement. Under different conditions this time has been found to range from a half to five minutes.

When the thermometer is to be used for precision measurements of temperature in places where the temperature is maintained beyond the outside boundary of the protecting envelope, the reliable way to make the resistance determinations is to measure the resistances at two different currents and extrapolate to the resistance which it would have if no current were flowing through the thermometer coil. In instances where the highest precision is not demanded the temperature drop outside the thermometer

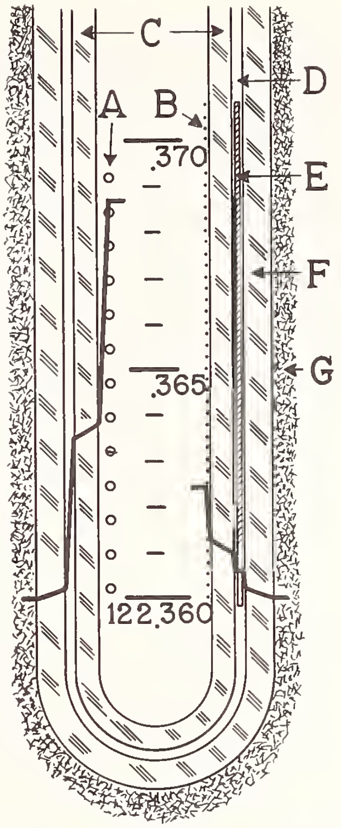


Fig. 3. Thermometers in benzoic-acid cell. Temperature distribution from axis of thermometer with 2 milliamperes current. A. Coiled filament. B. Single layer. C. Pyrex thermometer envelope. D. Air space. E. Metal bushing. F. Well. G. Solid and liquid benzoic acid.

envelope may be small enough to be neglected. For these, the thermometer coefficients obtained with 2 milliamperes in the coils may be used. In the Callendar formula the alpha coefficient for the 2 milliampere current, however, will probably differ from the calibration at zero milliamperes by several units in the sixth significant figure. The delta coefficients will not differ significantly. During the past few years, certificates from the National Bureau of Standards have stated: "The following values were found for the constants in the formula,

$$t = \frac{R_t - R_0}{\alpha R_0} + \delta\left(\frac{t}{100} - 1\right)\frac{t}{100},$$

in which t is the temperature at the outside surface of the tube protecting the platinum resistor—and R_t and R_0 are the resistances of the platinum resistor at $t°$ and 0°C respectively, measured with a continuous current of 2.0 milliamperes." In some instances, where the user needed to make measurements with higher precision, the alpha coefficients have been determined for the current extrapolated to zero. It is possible, however, as we shall see presently, to compute the difference in the alpha coefficient to a satisfactory approximation from a determination which one can make of the heating effect in an ice bath.

The alpha coefficient is defined by the equation $\alpha = (R_{100} - R_0)/100\ R_0$. When a measuring current (for example 2 ma) is flowing in the thermometer coil the resistances, R_0 and R_{100}, will be increased to $R_0 + \Delta R_0$ and $R_{100} + \Delta R_{100}$. If we now call α_Δ the apparent alpha coefficient, at this measuring current, then

$$\alpha_\Delta = \frac{(R_{100} + \Delta R_{100}) - (R_0 + \Delta R_0)}{100(R_0 + \Delta R_0)}$$

Performing the division indicated by the fraction we can write the equation in the form

$$\alpha_\Delta = \frac{R_{100} - R_0}{100 R_0} + \frac{\Delta R_{100} - (R_{100}/R_0)\Delta R_0}{100(R_0 + \Delta R_0)} = \alpha + \frac{\Delta R_{100} - (R_{100}/R_0)\Delta R_0}{100(R_0 + \Delta R_0)}$$

With any given measuring current, the power dissipated in a coil is proportional to its resistance, so at 100° the power dissipated is greater than the power dissipated at 0° by the ratio R_{100}/R_0. At 100°, however, the thermal conductivity of air is 30% greater than at 0° and the thermal conductivity of Pyrex glass is 13.5% greater. In thermometers of widely different construction the part of the temperature drop through glass from the platinum to the outside of the protecting envelope tube may range from 5% to 15% of the total drop. Although radiation from the platinum is a few times greater at 100° than at 0° it probably accounts for less than 1% of the heat transfer. The temperature drop from the platinum to the thermometer envelope tube, therefore, is predominantly through air so if we select the value, 1.29, for the ratio of the average coefficient of heat transfer at 100° to that at 0° our computations probably will not be in error by more than one or two percent. We can, therefore, take $\Delta R_{100} = \Delta R_0(R_{100}/R_0)/1.29$. Since the value R_{100}/R_0 is about 1.392 we can write

$$\alpha_\Delta = \alpha + \frac{1.392\Delta R_0(1/1.29 - 1)}{100(R_0 + \Delta R_0)} = \alpha - \frac{0.313\Delta R_0}{100 R_0} \text{ approximately.}$$

For two milliamperes current the values of ΔR_0 for two widely different thermometers were found to be 460 microhms and 125 microhms respectively. The corresponding values for $\alpha - \alpha_\Delta$ are 53×10^{-9} and 15×10^{-9}

respectively. We can get the significance of these values when we consider that 39 × 10^{-9} for $\alpha - \alpha_\Delta$ is equivalent to 0.001° in 100°, hence for these thermometers the values for $\alpha - \alpha_\Delta$ are equivalent to about 0.0014° and 0.0004° in 100° respectively. For one milliampere these values would be reduced by a factor of four.

In striving for a precision of a few microhms in the determination of the resistance extrapolated to zero current it is necessary to control carefully the ratio of the currents used for the measurements and to consider the variance of the measurements at each of these currents. Thermometers having larger heating of the platinum at a given current require greater precision in the determination of the ratio of the two currents. Ordinary milliammeters are not sufficient for the highest precision and an auxiliary potentiometer for setting the current is desirable. When using these measurements for extrapolation to zero-current determinations it will be shown that precision in the resistance measurements at the lower current is more important than precision in the measurements at the higher current. Statistical theory shows that

$$s_Y^2 = \left(\frac{x_2}{x_2 - x_1}\right)^2 s_{\bar{y}_1}^2 + \left(\frac{x_1}{x_2 - x_1}\right)^2 s_{\bar{y}_2}^2$$

where s_Y^2 is the estimate of the variance of the zero-current resistance, $s_{\bar{y}_1}^2$ and $s_{\bar{y}_2}^2$ are the estimates of the variance of the means of the lower and the higher-current resistances respectively, and x_1 and x_2 are proportional to the power (current squared) put into the thermometer coils at the lower and higher currents respectively. The values of $s_{\bar{y}_1}^2$ and $s_{\bar{y}_2}^2$ can be determined by experiment.

It sometimes happens that $s_{\bar{y}_1}^2$ is greater than the $s_{\bar{y}_2}^2$ because the lower current is so small that the deflections of the balancing instruments are more difficult to detect. At different periods in the past we have used currents ranging from 1 and 1.41 ma to 2 and 7.5 ma but with the instrumentation used at the National Bureau of Standards it was found that the optimum value of $s_{\bar{y}_1}^2$ was for currents of about 2 ma. With higher currents the amount of the extrapolation to the zero-current resistance is greater and the determination of the ratio of the high to the low current is more important. A potentiometer of moderate precision should be sufficient, but the higher the current the more attention has to be given to the control of the current.

Let us assume that n observations are to be made to determine the resistance at zero current and of these n_1 are at the lower current and n_2 are at the higher. Having determined the estimates $s_{\bar{y}_1}^2$ and $s_{\bar{y}_2}^2$ by experiment we can choose the proportion of the observations that should be made at the two currents in order to get the smallest value for s_Y^2. Again using statistical theory, we find

$$\frac{n_1}{n_2} = \frac{x_2 s_{\bar{y}_1}}{x_1 s_{\bar{y}_2}}$$

approximately. As an example let us assume that the currents are 2 ma and 5 ma. Then if we take; for simplicity, $s_{\bar{y}_1} = s_{\bar{y}_2}$ we have $n_1/n_2 = 25/4$ which is the ratio of the number of observations which must be made at x_1 to those at x_2 in order to get the best results. As another example let us assume with these same currents that $s_{\bar{y}_1} = 3s_{\bar{y}_2}/2$. We then have $n_1/n_2 = 25/4 \times 3/2 = 75/8$. In both of these examples it is evident that many more observations should be made at the lower current than at the higher in order to obtain the best precision with a given time spent in observing.

Thermometer Developments

In his symposium paper in 1939, Mueller mentioned the coiled filament thermometer construction described by C. H. Meyers.[5] The purpose of this construction was to confine the resistor of the thermometer to a shorter length and a smaller diameter than had been thought practical for standard thermometers before. About 25.5 ohms at 0°C of 0.087 mm wire are wound in a helix about 0.4 mm in diameter. This helix, in turn, is bifilar wound in a larger helix about 20 mm long which is supported on a mica cross within a Pyrex protecting tube ranging from 7 to 7.5 mm outside diameter. Gold leads extend up the protecting tube about 43 cm to a head where the leads pass through a hermetic seal to copper leads.

In 1943 there came to the author's attention some other small thermometers which were made in Russia. These thermometers were intended for measurements of temperature in a range extending up to temperatures which are too high for mica to be used for supporting the coils. The resistor has a resistance of about 10 ohms at 0°C and is wound in a helix of about 0.6 mm in diameter. This helix is supported bifilarly on opposite sides of a twisted silica ribbon and the coils extend about 40 mm. The coils are enclosed in a fused silica protecting envelope of about 6 mm outside diameter. Platinum leads extend up to a head corresponding to that of the Meyers-type thermometers.

A platinum thermometer of small dimensions was described by C. R. Barber[6] of the National Physical Laboratory in 1950. Some of these thermometers had a resistance of about 28 ohms at 0°C. They were made of 0.05-mm wire wound, while hard drawn, on a 1-mm mandrel and supported inside a fine Pyrex tube of 1.5-mm inside diameter and 0.2-mm wall thickness. The fine tube is bent into the form of a U, the helix is held in place by fusing at the bottom of the U and 0.2-mm platinum extensions of the helix are sealed into the top of the U. The coils are in a space over 30 mm long. At the top of the U the platinum leads are fused to 0.5-mm gold leads which extend up to a head as in the other small thermometers. A 6-mm outside diameter Pyrex protecting envelope encloses the leads and the U with the enclosed coils.

These three small thermometers which were developed within the last 25 years have proved their superiority for measuring temperatures in smaller diameter spaces than was heretofore possible. This superiority over the older type, however, has been somewhat offset in some of these small thermometers by the disadvantage that the platinum temperature is not as near the temperature of the outside of the protecting envelope. To be sure, the resistance at any temperature can be extrapolated to that at zero current, as we have seen; but the precision of this extrapolation does depend upon the amount to be extrapolated. In using these small coils some of the parts of the helices are several diameters of the wire away from the wall of the protecting envelopes, and furthermore the area through which heat flows to the protecting envelope is smaller in this type than it was in the older types. Meyers recognized this disadvantage in his coiled filament type of thermometer and developed another type to correct it. About 1943 he began making thermometers of this new design using 0.077-mm wire wound in a single-layer bifilar helix 22 mm long with the wire only 0.03 or 0.04 mm away from the inside wall of the protecting envelope. The helix is supported on a mica cross in U-shaped notches spaced about 0.25 mm on centers. The notches are about 1.5 diameters of the wire deep and just wide enough to allow freedom for the wire to adjust itself with a minimum of constraint. Gold leads 0.2 mm in diameter extend up the envelope to the head. In this type of construction the thermal contact of the wire with the envelope is so good that, when a current of 2 ma is in the coils, the temperature rise of the wire above the outside of the protecting envelope is less than 0.002°. In the other types of small thermometers, described above, the temperature rise ranges from 2 to 4 times as great.

One effect which must be guarded against in precision thermometry is the effect on the resistance of the thermometer coil caused by heat conduction along the leads. This effect is easily determined by experiment. One procedure is to pack the thermometer in a slush of ice and water till the ice is just above the coil of the thermometer. The resistance of the coil is then measured. Packing more ice up around the stem of the thermometer to increase the depth of immersion will change the resistance of the coil. This process is continued till further packing does not change the resistance by a significant amount. A plot of these data on semi-log paper shows the immersion necessary for the precision desired.

Thermometers with heavy gold leads in poor thermal contact with the envelope obviously will require greater immersion than those with light platinum leads near the envelope wall. The immersion necessary to reduce the effect to within the equivalent of 0.0001° on some of the small thermometers described above ranged from 11 cm to 26 cm from the ends of the protecting envelopes. Usually there is provision for sufficient immersion so that the lead conduction will produce no significant error in the determination of temperature, but this effect must be kept in mind for precision temperature determinations. Some special thermometers have been constructed where special attention was paid to thermal contact of the leads with the envelope wall in order to make the necessary immersion very small. Ordinarily this precaution is not demanded.

Thermometers for calorimetry at temperatures below the oxygen point are made of the coiled filament type and enclosed in platinum capsules, 5.5 mm in diameter and 48 mm long. When in use, these thermometers are usually soldered into the calorimeters with low melting solder so heat conduction outside the protecting envelopes is seldom a problem. Platinum leads are sealed through glass which covers the end of the platinum capsule. At the sulfur point, however, the glass seals become conducting and increase the difficulty and uncertainty of the calibrations at that temperature. The electrical conduction in the glass insulation of these resistance thermometers has been discussed by H. J. Hoge.[7] In order to have thermal contact of the platinum wire with the envelopes of these thermometers at temperatures ranging down to near 10°K these capsules are filled with hydrogen-free helium containing some oxygen.

In Mueller's paper in 1939[2] there was a speculation about the changes in the coefficients of a thermometer accompanying progressive changes in ice-point resistances. He stated "The changes of resistance which occur in the resistor of the thermometer are likely to be additive. Changes which affect the resistance of the thermometer at all temperatures in the same proportion are less likely to occur." This is to say $R_{100} - R_0$ was expected to be more constant than R_{100}/R_0 . Since that time we have some evidence, with thermometers made of high purity platinum, that the ratio R_{100}/R_0 remains constant within our precision of measurement even when the resistance of the thermometer at 0°C does increase by significant amounts. There is also some confirming evidence of this from other national laboratories. It appears, therefore, that changes affect the resistance of thermometers proportionally at all temperatures when the thermometers are of high purity platinum and well annealed.

R. J. Corruccini,[8] on the other hand, has shown that rapid chilling of platinum does cause changes which are more nearly additive. He attributes these changes to strains set up by the chilling because reannealing restores the platinum to the old condition. In general, however, it seems unlikely that standard resistance thermometers in protecting envelopes could be subjected to such drastic chillings as he was able to give to his platinum. We conclude, therefore, that additive changes are not likely in standard thermometers.

Bridge Developments

Since Mueller's paper[2] in 1939 two new bridges have been designed and constructed, and are being used for precision resistance thermometry. One is an improved Smith Bridge that is in use at the National Physical Laboratory. Since this bridge is described elsewhere[9] it will not be discussed here. The other is a bridge which Mueller, using his many years of experience, designed after his retirement from the National Bureau of Standards. Prototypes of this design were delivered to the Bureau in 1949. Since an extensive description of this bridge is not in prospect in the near future a brief description will be given here.

The intention of the design of this bridge was to make measurements possible within an uncertainty not exceeding two or three microhms. This bridge has a seventh decade which makes one step in the last decade the equivalent of ten microhms. One uncertainty which was recognized was that of the contact resistance in the dial switches of the decades. Experience shows that with care this uncertainty can be kept down to the order of 0.0001 ohm. Switches made with well-planed copper links bridging well-planed copper posts and making contact with an excess of mercury, have uncertainties of contact resistance of considerably less than one microhm.

In Mueller's design the ends of the equal-resistance ratio arms are at the dial-switch contacts on the one ohm and the tenth ohm decades. He has made the resistances of the ratio arms 3000 ohms so that the uncertainty of contact resistance, 0.0001 ohm, produces an uncertainty of only one part in 30,000,000. With 30 ohms, for example, in each of the other arms of the bridge, these two ratio-arm contacts should produce an uncertainty of resistance measurement of 1.41 microhms. The next largest uncertainty would appear to be in the hundredth ohm decade which has the largest steps of four Waidner-Wolff elements. In the zero position of this decade the 0.0001-ohm uncertainty in contact resistance is part of a shunt of over 20 ohms and produces an uncertainty of 0.4 microhm.

The 10-ohm decade has mercury contacts and the commutator switch has large mercury contacts. One new feature in the commutator switch is the addition of an extra pair of mercury-contact links which serve to reverse the ratio coils simultaneously with the thermometer leads. This feature was suggested by Hoge, who was then at the National Bureau of Standards. This feature automatically makes the combined error of the normal and reverse readings only one in a million, for example, when the ratio arms are unequal by as much as a part in a thousand, and thus practically eliminates an error from lack of balance in the ratio-arms. It does not eliminate any systematic error in the contact resistance at the end of the ratio arms on the decades, however, because the mercury reversing switch has to be in the arms.

The commutators on these bridges are made so as to open the battery circuit before breaking contacts in the resistance leads to the thermometer. This makes it possible to lift the commutator, rotate it, and set it down in the reversed position in less than a second and thus not disturb the galvanometer or the steady heating of the resistor by a very significant amount. In balancing the bridge, snap switches are used to reverse the current so the heating is interrupted only a small fraction of a second. This practice of reversing the current has proven very valuable. It not only keeps the current flowing almost continuously in the resistor but also gives double the signal of the bridge unbalances.

In striving for greater precision in resistance thermometry we may ask what our limit is. One limit which we cannot exceed is that imposed by the Johnson noise which exists in all resistors. The random voltage in resistors at 300°K is given by the formula $\delta V = 1.12 \times 10^{-10}\sqrt{R/\tau}$ where R is the resistance in ohms and τ is the time in seconds over which the voltage is averaged. The quantity, τ, could, for example, be the time constant of the galvanometer. From this formula it would appear that the magnitude of the Johnson noise in a circuit including an instrument having a one-second period would be of the same order of magnitude as an unbalance of 1 microhm in the measuring arm of a bridge when one milliampere was flowing in a 25-ohm thermometer. In practice there seems to be a discrepancy between this limit and what we realize. We have found that for a net time of over a minute of observing, for observations at 1.5 and 2.5 ma to extrapolate to zero current, the determinations of the resistance of thermometers in triple point cells have a standard deviation of a single determination of about 8 microhms. We have not yet been able to attribute this discrepancy either to the bridge, the thermometer, the galvanometer, the triple point cell, or the observer and it remains one of the unsolved problems of precision resistance thermometry.

Fixed Points

For the calibration of platinum resistance thermometers on the International Temperature Scale four equilibrium fixed points are defined, one of which is a freezing point and the others are boiling points. To realize these fixed points it is assumed that it is better to strive for realizations of the definitions rather than to follow recommended procedures which were set up as standard practice in the past. At the National Bureau of Standards the triple point of water sealed in cells is used exclusively to derive the ice point. The boiling points of sulfur and water are realized by active ebullition in boilers connected to a pressure-controlled reservoir of helium. The pressure of the helium is controlled manually by means of a precision manometer to give one atmosphere pressure at the level of the thermometer coils. The boiling point of oxygen is realized in an apparatus which contains saturated liquid oxygen and its vapor at one atmosphere pressure. The oxygen is separated from the helium of the reservoir by a thin metal diaphragm which indicates the balance between the oxygen and helium pressures.

Triple Point of Water

At the General Conference on Weights and Measures in 1948 the following resolution was adopted:

"With the present-day technique, the triple point of water is susceptible of being a more precise thermometric reference point than the 'melting point of ice'.

"The Advisory Committee considers, therefore, that the zero of the thermodynamic centigrade scale should be defined as being the temperature 0.0100 degree below that of the triple point of pure water."

The triple point of water has been realized for the past several years in glass cells of about 5 cm in diameter with reentrant coaxial walls for the thermometers about 39 cm long and 1.3 cm in inside diameter. Figure 4 shows a sectioned drawing of a triple point cell in an ice bath. Extending up from the cell is a tube which is sealed off above the cell after filling with gas-free distilled water. Below the sealing-off point is a side tube, extending horizontally which serves as a handle for lifting and turning the cell and also for supporting the cell when it is packed in a bath of flaked ice and water.

After the cells are blown and annealed they are cleaned with acid and distilled water and then steamed for several days until the condensed steam on the walls runs down in a continuous film over the entire inner surface. They are then connected to a still which removes 99.9 per cent of dissolved gases from distilled water. They are evacuated and filled with water to within about 2 cm of the top and sealed off.

To prepare the cell for measurements it is first immersed into an ordinary ice bath for several minutes to cool the cell and its contents. A mantle of ice from 3 to 10 mm thick is then frozen onto the outside of the well. One procedure for freezing the ice mantle is to dry the well and keep it filled with crushed dry ice (solid CO_2) until the ice mantle is thick enough. This procedure takes about thirty minutes. When the cooling with dry ice is first started it may take a minute or more to initiate freezing. Crystals first appear as fine needles along the outside of the well. As cooling is continued these initial needle crystals disappear and a clear glass-like mantle builds

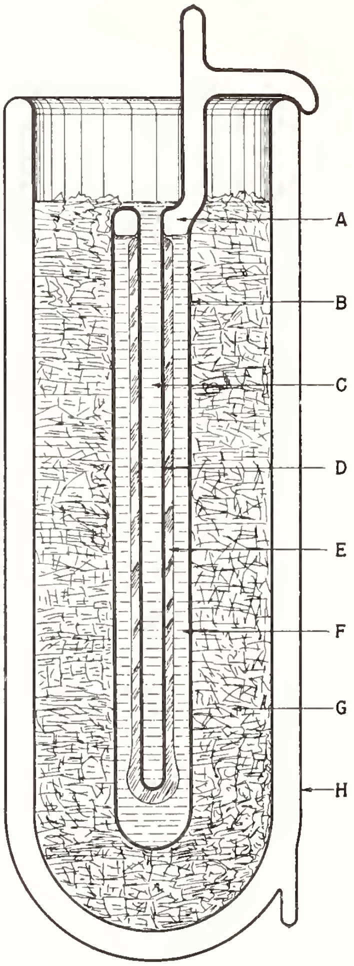


Fig. 4. Triple point cell. A. Water vapor. B. Pyrex cell. C. Water from ice bath. D. Thermometer well. E. Ice mantle. F. Air-free water. G. Flaked ice and water. H. Insulated container.

up. When sufficient ice has been frozen on the well, the dry ice is withdrawn from the well and the cell immersed below the water level in the ice bath so that ice-cold water fills the well in order to improve the thermal contact of the thermometer with the water-ice interface.

The process of freezing purifies the water and concentrates the impurities in the water ahead of the ice as it forms on the outside surface of the ice mantle. These concentrated impurities lower the temperature on the outside mantle surface by a significant amount unless the water was very pure before freezing. If, now, a warm tube is immersed into the well for a few seconds, enough of the pure ice next to the well will be melted to free the mantle and provide a new water-ice interface. It is easy to see when the ice mantle is free by giving the cell a quick rotation about the axis of the well and noting whether or not the mantle rotates with the cell. This new water-ice surface provides the temperature for calibrating thermometers. See Fig. 2.

This procedure of inner melting is believed to be very valuable for obtaining reproducibility of temperature. We have seen that freezing purifies the sample from the well outward and that the inner melting produces liquid from ice which is much purer than the water outside the mantle. This means that less effort has to be expended in preparing and filling the cells than would be necessary if other procedures for freezing were used. Experience shows that the *inner* melting procedure, in the cells at the National Bureau of Standards, provides temperatures which are as identical to each other and as reproducible as we are now able to differentiate temperatures, namely, within about 0.00008°C.

Temperatures at the *outside* of thick mantles in some cells about two years old, on the other hand, were found to be about 0.002° low, when first determined within a half hour of freezing, but were rising for several hours thereafter. These low temperatures are believed to be caused by impurities (including dissolved glass) and the rising temperatures by diffusion of the concentrated impurities away from the outside surface of the mantle into the water. The lower temperature at the outside of the mantle causes no error when the inner melting technique is used. Small transfers of heat caused by radial temperature gradients merely cause freezing or melting at the water-ice interfaces and do not change the temperature by significant amounts.

Previous investigators have frozen the water in their triple point cells by supercooling until spontaneous freezing fills the cells with mush ice. When the water in these same NBS cells was spontaneously frozen, the temperatures were a few ten-thousandths of a degree low, presumably due to impurities. This result again emphasizes the value of the simple inner-melting technique for obtaining reproducible temperatures.

Precision Manometer

The precision manometer at the National Bureau of Standards was designed for precision gas-thermometer measurements. The apparatus consists of two large cells for mercury surfaces connected by an articulate tube and supported on a base by long and short columns of end standards. The aim in the design was to make this manometer capable of determining pressure to an accuracy of one part in a million but this accuracy is not demanded by present-day precision thermometry. Fig. 5 shows a scale di-

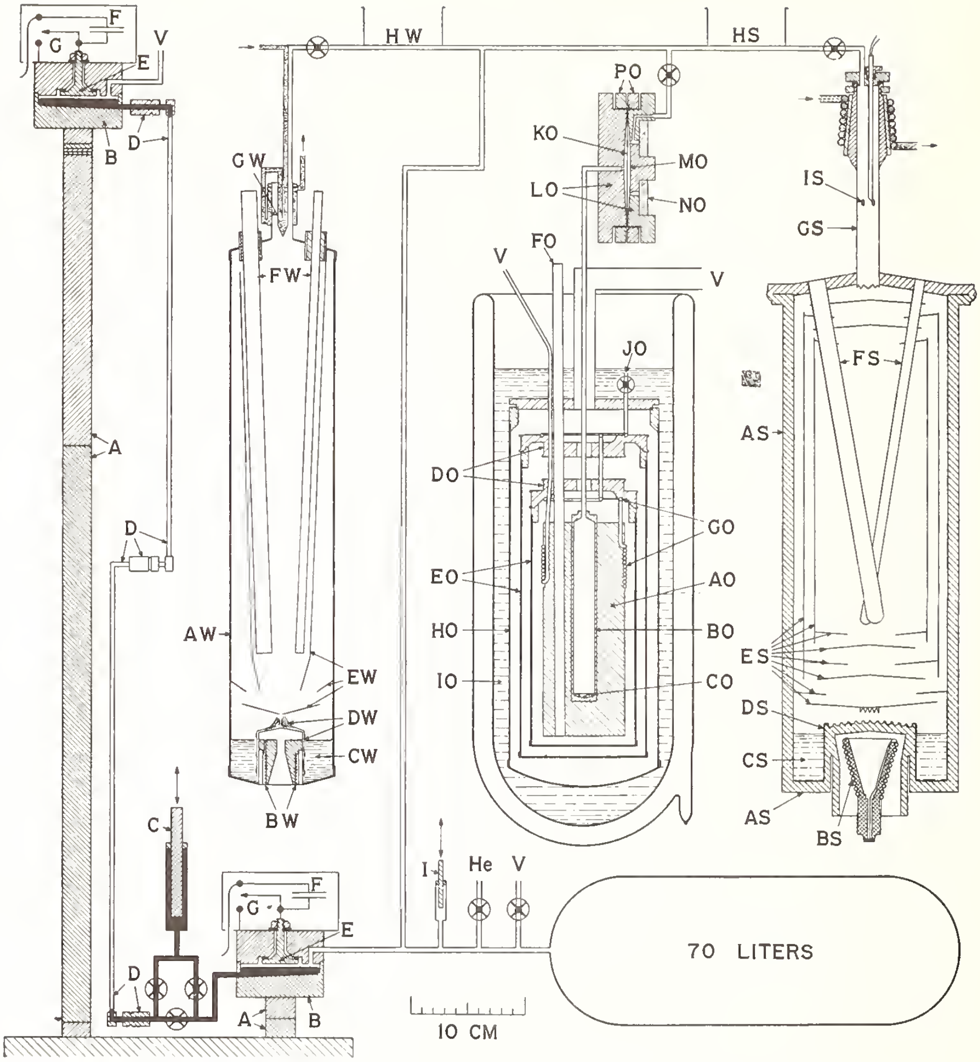


Fig. 5. Manometer: A. Hoke blocks. B. Mercury cell. C. Mercury pump. D. Articulate tube. E. Insulated capacitor plate. F. Reference capacitor. G. Pneumatic switch. H. Helium supply. I. Helium pump. V. Vacuum line.

Steam point boiler: AW. Boiler wall, tinned copper. BW. Heater. CW. Liquid water. DW. Layer of silver wires. EW. Radiation shields. FW. Thermometer wells. GW. Water vapor condenser. HW. Dry ice trap.

Oxygen point apparatus. AO. Copper block. BO. Oxygen bulb. CO. Liquid oxygen. DO. Heat interceptors. EO. Radiation shields. FO. Thermometer well. GO. Cooling tubes. HO. Envelope. IO. Liquid nitrogen. JO. Liquid nitrogen inlet for cooling. KO. Metal diaphragm. LO. Diaphragm cell wall. MO. Insulated island. NO. Glass insulator. PO. Clamp for diaphragm. V. Vacuum lines.

Sulfur point boiler. AS. Boiler wall, aluminum. BS. Radiant heater. CS. Liquid sulfur. DS. Layer of aluminum wires. ES. Radiation shields. FS. Thermometer wells. GS. Sulfur vapor condenser. HS. Dry ice trap. IS. Feeler thermocouple.

agram of the manometer at the left connected to the steam point boiler, the oxygen point apparatus, and the sulfur point boiler.

The pressure which is measured with this manometer is balanced by a column of mercury. Pressure is the product of the height of the column multiplied by the density of the mercury and by the gravitational acceleration. It is believed that the height of the column can be determined with this apparatus to the accuracy of calibration of the end standards, which heretofore has been about two parts in a million. The value of the density of mercury at 0°C, according to recent reports, may be uncertain to one or two parts in 100,000 but it is the opinion at the National Bureau of Standards that differences of more than about four parts in a million are not to be expected between different samples of virgin mercury, gathered anywhere on the earth. The value for the gravitational acceleration may be uncertain by nearly one part in 100,000 but values relative to the value determined at Potsdam are known with high precision. For these reasons it is believed that the reproducibility of the steam point in different laboratories could be in the order of 0.0001°C, inasmuch as this corresponds to about four parts per million in pressure.

The principal features of this manometer, which make such precision possible, are the large cells for the mercury surfaces to eliminate the uncertainties of capillary depression, an electrostatic capacitance scheme for determining the height of the mercury surface, and the use of end-standards 2.4 cm square for supporting these cells.

The mercury cells are about 7.3 cm in inside diameter. They are made of steel with the tops and bottoms about 2 cm thick, which is thick enough to prevent a significant flexure by a change of pressure of one atmosphere. A steel tube about 3 mm inside diameter permits mercury to flow from one cell to the other. To permit raising the upper cell to the desired height, this tube has three joints with horizontal axes, referred to as the "shoulder," "elbow," and "wrist" joints.

Both cells are supported on a cast iron base by Hoke gage blocks which are end-standards as precise as the better-known Johansson blocks, but, being square, are more suitable as columns for supporting the cells. The ends of these blocks are accurately parallel. The columns of blocks are 18 cm apart at the base. One block is fastened securely to the bottom of each cell and another block is fastened securely to the base at the bottom of each column. The two blocks under the lower cell are seldom moved but the intermediate blocks in the column supporting the upper cell are changed every time the length of the column is changed. The top surface of the supporting block for the upper cell was carefully leveled. The set has enough blocks to permit a column of blocks to be selected having a nominal height of any desired ten-thousandth of an inch. Blocks of this type can be wrung together with a separation of less than a hundredth of a micron. In 14 years the blocks have been calibrated a few times at the National Bureau of Standards and none has changed for more than four parts in a million.

Above the mercury there is an electrically insulated steel plate 3.5 cm in diameter for determining the height of the mercury in the cells. The electrostatic capacitance between the plate and the mercury is part of the capacitance in one of the two circuits of a beat frequency oscillator. In a shielded chamber above the cell is a reference capacitor which is adjusted so that its capacitance is equal to the capacitance between the plate and the mercury for the desired height of the mercury. A pneumatic mercury switch permits the interchange of these two capacitors in a few seconds. It has been found convenient to have the spacing of the mercury from the plate about 0.15 mm. At that height, a change of pressure of one micron changes the capacitance by 0.2 $\mu\mu$f which changes the beat frequency by 60 cycles; hence the manometer is sensitive to much less than 0.1 micron of mercury pressure.

Ripples are always present on the surface of the mercury in a cell of this diameter (7.3 cm) at any place within the National Bureau of Standards. Their wavelength is small in comparison with the radius of the plate and the effect of the crests of ripples compensates for that of the troughs. No effect of these ripples on the capacitance is noticeable until the mercury approaches to within 0.1 mm of the plate.

It is obvious that temperature control is important not only for the length of the steel blocks but especially for the density of mercury. The combined effect is such that a change in pressure of one part in a million is produced by a change in temperature of about 0.006°C. To provide for temperature control the manometer is mounted on a low pier in a cellar below the basement floor where temperature fluctuations are minimized. The cellar is about 4.5 meters deep, 4.3 meters long and 2.1 meters wide. The manometer is operated by remote control. The air is circulated in the cellar and the relative humidity reduced below 50 per cent by passing it over refrigerated coils and reheating it.

At the base of the manometer a platinum resistance thermometer is placed in a copper block. On the surface of this block are placed reference junctions of three sets of multiple-junction thermocouples for determining the mean temperature of three different parts of the mercury column. There are twelve measuring junctions in series on the manometer arm from the shoulder to the wrist joint, six junctions on the tube from the lower cell down to the shoulder joint, and three junctions from the wrist joint up to the upper cell. These provisions make it possible to determine the mean temperature of the mercury itself and, should the temperature not be the same on the tubes to the upper and lower cells, the difference in density can be accounted for. The temperature of the manometer ordinarily drifts only a few hundredths of a degree per day. This rate is so small that occasional measurements taken during the day are sufficient for corrections. The temperature of the blocks is assumed the same as the mean temperature of the mercury.

The procedure for obtaining the desired pressure by means of the height of mercury column is, first, to determine the "zero level," and then to increase the height of the upper cell by the height of the desired column. For the zero level, the proper blocks can be found and the reference capacitance made equal to the mercury capacitance on each cell when both cells are evacuated. When this equality of capacitances is again realized, with pressure in the lower cell and with the upper cell still evacuated, the height of the mercury column is the same as the extra height of blocks added to the upper cell column.

Since the two columns of gage blocks are spaced 18 cm apart it is important to know whether they maintain their relative heights. For this reason the zero level of the manometer has been followed for several days before and after the time when the manometer is used at one atmosphere. Experience shows that the drift in zero level is less than one micron. The effect of the change of level caused by the extra weight of 30 inches of gage blocks (about 3.4 kg) was determined experimentally and found to be about 0.2 micron. The compression of the 30 inches of gage blocks by half the weight of these blocks and by the weight of the cell with its mercury contents was found to be about 0.3 micron. These effects are small but are accounted for.

To control the pressure of the helium there are needle valves for admitting or removing helium from the lines. Small changes in the helium pressure are controlled by a piston about 0.75 cm^2 cross section area which can be moved in or out of a small chamber in the helium line at the control bench, 4.5 meters above the manometer. The piston is moved by a screw of such pitch that one turn changes the volume connected to the helium line by about one part in a million. The helium pressure may be affected by small drifts in the temperature of the 70-liter reservoir or by larger and more rapid changes in the temperature of the tubes above the floor. The pressure changes are indicated by the beat frequency oscillator and usually are so small they can be compensated for by a fraction of a turn of the piston screw. Such sensitive control of pressure enables the operator to keep the pressure controlled to within a part in a million for as long a time as is needed for thermometer calibrations.

Steam Point Boiler

The steam point apparatus is a closed system with helium gas transmitting the water vapor pressure to the precision manometer. See Fig. 5.

The boiler is made of copper heavily tinned on the inside to prevent contamination of the water. It is made of a tube 8.7 cm in diameter and 46 cm long, closed at the ends. There are six reentrant thermometer wells 35 cm long extending from the top cap down into the vapor space. These wells are of various diameters of thin-wall copper-nickel tubing which is also tinned on the surface exposed to the water. These wells are separated where they extend through the top but at the bottom they are as close together as is convenient without touching. Surrounding the wells is a conical radiation shield of tinned copper which is sufficiently open at the top and bottom for free passage of vapor around the wells.

At the bottom of the boiler there is a reentrant copper-nickel heater dome with a shallow conical cap at the top. Inside this dome is a heater, wound on mica on a copper spool which is enlarged at the top for a short length for soldering into the reentrant dome. By this construction most of the heating power is supplied in a zone just below the surface of the water in the annular space at the bottom of the boiler surrounding the heater dome. On the outside of the heater dome is a single layer of closely spaced vertical silver wires about 0.4 mm in diameter. These wires are bound to the surface with three horizontal hoops of silver wire. The vertical silver wires extend from the bottom of the dome to about 2 cm above the top of the dome and there the ends are brought together in a bundle around the axis. This construction was adopted for the purpose of holding a small residual of vapor in the cusp-shaped spaces between the dome and the wires, to avoid explosive vaporization. It has proven most effective.

Below the radiation shield around the thermometer wells are two shallow conical shields which serve to prevent direct radiation from the walls to the outside walls of the boiler and also serve to drain condensed water from the boiler wall to the axis where it drips onto the bundle of silver wires at the top of the dome. By this construction it is believed that these wires are kept wet continually during operation and there are no exposed surfaces at temperatures above the saturation temperature.

Since the temperature of the boiler is about 75° above that of the room, considerable heat flows out through the boiler wall. This heat is supplied on the inside of the boiler by condensation of the water vapor to liquid which flows down the wall in a film computed to be 0.05 mm thick. Assuming the liquid-vapor surface to be at the saturation temperature there is a temperature gradient through the liquid film so that the inside wall of the boiler is probably less than 0.1 degree below the saturation temperature. Since the boiler is a little below the saturation temperature, the radiation shield radiates a small amount of energy to the boiler most of which it receives by condensation of vapor on both its inner and outer wall surfaces. The radiation shield, therefore, is nearer to the saturation temperature than the wall of the boiler is by a factor of several hundred. The wells, in turn, radiate heat to the radiation shield; but, since the temperature of the radiation shield itself is very near the saturation temperature, the wells certainly should be at the saturation temperature within our precision of temperature measurements. Indeed, computations indicate that there might have been sufficient attenuation by the wells alone but the radiation shields provide enough more attenuation so there can be little chance that the wells containing the thermometers are at a temperature that is significantly low.

From the top of the boiler the excess vapor flows up through a short tube, about 1.8 cm inside diameter, to a condenser which starts above the boiler. The condenser is cooled by ice-cold water first flowing in a core on the axis and then in a water jacket on the outside of the 1.8-cm tube. The inner and outer water-cooled surfaces are about 3.7 cm long. This construction provides an annular space with a radial separation of about 0.4 cm for the vapor to flow through on its way to the cold walls where it is condensed to liquid. In this space the water vapor meets helium from above. The level of this water-vapor to helium interface depends on the amount of excess water vapor that must be condensed. The area over which condensation is taking place is determined by the temperature of the metal, the thickness and thermal conductivity of the liquid film, and the power flowing through this film. The liquid-vapor surface may be assumed to be at the saturation temperature.

Above the condenser, the helium extends up in a tube which is soldered to the incoming cold water tube. At this place there is a shut-off valve. From the valve the helium line extends in a 0.5-cm horizontal tube that is soldered to a copper tray for dry ice (solid CO_2) and then down to the manometer and a 70-liter helium reservoir on the pier in the cellar.

The radiation shields and wells in the boiler provide such effective protection against a temperature that is too low, that the question arose whether or not the wells might be superheated by the measuring current in the thermometers and the temperature be above the saturation temperature. To test this, two strips of silver gauze were placed so that one drains the liquid from the axial condenser surface to the surface of one well and the other drains the liquid from the outer condenser surface to another well. Thermometers interchanged from these wells to wells without draining have, so far, failed to indicate any difference in temperature depending on the wells. This indicates not only that the liquid film running down the wells has approached the saturation temperature but also that no superheating exists on the other wells.

On the outside the boiler is insulated by two coaxial radiation shields made of aluminum-coated paper and these are enclosed in a metal cover.

This construction furnishes enough thermal insulation so that only about 70 watts of power are necessary to maintain the boiler at 100°C. The power in excess of 70 watts goes to maintaining a flow of vapor into the condenser where it meets the helium. It is common practice to use 125 watts in the boiler at the steam point.

Since the steam point is defined as the temperature of equilibrium between liquid and its vapor at 1 atmosphere pressure it is necessary to determine this pressure at the height of the center of the thermometer coils when they are in the wells. The accounting for pressure considers the fluid heads of columns of water vapor, helium, and liquid mercury at their respective temperatures and the saturation pressure of mercury vapor at the upper cell temperature.

Increasing the power input to the boiler increases the flow of water vapor into the condenser and raises the helium because more surface is required for condensation of the water vapor. This increases the pressure a little because the head of water vapor is greater than that of helium. The more noticeable change, however, is the volume of helium which must be withdrawn from the system to maintain the pressure constant.

Some flow into the condenser is necessary to oppose diffusion of helium down to the level of the thermometer coils. Helium near the thermometer wells would decrease the water-vapor partial pressure and hence the temperature. It is for this reason that the tube to the condenser is not large. The fact that helium is lighter than water vapor is favorable for avoiding convective instability. Too great an excess of power can be undesirable, however, because it increases both the length and the velocity of the stream of vapor ascending into the condenser. This increases the head loss due to viscous or turbulent flow. Experience shows, however, that the excess power can be increased by 100 watts without producing any significant error in the determination of temperature near 100°C. It is not until low pressure measurements in the neighborhood of 30°C are being made with this boiler that these effects become significant.

Sulfur Point Boiler

In the text of the 1927 International Temperature Scale[10] the recommended experimental procedure for the sulfur point was specified in considerable detail. At that time the precision of temperature realization at the sulfur point was considered good when it was in the order of 0.01°. Since that time it has been demonstrated that a greater precision is attainable when the sulfur boiler is connected to a closed system. This led in 1948 to the definition of the sulfur point temperature as 444.600°C,[1] where the last figure only represents the degree of reproducibility of that fixed point. A temperature change of 0.001° at the sulfur point corresponds to a change of pressure of about 10 microns of mercury.

In 1951 a closed-system sulfur boiler was completed at the National Bureau of Standards and connected to the precision manometer. In the design of this boiler the same principles were used that proved successful in the steam boiler. In this new boiler the liquid and vapor sulfur are exposed only to 2S aluminum (which is the purest commercial grade). The boiler was constructed from sheet nearly 1 cm thick. It is 45 cm tall and 13 cm in inside diameter. The entire apparatus was welded together by means of an inert-gas arc using welding rods of the same 2S aluminum.

At the bottom is a heater dome which is analogous to that in the steam boiler. This dome is surrounded by a single layer of closely spaced vertical aluminum wires, 1.5 mm in diameter, analogous to the silver wires in the steam boiler. These also are effective for avoiding explosive vaporization. Heat for boiling is supplied by a radiant heater which has a nominal rating of 660 watts but only about 420 watts are normally used. On the boiler itself is wound an additional heater with a capacity of about 1000 watts which aids in raising the temperature of the boiler and contents from room temperature to near the sulfur temperature in about an hour. As the sulfur temperature is approached the power in this heater is reduced until the whole load can be taken on the radiant heater. The heat conducted away from the boiler itself is about 380 watts when the steady state has been established.

Ten thermometer wells of various sizes extend down from the top into the vapor space. The axes of these wells approach each other as they extend down into the vapor space so they are closest together at the level of the centers of the thermometer coils. Stainless steel liners 0.25 mm thick were drawn with the aluminum tubing for the thermometer wells. These liners serve not only to stiffen the wells but also to prevent the aluminum from rubbing off onto the protecting tubes of the thermometers when they are hot.

Between these wells and the walls of the boiler are two cylindrical radiation shields; at the top there are four, and at the bottom six conical radiation shields alternately diverting the fluid flow to and away from the axis yet preventing direct radiation away from the wells. These shields are spaced not less than 9 mm apart which should be ample to avoid any significant drop in pressure of the vapor as it enters these spaces. As it was found for the steam boiler, computations indicate that one less shield might have been sufficient, so, with the present number of radiation shields, there is little chance that the wells containing the thermometers are at a temperature significantly lower than the saturation temperature.

On the axis above the top of the boiler is a stack, 1.9 cm inside diameter, for condensing the excess of sulfur vapor. In all, the stack extends up with this diameter nearly 18 cm above the body of the boiler. For about 9 cm above the top of the boiler the stack has a wall thickness of only about 1 mm. Above this thin section is welded a thick section on which is turned a cone about 5.3 cm long with a taper of 1 in 10 from the axis. On this cone there rests a sleeve of brass to which are soldered several turns of copper tubing for cooling water. Above the cooling section is a cap, sealed with a Teflon gasket, from which a tube leads away to the manometer. Down through this cap there also extends an aluminum tube, about 4 mm in diameter, carrying a pair of thermoelement wires to a ring of aluminum within the thin section of the stack. This is a feeler thermoelement which serves to indicate the height at which the helium meets the hot sulfur vapor during the operation of the boiler. Its height is adjustable but it is usually kept about 3 cm below the thick section of the stack.

It may seem paradoxical that water cooling is used for sulfur which freezes at about 119°C. The hot saturated sulfur vapor at 1 atmosphere pressure, however, does not reach the thick section of the stack which is water cooled but stops at the level where the heat of vaporization has all been given up to the thin wall of the stack at temperatures well above the freezing point. At this level the stack temperature differs most from that of the saturated vapor so the rate of heat flow to the stack is a maximum as is also the temperature gradient in the stack. Above this level there is little condensation and the gradient decreases slightly owing to the loss of heat from the side of the stack.

Experiments were made changing the power input into the boiler to change the height of the hot saturated vapor in the stack. Temperature gradients along the stack were determined by means of ten thermocouples spaced uniformly. From these experiments it was concluded that the height of the top of the hot vapor was about at the level of the feeler thermocouple in the stack where the thermocouple electromotive force increases most rapidly with an increase in vapor height. From these experiments it also was concluded that viscous flow of vapor in the stack caused an insignificant loss of head, as it was found for the steam boiler.

It is important to know the height of the saturated vapor at one atmosphere, because, according to the values used at the Massachusetts Institute of Technology,[11] its density is such that 4.0 cm of vapor head corresponds to a change of saturation temperature of 0.001°. Having determined the height of the hot saturated vapor with the feeler thermocouple, a better accounting can be made of the pressure of the vapor at the height of the thermometer coils. In the helium above the top of the hot vapor the stack temperature is so much lower than the sulfur point that the cooler saturated sulfur vapor at these temperatures contributes very little partial pressure head.

The stability of this sulfur boiler has brought to light a phenomenon which heretofore had escaped attention. When the sulfur is started to boil, after a period of rest, the temperature is observed to fall for a period of about a day. The temperature then approaches constancy at about a hundredth of a degree below the initial temperature and has been found to remain there for periods lasting over a week. On account of this phenomenon the practice is to delay calibrations in the sulfur boiler until at least a day after the boiling is begun.

An analysis was made of the purity of the sulfur which had been used for sulfur boilers. It was found to contain less than a part in a million each of selenium, arsenic, and tellurium. Mueller[12] reported that one part in a thousand of selenium and arsenic added to the sulfur gave a combined raising in boiling temperature of less than 0.1°. After having been boiled the sulfur did, however, contain about 140 parts per million of carbon, 76 parts per million of nonvolatile matter, and about 8 parts per million of iron. Sulfur was purified by T. J. Murphy in the NBS Chemistry Division and the resulting sulfur was found to contain 2 parts per million of carbon, 3 parts per million of nonvolatile matter, and less than 1 part per million of iron. When this purified sulfur was used in the sulfur boiler no changes were found either in the final boiling temperature or the phenomenon of falling temperature. The practice in the use of the sulfur boiler has been to boil a new batch of sulfur for several hours to drive off gases and then to cool the sulfur in order to evacuate these gases before starting the boiling for calibration work. During use a small amount of helium is in the boiler stack for transmitting the pressure out to the manometer. Between runs this helium is left in the boiler. Our present conclusion is that the phenomenon of falling temperature is not a result of impurities in the sulfur, but is another unsolved problem concerning precision thermometry.

Oxygen Point Apparatus

A new oxygen boiling point apparatus is now in operation. It also is connected to the precision manometer. This apparatus uses the stable equilibrium between liquid oxygen and its vapor rather than active boiling as in the steam and sulfur boilers. The essential part of this apparatus is a copper block which contains an oxygen vapor-pressure bulb and eight wells for resistance thermometers. In operation the oxygen bulb contains a few drops of liquid oxygen in equilibrium with vapor near the position of the resistors of the thermometers being calibrated. Superheated oxygen vapor extends from the saturated oxygen in the bulb out to a diaphragm cell which is at about room temperature. The diaphragm transmits the pressure from the oxygen to the helium of the precision manometer.

The copper block is a cylinder about 7 cm in diameter and 18 cm tall. The eight wells of the thermometers extending up from the copper block are of thin copper-nickel tubing which has a low thermal conductivity.

These wells lead up through liquid nitrogen to the outside of the apparatus near room temperature. Above the copper block are two heat interceptors soldered to the wells. In thermal contact with these heat interceptors are copper shields which surround the entire copper block.

Outside the shields is a brass envelope placed in a bath of liquid nitrogen which boils at about 13° below the oxygen point. The brass envelope is evacuated in order to eliminate heat transfer by gaseous conduction from the copper block and the surrounding shields. The heat interceptors are heated electrically and controlled to temperatures close to that of the copper block. These interceptors serve to isolate the block so completely that temperature variations do not exceed 0.001° in the block near the thermometer resistors. For the initial cooling of the block and interceptors, tubes are soldered to them so that liquid nitrogen from the bath can be admitted through a valve above the envelope. The vaporization and heating of the nitrogen remove energy at a rate which makes it possible to cool the apparatus to a temperature below the oxygen point in about 2 hours.

In the helium line from the precision manometer to the steam and sulfur bath it is a simple matter to prevent either the steam or sulfur vapor from reaching the manometer by the use of dry ice to cool a horizontal portion of the transmitting line. For the oxygen point apparatus, however, it is not so simple. The method chosen is to use a plane metal diaphragm about 60 microns thick which separates the oxygen from the helium yet is so sensitive and so reproducible that it will permit the determination of the oxygen pressure within the equivalent of 0.0001° in its saturation temperature. The diaphragm is held in a cell with walls so close that the diaphragm is supported after it has been displaced a small amount by pressure, and thus the support prevents the diaphragm from being strained beyond its elastic limit.

The diaphragm cell is made of stainless steel and has an over-all diameter of about 13 cm. This diameter is for flanges, which extend out from each of two central supporting walls which are about 10.2 cm in diameter. The diaphragm is held between these supports on plane areas about 6 mm wide near the 5-cm radius. Inside this supporting surface the wall is ground, lapped, and polished to a spherical concave surface having a radius of curvature of about 15 meters. On the helium side of the diaphragm the cell wall has a central electrically insulated island about 4.5 cm in diameter which is used for determining the null position of the diaphragm. This island is spaced about 0.15 mm from the main wall. The insulation is an annular sheet of Pyrex glass about 8 mm thick which is clamped both to the island and to the body of the cell. The insulator was used to hold the island in place when the cell body wall was being made spherical. Subsequently the island was removed for cleaning and replaced so the spherical surface of the island was continuous with that of the body wall within a fringe of light. Between the flanges there is a recessed space for a pair of clamping rings, each about 13 cm in diameter and 1 cm thick, which clamp the diaphragm at a diameter of about 11 cm. When the diaphragm is clamped in its rings, it is laid on the island side of the cell and drawn axially toward the flange by means of screws. This stretches the diaphragm to a plane in a manner analogous to the tuning of a kettle drum.

The center of the diaphragm is about 70 microns from the island surface when the diaphragm is in equilibrium. The difference in electrostatic capacitance between that of a reference capacitor and that of the island to the diaphragm indicates the displacement of the diaphragm away from its equilibrium position. A beat frequency oscillator is used for this indication in a manner analogous to that for the precision manometer.

An excess of pressure on one side forces the diaphragm against the wall on the other side of the cell and further excess pressure makes little change. When the excess pressure is removed the diaphragm returns nearly to its original position. In order to be effective for a precision of 0.0001°, the diaphragm must return to its original position within the equivalent of 10 microns of mercury pressure. This has been done to within the equivalent of a few microns pressure so the reproducibility appears adequate. The diaphragm cell, however, has been found to be somewhat sensitive to temperature changes so it is enclosed inside a pair of thick-walled aluminum boxes with the outside box thermostatted at 28°C.

The diameters of the protecting envelopes of the thermometers which must be calibrated in this apparatus differ so much that various diameters of wells are provided, ranging from 7.5 to 13 mm in diameter. The length of the wells is a compromise at about 41 cm long. This provides sufficient immersion for most thermometers but may be too long for a few special thermometers with short stems. Since the boiling point of oxygen is below that of some of the gases in air, such as carbon dioxide and water vapor which are present in small quantities, it is desirable to avoid these gases in the wells. Provision is made, therefore, for sealing the thermometers in the wells by means of rubber sleeves at the top, evacuating the air, and introducing dry helium in the wells. The use of helium in the wells has the added advantage that helium has a greater thermal conductivity than air and hence improves the thermal contact of the well with the thermometer envelope.

Conclusion

In conclusion we may ask how far we have come in precision resistance thermometry and how much farther we may expect to go with the experimental possibilities that are known to us now. The precision of resistance thermometry has been increased by the attention to some details in the technique of measurement and by improved designs of instruments. It has been seen that the present triple point cells and the boilers for realizing the steam, sulfur, and oxygen points make it possible to attain an accuracy that is comparable to that indicated in the text of the International Temperature Scale. These accomplishments, however, yield results which fall short of the precision in resistance thermometry which appears to be possible before it is limited by Johnson noise.

References

1. Stimson, H. F., "The International Temperature Scale of 1948," *J. Research NBS*, **42**, 209 (1949).
2. Mueller, E. F., "Precision Resistance Thermometry," in "Temperature, Its Measurement and Control in Science and Industry," Reinhold Publishing Corp., 1941.
3. Beattie, J. A., and Blaisdell, B. E., "The Reproducibility of the Steam Point. The Effect of Pressure on the Steam Point," *Proc. Am. Acad. Arts Sci.*, **71**, 361 (1937).

   Beattie, J. A., Tzu-Ching Huang, and Benedict, M., "The Reproducibility of the Ice Point and the Triple-Point of Water. The Temperature of the Triple-Point of Water," *Proc. Am. Acad. Arts Sci.*, **72**, 137 (1938).
4. Schwab, F. W., and Wichers, E., "Freezing Temperature of Benzoic Acid as a Fixed Point in Thermometry," *J. Research NBS*, **34**, 333 (1945).
5. Meyers, C. H., "Coiled Filament Resistance Thermometers," *BS J. Research*, **9**, 807 (1932).
6. Barber, C. R., "Platinum Resistance Thermometers of Small Dimensions," *J. Sci. Instruments*, **27**, 47 (1950).
7. Hoge, H. J., "Electrical Conduction of Glass Insulation of Resistance Thermometers," *J. Research NBS*, **28**, 489 (1942).
8. Corruccini, R. J., "Annealing of Platinum Thermometers," *J. Research NBS*, **47**, 94 (1951).
9. Barber, C. R., Gridley, A., and Hall, J. A., "An improved construction of the Smith bridge, type 3," *J. Sci. Instruments*, **32**, 213 (1955).
10. Burgess, G. K., "The International Temperature Scale," *BS J. Research*, **1**, 635 (1928).
11. Beattie, J. A., Benedict, M., and Blaisdell, B. E. "The Reproducibility of the Sulfur Point. The Effects of Pressure on the Sulfur Point," *Proc. Am. Acad. Arts Sci.*, **71**, 327 (1937).
12. Mueller, E. F., and Burgess, H. A., "The Standardization of the Sulfur Boiling Point," *J. Am. Chem. Soc.*, **41**, 745 (1919).

NOTES TO SUPPLEMENT RESISTANCE THERMOMETER REPORTS

1 August, 1963
National Bureau of Standards
Washington, D. C. 20234

NOTES TO SUPPLEMENT RESISTANCE THERMOMETER REPORTS

The practical value of a standard resistance thermometer depends upon the precision and convenience with which it can be used to determine temperatures on a definite temperature scale. In view of the increasing use of platinum resistance thermometers and the increased precision sought with them, these notes have been prepared to supplement the calibration reports.

I. Temperature Scale

The International Practical Temperature Scale is based upon six defining fixed points to which numerical values have been assigned. Values between these fixed points are defined by the indications of specified measuring instruments and the use of specified interpolation formulas to relate these indications to temperature. Between -182.97 °C and 630.5 °C the instruments are platinum resistance thermometers which have been calibrated at specified defining fixed points to determine the constants in the interpolation formula. Over the range 0° to 630 °C the interpolation formula may be put in the form, [1]

$$t = \frac{R_t - R_o}{\alpha R_o} + \delta \left(\frac{t}{100} - 1\right) \frac{t}{100}$$

devised by Callendar and commonly used in this country for hand computation of values of t. In this formula, t is the temperature in °C, R_t is the resistance at the temperature, t, R_o is the resistance at 0 °C.

---

[1] Tables having entries at given values of t are more easily computed from the equivalent formula which is given in the text of International Practical Temperature Scale,

$$R_t = R_o \left(1 + at + Bt^2\right).$$

R_t is the resistance of the resistor of the thermometer at temperature t, and R_o is the resistance at 0 °C. A and B are constants which are related to α and δ of the Callendar formula by the identities,

$$A \equiv \alpha\ 1 + \left(\frac{\delta}{100}\right) \text{ and } B \equiv - \frac{\alpha\delta}{100^2}.$$

The constants, α and δ, have values which are characteristic of the individual thermometer. The constant α, which is equivalent to $\frac{R_{100} - R_o}{100 R_o}$, is determined from measurements of thermometer resistor at the triple point of water (0.01 °C) and the steam point. The value of α must be greater than 0.003920 to satisfy one of the international requirements for a standard thermometer. The constant δ, is determined from measurements at an additional fixed point, either the boiling point of sulfur, which is a defining fixed point, or the freezing point of zinc, which is recommended in the text of the International Practical Temperature Scale as an alternative.

Over the range 0° to -182.97 °C, the interpolation formula may be put in the modified Callendar form, [2]

$$t = \frac{R_t - R_o}{\alpha R_o} + \delta \left(\frac{t}{100} - 1\right) \frac{t}{100} + \beta\left(\frac{t}{100} - 1\right)\left(\frac{t}{100}\right)^3,$$

devised by Van Dusen. The constant β, is also characteristic of the individual thermometer and is determined from an additional measurement of the boiling point of oxygen.

II. Measurement for the Determination of Temperature

A standard platinum resistance thermometer is constructed so that precise measurements may be made of the resistance of its platinum resistor. The resistor is made of very pure platinum wire, is compact in form, and is contained in a protecting tube. At each end of the resistor is a branch point to which are joined two leads, commonly called "current" and "potential" leads. This construction makes it possible to measure the resistance of the resistor alone (i.e. between the branch points), independent of the resistance of the leads.

---

[2] The equivalent international formula for this part of the scale is

$$R_t = R_o [1 + At + Bt^2 + C(t - 100)t^3],$$

where R_t, R_o, A and B are as stated in footnote [1]. The constant C is related to the constants in the Callendar formula by the identity,

$$C = \frac{\alpha\beta}{100^4}.$$

The resistance of the thermometer may be measured in various ways. The Wheatstone bridge and commutator of Mueller's design are commonly used in this country. The function of the commutator is to interchange the thermometer leads in such a way that the average of the resistances measured with the commutator in the N (normal) position and in the R (reverse) position is the resistance of the resistor of the thermometer. The resistance of the leads is completely eliminated by this technique only if the difference in the resistance of the two leads appearing in the arms of the bridge is the same when measurements are made in the N as when measurements are made in the R position. By making a series of four measurements, at equal time intervals, in the order N R R N, any change of the difference of the lead resistance is computable and the average value of the four measurements is independent of any linear drift in this difference. The resistance may also be measured with a potentiometer and a stable reference resistor or with a Kelvin-type double bridge.

The calibration report for a resistance thermometer gives the values of α and δ which are found to apply to the resistor of that particular thermometer. If the thermometer were calibrated at the oxygen point, the value of β which was found is given for calculating temperatures below 0 °C. The constants are characteristic of the material in the particular resistor but do not depend on the magnitude of its resistance. [3] For accurate determinations of temperature with a platinum thermometer it is necessary to refer to some known and reproducible temperature (fixed point) which should be readily available whenever it is needed. This fixed temperature is most commonly either the ice point, or the triple point of water (0.01 °C). Measurement of the resistance of the thermometer in a suitable ice bath will give R_o directly, while a small correction, very nearly equivalent to 0.01 degree C, is necessary if a triple point cell is used. [4] The choice between these two fixed points is largely on the basis of the accuracy required. The triple point may be realized within ±0.0002 degrees C while the accuracy of realizing the ice point is typically five to ten times worse. The value of R_o is given in the report primarily to enable the determination of any change occurring in R_o between the time of calibration and the time the R_o is measured in the user's laboratory. In addition to the errors of realizing the ice point or triple point, the accuracy of such a check is limited by the uncertainty of the difference in the resistance units used.

---

[4] H. F. Stimson, Precision Resistance Thermometry and Fixed Points, Temperature, Its Measurement and Control in Science and Industry, Vol. II, pp 141-168 (Reinhold Publishing Corp., New York, N. Y., (1955).

The accuracy of temperatures determine from values of R_t/R_o obviously is not limited by the uncertainty of the resistance units if the values of R_t and R_o are determined in the same units. Hence, precision temperature determinations with any thermometer should be based upon a value of R_o determined from measurements with the bridge which is to be used. Since temperature determinations depend directly upon R_o, it should be redetermined frequently enough to assure the user that he has a sufficiently reliable value when measurements are made.

Since only ratios of resistances are required to determine temperature, the units may be absolute ohms, international ohms, or any arbitrary unit; but the calibrated bridge (or potentiometer) must be self-consistent. A bridge that is self-consistent may be used for precision temperature determinations using the constants reported for the thermometer or using the table of R_t/R_o values which has been derived from the reported constants. It is advisable to calibrate the bridge often enough to assure the user that the calibrations are reliable within the accuracy necessary for his work. Calibrations are not difficult and may be made in the same place and under the same laboratory conditions as the measurements for temperature determinations. A method of calibrating the bridge is described in section IV.

Certain precautions must be observed if reliable temperature determinations are to be made with a resistance thermometer. The thermometer coil must be immersed to a depth sufficient to prevent a significant error from transfer of heat along the thermometer leads and protecting tube. A check of the adequacy of the immersion in each uniform constant-temperature bath may be made by varying the depth of immersion of the thermometer and noting whether there is a change in resistance. When a measuring current flows in the thermometer, some heating of the resistor results; consequently the same current should be used in making measurements as was used in the calibration. Sufficient time must be allowed, after the current is turned on, for equilibrium to be established. The characteristic constants of a thermometer may change as a result of changes in the dimensions of the wire, strains in the wire, or the subjection of the thermometer to excessive temperatures. It is particularly important that care be taken to protect the thermometer from small mechanical shocks, each of which strain the wire slightly to produce small changes in the characteristics of the wire in the platinum resistor. If the measured resistance at a reliable fixed point is found to have changed by a significant amount, and the change cannot be attributed to the bridge, recalibration of the thermometer is advisable. The maximum change of the calibration indicated by a change in R_o may be estimated using the following expression:

$$(\text{Maximum Error at temperature } t) = t\left(\frac{Bt}{A} - 1\right)\frac{\Delta}{R_o},$$

where Δ is the change in R_o since calibration. This assumes that temperatures are computed from values of R_t/R_o using a current value of R_o. The value of the maximum error is based on experience with standard platinum thermometers. It is not likely to be valid for others.

III. Tables

The labor involved in computing temperatures can be greatly reduced by making use of the table which is computed for each thermometer. The table relates resistance ratios to temperature over that part of the temperature range appropriate to both the thermometer and the calibration, or over the range requested. The table gives the resistance ratios at intervals of one degree; a linear interpolation will not introduce an additional error greater than the equivalent of 0.0001 degree at any point on the scale.

The table is calculated for each degree in the range by a direct machine computation using the calibration constants of the Callendar formula in the form,

$$\frac{R_t}{R_o} = \left[1 + \alpha t - \alpha\delta\left(\frac{t}{100} - 1\right)\frac{t}{100}\right],$$

for temperatures above 0 °C, and in the modified Callendar formula in the form, [5]

$$\frac{R_t}{R_o} = \left[1 + \alpha t - \alpha\delta\left(\frac{t}{100} - 1\right)\frac{t}{100} - \alpha\beta\left(\frac{t}{100} - 1\right)\left(\frac{t}{100}\right)^3\right],$$

for temperatures below 0 °C.

---

[5] It will be noted that these forms resemble those of the international formulas; and, indeed, the substitution of the relations given in footnotes [1] and [2] shows the equivalence.

IV. Calibration of a Mueller-Type Bridge

The bridge may be calibrated in terms of any convenient unit of resistance such, for example, as a bridge unit which may be established by arbitrarily defining the sum of the resistance of the ten 1 ohm resistors in the 1 ohm decade to be equal to 10 bridge units. However, it is decidedly preferable for the bridge to be calibrated in terms of absolute ohms by means of a suitable standardized resistor because one may then make checks on the stability of the thermometer. In any case it is essential that the calibrated bridge be self-consistent, that is, that the resistance change corresponding to each decade step be expressed in terms of a single unit of resistance. The resistance of a decade step is the change in the effective resistance of the variable arm of the bridge when that step is added to or taken from the bridge setting.

The method of calibration is to compare the resistance of each decade step with the resistance of the χ (sum of all ten steps) of the next lower decade. This comparison is made by alternately including in the variable arm of the bridge either the step being calibrated or the χ of the next lower decade. The lower decades of the bridge are used to make the variable arm balance an external resistance. From these alternate balances, a relation between the step being calibrated and the χ of the next lower decade is obtained. The complete calibration consists of repeating this process for each decade step.

The comparisons require external resistors connected in such a manner that the resistance of the external circuit including all contacts will remain adequately constant during the short time required for each comparison. The external resistance may be that in a series circuit consisting of a resistance box, variable in 0.1 ohm steps up to 100 ohms, and a slide wire shunted to have a resistance slightly greater than 0.1 ohm. The shunted slide wire is convenient for getting the necessary external resistances for calibration of the 0.01 ohm and lower decades, and it is useful for the calibration of the 0.1 ohm and higher decades. When both the slide wire and the resistance box are connected to the bridge, the movable contact of the slide wire is connected to the c post of the bridge and one end of the slide wire to the C post. The resistance box is connected between the other end of the slide wire and the T post of the bridge. If the resistance box is used alone, one terminal of the box is connected to both the C and c posts on the bridge and the other to the T post.

The resistance of the individual steps of a decade will be designated by means of subscripts, for example, the successive steps of the 10 ohm decade will be designated as 10_1, 10_2, ---- 10_9, 10_x. The sum of the steps which are included in any setting will be designated without a subscript, for example, in the 10 ohm decade, as 10, 20, --- 90, X0.

Before beginning the bridge calibration the ratio arm should be adjusted to equality. This adjustment of the ratio arms is necessary because the 0.1 ohm decade is not in the same arm of the bridge as the other decades. The bridge zero is not used in calibration; but, if it is observed and found to have its usual value, there is added confidence in the calibration. The current may be increased to obtain greater sensitivity. If the external circuit is connected as indicated above, the commutator must be set in the N (normal) position and not in the R (reverse) position while calibrating.

The steps in the calibration are then as follows.

(a) Set 10 on the 10 ohm decade of the bridge and 0 on the 1 ohm decade and use the lower decades to balance an appropriate resistance in the external circuit. It is good practice to interpolate with galvanometer deflections to one tenth of a step on the lowest decade.

(b) Without disturbing the external circuit, change the bridge setting to 0 on the 10 ohm decade and X. on the 1 ohm decade and again use the lower decades to balance. It is convenient to adjust the slide wire in the external circuit so that the lower decade balances are near zero for the lesser of (a) or (b).

(c) Repeat (b) and then (a).

(d) Set 20 on the 10 ohm decade of the bridge and 0 on the 1 ohm decade and balance with a corresponding resistance in the external circuit, as in (a).

(e) Change the bridge setting to 10 in the 10 ohm decade and X. in the 1 ohm decade and proceed as in (b) and (c).

(f) Continue this process until each of the 10 ohm steps has been compared with the sum of the ten 1 ohm steps. The observations under (a) (b) and (c) yield the relation $10_1 + \alpha_1 \doteq \chi + b_1$ where a_1 and b_1 are the corrected averages of the respective lower decade readings, including galvanometer interpolations, which were obtained in the balancings of the bridge.

Similar equations are obtained from (d) and (e) leading to the complete set.

$10_1 + a_1 = X. + b_1$

$10_2 + a_2 = X. + b_2$

$10_9 + a_9 = X. + b_9$

$10_x + a_x = X. + b_x$

It is convenient to define the bridge unit by means of the relation,

$$X. = 10 \text{ bridge units} = 10 \text{ ohms (approximately)}.$$

The above relations will then yield the resistance of 10_1, 10_2, 10_3, etc. and by adding these successively the resistances of 10, 20, 30 etc. will be obtained.

For the 1 ohm decade, the procedure is similar and leads to similar equations. However, the resistance of 0.X must be determined. To do this the equations are added to obtain their sum,

$$X. + \sum a = 10(0.X) + \sum b, \text{ so that}$$
$$0.X = \frac{X. + \sum (a - b)}{10}.$$

This value for the resistance of 0.X is then substituted in the original equations and the rest of the procedure is the same as for the 10 ohm decade.

The calibration of the 0.1 ohm decade proceeds similarly.

So far the procedure has yielded calibration data for the 10, 1 and 0.1 ohm decades, and also the resistance of 0.0X of the 0.01 ohm decade. A comparison of the value obtained for the resistance of 0.0X with that of a previous calibration will indicate whether recalibration of the lower decades is advisable.

Calibration of the 0.01 ohm and lower decades is done in a similar manner by using the slide wire alone. The .0001 ohm steps, which ordinarily are the lowest, may be calibrated by comparing galvanometer deflections for each successive step.

If it is desired to calibrate the bridge in terms of absolute ohms or other units represented by a calibrated resistance standard, the resistance standard, preferably one of 10 ohms, may be connected to the bridge, just as a four lead thermometer, and measured in terms of the X. of the 1 ohm decade. The result of this measurement (bridge zero to be taken into account) leads to a relation between the "bridge unit" and the unit of the standard. The corrections previously obtained may be modified so that resistances are expressed in terms of the unit represented by the standard.

The use of a reliable resistance standard has the advantage of holding the bridge unit as constant as the resistance standard and thus it may enable one to determine whether apparent drifts in R_o are due to the thermometer or to the bridge. Another advantage in using a resistance standard in calibrating bridges is that a thermometer may be used interchangeably on these bridges with the precision to which the bridge units agree. For work of the highest precision, however, it is considered better practice, when using any thermometer, to determine R_o at the time measurements are made and to be sure that the bridge is self-consistent. The art of standard platinum resistance thermometer construction and stablization has now developed to such an extent that the resistance of a well-treated thermometer at a reliable fixed point may have a constancy comparable with that of resistance standards.

CONSTANTS OF THE INTERPOLATION FORMULA FOR PLATINUM RESISTANCE THERMOMETERS

J. L. Riddle
National Bureau of Standards
Washington, D. C. 20234

ABSTRACT

Values of the constants in the interpolation formula for a large number of thermometers recently submitted to the National Bureau of Standards for calibration are summarized. All thermometers suitable as standards which were received over a period of about one year during 1959 and 1960 are included. Limitations on such constants can serve either to make the International Practical Temperature Scale (IPTS) more precisely defined or to reduce the number of calibration points required for application over limited temperature ranges.

For presentation at the sixth session of the

Advisory Committee on Thermometry

to the

International Bureau of Weights and Measures

September 1962

Constants of the Interpolation Formula for Platinum Resistance Thermometers

J. L. Riddle
National Bureau of Standards
Washington, D. C. 20234

Values of the constants in the interpolation formula $R_t = R_o [1 + At + Bt^2 + Ct^3(t - t_{100})]$ for a large number of thermometers recently submitted to the National Bureau of Standards for calibration are summarized in Table 1. All thermometers suitable as standards which were received over a period of about one year during 1959 and 1960 are included. Limitations on such constants can serve either to make the International Practical Temperature Scale (IPTS) more precisely defined[1,2] or to reduce the number of calibration points required for application over limited temperature ranges. However, any such limitation must not unduly restrict the supply of platinum and hence the data in Table 1 and the following comments which reflect the results of measurements on a restricted source of platinum are not to be construed as recommendations but only as a part of the information necessary to form the basis for considering such a recommendation.

The present IPTS text pertaining to resistance thermometers tacitly assumes one can ignore any need for terms other than those which appear in the formula relating resistance ratios to temperatures and yet realize the same scale sufficiently well with different resistance thermometers. It is well known that this is not a satisfactory assumption with sufficiently impure platinum or with some types of construction, and hence the text of the IPTS tends to limit both the platinum and the construction used for standard platinum resistance thermometers. It seems reasonable that as the techniques of purifying platinum and constructing thermometers improve one should be able to further limit the variations of platinum thermometers and thus to assume, rather than measure, values for one or more of the higher order terms of the interpolation formula. Significant ranges of temperature should exist where the deviation of the computed temperature caused by the difference between the actual and the assumed values of the constant would be small as compared with the deviation caused by errors of calibration.

For several years the NBS has, with some restraint, applied the foregoing idea in calibrating thermometers on the IPTS. For example, thermometers calibrated only at the triple point of water, steam point, and sulfur point are given tables of R_t/R_o down to -50 °C using an assumed value for the coefficient "C" below 0 °C. Above -50 °C the contribution of the term involving "C" is less than the equivalent of 0.02 deg C. If this technique had been applied to any of the 173 thermometers for which "C" was actually determined, the maximum error introduced would have been less than 2×10^{-4} deg C. A second example involves the calibration of thermometers which are not well suited for measurement at the sulfur point because of electrical conduction between leads at that temperature (through a glass seal from which the leads emerge). Frequently if such a thermometer is to be used only below 175 °C, a value of "B" is assumed and calibration is made only at the triple point of water, steam point, and oxygen point. The maximum error below +175 °C occurs at -120 °C where, if this technique had been applied to any of the 204 thermometers for which "B" was actually measured, the error introduced by assuming a value of "B" would not have exceeded the equivalent of 7×10^{-4} deg C.

In addition to the possibility of a desirable reduction of calibration points necessary for thermometers to be used above the oxygen point, limitations on the permitted range of constants would facilitate the extension of the scale to lower temperatures. One of the problems inherent in extending the scale by any means not directly involving the present IPTS formula is the difficulty of joining such an extension smoothly with the existing scale. If there are limitations on the values of the constants "B" and "C", the slope of the IPTS formula at the point of joining is well defined without involving measurements above the triple point of water. This would seem highly desirable for thermometers that are to be used only at low temperatures. A second problem of extending the IPTS is that of adequately describing the differences between thermometers below 90 °K. The solution will undoubtedly represent a compromise between the complication of the calibration procedure and the limitation of the characteristics of the thermometers. Although a limited range of "A", "B" and "C" may not assure similarity of thermometers below 90 °K, such a similarity does exist for the thermometers tested in the low temperature region by the NBS. All of the last 180 thermometers calibrated in the range from 12 to 90 °K by means of a 16-point comparison with a group of standards would have received the same calibration from 20 to 90 °K to within less than $\pm 2 \times 10^{-2}$ deg K if they had been calibrated simply by using the oxygen point and the hydrogen point with interpolation in the simple manner described by Cragoe.[3] Only 17 of the 180 thermometers would have received a calibration different by more than $\pm 1 \times 10^{-2}$ deg C.

Of these 180 thermometers, those which were also calibrated on the IPTS had constants within the limitations stated. However, other criteria involving measurements at lower temperatures would be expected to be more accurate limitations in this range.

Table 1. Summary of results found on all standard thermometers submitted for calibration over a continuous period of about one year (1959-60).

Constant	A x 10^3	B x 10^7	C x 10^{12}
Maximum	3.9860	5.8591	4.379
Minimum	3.9810	5.8541	4.319
Mean	3.9846	5.8563	4.330
Number of Thermometers	203	203	173

REFERENCES

1. H. J. Hoge and F. G. Brickwedde, "Intercomparison of Platinum Resistance Thermometers between -190° and 445 °C," J. Research NBS, 28, 217 (1942).

2. E. H. McLaren, "Intercomparison of Eleven Resistance Thermometers at the Ice, Steam, Tin, Cadmium and Zinc Points,", Can. J. Phys., 37, 422, (1959).

3. C. S. Cragoe, "Mémorandum Relatif a une 5e Section pour la Quatrième Partie du Project D'Echelle Internationale de Température," Comité International de Poids et Mesures, Procès-Verbaux Des Séances, Session de 1948, Annexe III, T84.

Reprinted from TEMPERATURE—ITS MEASUREMENT AND CONTROL IN SCIENCE AND INDUSTRY, Vol. 3, Part 1
1962 Reinhold Publishing Corp., New York, N. Y.

34. A Study of Stability of High Temperature Platinum Resistance Thermometers

J. P. EVANS AND G. W. BURNS

The National Bureau of Standards, Washington, D.C.

Below 630.5°C the most precise and accurate temperature measurements are made with platinum resistance thermometers. Present-day science and technology is experiencing an increasing need for more precise and accurate measurements at higher temperatures. Consequently, the NBS is studying the performance of platinum resistance thermometers at temperatures up to the gold point, 1063°C.

The International Practical Temperature Scale of 1948[1] is defined in the region 630.5° to 1063°C by a platinum versus platinum-10% rhodium thermocouple calibrated at 630.5°C, the silver and gold points. The precision of such a thermocouple is about 0.1 degree, and its absolute accuracy with respect to the International Practical Temperature Scale is about 0.2 degree C.[2] Experiments by other investigators have indicated that it is possible to determine values of temperature in this range more precisely and reliably with platinum resistance thermometers than with thermocouples

Waidner and Burgess first investigated the use of platinum resistance thermometers up to 1100°C at the NBS in 1909.[3] They found that temperatures determined with their thermometers agreed with thermocouple determinations within about 1 degree. Their thermometers changed considerably with use; this may now be attributed, for the most part, to the relatively low purity of the platinum available at that time. In 1930 Moser made a similar study and found that temperature determinations with his thermometers were reproducible to about 0.1 degree.[4] His thermometers were made of a higher purity platinum and they were significantly more stable than those of Waidner and Burgess.

It is evident from the earlier work that if a platinum resistance thermometer is to be stable at high temperatures, its temperature sensing resistor must be made from very pure platinum wire supported in a strain-free manner. Furthermore, the materials used for support and protection must not contaminate the resistor during use. Materials suitable for support become poorer electrical insulators at high temperatures, hence the resistance of the thermometer should be kept low to minimize the effect of electrical leakage.

Figure 1 is a photograph of one type of temperature sensing resistor. It consists of 8 straight lengths of platinum wire 0.4 or 0.5 millimeter in diameter threaded through holes in synthetic sapphire disks. These wires are welded together in series. A central platinum rod serves to support and position the disks. The assembled resistor has become known as a "bird cage resistor" because of its shape. It is 5 millimeters in diameter, 35 to 40 millimeters long, and has a nominal resistance at 0°C of 0.25 ohm. It is nearly noninductive.

Four platinum leads are welded to the resistor. The leads are separated by four-hole sapphire disks, and between the disks are sapphire rod spacers ½ inch long. The resistor and lead assembly is placed in a closed end protecting tube about 450 millimeters long, which has been cleaned with acid and fired in oxygen at 1100°C. The four platimum leads extend to within a few millimeters of the open end of the tube where they are butt welded to bare copper wires of the same diameter. The copper to platinum junctions are located side by side in a small piece of four-hole porcelain tubing which is surrounded by a close-fitting copper sleeve. In this manner the junctions are kept at nearly the same temperature, thereby reducing thermal emf in the thermometer. For sealed thermometers, the open end of the protecting tube is fitted with a hermetic seal header through which the bare copper wires are sealed. The copper wires are then soldered to insulated thermometer lead wires. An aluminum head attached to the end of the thermometer completes the construction.

Many resistance thermometers have been found to suffer an increase in resistance at 0°C when mistreated by tapping. This increase in resistance is believed to be the result of work hardening of the platinum. The bird cage resistors, however, have proven to be very rugged mechanically. Although one thermometer with this type resistor was tapped on a solid object 5000 times, this treatment resulted only in a barely detectable change in the resistance of the thermometer at 0°C.

Resistance measurements are made with a resistance thermometer bridge of the type designed by Mueller.[5] A recent version of this bridge has a range 0 to 422 ohms in 1 microhm steps.[6] This instrument may also be used as a decade resistor in a potentiometric circuit similar to that described by Dauphinee.[7] It should be pointed out that the resistance of the platinum leads of these thermometers exceeds that of the temperature sensing resistor. Temperature changes along the leads thus cause resistance changes which can be very disturbing when using a Mueller bridge. A potentiometric method of resistance determination would eliminate this difficulty.

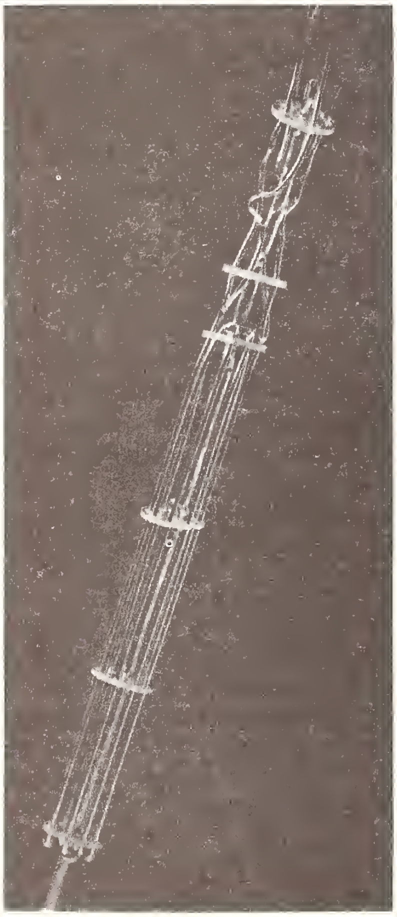


Fig. 1. The bird-cage resistor, one type of temperature sensing resistor employed in the high-temperature platinum resistance thermometers.

The stability of the thermometers at high temperatures was tested by heating the thermometers for long times in a tube furnace. Periodically the thermometers were removed from the furnace for determination of their resistance at 0 and 100°C. The resistance at 100°C was determined by placing the thermometer under test, together with a calibrated resistance thermometer, in a copper block bathed in steam at atmospheric pressure. Simultaneous measurements of the resistance of both thermometers were made. The resistance at 0°C was determined by measuring the resistance of the test thermometer at the triple point of water, 0.01°C. Simple corrections were applied to obtain the resistances at 0 and 100°C. The constancy of the ratio R_{100}/R_0, where R_{100} is the resistance of the thermometer at 100°C and R_0 is the resistance at 0°C, is taken as an indicator of thermometer stability.

The ratio R_{100}/R_0 was chosen to indicate thermometer stability for several reasons. First, it is relatively easy to obtain R_{100} and R_0 with sufficient precision. Second, it is believed that 100°C is not a high enough temperature to cause changes in a thermometer during the time it takes to make a resistance measurement. Third, the ratio R_{100}/R_0 is independent of purely dimensional changes in the platinum wire.

A number of thermometers have been constructed and heated in a furnace at various temperatures between 500 and 1100°C for periods up to 500 hours. The data shown in Figs. 2 and 3 are representative of results obtained for thermometers employing different resistor designs, various protecting tube materials, and two types of platinum wire. From time to time the thermometers were removed from the furnace for determination of R_{100} and R_0.

The upper set of curves in Fig. 2 shows the results of heating a thermometer designated HTSS-3. This thermometer was encased in a porcelain protecting tube. Heating at 850°C produced a definite change in the thermometer, and at 1000°C the change became so rapid as to make the thermometer virtually useless. The rapid decrease in R_{100}/R_0 with heating at high temperatures was probably due to contamination of the platinum with metals or metal oxides from the porcelain. It thus appears that porcelain is not a suitable protecting tube material. The lower two sets of curves in Fig. 2 present data obtained with thermometers HTSS-4 and HTSS-5, both of which were encased in pure alumina tubes. During the 500-hour heating period, the average change in R_{100}/R_0 for these thermometers was equivalent to a drift in thermometer calibration of about 0.001 degree per hour at 1000°C, indicating that pure alumina is more suitable than porcelain as a protecting tube material.

The resistor in thermometer HTSS-4 was in the form of a bifilar helix wound on a synthetic sapphire cross, while a bird-cage resistor was used in thermometer HTSS-5. Comparison of the curves in Fig. 2 indicates that thermometer stability is not significantly dependent on resistor configuration. Other experiments tend to confirm this.

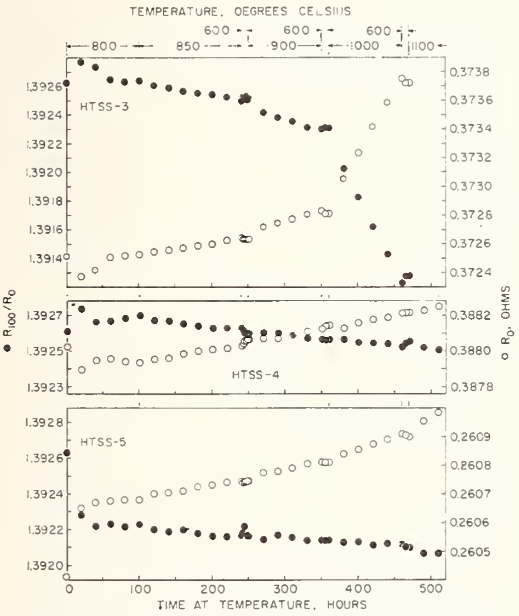


FIG. 2. Change in R_{100}/R_0 with time for three resistance thermometers heated to various temperatures. HTSS-3, bifilar helix resistor in porcelain tube open to air. HTSS-4, bifilar helix resistor in alumina tube open to air. HTSS-5, bird-cage resistor in alumina tube open to air. The corresponding change in R_0 is also shown.

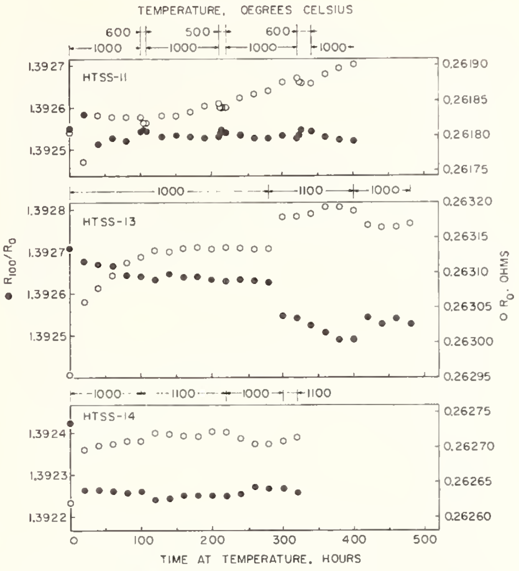


FIG. 3. Change in R_{100}/R_0 with time for three resistance thermometers heated to various temperatures. HTSS-11, bird-cage resistor (Fibro platinum wire) in alumina tube open to air. HTSS-13, bird-cage resistor in silica tube open to air. HTSS-14, bird-cage resistor (Fibro platinum wire) in platinum tube sealed in argon. The corresponding change in R_0 is also shown.

Figure 3 presents another comparison of various protecting tube materials. Thermometer HTSS-11 was encased in alumina, thermometer HTSS-13 in silica, and thermometer HTSS-14 in pure platinum. The silica tube thermometer appears relatively stable below 1000°C, but above that temperature R_{100}/R_0 begins to decrease, probably because of silicon contamination. No clear-cut superiority of platinum over alumina as a protecting tube material is shown by the curves in Fig. 3.

Recently a new material called Fibro platinum has come on the market.[8] Wires made of Fibro platinum have a fibrous structure which is asserted to prevent excessively large grain growth upon recrystallization at high temperatures. Two of the thermometers for which data are shown in Fig. 3 (HTSS-11 and HTSS-14) were made with this wire.

Thermometers made with platinum tubes could be hermetically sealed, while thermometers made with alumina tubes were left open to the air since it was questionable whether the alumina tubes were gas tight. The platinum tube thermometer HTSS-14 was sealed in an argon atmosphere. In general, platinum tube thermometers sealed in argon and alumina tube thermometers open to the air exhibited no significant difference in stability which could be attributed to the surrounding atmosphere. Other investigators working at higher and lower temperatures, however, have found that various gases have considerable effect on the resistance characteristics of platinum.[9-11] The situation concerning gaseous atmospheres, as it relates to thermometer stability, is not clear at this time, but thermometers made with metal oxide protecting tubes should probably be filled with a gas containing some oxygen. The oxygen would tend to inhibit the formation of free metal atoms which alloy with the platinum.

It appears desirable that the thermometers be sealed to keep out contaminants and water vapor, but this has not always been done. Barber,[12] for example, has allowed the thermometer free access to the air but has incorporated a drying agent in the thermometer head. Only by carefully removing water vapor and carbonaceous material from the thermometers constructed for the present study has it been possible to maintain consistently an insulation resistance across the thermometers greater than 1 megohm at 1100°C. Although the error in resistance determinations due to electrical leakage is negligible at low temperatures, it becomes significant at high temperatures. At 1000°C, where the thermometer resistance may exceed 1 ohm, a shunting resistance of 1 megohm introduces an error greater than a part per million in the resistance determination. This corresponds to an uncertainty in temperature determination of more than 0.001 degree.

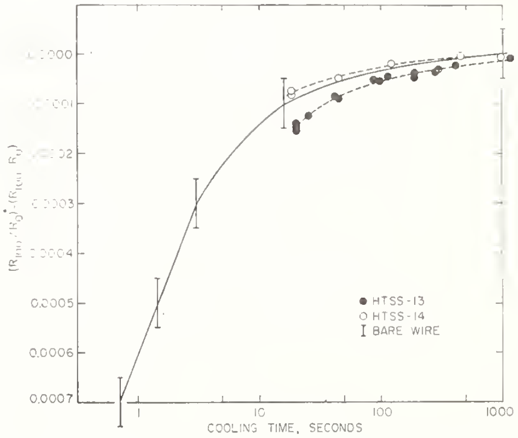


FIG. 4. Decrease R_{100}/R_0 with cooling times from high temperatures. HTSS-13, bird-cage resistor in silica tube open to air. HTSS-14, bird-cage resistor (Fibro platinum wire) in platinum tube sealed in argon. The solid curve represents Corruccini's data on bare wire heated electrically (see reference 13). $(R_{100}/R_0)^*$ is the value of the ratio after an anneal at 500 or 600°C followed by a slow cool.

Two interesting aspects of the curves in Figs. 2 and 3 for thermometers encased in alumina and platinum should be noted. First, it is seen that after initial annealing, these thermometers, in general, exhibit a slow decrease in R_{100}/R_0 with heating which is not strongly dependent on the heating temperature. The cause of this slow decrease is not known. There are possibly several contributing factors; among these are: the effect of recrystallization and grain growth at high temperatures, a slow diffusion of surface impurities into the platinum, contamination of the platinum by the protecting tube material, and the taking into solution by the platinum of gases surrounding it. In any case, the decrease apparently can be made small by suitable construction. For example, the thermometer sealed in argon in a platinum tube changed, on the average, by less than the equivalent of 0.05 degree at 1063°C when heated for 300 hours at 1000°C or higher.

The second interesting aspect is that heating a thermometer for a period at a temperature lower than previously produces a "recovery" in R_{100}/R_0. Upon further heating at the higher temperature, R_{100}/R_0 returns to its lower value. This reversibility in the value of R_{100}/R_0 dependent on heating temperature was observed by Moser, and also by Meyers in an unpublished work at the NBS. Corruccini, in his investigations on the annealing of platinum for thermometery,[13] recognized that the effect could be caused by a comparatively rapid cooling from high temperatures and would be dependent on the cooling rate. He found that the effect was reversible; R_{100}/R_0 could be restored to its initial value by subsequent annealing. He also found that the quantity $R_{100} - R_0$ remained essentially unchanged during the course of the experiments.

Some of Corruccini's results are represented by the solid curve in Fig. 4, which gives the change in R_{100}/R_0 from its value in the well-annealed state, as a function of cooling time. Bare wires were heated at 1450°C by passing an electric current through them. The estimated time for incandescence to disappear after the removal or reduction of current was taken as the comparative index of the cooling rate.

The dashed curves in Fig. 4 show results of experiments performed with a silica tube thermometer and a platinum tube thermometer. The thermometers were heated in a furnace at 1100°C. The resistance, as a thermometer was withdrawn from the furnace, was followed with a recorder. In this experiment, the comparative index is based on the estimated average time of cooling from 1100 to 600°C. If the three curves in Fig. 4 are adjusted to have the same starting point, they appear to be closely similar for cooling times greater than about 50 seconds. No serious attempt has been made to explain the slight divergence of the curves for shorter cooling times. If the change in R_{100}/R_0 is strongly dependent on the cooling rate during the first part of a cooling period, some divergence could be expected.

Throughout these experiments the quantity $R_{100} - R_0$ remained considerably more stable than the quantity R_{100}/R_0. In fact, the platinum tube thermometer sealed in argon exhibited no significant change in $R_{100} - R_0$ during the 300-hour heating period and during the cooling rate experiments.

An explanation of these results can be found in recent work on quenched-in point defects in platinum.[14-16] The procedure in these quenching experiments was to cool a sample of platinum wire from temperatures in the range 1000 to 1600°C to room temperature. The cooling rates were such that the temperature of the sample was within a few degrees of its final value in less than a second. Ascoli *et al.* found that when the quenching time was less than 0.1 second, the increase in resistivity $\Delta\rho$ of platinum at 15°C due to quenching could be represented by

$$\Delta\rho = 1.3 \times 10^{-4} \exp(-1.23/kT) \text{ ohm-cm}$$

where kT is expressed in electron volts, and T is the temperature in °K from which the sample was quenched. For slower quenching rates the situation was more complicated, and the added resistivity tended to depend on the quenching rate as well. It never exceeded the value given by the above equation, however. The explanation given by these authors is that a temperature-dependent equilibrium concentration of lattice-site vacancies is produced at the quenching temperature T, and that for quenching times of less than 0.1 second practically all of the vacancies are frozen in the platinum crystals. It is assumed that the added resistivity is proportional to the concentration of frozen-in vacancies.

It was stated that for at least one of the thermometers the quantity $R_{100} - R_0$ remained unchanged during the cooling rate experiments. This fact suggests that the changes in resistance produced by cooling obey Matthiessen's rule. Further, added resistivity measured at a low temperature (15°C in the experiments described above) when all the vacancies are quenched in would equal that part of the total resistivity at temperature T contributed by the vacancies. If the equation above is applied to resistance thermometers in their range of interest, it is found that vacancies contribute to thermometer resistance an amount which is eqiuivalent to a temperature increment of the order of 0.3 degree at 1063°C and 0.001 degree at 600°C. One can also deduce that, since the equation gives the maximum added resistivity that can be quenched in from temperature T, cooling the thermometers at any rate from temperatures below 600°C would produce insignificant changes due to quenched-in vacancies.

The assumptions and conclusions of the preceding paragraph may or may not be generally valid. Certainly the situation would be confused if the platinum wire in a thermometer were constrained in any way during the cooling process, or if quenching were to produce point defects other than vacancies. Suffice it to say that no thermometer changes attributable to quenched-in point defects have been observed upon cooling from 600°C and below.

Ascoli *et al.* found that more than 90% of the quenched-in resistivity could be removed upon annealing for about one minute at 700°C. The kinetics of annealing may not be simple. Annealing behavior may depend on vacancy concentrations and quenching rate.[15] In any case, Corruccini found that he could reestablish the initial values of R_{100}/R_0 with two hours annealing at 500°C. The thermometers described here were restored to their highest values of R_{100}/R_0 in an annealing period of from one to two hours at 600°C.

It is clear that the presence of vacancies and the fact that vacancies can be quenched in upon cooling must be taken into account in considering thermometer stability. If a temperature determination is to be based on a resistance measurement made at a reference temperature that is low, say 0°C, as well as a resistance measurement made at the temperature to be determined, then something must be known about the vacancy concentration at the low temperature. For example, at the low temperature the platinum might be required to contain all the vacancies that were present at the high temperature. Conversely, one might require that the platinum contain at every temperature a vacancy concentration differing insignificantly if at all from its equilibrium concentration. Since it seems improbable that practical thermometers can be cooled rapidly enough to quench in all vacancies, the alternative requirement, which can be met by proper annealing prior to a low-temperature determination, appears preferable.

These studies at the NBS have shown that stable high-temperature platinum resistance thermometers can be made. Thermometers have been developed which drifted the equivalent of only a few hundredths of a degree at 1000°C when heated for several hundred hours at 1000°C or higher. Synthetic sapphire has been found suitable for the support of the resistor wires, and both pure platinum and pure alumina have been used successfully as protecting tube materials. An easily constructed, mechanically rugged resistor, the bird cage resistor, has been built and tested.

These studies have also shown that thermometer stability is dependent on the rate at which thermometers are cooled from temperatures above 600°C. This cooling rate effect has been explained by the quenching-in of point defects, probably lattice site vacancies, in the platinum. It has been found that the effect is reversible; the thermometers can be restored to the condition existing before a rapid cooling by annealing at 600°C and lower. Consequently, the cooling rate effect must be taken into account when calibrating and using high-temperature platinum resistance thermometers.

References

1. H. F. Stimson, "The International Practical Temperature Scale of 1948," J. Research Natl. Bur. Standards **65A**, 139 (1961).
2. H. J. Kostkowski, "The Accuracy and Precision of Measuring Temperatures above 1000°K," *Proceedings of an International Symposium on High Temperature Technology* (McGraw-Hill Book Company, New York, 1960). Accuracy and precision are defined in this reference as follows: "Accuracy here means estimated standard deviation of the mean of determinations from each laboratory in which attempts have been made to realize either the international or the thermodynamic temperature scales about the mean of all laboratories. Precision of a thermometer means the estimated standard deviation of the determinations of any laboratory about the mean of the determinations in the same laboratory."
3. C. W. Waidner and G. K. Burgess, "Platinum resistance thermometry at high temperatures," Bull. Bur. Standards **6,** 149 (1909).
4. Helmut Moser, "Temperature measurement with platinum resistance thermometers up to 1100°C," Ann. Physik (5) **6,** 852 (1930).
5. See, for example, E. F. Mueller, "Precision Resistance Thermometry," *Temperature, Its Measurement and Control in Science and Industry* (Reinhold Publishing Corporation, New York, 1941), Vol. 1, p. 162.
6. J. P. Evans, "An Improved Resistance Thermometer Bridge," *Temperature, Its Measurement and Control in Science and Industry* (Reinhold Publishing Corporation, New York, 1962), Vol. 3.
7. T. M. Dauphinee, "An isolating potential comparator," Can. J. Phys. **31,** 577 (1953). See also "Potentiometric Methods of Resistance Measurement," *Temperature, Its Measurement and Control in Science and Industry* (Reinhold Publishing Corporation, New York, 1962), Vol. 3.
8. J. S. Hill, "Fibro Pt for Thermal Elements," *Temperature, Its Measurement and Control in Science and Industry* (Reinhold Publishing Corporation, New York, 1962), Vol. 3.
9. Comité International des Poids et Mesures, Procès-Verbaux des Seances de 1954 **24,** T166 (1955).
10. R. J. Berry, "Stability of Platinum Resistance Thermometers at Temperatures up to +630°C," *Temperature, Its Measurement and Control in Science and Industry* (Reinhold Publishing Corporation, New York, 1962), Vol. 3.
11. D. Bradley and A. G. Entwistle, "Anomalous Resistance Effects in Small Diameter Platinum and Platinum-Rhodium Resistance Elements at Temperatures in Excess of 1000°C in a Gaseous Environment," *Temperature, Its Measurement and Control in Science and Industry* (Reinhold Publishing Corporation, New York, 1962), Vol. 3.
12. C. R. Barber and W. W. Blanke, "A platinum resistance thermometer for use at high temperatures," J. Sci. Instr. **38,** 17 (1961).
13. R. J. Corruccini, "Annealing of platinum for thermometry," J. Research Natl. Bur. Standards **47,** 94 (1951), RP 2232.
14. A. Ascoli, M. Asdente, E. Germagnoli, and A. Manara, "Activation energies for the production and migration of vacancies in platinum," J. Phys. Chem. Solids **6,** 59 (1958).
15. G. L. Bacchella, E. Germagnoli, and S. Granata, "On the kinetics of quenched-in lattice vacancies in platinum," J. Appl. Phys. **30,** 748 (1959).
16. G. R. Piercy, "Point defects in platinum," Phil. Mag. (8) **5,** 201 (1960).

Reprinted from TEMPERATURE—ITS MEASUREMENT AND CONTROL IN SCIENCE AND INDUSTRY, Vol. 3, Part 1
1962 Reinhold Publishing Corp., New York, N. Y.

36. Interpolation of Platinum Resistance Thermometers, 10° to 273.15°K

ROBERT J. CORRUCCINI

Cryogenic Engineering Laboratory, National Bureau of Standards, Boulder, Colo.

Recently a numerical method has been proposed[1] for interpolating the resistance-temperature relations of platinum resistance thermometers by utilizing similarities in the form of their departures from Matthiessen's rule. The method requires that the thermometers be calibrated at three well-spaced temperatures. The interpolation is then carried out by using detailed tables of the resistance-temperature relations of two other thermometers.

The method can be developed as follows. We can deduce from Matthiessen's rule that the resistance R_X of a thermometer X at temperature T can be written as

$$R_X = G_X\rho_i + R_{0X} \tag{1}$$

in which G_X is the shape factor of the resistor, and ρ_i is the "ideal" or lattice resistivity of platinum, a function of temperature only. The residual resistance at absolute zero R_{0X} may not be known but can be eliminated by working with differences of resistance between temperatures T and some fixed temperature T_1.

$$R_X - R_{1X} = G_X(\rho_i - \rho_{1i}) \tag{2}$$

Similarly, for a second thermometer A,

$$R_A - R_{1A} = G_A(\rho_i - \rho_{1i}) \tag{3}$$

The lattice resistivity can be eliminated by combining Eqs. (2) and (3).

$$R_X - R_{1X} = a_X(R_A - R_{1A}) \tag{4}$$

The constant a_X is the ratio of the two shape factors. It can be determined from the resistances alone if they are known at a second fixed point T_2. Then

$$a_X = (R_{2X} - R_{1X})/(R_{2A} - R_{1A}) \tag{5}$$

Thus, if we know the complete resistance-temperature relation of thermometer A, and if we calibrate thermometer X at T_1 and T_2, then the resistance-temperature relation of thermometer X can be constructed using Eq. (4). Let us denote resistances estimated in this way as R', and let us use R to indicate experimentally measured values. Thus Eq. (4) becomes

$$R_X' = R_{1X} + a_X(R_A - R_{1A}) \tag{6}$$

From Eqs. (4) and (5) it follows that

$$\frac{R_X - R_{1X}}{R_{2X} - R_{1X}} = \frac{R_A - R_{1A}}{R_{2A} - R_{1A}} \tag{7}$$

or

$$Z_X = Z_A = Z \tag{8}$$

where

$$Z_X \equiv (R_X - R_{1X})/(R_{2X} - R_{1X}), \text{ etc.} \tag{9}$$

Thus, the use of a universal Z function for interpolation as proposed by Cragoe[2] is equivalent to requiring that Matthiessen's rule should be obeyed within the temperature interval in which the function is used. However, it is well-known that departures of the order of 0.01° occur when T_1 is 20°K and T_2 is 54 or 90°K.

The present method makes use of the fact that the departures in resistance $(R_X' - R_X)$ versus T are found to be of similar shape. Then a departure function of representative shape can be adopted as a reference standard. Let us designate the thermometer used to provide the standard departure function as B. If the departure of the unknown thermometer X at a third fixed point T_3 is determined experimentally, then the departure function for X is constructed by multiplying the standard departure function by the ratio of the departures of X and B at T_3. That is, we calculate

$$R_X'' = R_X' - b_X(R_B' - R_B) \tag{10}$$

where

$$b_X = (R_{3X}' - R_{3X})/(R_{3B}' - R_{3B}) \tag{11}$$

The same result can be obtained by working with Z functions. Thus Eq. (10) can be put in the form,

$$\begin{aligned} Z_X'' &\equiv (R_X'' - R_{1X})/(R_{2X} - R_{1X}) \\ &= Z_A + c_X(Z_B - Z_A) \end{aligned} \tag{12}$$

where

$$c_X = (Z_{3X} - Z_{3A})/(Z_{3B} - Z_{3A}) \tag{13}$$

A preliminary test was made[1] by using calibration data of five thermometers and taking $T_1 = 20$, $T_2 = 80$, and $T_3 = 273.15$°K. It was found that, whereas Eq. (6) gave deviations as large as 0.01° between 20 and 80°K, Eq. (10) fit the actual calibrations within about 0.001° from 20 to 273.15°K. However, it was felt that this excellent result might be fortuitous, and that further evaluation of the method on a larger and more varied group of thermometers would be desirable. This paper gives such an evaluation.

DESCRIPTION OF THE THERMOMETERS

The resistance-temperature relations of many platinum thermometers have been published. The temperature scale used has always been, nominally, the absolute thermodynamic scale as established by gas thermometry. Unfortunately, the best gas thermometry has only been accurate to the order of 0.01°, whereas the stability and precision of platinum thermometry can be an order of magnitude better than this. Thus it is hardly possible to evaluate any interpolation method within less than 0.01° using data from different laboratories that maintain their own fundamental scales.

Fortunately, a rather large number of thermometers have been calibrated by the Heat Division of the NBS on the provisional scale of Hoge and Brickwedde.[3] Inasmuch as this scale has been maintained by secondary standard platinum thermometers, it presumably has been constant and reproducible within much narrower limits than the uncertainty attending its establishment. The latter uncertainty was estimated by Hoge and Brickwedde as 0.02°. However, for the present purpose only the reproducibility matters. This has never been stated explicitly. On the assumption that no more than one extra or "insignificant" figure is given on the NBS certificates, one would conclude that the precision, reproducibility, or "significance" must be no worse than a few millidegrees above 20°K. Our purpose, then, was to obtain as many calibration data on the NBS provisional scale as were available, and to evaluate the proposed interpolation method using only those data.

For this purpose, there were available the five Cryogenic Engineering Laboratory (CEL) thermometers used originally[1] plus five newer CEL thermometers for which calibrations had been purchased in 1959–1960. Also, the Heat Division of the NBS supplied a portion of the data in its files. This consisted of calibrations of 24 other thermometers that had been performed for the public in the period 1950–1953. Published data on thermometer T4 of the National Research Council, Ottawa were used also.[4] Thus, there were 35 thermometers in all. All except T4 were Leeds and Northrup Co., Catalog No. 8164 capsule types. The serial numbers ranged from 673,748 to 1,530,182. All calibration data were expressed on the NBS (1955) scale, on which the normal boiling point of oxygen is 90.18°K, consistent with the International Temperature Scale (ITS) values of −182.97°C for the oxygen point and 273.15°K for the ice point. Resistance data certified before 1955 had to be increased by the equivalent of 0.01° at all temperatures below the oxygen point, inasmuch as the NBS scale before 1955 was based on 90.19 and 273.16°K for the oxygen and ice points, respectively.

Figures 1, 2, and 3 have been prepared to show the ranges of various parameters derived from the resistance-temperature relations of the 35 thermometers. The thermometers evidently had normal characteristics, inasmuch as they are approximately represented by the correlating functions that others have proposed. It will be noted that the values of $W_{20.263}$ fall into two groups. In what follows, it was of some interest to see if selecting the parameters of A and B for best fit within one group only could result in better accuracy than would be possible if a given A-B pair were used to fit both groups. It is estimated that the residual resistance ratios $W_0 \equiv R_0/R_{273.15}$ were in the range 0.00039 to 0.00071.

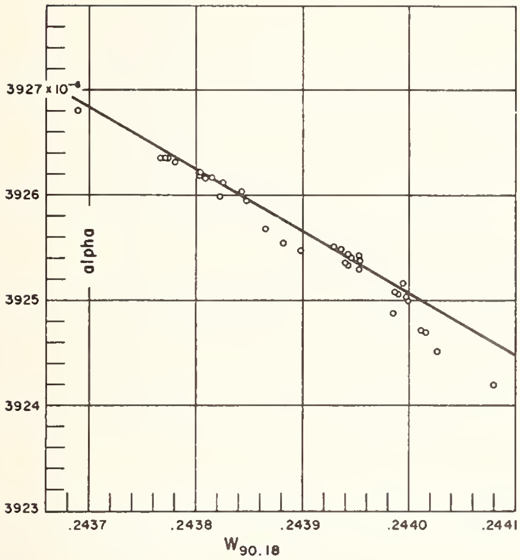


FIG. 1. The correlation between the Callendar constant α and $W_{90.18}$ for the 35 thermometers studied. The parameter W_T is defined as $R_T/R_{273.15}$. The straight line is given by $W_{90.18} = 0.910265 - 169.746\alpha$. It was derived from the Callendar-van Dusen equation using the empirical relations, $\alpha\delta = 0.005857$ and $\beta = 0.5852\delta - 0.7629$, suggested by Stimson, Proces-Verbaux Comité Intern. Poids et Mesures **23B**, T104 (1952).

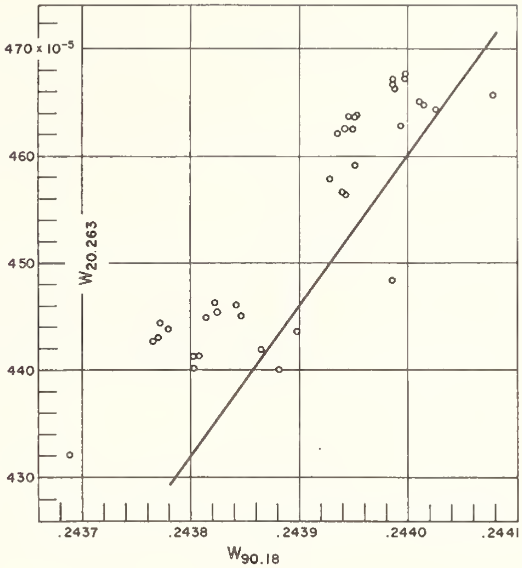


FIG. 2. The correlation between $W_{20.263}$ and $W_{90.18}$ for the 35 thermometers. The temperature 20.263 is taken to be the boiling point of equilibrium H_2 on the NBS (1955) scale (H. W. Woolley, R. B. Scott, and F. G. Brickwedde, J. Research, Natl. Bur. Standards **41**, 453, 1948). The straight line $W_{20.263} = 1.4086\, W_{90.18} - 0.33910$ is derived from a correlation suggested by Lowenthal, Kemp, and Harper, Bull. Inst. Intern. Froid, Annexe 1958-1, p. 107.

RESULTS OF THE INTERPOLATIONS

Equation (6) was tested first, but merely in order to establish a standard against which the performance of Eq. (10) could be measured. The latter then was tested using various sets of calibration temperatures. The following results were obtained.

Equation (6) with $T_1 = 20°$, $T_2 = 90°K$

Figure 4 shows resistance errors $R_X' - R_X$ of some representative thermometers. The reference thermometer A was one of the group which was selected because it had nearly average characteristics. While the error curves are superficially of similar shape, some variations can be noted, especially below 50°K. The largest error obtained in the interval 20 to 90° was equivalent to 0.016°. The average of all the maximum errors in this interval was equivalent to 0.005°. The temperature errors were a much less regular function of temperature than the resistance errors. The maxima in the former occurred as low as 24° and as high as 60°K.

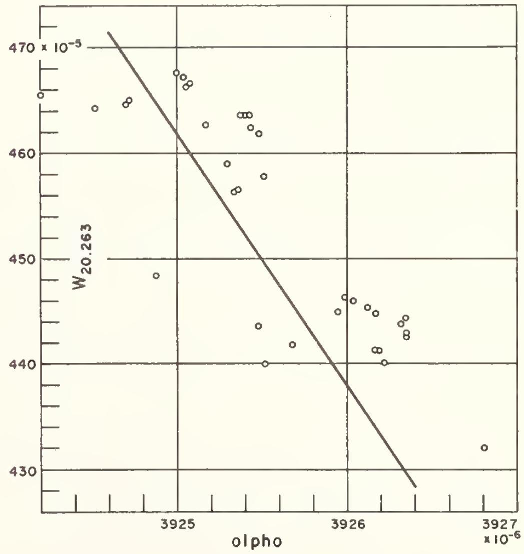


FIG. 3. The correlation between $W_{20.263}$ and α for the 35 thermometers. The straight line $W_{20.263} = 0.94310 - 239.10\,\alpha$ was obtained by combination of the linear functions of figs. 1 and 2.

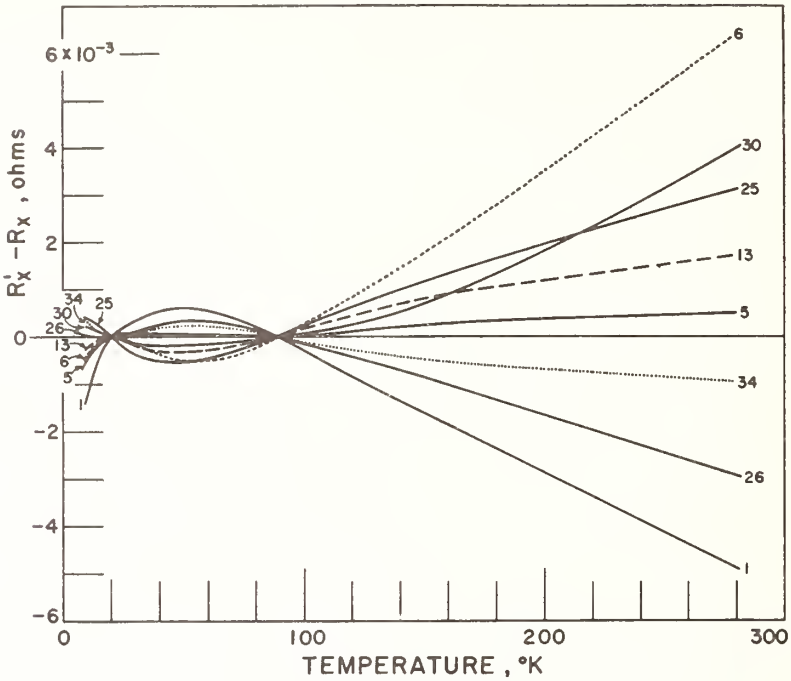


Fig. 4. Resistance errors for some representative thermometers using Eq. (6) with $T_1 = 20$, $T_2 = 90$°K. The reference thermometer *A* had nearly average parameters.

Equation (10) with $T_1 = 20°$, $T_2 = 90°$, $T_3 = 273.15°K$

Six different pairs of thermometers were chosen from the group to serve as the reference standards *A* and *B*. Of these, two pairs used one reference thermometer from the group with low values of $W_{20\text{-}263}$ and the other from near the middle, one pair combined an average thermometer with one from the high group, and the other pairs combined a "low" with a "low," a "high" with a "high," and a "low" with a "high," respectively. There was no error exceeding 0.009° in the interval 20 to 90°K and, for three of the pairs, there was no error exceeding 0.006°. The degree of fit obtained with any given *X* thermometer might vary considerably according to the choice of *A* and *B*, and was somewhat better if *A* and *B* were both from the same subgroup as the *X* thermometer. However, the average behavior of the entire group did not depend critically on this choice. Figure 5 shows the temperature errors for representative *X* thermometers using one of the better *A* and *B* choices. With this particular *A* and *B* pair the maximum error in the interval 20 to 90°K was 0.006°, while the average over all thermometers of the maximum error in this interval was 0.003°.

Thus, as was feared, the excellent result obtained in the preliminary study[1] could not be duplicated with this larger and more varied group of thermometers. Nevertheless, the result obtained seems to be sufficiently good for practical thermometry in view of the larger uncertainty in the fundamental NBS scale. It should be emphasized that the substantial improvement that has been obtained relative to the preceding case involved no additional experimental work, inasmuch as $R_{273.15}$ is always determined, being a key datum for any precise thermometer whether it is intended for use at high or low temperatures.

The results obtained below 20 and above 90° should also be noted, though the behavior in these regions is of less interest. In the interval 90 to 273.15°K, with the *A*-*B* pair that was used to obtain Fig. 5, the largest error was 0.009°. The average over all of the *X* thermometers of the maximum errors in this interval was 0.004°. For the *A*-*B* pair that gave the best results in this interval, the maximum error was 0.006° and the average of the various maximum errors was 0.002°. With decreasing temperature below 20°K, the errors increased rapidly and always reached 0.01° for some of the *X* thermometers by 18°K, with further increases occurring rapidly below this temperature.

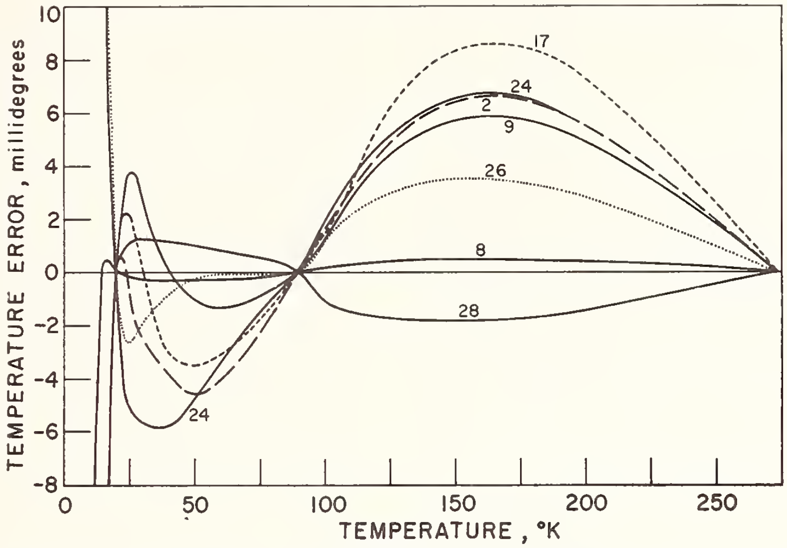


FIG. 5. Temperature errors for some representative thermometers using Eq. (10) with $T_1 = 20$, $T_2 = 90$, $T_3 = 273.15$°K. The reference thermometers *A* and *B* are those represented in Table 2.

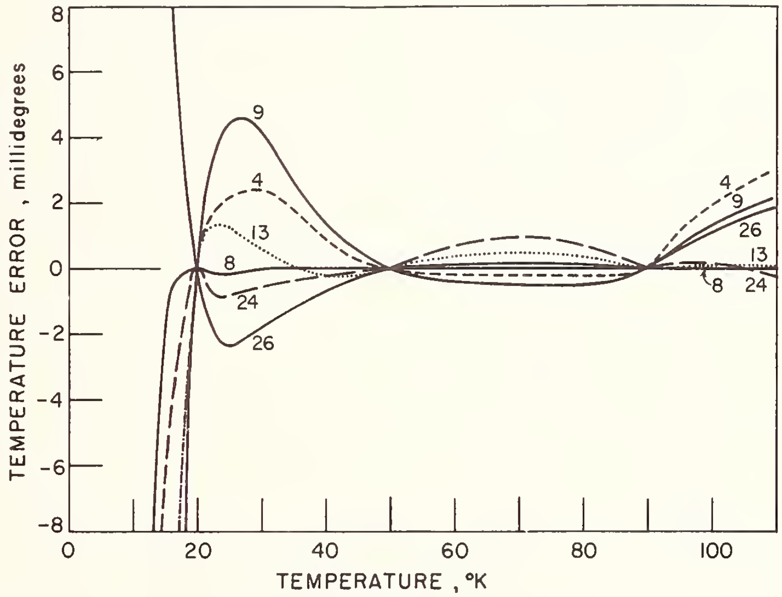


FIG. 6. Temperature errors for some representative thermometers using Eq. (10) with $T_1 = 20$, $T_2 = 90$, $T_3 = 50$°K. The reference thermometers *A* and *B* are those represented in Table 2.

Equation (10) with $T_1 = 20$, $T_2 = 90$, $T_3 = 50$°K

It might be thought from Fig. 4 that, if the best possible fit between 20 and 90°K were desired without regard to other considerations, then T_3 should be located about midway in this interval.[5] The triple point of oxygen at about 54° is a suitably located fixed point. Use of the rounded value $T_3 = 50$° was evaluated using the same six *A*-*B* pairs as before. For four of the six sets, no error exceeded 0.005° and the average of the maximum errors was 0.002. Figure 6 shows some representative error curves calculated using the same *A*-*B* pair as in Fig. 5.

The benefit derived from using $T_3 = 50$° as compared to 273.15°K is disappointingly small and would not seem to justify the extra experimental labor. This conclusion results from the fact that the small irregularities below 50° that were noted in Fig. 4 become magnified as temperature errors by the rapid decrease in dR/dT below 50°K.

Use of a Calibration Point near 30°K

The foregoing result might suggest that there would be considerable improvement if T_1 should be located below 50 but not so low as 20°K. The same conclusion was reached by Lowenthal and Harper[6] as the result of an analysis of the differences between the W-T functions of various thermometers. They recommended the use of a Z function with $T_1 = 27$, $T_2 = 90$°K. The normal boiling point of neon ($\sim$27°K) was suggested as a convenient fixed point to use in carrying out their proposal. The basis of their suggestion is somewhat clouded by their use of published data expressed on four different temperature scales. Accordingly, a plot similar to one of theirs has been prepared using selected thermometers from the group under study, and is shown in Fig. 7. Though it is not clear that the temperature 26°K has the unique significance attributed to it by Lowenthal and Harper, it is evident that excluding the region below this would avoid some major irregularities.

In order to evaluate their proposal to use a Z function based on 27 and 90°, the equivalent procedure of using Eq. (6) has been tried. The rounded value 30° was adopted for T_1 with $T_2 = 90$°K. The same A thermometer was used as before. The maximum error found in the interval, 30 to 90, was 0.010° The average over all thermometers of their maximum errors was 0.003°. Thus, on the average, the use of 30 rather than 20° reduced the maximum errors by the factor 0.6. However, on the assumption of a parabolic error function, the maxima should have been reduced by the factor $(90 - 30)^2/(90 - 20)^2 = 0.7$ due to the shortening of the span. Thus the reduction actually achieved over and above this was unexpectedly not very striking.

A more substantial improvement resulted from

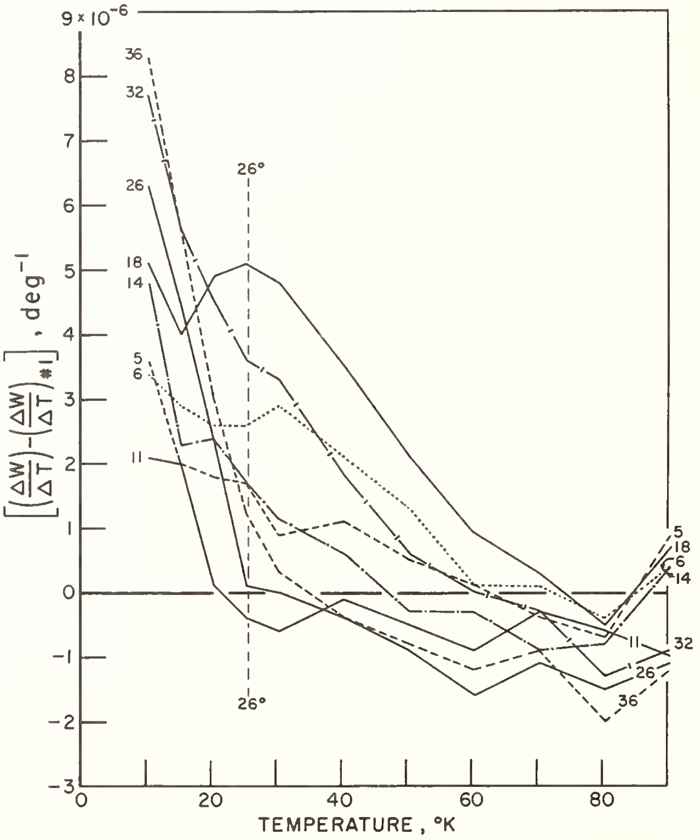


Fig. 7. Differences between $\Delta W/\Delta T$ for representative thermometers and the one with lowest $W_{20.263}$ (calculated for temperature intervals of 1°).

applying Eq. (10) with $T_1 = 30$, $T_2 = 90$, $T_3 = 273.15$°K. The maximum error in the interval 30 to 90° could be held to 0.004°, and the average of the maximum errors was 0.0013°.

Also, the combination 20, 30, and 90°K may be compared with 20, 50, and 90°K. The former was, indeed, found to be substantially better. With it, the largest error in the interval 20 to 90° was 0.003°, and the average of the maximum errors of all thermometers was 0.0012°. Errors of representative thermometers using 20, 30, and 90°K as calibration points are shown in Fig. 8.

Finally, the use of two calibration points between 20 and 90° may be considered. It was found that two overlapping fits obtained using Eq. (10) with 20, 30, and 50° and 30, 50, and 90°K, respectively, permitted fitting all the thermometers from 20 to 90°K within 0.002°. The average of the maximum errors in this interval was less than 0.001°.

Application of Eq. (10) to Temperatures above 90 or below 20°K

The region above 90° is conventionally represented by means of the Callendar-Van Dusen equation. Calibration at four temperatures is required in order to evaluate the constants of this equation. Equation (10) may be useful as a substitute over limited ranges of temperature inasmuch as it requires only three calibration points. In order to provide an illustration, it was tested using $T_1 = 90$, $T_2 = 200$, $T_3 = 273.15$°K and the same A-B pair as in Figs. 5 and 6. The maximum error found in the interval 90 to 273.15°K was 0.0006°. It seems probable that interpolation within about a millidegree could have been accomplished using any three well-spaced calibration temperatures between 90 and 373°K.

Because of the rapid decrease in dR/dT with decrease in temperature, the platinum resistance thermometer is at a disadvantage below 20°K relative to semiconductors. Nevertheless, it is sometimes useful in this region, and so it is of some interest to see if the present method has any utility there. Applying Eq. (10) with $T_1 = 14$, $T_2 = 20$, and $T_3 = 90$°K and some of the same A-B pairs as before, it was found possible to fit all of the thermometers within about 0.005° in the interval 14 to 20°K. The temperature 14°K is approximately the triple point of hydrogen. The errors increased rapidly below 14°K and approached 0.1° at 10°K for some thermometers. As might be expected, the combination 10, 20, and 90°K was considerably less satisfactory. Errors between 10 and 20°K exceeded 0.02°.

Summary

Table 1 summarizes the results described in this section. The same A thermometer was used in both applications of Eq. (6) in order that valid

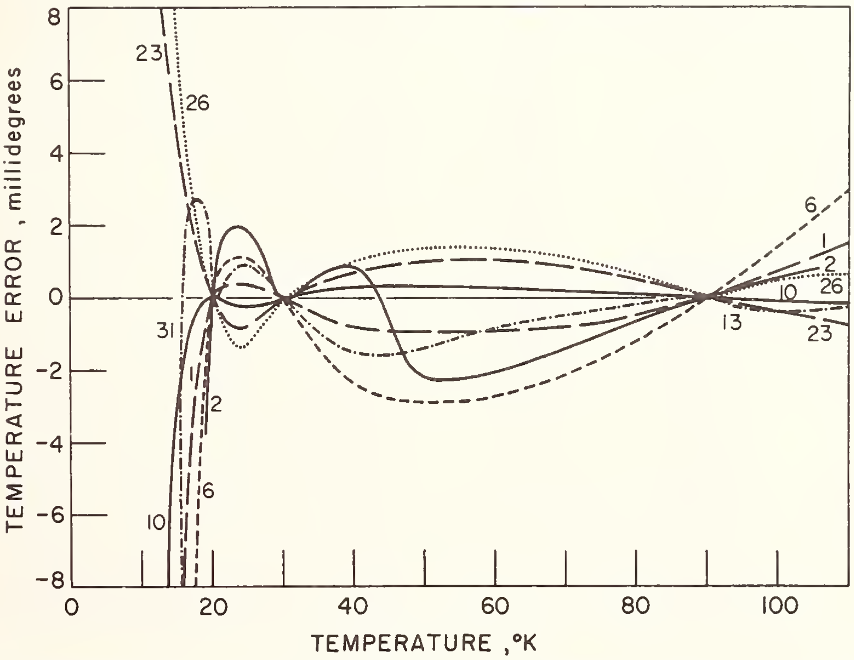


FIG. 8. Temperature errors for some representative thermometers using Eq. (10) with $T_1 = 20$, $T_2 = 90$, $T_3 = 30$°K. The reference thermometers A and B are those represented in Table 2.

comparisons might be drawn. The two A-B pairs listed in applications of Eq. (10) gave nearly the same results in all cases. These reference thermometers were not necessarily the best ones that might have been adopted for the purpose of minimizing errors.

Table 1. Summary of interpolation errors

Equation used	T_1	T_2	T_3	Interval examined	Max. error in interval	Average of max. errors	Reference thermometers[a]
	°K	°K	°K	°K	deg	deg	#
6	20	90		20 to 90	0.016	0.005	20
10	20	90	273.15	20 to 90	.006	.003	11, 29
				90 to 273.15	.009	.002	11, 20
10	20	90	50	20 to 90	.005	.002	11, 29
6	30	90		30 to 90	.010	.003	20
10	30	90	273.15	20 to 30	.024	.007	
				30 to 90	.004	.0013	11, 20
				90 to 273.15	.009	.002	
10	20	90	30	20 to 30	.003	.0012	11, 20
				30 to 90	.003	.0012	
10	20	50	30	20 to 30	.002	.0008	11, 29
				30 to 50	.002	.0003	
10	30	90	50	20 to 30	.015	.005	
				30 to 50	.002	.0002	11, 20
				50 to 90	.001	.0002	
10	14	20	90	14 to 20	.005	.003	11, 29
10	10	20	90	10 to 20	.023	.009	11, 20
10	90	200	273.15	90 to 273.15	.0006		11, 29

[a] The thermometers were numbered from 1 to 35 in order of increasing $W_{20.263}$.

Table 2. Resistance-temperature relations of suggested reference thermometers

T	R	
	#11	#29
°K(NBS 1955)	ohms	ohms
10	0.01967	0.02403
12	.02609	.03062
14	.03659	.04121
16	.05277	.05751
18	.07620	.08107
20	.10839	.11336
20.263	.11335	.11832
22	.15067	.15569
24	.20411	.20916
26	.26943	.27448
28	.34704	.35204
30	.43706	.44199
35	.71553	.72018
40	1.06394	1.06816
50	1.92266	1.92557
60	2.92113	2.92238
70	3.99156	3.99089
80	5.08986	5.08715
90	6.19913	6.19426
90.18	6.21909	6.21418
273.15	25.51191	25.46641
α	.003926352	.00392470
δ	1.49146	1.4927
β	.11026	.1110

CONCLUSIONS AND I.T.S. PROPOSAL

The present interpolation method was devised primarily for American users of platinum resistance thermometers with the hope of establishing a technique which could serve as an alternative to direct NBS calibration. It is concluded that the method is feasible for this purpose because of the wide use in this country of the particular type of thermometer studied in this paper and the reproducibility of that product. This type of thermometer has already been adopted for cooperative use by American workers in calorimetry.[7] The interpolation accuracy to be expected when applying the present method to this type of thermometer will be clear from Table 1.

The present method may also provide a means for extending the ITS below 90.18°K. A necessary condition would be agreement upon the temperatures to be assigned to necessary fixed points not presently defined in the ITS, such as the boiling point of hydrogen. It is uncertain to what extent the method will apply to thermometers that lack the uniformity of those studied here. In order to facilitate evaluation of the method by others, a set of selected values of R_A and R_B is given in Table 2, using two of the thermometers that were found to provide good results in all of the calculations based on Eq. (10).

It is tentatively proposed that the ITS should be extended from 90.18 to 20°K using Eq. (10) and taking the normal boiling points of equilibrium hydrogen and oxygen and the triple point of water as the three calibration temperatures. It is proposed further that the ITS thermometers for this region should be limited to those for which $\alpha > 0.003924$ and $W_{20.263} < 0.00470$. An equivalent statement of the limitation on α is $W_{90.18} < 0.2442$. It would also be necessary to adopt tabular reference functions like those in Table 2, but corrected to the absolute thermodynamic scale insofar as present knowledge would permit.

Of the various possibilities suggested in Table 1, the one selected for this proposal is the simplest, which provides interpolation accuracy comparable to or better than the best gas thermometry. The implied limitation on purity should not be a hardship, inasmuch as platinum with α of 0.003926 is available from several sources throughout the world. As was suggested in the preliminary study,[1] the limitation on α apparently cannot be relaxed very much without losing the improvement in accuracy over that achievable with Eq. (6).

Should the accuracy in Table 1 corresponding to this proposal be thought insufficient so that another calibration point must be introduced, it is recommended that this additional point should be at about 30°K, or, specifically, that Eq. (10) should be used with the normal boiling points of equilibrium hydrogen and oxygen and a point near 30°K as the three calibration temperatures. This recommendation is consistent with the Australian proposal[6] for use of a point at 27°, but it makes use of this point in a way that provides a better fit than does the use of an unmodified Z function. The further refinement of using four points, such as 20, ~30, ~50, and 90°K, does not seem to be justified. (The NBS calibration procedure uses 16 points in the range 10 to 90°K. In the light of the results of this study, this seems to be two to three times as many points as are necessary in order to obtain millidegree accuracy.)

It has been proposed that extension of the ITS below 90° should be accompanied by revisions above 90° because of evidence that the Callendar-van Dusen equation fails to correspond closely to the absolute thermodynamic scale.[6] Whenever the relation between the present ITS and the absolute thermodynmic scale can be established in this region with sufficient certainty, Eq. (10) could probably assume the present function of the Callendar-van Dusen equation, using as calibration temperatures, 90.18 and 273.15°K, and a third point which could be either near 200°K or 373°K.

If, as seems likely, the ITS is extended below 20° by means of the germanium resistance thermometer, there will be no need to refine the interpolation techniques below 20°K for platinum. Nevertheless, it may sometimes be helpful to recognize means of using platinum as low as 14°K, as for example in third-law calorimetry of organic substances. As shown in Table 1, an additional calibration point at 14°K will give interpolation accuracy better than 0.01° from 14 to 20°K.

Acknowledgment

Mr. Hans M. Roder programmed these calculations for automatic computer. His help is gratefully acknowledged.

APPENDIX

Kohler's Formula

Kohler has shown[8] from general considerations that deviations from Matthiessen's rule must be positive and has derived an approximate deviation term containing the product of the residual and lattice resistivities, thus, $pq\rho_0\rho_i/(p\rho_0 + q\rho_i)$. The appropriate expression for the reduced resistance W, which takes this term into account, has been given by Schultz.[9] This was applied to a few of the present thermometers. The residual resistances were estimated where experimental values were lacking by using an empirical correlation of van der Leeden.[10, 11] The reduced ideal resistance was estimated from the resistance of the thermometer having lowest residual resistance on the assumption that for it, the Kohler term was zero. The constants in Kohler's term for the other thermometers were then evaluated by fitting at 20 and 90°K. The results obtained in this preliminary test were not satisfactory, since the errors sometimes exceeded 0.01°. Some improvement may be possible by adjusting the values of reduced ideal resistance.

Van der Leeden's Formula

Van der Leeden[10] has modified Matthiessen's rule by multiplying the residual resistance by an empirical function which depends on temperature only, being the same for all platinums. Van Dijk has extended this treatment and has tabulated the above function and the reduced ideal resistance.[11] However, the formula requires that differences in W among various thermometers should be proportional to the above empirical function, whereas one finds appreciable differences in the form of ΔW, even among thermometers from the present group with closely similar constants. The formula is useful as an approximate representation and requires a knowledge of only the reduced residual resistance of the thermometer. However, it did not fit the present resistance data closely enough for precise thermometry.

Size Effect

It is of some interest to examine if size effects are appreciable in thermometer wires. Let us adopt the approximate relation[12] for electron mean free path L,

$$\rho_\infty L \approx 10^{-11} \text{ ohm cm}^2 \qquad (14)$$

JOURNAL OF RESEARCH of the National Bureau of Standards—A. Physics and Chemistry
Vol. 70A. No. 3, May-June 1966

Calibration of Germanium Resistors at Low Temperatures (2–20° Kelvin)

G. Cataland and H. H. Plumb

Institute for Basic Standards, National Bureau of Standards, Washington, D.C.

(February 11, 1966)

Two germanium resistors, C and D, have been referenced to values of temperature determined by the NBS acoustical thermometer. The resistance-temperature calibration data for these resistors have been fitted to a function of the form $\log_{10} R=\sum_{n=0}^{m} A_n(\log_{10} T)^n$ and the results are presented. The resistors C and D that are used as secondary standards maintain the scale, NBS Provisional Scale 2−20 (1965), to which public calibrations of germanium thermometers are referenced.

The calibration apparatus and measurement techniques that are employed in calibrating submitted resistors are described in detail. Additionally, data of three typical calibrations and their treatment by polynomial fitting are included to demonstrate the characteristics of some commercially available germanium resistors.

Key Words: Calibration, germanium resistors, low temperatures, secondary thermometers, thermometry.

1. Introduction

Recently at the National Bureau of Standards a provisional temperature scale in the region of 2 to 20 °K was established, based on temperature values derived with the Acoustical Thermometer [1, 2],[1] a primary thermometer. The temperature scale is presently maintained with six germanium resistance thermometers. Their calibration is in close agreement [2] with other secondary thermometers in regions where temperature calibrations overlap, i.e., 2 to 5 °K, the T_{58} He^4 Vapor Pressure Scale [3] and 12 to 20 °K, NBS (1955) Scale [4].[2]

In practice, temperature sensing devices should be independent of thermal history and have a measurable temperature coefficient which covers a prescribed temperature range as a smooth function of some parameter. Some materials, i.e., carbon, [5, 6, 7, 8], metals, [9, 10, 11], and piezoelectrics [12] meet these requirements but are limited in the cryogenic temperature range 2 to 20 °K because of insensitivity, instability, or nonreproducibility. Some of the pure metals become superconducting, i.e., indium [13] and lead at temperatures of 3.4 and 7.2 °K, respectively. Impurity doped germanium semiconductors [14, 15, 16, 17, 18, 19] exhibit a temperature-dependence of electrical resistance such that they are readily adaptable to the needs of precise low temperature thermometers. By controlling the impurity doping of germanium, thermometers can be produced to cover temperatures within various ranges of interest, i.e., 1 to 20 °K, 20 to 50 °K, etc. Within the useful range of these thermometers two conduction processes are involved [20]; at temperatures below 10 °K, impurity conduction is the dominant mechanism, while free hole conduction limits the resistivity at the higher temperatures. To cover the region 2 to 20 °K, a point-by-point calibration is necessary because of the complicated conduction processes; at the present time an accurate simple analytical representation of resistance versus temperature for germanium resistors does not exist.

We will discuss the NBS Provisional Scale 2–20 (1965) and a "Germanium Thermometer Calibrator" which is employed in calibrating germanium thermometers against it.

2. NBS Provisional Temperature Scale 2–20 (1965)

The temperature scale, against which calibrations are performed, is called NBS P 2–20 (1965) and is based upon values of absolute temperature that have been determined with the NBS Acoustical Thermometer. This instrument and its operation have recently been described [2] but a more detailed description (including tabular data that defines the isotherms) will appear in the near future.[3]

During the operation of the acoustical thermometer it was essential that secondary thermometers (in this

---

[1] Figures in brackets indicate the literature references at the end of this paper.

[2] The present NBS temperature scale in this region, 12 °K and above is maintained with platinum resistors, designated NBS (1955), and defined to be 0.01 deg lower than the scale given in reference [4].

[3] To be published in a future issue of Metrologia.

instance, germanium resistors that were in intimate thermal contact with the acoustical thermometer were used) be employed to indicate the constancy of maintaining an isotherm temperature,[4] as well as to retain a calibration of the acoustically determined isotherm temperature. This is accomplished by periodically monitoring the resistance values of the germanium resistors while the acoustical thermometer is in operation. Two particular germanium resistors, which we can label A and B, have always served this function and thus they have been calibrated by the acoustical thermometer. Additionally, two other germanium resistors have been mounted in the apparatus and have been used as additional monitoring resistors in the acoustical thermometer. We shall name two such resistors C and D. While C and D have been used for monitoring the acoustical thermometer for certain specific isotherms, they give reference to all of the isotherms through calibrations against resistors A and B.

Quite naturally the calibrations of C and D against A and B did not always take place at exactly the original acoustically-determined isotherm temperatures and thus a knowledge of $\frac{dR}{dT}$ (for resistors A and B) was required for properly assigning temperatures to C and D. Because the calibration temperatures of C and D were never more than 0.035 °K from the acoustically determined isotherms, the required interpolations and knowledge of $\frac{dR}{dT}$ (for A and B) did not critically affect the calibration of resistors C and D $\left(\frac{dR}{dT}\right.$ values could be established with sufficient accuracy for this interpolation from the calibrations of A and B$\left.\right)$. In fact the temperature of only six calibration points for resistor C differed more than 0.020 °K from the original acoustically defined isotherm-temperatures; for D, one was 0.016 °K and the remainder less than 0.012 °K. The resistors C and D were never in the acoustical thermometer together so their calibrations were performed independently with regard to time and environmental location within the acoustical thermometer apparatus.

At this point it is necessary to note that previous to their calibration some laboratory history of resistors C and D had been accumulated; this has been reported in an earlier article [21]. The resistors were repetitively, thermally cycled between room temperature and 4.2 °K, with systematic resistance-temperature calibrations performed at a temperature close to 4.2 °K. A "constant temperature" liquid helium bath contained the resistors during the 4.2 °K portion of the cycle and thus, by measurements of the liquid helium vapor pressure, a very reproducible temperature reference (to the T_{58} scale) was obtained. Resistor C had been thermally cycled 88 times and demonstrated a reproducibility of the 4.2 °K calibration within 0.0011 °K; resistor D underwent 86 cycles and demonstrated a constancy within 0.0005 °K. The estimated error from various measurements in the cycling process was equivalent to 0.0004 °K. Appropriate attention has always been applied to the measuring currents through the resistors to avoid undesired, appreciable Joule heating.

After being calibrated with reference to the acoustical thermometer, the resistors C and D were placed within the calibrator, which will be described in this article, and measurements of their resistances were conducted at temperatures which closely approximated the original isotherm temperatures. More specifically, the temperature of the apparatus was controlled until the resistance measurement of one resistor, for example, C, indicated that approximation to an original acoustical isotherm temperature had been achieved. Next, at this temperature a value was obtained for the resistance of D. Thus there was afforded a comparison of indicated temperatures between C and D within the calibrator since, to repeat, each resistor had been previously independently calibrated with reference to the acoustical thermometer. Temperature discrepancies between C and D (after appropriate small interpolations had been made), from comparison measurements within the calibrator, never exceeded 0.003 °K. Consequently our assignment of temperature values to future calibrations in the calibrator against C and D is slightly arbitrary. The maximum temperature discrepancy of 0.003 °K between resistors C and D, as obtained during the calibrator use, probably indicates that the combined errors of electrical measurements and temperature controlling correspond to about ±0.002 °K.

Thus temperatures have been associated with resistors C and D for their use as secondary standards in the calibrator. This information is presented in columns 1 and 2 of tables 1 and 2. We were desirous of possessing more information about the resistors' calibrations and consequently have performed a computer analysis of the data. A polynomial of the form

$$\log_{10} R = \sum_{n=0}^{m} A_n (\log_{10} T)^n$$

was fitted to the R_{data} and T_{data} calibration data of each resistor by the method of least squares. A double precision computer program prepared by the Statistical Engineering Laboratory was used to overcome the roundoff error characteristic of fitting high order polynomials, and in this case the roundoff error was several orders of magnitude smaller than other experimental uncertainties. All data were given equal weight and m, the degree of the polynomial, was varied from 3 to 8. The eighth order polynomial produced a fit to the input data such that no datum point deviated from the polynomial by more than 0.0045 °K. The reduction in the sum of squares of deviations due to the addition of terms of higher order was statistically significant (0.05-probability level) in all cases up to and including the 8th degree. We have not extended the analysis since we feel that fit-

---

[4] An isotherm as determined by the acoustical thermometer consists of the speed of sound in helium gas as a function of the gas pressure.

ting the data within 0.004 °K is a reasonable limit. It is noteworthy to mention that as the lower temperature data points are excluded, comparable fitting is possible with fewer terms in the polynomial.

After obtaining values of the 9 coefficients we effected a computer generation of temperature, resistance, $\frac{dR}{dT}$, $\frac{d^2R}{dT^2}$, and $\frac{1}{R}\frac{dR}{dT}$ at intervals of 0.010 °K. Using the generated $\frac{dR}{dT}$, simple interpolations have been made to obtain values of generated resistance, R_{gen}, which correspond to the input temperatures, T_{data}. These resistances, R_{gen}, are listed in column 3 of tables 1 and 2. Column 4 shows the difference between the input and generated resistance: by again employing the generated $\frac{dR}{dT}$ of column 5 we obtain the temperature difference (ΔT of column 6) which corresponds to the resistance differences of column 4. It is readily apparent from column 6 of tables 1 and 2 that the temperature-resistance data for resistors C and D can be represented by an eighth order polynomial within 0.005 °K.

TABLE 1. *Resistor C*

T_{data}[a]	R_{data}[a]	R_{gen}[b]	$R_{\text{data}}-R_{\text{gen}}$ ΔR	dR/dT[c] (Ohms/0.001 °K)	ΔT[d] (0.001 °K)
°K	*Ohms*	*Ohms*	*Ohms*		
2.321	11,481.	11,481.4	−0.4	−13.5	0.0
2.805	7,058.7	7,056.7	2.0	−6.12	−.3
3.207	5,122.5	5,125.0	−2.5	−3.71	.7
4.206	2,800.9	2,798.9	2.0	−1.43	−1.4
5.020	1,916.0	1,917.8	−1.8	−0.817	2.2
6.060	1,272.9	1,271.8	1.1	−.471	−2.3
6.977	918.51	919.16	−0.65	−.312	2.1
8.066	645.32	645.29	.03	−.200	−1.5
8.989	489.99	489.93	.06	−.140	−0.4
9.889	382.65	382.53	.12	−.101	−1.2
10.901	296.86	296.82	.04	−.070	−0.6
12.018	230.85	230.97	−.12	−.049	2.4
12.962	190.74	190.82	−.08	−.037	2.2
14.036	157.05	157.01	.04	−.027	−1.5
14.993	134.26	134.24	.02	−.021	−1.0
16.050	114.77	144.76	.01	−.016	−0.6
16.970	101.36	101.32	.04	−.013	−3.1
18.004	89.051	89.100	−.049	−.011	4.5
18.940	79.997	80.006	−.009	−.0088	1.0
20.054	71.084				

[a] T_{data} and R_{data} refer to calibration quantities, temperature and resistance.
[b] R_{gen} is the resistance, at the temperature T_{data}, obtained by generating resistance as a function of temperature from the evaluated polynomial coefficients A_n.
[c] $\frac{dR}{dT}$ is generated from the evaluated coefficients A_n.
[d] ΔT is obtained by dividing $(R_{\text{data}}-R_{\text{gen}})$ by $\frac{dR}{dT}$.

TABLE 2. *Resistor D*

T_{data}[a]	R_{data}[a]	R_{gen}[b]	$R_{\text{data}}-R_{\text{gen}}$ ΔR	dR/dT[c] (Ohms/0.001 °K)	ΔT[d] (0.001 °K)
°K	*Ohms*	*Ohms*	*Ohms*		
2.321	10,847.	10,848.	−1.0	−12.8	0.1
2.805	6,656.1	6,653.2	2.9	−5.8	−0.5
3.207	4,820.3	4,824.2	−3.9	−3.5	1.1
4.206	2,630.3	2,627.0	3.3	−1.4	−2.4
5.020	1,792.5	1,795.1	−2.6	−0.77	3.4
6.060	1,186.3	1,185.2	1.1	−.44	−2.5
6.977	852.60	853.10	−0.50	−.29	1.7
8.066	596.36	596.29	.07	−.19	−0.4
8.989	451.44	451.34	.10	−.13	−.8
9.889	351.63	351.60	.03	−.093	−.3
10.901	272.27	272.32	−.05	−.065	.8
12.018	211.53	211.55	−.02	−.045	.4
12.962	174.68	174.77	−.09	−.034	2.6
14.036	143.80	143.78	.02	−.025	−0.8
14.993	122.98	122.98	.0	−.019	−.0
16.050	105.21	105.20	.01	−.015	−.7
16.970	92.96	92.94	.02	−.012	−1.7
18.004	81.743	81.785	−.042	−.0097	4.3
18.940	73.469	73.494	−.025	−.0080	3.1
20.054	65.351	65.341	.010	−.0066	−1.5

[a] T_{data} and R_{data} refer to calibration quantities, temperature and resistance.
[b] R_{gen} is the resistance, at the temperature T_{data}, obtained by generating resistance as a function of temperature from the evaluated polynomial coefficients A_n.
[c] $\frac{dR}{dT}$ is generated from the evaluated coefficients A_n.
[d] ΔT is obtained by dividing $(R_{\text{data}}-R_{\text{gen}})$ by $\frac{dR}{dT}$.

Additional information is obtained concerning the polynomial and therefore, the resistors also, since (for each resistor) the generated $\frac{d^2R}{dT^2}$ does not change its sign; the fitted polynomial function is monotonically smooth. Consequently one is reasonably confident that the fitted polynomials can be used for interpolating between original calibration points. Figures 1 and 2 depict the variation of R versus T, and $\frac{1}{R}\frac{dR}{dT}$ versus T, respectively, for both resistors, C and D.

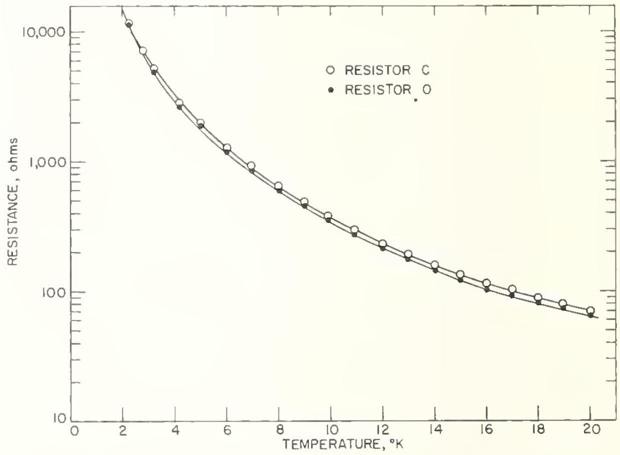


FIGURE 1. *A plot of resistance as a function of temperature:* ○, *Resistor C;* ● *Resistor D.*

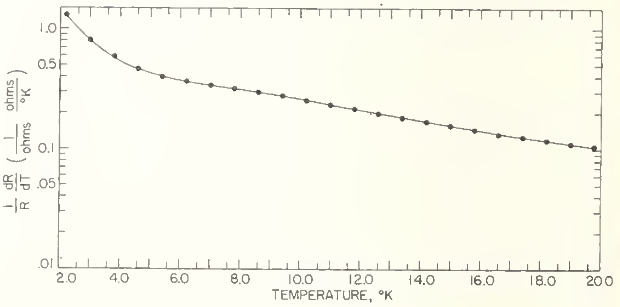


FIGURE 2. *Resistance-temperature sensitivity,* $\frac{1}{R}\frac{dR}{dT}\left(\frac{1}{°K}\right)$, *as a function of temperature (°K).*

The plot is applicable to both C and D since their temperature sensitivities do not differ more than one percent.

While resistors C and D are the basis for present calibrations from 2 to 20 °K at the National Bureau of Standards, several other resistors exist that have been similarly treated; additionally, resistors A and B are still intact within the acoustical thermometer. Resistor D, prior to its mounting in the acoustical thermometer, had been calibrated at the National Bureau of Standards against the NBS (1955) scale below 20 °K. It was one of the two thermometers that afforded a comparison, (which has been reported previously [1, 2]) between values of acoustically determined temperatures and the NBS (1955) scale.

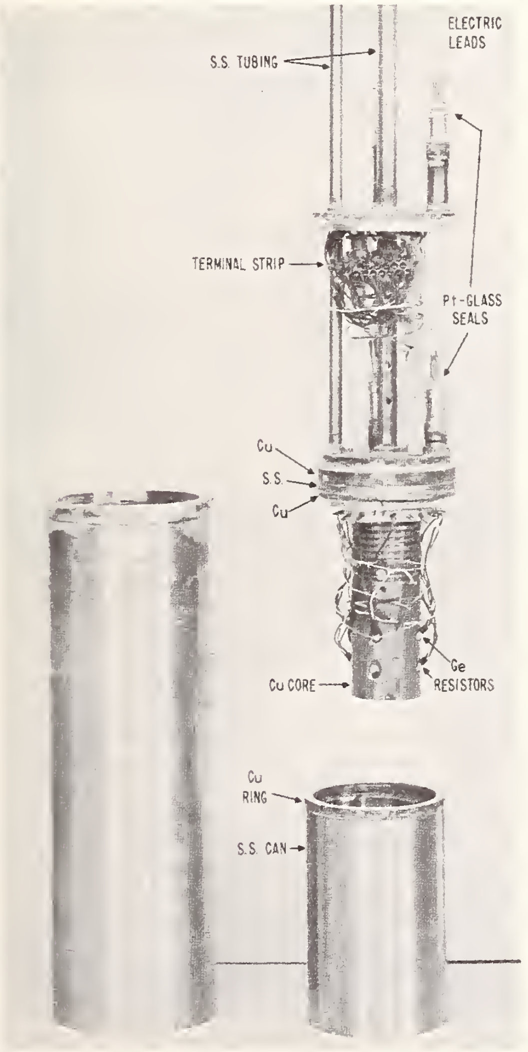


FIGURE 3. *Closeup photograph of the calibrator that is used in the temperature calibration of germanium resistors.*

3. Calibrator[5]

3.1. General Design Considerations of Calibrator

Central to apparatus which we have constructed is a solid copper cylinder. It is required, during the course of calibration measurements, that the copper mass and its contained resistors be maintained at accurately controllable temperatures at approximately every degree from 2 to 20 °K. To achieve this temperature regulation the system must be quasi-thermally isolated from its surroundings. The copper mass and imbedded thermometers are shown in figure 3. In operation (the smaller can having been soldered in place) the copper mass and small can are included in the large can. If a vacuum is maintained within the larger can, then the small can and its contents are partially isolated, thermally, from the environment that contains the large can.

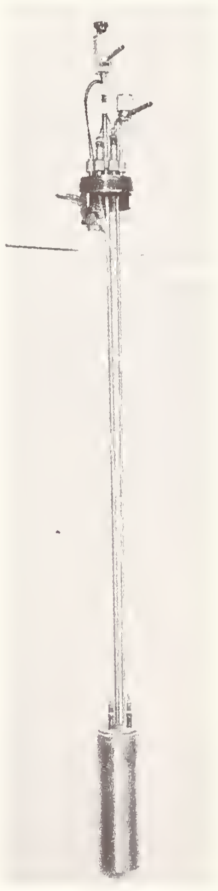


FIGURE 4. *Assembled calibrator.*

---

[5] Certain commercial materials and equipment are identified in this section in order to adequately specify the experimental procedure. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the material or equipment identified is necessarily the best available for the purpose.

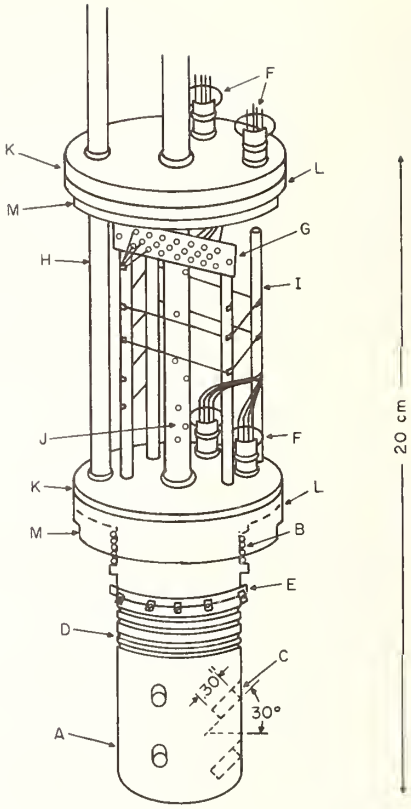
Within the vacuum enclosure heat transfer by gas conduction and convection is essentially eliminated, and the small can will reduce radiant heat flow between the thermometers and the outer vacuum can. There remains, however, a thermal connection between the inner assembly and the outer can via electrical leads and mechanically supporting members, i.e., the two stainless steel tubes. The inner assembly is thermally floated at temperatures that exceed the environmental temperature of the outer can, with a resultant temperature gradient along the electrical lead wires and stainless steel tubes.

A more complete view of the calibrator is depicted in figure 4. Uppermost is the Dewar cap, which affords ingress of electrical leads and the stainless steel tubings. Because the lower portion is in a liquid helium bath during calibrations any heat from ambient temperatures that is conducted downward along the leads and tubings is dissipated in the refrigerant. Thus it is evident that under steady state conditions, the interesting heat flow occurs from the inner assembly toward the top of the outer vacuum can. The dimensions of the supporting tubes and electrical leads have been selected so that accurate temperature control of the copper core and resistors is attained through a reasonable expenditure of electrical heating to the copper core.

3.2. Main Copper Core

The main core (A) of the isothermal system in figure 5 was constructed of 58.93 mm (diameter) copper rod. Cavities 3.58 mm (diameter) drilled at 60° angles to its axis serve as receptacles for the germanium thermometers. Also machined in the core was a spool-like section (B) upon which the heater coil was wound. Directly above the coil form is the cap (K) for the inner chamber. Silver soldered to the cap's perimeter is a stainless steel tubing sleeve (L) 0.30 mm thick, 12.70 mm long. Soldered on the lower end of the tubing is a copper ring (M) with a tongued edge to receive the groove of the small vacuum can of figure 3. In the cap (K) two 9.53 mm holes were drilled for the platinum glass seals, a 6.35 mm hole for an evacuation tube (H), a 9.53 mm opening for the supporting tubing (J), and four screw threads were tapped for the nylon rods (I). On the copper core below the coil form a spiral groove (D), 1.27 mm deep, three threads per cm, was routed from the core's perimeter to serve as a channel for thermally anchoring the lead-in wires that return upwards to the terminal ring (E).

The terminal ring was fabricated from Teflon tubing and contains terminal lugs made of 0.76 mm platinum wire. The wire has been flattened on one extremity and cut to extend 9.53 mm beyond the Teflon ring. Holes 0.50 mm were drilled at the end of the platinum lugs to secure the thermometer electrical leads prior to their soldering. Two set screws attached the ring to the copper core.



A	Cu Core
B	HEATER COIL
C	CAVITIES FOR THERMOMETERS
D	.05" DIA. GROOVES FOR WIRES
E	ANNULAR TERMINAL STRIP
F	PLATINUM GLASS SEALS
G	TERMINAL STRIP
H	PUMPING LINE (INNER CAN)
I	NYLON
J	OUTER CAN PUMPING LINE
K	Cu CAPS OF CANS
L	STAINLESS STEEL RING
M	Cu RING

FIGURE 5. *Detailed drawing of the calibrator low-temperature components.*

3.3. Vacuum Chambers

For thermal isolation the above components were encased within a vacuum tight cannister. The vacuum can was constructed of stainless steel tubing 58.93 mm diam, 114.30 mm long and 0.30 mm thick with one capped end of 0.50 mm thickness. A copper ring was silver soldered to the open end of the can; the ring was grooved to receive the tongued edge (M) of the can top.

The outer can top was also made of copper and holes, similar to those of the inner can, were drilled for the insertion of seals and evacuation lines. There also, a stainless steel sleeve that terminates in a tongued copper ring was soldered to the cap's circumference. The reason for using the stainless steel sleeves in both vacuum systems may not be obvious. In assembling the apparatus, heating is required to solder the vacuum cans to the flanges (M). If the heat were sufficiently great, electrical lead insulation might be damaged in regions where the insulation is in contact with copper (the spiral groove (D) and the vacuum can tops). Additionally, heating of the large copper core would elevate the temperature of the germanium thermometers to such an extent that they might be damaged. Precautions have been taken to avoid such heating. (a) Wood's metal solder is used for assembly because its melting point is relatively low. (b) The stainless steel paths (L) provide a sufficiently large thermal resistance that the solder joints can be made with only a slightly perceptible temperature rise in the vacuum can tops and the copper mass (A). A similar design has been employed in mounting the platinum glass seals (F) to simplify their replacement.

3.4. Electrical Seals and Wiring

Glass-metal type electrical lead-in seals were used exclusively in the construction of the isothermal calibrating system. For ambient conditions, Kovar-glass type capillary-tubing seals were utilized. At temperatures where components are immersed in cryogenic liquids, our experience has shown the necessity for using platinum-glass type seals. The NBS glass shop made the 9-capillary platinum-glass seals[6] that were incorporated in the system.

At ambient temperatures where electrical leads entered the Dewar system, eighteen #38 AWG double nylon, enamel coated copper wires were fed through and soldered to individual capillaries of two 9-capillary Kovar-glass seals that were located on the Dewar cap. The wires continued from the ambient seals, were strung through and soldered to individual capillaries of two platinum-glass seals (F) of the outer can, and terminated at the 20-pin rectangular terminal strip (G).

From the terminal strip, 1.54 m lengths of Evanohm wire were spiraled around the notched nylon supporting rods (I) in six windings and the remaining lengths of wire were passed through and soldered at the individual capillaries of the two platinum-glass seals that are mounted on the top of the inner vacuum can. The remaining lengths of wire within the inner can region were then snugly wound into the spiral groove (D) of the main copper core (A) and terminated at the nylon ring (E). The strands of Evanohm wire were wound around the nylon rods to lengthen the thermal resistance path along the lead wires, in effect, to reduce the temperature gradient along the electrical leads, since the temperature difference between the isothermal system and its heat sink (cryogenic bath) can differ by as much as 18° during a calibration run. The enamel coated Evanohm lead wires were placed in physical contact with the copper core to enhance thermal equilibrium between resistance thermometers, electrical leads and the environment within the calibrating unit. Evanohm wire was used because its resistance-temperature coefficient is quite low.[7] The heater coil was noninductively wound on spool (B) of figure 5, with 61.5 m of the above wire. The wire diameter is 0.10 mm and the wire has a resistance of 1.65 Ω/cm.

4. Germanium Thermometers

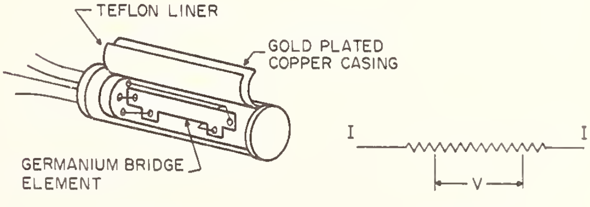
4.1. General Description

The bridge-shaped encapsulated germanium thermometer, shown in figure 6 with current contacts external to the potential contacts, has advantages not found in some other types. The germanium element is mounted in a relatively strain-free manner within its encapsulation to reduce piezoresistance [20, 22] that is exhibited by germanium at low temperatures. Effects of contact resistances and possible thermal strains in the contacts are relatively unimportant because measurements are made potentiometrically and temporal changes in contacts do not necessarily change the thermometer calibration [20]. Encapsulation of the thermometer element in helium exchange gas aids the germanium element in achieving thermal equilibrium with its metallic capsule.

4.2. Mounting of Thermometers

Leads of the germanium thermometers are soldered with Wood's metal to the platinum lugs of the nylon terminal ring (E) using a low-powered soldering iron to minimize overheating of the germanium element through heat conduction. A very dilute solution of Baker's Flux (aqueous solution of the chlorides of Zn and NH_4) is used and upon completion of the soldering, the terminal junctions are flushed with a swab and hot water to remove traces of flux.

The casings of the thermometers are placed within the copper cavities. A primary consideration in the calibrator design is the attainment of thermal equilibrium between the resistors (the sensor, secondary standards, and those to be calibrated). Since the resistors are generally encapsulated, one must be concerned with the thermal equilibrium between each resistor and its encapsulation, as well as between all



CUTAWAY VIEW SCHEMATIC

FIGURE 6. *Schematic portrayal of a typical germanium resistor encapsulation.*

---

[6] The seals were thermally cycled from ambient to liquid helium temperatures at least three times and leak tested on a mass spectrometer type helium leak detector prior to their use in the calibrator.

[7] At 20 and 273 °K, its resistivity is 132.5 and 133.3 $\mu\Omega$ cm, respectively [23].

encapsulations. After the germanium thermometers are wired into the circuit and continuity and shorting checks made, the inner-most vacuum can is soldered into place with Wood's metal, using a modified soldering gun that possesses an annular copper heater element for uniform heating. Then the outer vacuum can is soldered into place using a gas-air torch of fine orifice. Both vacuum systems are leak detected, and again checks are made to assure circuit continuity and adequate electrical insulation between the d-c electrical circuits and "ground." Insulation resistances of 10 MΩ – the limit of a portable Wheatstone bridge – are commonly measured.

5. Temperature Measurements and Control

5.1. Refrigerant Reservoir

For temperature-calibration measurements 5 to 20 °K or above, the helium bath into which the calibrator is immersed, is vented to atmospheric pressures. The bath at this temperature provides an adequate heat sink for dissipating the energy emitted from the calibrator. For temperature measurements 2 to 5 °K, the bath pressure is reduced to achieve a bath temperature of 1.8 °K or less. A requirement for temperature stability within the calibrator is that there should be a current flow to the heater coil at all times, and experience has shown that the minimum power output of the heater should be 6.25 μW (25 μA through the 10,000 Ω heater coil), otherwise the required stability and reproducibility of temperatures is not possible.

5.2. Temperature Control

Temperature control is attained through the use of bridge and amplifier circuits and a three-action control unit with recorder. The temperature sensor (one leg of a Wheatstone bridge) is a germanium resistor that has been repeatedly cycled from ambient to liquid helium temperatures to determine its stability and reproducibility. The unbalance of the bridge circuit is detected and fed into a servo-control unit, which possesses the controlling actions of proportional band, rate time and reset – the servo-unit's controlled current output is fed directly to the calibrator's heater coil. Current to the Wheatstone bridge circuit is supplied by a voltage divider circuit to permit a variation of current through the germanium sensor. This variable control is essential since, for sensitive temperature control the apparatus, the same currents cannot be applied at all temperatures. Because of the low specific heats and extremely high values of sensor resistance at low temperatures, too large a sensor current can cause: (a) excessive Joule heating of the sensor; and (b) a dissipation of heat (from the sensor into the calibrator) that is large compared with the heat output of the controlling heater coil. At the high calibration temperatures larger sensor currents are required, than at low temperatures, to obtain sufficient sensor sensitivity. In general, the temperature is controlled by the above method to about 0.0001 °K.

5.3. Resistance Measurements

Potential and current measurements are made on a double-bank six-dial potentiometer equipped with an external reversing switch. The advantage of the double-bank unit is that it relieves the necessity of repositioning dials when transferring from potential to current measurements. One bank of the potentiometer is used for measuring current. An external standard resistor is connected in series with the resistors to be calibrated and thus, from a measurement of the potential across the standard resistor $\left(I=\frac{E}{R}\right)$, a value is obtained for the current through the total external circuit. The external reversing switch permits reversal of currents within the potentiometer and the external circuit, which includes the germanium thermometers. The measuring circuit is shown in figure 7. With this arrangement the thermal emf's may be detected and their effect on the measurements eliminated.

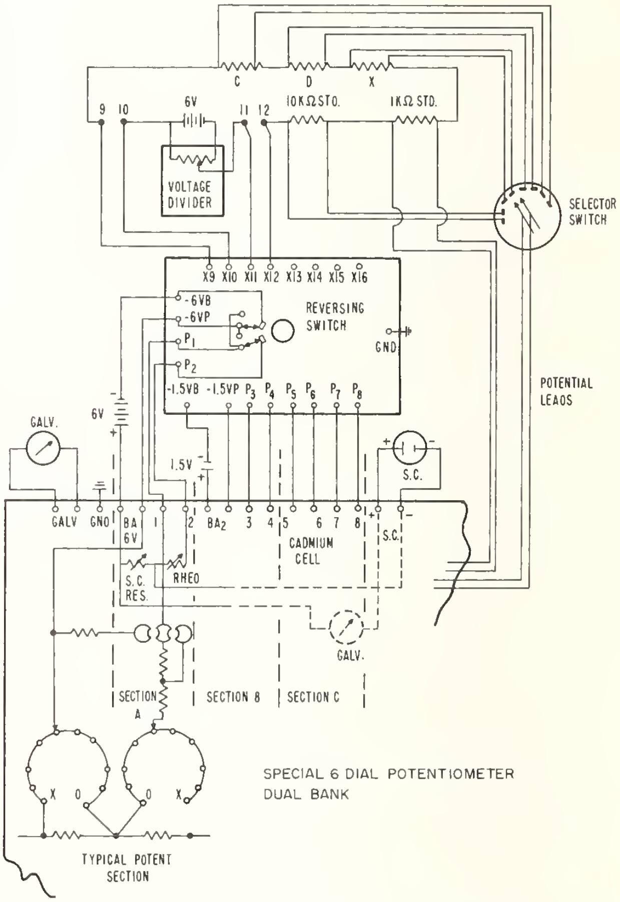


FIGURE 7. *Schematic of the d-c resistance measurement circuit.*
This potentiometer actually consists of 3 potentiometer units in series (A, B, and C). Two sets of switches are connected to each decade to provide the "dual bank" feature.

5.4. Calibration Techniques

For many germanium thermometers, the resistor is a four-lead element, as shown in figure 6; two leads are for the current source and two for potential measurements. In the calibrator the current leads of the uncalibrated resistors are connected in series with the current leads of the calibrated thermometers to the current source at the terminal ring (E) of figure 5. The potential leads are wired individually to the platinum lugs which have electrical lead lines communicating to the potentiometer. The calibrated thermometers C and D are controlling parameters for determining the point-by-point resistance-temperature relation of the uncalibrated thermometers. Since an approximate temperature-resistance calibration of the sensor resistor is available, we are able to dial (for each calibration point) a particular value for this resistance on the Wheatstone bridge and then make final adjustments after comparing the two calibrated thermometer resistance-measurements with their previous values, i.e., temperature-resistance relation from the acoustical thermometer measurements. After the temperature constancy of the desired calibration point is clearly demonstrated, several series of potential measurements are made to determine the resistance of both the calibrated reference standards (C and D) and the submitted unknowns.

The complete calibration of submitted resistors is performed twice, covering the range 2 to 20 °K; in general, the temperature of a calibration point (column 1 of tables 3 through 5) must be within a few millidegrees of the calibration temperatures associated with resistors C and D (column 1 of tables 1 and 2); the differences of indicated temperatures between the standards C and D cannot exceed ±0.001 °K; and, if possible, the two separate calibrations of the submitted resistors should be consistent within ±0.002 °K.

TABLE 3. *Resistor X*

T_{data} [a]	R_{data} [a]	R_{gen} [b]	$R_{data}-R_{gen}$ ΔR	dR/dT [c] (Ohms/0.001 °K)	ΔT [d] (0.001 °K)
°*K*	*Ohms*	*Ohms*	*Ohms*		
2.321	12,473.	12,473.6	−1.0	−15.0	.1
2.805	7,584.2	7,580.8	3.4	−6.74	−0.5
3.207	5,458.2	5,462.6	−4.4	−4.5	1.1
4.206	2,944.3	2,940.5	3.8	−1.54	−2.5
5.020	1,991.5	1,994.6	−3.1	−0.87	3.5
6.060	1,307.5	1,306.0	1.5	−.50	−3.0
6.977	932.73	933.39	−0.66	−.33	2.0
8.065	647.37	647.17	.20	−.21	−1.0
8.989	486.30	486.32	−.02	−.14	.1
9.889	376.44	376.40	.04	−.103	−.4
10.905	289.37	289.26	.11	−.071	−1.6
12.018	223.35	223.44	−.09	−.049	1.8
12.963	183.57	183.64	−.07	−.036	1.9
14.036	150.42	150.41	.01	−.026	−0.4
14.994	128.21	128.18	.03	−.020	−1.5
16.050	109.35	109.33	.02	−.016	−1.3
16.970	96.422	96.376	.046	−.013	−3.5
18.004	84.619	84.657	−.038	−.010	3.8
18.938	75.967	75.981	−.014	−.0085	1.7
20.048	67.490				

[a] T_{data} and R_{data} refer to calibration quantities, temperature and resistance.
[b] R_{gen} is the resistance, at the temperature T_{data}, obtained by generating resistance as a function of temperature from the evaluated polynomial coefficients A_n.
[c] $\frac{dR}{dT}$ is generated from the evaluated coefficients A_n.
[d] ΔT is obtained by dividing $(R_{data}-R_{gen})$ by $\frac{dR}{dT}$.

TABLE 4. *Resistor Y*

T_{data} [a]	R_{data} [a]	R_{gen} [b]	$R_{data}-R_{gen}$ ΔR	dR/dT [c] (Ohms/0.001 °K)	ΔT [d] (0.001 °K)
°*K*	*Ohms*	*Ohms*	*Ohms*		
2.322	71,352.	71,441.	−89.0	−180.	0.5
2.807	22,038.	21,946.	92.0	−50.	−1.8
3.208	9,273.	9,311.3	−38.	−18.2	2.1
4.208	1,921.0	1,919.5	1.5	−2.4	−0.6
5.019	826.04	828.27	−2.23	−0.71	3.1
6.060	400.48	398.17	2.31	−.23	−10.0
6.976	253.51	253.44	0.07	−.107	−0.7
8.066	169.44	169.70	−.26	−.054	4.8
8.990	129.30	129.70	−.40	−.034	11.8
9.887	103.81	103.98	−.17	−.024	7.0
10.901	83.627	83.623	.004	−.017	−0.2
12.017	67.719	67.607	.112	−.012	−9.3
12.962	57.492	57.388	.104	−.0096	−10.8
14.048	48.274	48.201	.073	−.0075	−9.7
14.993	41.852	41.820	.0321	−.0061	−5.2
16.051	35.977	35.996	−.019	−.0050	3.8
16.969	31.781	31.816	−.035	−.0042	8.3
18.006	27.805	27.859	−.054	−.0035	15.4
18.940	24.820	24.852	−.032	−.0030	10.7
20.049	21.880	21.831	.049	−.0025	−19.6

[a] T_{data} and R_{data} refer to calibration quantities, temperature and resistance.
[b] R_{gen} is the resistance, at the temperature T_{data}, obtained by generating resistance as a function of temperature from the evaluated polynomial coefficients A_n.
[c] $\frac{dR}{dT}$ is generated from the evaluated coefficients A_n.
[d] ΔT is obtained by dividing $(R_{data}-R_{gen})$ by $\frac{dR}{dT}$.

TABLE 5. *Resistor Z*

T_{data} [a]	R_{data} [a]	R_{gen} [b]	$R_{data}-R_{gen}$ ΔR	dR/dT [c] (Ohms/0.001 °K)	ΔT [d] (0.001 °K)
°*K*	*Ohms*	*Ohms*	*Ohms*		
2.319	1,918.8	1,918.9	−0.1	−1.45	0.07
2.806	1,404.7	1,404.5	.2	−0.76	−.3
3.208	1,156.3	1,156.6	−.3	−.50	.6
4.203	829.83	829.54	.29	−.21	−1.4
5.018	695.22	695.42	−.20	−.13	1.5
6.059	596.69	596.58	.11	−.071	−1.5
6.977	543.81	543.93	−.12	−.046	2.6
8.068	504.17	504.17	.00	−.029	0.0
8.988	482.13	482.07	.06	−.020	−3.0
9.889	466.52	466.45	.07	−.015	−4.7
10.901	452.99	452.97	.02	−.012	−1.7
12.018	440.23	440.30	−.07	−.011	6.4
12.962	429.69	429.78	−.09	−.011	8.2
14.048	416.56	416.59	−.03	−.013	2.3
14.993	403.63	403.60	.03	−.015	−2.0
16.049	387.11	387.05	.06	−.017	−3.5
16.970	370.98	370.89	.09	−.018	−5.0
18.004	351.02	351.08	−.06	−.020	3.0
18.940	331.84	331.96	−.12	−.021	5.7
20.048	308.51	308.45	.06	−.021	−2.9

[a] T_{data} and R_{data} refer to calibration quantities, temperature and resistance.
[b] R_{gen} is the resistance, at the temperature T_{data}, obtained by generating resistance as a function of temperature from the evaluated polynomial coefficients A_n.
[c] $\frac{dR}{dT}$ is generated from the evaluated coefficients A_n.
[d] ΔT is obtained by dividing $(R_{data}-R_{gen})$ by $\frac{dR}{dT}$.

Periodically during calibrations, when the extent of Joule heating in a submitted resistor is not known, power tests are performed. This is to insure that the resistor current is sufficiently low that Joule heating effects are well below 1 mdeg.

Certain features of the calibration apparatus merit mentioning. A high vacuum is maintained within the inner can; the resistors are mounted (within the copper core) in a stopcock grease medium; the region of the copper core, which contains the spiralled leads, has been covered with a suitable varnish to enhance thermal equilibrium between the core and leads; the heater coil has been varnished onto its containing form; and the current leads from each resistor are thermally anchored to the copper core. These features aid in promoting thermal equilibrium (between the germanium resistors) to such an extent that a thermal gradient has not been detected—even though the heater has been operated at powers that have varied by an order of magnitude. (The power variance occurs, during measurements at a constant temperature, as the vacuum in the outer can [figure 3] is allowed to change.)

6. Results and Conclusions

The calibration data for three resistors that have been calibrated against resistor C and D are presented in figure 8 and in columns 1 and 2 of tables 3, 4, and 5. The resistors are from three different commercial sources and may, perhaps, be considered typical of available resistors. The resistors are labeled as X, Y, and Z and their calibration data have been treated on the computer in a manner paralleling that previously described in this paper for resistors C and D. We have attempted to fit the data for each resistor to a polynomial of the form

$$\log_{10} R = \sum_{n=0}^{m} A_n (\log_{10} T)^n$$

Resistors X and Z appeared to be reasonably represented by an eighth order polynomial; for Y, the significance of the polynomial coefficients became doubtful for the seventh and eighth orders. Generations for X, Y, and Z, based upon 9, 7, and 9 coefficients, respectively, were performed to obtain the quantities

$$R, \frac{dR}{dT}, \frac{d^2R}{dT^2} \text{ and } \frac{1}{R}\frac{dR}{dT}$$

as a function of temperature. Since the columns of tables 3, 4, and 5 correspond to those of tables 1 and 2, columns 6 indicate how well the calibrations of resistors X, Y, and Z are represented by the fitted polynomials. For these resistors also, elimination of the data at the lowest temperature will generally result in a more accurate functional fit at lower polynomial orders.

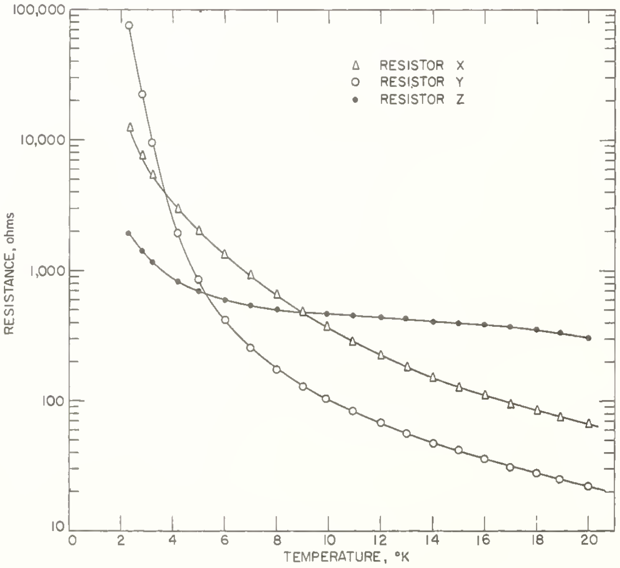


Figure 8. *Plot of resistance as a function of temperature: △, resistor X; ○, resistor Y; and ●, resistor Z.*

It is to be noted, for resistor Z in figure 8 that the $R-T$ relationship is not characterized by a monotonically decreasing derivative $\frac{dR}{dT}$. Indeed the generation of the second derivative $\frac{d^2R}{dT^2}$ clearly exhibits a change in sign between 12.060 and 12.070 °K, and also between 20.480 and 20.490 °K. (The change in sign is not significant at the higher temperatures, since 20.480 °K exceeds the range of the calibration data.) Such a condition indicates that caution must be exercised in attempting to use our functional relationship for interpolating temperatures and resistances that are intermediate to the calibration points of resistor Z. Perhaps a better approach for interpolation would result from functionally fitting selected segments of the calibration data.

To repeat, columns 6 of tables 3, 4, and 5 demonstrate that the functional representations for resistors X and Z are more accurate than is indicated for resistor Y. While this can possibly be partially attributed to Y's low values of $\frac{dR}{dT}$ at the highest temperatures, one must note that the polynomial fit for resistor Y covers a much larger range of resistance than is the case for resistors X and Z. However, it is probably more significant to note that Y is basically a two lead resistor while X and Z involve four lead contacts. As has been described earlier in this paper, the electrical measurements of resistance are made by a direct-current, potentiometric technique. In the case of resistors X and Z, current connections to the germanium crystal are distinctly separate from the potential

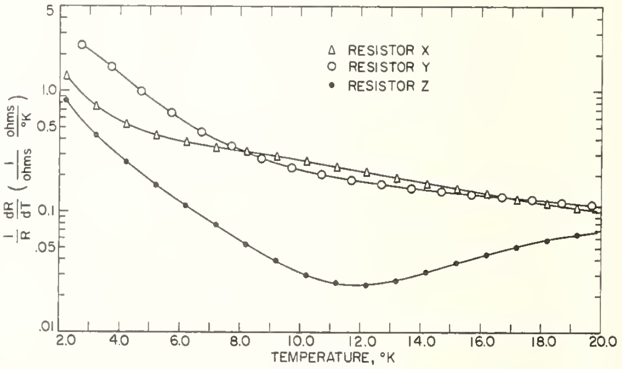


Figure 9. *Resistance-temperature sensitivity,* $\frac{1}{R}\frac{dR}{dT}\left(\frac{1}{°K}\right)$, *as a function of temperature (°K): △, resistor X; ○, resistor Y; and ●, resistor Z.*

leads. For resistor Y, a current and potential lead are connected to each of the two leads that lead to the germanium resistor. It is possible that lead or contact resistances introduce additional uncertainties in the determination of Y's resistance.

Figure 9 indicates resistor sensitivities. The sensitivity is the fractional change of resistance per °K as a function of the absolute temperature. Quite obviously, depending upon the user's requirements, selection of a particular type of resistor is important since the sensitivities, $\frac{1}{R}\frac{dR}{dT}$, as well as the absolute magnitude of resistance, R, are variable—depending upon the concentration of impurities that have been added to the germanium.

Calibration certificates for submitted resistors are issued for calibrations at approximately the temperatures indicated in column 1 of table 1 or table 2; it is expected that these values of temperature are reproduced within ± 0.002 °K; and the measuring current at each temperature is specified. For the user's information we attempt to fit the calibration data with a polynomial and include the results as part of the calibration service.

7. References

[1] H. H. Plumb and G. Cataland, J. Res. NBS **69A** (Phys. and Chem.) No. 4,375 (1965); Technical News Release, May 1965–Str–3198.

[2] H. H. Plumb and G. Cataland, Science **150,** 3693 (1965) p. 155.

[3] F. G. Brickwedde, H. van Dijk, M. Durieux, J. R. Clement, and J. K. Logan, The 1958 He^4 Scale of Temperature, J. Res. NBS **64A** (Phys. and Chem) No. 1, 1 (1960).

[4] H. J. Hoge and F. G. Brickwedde, The Establishment of a Temperature Scale for the Calibration of Thermometers between 14° and 83 °K, J. Res. NBS **22,** 351 (1939) RP1188.

[5] J. R. Clement and E. H. Quinnell, Rev. Sci. Instr. **23,** 213 (1952).

[6] A. Brown, M. W. Zemansky and H. A. Boorse, Phys. Rev. **84,** 1050 (1951).

[7] M. H. Edlow and H. H. Plumb, Temperature, Its Measurement and Control in Science and Industry (Reinhold, New York 1963), Vol. **3,** C. M. Herzfeld ed., Part 1, F. G. Brickwedde ed., p. 407.

[8] P. Lindenfeld, Rev. Sci. Instr. **32,** 1 (1961).

[9] T. M. Dauphinee and H. Preston-Thomas, Rev. Sci. Instr. **25,** 9 (1954).

[10] H. van Dijk, Comité International des Poids et Mesures, Comité Consultatif de Thermométrie, 6^e Session-1962, Annexe 25, p. 151.

[11] R. J. Corruccini, Advances in Cryogenic Engineering, Vol. **8,** p. 315 (Plenum Press, New York, 1963).

[12] T. M. Flynn, H. Hinnah, and D. E. Newell, Advances in Cryogenic Engineering, Vol. **8,** p. 334 (Plenum Press, New York, 1963).

[13] G. K. White and S. B. Woods, Rev. Sci. Instr. **28,** 8 (1957).

[14] I. Estermann, Phys. Rev. **78,** 83 (1950).

[15] S. A. Friedberg, Phys. Rev. **82,** 764 (1951); S. A. Friedberg, Temperature, Its Measurement and Control in Science and Industry (Reinhold, New York, 1955) Vol. 2, H. C. Wolfe, ed., p. 359.

[16] T. H. Geballe, F. J. Morin, and J. P. Marta, Conférence de Physique des Basses Températures, Paris (1955) p. 87.

[17] J. E. Kunzler, T. H. Geballe, and G. W. Hill, Rev. Sci. Instr. **28,** 96 (1957).

[18] J. S. Blakemore, Rev. Sci. Instr. **33,** 106 (1962).

[19] F. J. Low, Advances in Cryogenic Engineering, Vol. **7,** p. 514 (Plenum Press, New York, 1962).

[20] J. S. Blakemore, J. W. Schultz, and J. G. Myers, Rev. Sci. Instr. **33,** 545 (1962).

[21] M. H. Edlow and H. H. Plumb. (Being edited at NBS).

[22] H. Fritzsche, Phys. Rev. **119,** 1899 (1960).

[23] R. B. Scott, Cryogenic Engineering, p. 337 (D. van Nostrand Co., Inc., Princeton, New Jersey, 1959).

(Paper 70A3–400)

JOURNAL OF RESEARCH of the National Bureau of Standards—C. Engineering and Instrumentation
Vol. 70C, No. 4, October–December 1966

Reproducibility of Germanium Resistance Thermometers at 4.2 °K

M. H. Edlow[1] and H. H. Plumb

Institute for Basic Standards, National Bureau of Standards, Washington, D.C., 20234

(June 13, 1966)

NBS has needed a set of very reproducible germanium resistors that would be capable of maintaining temperature scales. This paper describes our procedure for selecting such a set.

A group of germanium resistors from three commercial sources have been thermally cycled between 4.2 °K and room temperature. The resistance-temperature calibrations at 4.2 °K were made with reference to a liquid helium bath so that reproducible temperatures could be determined from liquid helium vapor pressure measurements. Seven resistors out of 25 demonstrated reproducibilities (of the 4.2 °K calibration) of about 0.001 °K after undergoing the multiple cyclings. Guided by these results, we procured twelve, new, similar resistors which were cycled in a comparable procedure. After 85 cycles, in which 14 resistance-temperature calibrations were performed at 4.2 °K for each resistor, 10 of the 12 resistors demonstrated reproducibilities of approximately 0.001 °K.

The resulting set of secondary thermometers have undergone calibrations in the temperature ranges, 2 to 5 °K and 2 to 20 °K; reports of this work will be published in the near future.

Key Words: Germanium resistors, germanium resistor reproducibility, low temperature thermometry, reproducibility of germanium resistors, thermal cycling at low temperature, thermometry.

1. Introduction

A major problem in low temperature work has been the lack of a highly reproducible, precisely calibrated secondary thermometer in the region of 1 to 20 °K. Carbon composition resistors found wide popularity after Clement et al. [1],[2] had reported their reproducibilities and calibrations in the temperature regions of liquid helium and liquid hydrogen. However, carbon composition resistors show limited reproducibilities after cycling from room temperatures to 4.2 °K [2,3], and exhibit an aging effect when maintained in a highly stabilized liquid helium bath for several weeks [4].

Encouraging results for resistance thermometry in the liquid helium and liquid hydrogen temperature ranges were reported by Estermann [5] for doped germanium and silicon; by Friedberg [6] for polycrystalline *p*-type germanium; and by the Bell Telephone Laboratories group [7, 8] using arsenic-doped germanium that was encapsulated in platinum cans. A very limited number of the B.T.L. specimens were distributed by the Calorimetry Conference to several laboratories for evaluation. Results from the several laboratories [9] indicated, in general, reproducibilities of 0.001 °K. Since that time, the properties of impurity doped germanium resistors have been reported by several commercial sources [10,11,12]. This paper is concerned with the determination of calibration reproducibilities of commercial specimens[3] at or near the normal boiling point of liquid helium. The objective of the work was to obtain a group of 10 or 12 similar resistors that exhibited reproducibilities of 1 mdeg or better. This group of resistors will serve as secondary thermometer standards for maintaining temperature scales below 20 °K. Subsequent papers will cover their precise resistance-temperature relationships in the region 2 to 5 °K and 2 to 20 °K.

2. Experimental Apparatus

Our determinations of resistance are based upon d-c potentiometric measurements and the attendant techniques—four leads to a resistor are required for the measurement. A dual-six-dial potentiometer is used in conjunction with a special reversing switch that affords a reversal of current in all circuits—internal potentiometer and external resistors (fig. 1)—to compensate for undesired thermal e.m.f.'s. The null detector, a millimicrovoltmeter, has a useful range of source resistance from 1 to 100,000 Ω with the capability of detecting changes as small as one part in sixty thousand for measured resistances of 3,000 Ω. The germanium resistors are connected in series with 1,000 and 10,000 Ω standard resistors [13] to the exter-

---

[1] M. H. Edlow is presently associated with the United States Patent Office.

[2] Figures in brackets indicate the literature references at the end of this paper.

[3] At the time that the resistors were procured these were, to the best of our knowledge, the only products of American manufacture available.

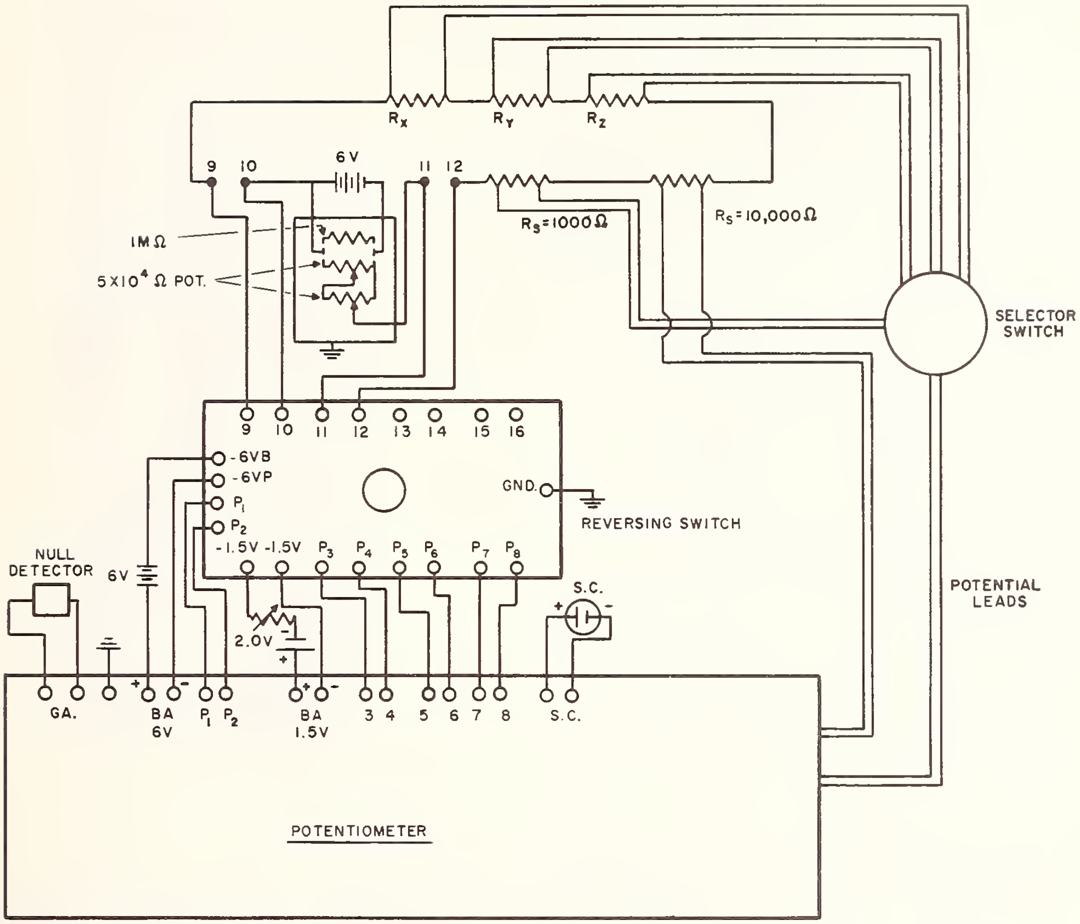


FIGURE 1. *D-c electrical circuit for measuring germanium resistors.*

R_s are standard resistors; R_x, R_y, and R_z, the resistors to be calibrated.

nal reversing switch; currents through this circuit are determined from potentials measured across the standard resistors. Measuring currents of the order 1 to 2 μA, are obtained by using two 50,000 Ω voltage dividers connected in parallel across the battery. A double-throw, double-pole toggle switch connects the current supply to either the germanium resistor circuit or a 1 MΩ "bleeder" resistor: the bleeder resistor allows the battery to deliver a small, continuous current when not in use with the germanium resistors. A two-volt, low discharge battery (series connected to a resistance decade box) supplies current to the middle internal potentiometer circuit while six-volt, low discharge batteries supply current for both the external series circuit containing the germanium resistors and the upper internal potentiometer circuit. The batteries are surrounded by thermal insulation to minimize temperature changes of the electrolyte that would produce variations in the discharge voltage. Current standardizations need only be performed a few times per day, although more frequent standardization checks were routinely performed.

The potentiometer, external reversing switch, batteries, null detector and standard resistors are supported on acrylic plates, which in turn rest on copper sheets that are interconnected by copper wires. A lead from one of the sheets is connected to a surrounding screen cage which is at earth potential. The double-wall, copper-screen cage completely encloses the d-c measuring apparatus and eliminates a-c joule heating that is caused by signals which emanate from nearby commercial transmitters [14].

The germanium resistors are immersed in a constant-temperature liquid helium bath contained in a 25-liter metal storage Dewar [15]. A vacuum tight Dewar cap has been designed to fit over the Dewar neck J (fig. 2) and permits routine thermal cycling of the resistors. A, B, C, and D are "quick couplings" and are hard soldered to the top E; E and a threaded brass cylinder G (internal component of quick coupling H) are soft soldered into the copper body F. The vapor from the helium bath passes through a side arm M that is connected to a 2.8 cm vapor-pressure pump-line.

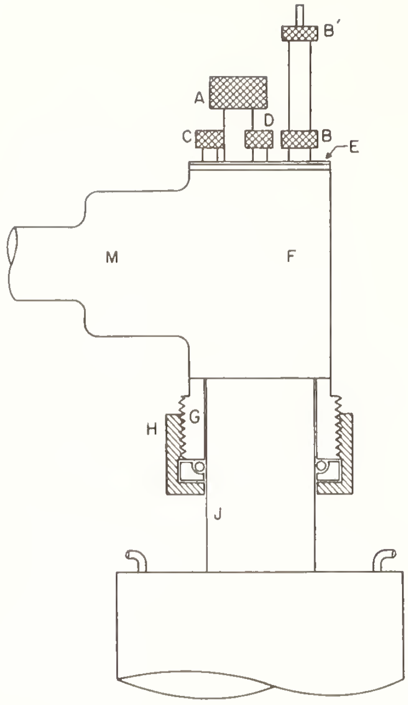


Figure 2. *Dewar cap.*

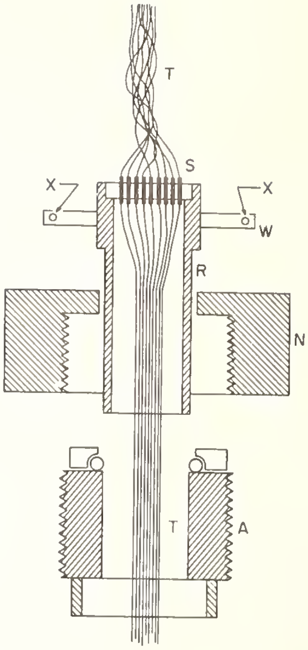


Figure 3. *Dewar cap component that is moved during thermal cycling procedure.*

A stainless steel tube that passes through coupling C leads to a jacketed vapor pressure thermometer [16] that is positioned 0.3 cm from the bottom of the Dewar. A surface vapor pressure tube passes through coupling D and extends from about 10 cm above the coupling to about 8 cm below the neck of the Dewar. Both vapor pressure tubes consist of stainless steel, thin-wall (0.015 cm) tubing of 0.65 cm diam. A rubber line, when necessary, connects an external helium cylinder to the surface tube and permits helium gas to be bled into the Dewar. The gas flows out of coupling A during resistor thermal cycling and prevents frozen air from accumulating on the inside surface of the Dewar neck. The coupling B contains a 0.25 cm quick coupling B′ that is closed by a metal rod; it will contain a He^3 vapor pressure thermometer in future work.

The component of the cap that is displaced during thermal cycling of the resistors is shown in figure 3. A hollow copper cylinder R, 1.9 cm o.d., slides through the coupling A. A multi-tube Kovar-glass seal at S is set in a small recess machined at the end of the cylinder R. Six pairs of #38 A.W.G. Formvar-coated copper wire, T, are strung through the capillary tubes; and the region of the seal, tubes and leads is covered with wax to achieve a vacuum seal. The copper leads are permanently maintained in a compact bundle within the Dewar by applying a cement to the taut wires. The resistors (positioned at the end of the leads) touch the Dewar bottom. Spun glass spaghetti insulation covers the connections between resistor leads and permanent connecting wires. Thread is tied around the spaghetti-covered leads to achieve a compact bundle which easily passes through the 1.9 cm opening of A during thermal cycling. Copper wire strung through holes X of the arms W and wound tightly around the Dewar handles secures the cylinder R to the cap. The cap is secured to the Dewar handles in a similar manner. These precautions are necessary in the work from 4.2 to 5 °K where the helium vapor pressure is greater than atmospheric, and exerts sufficient force to dislodge the Dewar cap. A complete picture of the storage Dewar and cap is shown in figure 4.

Groups of three resistors are solder-connected to the lower extremities of the wires. (Experience with impurity-doped germanium resistors has shown that it is necessary to minimize the heat conducted to the specimen while soldering resistor leads to connecting wires. We have found that a reproducible calibration at 4.2 °K has been changed by several millidegrees when solder such as 50/50 lead-tin was used; consequently, Wood's metal is used to solder the resistor leads to the connecting wires. A pencil iron is used to supply the minimum heat required to melt the solder.) Each resistor has four leads—two for current and two for potential—that extend from within the Dewar, out through the seal at S (fig. 3) to ambient conditions. The current leads are series connected external to the Dewar so that in event of a

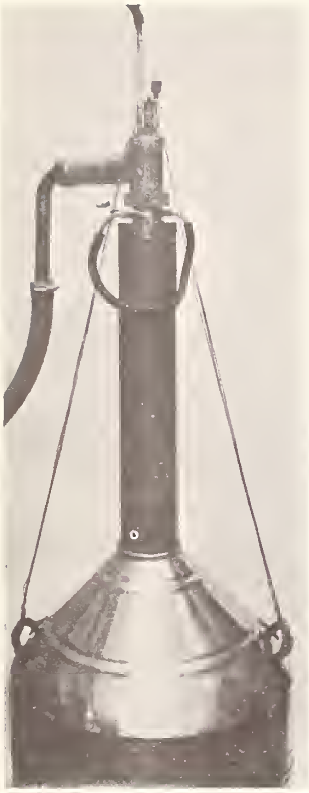


FIGURE 4. *Complete picture of storage Dewar and cap.*

resistor failure the faulty resistor can be quickly disconnected from the current circuit and measurements continued on the other two resistors. The potential leads emerging from the Kovar-glass seal and the 1,000 Ω standard resistor potential leads are appropriately soldered to terminals of a rotary selector switch. The rotary switch is mounted on the lid of a glass jar so that the switch is completely surrounded by a glass wall to provide a degree of thermal insulation from possible spurious temperature fluctuations. The common terminals of the switch are connected to one pair of emf terminals of the potentiometer by #38 A.W.G. double-nylon covered, Formvar-coated copper wire. The potential leads from the 10,000 Ω standard resistor are directly connected to the second pair of emf terminals on the potentiometer.

The manometer for measuring the helium vapor pressure in this work is a digital readout 152.4 cm mercury manometer [4]. Either the vapor pressure thermometer-bulb or the bath surface vapor pressure can be connected to the manometer by means of insulated 0.6 cm copper tubing (A, A′, and G) and the vacuum bellows-type valves C and D (fig. 5). Valve F affords isolation of the manometer while the vacuum pumping line, through valve K, enables one to evacuate any of the components that lead to the manifold E.

The gas filling system consists of a 1-liter storage can, L, and needle valve J through which helium gas can be metered into the system via rubber tubing H and vacuum valve I. Needle valve J′ permits refilling the can from a nearby helium cylinder. The manifold of figure 5, the mercury manometer, manifold evacuating apparatus, and helium bath vacuum "pumping" source are all external to the screened room. Tubing ingress to the room is afforded by portholes that have been built into a wall of the screened room. Our experience has shown that effective shielding by the screened room is destroyed when an undergrounded conductor is brought through the portholes; consequently, the Dewar pumping line has been appropriately grounded to the screened room. The space in porthole B (fig. 5), containing the two vapor pressure lines, is packed tightly with brass filament sponge and no evidence of R. F. signals is detected. The shielding of the screened room is tested at the beginning of every week using a battery operated F.M. receiver.

The well-known phenomenon of an oscillating helium gas column [18] was occasionally detected in the present setup. When this condition occurred in connection with the surface vapor-pressure tube, the liquid helium evaporation rate, as detected by a flow-meter, increased by a factor of 3 and oscillations of the manometer mercury miniscus were readily observed. A sheet of fine copper screening rolled into a tight bundle and inserted in the open end of the surface vapor-pressure tube for a length of 7 to 10 cm eliminated the troublesome oscillations in this instance.

3. Method of Cycling

The following procedure has been found satisfactory (damage to the resistor leads and freezing of the leads or resistor specimens to the Dewar neck have been avoided) for repetitive thermal cyclings of resistors from room temperature to 4.2 °K. Rubber tubing connected a cylinder of helium gas to the surface vapor pressure tube and a slight overpressure of gas was accumulated in the Dewar. The nut N of coupling A (fig. 3) was loosened and the ensemble of cylinder, coupling nut N and portions of the connecting wires were withdrawn from the Dewar cap; the slight gas overpressure caused a stream of helium gas to continually pass through the opening of coupling A and thereby minimized any flow of air into the Dewar. After the resistors were raised to the vicinity of the Dewar cap, several layers of tissue paper (or raw cotton) were wrapped around the leads and positioned in the opening of the coupling A. The helium cylinder was then closed off. The resistors remained for three minutes within the Dewar cap, which is at approximately room temperature, and then were brought out into the room for approx-

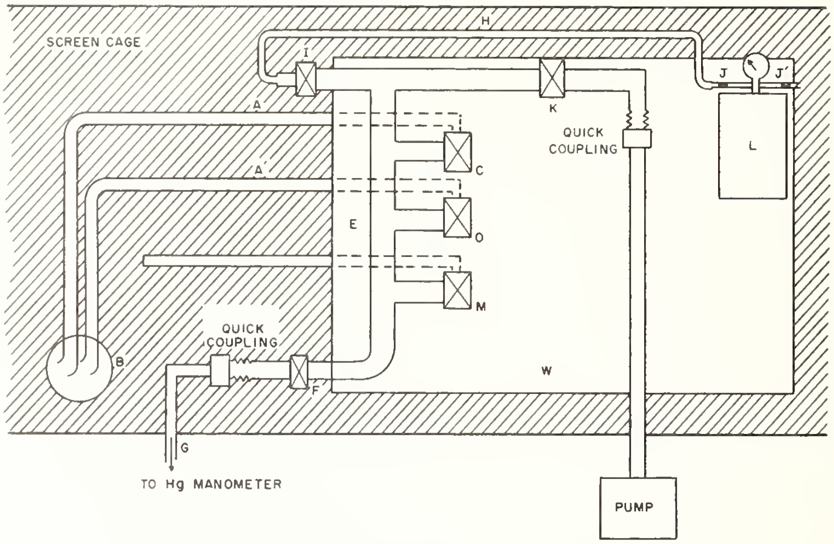


FIGURE 5. *Vapor pressure manifold.*

imately 1 min.[4] (The resistors were not brought immediately out into the room in order to minimize the accumulation of condensed room moisture on the encapsulations. A sufficient quantity of moisture can lead to mechanical stressing of the resistor leads.)

Before the resistors were cycled back into the liquid bath, the helium cylinder valve was again opened to produce a steady stream of gas-flow through coupling A. As soon as the resistors approached the surface of the bath, the helium cylinder valve was closed since the then-increased evaporation rate of the bath was sufficient to maintain a slight overpressure. The entire process of lowering the resistors into the helium bath consumed only a minute and inflicted a thermal shock on the resistors.

The resistances of the specimens were measured soon after they were immersed in the liquid helium; at least 15 seconds were required to make measurements that would yield a value of resistance, which indicated an approximate condition of thermal equilibrium between the resistors and the surrounding liquid helium bath. However, the resistors were allowed to remain in the bath for about one minute prior to another cycle (see footnote 4).

3.1. Determination of a Calibration Temperature

When a well defined calibration point is desired, a meaningful thermal equilibrium must be achieved within the liquid helium bath and between the bath and resistors. The vapor pressure of the bath is placed under control of the pressure regulator [17] and values of vapor pressure (from the vapor pressure thermometer) and resistance are monitored until a steady state condition results. This requires about 45 min and on many occasions we have ascertained that the thermal equilibrium attained in this period of time will not change more than a few tenths of a millidegree over periods of days or weeks.

In practice we do not experience difficulty in associating a temperature (near 4.2 °K) with a resistance value for a reproducible germanium resistor. The surface vapor pressure of the liquid helium bath is easily controlled, using our pressure regulator [17], within 0.05 mm of mercury—this corresponds to 0.00007 °K at 4.2 °K—so the reproduction of a bath surface vapor pressure does not constitute a problem. We have previously reported [16] the existence of a pressure gradient in the vicinity of the liquid helium surface for the type of bath we employ; in the bulk of the liquid helium the temperature is relatively constant. Since the surface gradient is dependent upon the Dewar evaporation rate, and perhaps the Dewar geometry also, it is essential that a helium vapor pressure bulb and the resistors be located within the liquid helium bulk. (From the vapor pressure determination and the "1958 He^4 Scale of Temperature" [19], a temperature can be ascertained.) We have also found that the vapor pressure thermometer tube must be insulated so that it does not make thermal contact with the "colder" liquid helium surface through which the tube must pass. Vacuum-jacketing of the tube along the length that would make contact with the surface provides proper thermal insulation and avoids the effect of a "cold spot" [16, 20]. Radiant energy is prevented from reach-

---

[4] Our experience has always indicated that the germanium resistors, when warming to ambient conditions after a 4.2 °K exposure, require a lapse of only 2 or 3 min before attaining nominal ambient temperature. The reverse operation, cooling to a nominal 4.2 °K from ambient temperatures, is accomplished 10 or 15 sec after immersion of the resistor in liquid helium. Private communications from Mr. Herder (Cryocal) and Mr. Halverson (Radiation Research) reveal, for comparable cooling and heating treatment, very similar experiences.

ing the vapor pressure bulb by a radiation shield that is soldered within the tube and extends from 7.6 cm above the top of the jacket upward for 10.2 cm. When vapor pressure and temperature have been derived from a jacketed vapor pressure thermometer, and when an immersed germanium resistor has been stable, we have been able to associate resistance measurements with temperature to a constancy that is equivalent to 0.0003 °K. However, if temperatures are referenced to surface vapor pressure measurements, the above constancy can decrease to an equivalent of 0.001 °K. The decrease, in part, can be attributed to variations in the liquid helium evaporation rate and the helium level within the Dewar.

Within the bulk liquid helium a steady-state temperature can be routinely reproduced within 0.001 °K. For most of the resistors being reported, the well-defined calibrations have been conducted at temperatures that generally were reproduced within 0.0003 °K (with reference to jacketed vapor pressure thermometer measurements). A few of the resistors were calibrated at reference bath-temperatures which differed by as much as 0.001 °K. We obtained dR/dT at approximately 4.2 °K for the individual resistors by performing an additional calibration of resistance versus temperature (0.050 °K or 0.100 °K removed from the reference temperature for calibration after thermal cycling); this enabled us, through interpolation, to correct all of the nominal 4.2 °K calibrations of a resistor to a particular temperature.

4. Description of the Resistors

The resistors were obtained from three manufacturers who have periodically supplied us with specimens for experimentation [21]. Some of the prototypes have been described [10, 11, 12] but for purposes of adequate comparison we shall briefly describe each. Resistors from one source (Minneapolis-Honeywell) are encapsulated in a platinum can that contains hermetically sealed helium gas. Four thin platinum wires from the resistor are brought through a glass header of the can and soldered to multistrand, plastic covered, copper leads. Mechanical support for the leads is achieved by "potting" an epoxy resin around the soldered platinum wire-copper lead connections. Resistors from a second source (Radiation Research) are also encapsulated in a platinum can which contains hermetically sealed helium gas. These resistors have four 0.025 cm platinum leads that are brought through a glass header for electrical measurements. Resistors from a third source (Texas Instruments) are in a soft, opaque glass envelope and have two 0.025 cm platinum leads for electrical measurements. (Envelopes or encapsulations may be perforated depending upon the user's requirements.) Later specimens have been encapsulated in a metal can with a transistor header. Various manufacturers have used arsenic and gallium as the major doping impurities; both the resistivity and its temperature coefficient are effected by control of the impurity concentrations.

4.1. Thermal Properties

Joule heating, developed when current passes through a resistor, raises the temperature of the specimen to a value higher than that of its surroundings. Since the usefulness of the germanium resistance thermometer depends upon its representation of the correct temperature of the surrounding medium, this effect must be minimized. The results for two typical resistors follow. The resistance variation with current squared for a reproducible, hermetically sealed Minneapolis-Honeywell resistor in a stabilized liquid helium bath at 4.2 °K is shown in figure 6. The abscissa is the square of the current which is approximately proportional to the power being dissipated; at the left, the ordinate is the fractional change of resistance caused by joule heating, while at the right it is the corresponding increase in temperature, ΔT, obtained from the temperature coefficient of resistance. The increase in temperature, ΔT, varies linearly with I^2 up to the value $I^2 \cong 1.3 \times 10^{-9}$ amperes^2 which is in reasonable agreement with Blakemore's result [11]. Tested with the above resistor was a Minneapolis-Honeywell resistor contained in a perforated encapsulation; its fractional change of resistance as well as the corresponding increase in temperature are also plotted as a function of I^2 in figure 6. Comparison of the two plots shows relatively little or no joule heating for the perforated encapsulation, indicating that the helium gas (in hermetically sealed specimens) is a relatively inefficient heat exchanger. A similar plot of $\Delta R/R$, ΔT versus I^2 for a Texas Instruments encapsulated specimen is shown in figure 7. The result indicates ΔT varying linearly through most of the I^2 range but exhibiting a noticeable deviation from linearity at $I^2 \cong 1.6 \times 10^{-9}$.

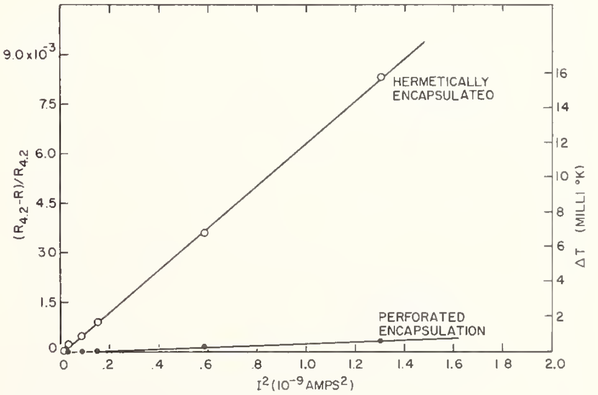


FIGURE 6. *Joule heating for two Minneapolis-Honeywell resistors.* $(R_{4.2}-R)/R_{4.2}$, the fractional change in resistance, and its temperature equivalent, ΔT, are plotted as a function of I^2. The nominal 4.2 °K resistance of the hermetically sealed and perforated encapsulations are 2800 and 4800 Ω, respectively.

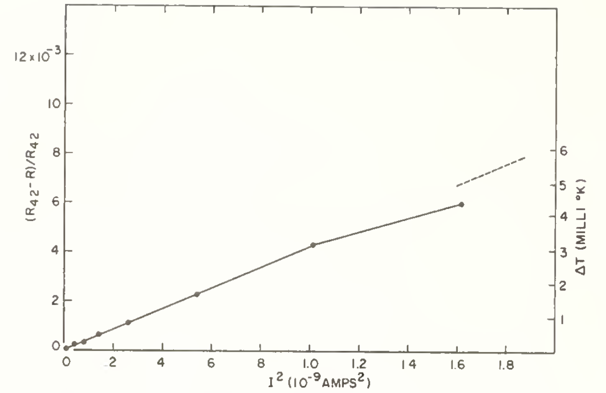


FIGURE 7. *Joule heating for a Texas Instrument resistor.*

$(R_{4.2}-R)/R_{4.2}$, the fractional change in resistance, and its temperature equivalent, ΔT, are plotted as a function of I^2. The nominal 4.2 °K resistance of the hermetically encapsulated resistor is 1800 Ω.

The lowest points of the curve for the encapsulated, hermetically sealed resistors (figs. 6 and 7) show a negligible change of temperature due to joule heating; consequently, a power dissipation of about 0.02 μW was taken as a reasonable maximum for joule heating and used as an upper limit for all subsequent measurements at 4.2 °K. From the linear portion of the curve in figure 6, we can determine the thermal resistance, $Q=dT/d(I^2R)$ (in degrees-per-microwatt), between the resistor element and its surroundings. For the Honeywell resistor $Q=0.0045$ °K/μW; Blakemore obtained, for a similar resistor, $Q=0.0023$ °K/μW [10]. From figure 7 we find for the Texas Instrument resistor $Q=0.0017$ °K/μW while Low obtained a value $Q=0.001$ °K/μW [12].

4.2. Reproducibility of Resistors

If a germanium resistor is thermally cycled *n* times from 300 °K to 4.2 °K and systematic calibrations are made and referenced to a particular temperature, i.e., 4.214 °K, we define the calibration reproducibility of the resistor to mean: the difference, ΔR (ohms), between the maximum and minimum values of resistance that were measured during the calibrations (properly referenced to 4.214 °K) made within the *n* cycles. From knowledge of the resistor's dR/dT at 4.2 °K, the ΔR can be more pertinently expressed in equivalent millidegrees—thus we refer to calibration reproducibilities at 4.2 °K in terms of millidegrees.

The results of thermal cycling between 300 °K and 4.2 °K for 25 resistors are listed in table 1. The resistors were obtained from three commercial sources and we were seeking information that might lead to the selection of a group of similar resistors that could be used as secondary standards in our laboratory. We established the requirement that to be useful for our purposes resistors should have a 4.2 °K calibration reproducibility which was 0.001 °K or better. Resistors which failed mechanically during the thermal cycling have not been included in table 1. Some of the resistors (numbers 19, 22, 23, and 25) failed to meet our calibration reproducibility criterion rather early in the cycling procedure while others failed to perform satisfactorily after a greater number of cycles.[5] In general, accurate 4.2 °K calibrations were performed for the first few cycles, and thereafter every 10 cycles. Seven of the twenty-five resistors were reproducible to 0.0011 °K and have subsequently been used rather extensively in our laboratory. For example, resistors A and B have been incorporated with the acoustical thermometer for several years and will be directly referred to in forthcoming publications.

TABLE 1. *Reproducibility of germanium resistors from three commercial sources under thermal cycling from 4.2 °K to room temperature*

Resistor serial #	Number of cycles	Average R (ohms) 4.2 °K	Reproducibility (milli- °K)
1	61	2829.0	1.3
2	123	2552.5	0.9
3	275	2628.0	.9
4	11	6260.0	.3
A	50	2868.3	1.0
B	40	3086.0	1.1
7	87	3945.4	1.3
8	50	1074.0	1.3
9[a]	51	1764.2	1.5
10[a]	83	2743.0	2.3
11	36	367.75	1.1
12	36	617.74	1.2
13	36	292.75	1.5
14	36	292.50	1.4
15	64	236.84	6.6
16	64	327	5.8
17	40	327	17.4
18	64	675.1	7.[1]
19	8	671.60	4.6
20	30	1890	0.7
21	30	720	9.0
22	14	23100	10.0 (estimated)
23	14	14500	10.0 (estimated)
24	23	1825	2.1
25	8	1940	3.8

[a] Resistor encapsulation was perforated.

An exhaustive, accumulative cycling test was continued for resistor number 3. It was thermally cycled 275 times with equilibrium resistance measurements determined in 43 instances. The results are shown in figure 8. The first series of tests occurred in July 1963 and the resistor was then set aside. On January 7, 1964, the resistor was again connected and the cycling test continued during January–February 1964. The resistance measurements demonstrate a reproducibility of 0.9 mdeg at 4.2 °K.

Figure 9 shows the equilibrium resistance-accumulated cycles plot for resistor number 1. We first measured this resistance in July 1963 and, subse-

---

[5] Resistor number 4 was needed for other experimentation so its thermal cycling was not continued.

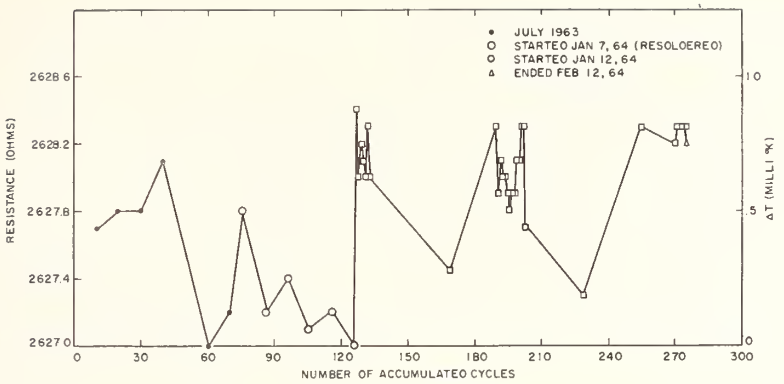


FIGURE 8. *Equilibrium resistance as a function of the number of accumulated cycles for #3.*
$T = 4.2$ °K.

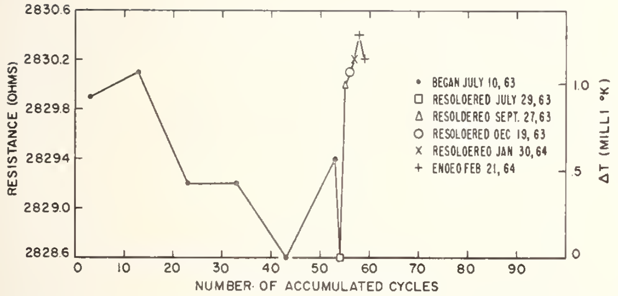


FIGURE 9. *Equilibrium resistance as a function of the number of accumulated cycles for #1.*
$T = 4.2$ °K.

quently, made measurements after every 10 cycles until an accumulated total of 53 cycles was reached. The resistor leads were disconnected and subsequently resoldered to the connecting wires five times over a period of six months. Despite this treatment, the resistance shows a reproducibility of 0.0013 °K. Between the 56th and 57th cycles, the resistor was inadvertently physically shocked. New connecting wires were soldered to number 1 and additional cycling demonstrated little change from the measurements made two and a half months earlier.

5. Select Resistor Group

After obtaining a group of resistors that offered promising calibration-reproducibilities, we adopted the following method as a criterion for determining resistance-temperature reproducibilities under thermal cycling. First, resistors were to be cycled three to five times from room temperature to 4.2 °K prior to a first measurement of resistance. This was adopted when the accumulated data over a number of resistors occasionally exhibited, for individual resistors, a 4.2 °K resistance value for the first cycle that appreciably differed from the rest of the cycling data. This effect may be due to strains developed in the specimen. Naturally, the performance of several cycles prior to a first measurement will eliminate dependence upon this effect [22]. Second, resistors were to be cycled ten times with an equilibrium resistance measurement performed after each cycle. Third, if the data showed a reproducibility of approximately 1 mdeg (during the previous 10 cycles), resistors were to be cycled 75 more times with an equilibrium resistance measurement performed after every 25th cycle. A cycle in which a resistance measurement is not performed consists of retaining the resistor for 3 min at the top of the Dewar neck, 1 min in the room and returning it for one minute's exposure at the Dewar bottom. By this procedure, accumulative effects of cycling, if any, were to be detected. Thus, a total of some 85 cycles with 14 resistance-temperature calibrations were to be performed in this "search." The results, shown in table 2, demonstrate that 10 out of 12 resistors were reproducible to approximately 0.001 °K; four to 0.0007 °K or better. The equilibrium resistances for resistors L, G, and I as a function of accumulated thermal cycles are shown in figures 10 to 12. All three resistors were cycled simultaneously and measured within several minutes of each other during the test. Resistors L and I appear to be good thermometers with reproducibilities of 0.0007 °K and 0.0008 °K while G exhibits a reproducibility of only 0.0019 °K. Another group of three resistors D, J, and N were tested simultaneously and their equilibrium resistances versus accumulated cycles are displayed in figures 13 to 15. Resistors D, J, and N exhibit reproducibilities of 0.45, 0.66, and 0.7 m°K, respectively.

Table 2. *Reproducibility of a selected group of resistors under thermal cycling from 4.2 °K to room temperature*

Resistor	Number of cycles	Average *R* (ohms) 4.2 °K	Reproducibility (milli- °K)
C	88	2800	1.1
D	86	2565	0.5
E	85	2890	1.0
F	88	2678	1.1
G	86	2561	1.9
H	87	2718	[a] 1.2
I	86	2790	0.8
J	86	2593	.7
K	87	2620	1.1
L	86	2672	0.7
M	87	2659	.9
N	86	2769	.7

[a] Resistor not cycled prior to a first measurement.

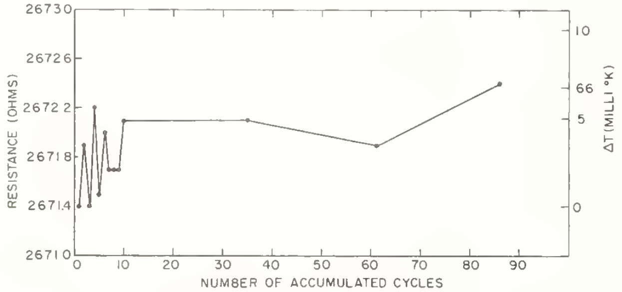


Figure 10. *Equilibrium resistance as a function of the number of accumulated cycles for resistor L.*
T=4.2 °K.

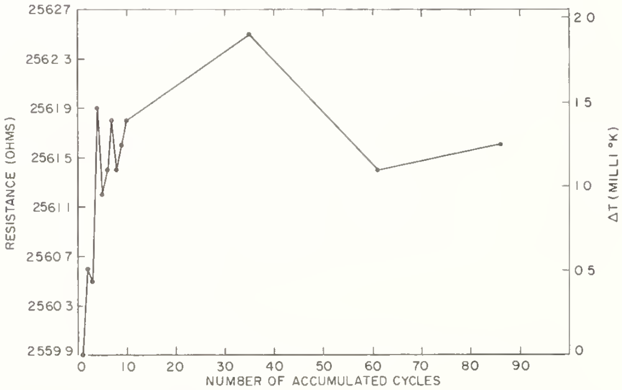


Figure 11. *Equilibrium resistance as a function of the number of accumulated cycles for resistor G.*
T=4.2 °K.

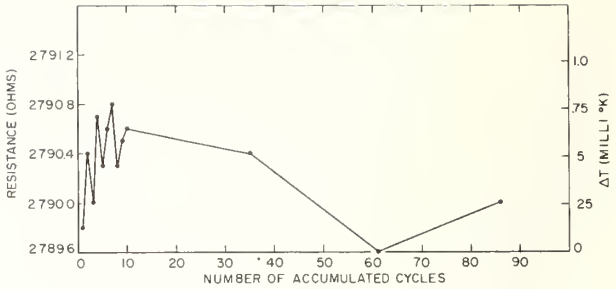


Figure 12. *Equilibrium resistance as a function of the number of accumulated cycles for resistor I.*
T=4.2 °K.

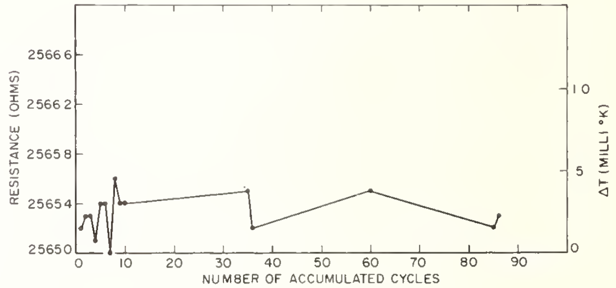


Figure 13. *Equilibrium resistance as a function of the number of accumulated cycles for resistor D.*
T=4.2 °K.

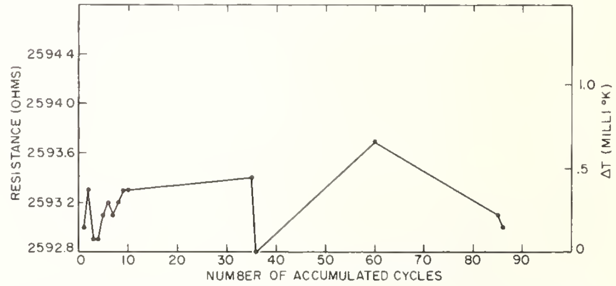


Figure 14. *Equilibrium resistance as a function of the number of accumulated cycles for resistor J.*
T=4.2 °K.

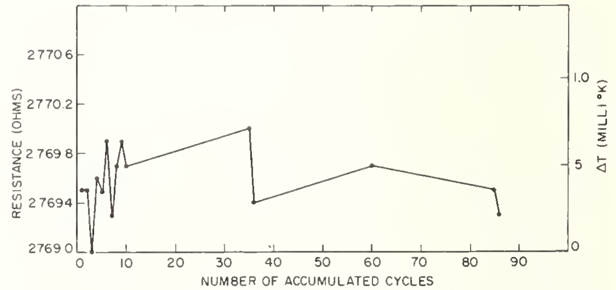


Figure 15. *Equilibrium resistance as a function of the number of accumulated cycles for resistor N.*
T=4.2 °K.

6. Measurement Errors

The measurement errors for the potential and current readings are estimated to be approximately 0.005 percent. At 4.2 °K the resistance-temperature coefficients $\left(\frac{1}{R}\frac{dR}{dT}\right)$ are approximately 0.06 percent per m°K. The error in a resistance determination, therefore, is equivalent to 0.17 m°K. The estimated error in pressure measurements is 0.01 percent; since $\frac{1}{P}\frac{dP}{dT}$ for helium vapor pressures at 4.2 °K is close to 0.1 percent per m°K, the estimated error in pressure determinations is equivalent to 0.1 m°K. Spurious temperature fluctuations within the bulk liquid helium bath are estimated as 0.1 or 0.2 m°K. Thus the total measurement error in determining resistance-temperature calibration reproducibilities at 4.2 °K could become as large as a temperature indeterminacy of 0.4 or 0.5 m°K. Recognizing that the reproducibilities of column 4, table 2, are maximum calibration variations (over an average of 14 calibration determinations for each resistor), the experimental reproducibilities (0.7 m°K or less) for the best resistors are in satisfactory agreement with the estimated error (0.4 or 0.5 m°K).

7. Conclusions

The germanium resistors that have been reported in table 1 were, to our knowledge, not preferentially selected. Rather, they constitute representative resistors from three commercial sources. Our experiments have indicated that 14 of the 25 resistors reproduce a 4.2 °K resistance-temperature calibration within 2.0 m°K while only 7 of the group failed to reproduce within 5.0 m°K. This would seem to indicate a general availability of germanium resistors that are suitable for many low temperature purposes where the thermometry needs are not exacting.

The selection of resistors reported in table 2 was preferential (guidance was furnished by the results of investigations on the first group—table 1) and the reproducibilities listed in column 4 clearly indicate the general superiority of this selection—7 of the 12 resistors were reproducible within 1.0 m°K.

This investigation has fulfilled our original purpose—to obtain a group of germanium resistance thermometers that offered the promise of being suitable for use as secondary thermometers. Since the investigation was completed nearly 2 years ago, there has been ample time for employing the resistors as secondary thermometers in subsequent endeavors. Resistors A and B (table 1) have been used extensively in acoustical thermometry; C and D (table 2) have been calibrated with reference to the acoustical thermometer and are the basic reference for calibrations between 2 and 20 °K at the National Bureau of Standards. Articles on analytical representations of germanium resistor calibration data are in preparation and will appear in the literature.

Since some of the germanium resistors listed in table 1 were obtained as long ago as 5 or 6 years, we have no opinions concerning the current availability of particular models. Without doubt some are now outdated due to advances in manufacturing technology. We have not had the opportunity to investigate groups of resistors which have been commercially available during the last 3 years.

8. References and Notes

[1] J. R. Clement and E. H. Quinnel, Rev. Sci. Instr. **23**, 213 (1952).

[2] J. R. Clement, Temperature, Its Measurement and Control in Science and Industry (Reinhold Publishing Corporation, New York, 1955), Vol. **2**, H. C. Wolfe, ed., p. 380.

[3] P. Lindenfeld, Temperature, Its Measurement and Control in Science and Industry (Reinhold Publishing Corporation, New York, 1962), Vol **3**, C. M. Herzfeld, ed., Part 1, F. G. Brickwedde, ed., p. 399.

[4] M. H. Edlow and H. H. Plumb, Advances in Cryogenic Engineering (Plenum Press, New York, 1961) Vol. **6**, p. 542.

[5] I. Estermann, Phys. Rev. **78**, 83 (1950).

[6] S. W. Friedberg, Phys. Rev. **82**, 764 (1951).

[7] T. H. Geballe, F. J. Morin, and J. P. Marta, Conference de Physique des Basses Temperature, Paris (1955) p. 87.

[8] J. E. Kunzler, T. H. Geballe, and G. W. Hull, Rev. Sci. Instr. **28**, 96 (1957).

[9] P. Lindenfeld, Opt. Cit., p. 399.

[10] J. S. Blakemore et al., Rev. Sci. Instr. **33**, 106 (1962).

[11] J. S. Blakemore, Rev. Sci. Instr. **33**, 545 (1962).

[12] F. J. Low, Advances in Cryogenic Engineering, (Plenum Press, New York, 1961) Vol. **7**, p. 514.

[13] Standard Resistors are certified by the National Bureau of Standards.

[14] E. Ambler and H. H. Plumb, Rev. Sci. Instr., **31**, 636 (1960).

[15] H. H. Plumb and M. H. Edlow, Rev. Sci. Instr. **30**, 376 (1959).

[16] G. Cataland, M. H. Edlow and H. H. Plumb, Temperature, Its Measurement and Control in Science and Industry (Reinhold Publishing Corporation, New York, 1962), Vol. **3**, C. M. Herzfeld, ed., Pt. 1, F. G. Brickwedde, ed., p. 413.

[17] G. Cataland, M. H. Edlow, and H. H. Plumb, Rev. Sci. Instr. **32**, 980 (1961).

[18] D. Ditmars and G. Furukawa, J. Res. NBS, 69C (Engr. and Instr.) No. 1, 35 (1965); K. W. Taconis, J. J. Beenakker, A. O. C. Nier, and L. T. Aldrich, Physica **15**, 733 (1949); H. A. Kramers, ibid, 971 (1949).

[19] F. G. Brickwedde, H. van Dijk, M. Durieux, J. R. Clement, and J. K. Logan, NBS Monograph 10 (1960); J. Res. NBS, 64A (Phys. and Chem.) No. 1, 1 (1960).

[20] M. Durieux, thesis, University of Leiden (1960).

[21] Our thanks to the following people who have supplied us with resistors for these experiments:
Mr. Tom Herder, formerly of Minneapolis-Honeywell Company, Semiconductor Division, Riviera Beach, Florida:
Mr. Gilbert Halverson, Radiation Research Corporation, West Palm Beach, Florida;
Mr. Jack Veasaw, Industrial Products Group, Texas Instruments, Inc., Houston, Texas.

[22] During the period that Mr. Herder was associated with Minneapolis-Honeywell Company, he noted and reported similar effects in a private communication to us.

(Paper 70C4–235)

JOURNAL OF RESEARCH of the National Bureau of Standards—C. Engineering and Instrumentation
Vol. 71C, No. 1, January–March 1967

Germanium Resistance Thermometry in the Range 2.1 to 5.0 °K

M. H. Edlow [1] **and H. H. Plumb**

Institute for Basic Standards, National Bureau of Standards, Washington, D.C. 20234

(September 9, 1966)

The resistances of three encapsulated, hermetically sealed, arsenic-doped germanium resistors from a commerical source have been measured at every 0.1 °K from 2.1 to 5.0 °K in highly stabilized liquid helium baths; values of temperature were derived from vapor pressure measurements associated with the liquid bath.

Ten similar germanium resistors of common origin have been calibrated from 2.1 to 5.0 °K in a calibration comparator apparatus that is similar to a calorimeter in design. Calibrations were performed against a resistor that had been previously referenced to temperature through a helium-4 vapor pressure calibration.

Next, three of the resistors that were calibrated in the comparator apparatus were recalibrated in a liquid helium bath (at 2.2, 3.0, and 4.2 °K) and results from the two methods agree within ± 1 millidegree. The resistance-temperature data from both methods have been fitted to the polynomial equation $\log_{10} R = \sum_{n=0}^{m} A_n \cdot (\log_{10} T)^n$ and the results of a computer program, which evaluates the coefficients, are presented.

1. Introduction

We have a group of impurity-doped germanium resistors that possess desirable thermometric properties at low temperatures—negative coefficient of temperature, good sensitivity and excellent reproducibility under thermal cycling [1].[2] This paper describes the calibration (in the range 2.1 to 5.0 °K) of the abovementioned resistor group.

Several resistors have been calibrated directly against liquid helium-4 vapor pressures thus giving reference to temperatures from the "1958 He^4 Scale of Temperatures" [2]. Since this method of calibration is costly in both time and refrigerant materials, a different procedure was utilized for extending the calibration over a greater number of resistors. An apparatus was constructed for comparison calibrations between "unknowns" and resistors that had been previously calibrated against helium-4 vapor pressures.

2. Calibration in a Liquid Helium Bath

2.1. Liquid Helium Bath

The apparatus, used for calibrating germanium resistors in a highly stabilized liquid helium bath, has been described in an earlier paper [1]. While the previous report was based upon calibrations in the vicinity of 4.2 °K only, no modification of the apparatus was necessary for expanding the calibration range to include 2.1 to 5.0 °K.

The bath consisted of about 8 liters of liquid helium which filled the spherical liquid helium storage Dewar (25 liters) to a height of 14 cm. This provided a liquid helium surface level that did not extend above the thermally insulating vacuum jacket of the vapor pressure bulb. The storage Dewar was then connected to a vapor pressure regulator [3] and the surface vapor pressure monitored by a mercury manometer. Small amounts of helium gas from a 1-liter filling can were bled into the jacketed vapor pressure thermometer. After the helium gas pressure in the thermometer equaled the controlled bath surface pressure, ⅓ of an atmosphere of helium gas was slowly metered into the bulb to condense approximately 0.5 cm^3 of liquid. Since the thermometer bulb volume was 2 cm^3, the fluid level was well below the top of the bulb and the remaining volume was sufficiently large to contain some additional condensate-condensation of gas from the vapor pressure thermometer tubing occurred when the vapor pressure of the helium bath was intentionally decreased during the course of a calibration.

The calibration from 2.1 to 5.0 °K was procedurally divided into three stages. Obvious checks were made to ascertain that there was appropriate electrical continuity of resistor leads and no undesired grounding in the resistance measuring circuit before the resistors were lowered into helium bath. Then the Dewar bath was cooled to appropriate temperatures

---

[1] M. H. Edlow is presently associated with the United States Patent Office.

[2] Figures in brackets indicate the literature references at the end of this paper.

by pumping through the vapor pressure regulating manostat and calibrations were performed at every 0.1 °K in the range 4.2 to 2.6 °K. Next, the Dewar bath was warmed to the helium boiling point (by bleeding helium gas into the Dewar) and a second liquid helium transfer made. The second transfer was necessary since a height of only 3.2 cm of liquid helium remained in the Dewar after the calibration at 2.6 °K was finished. The bath was then cooled directly to 2.5 °K and subsequent calibrations performed at the five lower temperature points −2.5, 2.4, 2.3, 2.2, and 2.1 °K. Thirdly, the Dewar bath was warmed to 4.2 °K, a necessary third liquid helium transfer made and the calibration performed in the range 4.2 to 5.0 °K. (Vapor pressures that exceed atmospheric pressure were obtained by closing off the manostat and allowing the Dewar vapor pressure to build up to a desired value at which time it was again manostatically controlled. The normal evaporation rate within the Dewar provided the gas for the increased pressure.)

2.2. Vapor Pressure Thermometry

The vapor pressure measuring techniques, used in these measurements, were consonant with procedures that we have previously reported [4]. Since a temperature gradient exists at the surface of the "constant temperature" liquid bath, the vapor pressure thermometer tubing must be thermally insulated from the colder surface to avoid spurious effects caused by "cold spots" [4,5]. Consequently, the thermometer tubing was surrounded by a vacuum jacket—the tubing length that otherwise would be in contact with the liquid surface—thus insuring that the vapor pressure thermometer indicated a vapor pressure that was associated with the bulk liquid. Vapor pressure measurements of both the helium surface and the thermometer bulb were routinely performed and recorded. In a previous paper [4], we have listed the observed differences in these two measurements for tenth-degree intervals from 2.1 to 4.2 °K. Table 1 lists typical comparisons derived from the calibration data that are the basis for this paper. The differences between the two vapor pressures, P_J and P_S, are not unique since the pressure and temperature gradients, at the liquid helium surface, appear to be dependent upon at least two conditions—the geometry of the contained liquid helium and the Dewar evaporation rate. Nevertheless the qualitative change in magnitude of the surface temperature gradient (ΔT) as a function of the helium bath temperature is supported by the results of many experimental "runs" in our laboratory. Additionally, as we have previously reported [4], calibrations of germanium resistors across the helium—λ point have been "smooth" when temperatures in the helium-I region were derived from pressures measured in conjunction with the jacketed vapor pressure thermometer. We have been unable to obtain a "smooth" calibration across the λ-point when temperatures are derived from surface vapor pressure measurements; as might be suspected, temperatures derived from either method are satisfactory in the temperature region of helium-II provided the effects of helium film creep do not enter as a variable.

In the range 4.2 to 5.0 °K, the vapor pressure bulb required periodic additions of helium gas since, as the vapor pressure was increased, some of the previously condensed liquid helium must be evaporated to supply the required helium gas in the vapor pressure thermometer tubing. The inverse operation was necessary as temperatures were reduced below 4.2 °K i.e., liquid helium was occasionally removed from the bulb to avoid an overfilling of the bulb.

TABLE 1. *Vapor pressure measurements in a "constant" temperature liquid helium-4 bath*

Temperature	$P_J{}^a - P_S{}^b$	ΔT^c	Temperature	$P_J{}^a - P_S{}^b$	ΔT^c
°K	*mm* Hg	*mdeg*	*°K*	*mm* Hg	*mdeg*
5.0	0.43	0.4	3.5	0.84	2.0
4.9	.38	.4	3.4	.76	1.9
4.8	.66	.7	3.3	.71	2.0
4.7	.71	.7	3.2	.66	2.0
4.6	.86	1.0	3.1	.61	2.0
4.5	.97	1.1	3.0	.58	2.1
4.4	.99	1.2	2.9	.58	2.4
4.3	1.02	1.4	2.8	.56	2.6
4.2	0.91	1.3	2.7	.48	2.5
4.1	1.07	1.6	2.6	.48	2.8
4.0	0.97	1.6	2.5	.43	2.8
3.9	.91	1.6	2.4	.38	2.9
3.8	.90	1.7	2.3	.38	3.3
3.7	.90	1.8	2.2	.33	3.4
3.6	.81	1.8	2.1	.00	0.0

[a] P_J is the helium vapor pressure of the jacketed thermometer.

[b] P_S is the helium vapor pressure of the bath surface.

[c] ΔT (the temperature equivalent of the pressure difference, $P_J - P_S$) is equal to $\frac{(P_J - P_S)}{\frac{dP}{dT}}$. $\frac{dP}{dT}$ is obtained from the "1958 He^4 Scale of Temperatures" [2].

In the range 4.8 to 5.0 °K there were a few instances when the helium gas oscillated in the jacketed vapor pressure tube. These oscillations [6] were indicated by: (1) Thermometer vapor pressures greatly exceeded surface vapor pressures of the bath after surface pressure control had been established for several hours; (2) the evaporation rate of the helium bath, as measured with a flow meter, was greatly increased (by as much as a factor of three) but returned to its normal value when the bulb was evacuated; and (3) large oscillations were observed in the mercury manometer. Reliable measurements were obtained in these instances by altering the liquid bath temperature to a value where oscillations were not encountered.

Resistance determinations, at each stabilized temperature, were measured potentiometrically; the electrical power applied to a resistor generally did not exceed 0.02 μW, but at temperatures above 4.6 °K, it was possible to apply 0.1 μW without causing appreciable joule heating in the resistors.

2.3. Discussion

The calibration at each temperature in the range 2.1 to 4.2 °K required approximately 3 hr—½ to 1 hr for cooling the bath to the desired surface vapor pressure, 2 hrs for the bath to stabilize and ½ hr for performing electrical measurements. In one range above the boiling point, 4.7 to 5.0 °K, it required about 24 hrs to increase the bath temperature by 0.1 °K. Therefore, it was not unusual to expend three weeks in performing a calibration at every 0.1 °K from 2.1 to 5.0 °K. The fact that at least three liquid helium transfers were necessary to cover the range made this calibration expensive as well as time consuming. For these reasons, an isothermal comparator was constructed for calibrating a large number of resistors more efficiently.

3. Calibration in an Isothermal Comparator

3.1. Comparator

The comparator design and construction is shown in figure 1. The copper top A of the outside can B is 6.04 cm in diameter and has an internal extended sleeve A′ (1.90 cm O.D., 2.22 cm long, and 1.27 cm wall thickness). The outside can B is mainly brass and has the dimensions of 6.67 cm diam, 21 cm long, and 0.159 cm wall thickness; the upper 1.27 cm of the can is a piece that was machined to receive the cylindrical tongue of top A. Wood's metal is used to solder the copper top to the brass can. The bottom of the brass can C is a brass disk that has been silver soldered to the outside cylinder. During a calibration, the can B is contained in a liquid bath whose liquid level is well above the top A. The thermal anchor post T, 0.477 cm copper rod, is screwed into A. Three Teflon rods, each of 0.32 cm diam and 3.2 cm long, are equally spaced on the end of cylinder A′ and screwed into the wall thickness. A 0.64 cm perforated stainless steel tube E was silver soldered to the copper top A; its opposite end was soft soldered to the top of the 2.5 cm solid copper cylinder J. Twelve 0.36 cm diam holes N were drilled at an angle of 45 degrees to the axis of J and to a depth of 1.12 cm, which is sufficiently deep to contain the length of a germanium resistor encapsulation. The inner copper can K, 6.4 cm outside diameter, 9.5 cm long, screws onto the threaded surface of the shoulder M. K serves as a radiation shield for the portion of the cylinder that contains the resistors. Several 0.16 cm holes O were drilled through K to enhance evacuation of the volume within K. F and F′ (0.64 cm, thin wall, stainless steel tubings), were soft soldered through A and serve respectively, as a helium gas filling or evacuation line and conduit for lead wires to the resistors and heater coil. A total of 14 leads (#38 A. W. G. formvar coated, double nylon insulated, copper wire) are used as connecting wires—4 pairs as potential leads to the germanium resistors that are involved in a calibration, 1 pair for current leads to the series connected resistors and 1 pair each for the sensor and heater coil. For the heater coil, #36 A.W.G. manganin wire was non-inductively wound on the bobbin H to provide a total resistance of 38,000 Ω at room temperature.

The seven pairs of connecting wires were conducted down from the Dewar cap through F′ (see fig. 2) and wound around the thermal anchor T—prior to wrapping around *T*, a small loop was made to allow for thermal contraction of the leads within the tube F′. Next, about 60 cm of the leads were spirally wound about the thermal anchor A′ and afterwards, coatings of G.E. varnish #7031 were applied to the wires and surfaces of T and A′ to enhance the thermal contact between

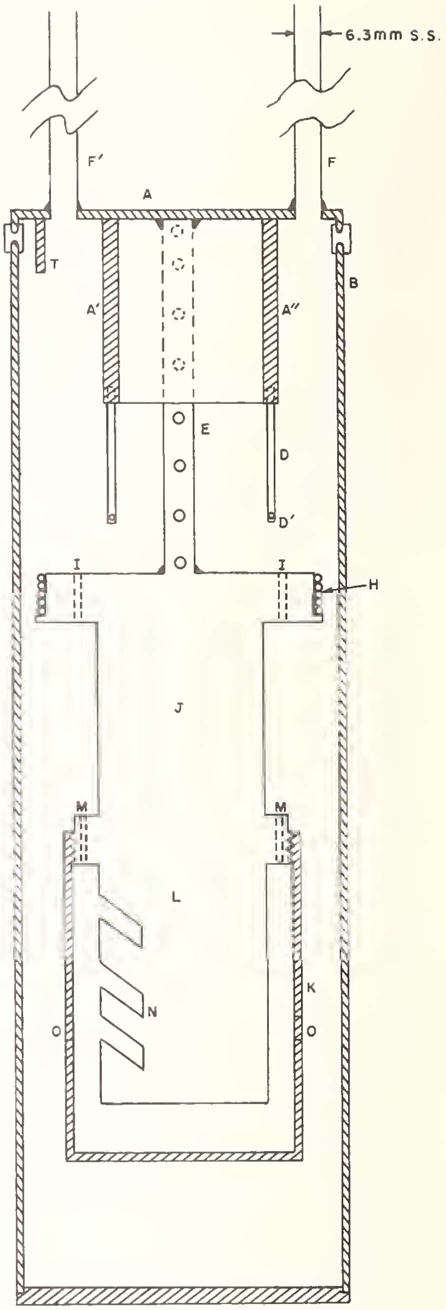


FIGURE 1. *Design of comparator—the low temperature component of apparatus employed in calibrating germanium thermometers from 2.1° to 5.0 °K.*

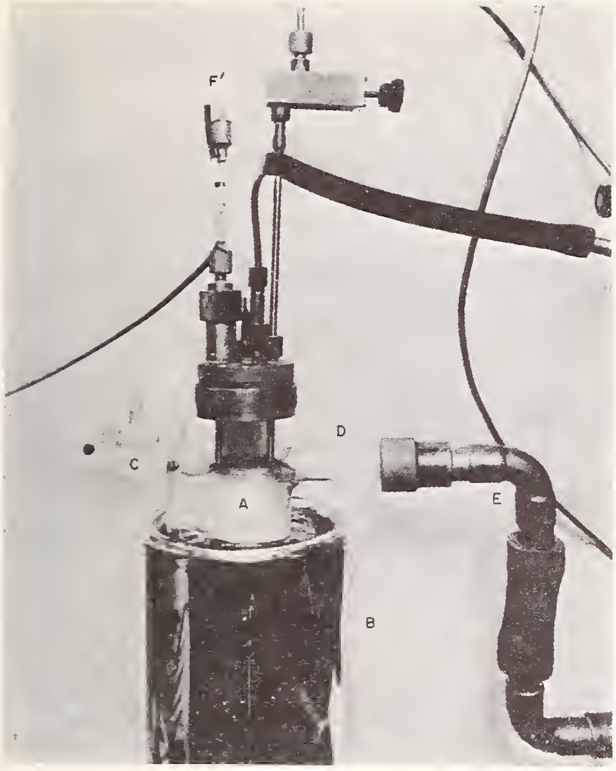


FIGURE 2. *A view of the upper portion of the cryostat that contains the calibration comparator.*

the lead wires and thermal anchors. This treatment will greatly reduce the heat leaks along the wires from room temperatures to the resistors. Additional lengths of wire were then spiralled around the three Teflon posts D and strung through holes D′ drilled near the end of the Teflon rods. One pair of leads was separated from the group and connected to the heater coil. The remaining 6 pairs were conducted through I, 0.159 cm holes that had been previously lined with Teflon, and thence spiralled around J where #7031 varnish was also applied. Next, the wires were then led through M, 0.159 cm holes also lined with Teflon, wrapped once around L and thence soldered to the germanium resistor leads with Wood's metal. The soldered connections are enclosed by spun glass spaghetti to avoid electrical shorting or grounding of the leads.

In use, the vacuum can B and its top A are exposed to a bath temperature that is less than 2 °K, while the cylindrical block J is maintained at calibration temperatures that exceed 2 °K. Thus, without proper precautions, large undesired heat-flows could occur and cause: (i) a temperature instability of the block J with resultant gradients; (ii) abnormally large evaporation rates of the surrounding liquid helium bath; and (iii) a lack of thermal equilibrium between the resistors that are to be calibrated. The comparator has been designed to reduce and control the flow of heat toward and away from J. (1). Radiant transfer from J or K to the outer can B is small. (2). The continuous evacuation of B minimizes heat transfer through gas conduction and convection. (3) Heat conduction through the leads and mechanically supporting members has been reduced.

There are several other component systems that are used in conjunction with the comparator. Temperature control of L or J (fig. 1) is effected by an automatic electronic system. A germanium sensor, mounted in a cavity N of L (fig. 1) serves as one leg of a Wheatstone bridge. Any unbalance of the bridge is amplified and fed into a controller which in turn regulates current flow through the heater H (fig. 1).

Shown in figure 2, is the upper portion of the cryostat that consists of a glass Dewar A (7.0 cm I.D. and 100 cm long), which contains the liquid helium in which the comparator is immersed, and an external Dewar that contains liquid nitrogen for thermally shielding the liquid helium Dewar. The figure shows a vacuum tight Dewar cap that accommodates the two tubes, which lead to the comparator (tubes F and F′ of fig. 1), and permits filling of the Dewar with liquid helium. Also shown, is the Dewar's horizontal sidearm D that connects to a vacuum pumping line E—by "pumping" on the vapor pressure through this line, helium bath temperatures of less than 2 °K are achieved. The vertical tubing, which includes the vacuum valve, leads from an external "high vacuum" pumping system to the insulating vacuum space of the comparator; electrical lead ingress to the comparator is afforded by the tubing on the left. All of the apparatus, with the exception of the helium vapor pressure pumping system, is located within a shielded room that isolates the equipment from local rf interference [7].

3.2. Comparator Operating Procedure

The resistors that were involved in a calibration were mounted in the copper block J (fig. 1) in a medium of Apiezon stopcock grease to enhance thermal contact. The outer can B was soldered in place with Wood's metal and the 14 electrical leads then checked for electrical continuity. After appropriate leak detection the comparator was mounted in the cryostat, a small amount of helium gas was bled into the vacuum space (within can B) and the apparatus precooled to liquid nitrogen temperatures. Next, liquid helium was transferred into the inner Dewar, resistor lead continuity checks performed again, and then the liquid helium bath cooled to 1.5 °K. After the helium exchange gas was sufficiently evacuated, the resistance of the Wheatstone bridge was set to correspond to the 2.1 °K resistance value (determined in an initial calibration) of the temperature controlling sensor. The three control dials—proportional band, rate time and reset—of the servocontrol unit were set to obtain adequate temperature control of the comparator. Proper settings of the three controls result in a temperature control as fine as 1×10^{-4} °K at 2.1 °K. This has been evidenced by repetitive resistance determinations for resistor #1 over a period of 30 min. Generally, once a good setting has been obtained at the lowest calibration temperature, the dials need not be changed for the remainder of the calibration.

In establishing any given calibration control point, a value of resistance was dialed on the Wheatstone bridge and sufficient time was allowed for the recorder pen of the temperature controlling unit to reach the control or zero position. (Generally about 10 min was required to attain temperature stability after an increase of 0.1 °K in the temperature of the comparator.) Initial measurements on resistor #1 often indicated a deviation of approximately several millidegrees from a desired calibration temperature. In this event appropriate corrections were made on the Wheatstone bridge settings, five additional minutes allowed for equilibrium and measurements were again made across #1. This process was repeated until the resistance of #1 indicated a value that was within ±0.5 mdeg of the desired calibration temperature.

4. Germanium Resistance Thermometers

For all of the germanium resistors, whose calibrations are being reported in this paper, we have a thermal cycling history. That is, the resistors have been thermally cycled from room temperature to 4.2 °K and systematic calibrations of resistance and temperature performed at 4.2 °K. The methods of cycling and calibration have been previously described [1], and the reproducibilities of particular resistors were stated. The previous resistor identification symbols will apply to precisely the same resistors in this report. All of the resistors are four lead models and are hermetically encapsulated in platinum containers filled with helium gas. However, the calibrator design and method of mounting resistors in the comparator are such that a leaking encapsulation will probably not affect the general validity of a calibration. Most of the resistors are similar in that their values of resistance are comparable at 4.2 °K—this probably means that their "dopings" are similar and consequently, that similar equations will represent the resistance temperature calibration data.

5. Experimental Results

5.1. From the Stabilized Helium Bath

Resistors 1, 2, and 3 (reproducible to approximately 1 mdeg under thermal cycling [1]) have been calibrated simultaneously in the "constant temperature" helium bath from 2.1 to 5.0 °K at intervals of 0.1 °K; the results are listed in table 2. A log-log plot of resistance versus temperature for #1, #2, and #3, shown in figure 3, suggests the possibility of representing the calibration data by a polynomial of the form

$$\log_{10} R = \sum_{n=0}^{m} A_n (\log_{10} T)^n.$$

TABLE 2. *Calibrated resistances obtained in the highly stabilized liquid helium baths*

Resistor #1	#2	#3	Temperature [a]
Ω	Ω	Ω	°K
13281.	12435.	13739.	2.0993
11749.	10982.	12064.	2.2013
10528.	9821.0	10740.	2.2995
9491.6	8839.0	9611.0	2.3984
8588.0	7979.0	8632.0	2.5003
7841.0	7271.7	7832.3	2.5994
7106.4	6572.9	7042.0	2.7130
6611.8	6108.0	6519.0	2.8005
6119.1	5639.4	6000.0	2.8996
5681.2	5227.1	5537.5	2.9986
5287.2	4855.8	5128.3	3.0997
4938.8	4527.8	4766.3	3.1997
4625.8	4232.8	4443.0	3.2997
4345.1	3968.7	4155.1	3.3996
4090.2	3729.9	3894.6	3.4999
3859.6	3513.4	3660.6	3.5996
3650.4	3317.0	3448.2	3.6996
3457.4	3136.9	3253.8	3.7999
3279.7	2970.6	3075.3	3.9007
3118.8	2820.7	2914.7	4.0000
2972.0	2683.4	2768.6	4.0981
2829.8	2551.8	2627.8	4.2000
2699.2	2430.2	2498.7	4.3014
2579.6	2318.9	2381.1	4.4011
2468.6	2216.2	2272.1	4.5002
2363.2	2119.0	2169.7	4.6009
2266.3	2029.0	2075.1	4.6998
2173.4	1942.8	1985.4	4.7999
2086.6	1862.7	1901.4	4.9004
2005.4	1787.9	1823.1	5.0005

[a] Temperatures are derived from the "1958 He^4 Scale of Temperatures" [2] using values of vapor pressure that were obtained with a jacketed vapor pressure thermometer.

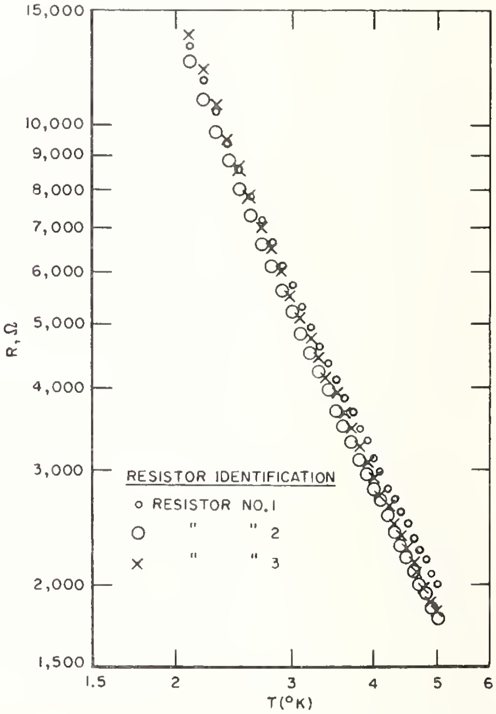


FIGURE 3. *A plot of the resistance-temperature calibration data for resistors 1, 2 and 3.*

Temperatures were derived from liquid helium-4 vapor pressures.

Consequently, the resistance temperature calibration data (obtained from the bath calibration) were programmed on a computer for a least squares fitting to the above polynomial. The program was "cascaded" so that a succession of least squares fitting was performed for upper limits of m that extended consecutively from 3, . . ., 8. The results require discussion since there are at least two ways of considering the representation of the calibration data.

(a) Except for the effect of spurious errors, the limiting accuracy of a calibration could possibly approach ±0.001 °K. This would probably occur at the lowest temperatures and would be mainly associated with the accuracy of our helium vapor pressure measurements.

(b) If, however, one feels that the 0.001 °K assessment of error is high or might be smoothed out in the polynomial fitting, it is not obvious as to how far one should proceed with the polynomial fitting.

Because of these two considerations we felt compelled to present, in this paper, results which would be in accordance with either (a) or (b) of the preceding paragraph. In the computer analyses for the three resistors, the polynomial $\log_{10} R = \sum_{n=0}^{3} A_n (\log_{10} T)^n$ could possibly represent the data within the limits of condition (a). However there exists an obvious systematic deviation between the fitted function (R_{calc}, T) and the input calibration data (R_{data}, T_{data}). This is apparent in figure 4 where points of inflection occur near 2.8, 3.6, and 4.4 °K. While the general conclusion from figure 4 might be the indication that the input data has been adequately fitted within the limits of experimental errors, another possibility is suggested—the data is more consistent than ±0.001 °K and the function that would represent the data is not adequately approximated by $\log_{10} R = \sum_{n=0}^{3} A_n (\log_{10} T)^n$. Consequently we have continued the analysis to higher order polynomials. Table 3 contains the evaluated polynomial coefficients for resistor #1; a double precision computer program prepared by the National Bureau of Standards Statistical Engineering Laboratory was used to overcome the roundoff error characteristic of fitting high order polynomials, and in this case the roundoff error was several orders of magnitude smaller than other experimental uncertainties.

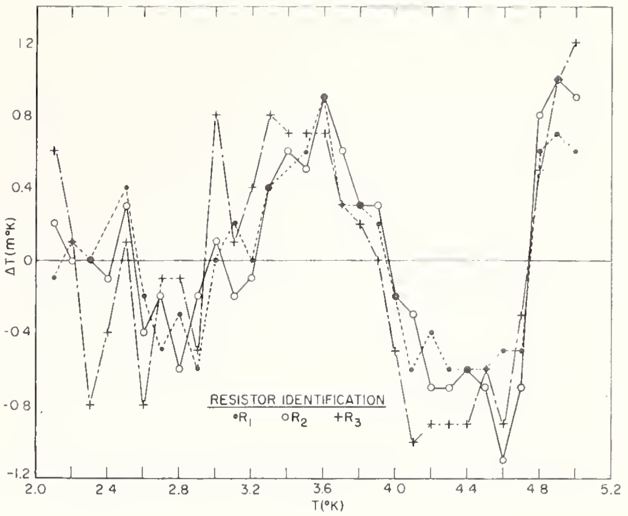


FIGURE 4. *Differences between the fitted functions, log* $R = \sum_{n=0}^{3} A_n (\log T)^n$ *and the calibration data for resistors 1, 2 and 3.*

(a) The residuals $\Delta T = (R_{\text{Gen.}} - R_{\text{Data}}) dT/dR$ is the temperature equivalent of $(R_{\text{Gen}} - R_{\text{Data}})$ which is the difference between the fitted polynomial function evaluated at T_{Data} (R_{Gen}) and the resistance value of the calibration (R_{Data}, T_{Data}). dR/dT is the temperature coefficient of resistance.

(b) The residual plots apply to the three resistors [#1 (.), #2 (0) and #3 (+)]; the calibration data for each resistor have been individually fitted to third order polynomials.

As higher order polynomials are used, the systematic differences—between the fitted polynomial and the input data—gradually diminish up to the 7th order where apparently random residuals result. Figure 5 is the plot of these residuals resulting from fitting the seventh order polynomial for resistors 1, 2, and 3. For $n = 7$ of table 3, it is apparent that the

TABLE 3. *Coefficients of the polynomial,* $\log_{10} R = \sum_{n=0}^{m} A_n (\log_{10} T)^n$, *fitted to the calibration data of Resistor #1*

Polynomial order	$m=3$		$m=4$		$m=5$		$m=6$		$m=7$		$m=8$	
Coefficient	Coef.	δC [a]	Coef.	δC [a]	Coef.	δC [a]	Coef.	δC [a]	Coef.	δC [a]	Coef.	δC [a]
A_0	5.202	(0.0023)	5.180	(0.0112)	5.380	(0.0396)	5.685	(0.198)	2.219	(0.735)	[1.86]	(2.63)
A_1	−4.249	(.0145)	−4.062	(.0922)	−6.160	(.411)	−9.995	(2.48)	40.873	(10.72)	[46.9]	(43.7)
A_2	3.304	(.0287)	2.732	(.279)	11.348	(1.68)	31.136	(12.74)	−284.78	(66.3)	[−329.]	(316)
A_3	−1.593	(.0185)	−.8355	(.369)	−18.206	(3.37)	−71.870	(34.41)	1004.6	(225)	[1186]	(1291)
A_4			−.3687	(.179)	16.846	(3.33)	[b] [97.546]	(51.61)	−2076.8	(454)	[−2538]	(3268)
A_5					−6.715	(1.30)	[−70.554]	(40.77)	2533.5	(542)	[3278]	(5248)
A_6							[20.767]	(13.26)	−1692.1	(356)	[−2435]	(5221)
A_7									477.6	(99.3)	[897]	(2943)
A_8											[−103]	(720)
Std. Dev.	1.12×10^{-4}		1.06×10^{-4}		7.4×10^{-5}		7.2×10^{-5}		5.1×10^{-5}		5.2×10^{-5}	

[a] δC is the standard error of a coefficient.

[b] The brackets indicate that the enclosed coefficient is poorly defined; that is, the ratio of the coefficient to its standard error is less than 2.

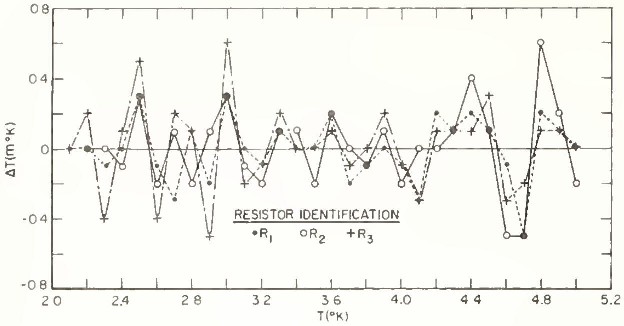


FIGURE 5. *Differences between the fitted functions, log* $\mathrm{R}=\sum_{n=0}^{7}\mathrm{A_n}$ *(log* $\mathrm{T})^n$ *and the calibration data for resistors 1, 2 and 3.*

(a) See (a) of figure 4.

(b) The residual plots apply to the three resistors [#1 (.), #2 (0) and #3 (+)]; the calibration data for each resistor have been individually fitted to seventh order polynomials.

first coefficient is the least defined coefficient of the column. Since random residuals, exhibited in figure 5, were achieved by the seventh degree polynomial and the coefficients of the eighth degree are poorly determined, we did not attempt to extend the fitting to higher order polynomials. (It does seem, for resistor 1 in table 3, that odd order polynomials provide a better functional fit than even orders. This observation is generally applicable to other germanium resistor calibrations between 2 and 5 °K and will be discussed later in the paper.)

In comparing figures 4 and 5, one observes that not only has the systematic deviation of figure 4 been removed by progressing to the polynomial fitting portrayed in figure 5, but also, the values of standard deviation that are listed in the last row of table 3 have been reduced by a factor of two. Despite this, one should be cautious about inferring: either (a), the calibration data were valid to ±0.0005 °K; or (b), the polynomial fitting is completely satisfactory; or (c), conclusions concerning the He^4 vapor pressure scale against which calibrations were performed. These items will require further clarification.

Since resistor #1 was to serve as a basis for calibrating additional resistors, a decision had to be made regarding its calibration representation. Although it is somewhat arbitrary, we decided to use the 7th order polynomial because it might have the effect of smoothing out experimental errors in resistor #1's calibration. The seventh order coefficients (table 3) were used to generate R, $\frac{dR}{dT}$ and $\frac{d^2R}{dT^2}$ for resistor #1 at intervals of 0.0001 °K from 2.1 to 5.0 °K; this generated table is the basis for calibrating additional resistors against resistor #1. It is pertinent to state that both the generated $\frac{dR}{dT}$ and $\frac{d^2R}{dT^2}$ did not exhibit a sign change in the range of generation; that is, the fitted seventh order polynomial is a smooth function in the range of use.

In general the polynomial fittings of resistors #2 and #3 produce results that parallel the findings for resistor #1. This is indicated by the plots of residuals for resistors #2 and #3 in figures 4 and 5.

5.2. Comparison Calibrations With Reference to Resistor #1

Ten resistors have been calibrated in the isothermal comparator with reference to the calibrated resistor #1 and the data are listed in tables 4 to 8. In each of the indicated runs, three "unknowns" were calibrated against resistor #1 (the data for the third resistor is not included in table 4). As a control on the stability of the calibrations, resistor I was measured in each of the five calibration runs. Thus there appears in each table the measured resistances of resistors #1 and I and two unknowns (one unknown in table 4). Temperatures, which are assigned to the resistance values of resistor #1, are taken from the Resistance-Temperature generation that was derived from a seventh order polynomial fitting (sec. 5.1).

It is also readily noted that particular calibration temperatures, in the 5 separate runs, are generally realized within a few millidegrees. This was intentional and eliminates interpolation inaccuracies that

TABLE 4

Run 3

Calibration data for Resistor I and Resistor L

R_1	T[a]	R_I	R_L
Ω	°K	Ω	Ω
13241	2.1017	17117	15178
11754	2.2010	14905	13304
10584	2.2945	13192	11849
9515.4	2.3960	11652	10530
8604.7	2.4985	10365	9420.9
7842.2	2.5991	9303.5	8499.4
7107.7	2.7125	8295.7	7620.1
6610.6	2.8008	7624.3	7030.5
6119.9	2.8992	6969.6	6453.0
5681.7	2.9987	6392.7	5941.1
5285.5	3.1001	5877.7	5483.3
4940.6	3.1990	5433.0	5085.5
4625.3	3.2999	5033.2	4726.3
4343.9	3.4000	4680.2	4407.7
4090.7	3.4996	4365.1	4121.8
3859.0	3.6000	4081.3	3863.6
3457.2	3.7999	3595.4	3419.0
3279.3	3.9009	3383.8	3224.3
3118.6	4.0000	3194.4	3049.0
2972.2	4.0976	3023.1	2890.0
2830.4	4.1997	2859.0	2737.3
2698.7	4.3019	2707.5	2596.1
2579.8	4.4010	2572.0	2469.2
2467.7	4.5010	2445.6	2350.3
2362.5	4.6013	2327.3	2239.0
2266.2	4.6993	2220.2	2137.7
2173.3	4.8001	2117.5	2040.3
2086.7	4.9002	2021.9	1949.9
2005.5	5.0002	1933.6	1865.6

[a] T is the temperature associated with the adjacent value of resistance for R_1, which was previously calibrated against T_{58} [2].

TABLE 5

Run 5

Calibration data for Resistor H, Resistor M, and Resistor I

R_t	T[a]	R_H	R_M	R_I
Ω	°K	Ω	Ω	Ω
13246.0	2.1014	14596	13819	17121
11742.0	2.2018	12801	12165	14882
10579.0	2.2949	11425	10894	13182
9507.0	2.3968	10173	9725.7	11639
8609.8	2.4979	9130.1	8754.7	10371
7840.1	2.5994	8245.1	7924.5	9298.5
7107.0	2.7127	7402.4	7137.8	8292.8
6609.6	2.8010	6845.5	6607.1	7620.4
6121.2	2.8990	6293.9	6088.5	6969.8
5682.7	2.9985	5804.0	5623.7	6392.8
5287.8	3.0995	5366.1	5208.4	5879.1
4941.5	3.1988	4981.9	4843.3	5433.9
4626.7	3.2995	4636.0	4513.9	5034.3
4344.7	3.3997	4329.6	4219.9	4681.1
4091.9	3.4991	4056.7	3956.7	4367.1
3859.6	3.5998	3806.8	3716.1	4082.2
3650.4	3.6993	3584.0	3500.1	3828.0
3458.5	3.7992	3379.7	3302.4	3597.3
3280.0	3.9005	3190.9	3118.9	3384.7
3118.9	3.9998	3020.9	2954.1	3194.5
2973.4	4.0968	2869.1	2805.7	3024.8
2830.1	4.1999	2718.8	2659.8	2858.5
2699.1	4.3015	2582.8	2526.6	2707.9
2579.1	4.4015	2459.8	2406.0	2571.5
2468.3	4.5004	2345.7	2294.1	2446.7
2363.9	4.5999	2238.3	2188.3	2328.9
2266.7	4.6988	2139.6	2091.0	2221.1
2173.6	4.7997	2044.6	1897.4	2117.8
2086.4	4.9006	1956.5	1910.2	2022.0
2005.1	5.0007	1874.4	1829.3	1933.3

[a] T is the temperature associated with the adjacent value of resistance for R_t, which was previously calibrated against T_{58} [2].

TABLE 6

Run 6

Calibration data for Resistor C, Resistor G, and Resistor I

R_t	T[a]	R_C	R_G	R_I
Ω	°K	Ω	Ω	Ω
13244	2.1015	14995	14431	17120
11747	2.2015	13165	12649.5	14889
10580.5	2.2949	11754	11276.5	13185.5
9513.5	2.3962	10471	10031	11649
8611.0	2.4977	9395.1	8986.7	10372.3
7841.3	2.5993	8486.1	8105.1	9300.4
7105.7	2.7129	7623.0	7268.8	8291.2
6612.7	2.8004	7048.8	6713.2	7626.1
6121.6	2.8989	6481.7	6165.1	6971.2
5681.5	2.9988	5976.7	5676.4	6390.3
5287.1	3.0997	5527.7	5243.6	5879.7
4939.7	3.1993	5132.5	4862.5	5432.2
4625.7	3.2998	4777.7	4520.8	5033.1
4344.8	3.3997	4463.5	4217.5	4680.6
4090.9	3.4995	4180.6	3945.2	4366.8
3859.7	3.5997	3924.0	3699.0	4082.5
3650.0	3.6995	3692.5	3476.8	3827.9
3457.9	3.7995	3482.0	3275.9	3597.2
3280.6	3.9001	3287.6	3089.0	3385.6
3119.1	3.9997	3112.2	2921.2	3194.9
2972.1	4.0977	2953.4	2769.9	3023.3
2829.8	4.2001	2799.9	2623.6	2858.0

[a] T is the temperature associated with the adjacent value of resistance for R_t, which was previously calibrated against T_{58} [2].

TABLE 7

Run 7

Calibration data for Resistor F, Resistor J, and Resistor I

R_t	T[a]	R_F	R_J	R_I
Ω	°K	Ω	Ω	Ω
13238	2.1019	15290	15228	17092.5
11745	2.2016	13364	13293.5	14873.5
10579.5	2.2949	11880.5	11807.0	13173.5
9509.8	2.3965	10532.0	10455.4	11632.6
8608.0	2.4981	9409.7	9336.2	10355.8
7843.9	2.5989	8472.0	8398.6	9297.2
7108.4	2.7124	7578.0	7509.6	8286.5
6609.3	2.8010	6979.5	6912.6	7615.6
6119.5	2.8993	6395.9	6332.4	6960.7
5680.5	2.9990	5880.2	5820.4	6384.4
5287.2	3.0996	5422.9	5366.3	5875.4
4938.4	3.1997	5018.7	4965.9	5427.2
4624.8	3.3001	4661.1	4611.4	5029.8
4345.4	3.3994	4342.6	4296.0	4680.1
4089.7	3.5000	4055.4	4011.6	4362.6
3859.9	3.5996	3799.7	3760.0	4081.6
3649.8	3.6996	3567.2	3530.2	3825.6
3457.3	3.7998	3355.6	3322.3	3594.6
3279.7	3.9006	3162.5	3131.4	3382.9
3118.7	3.9999	2987.0	2959.6	3192.4
2972.1	4.0977	2830.8	2805.2	3022.7
2830.1	4.1999	2678.2	2655.6	2856.5
2699.4	4.3013	2539.8	2519.1	2707.0
2579.6	4.4011	2414.4	2396.0	2571.2
2467.9	4.5008	2296.9	2280.6	2445.1
2363.1	4.6007	2187.8	2173.4	2327.3
2266.4	4.6991	2088.0	2075.3	2219.9
2173.0	4.8004	1992.0	1981.4	2116.6
2086.8	4.9001	1903.5	1894.2	2022.1
2005.1	5.0007	1820.7	1813.2	1932.9

[a] T is the temperature associated with the adjacent value of resistance for R_t, which was previously calibrated against T_{58} [2].

might otherwise arise in comparing the five individual calibrations of resistor I. Table 6 possesses no calibration data above 4.2 °K because obvious experimental difficulties,[3] which rendered the data invalid, occurred at calibration temperatures above 4.2 °K.

The calibration data for resistor I will be treated separately in a later section of the paper. The data for the other nine resistors has been subjected to computer fitting and analysis for a polynomial of the form

$$\log_{10} R = \sum_{n=0}^{m} A_n (\log_{10} T)^n.$$

The determined coefficients and their uncertainties are given in table 9. Again it is to be noted that: the calibrations of resistors in run VI cover a shorter temperature interval (2.1 to 4.2 °K); and the polynomial fitting of this data would be expected to produce coefficients that are significantly different from the coefficients representing the calibration of other resistors.

---

[3] The experimental difficulty applies to run 6 (table 6) only, and was connected with the determination of the current that flowed through the resistor circuit during the 4.3 to 5.0 °K calibration.

TABLE 8

Run 9

Calibration data for Resistor K, Resistor E, and Resistor I

R_1	T[a]	R_K	R_E	R_I
Ω	°K	Ω	Ω	Ω
13251	2.1011	14099	16802	17134
11750	2.2013	12377	14658	14889
10603	2.2928	11073	13043	13215
9519.2	2.3956	9845.9	11541	11645
8605.8	2.4984	8827.4	10291	10366
7845.3	2.5987	7979.3	9257.5	9302.0
7108.5	2.7124	7167.2	8273.2	8293.0
6615.9	2.7998	6628.7	7622.6	7626.2
6124.4	2.8983	6094.3	6979.8	6971.4
5683.6	2.9983	5616.8	6411.0	6392.9
5291.4	3.0985	5198.0	5908.8	5883.6
4946.7	3.1972	4827.1	5470.8	5440.2
4631.6	3.2978	4492.5	5075.0	5040.1
4350.9	3.3974	4195.7	4725.7	4688.3
4096.8	3.4971	3928.4	4411.8	4372.5
3865.3	3.5972	3686.7	4129.0	4088.7
3656.9	3.6961	3469.9	3876.4	3835.6
3465.5	3.7954	3271.4	3646.0	3605.0
3281.9	3.8993	3082.2	3426.8	3386.4
3120.3	3.9989	2916.5	3235.7	3195.7
2971.1	4.0984	2763.9	3060.6	3021.5
2827.7	4.2017	2618.0	2892.8	2855.2
2700.5	4.3004	2489.1	2745.6	2709.4
2580.8	4.4001	2368.1	2607.5	2572.8
2469.4	4.4994	2255.3	2479.6	2446.8
2363.8	4.6000	2150.2	2360.2	2329.3
2266.7	4.6988	2052.7	2250.1	2220.6
2173.8	4.7995	1960.1	2145.3	2117.9
2086.9	4.8999	1874.0	2048.9	2022.6
2006.4	4.9990	1794.5	1958.9	1934.7

[a] T is the temperature associated with the adjacent value of resistance for R_1, which was previously calibrated against T_{5H} [2].

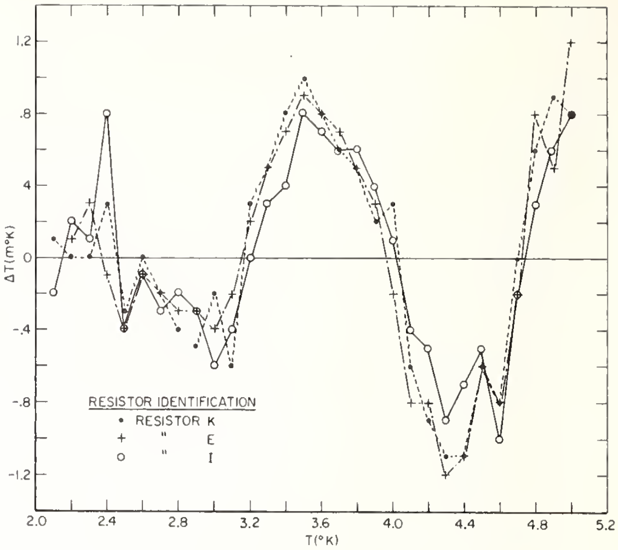


FIGURE 6. *Differences between the fitted functions,*

$$\log R=\sum_{n=0}^{3} A_n (\log T)^n$$

and the calibration data for resistors K, E, *and* I.

(a) See (a) of figure 4.

(b) The residual plots apply to the three resistors [K (.), E (+) and I (0)]; the calibration data for each resistor have been individually fitted to third order polynomials.

Similarities are to be detected in comparing the general characteristics of the coefficients in table 9. The third and fifth order polynomial fittings yield well determined coefficients while the fourth and sixth order coefficients, in some instances, leave much to be desired. The A_0's of the seventh order are generally not statistically significant.

The plots, for resistors K and E, in figures 6, 7, and 8 are representative of corresponding plots for resistors C, F, G, H, J, L, and M. That is, the systematic deviations (between the calibration data points [R_{data}, T_{data}] and the fitted functions [R_{calc}, T_{data}]) portrayed in figures 6 and 7 are most similar to residual plots of identical polynomial orders for the other seven resistors. The randomness of deviations for the seventh order polynomial (fig. 8) is also representative.

It is interesting to note that, with the exception of run VI, the corresponding coefficients for all of the resistors are generally of comparable magnitudes and identical signs. This observation is most pertinent to the coefficients of the third and fifth order polynomials, where the coefficients are properly significant; and, excepting A_0's, to the coefficients of the seventh order as well.

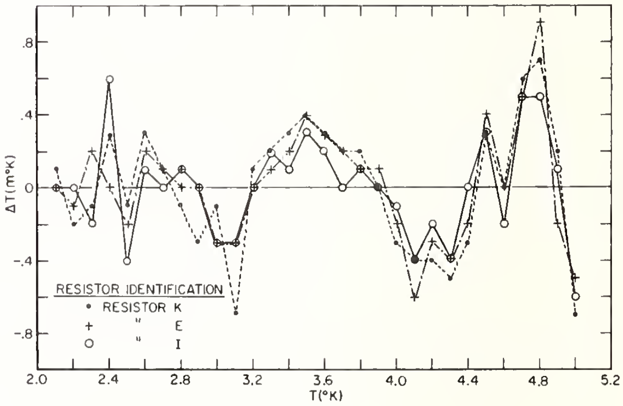


FIGURE 7. *Differences between the fitted functions,*

$$\log R=\sum_{n=0}^{5} A_n (\log T)^n$$

and the calibration data for resistors K, E, *and* I.

(a) See (a) of figure 4.

(b) The residual plots apply to the three resistors [K (.), E (+) and I (0)]; the calibration data for each resistor have been individually fitted to fifth order polynomials.

TABLE 9. *Coefficients determined from fitting the polynomial* $\log_{10} R = \sum_{n=0}^{m} A_n(\log_{10} T)^n$ *to the calibration data of resistors*

		Run III		Run V				Run VI				Run VII				Run IX			
		Resistor L		Resistor H		Resistor M		Resistor C		Resistor G		Resistor F		Resistor J		Resistor K		Resistor E	
		Coef.	δC[b]	Coef.	δC[b]	Coef.	δC[b]	Coef.	δC[b]	Coef.	δC[b]	Coef.	δC[b]	Coef.	δC[b]	Coef.	δC[b]	Coef.	δC[b]
$n=3$	A_0	5.367	(0.003)	5.328	(0.004)	5.280	(0.003)	5.330	(0.003)	5.317	(0.004)	5.388	(0.003)	5.398	(0.003)	5.319	(0.003)	5.439	(0.003)
	A_1	−4.638	(.02)	−4.538	(.02)	−4.478	(.02)	−4.486	(.02)	−4.467	(.03)	−4.683	(.02)	−4.724	(.02)	−4.597	(.02)	−4.733	(.02)
	A_2	3.522	(.04)	3.385	(.05)	3.492	(.03)	3.308	(.04)	3.196	(.06)	3.471	(.04)	3.466	(.04)	3.575	(.04)	3.542	(.04)
	A_3	−1.685	(.03)	−1.573	(.03)	−1.737	(.02)	−1.537	(.03)	−1.467	(.04)	−1.611	(.02)	−1.556	(.03)	−1.752	(.03)	−1.667	(.03)
	σ[a]	1.6×10^{-4}		1.8×10^{-4}		1.4×10^{-4}		8.5×10^{-5}		1.1×10^{-4}		1.4×10^{-4}		1.6×10^{-4}		1.6×10^{-4}		1.6×10^{-4}	
$n=4$	A_0	5.313	(.014)	5.285	(.017)	5.239	(.012)	5.385	(.014)	5.395	(.016)	5.343	(.012)	5.346	(.014)	5.271	(0.14)	5.385	(.014)
	A_1	−4.186	(.11)	−4.174	(.14)	−4.136	(.10)	−4.969	(.12)	−5.164	(.14)	−4.308	(.10)	−4.293	(.11)	−4.200	(.11)	−4.282	(.11)
	A_2	2.147	(.34)	2.276	(.43)	2.448	(.30)	4.884	(.40)	5.469	(.45)	2.329	(.29)	2.154	(.36)	2.364	(.35)	2.167	(.34)
	A_3	[.135]	(.45)	[−.104]	(.56)	[−.355]	(.40)	−3.787	(.56)	−4.711	(.65)	[−.099]	(.39)	[.182]	(.47)	[−.147]	(.46)	[.154]	(.45)
	A_4	−.885	(.22)	−.715	(.27)	−.672	(.20)	1.185	(.3)	1.709	(.34)	−.736	(.19)	−.845	(.23)	−.781	(.22)	−.886	(.22)
	σ[a]	1.3×10^{-4}		1.6×10^{-4}		1.1×10^{-4}		6.2×10^{-5}		7.2×10^{-5}		1.1×10^{-4}		1.3×10^{-4}		1.3×10^{-4}		1.3×10^{-4}	
$n=5$	A_0	5.588	(.04)	5.578	(.06)	5.466	(.04)	5.422	(.084)	5.412	(.097)	5.531	(.05)	5.580	(.06)	5.506	(.05)	5.642	(.04)
	A_1	−7.059	(.44)	−7.243	(.66)	−6.511	(.42)	−5.379	(.93)	−5.344	(1.1)	−6.273	(.48)	−6.733	(.58)	−6.662	(.55)	−6.968	(.46)
	A_2	13.94	(1.8)	14.87	(2.7)	12.19	(1.7)	[6.683]	(4.0)	[6.26]	(4.7)	10.389	(2.0)	12.164	(2.3)	12.466	(2.2)	13.19	(1.9)
	A_3	−23.65	(3.6)	−25.47	(5.4)	−19.98	(3.4)	[−7.677]	(8.7)	[−6.42]	(10.1)	−16.337	(4.0)	−19.984	(4.7)	−20.506	(4.5)	−22.05	(3.8)
	A_4	22.69	(3.6)	24.41	(5.4)	18.77	(3.4)	[5.340]	(9.3)	[3.53]	(11.)	15.347	(3.9)	19.128	(4.7)	19.39	(4.5)	21.11	(3.7)
	A_5	−9.198	(1.4)	−9.797	(2.1)	−7.580	(1.3)	[−1.753]	(3.9)	[−.78]	(4.6)	−6.270	(1.5)	−7.787	(1.8)	−7.864	(1.7)	−8.577	(1.4)
	σ[a]	7.7×10^{-5}		1.2×10^{-4}		7.6×10^{-5}		6.4×10^{-5}		7.5×10^{-5}		8.6×10^{-5}		1.0×10^{-4}		9.9×10^{-5}		8.3×10^{-5}	
$n=6$	A_0	6.015	(0.2)	6.197	(0.31)	5.656	(0.21)	3.992	(0.37)	3.941	(0.48)	5.7	(0.24)	5.9	(2.8)	5.8	(0.27)	6.03	(0.22)
	A_1	−12.43	(2.5)	−15.02	(3.9)	−8.89	(2.6)	13.69	(5.0)	14.27	(6.4)	−8.8	(3.)	−11.3	(3.5)	−10.3	(3.4)	−11.79	(2.7)
	A_2	41.63	(13.)	54.96	(20.)	[24.49]	(13.5)	−98.1	(27.)	−101.5	(35.)	[23.]	(15.)	35.66	(18.)	[31.]	(17.)	38.06	(14.)
	A_3	−98.72	(35.)	−134.2	(54.)	[−53.31]	(37.)	296.	(79.)	306.2	(101.)	[−52.]	(42.)	[−84.]	(49.)	[−71.]	(47.)	−89.49	(38.)
	A_4	135.6	(52.)	187.8	(80.)	[68.87]	(55.)	−485.	(127.)	−501.1	(162.)	[69.]	(62.)	[115.]	(73.)	[95.]	(71.)	122.5	(57.)
	A_5	−98.49	(41.)	−139.0	(63.)	[−47.20]	(43.)	416.	(108.)	429.3	(138.)	[−49.]	(49.)	[−83.]	(58.)	[−68.]	(56.)	−88.79	(45.)
	A_6	29.05	(13.)	42.01	(21.)	[12.9]	(14.)	−147.	(38.)	−151.2	(49.)	[14.]	(16.)	[25.]	(19.)	[20.]	(18.)	[26.09]	(15.)
	σ[a]	7.2×10^{-5}		1.1×10^{-4}		7.6×10^{-5}		4.7×10^{-5}		6.0×10^{-5}		8.6×10^{-5}		1.0×10^{-4}		9.8×10^{-5}		7.9×10^{-5}	
$n=7$	A_0	1.635	(0.5)	[1.780]	(1.4)	1.371	(0.66)	[3.8]	(2.3)	[4.3]	(3.0)	[1.396]	(0.9)	[.545]	(1.0)	[.305]	(0.8)	2.353	(0.9)
	A_1	51.82	(7.5)	49.78	(20.)	53.96	(9.7)	[16.]	(36.)	[9.]	(46.)	54.79	(13.)	67.86	(14.6)	70.26	(12.)	42.10	(13.)
	A_2	−357.2	(46.)	−347.2	(124.)	−365.7	(60.)	[−116.]	(238.)	[−68.]	(303.)	−371.3	(83.)	−455.6	(90.)	−469.	(75.)	−296.5	(77.)
	A_3	1260.	(157.)	1236.	(419.)	1276.	(203.)	[362.]	(863.)	[183.]	(1100.)	1292.5	(280.)	1589.	(306.)	1633.	(256.)	1051.	(263.)
	A_4	−2607.	(316.)	−2578.	(845.)	−2614.	(408.)	[−629.]	(1860.)	[−235.]	(2400.)	−2645.	(564.)	−3262.	(620.)	−3346.	(516.)	−2180.	(529.)
	A_5	3184.	(378.)	3172.	(1010.)	3165.	(488.)	[601.]	(2390.)	[87.]	(3060.)	3200.	(674.)	3959.	(736.)	4053.	(616.)	2669.	(632.)
	A_6	−2129.	(248.)	−2135.	(663.)	−2099.	(321.)	[−278.]	(1700.)	[91.]	(2200.)	−2122.	(443.)	−2633.	(484.)	−2691.	(405.)	−1788.	(415.)
	A_7	601.3	(69.)	606.9	(185.)	589.	(89.)	[39.]	(510.)	[−73.]	(650.)	595.3	(123.)	740.7	(135.)	756.	(113.)	505.6	(116.)
	σ[a]	3.4×10^{-5}		9.3×10^{-5}		4.5×10^{-5}		4.9×10^{-5}		6.2×10^{-5}		6.2×10^{-5}		6.8×10^{-5}		5.8×10^{-5}		5.9×10^{-5}	

[a] σ is the standard deviation computed from the residuals resulting from the polynomial least squares fitting.
[b] δC is the standard error of the adjacent coefficient.
[ ] Statistically, the bracketed coefficients are poorly determined.

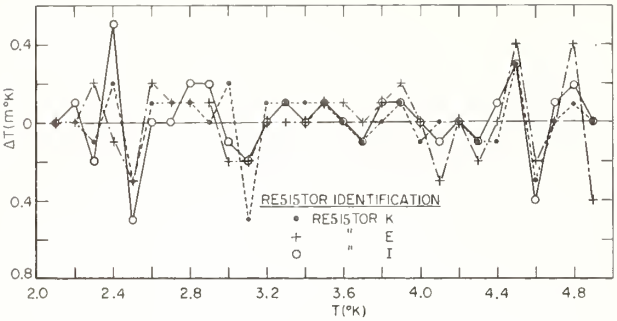


FIGURE 8. *Differences between the fitted functions,*

$$log\ R = \sum_{n=0}^{7} A_n\ (log\ T)^n,$$

and the calibration data for resistors K, E, *and* I.

(a) See (a) of figure 4.
(b) The residual plots apply to the three resistors [K (.), E (+) and I (0)]; the calibration data for each resistor have been individually fitted to seventh order polynomials.

5.3. Analysis of the Control Resistor Data

The five individual calibrations of resistor I have been afforded a separate consideration since this resistor served as a "control" through all of the reported calibrations. Its values of resistance, when compared with the corresponding values for resistor #1 (or more appropriately temperatures derived from resistor #1), indicated that all calibrations of resistor I were consistant within ±0.0007 °K. While no progressive drifting of the calibrations was observed (from Run III to IX), Run VII accounted for the largest portion of the maximum calibration deviation within the group of five runs; we are unable to ascertain specific causes for this occurrence.

The calibration data for resistor I have been functionally fitted in the same manner as was described in 5.1. Each of the five calibrations was treated independently and the resulting coefficients are listed in table 10. (The statistical uncertainty of each coefficient is within the adjacent parenthesis.) Since the coefficients of Run VI (table 9) are based upon calibration data that terminated at 4.2 °K, one must be cautious in comparing these coefficients with those of the other four calibration runs. Consequently, the general comparison between corresponding coefficients will be limited to Runs III, V, VII, and IX. Several conclusions are readily apparent.

(a) Third order fittings—the four coefficients are in excellent agreement (within, of course, the limits of

TABLE 10. *Coefficients determined from fitting the polynomial* $log_{10}\ R = \sum_{n=0}^{m} A_n(log_{10}T)^n$ *to the calibration data of resistor I*

	Run III		Run V		Run VI		Run VII		Run IX		Combined data	
	Resistor	IδC[b]	Resistor	IδC[b]	Resistor	IδC[b]	Resistor	IδC[b]	Resistor	IδC[b]	Resistor	IδC[b]
A_0	5.473	(0.0036)	5.473	(0.003)	5.459	(0.004)	5.474	(0.0027)	5.476	(0.0034)	5.473	(0.002)
A_1	−4.806	(.02)	−4.805	(.020)	−4.713	(.025)	−4.815	(.017)	−4.823	(.0206)	−4.806	(.011)
A_2	3.488	(.04)	3.487	(.039)	3.289	(.054)	3.508	(.033)	3.522	(.0409)	3.489	(.022)
A_3	−1.556	(.03)	−1.555	(.025)	−1.416	(.038)	−1.569	(.021)	−1.577	(.026)	−1.556	(.014)
σ[a]	1.7×10^{-4}		1.5×10^{-4}		1.0×10^{-4}		1.2×10^{-4}		1.6×10^{-4}		1.8×10^{-4}	
A_0	5.425	(.015)	5.426	(.013)	5.521	(.017)	5.441	(.012)	5.454	(.017)	5.438	(.008)
A_1	−4.404	(.13)	−4.42	(.11)	−5.265	(.15)	−4.540	(.10)	−4.639	(.14)	−4.512	(.070)
A_2	2.265	(.39)	2.31	(.34)	5.089	(.49)	2.671	(.31)	2.962	(.42)	2.590	(.21)
A_3	[.0632]	(.51)	[.0008]	(.44)	− 3.985	(.7)	[−.460]	(.41)	[−.835]	(.55)	[−.363]	(.28)
A_4	−.787	(.25)	−.76	(.22)	1.354	(.37)	−.539	(.20)	[−.361]	(.27)	−.582	(.14)
σ[a]	1.4×10^{-4}		1.3×10^{-4}		8×10^{-5}		1.2×10^{-4}		1.6×10^{-4}		1.7×10^{-4}	
A_0	5.724	(.05)	5.710	(.04)	5.714	(.094)	5.653	(.046)	5.780	(.053)	5.714	(.035)
A_1	−7.539	(.51)	−7.386	(.38)	−7.407	(1.03)	−6.757	(.47)	−8.045	(.55)	−7.409	(.37)
A_2	15.14	(2.1)	14.48	(1.5)	14.48	(4.5)	11.765	(1.9)	16.936	(2.2)	14.50	(1.5)
A_3	−25.89	(4.2)	−24.52	(3.1)	−24.30	(9.8)	−18.782	(3.9)	−29.00	(4.5)	−24.43	(3.0)
A_4	24.94	(4.2)	23.53	(3.0)	23.05	(10.4)	17.607	(3.8)	27.54	(4.4)	23.31	(3.0)
A_5	−10.04	(1.6)	−9.47	(1.2)	−9.154	(4.4)	−7.074	(1.5)	−10.88	(1.7)	−9.34	(1.2)
σ[a]	9.0×10^{-5}		6.7×10^{-5}		7.2×10^{-5}		8.4×10^{-5}		9.8×10^{-5}		1.4×10^{-4}	
A_0	5.966	(0.25)	5.98	(.18)	4.069	(0.41)	5.60	0.24	6.09	.27	5.89	0.18
A_1	−10.57	(3.1)	−10.8	(2.3)	14.536	(5.4)	16.04	(3.0)	−11.98	(3.4)	−9.61	(2.3)
A_2	[30.78]	(16.)	32.0	(11.7)	−106.14	(30.)	[8.06]	(15.)	37.21	(17.4)	25.86	(11.7)
A_3	[−68.31]	(43.)	−71.9	(32.)	325.5	(86.)	[−8.73]	(41.)	[−84.00]	(47.0)	[−55.27]	(32.)
A_4	[88.7]	(65.)	94.7	(47.4)	−541.6	(138.)	[2.51]	(62.)	[110.2]	(70.5)	[69.8]	(47.)
A_5	[−60.5]	(51.)	[−65.8]	(37.4)	472.1	(118.)	[4.87]	(49.)	[−76.267]	(55.7)	[−46.]	(38.)
A_6	[16.4]	(17.)	[18.3]	(12.1)	−169.2	(41.)	[−3.88]	(16.)	[21.3]	(18.1)	[12.]	(12.)
σ[a]	9.0×10^{-5}		6.6×10^{-5}		5.1×10^{-5}		8.6×10^{-5}		9.8×10^{-5}		1.4×10^{-4}	
A_0	[0.193]	(0.5)	2.0915	(.51)	[2.7]	(2.5)	2.049	(1.1)	3.015	(1.3)	1.857	(0.90)
A_1	74.11	(7.4)	46.26	(7.4)	[35.]	(39.)	45.98	(15.)	33.18	(18.7)	49.60	(13.1)
A_2	−495.	(46.)	−322.	(46.)	[−244.]	(255.)	−314.8	(95.)	−243.2	(116.)	−342.1	(81.2)
A_3	1722.	(155.)	1134.	(155.)	[828.]	(926.)	1091.	(322.)	871.4	(394.)	1200.	(276.)
A_4	−3526.	(312.)	−2340.	(313.)	[−1628.]	(2000.)	−2217.	(649.)	−1819.	(793.)	−2467.	(557.)
A_5	4266.	(373.)	2849.	(374.)	[−1870.]	(2568.)	2661.	(775.)	2234.	(948.)	2995.	(666.)
A_6	−2828.	(245.)	−1899.	(246.)	[−1160.]	(1819.)	−1750.	(509.)	−1499.	(623.)	−1990.	(438.)
A_7	793.	(68.)	534.	(68.)	[299.]	(548.)	4867.	(142.)	424.	(174.)	559.	(1.22)
σ[a]	3.4×10^{-5}		3.5×10^{-5}		5.2×10^{-5}		7.1×10^{-5}		8.9×10^{-5}		1.3×10^{-4}	

[a] σ is the standard deviation computed from the residuals resulting from the polynomial least squares fitting.
[b] δC is the standard error of the adjacent coefficient.
[ ] Statistically, the bracketed coefficients are poorly determined.

the stated statistical uncertainties). Furthermore, the ratio of an individual coefficient to its respective uncertainty indicates rather well defined coefficients, and the standard deviations of the individual least squares fittings are comparable.

(b) Fourth order fittings—while similarities exist between some coefficients, two features clearly indicate that this order of polynomial fitting presents no advantage. The A_3's are not defined, and the standard deviations, σ, show little improvement over the third order of fittings.

(c) Fifth order fittings—the coefficients, with respect to their statistical uncertainties, are clearly not as well defined as those of the third order polynomial; but the ratios are generally greater than six to one. More important, the standard deviations in polynomial fitting have materially improved over the third order thus indicating the superiority of the fifth degree for representing the calibration data. Here also, most of the corresponding coefficients i.e., A_0's, . . . A_5's, are nearly identical within the limits of their statistical uncertainties. Those from run VII exhibit noticeable divergencies; several paragraphs earlier we pointed out that the calibration data for run VII exhibited maximum variance with the other calibrations.

(d) Sixth order fittings—clearly, a sixth order polynomial produces no beneficial result.

(e) Seventh order fitting—while we should like to employ a seventh order polynomial for the data representation, the inconsistencies of the coefficients (A_0 and A_1 in particular) for run III clearly imply the possibility of its impropriety.

The polynomial coefficients for run VI, where the data is terminated at the upper limit of 4.2 °K, generally exhibit different qualitative trends, but are in quantitative agreement with the corresponding coefficients of the other runs for the fifth order polynomial. The general conclusion, which may be drawn from the comparison of the determined coefficients, strongly suggests that a fifth order polynomial offers a consistant representation for all of the calibration data (for resistor I) and that the standard deviation of such a fitting is about 9×10^{-5}. Deviations of the individual data points (Resistor I) from the fitted third order polynomial (run IX) are shown in figure 6. The curves' significant features are duplicated, within a spread of ± 0.0002 °K, for the corresponding representations of runs III, V, and VII. In the case of run VI, the general departures from the base line are reduced in size.

Figure 7, which portrays the deviations of individual data points (Resistor I) from the fitted fifth order polynomial (run IX), is also representative of the other complete calibrations of resistor I. While it exhibits systematic deviations, they are much less than those exhibited in figure 6. A comparable plot (figure 8), associated with the seventh order polynomial, exhibits a random distribution; although this condition is desirable, the indeterminacy of run III's seventh order coefficients causes us to hesitate in advocating use of the seventh order polynomial for representing this calibration data.

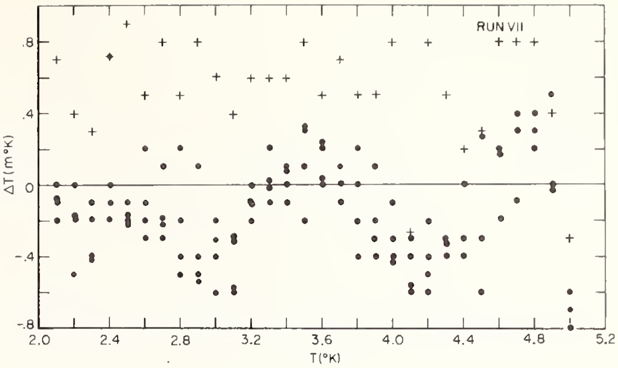


FIGURE 9. *Differences between the fitted function,*

$$\log R = \sum_{n=0}^{5} A_n (\log T)^n,$$

and all of the calibration data for resistor I.

(a) See (a) of figure 4.

(b) The residual plots apply to all of resistor I's calibration data (Runs III, V, VI, VII, and IX) which have been fitted to a fifth order polynomial. Residuals for Run VII are specifically identified (+).

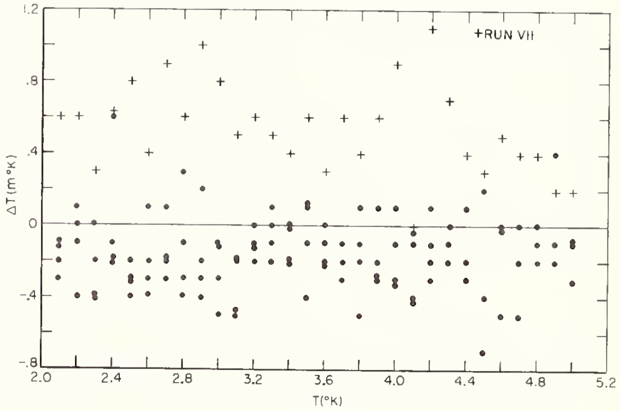


FIGURE 10. *Differences between the fitted function,*

$$\log R = \sum_{n=0}^{7} A_n (\log T)^n$$

and all of the calibration data for resistor I.

(a) See (a) of figure 4.

(b) The residual plots apply to all of resistor I's calibrated data (Runs III, VI, VII, and IX) which have been fitted to a seventh order polynomial. Residuals for Run VII are specifically identified.

In summary, the preceeding paragraphs have indicated that through the five calibration runs: the reference resistor #1 and the control resistor I have exhibited relative calibration constancies that are within a temperature equivalent of ±0.0007 °K; additionally, for I, the third and fifth order polynomial coefficients are consistantly determined within the limits of their computed uncertainties.

Recognizing that the polynomial fittings of individual calibrations for I are somewhat restrictive in intercomparisons between different calibrations, we have "polyfitted" all of the resistor I data. The resulting coefficients, listed in the last column of table 10, are generally not significantly different (within the limits of the coefficients' uncertainties) from the coefficients of runs III, V, VII, and IX. Figures 9 and 10 are plots of deviations between the calibration data (R_{data}, T_{data}) and the fitted polynomials (R_{calc}, T_{data}) for the 5th and 7th order polynomials respectively. It is obvious in both plots that the data points from run VII consistently deviate from the rest of the calibration data and this accounts for the increased standard deviation that appears in the polynomial fittings of the last column. For each calibration temperature in figures 9 and 10 it is apparent that all of the calibrations agree within ±0.0007 °K.

As a final criterion on the general validity of calibrations within the calibrator we have spot-checked the calibrations of run IX. Resistors I, K, and E were calibrated directly against helium-4 vapor pressures, in a constant temperature bath, at 2.2, 3.0, and 4.2 °K. Comparisons were made with the previous calibrations of run IX and the calibration differences (in temperature equivalents) are shown in table 11. Overall, the agreement between the calibrations is reasonable although the discrepancies at 4.2 and 3.0 °K for resistor I are somewhat large.

TABLE 11. *Intercomparison of colibrotions from two methods* [a]

	Temperature difference		
4.2 °K	*mdeg* [b] +1.4	*mdeg* [b] +0.2	*mdeg* [b] −0.75
3.0 °K	−1.2	0.0	−0.7
2.2 °K	+0.5	+0.2	−0.1
	Resistor I [c]	Resistor K [c]	Resistor E [c]

[a] Method A—the resistors were calibrated within the calibrator against resistor #1.

Method B—the resistors were calibrated within a "constant temperature" liquid helium bath against T_{58} [2] by means of vapor pressure measurements.

[b] The positive sign (+) means, for the same value of resistance, T (°K) of method B is greater than T (°K) of method A.

[c] Previous thermal histories indicated that, under 86 thermal cyclings between ambient temperatures and 4.2 °K, the 4.2 °K calibrations of resistors I, K, and E were reproducible to 0.8, 1.1 and 1.0 mdeg respectively.

6. Conclusions

We have shown that the resistance-temperature calibration (from 2.1 to 5.0 °K) for a particular group of ten similar germanium resistors can be represented by a polynomial function within the approximate limits of the calibration errors. In each case, based upon appropriate polynomial coefficients (fourth degree polynomials for resistors C and G, and fifth degree for the rest), generations of R, $\frac{dR}{dT}$ and $\frac{d^2R}{dT^2}$ as a function of T (every 0.010 °K) have demonstrated that the determined polynomials are smooth (within the range 2.1 to 5.0 °K); the first and second derivatives do not change sign. While these conclusions are encouraging for the prospects of employing a fitted polynomial function to interpolate between calibration points, it should be stressed that the results apply to a select group of resistors. Also, caution should be employed in any attempts to use the polynomials for extrapolations beyond the calibration region.

The type of polynomial that has been used in this work,

$$\log_{10} R = \sum_{n=0}^{m} A_n (\log_{10} T)^n,$$

has been selected somewhat arbitrarily. There is no theoretical basis for selecting this polynomial to represent the resistors' calibration data, and the fitting of the polynomial has been an empirical procedure that is applicable to the limited range of calibration data. The values of the determined A_0's for any given resistor in table 10, indicate the inappropriateness of extrapolations based upon the determined polynomials. Additionally, when we have occasionally performed R, $\frac{dR}{dT}$ and $\frac{d^2R}{dT^2}$ generations (based on fitted polynomials) that extended beyond the calibration range, we found that the functions became erratic at external temperatures.

We believe that the polynomial, which we have employed, is not necessarily the most appropriate function for representing the calibration data of these resistors. However it does serve as an interpolation aid that can be cautiously used until a more meaningful representation is achieved. In the immediate future we shall seek to find improved functions not only for the data presented in this paper but for more extensive calibration data (2.3 to 20 °K) that we have previously published [1].

7. References

[1] M. H. Edlow and H. H. Plumb, J. Res. NBS **70C** (Eng. and Instr.), No. 4, 245 (1966).

[2] F. G. Brickwedde, H. van Dijk, M. Durieux, J. R. Clement, and J. K. Logan, J. Res. NBS **64A** (Phys. and Chem.), No. 1, 1 (1960).

[3] G. Cataland, M. H. Edlow, and H. H. Plumb, Rev. Sci. Instr. **32,** 980 (1961); W. G. Brombacher, D. P. Johnson, and J. L. Cross, NBS Monograph **8** (1960).

[4] G. Cataland, M. H. Edlow, and H. H. Plumb, in Temperature, Its Measurement and Control in Science and Industry, C. M. Herzfeld, ed., **3,** F. G. Brickwedde, ed., Pt. 1, 413 (Reinhold Publishing Corp., New York, 1962).

[5] M. Durieux, Thesis, University of Leiden (1960); M. H. Edlow and H. H. Plumb in Advances in Cryogenic Engineering, K. D. Timmerhaus, ed. **6,** 542 (Plenum Press, Inc., New York, 1961).

[6] K. W. Taconis, J. J. Beenakker, A. O. C. Nier, and L. T. Aldrich, Physica **15,** 733 (1949); H. A. Kramers, ibid, p. 971; D. A. Ditmars and G. T. Furukawa, J. Res. NBS **69C** (Phys. and Chem.), No. 1, 35 (1965).

[7] E. Ambler and H. H. Plumb, Rev. Sci. Instru. **31,** 656 (1960).

(Paper 71C1–441)

Thermoelectric Thermometry

Thermoelectric Thermometry*

By Wm. F. Roeser

National Bureau of Standards, Washington, D. C.

The fundamental laws and theories of thermoelectric phenomena and their historical development as well as the application of these phenomena to the measurement of temperature are discussed in this paper in considerable detail. Thermoelectric thermometry, with particular regard to types of thermocouples, protection of thermocouples, fundamental considerations in temperature measurements, etc. are treated primarily from the practical standpoint.

I. Introduction

STUDY in the field of thermoelectricity began in 1821 with the discovery of Seebeck[1] that an electric current flows continuously in a closed circuit of two dissimilar metals when the junctions of the metals are maintained at different temperatures. In the early investigations of thermoelectric effects the results were expressed more qualitatively (in terms of the direction of the current flowing in a closed circuit) than quantitatively, because the relations between the measurable quantities in an electric circuit were not well known at the time.†

II. Fundamental Laws

As a result of a large number of investigations of thermoelectric circuits in which accurate measurements were made of the electromotive force, current, and resistance, several "established facts" or "laws" have been formulated. These facts or laws, variously stated in different ways and combinations and sometimes consolidated into a general statement of the phenomenon discovered by Seebeck, can be reduced to three fundamentals:

(1) The law of the homogeneous circuit
(2) The law of intermediate metals
(3) The law of successive or intermediate temperatures.

The latter two may be arrived at by applying the laws of thermodynamics to the thermoelectric circuit, but the fundamental experimental fact regarding a homogeneous circuit, which enters into all measurements of temperature by thermoelectric methods, cannot be derived from such considerations. The law of the homogeneous circuit is incorporated into most statements of the law of intermediate metals. In any case all of these facts or laws, as stated below and used in the measurement of temperatures, have been established experimentally beyond a reasonable doubt and in order that temperatures may be measured by this method the laws must be accepted in spite of any lack of rigor that may appear in any of the thermodynamic derivations given here or elsewhere.

The discussion will be simplified by defining a few terms at this point. It will be considered that all the metals comprising a thermoelectric circuit are solids unless otherwise stated.

A pair of electrical conductors so joined as to produce a thermal e.m.f. when the junctions are at different temperatures is known as a thermocouple. The resultant e.m.f. developed by the thermocouples generally used for measuring temperatures ranges from 1 to 7 millivolts when the temperature difference between the junctions is 100°C.

If in a simple thermoelectric circuit, Fig. 1, the current flows from metal *A* to metal *B* at the colder junction, *A* is generally referred to as thermoelectrically positive to *B*. In determining or expressing the e.m.f. of a thermocouple as a

---

* Presented at the American Institute of Physics Symposium on Temperature, Its Measurement and Control in Science and Industry, November 4, 1939.

† The relation between the current and potential difference in an electric circuit was first clearly stated by G. S. Ohm in 1826. Schweigger's J. 46, 137 (1826).

Reprinted from Journal of Applied Physics, Vol. 11, No. 6, 388–407, June, 1940

function of the temperature, one junction is maintained at some constant reference temperature, such as 0°C, and the other is at the temperature corresponding to the e.m.f. In the present paper, the order in which the metals are named and the sign of the numerical value of the e.m.f. will be used to indicate which of the metals is positive to the other at the junction which is at the reference temperature. For example, if, in Fig. 1, T_1 is the reference temperature and the current flows in the direction indicated, the e.m.f. of thermocouple AB will be positive, and the e.m.f. of thermocouple BA will be negative.

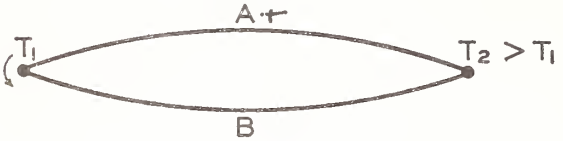


FIG. 1. Simple thermoelectric circuit.

1. THE LAW OF THE HOMOGENEOUS CIRCUIT

An electric current cannot be sustained in a circuit of a single homogeneous metal, however varying in section, by the application of heat alone. As far as we know this principle has not been derived theoretically. It has been claimed from certain types of experiments that a nonsymmetrical temperature gradient in a homogeneous wire gives rise to a galvanometrically measurable thermoelectric e.m.f. However, the overwhelming weight of evidence indicates that any e.m.f. observed in such a circuit is to be attributed to the effects of local inhomogeneities. As a matter of fact, at the present time any current detected in such a circuit when the wire is heated in any way whatever, is taken as evidence that the wire is inhomogeneous. The more important of a large number of investigations of this subject are adequately discussed by Foote and Harrison.[2]

In the present paper, we accept, as an experimental fact, the general statement that the algebraic sum of the electromotive forces in a circuit of a single homogeneous metal however varying in section and temperature is zero. As a consequence of this fact, if one junction of two dissimilar homogeneous metals is maintained at a temperature T_1 and the other junction at a temperature T_2, the thermal e.m.f. developed is independent of the temperature gradient and distribution along the wires.

2. LAW OF INTERMEDIATE METALS

This law is stated in one of several ways, and although the statements may appear quite different, they are really equivalent with the exception that the law of the homogeneous circuit is included in some of the statements. One statement of this law is: *The algebraic sum of the thermoelectromotive forces in a circuit composed of any number of dissimilar metals is zero, if all of the circuit is at a uniform temperature.* This law follows as a direct consequence of the second law of thermodynamics, because if the sum of the thermoelectromotive forces in such a circuit were not zero, a current would flow in the circuit. If a current should flow in the circuit, some parts of it would be heated and other parts cooled, which would mean that heat was being transferred from a lower to a higher temperature without the application of external work. Such a process is a contradiction of the second law of thermodynamics and therefore we conclude that the algebraic sum of the thermoelectromotive forces is zero in such a circuit.

Combining this law with that for a homogeneous circuit, it is seen that in any circuit, if the individual metals between junctions are homogeneous, the sum of the thermal electromotive forces will be zero provided only that the junctions of the metals are all at the same temperature.

Another way of stating the law of intermediate metals is:

If in any circuit of solid conductors the temperature is uniform from any point P through all the conducting matter to a point Q, the algebraic sum of the thermoelectromotive forces in the entire circuit is totally independent of this intermediate matter and is the same as if P and Q were put in contact. Thus it is seen that a device for measuring the thermoelectromotive force may be introduced into a circuit at any point without altering the resultant e.m.f. provided that the junctions which are added to the circuit by introducing the device are all at the same temperature. It is also obvious that the e.m.f. in a thermoelectric circuit is independent of the method employed in forming the junction as long as all of the junction is at a uniform temperature, and the two wires make good electrical contact at the junction, such as is obtained by welding or soldering.

A third way of stating the law of intermediate metals is:

The thermal e.m.f. generated by any thermocouple AB with its junctions at any two temperatures T_1 *and* T_2, *is the algebraic sum of the e.m.f. of a thermocouple composed of A and any metal C and that of one composed of C and B, both with their junctions at* T_1 *and* T_2 or $E_{AB}=E_{AC}+E_{CB}$.

From this statement of the law it is seen that if the thermal e.m.f. of each of the metals *A*, *B*, *C*, *D*, etc. against some reference metal is known, then the e.m.f. of any combination of these metals can be obtained by taking the algebraic differences of the e.m.f.'s of each of the metals against the reference metal. Investigators tabulating thermoelectric data have employed various reference metals such as mercury, lead, copper, and platinum. At present it is customary to use platinum because of its high melting point, stability, reproducibility, and freedom from transformation points.

3. LAW OF SUCCESSIVE OR INTERMEDIATE TEMPERATURES

The thermal e.m.f. developed by any thermocouple of homogeneous metals with its junctions at any two temperatures T_1 *and* T_3 *is the algebraic sum of the e.m.f. of the thermocouple with one junction at* T_1 *and the other at any other temperature* T_2 *and the e.m.f. of the same thermocouple with its junctions at* T_2 *and* T_3. Considering the thermocouple as a reversible heat engine and applying the laws of thermodynamics to the circuit, it will be shown in the next section that

$$E=\int_{T_1}^{T_3}\phi dT,$$

from which it follows that

$$E=\int_{T_1}^{T_2}\phi dT+\int_{T_2}^{T_3}\phi dT.$$

This law is frequently invoked in the calibration of thermocouples and in the use of thermocouples for measuring temperatures. It will be discussed in detail in Section IV.

The above are all the fundamental laws required in the measurement of temperatures with thermocouples. They may be and frequently are combined and stated as follows: The algebraic sum of the thermoelectromotive forces generated in any given circuit containing any number of dissimilar homogeneous metals is a function only of the temperatures of the junctions. It is seen then that if all but one of the junctions of such a given circuit are maintained at some constant reference temperature, the e.m.f. developed in the circuit is a function of the temperature of that junction only. Therefore, by the proper calibration of such a device, it may be used to measure temperatures.

It should be pointed out here that none of the fundamental laws of thermoelectric circuits which make it possible to utilize thermocouples in the measurement of temperatures, depends upon any assumption whatever regarding the mechanism of interconversion of heat and electrical energy, the location of the e.m.f.'s in the circuit, or the manner in which the e.m.f. varies with temperature.

III. Historical Investigation and Theory

Although a knowledge of the location of the electromotive forces in a thermoelectric circuit and the mechanism by which heat is converted into electrical energy, is not required in order to measure temperatures with thermocouples, any information available on these subjects may be used advantageously in studying the characteristics of thermocouples and their behavior during use. Various theoretical and experimental investigations of thermoelectric circuits give us the location of the electromotive forces in such a circuit, and the relation between these electromotive forces, but they have not yielded a satisfactory explanation of the mechanism by which heat is converted into electrical energy or of the manner in which the electromotive force varies with temperature, except empirical relations.

In 1834 Peltier[3] found that when a current is passed across the junction of two dissimilar metals in one direction heat is absorbed and the junction cooled, and that when the current is passed in the opposite direction the junction is heated. Peltier and others observed that for a given current the rate of absorption or liberation of heat at the junction of two dissimilar metals depends upon the thermoelectric power (dE/dt) of the two metals and is independent of the form and dimensions of the metals at the junction. In 1853 Quintus Icilius[4] showed that the rate at which heat is absorbed or generated at a junction of two dissimilar metals is proportional to the current. This heating or cooling effect discovered by Peltier should not be confused with the Joule heating effect which, being proportional to the electrical resistance and to the square of the current, depends upon the dimensions of the conductor and does not change sign when the current is reversed.

Inasmuch as heat is absorbed when a current flows up a potential gradient and heat generated when the current flows down a potential gradient, the heating or cooling effect at a junction of two dissimilar metals (being proportional to the current) is evidence that the junction is the seat of an electromotive force. If we let P be the rate at which heat (in joules per second or in watts) is generated or absorbed when a current of one ampere flows across a junction, then P is the Peltier coefficient of the junction (in watts per ampere) or more simply the Peltier e.m.f. (in volts). The direction and magnitude of this e.m.f. depend upon the metals which form the junctions and upon the temperature.

In 1851, W. Thomson[5] (later Lord Kelvin) concluded from thermodynamic reasoning and the then known characteristics of thermocouples, that the reversible absorption of heat at the junctions of dissimilar metals was not the only reversible heat effect in a thermoelectric circuit. In brief he reasoned as follows:

(1) Assuming that the Peltier e.m.f.'s represent the only reversible effects in a simple thermoelectric circuit, the resultant e.m.f. E in the circuit is given by

$$E=P_2-P_1, \tag{1}$$

where P_1 is the Peltier e.m.f. of the junction which is at temperature T_1 and P_2 is the Peltier e.m.f. of the junction which is at temperature T_2.

(2) Neglecting the effect of thermal conduction (an irreversible process) and considering the thermocouple as a reversible heat engine with a source at the temperature T_2 in degrees Kelvin and a sink at the temperature T_1, we have as a consequence of the second law of thermodynamics

$$P_2/T_2-P_1/T_1=0 \tag{2}$$

or

$$(P_2-P_1)/P_1=(T_2-T_1)/T_1, \tag{3}$$

which combined with (1) gives

$$E=P_1(T_2-T_1)/T_1. \tag{4}$$

It would follow therefore that if one junction were maintained at a constant temperature T_1, P_1 would be constant, and the e.m.f. E would be proportional to (T_2-T_1). It had been definitely shown by a number of investigators that E was not proportional to (T_2-T_1). Thomson therefore concluded that the Peltier effects were not the only reversible heat effects in such a circuit and that there must be a reversible absorption of heat due to the flow of current through that part of the conductors in which there is a temperature gradient.

In 1854 Thomson[6] succeeded in showing experimentally that in certain homogeneous metals, heat is absorbed when an electric current flows from colder to hotter parts of the metal and heat is generated when the current flows from the hotter to colder parts. In certain other metals the opposite of this effect occurs, that is, heat is absorbed when an electric current flows from the hotter to colder parts, and in still other metals, the effect is too small to be detected by the methods used. This heating or cooling effect, called the Thomson effect, being reversible and occurring only where there is a temperature gradient in a metal, is entirely distinct from the irreversible Joule heating.

The reversible absorption of heat in a homogeneous conductor has the same effect as if an electromotive force existed in the temperature gradient. The direction and magnitude of this e.m.f. between any two points depend upon the metal, the temperature, and the temperature difference between the two points. If in any metal we let σ equal the rate at which heat is absorbed or generated per unit difference of temperature when a current of one ampere flows, then the total e.m.f. between any two points at temperatures T_1 and T_2 is given by

$$\int_{T_1}^{T_2} \sigma dT.$$

In a simple thermoelectric circuit of two metals A and B, Fig. 2, there exist then four separate and distinct electromotive forces, the Peltier e.m.f.'s at the two junctions and the Thomson e.m.f.'s along that part of each wire which lies in the temperature gradient. The only e.m.f. that can be measured as such in this circuit is the resultant e.m.f. The identity of the individual e.m.f.'s can only be established by observations of the reversible heat effects. The Thomson e.m.f. will be considered positive if heat is generated when the current flows from the hotter to colder parts of the conductor and negative if the reverse occurs.

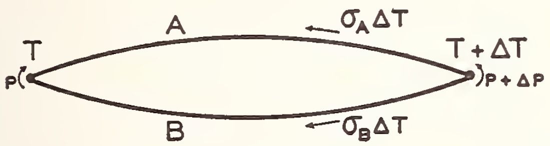


FIG. 2. The location of the electromotive forces in a thermoelectric circuit.

Thomson took into consideration the reversible heat effects in the temperature gradient of the conductors, (Thomson effects), as well as those at the junctions, (Peltier effects), and applied the laws of thermodynamics to the thermoelectric circuit. A complete discussion of this application together with the hypothesis involved is given in the original paper by Thomson.[7]

Consider a simple thermoelectric circuit of two metals A and B, Fig. 2 and let P and $P+\Delta P$ be the Peltier e.m.f.'s of the junctions at temperature T and $T+\Delta T$ in degrees Kelvin, respectively, and let σ_A and σ_B be the Thomson e.m.f.'s per degree along conductors A and B, respectively. Let the metals and temperatures be such that the e.m.f.'s are in the directions indicated by the arrows. The resultant e.m.f. ΔE in the circuit is given by

$$\Delta E = P + \Delta P - P + \sigma_A \Delta T - \sigma_B \Delta T, \tag{5}$$

$$\Delta E = \Delta P + (\sigma_A - \sigma_B)\Delta T, \tag{6}$$

or in the limit

$$dE/dT = dP/dT + (\sigma_A - \sigma_B). \tag{7}$$

By virtue of the second law of thermodynamics $\Sigma Q/T = 0$, for a reversible process. If then we regard the thermocouple as a reversible heat engine and pass a unit charge of electricity q around the circuit, we obtain by considering only the reversible effects*

$$\frac{q(P+\Delta P)}{T+\Delta T} - \frac{qP}{T} + \frac{q\sigma_A \Delta T}{T + \frac{\Delta T}{2}} - \frac{q\sigma_B \Delta T}{T + \frac{\Delta T}{2}} = 0, \tag{8}$$

---

* The following quotations are from the paper by W. Thomson.

"· · · The following proposition is therefore assumed as a fundamental hypothesis in the Theory at present laid before the Royal Society.

"The electro-motive forces produced by inequalities of temperature in a circuit of different metals, and the thermal effects of electric currents circulating in it, are subject to the laws which would follow from the general principles of the dynamical theory of heat if there were no conduction of heat from one part of the circuit to another.

"In adopting this hypothesis, it must be distinctly understood that it is only a hypothesis, and that, however probable it may appear, experimental evidence in the special phenomena of thermo-electricity is quite necessary to prove it. Not only are the conditions prescribed in the second Law of the Dynamical Theory not completely fulfilled, but the part of the agency which does fulfill them is in all known circumstances of thermo-electric currents excessively small in proportion to the agency inseparably accompanying it and essentially violating those conditions. Thus, if the current be of the full strength which the thermal electromotor alone can sustain against the resistance in the circuit, the whole mechanical energy of the thermo-electric action is at once spent in generating heat in the conductor;—an essentially irreversible process. The whole thermal agency immediately concerned in the current, even in this case when the current is at the strongest, is (from all we know of the magnitude of the thermo-electric force and absorptions and evolutions of heat) probably very small in comparison with the transference of heat from hot to cold by ordinary conduction through the metal of the circuit. . . . It is true, we may, as has been shown above, diminish without limit the waste of energy by frictional generation of heat in the circuit, by using an engine to do work and react against the thermal electromotive force; but as we have also seen, this can only be done by keeping the strength of the current very small compared with what it would be if allowed to waste all the energy of the electromotive force on the frictional generation of heat; and it therefore requires a very slow use of the thermo-electric action. At the same time, it does not in any degree restrain the dissipation of energy by conduction, which is always going on, and which will therefore bear an even much greater proportion to the thermal agency electrically spent than in the case in which the latter was supposed to be unrestrained by the operation of the engine. By far the greater part of the heat taken in at all, then, in any thermo-electric arrangement, is essentially dissipated, and there would be no violation of the great natural law expressed in Carnot's principle, if the small part of the whole action, which is reversible, gave different, even an enormously different, and either a greater or a less, proportion of heat converted into work to heat taken in, than that law requires in all completely reversible processes. . . ."

which may be written

$$\Delta\left(\frac{P}{T}\right)+\frac{(\sigma_A-\sigma_B)\Delta T}{T+\frac{\Delta T}{2}}=0, \tag{9}$$

or in the limit

$$\frac{d}{dT}\left(\frac{P}{T}\right)+\frac{1}{T}(\sigma_A-\sigma_B)=0 \tag{10}$$

or

$$\sigma_A-\sigma_B=P/T-dP/dT. \tag{11}$$

Eliminating $(\sigma_A-\sigma_B)$ between (7) and (11) we have

$$P=TdE/dT. \tag{12}$$

Substituting (12) in (10) we have

$$(\sigma_A-\sigma_B)=Td^2E/dT^2. \tag{13}$$

From (12) it is seen that

$$E=\int_{T'}^{T}\frac{P}{T}dT=\int_{T'}^{T}\phi dT, \tag{14}$$

which is the expression referred to earlier.

The Peltier e.m.f. at the junction of any two dissimilar metals at any temperature can be calculated from Eq. (12) and measurements of the variation of the thermal e.m.f. with temperature. The magnitude of the e.m.f. existing at the junction of two dissimilar metals ranges from 0 to about 0.1 volt for the metals generally used in temperature measurements.

Although the thermoelectric theory as developed above does not enable us to determine directly the magnitude of the Thomson coefficient in any individual metal, the difference between the Thomson coefficients in two metals can be calculated from Eq. (13) and measurements of the variation in thermal e.m.f. with temperature. Various types of experiments indicate that the Thomson effect in lead is extremely small, if not zero, at ordinary atmospheric temperatures. Consequently some information regarding the magnitude of the Thomson coefficients in other metals at these temperatures can be determined if it is assumed that this coefficient is zero for lead. On this basis it is found that the Thomson coefficient at 0°C in microvolts per °C is −9 for platinum, −8 for iron, +2 for copper, −23 for constantan,† −8 for Alumel,† −2 for 90 platinum −10 rhodium,† and +9 for Chromel-P.†

In order to justify the assumption involved in the application of the second law of thermodynamics, it is necessary and sufficient to verify experimentally the relation

$$P=TdE/dT \tag{12}$$

or

$$\sigma_A-\sigma_B=Td^2E/dT^2. \tag{13}$$

Inasmuch as the individual e.m.f.'s cannot be measured as such, we must depend upon calorimetric measurements of the heating and cooling effects. In order to measure these small reversible effects, it is necessary to separate them from the much larger irreversible Joule heating and the thermal conduction which take place in any experiment of this nature. Practically all of the experimental work on this subject has been on the relation given by Eq. (12) because the reversible heating effects involved in it are in general much larger and more localized than those in Eq. (13).

The most carefully conducted experiments particularly those of Edlund,[8] Jahn,[9] Caswell,[10] and Borelius[11] indicate that the above relations hold within the accuracy of the measurements, about 5 to 10 percent. As far as we know, there is no evidence available which would indicate that the above relations are not exact.

We cannot integrate Eq. (12) or (13) and obtain a general relation between E and T, without some information on the manner in which P or σ varies with T. Experiments indicate that P and σ both depend upon T but the manner in which they vary with T has not been established either theoretically or experimentally with any degree of accuracy.

A number of hypotheses have been made as to the manner in which σ varies with the temperature and Eq. (13) then integrated, but in each case it has been found that the type of equation so obtained represents the experimentally determined values of E and T only over limited temperature ranges. Consequently the relation between E and T for any pair of metals must be determined experimentally and corresponding

---

† Alloys used in the measurement of temperatures.

values given by tables or empirical relations for limited temperature ranges.

Later theories of thermoelectricity may be divided into two general classes: (1) those in which attempts are made to avoid the hypothesis made by Thomson, and (2) those in which the theory as developed by Thomson is accepted as far as it goes, and attempts are made to derive a reversible mechanism or process for converting heat into electrical energy by the application of the electron theories of metals. The theories in the first general class have added little, if anything, to our knowledge of thermoelectricity. The assumptions involved in most of these appear more objectionable than the one made by Thomson. The relations derived between the quantities involved are either equivalent to or less useful than those derived by Thomson.

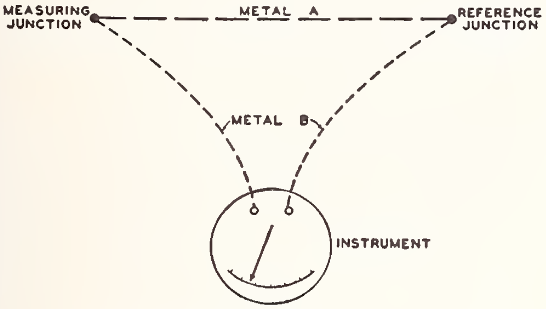


FIG. 3. Simple thermoelectric thermometer.

The existence of the Peltier and Thomson e.m.f.'s in a thermoelectric circuit may be deduced, qualitatively at least, from the electron theories of metals, but the uncertainties in the quantities involved are so large that we cannot determine whether the theories are in agreement with experimental data or not. The most that can be claimed for the more complete of these theories at the present time, is that they give the order of magnitude of the various effects for certain metals.

IV. Thermoelectric Thermometers

A thermoelectric thermometer is a device for measuring temperatures by utilizing the thermoelectric effects. In its simplest form, it consists of a thermocouple of two dissimilar metals which develop an e.m.f. when the junctions are at different temperatures and an instrument for measuring the e.m.f. developed by the thermocouple, connected together as shown in Fig. 3.

As long as the instrument is at essentially a uniform temperature, all the junctions in the instrument including the terminals, will be at the same temperature, and the resultant thermal e.m.f. developed in the circuit is not modified by including the instrument. If the reference junction is maintained at some reference temperature, such as 0°C, the e.m.f. developed by the thermocouple can be determined as a function of the temperature of the measuring junction. The device can then be used for measuring temperatures. It is not necessary to maintain the reference junction at the same temperature during use as during calibration. However, the temperature of the reference junction in each case must be known. For example, let the curve in Fig. 4 be the relation between the e.m.f. E and temperature t for a particular thermocouple with the reference junction at 0°C. Suppose the device is used to measure some temperature and an e.m.f. E_x is observed when the reference junction is at 30°C. We may add the observed e.m.f. E_x to E_{30} (the e.m.f. given by the thermocouple when one junction is at 0 and the other at 30°C) and obtain from the curve the true temperature t_A of the measuring junction. Certain types of instruments which are used with thermocouples in the manner shown in Fig. 3 are such that they can be adjusted manually for changes in the reference junction temperature and the e.m.f. E_A read directly on the instrument.

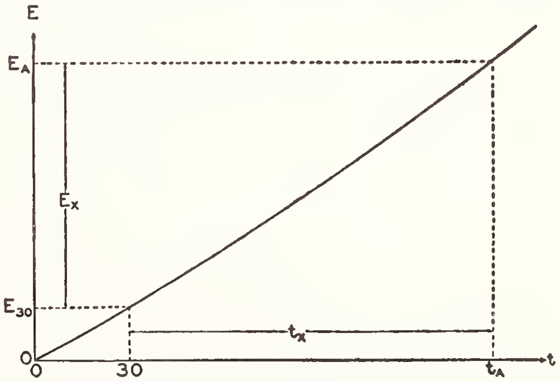


FIG. 4. Illustrating how corrections may be applied for variations in the temperature of the reference junction.

Inasmuch as the curves giving the relation between e.m.f. and temperature are not, in general, straight lines, equal increments of temperature do not correspond to equal increments of e.m.f.

In many cases the thermocouple is connected to the instrument by means of copper leads as shown in Fig. 5.

If the junctions *C* and *C′* are maintained at the same temperature, which is usually the case, the circuit shown in Fig. 5 is equivalent to that shown in Fig. 3. If the junctions *C* and *C′* are not maintained at the same temperature the resultant thermal e.m.f. in the circuit will depend not only upon the thermocouple materials and the temperature of the measuring junction but also upon the temperatures of these junctions and the thermoelectric properties of copper against each of the individual wires. Such a condition should be and usually is avoided.

Circuits such as shown in Figs. 3 and 5 are used extensively in laboratory work where it is usually convenient to maintain the reference junctions either at 0°C by placing them in a thermos bottle filled with cracked or shaved ice and distilled water or at some other conveniently controlled temperature.

In most commercial installations where it is not convenient to maintain the reference junctions at some constant temperature, each thermocouple wire is connected to the instrument with a lead of essentially the same chemical composition and thermoelectric characteristics as the thermocouple wire, in the manner shown in Fig. 6. This is equivalent to using a thermocouple with the reference junctions at the instrument terminals. Leads which have the same thermoelectric characteristics as the thermocouple wires are called extension leads. In most installations of this nature the instrument is equipped with an automatic reference junction compensator which automatically changes the indication of the instrument to compensate for changes in the temperature of the reference junctions, thus eliminating the necessity of measuring or controlling the reference junction temperature. Such automatic devices are usually part of the instrument and in such cases the reference junctions should be located in or at the instrument or at some point which is at the same temperature as the instrument.

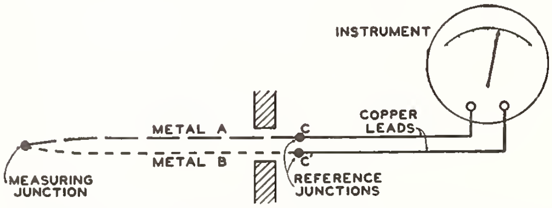


Fig. 5. Diagram for thermoelectric thermometer with copper leads for connecting thermocouple to instrument.

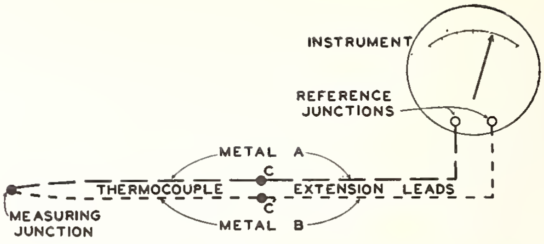


Fig. 6. Thermoelectric thermometer with extension leads.

In some cases where expensive thermocouple wires are used, extension lead wires of less expensive materials are available which give practically the same temperature-e.m.f. relation as the thermocouple over a limited temperature range, usually 0 to 100°C. Although the combined leads give practically the same temperature-e.m.f. relation as the thermocouple wires, the individual lead wires are not identical thermoelectrically with the thermocouple wires to which they are attached and therefore the two junctions where the leads are attached to the thermocouples (*C* and *C′* in Fig. 6) should be kept at the same temperature. This is not necessary in the case of thermocouples where each lead and thermocouple wire to which it is attached are of the same material.

V. Types of Thermocouples

Although a thermal e.m.f. is developed when the junctions of any two dissimilar metals are maintained at different temperatures, only certain combinations of metals have been found suitable for use as thermocouples in the measurement of temperatures. Obviously these thermocouples must be such that:

(1) The thermal e.m.f. increases continuously with increasing temperature over the temperature range in which the thermocouple is to be used.

(2) The thermal e.m.f. is great enough to be measured with a reasonable accuracy.

(3) Their thermoelectric characteristics are not appreciably altered during calibration and use either by internal changes such as recrystallization or by contamination from action of surrounding materials.

(4) They are resistant to any action such as oxidation, corrosion, etc. which destroys the wire.

(5) The melting points of the metals used must be above any temperature at which the thermocouple is to be used.

(6) The metals are reproducible and readily obtainable in uniform quality.

The combinations of metals and alloys extensively used as thermocouples for the measurement of temperatures in this country, are listed in Table I, together with the temperature ranges in which they are generally used and the maximum temperature at which they can be used for short periods. The period of usefulness of a thermocouple depends upon such factors as the temperature, diameter of wires, accuracy required, conditions under which it is used, etc.

There are two types* of platinum to platinum-rhodium thermocouples used in this country, the platinum to 90 platinum-10 rhodium and the platinum to 87 platinum-13 rhodium. These thermocouples develop, at high temperatures, 10 to 14 microvolts per °C as compared to 40 to 55 for the other thermocouples listed in Table I. The platinum to platinum-rhodium thermocouples at temperatures from about 400 to 1600°C being more stable than any other combination of metals, are used (1) for defining the International Temperature Scale from 660°C to the freezing point of gold, 1063°C (only the platinum to 90 platinum-10 rhodium thermocouple is used for this purpose), (2) for very accurate temperature measurements from 400 to 1500°C, and (3) for temperature measurements where the lower melting point materials cannot be used. They are not suitable for temperature measurements below 0°C because the thermoelectric power (dE/dT) is only about 5 microvolts per °C at 0°C and decreases to zero at about −138°C.

The nominal composition of the Chromel-P alloy is 90 percent nickel and 10 percent chromium. Alumel contains approximately 95 percent nickel, with aluminum, silicon, and manganese making up the other 5 percent. Chromel-P-Alumel thermocouples, being more resistant to oxidation than the other base metal thermocouples listed in Table I, are generally more satisfactory than the other base metal thermocouples for temperature measurements from about 650 to 1200°C (1200 to 2200°F). The life of a No. 8 gage (0.128″) Chromel-P-Alumel thermocouple is about 1000 hours in air at about 1150°C (2100°F).

Constantan was originally the name applied to copper-nickel alloys with a very small temperature coefficient of resistance but it now has become a general name which covers a group of alloys containing 60 to 45 percent of copper and 40 to 55 percent of nickel (with or without small percentages of manganese, iron, and carbon) because all the alloys in this range of composition have a more or less negligible temperature coefficient of resistance. Constantan thus includes the alloys made in this country under such trade names as Advance (Ideal), Copel, Copnic, Cupron, etc., most of which contain approximately 55 percent of copper and 45 percent of nickel.

Iron-constantan thermocouples give a slightly higher e.m.f. than the other base metal thermocouples in Table I. They are extensively used at temperatures below about 760°C (1400°F). The life of a No. 8 gage iron-constantan thermocouple is about 1000 hours in air at about 760°C (1400°F).

---

* Neither one of these thermocouples has any distinct advantage over the other. For several years prior to 1922, there were two classes of supposedly platinum to 90 platinum-10 rhodium thermocouples available which differed in thermoelectric properties by about 10 percent. It was found that one of these contained a large percentage of impurities and that the removal of these impurities eliminated one class of platinum to 90 platinum-10 rhodium thermocouples. However, the scales of a large number of instruments had been graduated to read temperatures directly with these impure thermocouples and in order to provide thermocouples which would give approximately correct readings with these instruments the manufacturers supplied platinum to 87 platinum-13 rhodium thermocouples, which were found to give roughly the same temperature-e.m.f. relation as the "impure 10 percent rhodium thermocouple." New instruments were graduated to read temperatures directly with these new thermocouples and consequently more thermocouples were required. This has gone on and now this type of thermocouple is considered unavoidable.

Copper-constantan thermocouples are generally used for accurate temperature measurements below about 350°C (660°F). They are not suitable for much higher temperatures in air because of the oxidation of the copper.

Combinations of metals other than those listed in Table I are sometimes used for special purposes. As examples, at temperatures above −200°C (−300°F) Chromel-P-constantan gives a thermal e.m.f. per degree somewhat greater than that of any of the thermocouples listed in Table I and is sometimes used when the greater e.m.f. is required. Graphite to silicon carbide has been recommended[12] for temperatures up to 1800°C (3300°F) and for certain applications in steel plants.

VI. Reproducibility of Thermocouples

One of the first requirements of thermoelectric pyrometers for general industrial use is that the scales of the instruments shall be graduated to read temperature directly. Although the indications of the measuring instruments used with thermocouples depend upon the resultant e.m.f. developed in the circuit, the scale of the instrument can be graduated in degrees of temperature by incorporating a definite temperature-e.m.f. relation into the graduation of the scale. The temperature can then be read directly if the temperature-e.m.f. relation of the thermocouple is identical with that incorporated in the scale of the instrument.

All the thermocouples which have the same nominal composition do not give identical relations between e.m.f. and temperature. As a matter of fact, in most cases, two samples of metal which are identical as far as can be determined by chemical methods, are not identical thermoelectrically. This is due in part, to the fact that the thermoelectric properties of a metal depend to some extent upon the physical condition of the metal.

It is not practicable to calibrate the scale of an instrument in accordance with the temperature-e.m.f. relation of a particular thermocouple and to change the scale each time the thermocouple is replaced. Consequently the scales of such instruments are calibrated in accordance with a particular temperature-e.m.f. relation which is considered representative of the type of thermocouple, and new thermocouples are purchased or selected to approximate the particular temperature-e.m.f. relation.

If the temperature-e.m.f. relations of various thermocouples of the same type are not very nearly the same, corrections must be applied to the readings of the indicator, and the corrections will be different for each thermocouple. When several thermocouples are operated with one indicator, and when thermocouples are frequently renewed, the application of these corrections becomes very troublesome. For extreme accuracy it is always necessary to apply such corrections, but for most industrial processes, thermocouples can be manufactured or selected with temperature-e.m.f. relations which are so nearly the same that the corrections become negligibly small.

The accuracy with which the various types of thermocouple materials can be selected and matched to give a particular temperature-e.m.f. relation, depends upon the materials and the degree to which the temperature-e.m.f. relation is characteristic of the materials available. The differences in the temperature-e.m.f. relations of the new platinum to platinum-rhodium thermocouples available in this country rarely exceed 4 to 5°C at temperatures up to 1200°C. Consequently, there is no difficulty in selecting a relation between e.m.f. and temperature which is adequately characteristic of these thermocouples. The temperature-e.m.f. relations used in this

TABLE I. *Types of thermocouples and temperature ranges in which they are used.*

TYPE OF THERMOCOUPLE	USUAL TEMPERATURE RANGE		MAXIMUM TEMPERATURES	
	°C	°F	°C	°F
Platinum to platinum rhodium	0 to 1450	0 to 2650	1700	3100
Chromel-P to Alumel	−200 to 1200	−300 to 2200	1350	2450
Iron to constantan	−200 to 750	−300 to 1400	1000	1800
Copper to constantan	−200 to 350	−300 to 650	600	1100

country for platinum to platinum-rhodium thermocouples are such that new thermocouples which yield these relations within 2 or 3°C up to 1200°C are readily available.

The differences in the temperature-e.m.f. relations of base metal thermocouples of any one type are so large that the selection of a temperature-e.m.f. relation which might be considered characteristic of the type of thermocouple is difficult and more or less arbitrary. The relations generally used for some of these thermocouples by some manufacturers have been changed from time to time because of differences introduced in the thermoelectric properties of the materials by variations in raw materials and methods of manufacture. However, the relations in use at the present time are such that materials can generally be selected and matched to yield the adopted relations with an accuracy of about ±3°C up to 400°C and to $\pm\frac{3}{4}$ percent at higher temperatures. In special cases, materials may be selected to yield the adopted relations within 2 or 3°C for limited temperature ranges.

VII. Temperature-E.M.F. Relations

Corresponding values of temperature and e.m.f. which are considered characteristic of the various types of thermocouples are given in Table II. More detailed tables will be found in the references given in the table. As far as we know the corresponding values given for platinum to 90 platinum-10 rhodium, platinum to 87 platinum-13 rhodium, and Chromel-P-Alumel thermocouples are more or less standard and are the only ones used in this country for these types of thermocouples. The temperature-e.m.f. relation of Chromel-P-Alumel thermocouples has been fairly well controlled because these materials are manufactured primarily with controlled thermoelectric properties for thermocouples by only one company.

The values for iron-constantan headed *A* were determined at the National Bureau of Standards a few years ago as being characteristic of the iron and constantan generally available at that time. The values for iron-constantan headed *B* have been used by certain pyrometer manufacturers for a number of years and presumably are characteristic of the materials available at the time the corresponding values were determined. Owing to the differences in the thermoelectric properties of different lots of iron and constantan, materials must be selected and properly matched in order to obtain a thermocouple which will approximate a selected temperature-e.m.f. relation for this type of thermocouple.

Until recent years copper-constantan thermocouples were used primarily for accurate measurements at temperatures below about 350°C, and in such cases it is customary to calibrate each thermocouple or lot of wire and use an instrument calibrated in millivolts. However, in recent years, there has been an increasing demand for direct reading instruments for use with copper-constantan thermocouples. There are large differences in the temperature-e.m.f. relations of copper-constantan thermocouples and consequently the materials must be selected in order to obtain thermocouples which will yield any specified temperature-e.m.f. relation. No difficulty has been encountered in obtaining thermocouples which will give very closely the temperature-e.m.f. relation in Table II.

VIII. Instruments

Instruments used to measure the e.m.f. developed by thermocouples or to indicate the

TABLE II. *Corresponding values of tmperature and e.m.f. for various types of thermocouples.*

TEMP. °C	90 Pt-10 Rh TO PLATINUM[1] MV	87 Pt-13 Rh TO PLATINUM[1] MV	CHROMEL-P TO ALUMEL[2] MV	IRON TO CONSTANTAN		COPPER TO CONSTANTAN[5] MV
				A[3] MV	*B*[4] MV	
−200			−5.75	−8.27		−5.539
−100			−3.49	−4.82		−3.349
0	0.000	0.000	0.00	0.00	0.00	0.000
+100	0.643	0.646	+4.10	+5.40	+5.28	+4.276
200	1.436	1.464	8.13	10.99	10.78	9.285
300	2.315	2.394	12.21	16.56	16.30	14.859
400	3.250	3.398	16.39	22.07	21.82	20.865
500	4.219	4.454	20.64	27.58	27.39	
600	5.222	5.561	24.90	33.27	33.16	
700	6.260	6.720	29.14	39.30	39.19	
800	7.330	7.927	33.31	45.72	45.48	
900	8.434	9.177	37.36	52.29	51.82	
1000	9.569	10.470	41.31	58.22	58.16	
1100	10.736	11.811	45.14		64.50	
1200	11.924	13.181	48.85			
1300	13.120	14.562	52.41			
1400	14.312	15.940	55.81			
1500	15.498	17.316				
1600	16.674	18.679				
1700	17.841	20.032				

[1] Nat. Bur. Stand. J. Research 10, 275 (1933), R.P. 530.

[2] Nat. Bur. Stand. J. Research 14, 239 (1935), R.P. 767.

[3] Nat. Bur. Stand J. Research 20, 337 (1938), R.P. 1080.

[4] Catalogs. Leeds & Northrup Co. and Brown Instrument Co.

[5] *Pyrometry*, (Symposium published by Am. Inst. Mining Met. Engrs. 1920), p. 165. Int. Crit. Tab. 1, 58 (1926). Nat. Bur. Stand. J. Research 20, 337 (1938), R.P. 1080.

temperature of the measuring junction of a thermocouple may be divided into two general classes: (1) Those operating upon the galvanometric principle such as ordinary millivoltmeters; and (2) those operating upon the potentiometric principle. At one time there was considerable interest in a class of instruments which operate upon a combination of the galvanometric and potentiometric principles but at the present time there appears to be no place or demand for such instruments.

MILLIVOLTMETERS

A millivoltmeter consists of a coil of wire suspended between the poles of a permanent magnet so that the coil is free to move. A pointer is attached to the coil and moves over a scale graduated in millivolts or in degrees. Leads from the thermocouple are connected to the terminals of the coil usually through a series resistance, and the e.m.f. generated in the thermocouple circuit sends a current through the coil, causing it to deflect in the magnetic field. The magnitude of the deflection depends upon the current through the coil which in turn depends on the e.m.f. generated by the thermocouple and the resistance of the circuit.

The current I in the circuit is given by

$$I=E/(R_g+R_x),$$

where E is the resultant e.m.f. in the circuit, R_g the resistance of the millivoltmeter, and R_x the resistance of the thermocouple and leads. The potential difference, E_g, across the terminals of the instrument is given by

$$E_g=\frac{R_g}{R_g+R_x}E.$$

Millivoltmeters are ordinarily calibrated to indicate E correctly when connected to a thermocouple and leads of combined resistance R_x. Any change then in either R_g or R_x causes a change in the indications of the instrument. Inasmuch as instruments are frequently used with more than one thermocouple and inasmuch as R_x varies with the temperature and the amount of the wire heated, it is desirable to make R_g large compared to R_x or at least to variations in R_x. However, this cannot be accomplished in most instances because the design of a millivoltmeter for any particular service is a compromise between sensitivity and ruggedness, which to a large extent determines the resistance. Millivoltmeters with a resistance of much over 600 ohms become extremely delicate and cannot be used in many locations. In order to obtain the ruggedness required it is necessary in some instances to make R_g as low as 12 or 15 ohms. This means that variations in the resistance of the circuit have an appreciable effect upon the indications of the instrument. Owing to these inherent sources of error, millivoltmeters are not very extensively used at the present time.

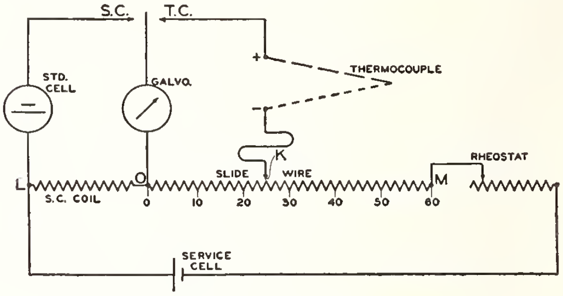


FIG. 7. Diagram of a potentiometer circuit.

POTENTIOMETERS

The fundamental principle of the potentiometer may be seen by referring to Fig. 7. The current from a service cell which may be a dry cell or a storage cell, passes through the main circuit composed of a series of fixed resistors and can be adjusted by a variable rheostat. The relative values of the fixed resistors and the magnitude of the current determine the range of the instrument. By means of a switch either the standard cell or the thermocouple can be connected to the main circuit and its voltage balanced, through a galvanometer, against an equal voltage drop developed in a portion of the main circuit. The potential drop across the various fixed resistors is made to correspond to definite and reproducible values of voltage by adjusting the current to some standard value.

To standardize the battery current, the switch *S.C.* is closed and the current adjusted until the potential drop across the resistor *LO* is equal to the e.m.f. of the standard cell. The e.m.f. of the thermocouple can then be determined by closing the *T.C.* switch and moving the contact *K* until the potential drop in the resistors in the main circuit from *O* to *K* is equal to the e.m.f. of the thermocouple. The potential drop from *O* to *K* is read on some suitable scale. The resistors included between *O* and *M* may be made up of fixed coils, a slidewire, or a combination of the two.

The galvanometer has no measuring function but serves solely to indicate zero current in its branch of the circuit. As there is no current through the galvanometer and thermocouple when a balance is obtained, the reading of the potentiometer is independent of the resistance of the thermocouple circuit. However, large changes in this resistance affect the precision of balancing because as the resistance is increased the sensitivity of response of the galvanometer is decreased and the greater is the change in e.m.f. required to produce a perceptible deflection of the galvanometer. It is therefore advisable to keep the resistance of the thermocouple and leads within reasonable limits as determined by the characteristics of the galvanometer.

There are several important advantages in the potentiometer method. The scale is easily made very open, thus permitting precise readings if a suitable galvanometer is used. The accuracy of the potentiometer is in no way dependent upon the constancy of magnets, springs, or jewel bearings, nor upon the level of the instrument. Insofar as temperature measurements with thermocouples are concerned, the greatest advantages are the accuracy and the complete elimination of any error due to ordinary changes in the resistance of the thermocouple and leads. The objections to the potentiometer are its higher initial cost and the fact that, except for automatic instruments, a manual adjustment must be made to obtain a reading. In the recording and controlling potentiometer equipment, however, all the various manipulations may be performed automatically even to the standardizing of the battery current.

Potentiometers are used for practically all laboratory work where the highest accuracy is required. At the present time the large part of the instruments in industrial use operate upon the potentiometric principle.

The scales of millivoltmeters or potentiometers may be calibrated either in millivolts or in degrees of temperature for a particular type of thermocouple. Either type of instrument can be made automatically recording and can be equipped with devices for automatically controlling the temperature of a process or furnace.

Inasmuch as the e.m.f. developed by a thermocouple depends upon the temperature of the reference junctions as well as upon the temperature of the measuring junction, corrections must be made for changes in the reference junction temperature unless they are automatically taken care of by the instrument. If properly calibrated, an ordinary millivoltmeter will indicate the temperature of the measuring junction, when the pointer of the indicator is set to read the reference junction temperature on open circuit. If the reference junction temperature is well controlled, this adjustment may be made conveniently by hand. However, if this junction is subject to frequent temperature changes it is advisable to locate the reference junctions at the instrument and use an instrument which automatically changes the indication to compensate for changes in the reference junction temperature. In the case of millivoltmeters this is accomplished automatically by attaching a properly adjusted bimetallic spring to the control spring of the moving coil. If an instrument is equipped with an automatic reference junction compensator for one type of thermocouple, it should not be used with other types of thermocouples nor should it be used in any case unless the reference junctions are located at the instrument.

Potentiometers for industrial use are usually provided with either a hand-operated or an automatic reference junction compensator. A hand-operated compensator is an adjustable resistor, having a scale graduated in millivolts, which the operator sets to correspond with the observed reference-junction temperature. This operation is equivalent to moving the fixed end of the thermocouple circuit (point 0 Fig. 7) to a point corresponding with reference-junction temperature. For use with any one type of thermocouple the compensator may include a nickel coil which varies in resistance as the temperature changes and thus compensates automatically for changes in the reference-junction temperature. An instrument so equipped is usually calibrated directly in degrees of temperature. Although it is usually at the instrument, an automatic compensator can be located wherever desired. Lead wires from thermocouple to the compensator location in any case must have the same thermoelectric characteristics as the thermocouple wires.

Instruments calibrated in millivolts are generally used:

(1) When very accurate temperature measurements are to be made with individually calibrated thermocouples.
(2) When used with various types of thermocouples.

Instruments are generally calibrated in degrees of temperature:

(1) When used in industrial plants with only one type of thermocouple.
(2) When the inconvenience of converting millivolt values to temperature is considered more important than the errors introduced by the lack of reproducibility of thermocouples of any one type.

Instruments are ordinarily equipped with manually operated reference junction compensators:

(1) When used with various types of thermocouples.
(2) When the reference junctions are not located at the instrument.

Instruments are ordinarily equipped with automatic reference junction compensators:

(1) When the reference junctions are located at the instrument and subject to considerable variations in temperature.
(2) When the inconvenience of making manual adjustments or arithmetical corrections is considered more important than the errors introduced by using automatic compensators.

IX. Protection Tubes

One of the reasons why the materials listed in Table I have come into common use for thermocouples is that they are reasonably stable thermoelectrically when heated in a clean oxidizing atmosphere. The standards of performance which are generally accepted for the various combinations of thermocouple materials are based upon their performance in air. Although it has not been shown that a reducing atmosphere, in itself, necessarily contaminates or alters the thermoelectric properties of thermocouple materials, it is nevertheless generally observed that exposure of thermocouples to such atmospheres is accompanied by contamination or changes in the chemical composition which seriously alter the thermoelectric properties. In order to obtain the best performance of thermocouples, it appears necessary to maintain them in an atmosphere having essentially the same composition as air. Consequently the selection of a proper protection tube, which will protect the thermocouple from vapors, fumes, or furnace gases, is sometimes as important as the selection of the thermocouple materials.

Changes in thermoelectric characteristics result from causes such as the following.

(1) Metals (solid, liquid, or vapor) coming into contact with the thermocouple materials and altering their chemical composition.

(2) Furnace gases and fumes coming into contact with the thermocouple materials. Sulphur and sulphur compounds are particularly deleterious.

(3) Materials normally stable in an oxidizing atmosphere coming into contact with the thermocouples in a reducing atmosphere. One common cause of contamination, which is serious in the case of rare metal thermocouples, is the reduction of silica (usually present in insulating and ceramic protection tubes) to silicon which readily combines with the thermocouple materials.

(4) Preferential oxidation and reduction of base metal alloys exposed alternately to oxidizing and reducing atmospheres. This results in a gradual change in chemical composition, because all the elements which comprise an alloy are not oxidized and reduced at the same rates under all conditions.

Many types of protection tubes are required in order to meet all needs. In many cases, the conditions under which thermocouples are used are such that two tubes are required to provide the desired protection. For instance, a primary tube of porcelain or fused silica may be placed inside a secondary tube of metal, silicon carbide, or fire clay. The primary tube of low volatility is intended to provide imperviousness to gases at high temperatures, and the secondary tube to provide resistance to thermal and mechanical shock and to corrosion.

In thus providing protection for the thermocouple, however, one should not lose sight of the fact that a thermocouple can perform its function only when the conditions of heat transfer are such that the measuring junction attains or at least approaches the temperature to be measured. When a tube of large cross section or more than one tube is used, particularly if the tubes have a high thermal conductance, it should be carefully considered whether the depth of immersion is sufficient to insure that the temperature of the thermocouple junction is reasonably close to the temperature to be measured. Short thick-walled tubes may cool the junction so much that the indications are comparatively worthless.

Platinum to platinum-rhodium thermocouples are particularly susceptible to contamination and should be protected by ceramic tubes which are impervious to gases and vapors at all operating temperatures. Metal protection tubes usually provide sufficient protection for base metal thermocouples. The oxide coatings on the thermocouple wires are fairly effective in protecting the wires from contamination by metallic vapors. Metal tubes which provide sufficient protection in an oxidizing atmosphere may be entirely unsatisfactory if large amounts of furnace gases are present. In some installations it has been found advisable to ventilate the interior of the protection tube with a slow stream of air in order to minimize the deleterious effects of furnace gases.

The primary ceramic tubes which meet most requirements of stability and imperviousness to gases are: highly refractory porcelain, sometimes called "Sillimanite" or "Mullite" for temperatures up to about 1550°C (2800°F), fused silica for temperatures up to about 1050°C (1900°F) in an oxidizing atmosphere, and Pyrex glass for temperatures up to about 600°C (1100°F).

The secondary or metal tube most suitable for a particular application depends to a large extent upon the type of corrosion encountered. Nickel-chromium-iron tubes are particularly useful in oxidizing atmospheres, chromium-iron tubes in atmospheres containing sulphur, and nickel or iron tubes in hot caustic and molten metal baths. The temperature limits given in Table III for the various types of tubes are those which will, in general, result in a reasonably long life. The tubes may be used at higher temperatures than those given but higher operating temperatures will result in a shorter life.

Fire clay, silicon-carbide, and graphite meet certain requirements of secondary tubes at temperatures above the useful limits of metal tubes. Numerous other types of tubes have been developed for specific purposes. Recommendations regarding tubes for any particular purpose may be obtained from pyrometer manufacturers.

X. Calibration of Thermocouples

Various methods used for calibrating thermocouples and of testing thermocouple materials and the precautions which must be observed in order to attain various degrees of accuracy are given in a separate paper, which is essentially the same text as the paper entitled "Methods of testing thermocouples and thermocouple materials" published originally in the *Journal of Research of the National Bureau of Standards.*[13] The numerical values in the original text have been brought into agreement with later published data.

XI. Measurement of Temperatures

The measurement of the temperature of any particular object or space is in many cases a problem in itself, even after a suitable thermocouple has been selected and calibrated. The methods employed in many instances are described elsewhere in this symposium. However, there are certain fundamentals that must be observed in any case.

The temperature indicated by a thermocouple is that of its measuring junction, but usually this is of no interest in itself. The accuracy obtained in measuring the temperature of any object or space usually depends upon how closely the junction of the thermocouple can be brought to the same temperature as that of the object or space, or to some temperature which is definitely related to that of the object or space.

TABLE III. *Recommended maximum operating temperature of metal protection tubes.*

TYPE OF TUBE	RECOMMENDED MAXIMUM TEMPERATURE	
	°C	°F
Seamless steel	550	1000
Wrought iron	700	1300
Cast iron	700	1300
Calorized wrought iron	800	1500
14 percent chromium iron	800	1500
28 percent chromium iron	1100	2000
18 (Cr)-8 (Ni)-stainless steel	850	1600
32 Ni-20 Cr-48 Fe	1100	2000
62 Ni-13 Cr-25 Fe	1150	2100
Nickel	1100	2000

If under steady conditions there is a net exchange of heat between the thermocouple junction and an object, then there is a difference in temperature between the two. The magnitude of this difference in temperature depends upon the rate of heat transfer and the thermal resistance between the junction and the object. The idea then is to bring the thermocouple junction into as good thermal contact as possible with the object and to insulate the junction as well as possible against the transfer of heat to or from other objects or spaces. Greater precautions are obviously necessary in accurate measurements than in rough ones.

As an illustration, suppose we desire to measure the temperature of a metal plate which is heated from within by some means. The bare thermocouple junction is brought into contact with the metal plate. The junction will receive some heat from the plate by thermal conduction and probably a smaller amount, by radiation and convection. The junction will lose heat by conduction along the thermocouple wires, and by convection, conduction, and radiation to the surroundings. Obviously the junction will be at a lower temperature than the plate. However, this difference in temperature can be reduced by the following.

(A) By improving the thermal contact. (1) By flattening the junction to obtain a larger area of contact or better still (2) by soldering, brazing, or welding the junction to the plate.

(B) By reducing the heat loss from the junction. (1) By keeping the wires close to the plate for some distance so as to reduce the temperature gradient in the wires near the junction, and/or (2) by raising the temperature of the space immediately surrounding the junction (a) by insulating the junction from that space or (b) by utilizing an auxiliary source of heat as is done in the compensated contact thermometer.[14, 15]

The thermocouple junction may be at either a higher or lower temperature than the object depending upon the direction of the net heat transfer. The use of thermocouple protection tubes usually makes it more difficult to bring the thermocouple junction to nearly the same temperature as that of an object, because of the additional thermal resistance introduced between the junction and object and the additional transfer of heat along the protection tubes. For example, the junction of a thermocouple may be brought within a few hundredths of a degree of the temperature of a liquid by immersing the bare wires in the liquid for a distance of 5 to 10 diameters of the wire, whereas if a protection tube is used with the thermocouple it will be necessary to immerse the junction 5 to 10 diameters of the protection tube to obtain the same degree of accuracy. In most applications, the best that can be done is to bring the thermocouple junction and object as close together as possible and immerse the thermocouple as far as practicable in the heated medium.

In the measurement of certain temperatures, particularly those of small objects and materials of low thermal conductivity, consideration must be given to the possibility that the temperature to be measured may be altered by the introduction of the temperature measuring device.

In the measurement of temperatures varying with time, heat capacity of thermocouples and protecting tubes as well as thermal contacts are involved. If the temperature is rising, the temperature of the junction itself will at any instant be lower than that of the surroundings. The reverse will be true if the temperature is falling. This is referred to as thermal lag. By appropriate auxiliary measurements, however, it is usually possible to determine the lag[16] under the particular conditions of use, and apply corrections to the thermocouple readings.

XII. Installations

The cost of pyrometer equipment is great enough to warrant installing it, not only so that the desired temperature can be measured with the required accuracy but also in such a manner as to protect the equipment, as far as practicable, from changes and deterioration. The installation of simple pyrometer equipment for more or less temporary service in an air-conditioned laboratory, far removed from the vibrations set up by heavy equipment such as trip hammers, rolling mills, etc., is a comparatively simple matter. However, in the large installations required in many industrial plants, every precaution should be taken to protect the thermocouple, wiring, and instruments from the various deleterious conditions which may seriously affect their accuracy and life.

1. General Precautions

The installation of extensive thermocouple equipment requires the services of competent electricians. Just as much attention, if not more, should be given to the wiring, switches, switchboards, etc., as is given in the case of ordinary power installations. Proper fixtures should be used to mount the thermocouples in the furnaces. Lead wires should have a weatherproof covering and should be run in a metal conduit except possibly for a short length of flexible cable at the ends of the conduit. The conduit should be grounded to prevent leakage from power installations or lighting circuits. All joints in the lead wires should be soldered and taped. When indicators or recorders of low resistance are employed, it is of the greatest importance to have a well-constructed electrical installation to insure a constant line resistance. Since instruments of low resistance are usually calibrated for a low line resistance of definite value, special attention must be given to contact resistances at switches. Frequently switches rated at 100 amperes are required, although the actual thermoelectric current is only a few milliamperes. If the indicator is of high resistance, or operates upon the potentiometric principle, the factor of very low line resistance is not of great importance, but the wiring should be well installed, to avoid large changes in the resistance. Stationary indicating and recording instruments usually should be mounted upon switchboards, with suitable selective or commutating switches when several thermocouples are to be used with one indicator. When the junction between the thermocouple and leads is exposed to severe conditions, rain, etc., as in outside kilns, a weatherproof terminal head should be used. This consists of an outside casing which fits over both binding posts. The cover may be tapped for conduit wiring or provided with a packing gland or stuffing box if a length of flexible cable is used between the thermocouple and the conduit.

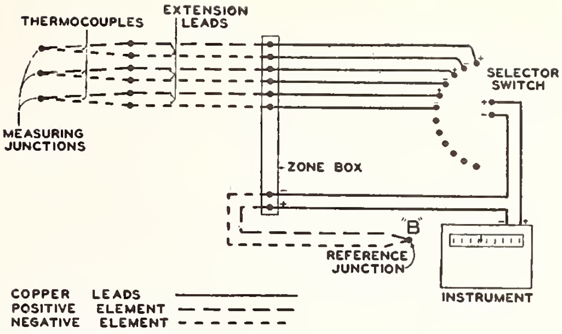


Fig. 8. Connections between several thermocouples and a distant instrument.

The indicator or recorder should be conveniently located. If the instrument is desired especially for the use of the operator of a furnace, it should be placed where it is readily visible. It should be mounted where vibration and excessive dirt and dust will not injure delicate parts of the mechanism. In almost all industrial installations an outside protecting case is required to prevent dust from filtering through the case of the indicator. Special devices are employed to damp out vibration when this is serious, as in the neighborhood of a trip hammer or rolling mill. Frequently the instruments are suspended on "vibration-proof mountings."

2. Location of Thermocouples

The proper location of the thermocouple in a furnace depends upon the particular process and the use to which the furnace is put. The primary consideration is to locate the measuring junction so that it acquires the temperature which it is desired to measure. This requires taking into consideration the thermal lag and heat transfer to and from the thermocouple junction. Both of these factors are materially affected by protection tubes. A secondary consideration, however, is to locate the thermocouple where the lead wires may be conveniently located. The space between the protecting tube and the furnace wall should be plugged with refractory cement, so that hot air cannot strike through the hole onto the terminals of the thermocouple, nor cold air be drawn in, thus cooling the measuring junction of the thermocouple.

3. Common Return

The use of a common return wire for a multiple installation is in general unsatisfactory. When grounds or short circuits occur at any point between the measuring junctions and the instrument—for example, between the common return and the other lead wire of one thermocouple—all the thermocouples on the common return have, in addition to their own e.m.f., an impressed potential drop due to the current flowing in the shorted thermocouple. This may cause a large error in the reading of every thermocouple in the system. With the common return, leakage from a power installation affects the readings of every thermocouple connected to the return and a leakage through a high resistance may alter the readings of every thermocouple by the same amount so that the presence of such leaks is not always readily detected. It is also possible by leakage from different thermocouples to the ground to obtain very erratic and erroneous readings when the common return is employed. The insulation resistance of materials becomes very low at high temperatures making it difficult to insulate the various thermocouple wires from one another and from the furnace parts, even when individual returns are used. Base-metal thermocouples are frequently constructed with the measuring junction welded to the end of the metal protecting tube in order to reduce thermal lag. Even when the thermocouple is not welded at this point, the measuring junction usually touches the protecting tube and is in good electrical contact with it. If a common return is used when the thermocouples are mounted in this way, any electrical connection or leakage between the metal protecting tubes (through the furnace structure, etc.) will produce serious errors. However, if individual returns are used, the metal protecting tubes need not be insulated from one another. The troubles ordinarily encountered with common return installations are sufficient to warrant the extra cost of the wire required to install individual thermocouple circuits.

4. Use of a Zone Box

Extension lead wires are rather costly and should not be employed extravagantly. Also the use of long lengths of extension leads increases the line resistance, since the resistivity of the lead materials is much higher than that of copper.

For an installation in which several thermocouples are connected through a selector switch to an instrument located at some distance from a furnace, a wiring scheme similar to that shown in Fig. 8 may be very useful in saving extension lead wire and consequently in reducing the cost and resistance of the line. The common reference junction *"B"* for each thermocouple can be located at any conveniently controlled point or at the instrument if the latter is equipped with an automatic reference junction compensator by running only one pair of extension leads from the zone box to the controlled point or the instrument. A zone box is a box or zone of uniform temperature which need not be measured or maintained constant. It should be pointed out that although a common reference junction is used for all the thermocouples, the system is not subject to any of the objections which have been raised against the use of a common return.

5. Thermocouples Purposely Insufficiently Immersed

In many processes a furnace is operated at such a high temperature that a thermocouple or protecting tube cannot withstand the severe conditions inside the furnace. In this case the thermocouple may be advantageously inserted only part way through the furnace wall, or flush with the inner wall of the furnace. The temperatures indicated by thermocouples installed in this manner are always lower than those of the furnace interior, but they may bear a fairly definite relationship to the temperature of the furnace, and hence the method may be satisfactory for temperature control and reproduction of furnace conditions from day to day.

6. Measurement of Average Temperature

It is frequently desirable to measure "the average temperature" of an object or a heated space by using thermocouples. No discussion of what is meant by the average temperature of an object or space or why anyone would be interested in measuring any such average will be given here. The average temperature that can be measured with thermocouples is only a mean of the temperatures of the measuring junctions of a number of thermocouples. This average may or may not be a close approximation to the average temperature which one desires to measure, depending upon such factors as the temperature distribution, the number and location of the thermocouples, etc.

If the measuring junctions of a number of thermocouples are placed in thermal contact with an object or located in a heated space, the average temperature of the junctions may be obtained by any one of three methods: (1) by reading the thermocouples individually and averaging the readings; (2) by connecting them in series and reading the total e.m.f.; or (3) by making all the thermocouples of equal resistance and connecting them in parallel so that the average e.m.f. is read directly. Although each of these methods has certain practical advantages over the others, they are all equivalent in that one is no more accurate than the others and that the same average temperature (that of the junctions) is measured in each case. In the following discussion, it will be assumed that the temperature-e.m.f. relations of all the thermocouples used in any one case are identical and that any correction or compensation required for the reference junctions is properly cared for.

The important advantages of taking readings of the individual thermocouples are that (1) one obtains not only the average temperature but also some idea of the temperature distribution, (2) the thermocouple junctions may be placed in contact with or welded to metal objects, thus insuring good thermal contact, and (3) the failure of any individual thermocouple is immediately detected. The disadvantage is that several observations must be taken, requiring several instruments if the observations are to be taken simultaneously or considerable time during which the temperatures may change if the observations are to be taken with one instrument.

One may average the values of the e.m.f. of the individual thermocouples and obtain the average temperature from the average e.m.f. or one may average the temperature values obtained for each thermocouple. The average values obtained in these two different ways will not necessarily agree exactly owing to the fact that the e.m.f. of a thermocouple is not a linear function of the temperature. If the temperature gradients in the object or heated space are not very large (less than about 50°C) the difference in the averages obtained in the two different ways is usually insignificant. If the temperature gradients in the object or heated space are so large (several hundreds of degrees) that there is an appreciable difference in the average temperature obtained in the two different ways, the average temperature obtained by using thermocouples located at several selected points probably has no exact significance.

Because values of temperature may be obtained with the individual thermocouples and averaged with this method, it is not necessary to use thermocouples with approximately the same temperature-e.m.f. relation.

The important advantage of connecting the thermocouples in series or in parallel is that only one observation is required to obtain the average e.m.f. of a number of thermocouples. However, such a single observation yields no information regarding the temperature distribution in the object or space. Connecting the thermocouples according to either method requires that the thermocouple wires and measuring junctions be electrically insulated from one another. This makes it difficult under certain conditions to bring the junctions in good thermal contact with an electrically conducting medium.

The objections to connecting a number of thermocouples in series are: (1) The e.m.f. developed by the thermocouples in series may be too great to be measured with the instruments available; (2) A short circuit which might materially reduce the e.m.f. of one of the thermocouples would not be detected by a single observation of the total e.m.f.

It can be shown by applying Kirchhoff's laws, that the potential difference across the terminals of a number of thermocouples of equal resistance connected in parallel is the average of the e.m.f.'s of the individual thermocouples. Inasmuch as the average e.m.f. is measured directly when the thermocouples are connected in parallel, the e.m.f. can be measured with any instrument that is used for measuring the e.m.f. of a single thermocouple.

It should be pointed out that the temperature indicated when the two individual thermocouple wires are attached to a metal object at two points which may be designated *P* and *Q* (so that the electric circuit is completed through the metal), depends upon the thermoelectric power of the metal with respect to the thermocouple wires and is not necessarily the temperature of the metal at any point between *P* and *Q* and consequently is not the average temperature of the metal between *P* and *Q* except in very special cases. If the metal to which the thermocouple wires are attached is thermoelectrically positive to one element of the thermocouple and negative to the other, the temperature measured will be somewhere between those of *P* and *Q*. The thermocouple will indicate a temperature approximately midway between those of *P* and *Q* only if the metal is approximately midway between the two thermocouple wires thermoelectrically.

It is readily seen that if the wires of an iron-constantan thermocouple are attached to a piece of iron, the temperature measured will be that where the constantan wire is attached and if they are attached to a piece of constantan the temperature measured will be that where the iron wire is attached.

If the metal to which the thermocouple wires are attached is thermoelectrically positive or negative to both wires of the thermocouple, the value of the temperature indicated will not be between those of *P* and *Q*. For example, suppose that the wires of a platinum to 90 platinum-10 rhodium thermocouple are attached to a piece of constantan, and that the temperature of the point where the platinum wire is attached is 700°C and that where the platinum-rhodium is attached is 750°C. Let the reference junctions of the thermocouple be at 0°C. The circuit is equivalent to a 90 platinum-10 rhodium to constantan thermocouple with its junctions at 750° and 0°C in series with a constantan to platinum thermocouple with its junctions at 700° and 0°C. The resultant e.m.f. developed in the circuit will be approximately 9.14 mv which corresponds to 962°C for the platinum to 90 platinum-10 rhodium thermocouple.

XIII. Conclusion

In conclusion the author would like to emphasize that the success attained in the measurement of temperatures with thermocouples depends primarily upon the ability of the observer to bring the junctions of the thermocouples to the desired temperatures and upon the stability of the thermocouple materials. The reader's attention is directed to a number of papers in this symposium which deal with (1) the measurement of temperatures in particular cases, (2) the stability of thermocouples, and (3) the instruments available for use with thermocouples in the measuring, recording, and controlling of temperatures.

XIV. Bibliography

1. T. J. Seebeck, Gilb. Ann. **73**, 115, 430 (1823); Pogg. Ann. **6** 1, 133, and 253 (1826).
2. P. D. Foote and T. R. Harrison, J. Wash. Acad. Sci. **8**, 545 (1918).
3. J. C. A. Peltier, Ann. chim. Phys. 2nd ser. **56**, 371 (1834).
4. Quintus Icilius, Ann. d. Phys. und Chem. Pogg. **89**, 377 (1853).
5. W. Thomson, Proc. Roy. Soc. Edin. December 15, 1851.
6. W. Thomson, Proc. Roy. Soc. Lon. **VII**, May, 1854. Phil. Mag. July, 1854.
7. W. Thomson, Trans. Roy. Soc. Edin. **21**, 123 (1857); Read May 1, 1854.
8. E. Edlund, Pogg, Ann. **140**, 435 (1870); Pogg. Ann. **143**, 404, 534 (1871).
9. H. Jahn, Wied. Ann. **270**, 755 (1888).
10. A. E. Caswell, Phys. Rev. **33**, 379 (1911).
11. G. Borelius, Ann. d. Physik. (4) **52**, 398 (1917); **56**, 388 (1918).
12. G. R. Fitterer, A. I. M. E., Iron & Steel Div. **105**, 290 (1933); A. I. M. E. **20**, 189 (1936).
13. W. F. Roeser and H. T. Wensel, J. Research Nat. Bur. Stand. **14**, 247 (1935), R.P. 768.
14. M. W. Boyer and J. Buss, Ind. & Eng. Chem. **18**, 728 (1926).
15. W. F. Roeser and E. F. Mueller, Bur. Stand. J. Research **5**, 793 (1930), R.P. 231.
16. D. R. Harper, 3rd, Bul. Bur. Stand. **8**, 659 (1912), S185.

UNITED STATES DEPARTMENT OF COMMERCE • Sinclair Weeks, *Secretary*
NATIONAL BUREAU OF STANDARDS • A. V. Astin, *Director*

Methods of Testing Thermocouples and Thermocouple Materials

Wm. F. Roeser and S. T. Lonberger

National Bureau of Standards Circular 590

Issued February 6, 1958
(Superesedes Research Paper 768)

233-I

Contents

Methods of Testing Thermocouples and Thermocouple Materials

Wm. F. Roeser and S. T. Lonberger[1]

Various methods used for testing thermocouples and thermocouple materials and the precautions that must be observed in order to attain various degrees of accuracy are described. In particular, the methods that have been developed and used at the National Bureau of Standards are outlined in detail, and some guidance is given to the reader in the selection of the method best adapted to a given set of conditions.

Consideration is given primarily to the calibration of platinum versus platinum-rhodium, copper-constantan, Chromel-Alumel, and iron-constantan thermocouples.

1. Introduction

Methods of testing thermocouples and thermocouple materials have been developed to supply the need of those industries to which the measurement and control of temperature are essential. The recognition by the various industries in this country that the measurement and control of temperature are essential to a uniformly high quality of product has led, in recent years, to a tremendous increase in the use of temperature-measuring equipment. Where the higher temperatures are involved, by far the greater portion of such measurements is made with thermocouples, and therefore these devices must be regarded as one of the important tools of modern industry.

The users of thermoelectric pyrometers have been demanding ever-increasing accuracy in these instruments. Thermocouple materials are being bought on closer specifications, and the pyrometer manufacturers have been setting up smaller tolerances in the inspection and calibration of their product, with the result that practically all pyrometric equipment now being sold is of very high quality. Reliable methods of testing thermocouples and thermocouple materials are required to realize the degree of accuracy now demanded. The purpose of this Circular is to describe the more important of these methods and to point out certain precautions that must be observed to secure reliable results. The essential features of many of these methods and much of the apparatus described here have been devised and described in whole or in part by various writers, but references to their papers will be made only when it is felt that a more detailed description than is given here will be helpful to the reader.

Combinations of metals and alloys extensively used in thermocouples for the measurement of temperatures in this country are listed in table 1, together with the temperature ranges in which they are generally used and the maximum temperatures at which they can be used for short periods. The period of usefulness at high temperatures depends largely upon the temperature and the diameter of the wires. The methods described in this Circular were devised primarily for calibrating thermocouples in the usual temperature ranges, but unless otherwise indicated they may be used up to the maximum temperatures at which the various types of thermocouples can be used.

TABLE 1. *Types of thermocouples and temperature ranges in which they are used*

Type of thermocouple	Usual temperature ranges		Maximum temperatures	
	° *C*	° *F*	° *C*	° *F*
Platinum versus platinum-rhodium	0 to 1,450	32 to 2,650	1,700	3,100
Chromel-Alumel	−190 to +1,100	−310 to +2,000	1,350	2,450
Iron-constantan	−190 to +760	−310 to +1,400	1,000	1,800
Copper-constantan	−190 to +300	−310 to +570	600	1,100

2. General Considerations

2.1. Temperature Scale

The object in the calibration of any thermocouple is to determine an emf-temperature relationship in which the temperature is expressed on a definite and reproducible scale. The International Temperature Scale, adopted in 1927 [1] [2] by 31 nations and revised in 1948 [2], is now in practically universal use. The methods of realizing this scale are described in detail in the references

---

[1] Now with American Machine & Foundry Co., Alexandria, Va.

[2] Figures in brackets indicate the literature references at the end of this Circular.

TABLE 2. *Instruments, calibration points, and interpolation equations of the International Temperature Scale of 1948*

Temperature ranges		Instruments	Calibration points (values for pressure of 1 standard atmosphere)			Interpolation equations [a]
° *C*	° *F*		*Fixed point*	° *C*	° *F*	
−182.970 to 0	−297.346 to 32	Platinum resistance thermometer.	Boiling point of oxygen.	−182.970	−297.346	$R_t=R_0[1+At+Bt^2+C(t-100)t^3]$.
			Ice point[b]	0	32	
			Boiling point of water	100	212	
			Boiling point of sulfur	444.600	832.280	
0 to 630.5	32 to 1,166.9	Platinum resistance thermometer.	Ice point [b]	0	32	$R_t=R_0(1+At+Bt^2)$.
			Boiling point of water	100	212	
			Boiling point of sulfur	444.600	832.280	
630.5 to 1,063.0	1,166.9 to 1,945.4	Platinum versus platinum-10-percent-rhodium thermocouple.	Freezing point of antimony.	[c] 630.5	[c] 1,166.9	$E=a+bt+ct^2$.
			Freezing point of silver.	960.8	1,761.4	
			Freezing point of gold	1,063.0	1,945.4	
1,063.0 and above	1,945.4 and above	Optical pyrometer	Freezing point of gold	1,063.0	1,945.4	$\frac{J_t}{J_{Au}}=\frac{\frac{c_2}{e^{\lambda(t_{Au}+T_0)}-1}}{\frac{c_2}{e^{\lambda(t+T_0)}-1}}$.

[a] R_t is the resistance at t°C, R_0, the resistance at 0°C; A and B are constants determined by calibration at the boiling points of water and sulfur, and C is an additional constant determined by calibration at the boiling point of oxygen. E is the emf at t°C, and a, b, and c are constants. J_t and J_{Au} are the radiant energies per unit wavelength interval at wavelength, λ, emitted per unit time by unit area of a black body at the temperature, t, and at the gold point, t_{Au}, respectively, c_2 is 1.438 cm degrees, T_0 is the temperature of the ice point in degrees K. λ, is a wavelength of the visible spectrum, and e is the base of Naperian logarithms.

[b] It is recommended that for work of the highest precision, the zero point be realized by means of the triple point of water, a point to which the temperature +0.0100° C has been assigned.

[c] The freezing temperature of the antimony used in determining these constants shall be determined with a standard resistance thermometer, and shall be not lower than 630.3° C. Alternatively, the thermocouple may be calibrated by direct comparison with a standard resistance thermometer in a bath at any uniform temperature between 630.3° and 630.7° C.

cited. The instruments, calibration points, and interpolation equations to be used in the various ranges of the scale are summarized in table 2.

Methods of improving the International Temperature Scale are subjects of continuous study in many laboratories. Although such studies may result in minor changes in the values assigned to fixed points or in the substitution of one fixed point for another, they will not alter, in general, the methods of calibrating thermocouples.

2.2. General Methods

In order to calibrate thermocouples to yield temperatures on the International Temperature Scale, it is apparent from the definition that they must be so calibrated that their indications agree with those of the standard platinum-resistance thermometer in the range −182.970° to 630.5° C, the standard platinum versus platinum-10-percent-rhodium thermocouple in the range 630.5° to 1,063.0° C, and the optical pyrometer above 1,063.0° C. The most direct procedure would therefore be to compare the thermocouples directly with these primary instruments in the appropriate temperature ranges. However, to follow such a procedure in the calibration of every thermocouple requires more time and apparatus than is justifiable or necessary because, in most cases, other methods are available which yield results sufficiently accurate. For example, a thermocouple may be compared indirectly with any of the primary instruments by determining its emf at a number of fixed points, either those which are used in defining the scale or others, the values for which have been determined with the primary instruments. If a few laboratories maintain the apparatus necessary to calibrate thermocouples as working standards to yield temperatures on the International Temperature Scale, these standards may be used subsequently to calibrate other thermocouples. This procedure is used far more than any other because the comparison of the indications of two thermocouples is usually simpler than the comparison of two different types of instruments.

The temperature-emf relationship of a homogeneous[3] thermocouple is a definite physical property and, therefore, does not depend upon the details of the apparatus or method employed in determining this relation. Consequently, there are innumerable methods of calibrating thermocouples, the choice of which depends upon the type of thermocouple, temperature range, accuracy required, size of wires, apparatus available, and personal preference.

Thermocouple calibrations are required with various degrees of accuracy, ranging from 0.1° to 5° or 10° C. For an accuracy of 0.1° C, agreement with the International Temperature Scale and methods of interpolating between the calibration points become problems of prime importance, but for an accuracy of about 10° C, comparatively simple methods of calibration will usually suffice. The most accurate calibrations in the range −190° to 300° C are made by comparing the thermocouples directly with a standard platinum resistance thermometer in a stirred liquid bath. In the range 300° to 630.5° C (and below if a platinum resistance thermometer or stirred liquid bath is not available) thermocouples are most accurately calibrated at the freezing or boiling points of pure substances. Between 630.5° and 1,063.0° C, the platinum versus

---

[3] A homogeneous thermocouple is one in which each element is homogeneous, in both chemical composition and physical condition, throughout its length.

platinum-10-percent-rhodium thermocouple calibrated at the freezing points of gold, silver, and antimony serves to define the International Temperature Scale, and other types of thermocouples are most accurately calibrated in this range by direct comparison with the standard thermocouple calibrated as specified. Other platinum, versus platinum-rhodium thermocouples may be calibrated just as accurately at the fixed points as the platinum versus platinum-10-percent-rhodium thermocouple, but interpolated values at intermediate points may depart slightly from the International Temperature Scale. Above 1,063.0° C, the most basic calibrations are made by observing the emf when one junction of the thermocouple is in a black-body furnace, the temperature of which is measured with an optical pyrometer. However, the difficulties encountered in bringing a black-body furnace to a uniform temperature make the direct comparison of these two types of instruments by no means a simple matter. Other methods of calibrating a thermocouple above 1,063.0° C are given under melting points and under methods of interpolation.

Although the platinum versus platinum-10-percent-rhodium thermocouple serves to define the scale only in the range 630.5° to 1,063.0° C, this type of thermocouple calibrated at fixed points is used extensively both above and below this range as a working standard in the calibration of other thermocouples. For most industrial purposes, a calibration accurate to 2° or 3° C in the range room temperature to 1,200° C is sufficient. Other thermocouples can be calibrated by comparison with such working standards almost as accurately as the calibration of the standard is known. However, it might be pointed out that outside the range 630.5° to 1,063.0° C any type of thermocouple suitable for the purpose, and calibrated to agree with the resistance thermometer or optical pyrometer in their respective ranges, has as much claim to yielding temperatures on the International Temperature Scale as the platinum versus platinum-10-percent-rhodium thermocouple. In fact, at the lower temperatures, certain types of base-metal thermocouples are definitely better adapted for precise measurements.

The calibration of thermocouples then may be divided into two general classes, depending upon the method of determining the temperature of the measuring junction, (1) calibration at fixed points and (2) calibration by comparison with standard instruments, such as thermocouples, resistance thermometers, etc.

In order to obtain the high accuracies referred to above and usually associated with calibrations at fixed points, it is necessary to follow certain prescribed methods and to take the special precautions described in detail in the following sections, but for an accuracy of about 5° C the more elaborate apparatus to be described need not be employed.

2.3. Homogeneity

The magnitude of the emf developed by a thermocouple depends upon the temperatures of the measuring and reference junctions and the composition of the wires in the region of temperature gradients. The emf developed by an inhomogeneous thermocouple is characteristic of the temperature of the measuring junction only when the region of inhomogeneity is not in a region of temperature gradients. Therefore, in order to obtain a high degree of accuracy with a thermocouple, the homogeneity of the wires must be established.

Thermocouple wire now being produced by the manufacturers in this country is sufficiently homogeneous in chemical composition for most purposes. Occasionally, inhomogeneity in a thermocouple may be traced to the manufacturer, but such cases are rare. More often it is introduced in the wires during tests or use. It usually is not necessary, therefore, to examine new thermocouples for inhomogeneity, but thermocouples that have been used for some time should be so examined before an accurate calibration is attempted.

Although rather simple methods are available for detecting thermoelectric inhomogeneity, no satisfactory method has been devised for quantitatively determining it or the resulting errors in the measurement of temperatures. Tests for inhomogeneity must be so designed that the method of testing does not of itself introduce inhomogeneities into the wire being tested. Abrupt changes in the thermoelectric power may be detected by connecting the two ends of the wire to a sensitive galvanometer and slowly moving a sharp temperature gradient, such as that produced by a piece of solid carbon dioxide, a Bunsen burner, or small electric furnace, along the wire. This method is not satisfactory for detecting gradual changes in the thermoelectric power along the length of the wire. Inhomogeneity of this nature may be detected by doubling the wire and inserting it to various depths in a uniformly heated furnace, the two ends of the wire being connected to a galvanometer as before. If, for example, the doubled end of the wire is immersed 25 cm in a furnace with a sharp temperature gradient so that two points on the wire 50 cm apart are in the temperature gradient, the emf determined with the galvanometer is a measure of the difference in the thermoelectric properties of the wire at these two points.

After reasonable homogeneity of one sample of wire has been established, it may be used in testing the homogeneity of similar wires by welding the two together and inserting the junction into a heated furnace. The resulting emf at various depths of immersion may be measured by any convenient method. Other similar methods have been described for detecting inhomogeneity [3].

Tests such as those described above will indicate the uncertainty in temperature measurements due to inhomogeneity in the wires. For example, if a difference in emf of 10 microvolts (abbreviated hereafter μv) is detected along either element of a platinum versus platinum-rhodium thermocouple by heating various parts of the wire to 600° C, measurements made with it are subject to an uncertainty of the order of 1° at 600° C or of 2° at 1,200° C. Similarly, if an emf of 10 μv is detected along an element of a base-metal thermocouple with a source of heat at 100° C, measurements made with it are subject to an uncertainty of the order of 0.2° C at this temperature. The effects of inhomogeneity in both wires may be either additive or subtractive, and, as the emf developed along an inhomogeneous wire depends upon the temperature distribution, it is evident that corrections for inhomogeneity are impracticable if not impossible.

2.4. Annealing

Practically all base-metal thermocouple wire produced in this country is annealed or given a "stabilizing heat treatment" by the manufacturer. Such treatment is generally considered sufficient, and seldom is it found advisable to further anneal the wire before testing.

Although the new platinum and platinum-rhodium thermocouple wires as sold by some manufacturers are already annealed, it has become regular practice in many laboratories to anneal or "stabilize" all platinum versus platinum-rhodium thermocouples, whether new or previously used, before attempting an accurate calibration. This is usually accomplished by heating the wire electrically in air. The entire length of wire is supported between two binding posts, which should be close together so that the tension in the wires and stretching while hot are kept at a minimum. The temperature of the wire is most conveniently determined with an optical pyrometer.[4] It is necessary, however, to add a correction to the observed apparent temperature to obtain the true temperature, which is always the higher. The correction (based on an emissivity of 0.33) amounts to 130° and 145° C, respectively, for apparent temperatures of 1,270° and 1,355° C.

There is some question as to the optimum temperature or length of time at which such thermocouples should be annealed to produce the most constant characteristics in later use [4]. As a matter of fact, there is some question as to whether annealing for more than a few minutes is harmful or beneficial. Most of the mechanical strains are relieved during the first few minutes of heating at 1,400° to 1,500° C, but it has been claimed that the changes in the thermal emf of a thermocouple in later use will be smaller if the wires are heated for several hours before calibration and use. The principal objection to annealing thermocouples for a long time at high temperatures, aside from the changes in emf taking place, is that the wires are weakened mechanically as a result of crystal growth. For a number of years prior to 1935, the practice at the National Bureau of Standards was to anneal all platinum versus platinum-rhodium thermocouples electrically in air for 6 hr at 1,500° C before calibration. The emf of a number of new thermocouples was determined both after annealing for 5 min and for 6 hr at 1,500° C, and in no case did the change in emf correspond to as much as 2° C at 1,200° C. After 6 hr of heating, the wires, particularly the platinum element, become much softer. It has been found, however, that annealing at temperatures much above 1,500° C produces rapid changes in the emf and leaves the wire very weak mechanically. The National Bureau of Standards, on January 2, 1935, adopted the procedure of annealing all platinum versus platinum-rhodium thermocouples for 1 hr at 1,450° C.

It has not been demonstrated conclusively that platinum versus platinum-rhodium thermocouples after contamination can be materially improved in homogeneity by prolonged heating in air, although it is logical to suppose that certain impurities can be driven off or, through oxidation, rendered less detrimental.

2.5. Instruments

One of the factors in the accuracy of the calibration of a thermocouple is the accuracy of the instrument used to measure the emf. Fortunately, in most instances, an instrument is available whose performance is such that the accuracy of the calibration need not be limited by the accuracy of the emf measurements. For work of the highest accuracy, it is advisable to use a potentiometer of the type designed by Diesselhorst [5], White [6], Wenner [7], or Bonn,[5] in which there are no slide wires and in which all the settings are made by means of dial switches. However, for most work, in which an accuracy of a few microvolts will suffice, slide-wire potentiometers of the laboratory type are sufficiently accurate. Portable potentiometers accurate within about 50 μv and capable of being read to about 5 μv are also available. Aside from the greater sensitivity obtained, an important advantage of using a potentiometer is the fact that the reading obtained is independent of the resistance of the thermocouple.

Indicators of the galvanometric type are seldom used in making calibrations. Galvanometer indicators should be graduated for a specified external resistance of thermocouple and extension wires, and the resistance of the indicator itself should be high in order to reduce the effects of changes in the resistance of the thermocouple and leads. A discussion of these factors is given in NBS Technologic Paper T170 (1921).

---

[4] The ordinary portable type of optical pyrometer is very satisfactory for this purpose. As commonly used, the magnification is too low for sighting upon an object as small as the wires of rare-metal thermocouples, but this is easily remedied by inserting an additional piece of telescoping tubing so that the objective lens of the pyrometer is about twice as far from the pyrometer lamp as it is when sighting upon distant objects, or by using an objective lens of higher magnification.

[5] Designed by N. E. Bonn, of the Rubicon Co.

3. Calibration at Fixed Points

One of the important applications of the method of calibrating thermocouples at fixed points is found in the calibration of platinum versus platinum-10-percent-rhodium thermocouples, to realize the International Temperature Scale in the range 630.5° to 1063.0° C. From such a calibration, together with methods of extrapolation described later, the temperature-emf relationship of this type of thermocouple may be determined with an accuracy of about 2° C at 1,450° C. Calibration at a few other selected points below 630.5° C will yield a working standard that is accurate to a few tenths of a degree in the range 0° to 1,100° C. Fixed points are also conveniently used with various degrees of accuracy ranging from 0.1° to 5° C in the calibration and checking of various types of thermocouples in the range −190° C to the melting point of platinum (1,769° C). The fixed points for which values have been assigned or determined accurately and at which it has been found convenient to calibrate thermocouples are given in table 3. The values in the table apply for a pressure of 1 standard atmosphere (760 mm of Hg) and the variations of the boiling temperatures with pressure are given in the last column.

Table 3. *Fixed points available for calibrating thermocouples*

Thermometric fixed point	Values on the International Temperature Scale of 1948				Temperature of equilibrim (t_p) in degrees C as a function of the pressure (p) between 680 and 780 mm of mercury. p_0 is standard atmospheric pressure.
	Assigned (primary points)		Determined (secondary points)		
	°C	°F	°C	°F	
Boiling point of oxygen	−182.970	−297.346	--------	--------	$t_p=-182.970+9.530\left(\frac{p}{p_0}-1\right)-3.72\left(\frac{p}{p_0}-1\right)^2+2.2\left(\frac{p}{p_0}-1\right)^3$
Sublimation point of carbon dioxide.	--------	--------	−78.5	−109.3	$t_p=-78.5+12.12\left(\frac{p}{p_0}-1\right)-6.4\left(\frac{p}{p_0}-1\right)^2$
Freezing point of mercury	--------	--------	−38.87	−37.97	
Ice point	0	32	--------	--------	
Triple point of water	--------	--------	+0.0100	32.0180	
Boiling point of water	100	212	--------	--------	$t_p=100+28.012\left(\frac{p}{p_0}-1\right)-11.64\left(\frac{p}{p_0}-1\right)^2+7.1\left(\frac{p}{p_0}-1\right)^3$
Triple point of benzoic acid	--------	--------	122.36	252.25	
Boiling point of naphthalene	--------	--------	218.0	424.4	$t_p=218.0+44.4\left(\frac{p}{p_0}-1\right)-19\left(\frac{p}{p_0}-1\right)^2$
Freezing point of tin[a]	--------	--------	231.9	449.4	
Boiling point of benzophenone	--------	--------	305.9	582.6	$t_p=305.9+48.8\left(\frac{p}{p_0}-1\right)-21\left(\frac{p}{p_0}-1\right)^2$
Freezing point of cadmium	--------	--------	320.9	609.6	
Freezing point of lead[a]	--------	--------	327.3	621.1	
Freezing point of zinc[a]	--------	--------	419.5	787.1	
Boiling point of sulfur	444.600	832.280	--------	--------	$t_p=444.600+69.010\left(\frac{p}{p_0}-1\right)-27.48\left(\frac{p}{p_0}-1\right)^2+19.14\left(\frac{p}{p_0}-1\right)^3$
Freezing point of antimony	--------	--------	630.5	1166.9	
Freezing point of aluminum[a]	--------	--------	660.1	1220.2	
Freezing point of silver	960.8	1761.4	--------	--------	
Freezing point of gold	1063.0	1945.4	--------	--------	
Freezing point of copper[a]	--------	--------	1083	1981	
Freezing point of palladium	--------	--------	1552	2826	
Freezing point of platinum	--------	--------	1769	3216	

[a] The values given in this table for these materials are the values stated in the International Temperature Scale of 1948. Standard Samples of these materials are procurable from the National Bureau of Standards with certificates giving the freezing point of the particular lot of metal.

In selecting the points at which to calibrate a thermocouple, one sometimes has a choice between a boiling or a freezing point[6] as, for example, between the boiling point of sulfur (444.600° C) and the freezing point of zinc (419.5° C); between the boiling point of naphthalene (218.0° C) and the freezing point of tin (231.9° C); or between the boiling point of benzophenone (305.9° C) and the freezing point of cadmium (320.9° C) or lead (327.3° C). In determining the emf of a thermocouple at a freezing point, the time in which observations may be taken is limited to the period of freezing, after which the material must be melted again before taking further observations. In the case of boiling points, there is no such limit in time since the material can be boiled continuously. In addition, there is sometimes a question as to the beginning and end of the interval of constant-temperature characteristic of freezing. On the other hand, it is not necessary to observe the pressure during freezing and, in general, simpler apparatus and less skill are required to obtain a given accuracy with freezing points.

---

[6] In this Circular, "boiling point" is used for the temperature of equilibrium between the liquid and vapor phases, although the point is usually realized experimentally by immersing the thermocouple in the condensing vapor. "Freezing point" is used for the temperature of equilibrium between the solid and liquid phases when the point is realized experimentally by immersing the thermocouple in the freezing material, and "melting point" is used for the same point when it is realized experimentally by determining the emf of a thermocouple while the material is melting. When conditions permit a choice, freezing points are preferable to melting points of metals because the molten metal can be brought to a uniform temperature just prior to freezing by stirring more easily than the solid can be brought to a uniform temperature just prior to melting, a condition that must be met to obtain accurate results.

3.1. Freezing Points

The emf developed by a homogeneous thermocouple at the freezing point of a metal is constant and reproducible if all of the following conditions are fulfilled: (1) The thermocouple is protected from contamination, (2) the thermocouple is immersed in the freezing-point sample sufficiently far to eliminate heating or cooling of the junction by heat flow along the wires and protection tube, (3) the reference junctions are maintained at a constant and reproducible temperature, (4) the freezing-point sample is pure, and (5) the metal is maintained at essentially a uniform temperature during freezing. The methods of obtaining these conditions are subject to a choice. However, the essential features of the methods employed at the National Bureau of Standards are described here.

a. Protection Tubes

Closed-end porcelain or Pyrex-glass tubes are generally used to protect thermocouples from contamination, which usually results from the thermocouple wires coming in contact with other metals or metallic vapors or from the action of reducing gases at high temperatures. In the latter case, the silica of the insulating or protecting tube is reduced to silicon, which alloys with the thermocouple wires [8]. For temperatures above 500° C, the wires should be insulated by porcelain tubing and protected from contamination by a glazed porcelain tube. It is advisable to heat these tubes before use, to about 1,200° C in an oxidizing atmosphere to burn out any carbonaceous material that may have collected in them during storage and shipping. Protection tubes 5-mm inside diameter, 7-mm outside diameter, and 50 cm long are convenient for platinum versus platinum-rhodium thermocouples insulated by two-hole insulating tubes 50 cm long and 4 mm in diameter with 1-mm holes. For temperatures below 500° C, Pyrex tubes are very satisfactory for both protecting and insulating the wires.

b. Depth of Immersion

The depth of the immersion necessary to avoid heating or cooling of the junction by heat flow along the thermocouple wires and protection tube depends upon the material and size of the wires, the dimensions of the insulating and protecting tubes, and the difference between the temperature of the freezing-point sample and that of the furnace and atmosphere immediately above it. The safest method of determining whether the depth of immersion is sufficient is by trial. It should be such that during the period of freezing the thermocouple can be lowered or raised at least 1 cm from its normal position without altering the indicated emf by as much as the allowable uncertainty in the calibration. For platinum versus platinum-rhodium thermocouples in the protection tube described above, a depth of 10 cm, which is greater than necessary, is used at the National Bureau of Standards.

c. Reference-Junction Temperature Control

The temperature of the reference junctions is most easily controlled at a known temperature by placing them in an ice bath. A wide-mouthed Dewar flask filled with shaved ice saturated with water is very satisfactory. Electrical connection between a thermocouple wire and a copper lead wire is easily made by inserting them into a small glass tube containing a few drops of mercury. The glass tubes are then inserted into the ice bath to a depth of about 10 cm. The extension wires must be insulated from the thermocouple wires, except where they make contact through the mercury. It is preferable that the insulation on the wires extends below the level of the mercury. The glass tubes should be kept clean and dry inside. Moisture is likely to condense in the tube from the atmosphere but should not be allowed to accumulate. A little moisture and dirt at the bottom of the tube will form a galvanic cell, which may vitiate the readings. A later section deals with reference-junction temperatures in general.

d. Purity of Freezing-Point Samples

The temperature at which a metal freezes depends upon the amount and kind of impurities present. The values in table 3 apply for metals, the purity of which is of the order of 99.99 percent. The freezing temperature of silver, gold, or copper may be lowered by as much as 0.1° C and that of antimony, aluminum, zinc, lead, cadmium, tin, or mercury by as much as 0.05° C by 0.01 percent of impurities. The purity of the Standard-Sample freezing-point materials issued by the National Bureau of Standards is not of great importance, as a certificate is issued with each sample giving the freezing temperature determined on that particular lot of metal. However, the purest metals available are selected for these Standard Samples because a high degree of purity is necessary in order that the metal may give a flat freezing curve.

e. Crucibles

Of the crucible materials ordinarily used, highly purified graphite has the greatest utility and is used almost exclusively at NBS for this work. It can be machined into any desired shape, and can be used in contact with any of the freezing-point materials in table 3 except palladium and platinum without detectable contamination of the metals. At high temperatures, the gases formed from its oxidation provide the reducing atmosphere usually necessary for the protection of the freezing-point metal. Copper and copper oxide form a eutectic which melts about 20° C lower than pure copper, and it is possible for molten silver to absorb enough oxygen from the air to lower its freezing point as much as 10° C [9]. Therefore, copper and silver must be protected from oxygen, and it is advisable also to protect aluminum and antimony from oxygen. This is

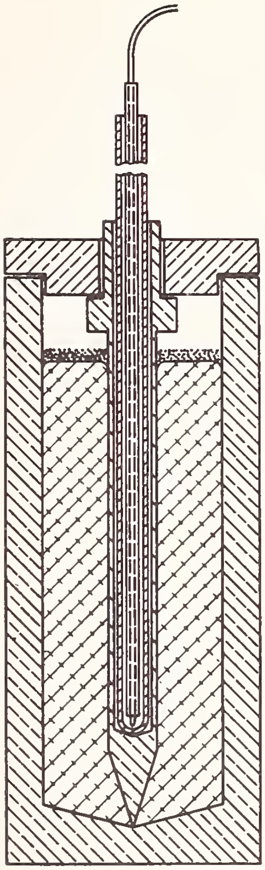


FIGURE 1. *Arrangement for protecting a thermocouple in molten aluminum.*

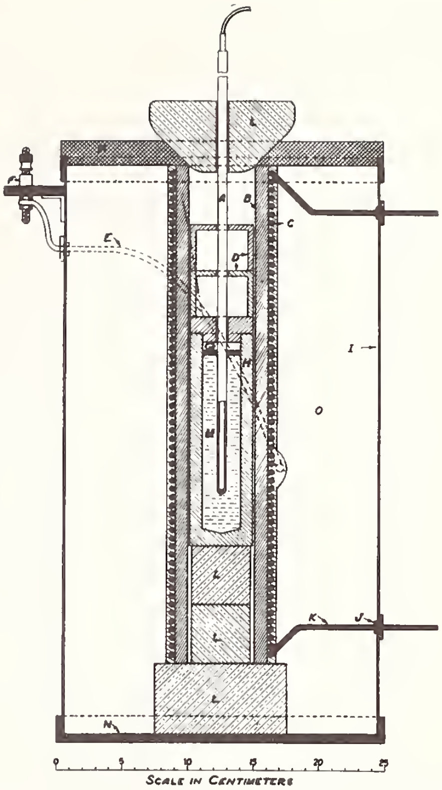


FIGURE 2. *Furnace used in calibrating thermocouples at freezing points of metals.*

A, Porcelain protecting tube; B, refractory furnace tube; C, heating element (80 nickel, 20 chromium); D, graphite diaphragms; E, control thermocouple (Chromel-Alumel); G, graphite powder; H, graphite crucible; I, sheet steel; L, insulating blocks; M, freezing-point metal; N, cast-iron base; O, powdered diatomaceous earth insulation.

done by using graphite crucibles with covers of the same material, and as an added precaution these freezing-point metals are covered with powdered graphite or charcoal.

Porcelain tubes or crucibles, or any material containing silica, cannot be used in contact with aluminum, as the silica is readily attacked. Aluminum is melted in a graphite crucible and the porcelain protecting tube separated from the aluminum by a very thin sheath of graphite. Figure 1 illustrates one convenient manner in which the sheath may be mounted in the crucible. The sheath is held down in the metal by the weight of the cover and is allowed to remain in the crucible after the aluminum is frozen. The thermocouple protecting tube fits snugly inside the sheath. At the National Bureau of Standards the graphite crucibles used for gold, silver, antimony, and zinc are 3-cm inside diameter and 15 cm deep. The crucibles used for copper, aluminum, lead, and tin are 5-cm inside diameter and 15 cm deep. Porcelain, silica, clay, clay graphite, and Pyrex glass are also used as crucible materials. Pyrex glass is very suitable for mercury.

f. Furnaces

Figure 2 shows the type of furnace used in the freezing-point determinations. The heating element is No. 6 or 8 gage nickel(80)-chromium(20) wire wound on a refractory tube and imbedded in refractory cement. The space between the heating element and the outside wall is filled with powdered diatomaceous earth. Graphite diaphragms are placed above the crucible in order to reduce the oxidation of the crucibles and to promote temperature uniformity in the metal.

g. Procedure

In the calibration of a thermocouple at freezing points, the thermocouple, properly protected, is slowly immersed in the molten metal. The metal is brought to essentially a uniform temperature at the beginning of freezing by holding its temperature constant at about 10° C above the freezing point for several minutes and then cooling slowly, or by agitating the metal with the thermocouple protection tube just before freezing begins. The emf of the thermocouple is observed at regular intervals of time. These values are plotted, and the emf corresponding to the flat portion of the cooling curve is the emf at the freezing point of the metal.

Antimony and tin have a marked tendency to undercool before freezing, but the undercooling will not be excessive if the liquid metal is stirred.

3.2. Melting Points

The emf of a thermocouple at the melting point of a metal may be obtained in the same manner and with the same apparatus as that just described for freezing points, but the latter are found to be more satisfactory. However, melting points are used to advantage when only a limited amount of material is available. One method of obtaining the emf of a thermocouple at a melting point with a small amount of material is the wire method [10]. In this method, the thermocouple wires are placed in a two-hole insulating tube and a short length of the melting-point sample, in the form of wire about the same diameter as the thermocouple elements, is welded between the measuring junction ends of the two wires. The dimensions of the melting-point sample are not critical, but there should be at least 1 mm of wire between the two welds. In order that the melting-point sample shall not break before the melting point is reached, the weld should be made and the thermocouple placed in the furnace so that there is a minimum of strain on the melting-point sample. The measuring junction end of the thermocouple with the melting-point sample, is placed in a uniformly heated section of a furnace and the temperature increased very slowly as the melting point is approached. When the sample reaches its melting point, its temperature and consequently the emf of the thermocouple remain constant for a fraction of a minute (varying with the rate of temperature rise). After melting is complete, the temperature of the wire and the emf may rise somewhat before the circuit is broken by the separation of the molten metal. The value of the emf corresponding to the melting point is, therefore, the value at the halt in the emf rise and is obtained by continuous observation of the emf as melting is approached or by plotting time versus emf.

The metal most often used in the calibration of thermocouples by the wire method is gold, and it has been demonstrated that results can be obtained which are in agreement with those obtained with a crucible of freezing gold to a few tenths of a degree. The same method has been used with palladium, but with much less satisfactory results because of electric leakage through the refractory insulation at high temperatures and the oxidation of the palladium. This method is not well adapted to metals that oxidize rapidly, and if used with materials whose melting temperature is altered by the oxide, the metal should be melted in a neutral atmosphere.

If very accurate observations of the emf are not required, the emf at the instant the circuit is broken may be taken, but if this is done the thermocouple should be withdrawn from the furnace immediately and the sample examined to see whether the circuit was broken by the sample melting or by strain on it before melting occurred.

It is not necessary to weld the wire between the thermocouple elements, as fairly good results may be obtained by wrapping a small amount of the wire around the junction. This practice is often applied to base-metal thermocouples by wrapping wires of tin, lead, zinc, or aluminum around the measuring junction and heating it until a halt is observed in the heating curve.

One method of checking platinum versus platinum-rhodium thermocouples at the highest possible point is by heating the junction of the thermocouple until the platinum wire melts. To avoid electric leakage, the insulating tube is withdrawn to the colder parts of the heating device leaving only the wires and junction in the hotter parts.

3.3. Boiling Points

Boiling points play an important part in the definition of the International Temperature Scale, because 3 of the 4 points upon which the scale between $-182.970°$ and $+630.5°$ C is based are the boiling points of oxygen, water, and sulfur. However, boiling points, with the exception of that of water, are seldom used in the calibration of thermocouples, and consequently the methods of realizing these various points will be mentioned only briefly here. References are given to complete discussions for those interested, as boiling points might profitably be employed to a greater extent, when a platinum-resistance thermometer or a stirred liquid bath is not available.

a. Water (Steam Point)

The temperature of condensing water vapor is realized experimentally by the use of a hypsometer so constructed as to avoid superheat of the vapor around the thermocouple and contamination with air and other impurities. Simple types of hypsometers are shown in various trade catalogs. Mueller and Sligh [11] give a detailed description of a hypsometer used in precision measurements. If the proper conditions are attained, the observed emf of the thermocouple will be independent of the rate of heat supply to the boiler, the length of time the hypsometer has been in operation, and the depth of immersion of the thermocouple. The thermocouple for some distance from the junction must be shielded from radiation from hotter and colder surfaces. The relationship between the temperature (t_p) (in degrees C) and the pressure (p) given in table 3 holds for the range 660 to 860 mm of Hg. The steam point as realized by utilizing the condensing vapor in a hypsometer is certainly accurate to 0.01° C. An accuracy of about 1° C can be obtained by merely immersing a thermocouple in boiling water.

b. Sulfur, Benzophenone, and Naphthalene

The boiling points of the three materials above are near the freezing points of available pure metals and are very seldom used in the calibration of thermocouples. The specifications to be followed in realizing the sulfur point are given in the International Temperature Scale [12]. Detailed description of the apparatus and precautions to be observed for the sulfur boiling point are given by Mueller and Burgess [13]. The relationship between temperature and pressure for sulfur in table 3 holds for the range 660 to 800 mm of Hg. The procedure and apparatus for realizing the boiling points of naphthalene and benzophenone are the same as those for the boiling point of sulfur. Detailed information regarding these points is given by Waidner and Burgess [14] and by Finck and Wilhelm [15].

c. Oxygen

The temperature of equilibrium between liquid and gaseous oxygen is best realized experimentally by the static method, the oxygen vapor-pressure thermometer being compared with the thermocouple to be calibrated in a suitable low-temperature bath. An oxygen vapor-pressure thermometer is nothing more than a glass tube containing very pure oxygen at a pressure of several atmospheres at room temperature, and connected to a mercury-filled manometer for measuring the pressure in the tube [16]. When the thermometer tube is immersed in the bath, part of the oxygen liquefies. The relationship between the temperature (t_p) (in degrees C) of the bath and the pressure (p) in the thermometer given in table 3 holds for the range 660 to 860 mm of Hg. This requires that the temperature of the bath be kept within the limits −184.3° to −181.8° C. This is most conveniently done by stirring liquid oxygen in a Dewar flask.

d. Carbon-Dioxide Point

Although the sublimation point of carbon dioxide is not a boiling point, the highest accuracy is obtained in utilizing this point, by employing the same method as that for the boiling point of oxygen. An instrument of this type suitable for use as a carbon-dioxide vapor-pressure thermometer is container type 3, described by Meyers and Van Dusen [17]. The sublimation point of carbon dioxide may also be utilized by immersing the thermocouple in a slush made by mixing carbon-dioxide snow with a liquid such as acetone. The slush should be stirred and the air excluded from the vapor above the surface of the slush. Whereas the accuracy obtained with a vapor-pressure thermometer is of the order of a few hundredths of a degree, an accuracy of 1° C is all that can be claimed for the temperature of the slush.

4. Calibration by Comparison Methods

The calibration of a thermocouple, by comparison with a working standard is sufficiently accurate for most purposes and can be done conveniently in most industrial and technical laboratories. The success of this method usually depends upon the ability of the observer to bring the junction of the thermocouple to the same temperature as the actuating element of the standard, such as the measuring junction of a standard thermocouple or the bulb of a resistance or liquid-in-glass thermometer. The accuracy obtained is further limited by the accuracy of the standard. Of course, the reference-junction temperature must be known, but this can usually be controlled by using an ice bath as described earlier or measured with a liquid-in-glass thermometer. The method of bringing the junction of the thermocouple to the same temperature as that of the actuating element of the standard depends upon the type of thermocouple, type of standard, and the method of heating.

4.1. Platinum Versus Platinum-Rhodium Thermocouples

Platinum versus platinum-rhodium thermocouples, either the 10- or 13-percent rhodium, are seldom used for accurate measurements below 300° C (572° F) and are practically never used below 0° C, because the thermal emf per degree of these thermocouples decreases rapidly at low temperatures, becoming zero at about −138° C (−216° F). These thermocouples are usually calibrated above 300° C by comparison with standard thermocouples in electrically heated furnaces. The standard thermocouple may be either a platinum versus platinum 10- or 13-percent-rhodium thermocouple that has been calibrated at fixed points or by comparison with other thermocouples so calibrated.

The method employed at the National Bureau of Standards for the comparison of two such thermocouples permits simultaneous reading of the emf of each thermocouple without waiting for the furnace to come to a constant temperature. In order to insure equality of temperature between the measuring junctions of the thermocouples, they are welded together. A separate potentiometer is used to measure each emf, one connected to each thermocouple, and each potentiometer is provided with a reflecting galvanometer. The two spots of light are reflected onto a single scale, the galvanometers being set in such a position that the spots coincide at the zero point on the scale when the circuits are open and, therefore, also when the potentiometers are set to balance the emf of each thermocouple. Simultaneous readings are obtained by setting one potentiometer to a desired value and adjusting the other so that both spots of light pass across the zero of the scale together as the temperature of the furnace is raised or lowered.

By making observations, first with a rising and then with a falling temperature, the rates of rise and fall being approximately equal, and taking the means of the results found, several minor errors, such as those due to differences in the periods of the galvanometers, etc., are eliminated or greatly reduced. The differences between the values observed with rising and falling temperatures are usually less than a few microvolts with platinum versus platinum-rhodium thermocouples, if the periods of the galvanometers are approximately the same.

This method is particularly adapted to the calibration of thermocouples at any number of selected points. For example, if it is desired to determine the temperature of a thermocouple corresponding to 10.0 mv, this emf is set up on the potentiometer connected to this thermocouple, the emf of the standard thermocouple observed as described above, and the temperature obtained from the emf of the standard. If it is desired to determine the emf of a thermocouple corresponding to 1,000° C, the emf of the standard corresponding to this temperature is set up on the potentiometer connected to the standard and the emf of the thermocouple being tested is observed directly.

In order to calibrate a thermocouple in the least possible time by this method, it is necessary to use a furnace that is so constructed that it will cool rapidly. The heating element of the furnace used at NBS for the routine testing of thermocouples consists of a nickel(80)-chromium(20) tube clamped between two water-cooled terminals. The tube, which is 13/16-in. inside diameter, 1$\frac{5}{16}$-in. outside diameter, and 24 in. long, is heated electrically, the tube itself serving as the heating element or resistor. The large current necessary to heat the tube is obtained from a transformer. A large cylindrical shield of sheet metal is mounted around the heating tube to reduce the radiation loss. To reduce lag no thermal insulation is used between the heating tube and the radiation shield. The middle part of this furnace, for about 18 in., is at practically a uniform temperature, and the water-cooled terminals produce a very sharp temperature gradient at each end. This furnace can be heated to 1,200° C in about 10 min with 12 kw and, if all the power is shut off, will cool from this temperature to 300° C in about the same time. This type of furnace can be used up to 1,250° C (2,282° F).

The thermocouples are insulated and protected by porcelain tubes. It is essential that the two potentiometers and thermocouple circuits be separate except at the point where the junctions are welded together. The reference junctions are maintained at 0° C.

The above method and apparatus were devised primarily for the rapid testing of thermocouples, but it is not necessary to follow this method literally or to procure identical apparatus to obtain good results. If it is not convenient to weld the junctions of the thermocouples together, they may be brought into fairly good contact by wrapping with platinum wire or foil. The only advantage of the furnace described above, over any other type of furnace in which several inches of the thermcocouples may be heated to a uniform temperature, is the flexibility of control. Electric tube furnances suitable for such comparison tests can be obtained, designed to operate on either 110 or 220 v, and may be obtained equipped with an adjustable power supply for regulating the current. For temperatures up to 1,150° C (2,102° F), a furnace with a heating element of nickel (80)-chromium (20) will suffice. Furnaces with heating elements of platinum or platinum-rhodium are available for higher temperatures. A convenient size of heating tube is 1 in. in diameter and 18 in. long. Even though the furnace tube is kept fairly clean, it is advisable to protect platinum versus platinum-rhodium thermocouples by a porcelain tube. If two potentiometers are not available for taking simultaneous readings, the furnace may be brought to essentially a constant temperature and the emf of each thermocouple read alternately on one instrument.

When the thermocouples are calibrated by welding or wrapping the junctions together, the difference between the temperatures of the junctions should not be great even when the temperature of the furnace is changing. If it is necessary or advisable to calibrate the thermocouples without removing them from the protection tubes, then the junctions of the thermocouple being tested and that of the standard should be brought as close together as possible in a uniformly heated portion of the furnace. In this case, it is necessary that the furnace be brought to approximately a constant temperature before taking observations. It is usually not possible to maintain the reference junctions at 0° C when the thermocouples are completely enclosed in protection tubes. However, extension leads may be used with the thermocouple or the temperature of the reference junctions may be measured with a thermometer.

There are a number of other methods of heating and of bringing the junctions to approximately the same temperature, for example, inserting the thermocouples properly protected into a bath of molten metal or into holes drilled in a large metal block. The block of metal may be heated in a muffle furnace or, if made of a good thermal conductor such as copper, may be heated electrically. Tin, which has a low melting point, 232° C (450° F), and low volatility, makes a satisfactory bath material. The thermocouples should be immersed to the same depth with the junctions close together. Porcelain tubes are sufficient protection, but to avoid breakage by thermal shock when immersed in molten metal it is preferable to place them inside of secondary tubes of iron, nickel-chromium, graphite, or similar material. In all of these methods, particularly in those cases in which the junctions of the thermocouples are not brought into direct contact, it is important that the depth of immersion be sufficient to eliminate cooling or heating of the junctions by heat flow along the thermocouple and the insulating and protecting tubes. This can be determined by observing the change in the emf of the thermocouple as the depth of immersion is changed slightly. If proper precautions are taken, the accuracy yielded by any method of heating or bringing the junctions to the same temperature may be as great as that obtained by any other method.

4.2. Base-Metal Thermocouples in Laboratory Furnaces

The methods of testing base-metal thermocouples above room temperature are generally the same as those just described for testing rare-metal thermocouples with the exception, in some cases, of the methods of bringing the junctions of the standard and the thermocouple being tested to the same temperature and the methods of protecting platinum versus platinum-rhodium standards from contamination. One arrangement of bringing the junction of a platinum versus platinum-rhodium standard to the same temperature as that of a large base-metal thermocouple for accurate calibration is to insert the junction of the standard into a small hole (about 1.5 mm in diameter) drilled in the measuring junction of the base-metal thermocouple as shown in figure 3. The platinum versus platinum-rhodium standard is protected by porcelain tubes to within a few millimeters of the measuring junction; and the end of the porcelain tube is sealed to the thermocouple by Pyrex glass or by a small amount of kaolin and water-glass cement. This prevents contamination of the standard thermocouple, with the exception of the small length of 2 or 3 mm, which is necessarily in contact with the base-metal thermocouple. If the furnace is uniformly heated in this region (and it is of little value to make such a test unless it is) contamination at this point will not cause any error. If the wire becomes brittle at the junction, this part of the wire may be cut off and enough wire drawn through the seal to form a new junction. The seal should be examined after each test and remade if it does not appear to be good. More than one base-metal thermocouple may be welded together and the hole drilled in the composite junction. The thermocouples should be clamped in place so that the junctions remain in contact. If two potentiometers are used for taking simultaneous readings, the temperature of the furnace may be changing as much as a few degrees per minute during an observation, but if a single instrument is used for measuring the emf, the furnace temperature should be maintained practically constant during observations.

In testing one or more small base-metal thermocouples, they may be welded to the junction of the standard. If a base-metal standard is used, the best method is to weld all the junctions together. If a large number of base-metal thermocouples are to be tested at the same temperature, the method of immersing the thermocouples in a molten-metal bath or into holes drilled in a large copper block is very advantageous. If a tin bath is used, iron or nickel-chromium tubes are sufficient protection for base-metal thermocouples. When wires, insulators, and protection tubes of base-metal thermocouples are large, tests should be made to insure that the depth of immersion is sufficient to eliminate heating or cooling of the junction by heat flow along these materials.

4.3. Thermocouples in Fixed Installations

After thermocouples have been used for some time at high temperatures, it is difficult if not impossible to determine how much the calibrations are in error by removing them from an installation and testing in a laboratory furnace. The thermocouples are usually inhomogeneous after such use and in such a condition the emf developed by the thermocouples depends upon the temperature distribution along the wires [18]. If possible, such thermocouples should be tested under the same conditions and in the same installation in which they are used. Although it is not usually possible to obtain as high a precision by testing the thermocouples in place as is obtained in laboratory tests, the results are far more accurate in the sense of being representative of the behavior of the thermocouples.

The exact method of procedure depends upon the type of installation. A standard thermocouple is usually employed with extension leads and preferably a portable potentiometer, although a portable high-resistance millivoltmeter may be used. In this case, as in the calibration of any thermocouple by comparison methods, the main objective is to bring the measuring junction of the standard thermocouple to the same temper-

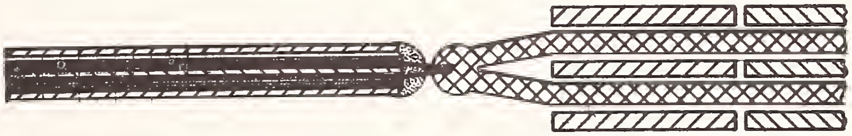


Figure 3. *Arrangement to assure good thermal contact between the junction of a base-metal thermocouple and that of a protected platinum versus platinum-rhodium thermocouple.*

ature as that of the thermocouple being tested. One method is to drill a hole in the furnace at the side of each thermocouple permanently installed, large enough to permit insertion of the checking thermocouple. The hole is kept plugged, except when tests are being made. The standard thermocouple is immersed in the furnace through this hole to the same depth as the thermocouple being tested, with the measuring junctions ends of the protection tubes as close together as possible.

In many installations, the base-metal thermocouple and protecting tube are mounted inside another protecting tube of iron, fire clay, silicon carbide, or some other refractory which is permanently cemented or fastened into the furnace wall. Frequently there is room to insert a small test thermocouple in this outer tube alongside of the fixed thermocouple. A third method, much less satisfactory, is to wait until the furnace has reached a constant temperature and make observations with the thermocouple being tested, then remove this thermocouple from the furnace, and insert the standard thermocouple to the same depth.

If desired, comparisons can be made preferably by either of the first or second methods at several temperatures, and a curve obtained for each permanently installed thermocouple showing the necessary corrections to be applied to its readings. Although testing a thermocouple at one temperature yields some information, it is not safe to assume that the changes in the emf of the thermocouple are proportional to the temperature or to the emf. For example, it has been observed that a thermocouple which had changed in use by the equivalent of 9° C at 315° C had changed only the equivalent of 6° C at 1,100° C.

It may be thought that this method of checking thermocouples is unsatisfactory because, in most furnaces used in industrial processes, large temperature gradients exist and there is no certainty that the standard thermocouple is at the same temperature as the thermocouple being tested. This objection, however, is not serious, because if temperature gradients do exist of such a magnitude as to cause much difference in temperature between two similarly mounted thermocouples located close together, the reading of the standard thermocouple represents the temperature of the fixed thermocouple as closely as the temperature of the latter represents that of the furnace.

The principal advantage of this method is that the thermocouple, leads, and indicator are tested as a unit and under the conditions of use.

4.4. Thermocouples in Stirred Liquid Baths

Thermocouples and resistance thermometers are not usually directly compared above 300° C because of the difficulty encountered in bringing the thermocouple junction and the thermometer bulb to the same temperature, but these two types of instruments may be very accurately compared below 300° C, where a stirred liquid bath can be conveniently used. A type of bath suitable for use above 0° C is shown in figure 5 of a paper by N. S. Osborne [19]. The container, which is insulated on the outside, consists of two cylindrical vertical tubes connected at the bottom and near the top by rectangular ports. A frame carrying the heating element, cooling coils if desired, and stirring propeller are inserted in one of the vertical tubes. The instruments being compared are placed in the other vertical tube and held in place by any convenient means. The chief advantage of this arrangement is that local irregularities, due to direct conduction from the vicinity of the heating or cooling elements, are eliminated. A stirred liquid bath for use below 0° C has been described by Scott and Brickwedde [20].

The liquids used in the baths should be capable of being stirred readily at any temperature at which they are used and they should not be highly flammable. At NBS oil is used between 100° and 300° C; water in the range 0° to 100° C; mixtures of carbon tetrachloride and chloroform in the range 0° to −75° C; a five-component mixture containing 14.5 percent of chloroform, 25.3 percent of methylene chloride, 33.4 percent of ethyl bromide, 10.4 percent of *trans*dichloroethylene, and 16.4 percent of trichloroethylene in the range −75° to −140° C; and commercial propane below −140° C. Propane is highly flammable, and every precaution must be taken to prevent it from mixing with liquid air or oxygen. A complete series of nonflammable liquids for cryostats is given by C. W. Kanolt [21] for temperatures down to −150° C.

A number of thermocouples can be calibrated at one time in a stirred liquid bath. Platinum-resistance or liquid-in-glass thermometers or thermocouples may be used as standards.

5. Methods of Interpolating Between Calibration Points

5.1. Platinum Versus Platinum-Rhodium Thermocouples

After a thermocouple has been calibrated at a number of points, the next requirement is a convenient means of obtaining corresponding values of emf and temperature at other points. A curve may be drawn or a table giving corresponding temperature and emf values may be prepared. The values in such a table may be obtained by computing an empirical equation or series of equations through the calibration points, by direct interpolation between points, or by drawing a difference curve from an arbitrary reference table which closely approximates the temperature-emf relationship of the thermocouple. The method to be selected for a particular calibration depends upon such factors as the type of thermocouple, number of calibration points, temperature range, accuracy required, and personal preference.

For the highest accuracy in the range 630.5° to 1063.0° C with platinum versus platinum-10-percent rhodium thermocouples, the method is that prescribed in the International Temperature Scale. An equation of the form $e=a+bt+ct^2$, where a, b, and c are constants determined by calibration at the freezing points of gold, silver, and antimony, is used. By calibrating the thermocouple also at the freezing point of zinc and using an equation of the form

$$e=a'+b't+c't^2+d't^3,$$

the temperature range can be extended down to 400° C without introducing an uncertainty [22] of more than 0.1° C in the range 630.5° to 1063.0° C. By calibrating the thermocouple at the freezing points of gold, antimony, and zinc and using an equation of the form $E=a''+b''t+c''t^2$, a calibration is obtained for the range 400° to 1,100° C, which agrees [22] with the International Temperature Scale to 0.5° C. The freezing point of copper may be used instead of the gold point, and the aluminum point used instead of the antimony point without introducing an additional uncertainty [22] of more than 0.1° C.

For temperatures outside the range 630.5° to 1063.0° C, the method of drawing a smooth curve through the temperature and emf values has just as much claim to accuracy as the method of passing empirical equations through the calibration points, because an empirical equation performs the same function as a curved ruler. For the temperature range 0° to 1,450° C, a curve for interpolation to 1° or 2° C requires calibration points not more than 200° C apart and a careful plot on a large sheet of paper, which is tedious to read. A reduction in the number of calibration points increases the uncertainty proportionately. If, however, we plot as ordinates the differences between the observed emf and that calculated from the first degree equation $e=10t$, and emf as abscissas, the difference at intermediate points may be taken from the curve and added to the quantity $10t$ to obtain values of emf corresponding to the appropriate temperature in which the uncertainty in the interpolated values is much less than in the case in which the emf is plotted directly against the temperature. If we go one step further and plot differences from an arbitrary reference table, the values of which closely represent the form of the temperature-emf relationship for the type of thermocouple in question, the maximum differences to be plotted will be only a few degrees. In this way, interpolated values are obtained in which the uncertainty in the interpolated values is not appreciably greater than that at the calibration points. The more accurately the values in the arbitrary reference table conform to the emf-temperature relationship of actual thermocouples, the fewer the number of calibration points required for a given accuracy.

Reference tables [23] for platinum versus platinum-rhodium thermocouples which are based on the temperature-emf relationships of a considerable number of representative thermocouples from various sources have recently been published. These tables represent the shape of the relations for both the 10- and 13-percent-rhodium thermocouples in the entire range 0° to 1,700° C. The difference curve for any thermocouple from the appropriate table is a smooth curve.

In the calibration of platinum versus platinum-10-percent-rhodium thermocouples to be used as working standards, the emf is observed at the freezing points of gold, silver, antimony, and zinc. The constants in the equation $E=a+bt+ct^2$ are computed from the observations at the gold, silver, and antimony points. The observed value at 419.5° C and the values calculated from the equation for the range 630.5° to 1063.0° C are used to construct a difference curve from the reference table mentioned previously. This difference curve is then extended graphically above 1063.0° C. When the highest accuracy is required at the lower temperatures, additional observations are taken at the freezing points of lead and tin and at the boiling point of water. Values taken from this difference curve when added algebraically to the values in the reference table yield the corresponding temperature-emf values at any temperature. A numerical example follows.

The observed values of emf at the calibration points are given in table 4, together with the values at 50° C intervals from 650° to 1,050° C computed from the equation,

$$E=-270.73+8.15786t+0.00169396t^2.$$

Corresponding values of E and Δe are plotted in figure 4.

Table 4. *Data for construction of difference curve*

Temperature, t	Reference table emf NBS Circular 561, E_r	Observed emf standard thermocouple, E	Difference, $\Delta e=E_r-E$
° C	μv	μv	μv
0.0	0.0	0.0	0.0
419.5	3437.6	3443.6	−6.0
630.5	5536.8	5546.2	−9.4
650.0	5738.0	5747.6	−9.6
700.0	6259.7	6269.8	−10.1
750.0	6790.0	6800.5	−10.5
800.0	7328.9	7339.7	−10.8
850.0	7876.4	7887.3	−10.9
900.0	8432.4	8443.4	−11.0
950.0	8996.9	9008.0	−11.1
960.8	9120.0	9131.1	−11.1
1000.0	9570.1	9581.1	−11.0
1050.0	10151.8	10162.6	−10.8
1063.0	10304.4	10315.2	−10.8

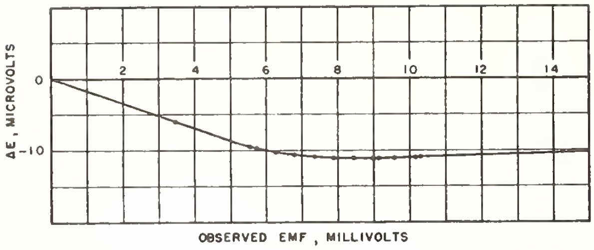


FIGURE 4. *Difference curve for a platinum versus platinum-10 percent-rhodium thermocouple, using the reference table in NBS Circular 561.*

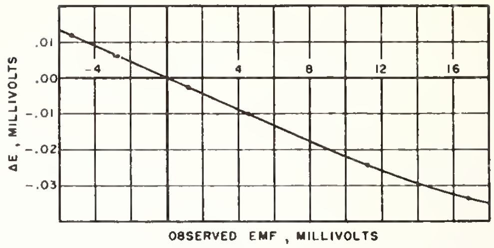


Figure 5. *Difference curve for a copper-constantan thermocouple, using the reference table in NBS Circular 561.*

For accurate extrapolation above the gold point, it is essential that the shape of the emf-temperature relationship given in the reference table conform closely to that of actual thermocouples so that the difference curves will be linear both above and below this point. If the difference curve has a large curvature or if there is an abrupt change in slope near the gold point, the extrapolation of the difference curve may involve considerable uncertainty. The difference curves of actual thermocouples both 10- and 13-percent-rhodium alloys from the reference tables given in NBS Circular 561 are in most cases smooth curves in the entire range 0° to 1,700° C and the difference curves can therefore be extrapolated with but little uncertainty. The extrapolated values for a number of thermocouples have been checked by means of actual comparison with an optical pyrometer, and in no case was the difference as great as 3° C at 1,500° C and in most cases it was not over 1° C. These differences are not much greater than the accidental errors in the comparisons.

Difference curves can be drawn from observations obtained in comparison calibrations as well as from observations at fixed points. Two points (accurate to ±0.3° C at about 600° and 1,100° C) are usually sufficient to determine the difference curve from the tables in NBS Circular 561 for either a 10- or a 13-percent-rhodium thermocouple, such that the resulting calibration is accurate to ±1° C at any point in the range 0° to 1,100° C and to ±3° C up to 1,450° C. (The reference junction temperature at which the emf difference is zero constitutes a third point.)

5.2. Copper-Constantan Thermocouples

The relationship between the temperature and emf of copper-constantan thermocouples has been very well established in the range −190° to +300° C. The temperature of the measuring junction of such a thermocouple can be very accurately determined in this range with a platinum-resistance thermometer in a stirred liquid bath. Consequently, the accuracy obtained with this type of thermocouple is, in general, limited by the stability of the wires above 200° C, and by the accuracy of the emf measurements and the homogeneity of the wire below 200° C. The stability of the larger sizes of wire is greater than that of the smaller wires under the same conditions.

Figure 5 shows a difference curve from the values in NBS Circular 561 for a typical copper-constantan thermocouple. Two points above and two below 0° C suitably spaced are usually sufficient to give an accuracy of 0.3° C.

Equations are used to good advantage with copper-constantan thermocouples for interpolating between calibration points, but it has not been demonstrated that the accuracy obtained with equations is any greater than that obtained by drawing difference curves from reference tables except when the differences are large. One convenient method of obtaining a calibration accurate to ±0.2° C in the range 0° to 100° C is to use an equation of the form $e=at+0.04t^2$ where a is a constant determined by calibration at 100° C, e the emf in microvolts, and t the temperature in degrees C. An equation of the form $e=at+bt^2+ct^3$, where a, b, and c are constants determined by calibration at three points (about 100°, 200°, and 300° C), will give interpolated values as accurately as the thermocouple can be relied upon to retain its calibration (about 0.2° C). The same type of equation with the constants determined at three points about equally spaced in the range 0° to −190° C, may be used in this range to give interpolated values almost as accurately as the emf can ordinarily be measured (about 2 μv). An equation of the form $e=at+bt^2$ will yield interpolated values in the range 0° to 100° C almost as accurately as the emf is determined at the calibration points, if the constants are determined by calibration at about 50° and 100° C. The same is true of this equation in the range 0° to −100° C if the constants are determined at −50° and −100° C.

5.3. Chromel-Alumel Thermocouples

Figure 6 shows a difference curve for a typical Chromel-Alumel thermocouple from the standard tables published in NBS Circular 561. The difference curve from these tables can be determined in the range 0° to 1,300° C (2,372° F) with an uncertainty not more than 1° C greater than at the calibration points by calibration at 500°, 800°, and 1,100° C (or at 1,000°, 1,600°, and

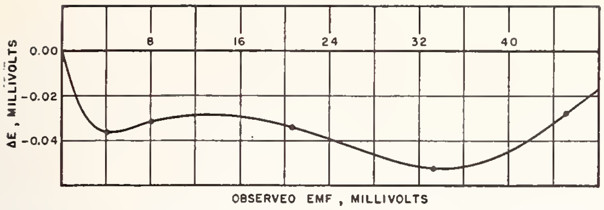


FIGURE 6. *Difference curve for a Chromel-Alumel thermocouple, using the reference table in NBS Circular 561.*

2,000° F). These tables represent the average temperature-emf relationship of Chromel-Alumel thermocouples now being manufactured.

Little success has been met in fitting equations to the calibration of Chromel-Alumel thermocouples in the range 0° to 300° C. An equation of the form $e=at+bt^2+ct^3$ may be in error by 1°C at 50° C if the constants are determined by calibration at about 100°, 200°, and 300° C. However, it will be accurate to about 0.5° C at 150° C and to about 0.2° C between 200° and 300° C. In the range 0° to −190° C, an equation through three points about equally spaced will give interpolated values in which the uncertainty is not more than 2 μv greater than at the calibration points.

5.4. Iron-Constantan Thermocouples

Until recently, several iron-constantan reference tables had been used by the suppliers of this material. One such table still being used by some Government agencies was published in a paper on "Reference Tables for Iron-Constantan and Copper-Constantan Thermocouples" [24].

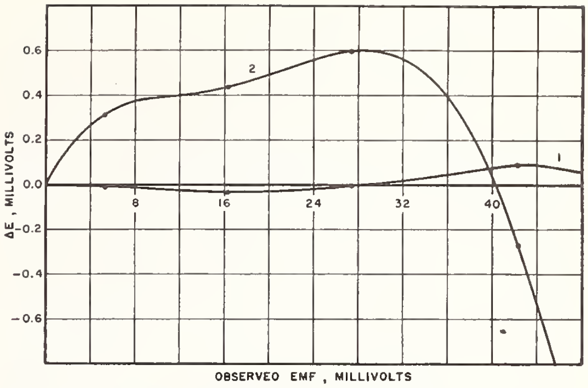


FIGURE 7. *Difference curves for an iron-constantan thermocouple, using (1) the reference table in NBS Circular 561 and (2) a straight line, $e=56t$.*

More recently, a reference table that closely represents the temperature-emf relationship of the iron-constantan thermocouples now being supplied by most producers of this type of thermocouple was developed. This table is not very different from that which had been in use by some producers since 1913 and consequently has been referred to as the "Modified 1913 Reference Tables for Iron-Constantan Thermocouples" [25].

Figure 7 shows a difference curve from the modified 1913 tables and from a straight line, $e=56t$ (where e is in microvolts and t is in degrees C) for a typical thermocouple. This latter method of drawing difference curves from a straight line may be used if the thermocouple does not match existing reference tables.

We have no data as to how closely the temperature-emf relationships of iron-constantan thermocouples may be fitted by equations.

6. Reference-Junction Corrections

It is not always possible to maintain the reference junctions (commonly called cold junctions) at a desired temperature during the calibration of a thermocouple, but if the temperature of the reference junctions is measured, it is possible to apply corrections to the observed emf, which will yield a calibration with the desired reference-junction temperature. If the emf of the thermocouple is measured with the reference junctions at temperature t, and a calibration is desired with these junctions at temperature t_0, the measured emf may be corrected for a reference-junction temperature of t_0 by adding to the observed value the emf which the thermocouple would give if the reference junctions were at t_0 and the measuring junction at t. For example, suppose the observed emf of a platinum versus platinum-10-percent-rhodium thermocouple with the measuring junction at 1,000° C and the reference junction at 25° C is 9.427 mv and the emf of the thermocouple with the measuring junction at 1,000° C and the reference junctions at 0° C is required. Since emf of the thermocouple when the reference junctions are at 0° C and the measuring junction at 25° C is 0.143 mv, the sum of these emf (9.427 and 0.143) gives the desired value.

The sign must be considered when applying reference-junction corrections. For example, suppose the observed emf of the thermocouple with the measuring junction at 1,000° C and the reference junctions at 0° C is 9.570 mv and the emf of the thermocouple with the measuring junction at 1,000° C and the reference junctions at 25° C is required. The emf of the thermocouple when the reference junctions are at 25° C and the measuring junction at 0° C is −0.143 mv, and when this is added to the observed emf the desired value 9.427 mv is obtained. Whether the reference-junction correction is positive or negative should not cause any confusion if it is remembered that the emf of the thermocouple is lowered by bringing the junction temperatures closer together and increased by making the difference greater.

In the calibration of thermocouples, the temperature-emf relationship is not always accurately determined in the range of reference-junction temperatures, in which case the average temperature-emf relationship of the type of thermocouple may be used. The average relations for the various types of thermocouples are given in table 5. The errors caused by using these average relations, instead of the actual relation, for a particular thermocouple are, in general, less than 1° C.

If the thermocouple is very short, so that the reference junctions are near the furnace and subject to considerable variations or uncertainty in temperature, it is usually more convenient to use extension leads to transfer the reference junctions to a region of more constant temperature than to measure the temperature of the reference junctions near the furnace. The extension leads of base-metal thermocouples are usually made of the same materials as the thermocouple wires, but in the case of platinum versus platinum-rhodium thermocouples, a copper lead is connected to the platinum-rhodium wire and a copper-nickel lead to the platinum wire. Leads for any of the thermocouples discussed here are available at all the pyrometer instrument manufacturers. Although the temperature-emf relationship of the copper versus copper-nickel lead wire is practically the same as that of platinum versus platinum-rhodium thermocouples, the individual lead wires are not identical thermoelectrically with the thermocouple wires to which they are attached and, therefore, the two junctions where the leads are attached to the thermocouple should be kept at nearly the same temperature. This is not as necessary in the case of base-metal thermocouples when each lead and the thermocouple wire to which it is attached are the same material.

TABLE 5. *Average temperature-emf relations for thermocouples for applying reference-junction corrections*

Temperature		Electromotive force			
		Platinum versus platinum-rhodium [a]	Chromel-Alumel	Iron-constantan	Copper-constantan
°C	*°F*	*mv*	*mv*	*mv*	*mv*
−20	−4	−0.103	−0.77	−1.00	−0.75
−15	+5	−.079	−.58	−0.75	−.57
−10	14	−.054	−.39	−.50	−.38
−5	23	−.027	−.19	−.25	−.19
0	32	.000	.00	.00	.00
+5	41	+.028	+.20	+.25	+.19
10	50	.056	.40	.50	.39
15	59	.084	.60	.76	.59
20	68	.113	.80	1.02	.79
25	77	.143	1.00	1.28	.99
30	86	.173	1.20	1.54	1.19
35	95	.204	1.40	1.80	1.40
40	104	.235	1.61	2.06	1.61
45	113	.266	1.81	2.32	1.82
50	122	.299	2.02	2.58	2.03

[a] The values in this column apply for either the 10- or 13-percent rhodium thermocouples. The difference between the average temperature-emf relationships in this range does not exceed 2 μv.

7. Testing of Thermocouple Materials

Thermocouples are ordinarily made up to yield a specified emf at one or more temperatures, and in order to select and match materials to do this, a convenient method of testing each element is required. One method of accomplishing this is to determine the thermal emf of the various materials against some stable and reproducible material. At low temperatures copper is sometimes used for this purpose, but platinum appears to be the most satisfactory because it can be used at any temperature up to its melting point, can be freed from all traces of impurities, and can be readily annealed in air. Two samples of platinum, both of which are spectrochemically pure, may differ slightly in thermal emf, but the same is true of any other metal. To avoid the ambiguity that might arise from this fact, the thermal emf of thermocouple materials tested at the National Bureau of Standards (since 1922) is referred to an arbitrary piece of platinum designated as standard Pt 27. This standard is spectrochemically pure, has been thoroughly annealed, and although it may not be the purest platinum that has been prepared, serves as a satisfactory standard to which the thermal emf of other materials may be referred. However, there is nothing to prevent any other laboratory from setting up a laboratory standard for their own use, but in order that the various laboratories and manufacturers may specify and express values of thermal emf on a common basis, a common and ultimate standard is necessary.

Platinum is used as a working standard for testing thermocouple materials in some laboratories, but it is generally more convenient to use a working standard of the same material as that being tested. In any case, the thermal emf of a material against the standard Pt 27 is the algebraic sum of the emf of the material against the working standard, and the emf of the working standard against the standard Pt 27 (the law of intermediate metals). When platinum is used as a working standard in testing some other material, the thermal emf measured is great. To obtain the thermal emf of the material against the standard Pt 27, the relatively small emf of the platinum working standard against the standard Pt 27 is added to the large measured emf. When the working standard is of the same kind of material as that being tested, the thermal emf measured is small. To obtain the thermal emf of the material against the standard Pt 27 in this case, the relatively large emf of the working standard against the standard Pt 27 is added to the small measured emf.

Except in the case of constantan, two samples of a similar material which will develop more than 0.5 μv/°C against one another are exceptional. In most cases, the value is less than 0.2 μv/°C. Even in the case of constantan, the thermal emf between 2 extreme samples does not exceed 3 μv/°C. Therefore, in determining the difference in thermal emf between two samples of a similar material, it is not necessary to measure the temperature accurately.

The average thermal emf per degree C of platinum against other thermocouple materials is given in table 6. It is seen that in measuring the thermal emf of these materials directly against platinum working standards, it is necessary to measure an emf which changes by a large amount for a small change in temperature. An accurate measurement of the emf corresponding to a given temperature, therefore, requires an accurate measurement of the temperature of the junctions. The necessity for this accurate measurement of temperature, however, is avoided when the measurements are made by using a working standard of material similar to that being tested, since in this case the emf developed is small and changes very little even for large changes in temperature. In the latter method, the accurate measurement of temperature is not entirely avoided but merely shifted to the laboratory that determines the thermal emf of the working standards against the standard Pt 27.

The small thermal emf of a platinum working standard against the standard Pt 27 at any temperature can be determined as accurately as the emf can be measured. These standards are subject to change during use but, if properly used and occasionally checked, can be relied upon to about 2 μv at 1,000° C. The thermal emf of working standards of other materials is determined and certified at the National Bureau of Standards to the equivalent of ±1° C at high temperatures.

TABLE 6. *Average thermal [a] emf per degree C of platinum against other thermocouple materials.*

Material	Temperature	Average change in thermal emf with temperature
	°C	μv/°C
Platinum-10-percent rhodium	1,000	11.6
Platinum-13-percent rhodium	1,000	13.2
Chromel	900	31.5
Alumel	900	8.7
Iron	600	11.6
Constantan	600	46.8
Constantan	100	37.4
Copper	100	9.4

In any event the testing of a thermocouple material is essentially the determination of the emf of a thermocouple in which the material being tested is one element and a working standard the other. Some of the precautions that must be observed to obtain accurate results are given in the following sections.

7.1. Platinum

The thermal emf of the thermocouple platinum against the standard Pt 27 is usually less than 20 μv at 1,200° C and in testing one sample of platinum against another it is not necessary to measure the temperature of the hot junction to closer than 50° C to obtain a comparison accurate to 1 μv. The reference-junction temperature need not be accurately controlled. The platinum standard (i. e., the wire previously compared with the standard Pt 27) is welded to the wire being tested to form a thermocouple and the emf measured at one or more temperatures by any of the methods described for calibrating platinum versus platinum-rhodium thermocouples. The wires should be carefully insulated and protected. Measurements at two temperatures, about 600° and 1,200° C, are sufficient to give the emf at any temperature as the emf is small and practically proportional to the temperature.

In many laboratories the platinum standard and the platinum element of the thermocouple used to measure the temperature are one and the same. The sample or wire being tested is then welded to the junction of the thermocouple and the emf of the thermocouple and that between the two platinum wires are measured simultaneously with two potentiometers or alternately with one instrument. Simultaneous readings of these electromotive forces should not be made with a millivoltmeter or with a current flowing in either circuit because one wire is common to both circuits and in this case the potential difference measured by one instrument is influenced by the current flowing in the other circuit. However, this objection is not encountered in the method described above in which the platinum standard is not the same wire as the platinum of the thermocouple.

7.2. Platinum-Rhodium Alloy

The testing of platinum-rhodium thermocouple wire directly against platinum is exactly the same as the calibration of platinum versus platinum-rhodium thermocouples. Platinum against platinum-10-percent rhodium gives 11.6 μv/°C and platinum against platinum-13-percent rhodium

---

[a] Complete tables giving the average thermal emf of platinum-10-percent rhodium, and platinum-13-percent rhodium against platinum are given in NBS Circular 561. The average thermal emf of Chromel and of Alumel against platinum are given in Research Paper 767; of copper and constantan against platinum in RP1080; of iron and constantan against platinum in RP2415.

gives 13.2 μv/°C at 1,000° C. Therefore, in order to determine the thermal emf of a sample of platinum-rhodium against platinum to ±20 μv, it is necessary to measure the temperature to ±1.5° C. Such an accuracy in temperature measurements is obtained only with a very homogeneous and accurately calibrated thermocouple in a uniformly heated furnace, but if the emf of one sample of wire is known with this accuracy, it may be used to determine the emf of other samples without the necessity of accurately measuring the temperature. For example, the thermal emf per degree of any sample of platinum-10-percent rhodium against any other sample rarely exceeds 0.05 μv/°C (50 μv at 1,000° C). Therefore, if the thermal emf of one sample against platinum is known to ±20 μv at 1,000° C, the emf of other samples against the same platinum can be determined to about the same accuracy by comparing the samples of platinum-rhodium and measuring the temperature of the hot junction to 10° or 20° C. The same applies for platinum-13-percent rhodium.

The working standard used to determine the thermal emf of the platinum-rhodium may be a sample of platinum, of platinum-rhodium, or either element of the thermocouple used in measuring the temperature. Platinum-10-percent rhodium against platinum-13-percent rhodium gives about 1.6 μv/°C at 1,000° C so that if the thermal emf of one of these materials against platinum is known to ±20 μv at 1,000° C, the thermal emf of the other against the same platinum can be determined to ±30 μv by comparing the two and measuring the temperature to ±6° C.

A number of wires can be welded together and tested by any of these methods.

7.3. Base-Metal Thermocouple Materials

a. At High Temperatures

In testing base-metal thermocouple materials (Alumel, Chromel, constantan, copper, and iron) the procedure is very much the same as in calibrating base-metal thermocouples. Although such thermal-emf measurements are ultimately referred to platinum, it is not necessary to measure each sample directly against platinum. When the measurements are made against platinum (and this must frequently be done), the platinum wire should be sealed through the end of a glazed porcelain protection tube with Pyrex glass, leaving about 1 cm of the wire exposed for welding to the base-metal wire or wires. The largest uncertainty in the measurements arises from the uncertainty in the determination of the temperature of the hot junction. The junction of a standard platinum versus platinum-rhodium thermocouple may be inserted into a hole drilled in the junction formed by welding the material to platinum. This brings the junctions to the same temperature.

In the use of platinum or platinum-rhodium for testing thermocouple materials, the wires are used a large number of times before checking or scrapping. Base-metal thermocouple wires used for testing similar materials should not be used more than once if the highest accuracy is required, because there is a slight change in these materials when heated to a high temperature and if they are used repeatedly, the wires become inhomogeneous. The procedure then is to select a coil of wire and test it for homogeneity by taking several samples from different parts of the coil, welding them all together, and measuring the emf between the various samples. If the coil is sufficiently homogeneous as found from such tests, one or more samples may be taken from it and the thermal emf determined as accurately as necessary by comparison with a standard, the emf of which against the standard Pt 27 is known. The average value for the thermal emf of the few selected samples from the coil against the standard Pt 27 will apply for the remainder of the coil with sufficient accuracy for most purposes. Any sample from this coil may then be used as a working standard for testing similar materials. The accuracy with which the temperature must be measured depends upon the difference between the standard and the material being tested. In case of some materials that have been well standardized, the differences are small enough that an accuracy of 50° C is sufficient. Seldom, if ever, should it be necessary to measure the temperature closer than 10° C.

b. At Low Temperatures

Annealed electrolytic copper is very uniform in its thermoelectric properties and is often used as a standard for thermoelectric testing at temperatures below 300° C. The thermal emf of other materials against either copper or platinum may be determined very accurately by using a stirred liquid bath or fixed points. The steam point is an excellent one for this purpose.

Table 7 gives the thermal emf of annealed electrolytic copper against NBS standard Pt 27 and may be used to convert values of the thermal emf of any material against one of these standard materials to values of emf of the same material against the other standard material.

TABLE 7. *Thermal emf of annealed electrolytic copper against NBS platinum standard Pt 27*

Temperature	Electromotive force	Temperature	Electromotive force
° C	*μv*	*° C*	*μv*
−200	−194	100	766
−150	−354	150	1, 265
−100	−367	200	1, 831
−50	−242	250	2, 459
0	0	300	3, 145
+50	+340	350	3, 885

7.4. Reference-Junction Corrections

It is not convenient for everyone to obtain the same reference-junction temperature in determining the emf of the various thermocouple materials against platinum and, therefore, corrections must be applied to arrive at values for a common reference-junction temperature. The method of applying these corrections is the same as that discussed under the testing of thermocouples. The average temperature-emf relationships for the various thermocouple materials against platinum are given in table 8 and may be used for making reference-junction corrections.

In comparing two samples of a similar thermocouple material at high temperatures, it is not necessary to measure or control accurately the temperature of the reference junctions. The emf developed by two samples of platinum-rhodium, even the 10- against the 13- percent-rhodium alloy, is practically independent of the temperature of the reference junctions between −20° and +50° C. In all other cases, with the possible exception of iron, the emf may be taken as proportional to the difference between the temperatures of the two junctions, and when the emf is small, the corrections for the temperature changes of the reference junctions are negligible. In comparing two samples of iron, the emf developed is changed more by changing the temperature of the reference junctions than by changing that of the hot junction by the same amount, for example it was observed (in one case) that the emf (320 μv) developed by two samples of iron when one junction was at 600° C and the other at 25° C changed by 0.1 μv for each degree change in the temperature of the hot junction and 1.4 μv for each degree change in the temperature of the reference junctions.

TABLE 8. *Average temperature-emf relationships of various thermocouple materials against platinum for applying reference-junction corrections*

Temperature		Electromotive force					
		Platinum versus platinum-rhodium [a]	Chromel versus platinum	Alumel versus platinum	Constantan versus platinum	Iron versus platinum	Copper versus platinum
° C	*° F*	*mv*	*mv*	*mv*	*mv*	*mv*	*mv*
−20	−4	−0.103	−0.50	0.27	0.64	−0.36	−0.109
−15	+5	−.079	−.38	.20	.48	−.27	−.084
−10	14	−.054	−.25	.14	.32	−.18	−.057
−5	23	−.027	−.13	.07	.16	−.09	−.029
0	32	.000	.00	.00	.00	.00	.000
+5	41	+.028	+.13	−.07	−.16	+.09	+.030
10	50	.056	.26	−.14	−.33	.18	.060
15	59	.084	.40	−.20	−.49	.27	.091
20	68	.113	.52	−.28	−.66	.36	.124
25	77	.143	.66	−.34	−.83	.45	.158
30	86	.173	.79	−.41	−1.00	.54	.193
35	95	.204	.93	−.47	−1.17	.63	.229
40	104	.235	1.07	−.54	−1.34	.72	.265
45	113	.266	1.21	−.60	−1.51	.81	.302
50	122	.299	1.35	−.67	−1.69	.90	.340

[a] These values apply for either 10- or 13-percent rhodium.

8. Accuracies Obtainable

The accuracies obtained in calibrating the various types of thermocouples by different methods and the uncertainty in the interpolated values by various methods are given in table 9.

These accuracies may be obtained with homogeneous thermocouples when reasonable care is exercised in the work. More or less accurate results can be obtained by the same methods. In the case of Chromel-Alumel and iron-constantan thermocouples at low temperatures, the accuracy given in table 9 is limited by the uncertainty in interpolated values. However, this uncertainty can be greatly reduced by observing the emf of the thermocouples at more points. The accuracy obtained with copper-constantan thermocouples at low temperatures is usually limited by the emf measurements and in such cases the accuracy may be improved by employing a number of thermocouples in series (multiple-junction couples). When it is desired to test a thermocouple and leads or thermocouple, leads, and indicator as a unit by any of the methods described in the preceding sections, no additional difficulties are encountered.

The following services are provided by the National Bureau of Standards for fees covering the cost.

(1) Thermocouples are calibrated and certified as accurately as the conditions of use and the homogeneity and stability of the wires justify. The accuracies given in table 9 have been found to meet most needs.

(2) Indicators used with thermocouples are calibrated separately or in combination with a particular thermocouple.

(3) The thermal electromotive forces of thermocouple materials against the standard Pt 27 are determined and the results certified to the limits justified by the material.

(4) Standard Samples of metals are distributed, each with a certificate giving the value of the freezing point. The freezing-point metals being distributed at present are tin, lead, zinc, aluminum, and copper.

Table 9. *Summary of methods and accuracies obtainable in calibrating thermocouples*

Type of thermocouple	Methods of calibration	Temperature range	Calibration points	Accuracy at observed points	Method of interpolating	Uncertainty in interpolated values
		° C		° C		° C
Platinum versus platinum-10-percent-rhodium.	International Temperature Scale (fixed points).	630.5 to 1,063.0	Freezing point of Sb, Ag, and Au	0.2	Equation: $E=a+bt+ct^2$	0.3
Platinum versus platinum-rhodium.[a]	Fixed points	0 to 1,450	Freezing point of Zn, Sb, Ag, and Au.	.2	Difference curve from reference table	0.5 to 1,100 and 2 at 1,450.
	NBS Standard Samples, fixed points	0 to 1,450	Freezing point of Sn, Zn, Al, and Cu.	.2	do	.5 to 1,100 and 2 at 1,450.
	Comparison with standard thermocouple.	0 to 1,450	About every 100° C	.3	do	.5 to 1,100 and 2 at 1,450.
	do	0 to 1,450	About 600° and 1,100° C (or more points).	.3	do	1 to 1,100 and 3 at 1,450.
Chromel-Alumel	Comparison with standard thermocouple.[a]	0 to 1,100	About every 100° C	.5	Linear	1
	do	0 to 1,100	About 500°, 800°, and 1,100° C (or more points).	.5	Difference curve from reference table	2
	Comparison with standard resistance thermometer [b] or at fixed points.	0 to 350	About every 100° C	.1	do	0.5
	Comparison with standard resistance thermometer.[b]	0 to −190	About every 50° C	.1	do	.5
Iron-constantan	Comparison with standard thermocouple.[a]	0 to 760	About every 100° C	.5	Linear	1
	do	0 to 760	About 100°, 300°, 500°, and 750° C	.5	Difference curve from reference table	1
	Comparison with standard resistance thermometer [b] or at fixed points.	0 to 350	About every 100° C	.1	do	0.5
	Comparison with standard resistance thermometer.[b]	0 to −190	About every 60° C	.1	do	.5
Copper-constantan	Comparison with standard resistance thermometer [b] or at fixed points.	0 to 300	About every 100° C	.1	Equation: $e=at+bt^2+ct^3$ or difference curve from reference table.	.2
	Comparison with standard resistance thermometer.[b]	0 to 100	About 50° and 100° C	.05	Equation: $e=at+bt^2$ or difference curve from reference table.	.1
	Fixed points	0 to 100	Boiling point of water	.05	Equation: $e=at+0.04t^2$	.2
	Comparison with standard resistance thermometer.[b]	0 to −190	About every 60° C	.1	Equation: $e=at+bt^2+ct^3$ or difference curve from reference table.	.2
	Fixed points	0 to −190	Sublimation point of CO_2 and boiling point of O_2.	.1	Difference curve from reference table	.3

[a] Either 10- or 13-percent rhodium. [b] In stirred liquid bath.

9. References

[1] George K. Burgess, BS J. Research **1,** 635 (1928) RP22.

[2] H. F. Stimson, J. Research NBS **42,** 209 (1949) RP1962; R. J. Corruccini, J. Research NBS **43,** 133 (1949) RP2014.

[3] W. P. White, Phys. Rev. **23,** 449 (1906); **31,** 135 (1910); J. Am. Chem. Soc. **36,** 2292 (1914); P. D. Foote, C. O. Fairchild, and T. R. Harrison, Tech. Pap. BS **14** (1920–21) T170.

[4] R. J. Corruccini, J. Research NBS **47,** 94 (1951) RP2232.

[5] H. Diesselhorst, Z. Instrumentenk. **28,** 1 (1908).

[6] W. P. White, Z. Instrumentenk. **27,** 210 (1907).

[7] L. Behr, The Wenner potentiometer, Rev. Sci. Instr. **3,** 109 (1932).

[8] A symposium on the contamination of platinum thermocouples, J. Iron Steel Inst. (London) **155,** 213 (1947).

[9] Wm. F. Roeser and A. I. Dahl, BS J. Research **10,** 661 (1933) RP557.

[10] Von Fr. Hoffmann and W. Meissner, Ann. phys. **60,** 201 (1919); Von Fr. Hoffmann, Z. Physik, **27,** 285 (1924); C. O. Fairchild, W. H. Hoover, and M. F. Peters, BS J. Research **2,** 931 (1929) RP65.

[11] E. F. Mueller and T. S. Sligh, J. Opt. Soc. Amer. and Rev. Sci. Instr. **6,** 958 (1922).

[12] George K. Burgess, BS J. Research **1,** 635 (1928) RP22; H. F. Stimson, J. Research NBS **42,** 209 (1949) RP1962.

[13] E. F. Mueller and H. A. Burgess, BS Sci. Pap. **15,** 163 (1919–20) S339.

[14] C. W. Waidner and G. K. Burgess, Bul. BS **7,** 1 (1911) S143.

[15] J. L. Finck and R. M. Wilhelm, J. Am. Chem. Soc. **47,** 1577 (1925).

[16] R. B. Scott, Temperature, its measurement and control in science and industry, p. 206 (Reinhold Publishing Corp., New York, N. Y., 1941).

[17] C. H. Meyers and M. S. Van Dusen, BS J. Research **10,** 381 (1933) RP538; R. B. Scott, Temperature, its measurement and control in science and industry, p. 212 (Reinhold Publishing Corp., New York, N. Y., 1941).

[18] A. I. Dahl, J. Research NBS **24,** 205 (1940) RP1278.

[19] N. S. Osborne, Bul. BS **14,** 133 (1918–19) S301.

[20] R. B. Scott and F. G. Brickwedde, BS J. Research **6,** 401 (1931) RP284.

[21] C. W. Kanolt, BS Sci. Pap. **20,** 619 (1924–26) S520.

[22] Wm. F. Roeser, BS J. Research **3,** 343 (1929) RP99.

[23] Henry Shenker, John I. Lauritzen, Jr., Robert J. Corruccini and S. T. Lonberger, NBS Circ. 561 (1955).

[24] Wm. F. Roeser and A. I. Dahl, J. Research NBS **20,** 337 (1938) RP1080.

[25] R. J. Corruccini and H. Shenker, J. Research NBS **50,** 229 (1953) RP2415; NBS Circ. 561, Reference tables for thermocouples (April 1955).

WASHINGTON, June 10, 1957.

JOURNAL OF RESEARCH of the National Bureau of Standards—C. Engineering and Instrumentation
Vol. 69C, No. 2, April–June 1965

Temperatures of Thermocouple Reference Junctions in an Ice Bath

Frank R. Caldwell

(January 5, 1965)

Errors obtained when using several sizes of ISA Type K thermocouple wires (14 to 20 AWG) and of copper lead wires (14 to 26 AWG) at different immersions in a properly prepared and maintained ice bath are given. Variables considered include in addition to the wire diameters and materials, depth of immersion (2 to 9 in.), solid cross section of the Pyrex junction tubes, and type of insulation on the copper lead wires. The wires studied represent the maximum (copper) and the minimum (Chromel) thermal conductivities of any of the normally used thermocouple wires. A small amount of data on platinum is included.

Depth of immersion and diameter of the copper wire are extremely important if a high degree of accuracy is to be attained. The solid cross section of the Pyrex junction tubes and type of insulation used are of lesser importance.

1. Introduction

A thermocouple used to measure temperature is, from its nature, a differential sensor which actually measures the thermal emf generated as a result of the difference in temperature between its two junctions. It follows then, that the temperature of one of its junctions must be known if the measured emf is to be related to the temperature being measured. This junction is known variously as the "cold," "ice," or "reference" junction; and the fact that in measurements at low temperatures it may be the warmest part of interest in the measuring circuit seems often to make no difference; this is still the "cold junction" to many, in spite of efforts of purists to have it called the "reference," or when applicable the "ice" junction. The other is the "measuring" junction that often similarly is called the "hot" junction. In the discussions that follow, the "reference" or "ice" junction refers to the electrical connection between the thermocouple and copper wires leading to the measuring instrument. This connection is made by mercury in the bottom of a Pyrex tube immersed in a bath of water-ice slush at, hopefully, 0 °C (32 °F). This is a conventional bath, descriptions of which can be found in the literature [1, 2].[1] A discussion of the makeup of the ice bath including effects on its temperature of using tap or distilled water with tap or distilled water ice is given by McElroy in reference [3]. He warns that the reference junction tubes should be located properly in the slush bath if errors "as serious as 2 to 3 °C" are to be avoided.

The studies reported herein followed discussions in Committee AE–2, Temperature Measurement Sensing, of the Society of Automotive Engineers, that led to the recommended practice of reference [2]. These emphasized the desirability of evaluating the errors resulting from varying geometries of tubes and wires in the ice bath. Conversely, such an evaluation would provide information on the sizes of tubes and wires and depths of immersion that would lead to certain tolerable limits of errors.

The purpose of this paper is, therefore, to point out and give quantitative information on errors that may arise from misuse of thermocouple reference junctions in ice baths, or on the limiting conditions that will cause an error not to exceed the maximum tolerable. Figure 1 is a sketch of an ice bath of the type used in this investigation.

The temptation to cover the entire field of conventional thermocouple wires has been withstood, and as a result, the data obtained are confined almost exclusively to the ISA type K thermocouple wires (Chromel P and Alumel in this case) and copper leads. A few observations were made with platinum wire and copper leads. The data presented thus are applicable to thermocouple elements of the lowest conductivity normally used (type K) and also of the highest (copper).

The assumption is made in presenting this paper that the reader is familiar with the basic principles of thermoelectric thermometry to the extent, at least, that he can intelligently apply them to practice.

---

[1] Figures in brackets indicate the literature references at the end of this paper.

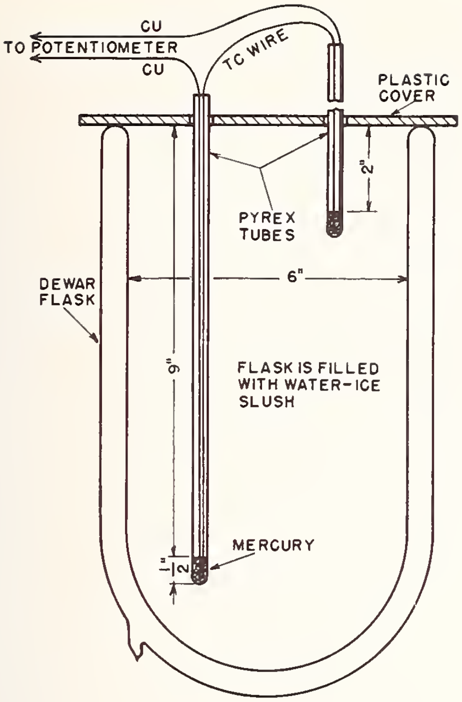


FIGURE 1. *Ice bath and reference junctions.*

2. Practical Considerations

If one end of a wire is immersed deeper and deeper into a bath of uniform temperature, a depth is reached at which greater immersion produces no further measurable or appreciable change in temperature of the immersed end. When the wire is in a glass tube as considered here and illustrated in figure 1, the same condition is reached, but at a somewhat greater depth. In addition to the depth of immersion, the thermal conductivity of the wires and material of the tubes, cross sections of the wires and tubes, depth of, and immersion of wires in the mercury in the tubes, type of insulation on the thermocouple wires or copper lead wires, and contact of the wires with the sides of the tubes all may affect the temperature at the reference junctions. The condition of the ice bath also is important, and it should be renewed or replenished often enough that no measurable gradient exists in either the vertical or horizontal direction in the area of the tubes.

Within limits, then, several choices are available for reducing the temperature of the reference junction in an ice bath and consequently the error introduced by the difference between the temperature of the junction and 0 °C. The choices examined in this work are: cross sections of wires, of both copper and thermocouple materials; type of insulation on the copper wire leads; immersion of junctions in the ice bath; and cross section of the glass tubes.

3. Materials and Procedure

The first thermocouple wires examined were four sizes of Chromel and Alumel (ISA type K): 8-, 14-, 20-, and 26-gage (American Wire Gage). Copper wires used with these were 14-, 20-, and 26-gage. The type K wires were oxidized, and the copper was enamel-insulated. Each increment between these wire sizes starting with the smallest represents an increase of about twice the diameter and four times the cross section. The dimensions of the several gages of wires used are given in table 1.

TABLE 1. *Diameters and cross-sectional areas at 20 °C of the wires used* [a]

American wire gage	Diameter		Cross section	
	in.	*mm*	*in.*^{2}	*mm*^{2}
8	0.1285	3.264	0.01297	8.366
14	.06408	1.628	.003225	2.081
20	.03196	.8118	.0008023	0.5176
26	.01594	.4049	.0001996	.1288

[a] From Smithsonian Physical Tables (Smithsonian Institution, Washington, D.C., 1954) ninth revised edition; W. E. Forsythe, Editor.

Thermal conductivities of Chromel, Alumel, copper, and Pyrex No. 7740 are given in table 2. Here copper is seen to have over 21 times the thermal conductivity of Chromel P, about 13 times that of Alumel, 5.5 times that of platinum, and nearly 350 times the thermal conductivity of Pyrex.

TABLE 2. *Thermal conductivities at 0 °C of copper, Chromel P, Alumel, and Pyrex, and of copper and Pyrex relative to the others*

Material	k	k_{cu}/k	k_{Pyrex}/k
Copper	[a] 0.912	1	0.00286
Chromel P	[b] .0420	21.71	.0621
Alumel	[b] .0679	13.43	.0384
Platinum	[c] .1660	5.49	.0157
Pyrex 7740	[d] .00261	349.4	1
Pyrex 7740	[e] .0027	------------	------------

[a] C. S. Smith, The Physical Constants of Copper, Metals Handbook p. 1380 (The American Society for Metals, 1939).

[b] Extrapolated from table in Hoskins Manufacturing Company Catalog M–61, C–A, 1961, p. 5, and converted from watts/cm °C. Chromel and Alumel are registered trade-marks of the Hoskins Mfg. Co.

[c] Calculated from equation of Holm and Störmer, Measurement of the thermal conductivity of a platinum specimen in the temperature range 19–1020 °C, Wiss. Veroffentlich. Siemens-Konzerns **9**, part II, 312 (1930).

[d] Private communication from T. W. Watson, Building Research Division, National Bureau of Standards, and converted from milliwatts/cm °C. Pyrex is a registered trade-mark of the Corning Olass Works. This is the value that is compared with those of the alloy and copper wires.

[e] Smithsonian Physical Tables, ninth revised edition; tahle 555, p. 534.

Note: k is thermal conductivity in cal/cm sec °C.

Thermal conductivities of all of the commonly used thermocouple materials are within the range between copper and Chromel. For wires of a particular diameter therefore, copper, having the highest conductivity, may be expected to cause the greatest error; and use of the low-conductivity Chromel alone, if possible, would result in the smallest. This latter condition is not practical, because copper is used almost universally for the lead from the ice bath regardless of the type of thermocouple used. For practical applications of copper in conjunction with other thermocouple wires whose combined thermal conduction lies between those of copper and Chromel, the errors also will lie between those resulting from the use of copper and Chromel alone.

The diameters and solid cross sections of the Pyrex tubes used are given in table 3. Sizes of tubes are identified in the table and in the text by the letters of column 1.

TABLE 3. *Diameters and solid cross-sectional areas of the Pyrex tubes used*

Tube	O.D.	I.D.	Solid cross section	
	in.	*in.*	*in.*^{2}	*mm*^{2}
I	0.312	0.230	0.0351	22.6
B	.245	.162	.0265	17.1
I_1	.234	.152	.0249	16.1
D	.199	.131	.0176	11.4
E	.154	.079	.0137	8.84
H	.121	.071	.0075	4.84

Thermal electromotive force (emf) was measured with a type K–3 potentiometer and a galvanometer with a sensitivity of about 5 mm/μV.

The ice bath illustrated in figure 1 was made in a large Dewar flask with a clear plastic cover, drilled to receive the Pyrex reference junction tubes. This cover was substituted for the often used cork stopper in order that the depth of immersion of the tubes could be measured more accurately. The intended depth of mercury in the tubes was ½ in. when the wires were immersed in it. Mercury does not, however, normally wet the Chromel and Alumel wires and so the depth of the mercury often was irregular across the tubes, deeper than ½ in. on one side and not so deep on the other. This effect was greater with the larger wires, and undoubtedly in some cases affected the indicated temperature of the junction between the alloy and copper wires. Although only two tubes are shown in the cross-sectional view of figure 1, observations often were taken with several in the ice bath at once.

All of the results presented herein were obtained in ice baths that were made and maintained according to the directions given in references [1] and [2]. Clear shaved ice and tap water were used, and a water-ice slush filled the Dewar flask at all times during observations. This latter precaution is important in the use of an ice bath, because the water at the bottom of a bath in which the ice is merely floating may be as high as 4 °C, the temperature of maximum density of water. This is not just academic; it has been observed in many instances in which long reference junction tubes have been used in an inadequately maintained ice bath. The junctions in these long tubes that extended through the slush into the water below actually have been found to be at temperatures well above 0 °C, and replenishing the ice bath has corrected conditions.

Use of tap water may, as discussed in reference [3], have some effect on the temperature of the ice bath, and this should be considered in cases where extreme accuracy is required. For the purposes of this paper though, this effect is unimportant; because all observations are differential. The chief requirement here has been that the ice bath be at as nearly a uniform temperature as possible throughout.

The procedure used was to immerse a tube containing one junction of, for example, a Chromel versus copper thermocouple so deeply in an ice bath that further immersion caused no detectible change in the thermal emf. This depth was found for the largest wires, both alloy and copper, and the largest glass tubes used, to be 9 in. or less; consequently, the stationary leg of the thermocouple in all cases was immersed to a depth at which the top of the mercury in the reference junction tube was at least 9 in. below the top of the ice bath. The other leg was immersed initially to a depth of 2 in. above the mercury and, with the thermocouple connected to the potentiometer by copper leads, a reading of the thermal emf was taken. The two junctions and the circuitry are shown in figure 1. The immersion was increased by an inch and another reading was taken. This was repeated for immersions up to 9 in., or to depths at which the emf became zero or constant. In the latter case the constant emf, normally a fraction of a microvolt was taken as an indication of inhomogeneity of the wires, and not a true reflection of a temperature difference between the two junctions. In such cases the constant readings were corrected to zero, and the same correction was added to the readings at all depths.

The first observations taken were obtained by repeating the procedures just described for all combinations of gages of Chromel P and copper and of Alumel and copper. At least two sets of data were taken in this phase for each combination, and in one case nine sets were taken. Three sizes of Pyrex tubes were used for the variable-immersion leg; the smallest had a solid cross section of about 71 percent of that of the largest. These are the first three sizes of table 3.

Although the thermal conductivity of the Pyrex reference junction tubes is very low relative to that of Chromel or Alumel, and extremely low relative to copper, separate data were taken to determine the effect, if any, of a change in the solid cross section of the tubes on the temperature of the reference junction.

Another set was taken to find whether or not the type of insulation on the copper lead wires to the reference junction had a measurable effect. In one case the single silk enameled insulation was used with 22-gage Alumel, and in the other the silk was removed, leaving only the enamel. The same leads were used with a platinum wire 0.020 in. in diameter (24-gage), a commonly used size. The Pyrex tube in each case was E with a solid cross section of 0.0137 in.^{2} and 0.079 in. I.D. This size was chosen as a compromise between the fragility of the smaller, thinner-walled tubes and the larger, more durable tubes of higher thermal conductance.

4. Results and Discussion

Data taken to find the effects of changing size and immersion of the type K and copper wires are presented in figures 2 and 3. Plotted in each figure are curves of emf of one type K wire of one gage against copper of three gages versus depth of immersion of the reference junctions in the ice bath. Figure 2 is for Chromel versus copper, and the data for Alumel are given in figure 3.

Chromel is thermoelectrically positive to copper, and Alumel and platinum are negative. This means, for example, that the positive Chromel element of a Chromel versus copper thermocouple must be connected to the plus terminal of a measuring instrument in order to get a positive reading when the measuring junction is at a temperature higher than that of the reference junction. Similarly, in the case of a copper versus Alumel thermocouple, the copper must be connected to the + terminal of the measuring instrument.

In the discussions and figures that follow all thermoelectric data are positive, i.e., the thermocouples considered are Chromel versus copper, copper versus Alumel, and copper versus platinum. The thermoelectric power at 0 °C of Chromel to copper is 19.57 μV/°C (10.87 μV/°F), of copper to Alumel is 19.71 μV/°C (10.95 μV/°F), and of copper to platinum is 6.15 μV/°C (3.42 μV/°F). The following list of abbreviations are those used in figures 2, 3, 4, and 5, and in the tables.

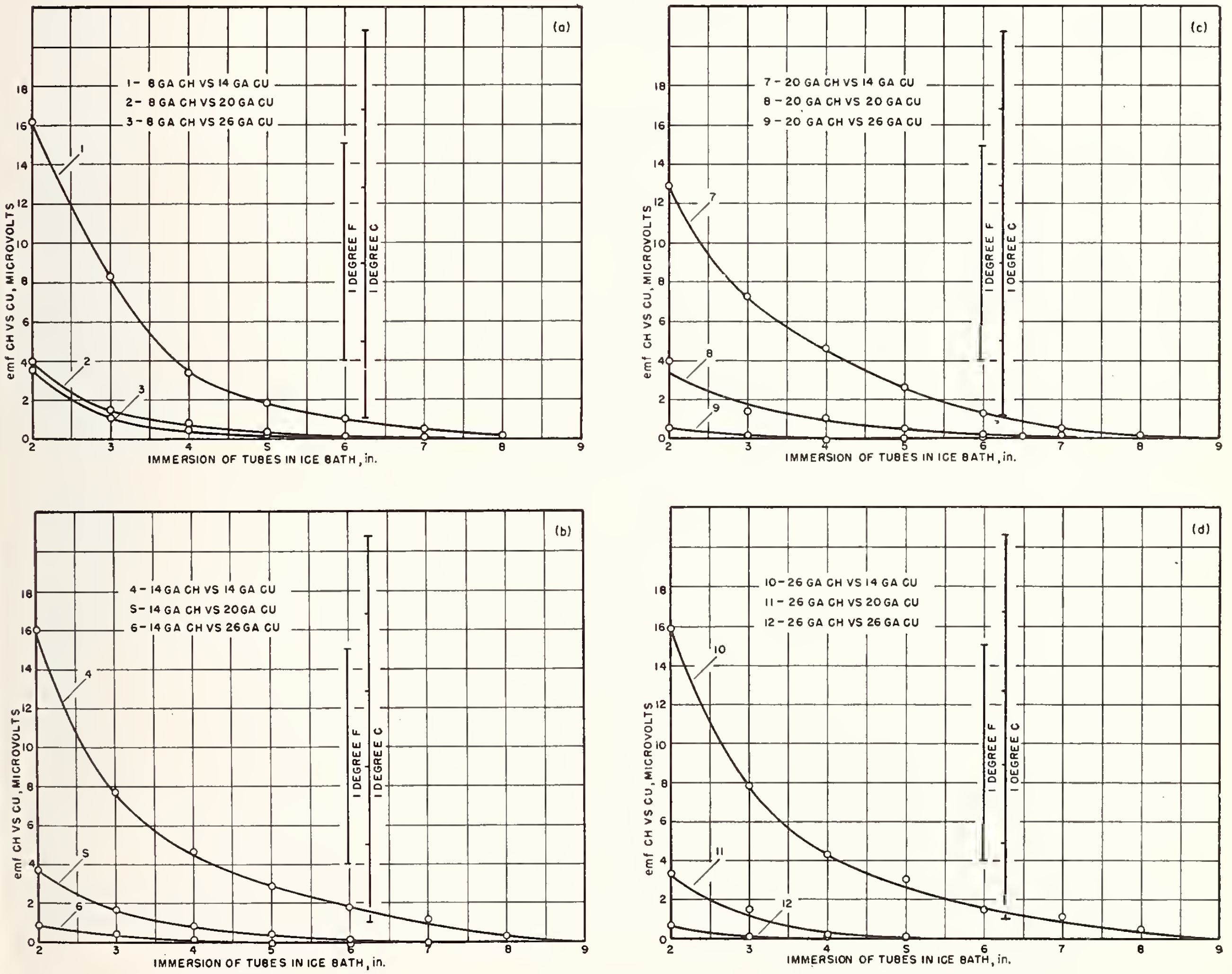


FIGURE 2. *Thermal emf of Chromel versus 14-, 20-, and 26-gage copper at various depths of immersion in an ice bath.*

a. 8-gage Chromel.
b. 14-gage Chromel.
c. 20-gage Chromel.
d. 26-gage Chromel.

ALU=Bare Alumel wire
C=Celsius
CH=Bare Chromel wire
CU=Copper wire
EN=Enamel electric insulation
F=Fahrenheit
GA=American wire gage
ID=Inside diameter
OD=Outside diameter
PT=Platinum wire
SE=Single layer silk + enamel electric insulation
TC=Thermocouple

Although the data are somewhat erratic, especially at the lowest immersions, some facts are immediately apparent. As expected, deeper immersion is seen to result in smaller error, or deviation of the temperature of the junction from 0 °C (32 °F). The error appears generally to be slightly smaller for Chromel than for Alumel, though this is masked in some cases by the lack of precision of the measurements; otherwise the patterns are quite similar.

The most potent variable is seen from the figures to be the size of the copper leads from the ice junctions. The relatively mild changes of solid cross

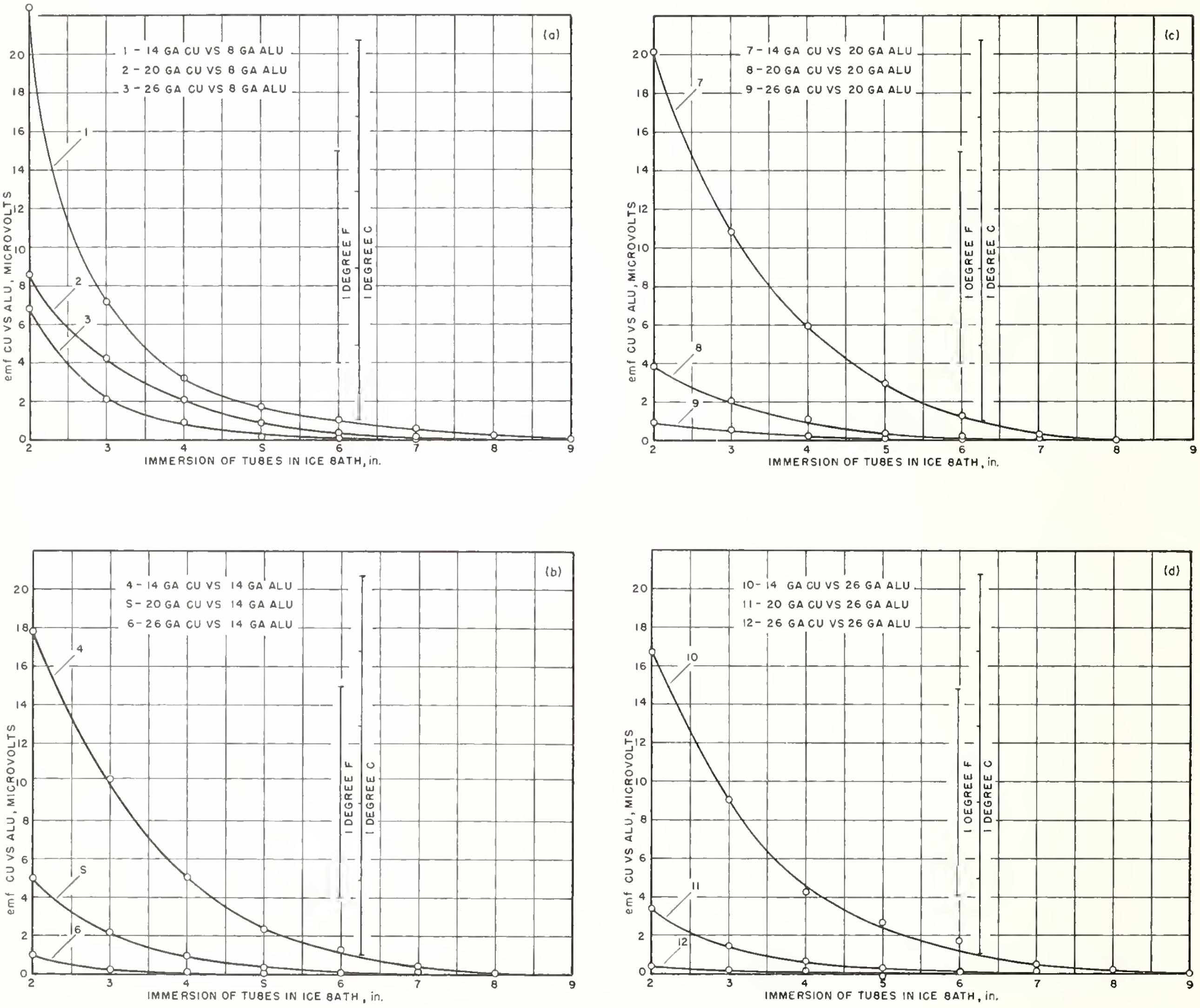


FIGURE 3. *Thermal emf of 14-, 20-, and 26-gage copper versus Alumel at various depths of immersion in an ice bath.*

a. 8-gage Alumel.
b. 14-gage Alumel.
c. 20-gage Alumel.
d. 26-gage Alumel.

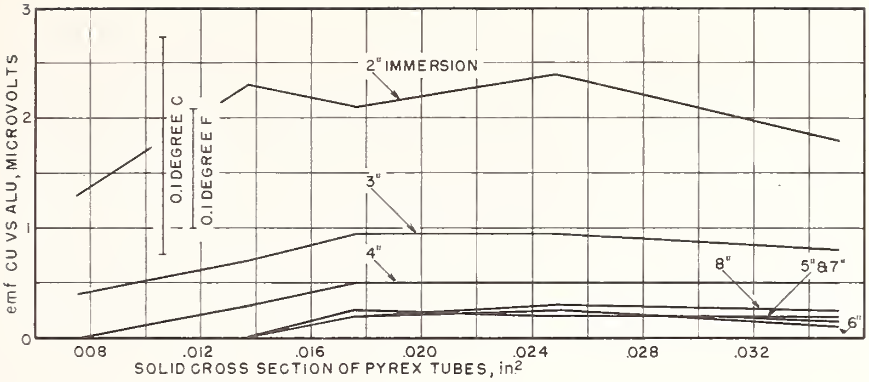


Figure 4. *Effect of solid cross section of Pyrex tubes on thermal emf of copper versus Alumel at various depths of immersion in an ice bath.*

Copper was 22-gage SE; Alumel was 22-gage.

section of the Pyrex reference junction tubes had no discernible effect. The largest copper wire used, 14-gage, was responsible for an error at an immersion of 2 in. of about ¾ °C for 8-gage Chromel and 1 °C (1.8 °F) for 8-gage Alumel. At the same immersion and for the 8-gage type K wires, 20-gage copper was responsible for errors of 0.2 °C or less when used with Chromel and up to 0.4 °C with Alumel. A depth of 4 in. is sufficient to reduce the error with either Chromel or Alumel of 14 gage or smaller and copper of 20 gage or smaller to 0.05 °C or less. With two exceptions where the error was 0.02 °C, immersion of the 26-gage copper wire to a depth of 3 in. gave an error of 0.01 °C or less. The errors resulting from use of copper leads of the latter two sizes at an immersion of 6 in. always are less than 0.01 °C.

The data of figure 4 were taken to determine the effect if any of the solid cross section of the Pyrex tubes on the temperature of the reference junction. The thermocouple used here was copper versus Alumel, both 22 gage; and the 22-gage copper was single silk, enamel insulated. Each curve of the chart is for a specific immersion of the top of the mercury in the tube into the ice bath.

Although the emfs developed here are generally lower at immersions up to 4 in. than are the approximately corresponding values of figure 3, the curves of figure 4 do point out the relative insensitivity of the junction temperature to the size of the Pyrex tubes used. In using the procedure described earlier to correct for any residual emf, the emf at 9 in. immersion was made to be 0 μV. The emfs at immersions from 5 to 8 in. as a result, then turned out to be from 0.1 to 0.3 μV for tube cross sections down to about 0.018 in.[2] The values for the two largest tubes are bracketed above by those for 8 in. immersion and for 6 in. immersion below. Practically, this latter emf is of such a magnitude that the spread undoubtedly is within the limits of precision of the observations; thus the error over an immersion of from 5 to 8 in. can be considered constant at 0.2 μV or so. This corresponds to about 0.01 °C. Another set of data similar to this, but with 26-gage Alumel showed the spread to be from 0 to about 0.5 μV for immersions of 5 to 9 in., or about 0.02 °C. The wider spread here, as in some other instances, may have been caused by inhomogeneities introduced by greater cold working of the smaller wire.

Data presented in figure 5 are intended to point out any difference that might result from the use of different types of insulation. Curve 1 (solid circles) is for bare 22-gage Alumel and 22-gage single silk, enamel insulated copper in tube E, and Curve 2 (open circles) is for the same wires with the silk insulation carefully removed. The difference in

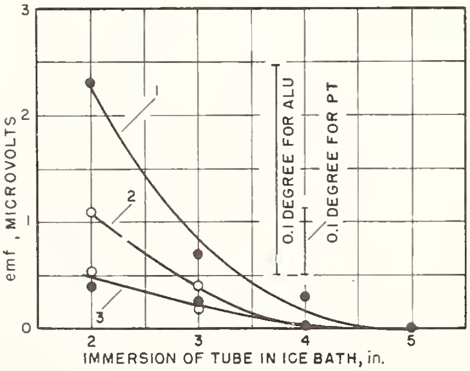


Figure 5. *Effects of insulation of copper leads on thermal emf of copper versus Alumel and copper versus platinum at various depths of immersion in an ice bath.*

●, denotes 22-gage SE Cu, versus 22-gage Alu in curve 1 and versus 24-gage Pt in curve 3.
○, denotes 22-gage EN Cu, versus 22-gage Alu in curve 1 and versus 24-gage Pt in curve 3.

thermal emf at an immersion of 2 in. corresponds to about 0.06 °C. Similar observations were taken with copper versus platinum thermocouples. The difference in this case, in the reverse direction, is so small as probably to be within the limit of precision. The one curve (3) drawn through the observations thus can be taken as an indication of errors to be encountered when using 24-gage platinum and a 22-gage copper wire lead. The error corresponds to about 0.07 °C at an immersion of 2 in., 0.03 °C at 3 in., and vanishes at 4 in.

5. Conclusions

The foregoing data point out that the errors caused by insufficient immersion in an ice bath, even under the extreme conditions of large wires and glass tubes, can be small enough that they will not be the primary causes of inaccuracy in many cases of engineering measurements. In those cases where the errors are of an intolerable magnitude, use of smaller wires and greater depth of immersion of the junction below the surface of the ice bath can reduce the error practically to the vanishing point. The size of the Pyrex tube used to contain the reference junction can be varied, within reasonable limits, without any appreciable effect on the temperature of the reference junction.

The type of insulation on the copper wire, single silk enamel or enamel alone were seen in the case of Alumel apparently to have a measurable effect on the temperature of the reference junction, but in a similar test with platinum, no such result was found. These results are, therefore, somewhat inconclusive although it does seem reasonable that an effect of the type of insulation used on moderate sized wires should be seen.

6. References

[1] SAE Aerospace Information Report No. 46, The preparation and use of Chromel-Alumel Thermocouples for turbojet engines, Committee AE–2, Temperature Measurement Sensing, Society of Automotive Engineers, Inc., 485 Lexington Avenue, New York 17, N.Y., March 15, 1956.

[2] SAE Aerospace Recommended Practice No. 691, Recommended ice bath for reference junctions, Committee AE–2, Temperature Measurement Sensing, Society of Automotive Engineers, Inc., 485 Lexington Avenue, New York 17, N.Y., August 1, 1964.

[3] D. L. McElroy, Progress Report 1. Thermocouple research report for the period November 1, 1956 to October 31, 1957, ORNL 2467.

(Paper 69C2–189)

U. S. Department of Commerce National Bureau of Standards

RESEARCH PAPER RP1278

Part of Journal of Research of the National Bureau of Standards, Volume 24, February 1940

STABILITY OF BASE-METAL THERMOCOUPLES IN AIR FROM 800° TO 2,200° F

By Andrew I. Dahl

ABSTRACT

A study has been made of the changes in the emf of Chromel-Alumel and iron-constantan thermocouples heated in an oxidizing atmosphere at various temperatures and for various periods of time. The thermocouples were held at definite temperatures, ranging from 800° to 2,200° F, in steps of 200° F. Calibrations were made of the thermocouples in their original condition, and again after heating them at each temperature for total times of 10, 50, 100, 200, 400, 600, 800, and 1,000 hours, or as long as the thermocouples remained serviceable. The thermal emf of each element against platinum was measured in order to determine the relative stability of the individual elements. A few tests were made to determine the effect of wire size on the stability. The effects of changing the depth of immersion of thermocouples after they had been used under controlled conditions were also studied.

Since all tests were made in an atmosphere of clean air, the results give no information on stability except under oxidizing conditions.

CONTENTS

I. INTRODUCTION

With the widespread use of base-metal thermocouples for temperature measurement and control in industrial processes, there are numerous instances where high accuracy is of vital importance. Some processes require that a given temperature be maintained within narrow limits for an extended period of time, if efficiency in operation and uniformity in production are to be maintained. In order to meet these requirements, a more complete knowledge of the thermoelectric stability of base-metal thermocouple materials is necessary.

Practically all base-metal thermocouple wire produced in this country is annealed or given a stabilizing heat treatment by the manufacturer. For most purposes this treatment renders the product sufficiently stable, so that further changes which may occur while the thermocouple is in service may be neglected. However, when high accuracy is required throughout the useful life of the thermocouple, these changes must be taken into account. In many industrial processes, thermocouples, when placed in service, are left undisturbed until there is evidence of either mechanical failure or of serious error in the temperatures indicated. However, long before this occurs, the thermocouple may have changed to such an extent as to make it unreliable for accurate temperature measurement. The changes in the thermoelectric characteristics of thermocouple materials due to ordinary service conditions are usually gradual and cumulative. They depend upon such factors as the temperatures encountered, the length of time in service, and the atmosphere surrounding the thermocouple. The various types of thermocouple materials are affected in various ways and to various degrees.

When the reference-junction temperature is maintained constant, the emf developed by a homogeneous thermocouple depends only on the temperature of the measuring junction. The emf developed by an inhomogeneous thermocouple depends not only on the temperature of the measuring junction but also on the temperature distribution throughout the inhomogeneous portions of the wires. All base-metal thermocouples become inhomogeneous with use at high temperatures. However, if all the inhomogeneous portions of the thermocouple wires are in a region of uniform temperature, the inhomogeneous portions have no effect upon the indications of the thermocouple. Therefore, an increase in the depth of immersion of a used couple has the effect of bringing previously unheated portions of the wires into the region of temperature gradient, and thus the indications of the thermocouple will correspond to the original emf-temperature relation, provided the increase in immersion is sufficient to bring all of the previously heated part of the wires within the zone of uniform temperature. If the immersion is decreased, the more inhomogeneous portions of the wires will be brought into the region of temperature gradient, thus giving rise to a change in the indicated emf. Furthermore, a change in the temperature distribution along inhomogeneous portions of the wire nearly always occurs when a couple is removed from one installation and placed in another, even though the measured immersion and the temperature of the measuring junction are the same in both cases. Thus the indicated emf is changed.

Although it is recognized that there are differences in composition and thermoelectric properties between various lots of thermocouple materials of the same general type, it is believed that the changes in the thermoelectric properties of a few selected lots of material will give a general idea of the changes which would occur in other lots of the same general type, provided that all the lots have received the same initial heat treatment.

II. MATERIALS INVESTIGATED

The thermocouple materials studied were Chromel *P*, Alumel, iron, and constantan. Chromel *P* and Alumel wire of No. 18 gage and iron and constantan of No. 14 gage were used for the tests at 800° and 1,000° F. For the tests at 1,200° F and above, No. 8 gage wires were used. To determine the relation of wire size to the thermoelectric stability, additional tests were made on No. 18 and No. 22 gage Chromel and Alumel at 1,200° and 1,600° F, and on No. 18 gage iron and constantan at 1,200° and 1,400° F.

Samples of the various materials were secured from several sources. Each of the materials used in the investigation had the temperature-emf relation characteristic of the large percentage of the material of its particular type now being manufactured. All of the wires had been heat treated by the manufacturers in the manner considered standard for the particular type of wire.

III. TEST METHODS

Since Chromel *P* is generally used in combination with Alumel, and iron with constantan, the materials were paired in this manner. In addition to determining the temperature-emf relation for each pair, the thermal emf of the individual elements of each pair against the platinum standard[1] Pt 27 was determined. In this way the thermoelectric changes of each thermocouple material were determined independently. The difference of the thermal emfs of the individual elements of a thermocouple against a third material is equal to the emf of the thermocouple. As all three were measured in this work, any two served as a check upon the third.

The temperatures were measured with a standard platinum to platinum—10 percent rhodium thermocouple calibrated in accordance with the specifications for the International Temperature Scale.[2] The platinum working standard used was checked periodically against Pt 27.

The pair or pairs of wire under test were insulated by two-hole porcelain insulators. The platinum reference wire was protected by a glazed porcelain tube and was sealed through the end of the protection tube with a Pyrex glass, leaving about 1 cm of the end of the wire protruding beyond the seal. The platinum-rhodium thermocouple, insulated with a two-hole porcelain tube inside a glazed porcelain protection tube, was likewise sealed through the end of its protection tube with a Pyrex glass, leaving the welded junction protruding about 1 cm beyond the seal. The ends of the base-metal wires, the platinum reference wire, and the standard thermocouple were then welded together to form a single composite junction.

The furnace used in this work was of the resistance type wound with platinum-rhodium wire. The furnace tube of Alundum was 60 cm long and 3-cm inside diameter. The wires under test, together with the platinum reference wire and the platinum-rhodium thermocouple, were placed in the furnace with the composite junction at about the midpoint. The wires were then securely clamped with respect to the furnace. Although the ends of the furnace tube were closed with asbestos wool to promote temperature uniformity, no attempt was made to exclude air from the heated chamber, so that the atmosphere prevailing within the tube was oxidizing. The reference junctions were maintained at 32° F during all the measurements. The temperature of the furnace was maintained practically constant during any observation at a given point by means of a hand-operated voltage regulator in the power circuit.

To obtain data on the effect of long-time exposure to high temperatures upon the thermoelectric properties of the materials, the following procedure was adopted. The initial measurements were made on the sample as received from the manufacturer. Measurements of the

---

[1] The thermoelectric reference standard maintained at the National Bureau of Standards.

[2] G. K. Burgess, BS J. Research 1, 635 (1928) RP22.

thermal emfs of the various combinations were made at intervals of 200° F up to and including in each case the temperature at which the effect of heating was to be determined. The furnace was then allowed to cool to room temperature, and the measurements were repeated. The differences between the two sets of measurements were ascribed to the initial heating and will be referred to as the "initial changes." Similar measurements were then made after the materials had been held at the test temperature for total elapsed times of 10, 50, 100, 200, 400, 600, 800, and 1,000 hours, or as long as the materials remained serviceable. The test temperatures included every temperature from 800° F to and including 2,000 °F, in steps of 200° F. Chromel *P* and Alumel were also tested at 2,200° F. A fresh sample was used for the test at each temperature. During heating periods, the temperature of the furnace was maintained constant within ±5° F by means of an automatic temperature controller.

The procedure followed in studying the effect of decreasing the depth of immersion was as follows:

The materials were heated in the electric furnace for a period of 20 hours at a constant temperature. Following this heat treatment, the thermal emf of the samples was determined, the position of the samples being maintained the same as that during the 20-hour heating period. The furnace was then allowed to cool to room temperature, and the immersion was decreased 3 inches and the thermal emf determined in this new position. The difference between the observations for a given sample is due only to the change in immersion, since no heating took place between the two sets of measurements. This type of test was carried out on No. 8 gage iron and constantan at temperatures from 600° to 1,800° F, in 200° F steps, and on No. 8 gage Chromel *P* and Alumel from 600° to 2,200° F.

IV. RESULTS

1. TEMPERATURE EXPOSURE TESTS

(a) CHROMEL P AND ALUMEL

Figures 1 and 2 show the results obtained on No. 18 gage Chromel *P* and Alumel heated at 800° and 1,000° F, respectively. The changes in the completed Chromel-Alumel thermocouples are also shown. The changes in the individual elements are in the same direction, so that each becomes thermoelectrically positive to the material in its original condition. The convention followed in regard to sign is as follows:

If in a simple thermoelectric circuit the current flows from metal *A* to metal *B* at the colder junction, *A* is thermoelectrically positive to *B*. On the basis of this convention, Chromel *P* is positive to Alumel. Therefore, a positive change in Chromel *P* will increase the emf of a Chromel-Alumel thermocouple, while a positive change in Alumel will decrease the emf of the thermocouple. The changes observed in the tests at 800° and 1,000° F are small, in all cases less than the equivalent of 1° F for a Chromel-Alumel thermocouple.

Figures 3 to 8, inclusive, show the results obtained with No. 8 gage Chromel *P* and Alumel at temperatures from 1,200° to 2,200° F, inclusive. The changes in the emf of Chromel *P* are in the positive direction throughout all tests, with the exception of the test at 2,200° F, where a negative change was observed at temperatures above 1,600°

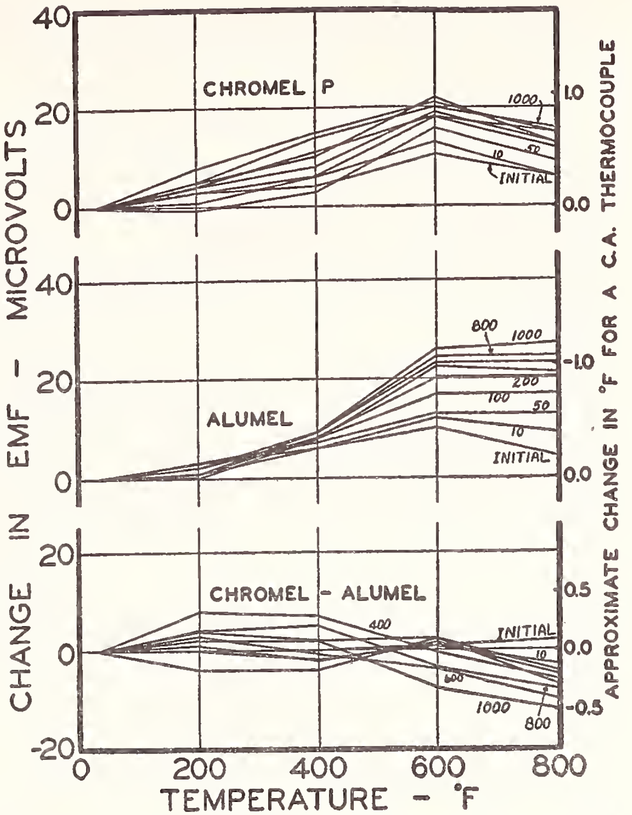


FIGURE 1.—*Changes in No. 18 gage Chromel P and Alumel due to heating at 800° F for the total times indicated on the graphs.*

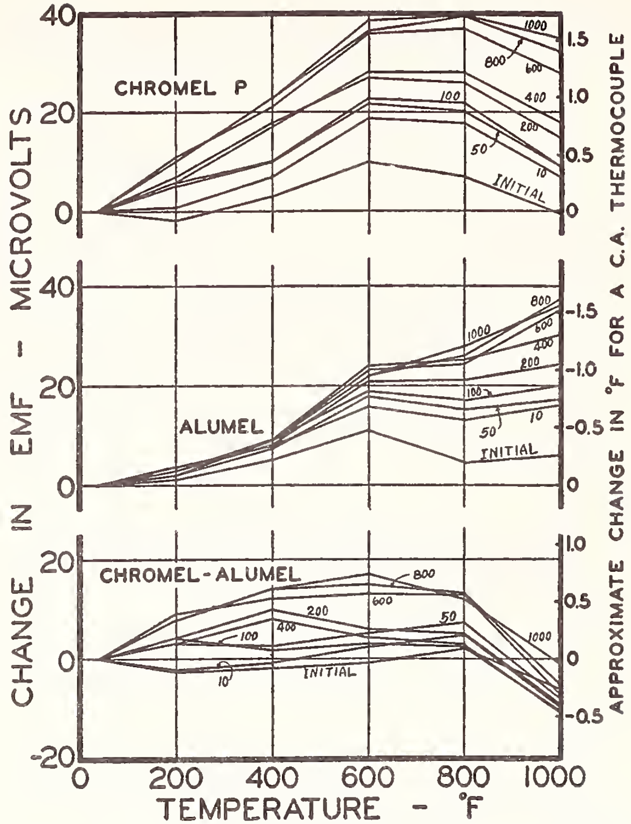


FIGURE 2.—*Changes in No. 18 gage Chromel P and Alumel due to heating at 1,000° F for the total times indicated on the graphs.*

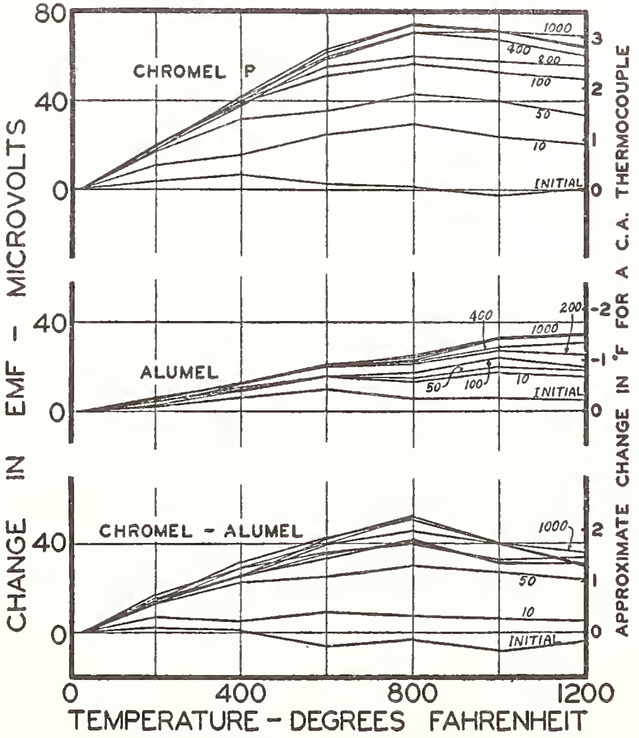


FIGURE 3.—*Changes in No. 8 gage Chromel P and Alumel due to heating at 1,200° F for the total times indicated on the graphs.*

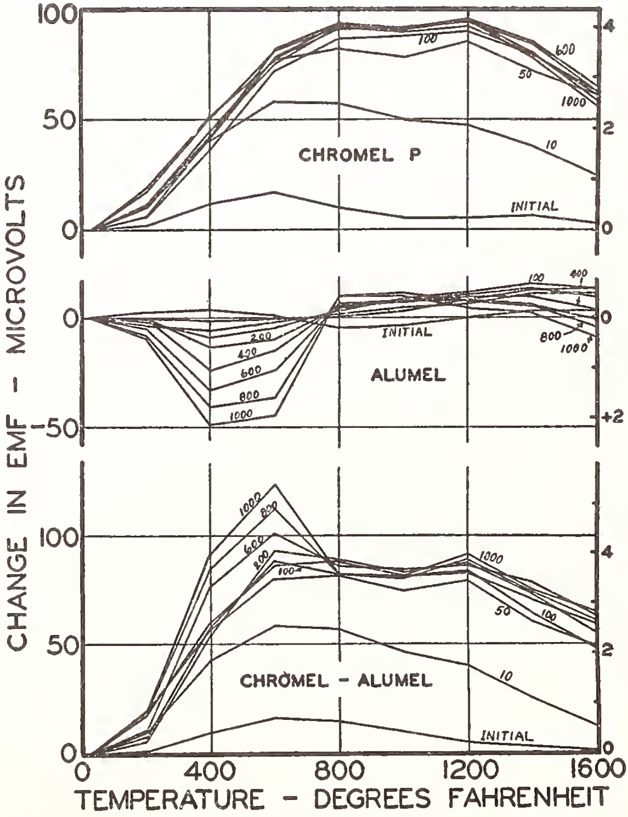


FIGURE 4.—*Changes in No. 8 gage Chromel P and Alumel due to heating at 1,400° F for the total times indicated on the graphs.*

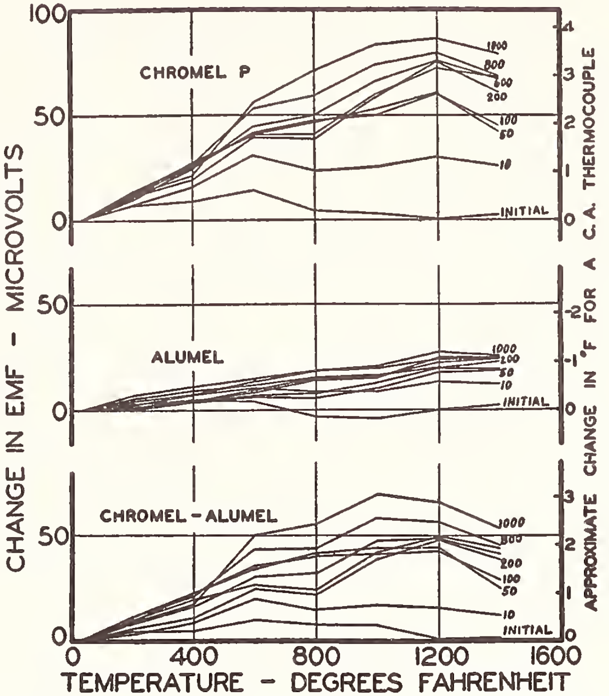


Figure 5.—*Changes in No. 8 gage Chromel P and Alumel due to heating at 1,600° F for the total times indicated on the graphs.*

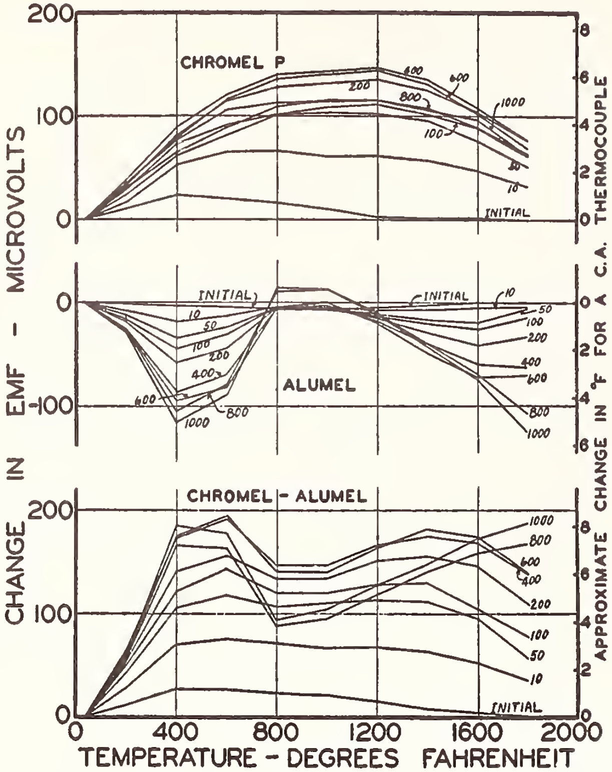


Figure 6.—*Changes in No. 8 gage Chromel P and Alumel due to heating at 1,800° F for the total times indicated on the graphs.*

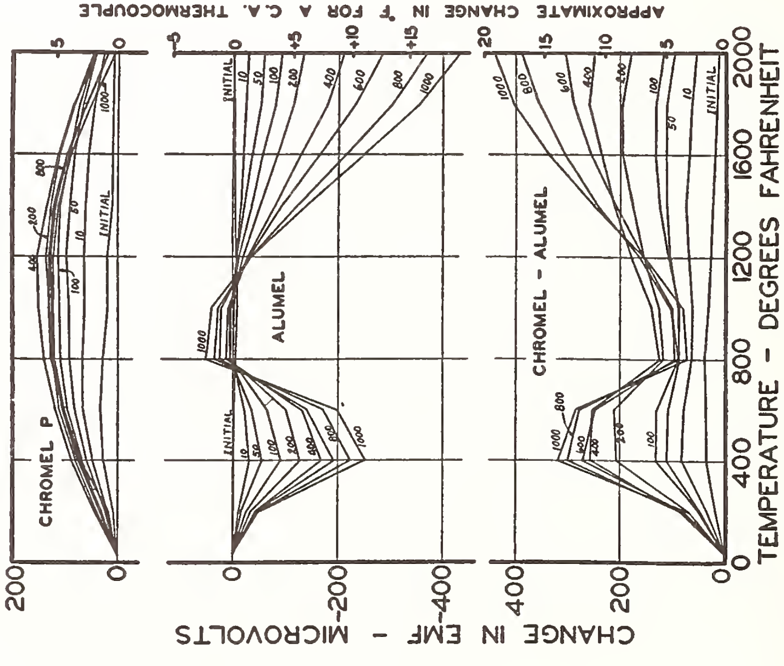


FIGURE 7.—*Changes in No. 8 gage Chromel P and Alumel due to heating at 2,000° F for the total times indicated on the graphs.*

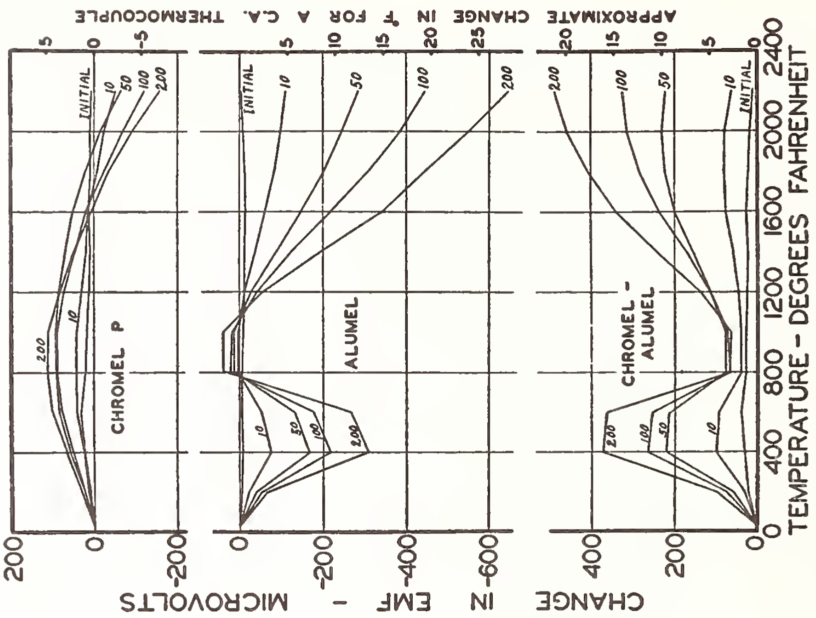


FIGURE 8.—*Changes in No. 8 gage Chromel P and Alumel due to heating at 2,200° F for the total times indicated on the graphs.*

F. The magnitude of the changes is, in nearly all cases, in the order of the duration of the heating periods, the maximum change occurring at about 1,200° F. The changes in the Alumel are in the positive direction throughout the tests at 1,200° and 1,400° F. In the tests at 1,600° F and above, the changes in the emf of the Alumel between about 800° and 1,100° F are extremely small. Above 1,100° F the changes are negative and of appreciable magnitude. This is most clearly shown in figure 7. The materials used in the test at 2,200° F failed after about 300 hours of heating.

Tests of No. 8, No. 18, and No. 22 gage Chromel-Alumel thermocouples heated at 1,200° F for a total of 1,000 hours indicated that the changes in the thermocouples of the various sizes were nearly the same, and in all cases less than the equivalent of 2.5° F. Figure 9 shows the effects on the same sizes of Chromel-Alumel thermocouples when heated at 1,600° F. The change in calibration at 400° F is largest in the smallest size, but the reverse is true for the change at 1,000° F.

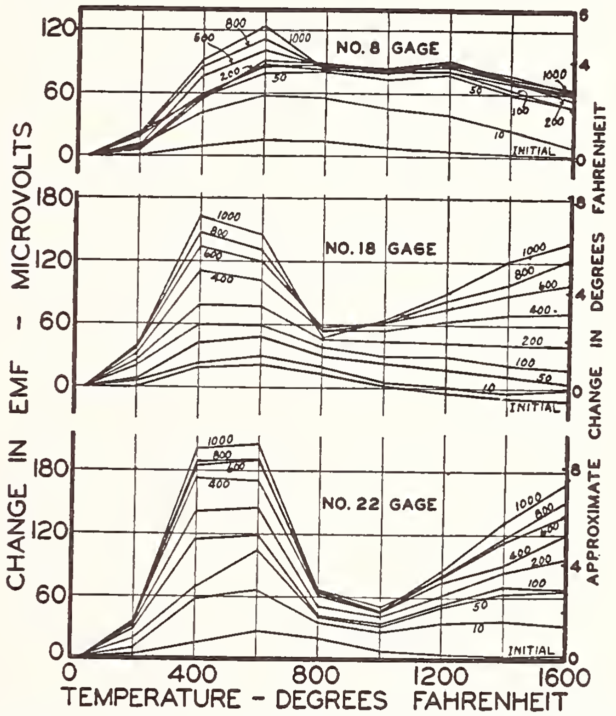


FIGURE 9.—*Changes in No. 8, No. 18, and No. 22 gage Chromel-Alumel thermocouples due to heating at 1,600° F for the total times indicated on the graphs.*

The changes in the emf of the Chromel-Alumel thermocouples produced by the total heating time in each of the tests are shown in figure 10 (reproduced from fig. 1 to 8, inclusive). In the test at 2,200° F the change after only 200 hours is shown, this being the elapsed time when the last measurements preceding failure were made. The peculiar change in the Alumel previously mentioned is reflected in change of the thermocouples.

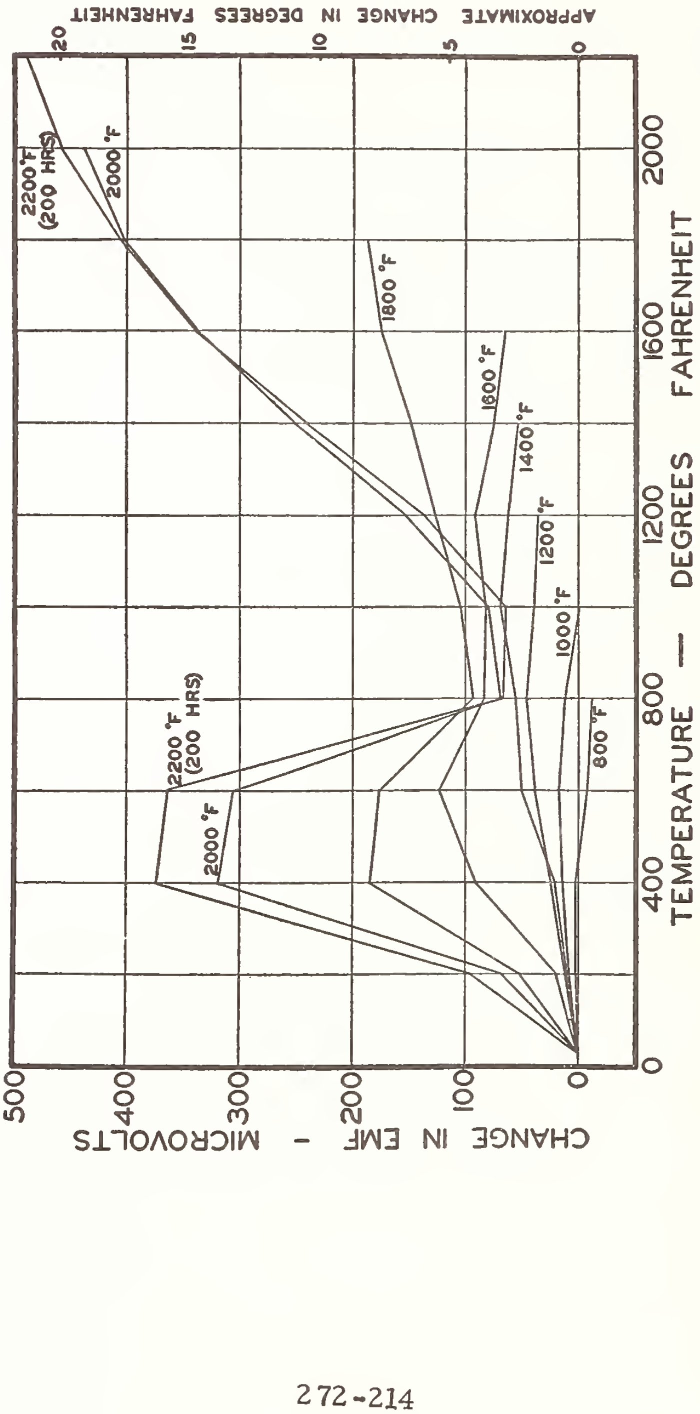


Figure 10.—*Changes in Chromel-Alumel thermocouples due to 1,000 hours of heating at temperatures indicated on the graphs.*

(b) IRON AND CONSTANTAN

Figures 11 and 12 show the results obtained on No. 14 gage iron and constantan tested at 800° and 1,000° F, respectively. The changes in all cases are small, being less than the equivalent of 1° F.

The results on No. 8 gage iron and constantan tested at 1,200° to 2,000° F, inclusive, are shown in figures 13 to 17. The time intervals between calibrations were shortened for the tests at 1,800° and 2,000° F, since at these temperatures the materials change at a rapid rate. The tests were continued until the materials failed.

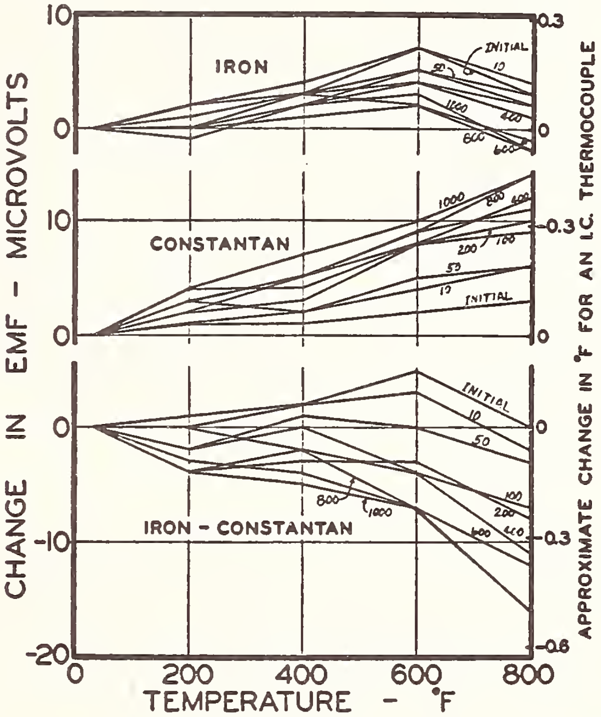


Figure 11.—*Changes in No. 14 gage iron and constantan due to heating at 800° F for the total times indicated on the graphs.*

The relative thermoelectric stability of No. 8 and No. 18 gage iron-constantan thermocouples heated at 1,400° F is shown in figure 18. As might be expected, the emf changes in the smaller wire proceed more rapidly. The No. 18 gage thermocouple failed after about 400 hours of heating, while the No. 8 gage remained serviceable throughout the 1,000 hours of the test. However, the measurements made on the thermocouple at the end of the 1,000-hour period indicated that failure was near. A test on these same sizes at 1,200° F showed no appreciable difference in their thermoelectric stability at this test temperature, the maximum change after 1,000 hours of heating being about the equivalent of 4° F.

The change in the emf of constantan was gradual and cumulative throughout each test. In the case of iron the change in emf was relatively small until failure of the wire was approached. When this stage was reached, the change was rapid and relatively large. This

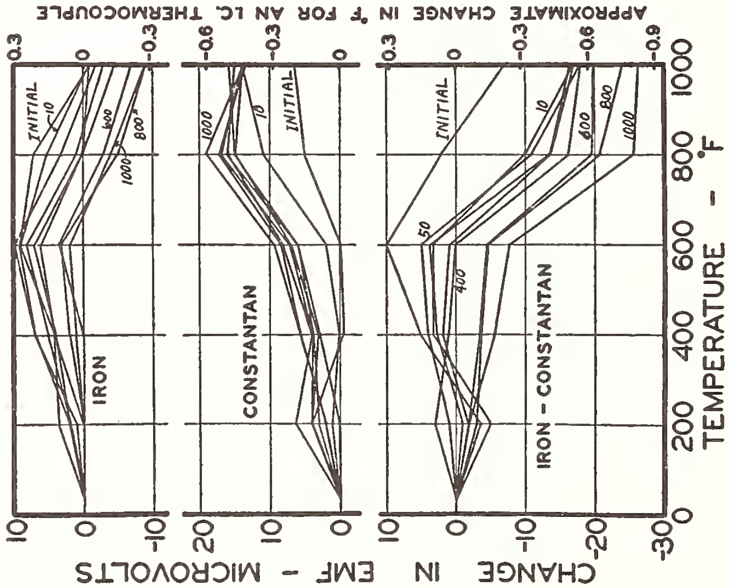


Figure 12.—*Changes in No. 14 gage iron and constantan due to heating at 1,000° F for the total times indicated on the graphs.*

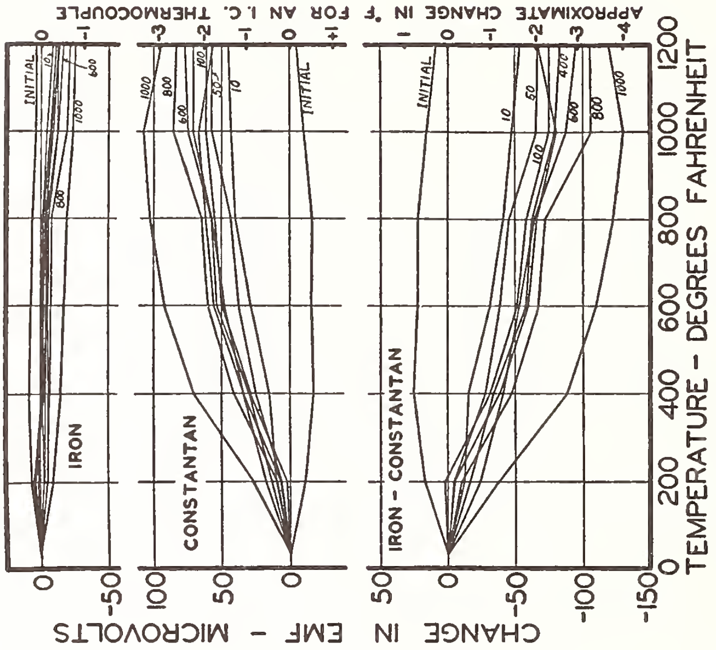


Figure 13.—*Changes in No. 8 gage iron and constantan due to heating at 1,200° F for the total times indicated on the graphs.*

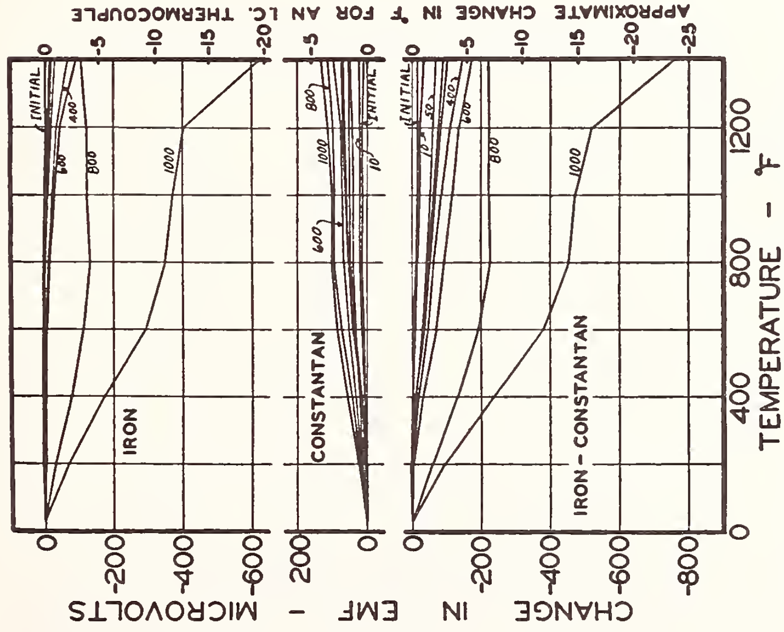


FIGURE 14.—*Changes in No. 8 gage iron and constantan due to heating at 1,400° F for the total times indicated on the graphs.*

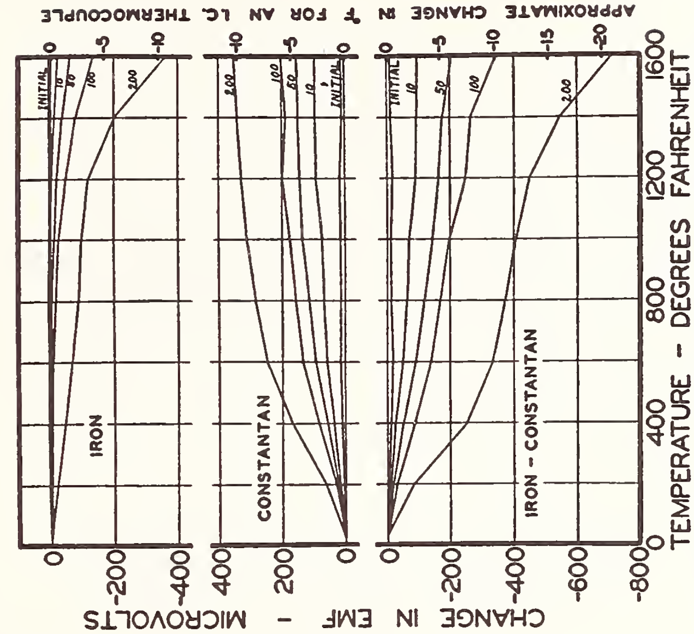


FIGURE 15.—*Changes in No. 8 gage iron and constantan due to heating at 1,600° F for the total times indicated on the graphs.*

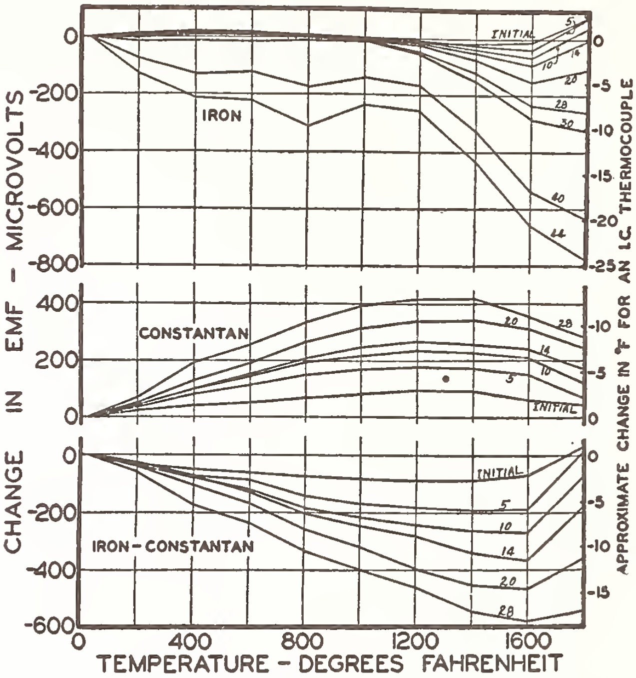


FIGURE 16.—*Changes in No. 8 gage iron and constantan due to heating at 1,800° F for the total times indicated on the graphs.*

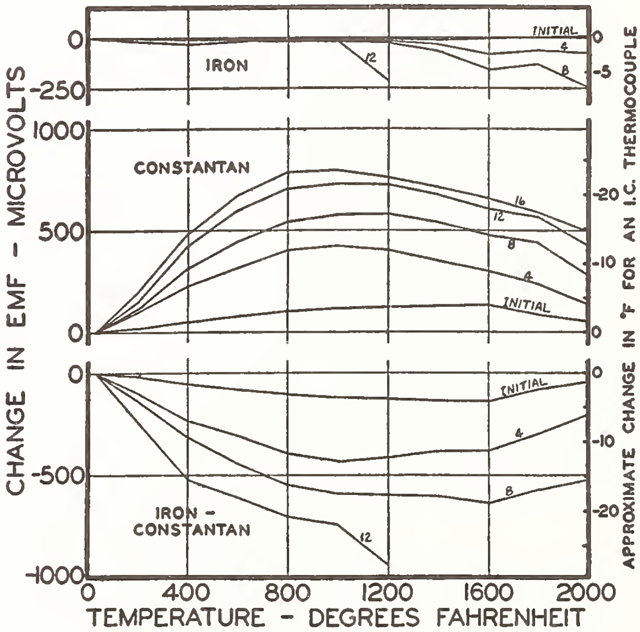


FIGURE 17.—*Changes in No. 8 gage iron and constantan due to heating at 2,000° F for the total times indicated on the graphs.*

was true for all tests in which iron was heated until failure occurred. The life of the iron element was found to be approximately the same as that of the constantan.

2. IMMERSION TESTS

Table 1 gives the observed changes in the thermal emf of No. 8 gage iron and constantan produced by a 3-inch decrease in immersion following the 20-hour heating period. The changes in both of the elements are gradual and regular throughout, the magnitude of the emf changes in constantan being everywhere considerably greater than in the case of iron. Figure 19 shows the change in the emf of the iron-constantan thermocouple under the various conditions of heating (test at 1,800° F not shown in graph). A greatly increased, though regular, change is clearly shown for the test at 1,600° F. At 1,800° F the change is about four times as great as that observed at 1,600° F.

TABLE 1.—*Changes (in thermal emf) at various temperatures caused by decreasing the depth of immersion 3 inches, after heating the wires in air at the temperatures indicated for 20 hours*

Calibration temperature	Heating temperature						
	600 °F	800 °F	1,000 °F	1,200 °F	1,400 °F	1,600 °F	1,800 °F
				IRON			
°F	*μv*	*μv*	*μv*	*μv*	*μv*	*μv*	*μv*
200	1	5	3	1	−2	−1	−2
400	0	7	4	3	−2	−4	−9
600	1	8	3	4	−2	−7	−18
800		7	2	4	−3	−12	−29
1,000			3	4	−6	−19	−43
1,200				1	−9	−30	−58
1,400					−13	−43	−72
1,600						−57	−80
1,800							−100
				CONSTANTAN			
200	4	10	13	14	14	25	83
400	7	18	20	30	28	62	224
600	9	27	26	43	41	93	374
800		35	37	52	53	127	504
1,000			49	60	54	156	615
1,200				65	65	182	735
1,400					68	208	837
1,600						223	935
1,800							1,078
				IRON-CONSTANTAN			
200	−3	−5	−10	−13	−16	−26	−85
400	−7	−11	−16	−27	−30	−66	−233
600	−8	−19	−23	−39	−43	−100	−392
800		−28	−35	−48	−56	−139	−533
1,000			−46	−56	−60	−175	−658
1,200				−64	−74	−212	−793
1,400					−81	−251	−909
1,600						−280	−1,015
1,800							−1,178

Table 2 gives the observed effects for No. 8 gage Chromel *P* and Alumel of changes in immersion, as outlined above. In the tests up to and including 1,600 °F the effect is gradual and approximately regular. At 1,800 °F and above, the Alumel element exhibited an irregular effect, somewhat similar to that observed in the exposure tests, which became more pronounced as the heating temperature was increased. Figure 20 illustrates the results for the Chromel-Alumel thermocouples.

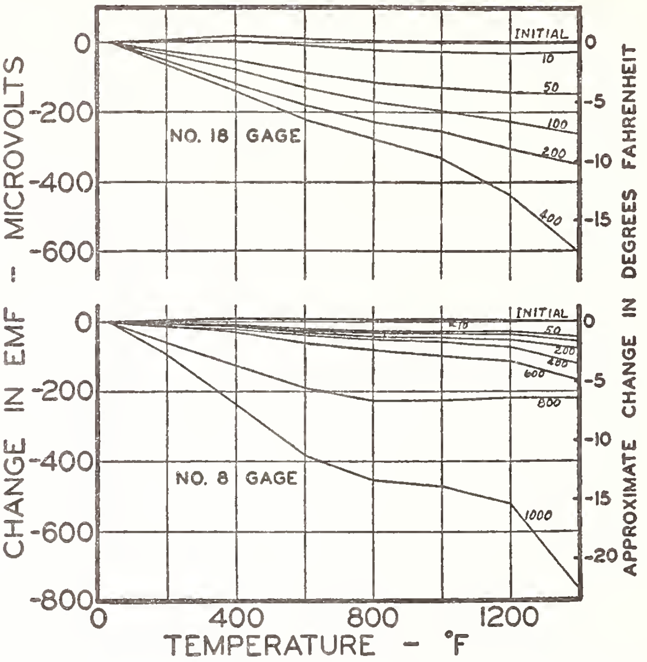


Figure 18.—*Changes in No. 8 and No. 18 gage iron-constantan thermocouples due to heating at 1,400° F for the total times indicated on the graphs.*

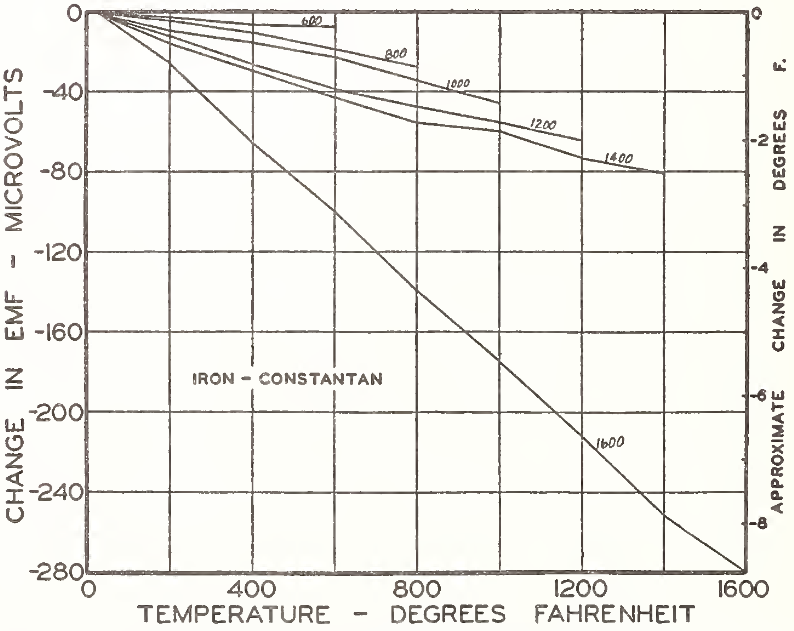


Figure 19.—*Changes in the indications of No. 8 gage iron-constantan thermocouples due to a 3-inch decrease in immersion after the couples had been heated for 20 hours at the temperatures indicated on the graphs.*

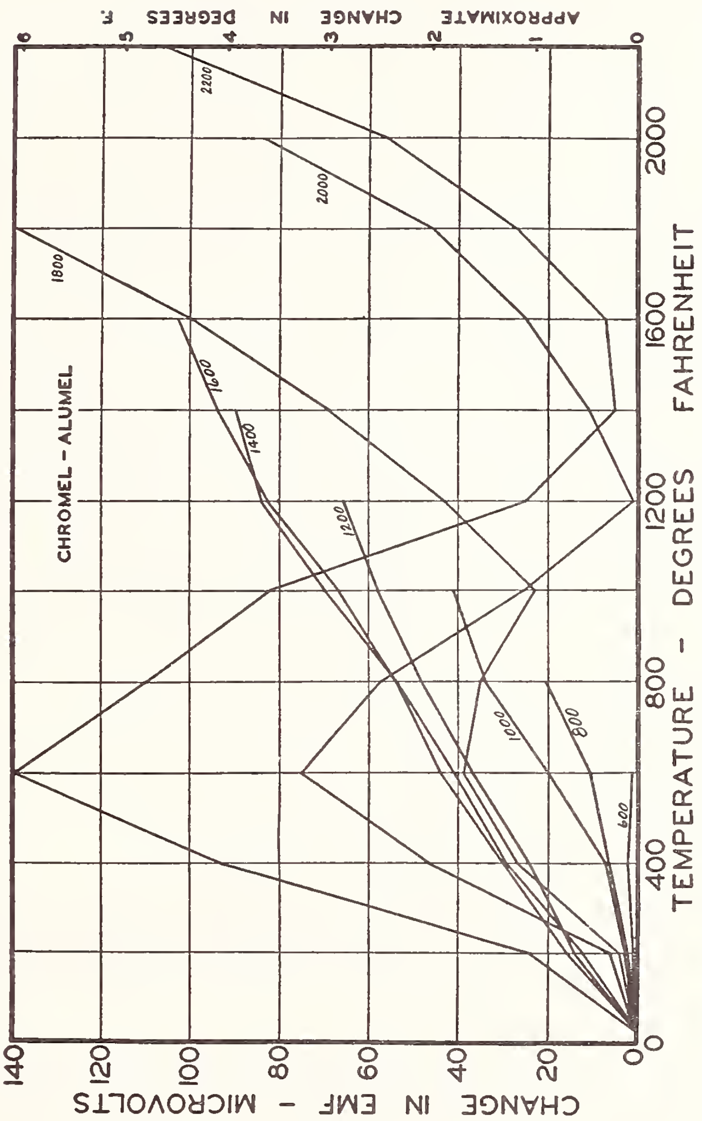


FIGURE 20.—*Changes in the indications of No. 8 gage Chromel-Alumel thermocouples due to a 3-inch decrease in immersion after the couples had been heated for 20 hours at the temperatures indicated on the graphs.*

TABLE 2.—*Changes (in thermal emf) at various temperatures caused by decreasing the depth of immersion 3 inches after heating the wires in air at the temperatures indicated for 20 hours*

CHROMEL *P*

Calibration temperature	Heating temperature								
	600° F	800° F	1,000° F	1,200° F	1,400° F	1,600° F	1,800° F	2,000° F	2,200° F
°F									
200	2	4	5	12	10	13	−1	−7	−7
400	5	9	8	21	25	24	+1	−12	−35
600	10	18	19	31	35	36	4	−14	−50
800	--------	31	30	36	45	45	10	−16	−49
1,000	--------	--------	40	41	54	57	13	−21	−52
1,200	--------	--------	--------	49	59	71	31	−32	−53
1,400	--------	--------	--------	--------	65	79	48	−28	−81
1,600	--------	--------	--------	--------	--------	86	68	−29	−103
1,800	--------	--------	--------	--------	--------	--------	95	−28	−130
2,000	--------	--------	--------	--------	--------	--------	--------	−18	−158
2,200	--------	--------	--------	--------	--------	--------	--------	--------	−176

ALUMEL

Calibration temperature	600° F	800° F	1,000° F	1,200° F	1,400° F	1,600° F	1,800° F	2,000° F	2,200° F
200	1	1	2	−2	−2	−3	−5	−13	−31
400	3	2	1	−3	−4	−6	−26	−59	−128
600	9	7	−1	−6	−6	−8	−35	−89	−193
800	--------	10	−4	−12	−11	−9	−25	−73	−159
1,000	--------	--------	+1	−17	−17	−10	−10	−46	−134
1,200	--------	--------	--------	−17	−25	−12	−13	−33	−78
1,400	--------	--------	--------	--------	−25	−15	−21	−39	−86
1,600	--------	--------	--------	--------	--------	−17	−32	−54	−110
1,800	--------	--------	--------	--------	--------	--------	−45	−74	−157
2,000	--------	--------	--------	--------	--------	--------	--------	−102	−214
2,200	--------	--------	--------	--------	--------	--------	--------	--------	−281

CHROMEL-ALUMEL

Calibration temperature	600° F	800° F	1,000° F	1,200° F	1,400° F	1,600° F	1,800° F	2,000° F	2,200° F
200	1	3	3	14	12	16	4	6	24
400	2	7	7	24	29	30	27	47	93
600	1	11	20	37	41	44	39	75	140
800	--------	21	34	48	55	54	35	57	110
1,000	--------	--------	41	58	71	67	23	25	82
1,200	--------	--------	--------	66	84	83	43	1	25
1,400	--------	--------	--------	--------	90	94	69	11	5
1,600	--------	--------	--------	--------	--------	103	100	25	7
1,800	--------	--------	--------	--------	--------	--------	140	46	27
2,000	--------	--------	--------	--------	--------	--------	--------	84	56
2,200	--------	--------	--------	--------	--------	--------	--------	--------	105

V. DISCUSSION OF RESULTS

As has been previously pointed out, the materials were heated in an oxidizing atmosphere. Furthermore, the depth of immersion of the materials in the furnace was constant throughout each exposure test. Direct application of the results obtained must be limited to cases where these conditions prevail.

From the observations reported, it is seen that long-time exposure of a Chromel-Alumel thermocouple to high temperatures causes the emf corresponding to a given temperature to increase or the temperature corresponding to a given emf to decrease. The effect on an iron-constantan thermocouple is just the reverse.

Failure of a Chromel-Alumel thermocouple (No. 8 gage) occurred within the 1,000-hour heating period only in the test at 2,200° F. In this case an open circuit was indicated after 300 hours, and examination of the sample showed that the metal forming the welded junction and the individual wires for some distance from the welded junction were oxidized nearly through.

The 1,000-hour heating periods at 2,000° and 1,800° F for No. 8 gage Chromel *P* and Alumel also produced appreciable oxidation of the materials. In the test at 2,000° F the diameter of the wires, after the oxide was removed, was 2.3 mm for the Alumel and 2.6 mm for the Chromel *P*, as compared with 3.3 mm for the original diameters. For the test at 1,800° F the diameter, after removing the oxide, was 2.6 mm for the Alumel and 3.1 mm for the Chromel *P*. In the tests at 1,600° F and below, the oxidation had not materially decreased the diameter of the wires.

The exposure tests on No. 8 gage iron-constantan thermocouples showed failure of the materials within the 1,000-hour heating time for the tests at 1,600° F and above. Failure occurred after 12 hours at 2,000° F, after 28 hours at 1,800° F, and after 300 hours at 1,600° F. The No. 18 gage iron-constantan thermocouple failed after about 500 hours at 1,400° F, while the No. 8 gage thermocouple remained serviceable throughout the 1,000-hour test at 1,400° F. However, at the conclusion of the test the diameters of the No. 8 gage materials had been reduced to about one-tenth of their original value.

A summary of the changes observed for Chromel-Alumel, iron-constantan, and Chromel-constantan thermocouples produced by long-time exposure to various temperatures is given in table 3. The values for Chromel-constantan were obtained indirectly by combining the changes in the individual elements. Though the changes in both Chromel *P* and constantan are considerably larger than those of the completed thermocouple, the directions are such that the changes counteract each other, so that the change in a Chromel-constantan thermocouple is small. The life of this thermocouple is limited by that of the constantan element.

TABLE 3.—*Changes in the calibration of base-metal thermocouples heated in air in an electric furnace*

Exposure temperature	Chromel-Alumel		Iron-constantan		Chromel-constantan	
	Hours of exposure	Maximum change	Hours of exposure	Maximum change	Hours of exposure	Maximum change
°F		*°F*		*°F*		*°F*
800	1,000	<1	1,000	<1	1,000	<1
1,000	1,000	<1	1,000	<1	1,000	<1
1,200	1,000	+2	1,000	−4	1,000	−1
1,400	1,000	3	800	−7	1,000	−2
1,600	1,000	5	100	−10	100	−4
1,800	1,000	8	28	−18		
2,000	1,000	19	8	−19		
2,200	200	21				

The relatively large changes in calibration observed for Chromel-Alumel thermocouples at 400° and 600° F, after the couples have been exposed to temperatures of 1,600° F and above, are not as serious as may at first appear. When a thermocouple is used for accurate measurement of temperatures of 1,600° F or above, it is seldom required that this same couple be used for accurate measurements at temperatures as low as 400° or 600° F. Therefore, the relatively large changes at these lower temperatures are of no great importance. A thermocouple which is to be used for accurate measurements below 1,000° F should not be exposed to the higher temperatures. If this procedure is followed, the relatively large changes at 400° and 600° F will be avoided.

The results on the immersion tests emphasize the importance of never decreasing the depth of immersion of a thermocouple after it has once been placed in service. The practice of using a single base-metal thermocouple for high-temperature measurements in a number of different installations should be avoided. It is even difficult to obtain consistent and accurate results by using a thermocouple in a single installation if the couple is withdrawn and replaced between periods of service. The results obtained by removing a used base-metal couple from an installation to determine the corrections to the original calibration by testing it in a laboratory furnace are unreliable. The temperature gradients in the two furnaces usually differ widely, and hence the results will not be applicable to the actual service conditions. If it is practicable by any means to remove the inhomogeneous portions of the thermocouple from the temperature gradient, then the original calibration of the couple is applicable.

WASHINGTON, December 14, 1939.

[The following discussions of Andrew I. Dahl's paper, Stability of Base-Metal Thermocouples in Air from 800° to 2,200° F, appeared in Temperature: Its Measurement and Control in Science and Industry, Reinhold Publishing Corp., New York, 1941.]

Discussion

W. A. Gatward, Chief Engineer, Hoskins Manufacturing Co., Detroit, Michigan: Mr. Dahl has very carefully limited his statements regarding this experiment to cover oxidizing conditions only. He has found under such conditions that generally, Chromel-Alumel thermocouples will produce higher emfs after use. In practice it is usually found that the opposite is true, that is, that when changes develop, the couples usually "read low." The tendency to read low will be caused by reducing gases which are likely to be present even under the best protection. We might say then, that the tendency to read high as caused by oxidation will in many instances be partially, wholly, or excessively compensated by the tendency to read low, as caused by gas contamination.

Mr. Dahl is dealing with very small changes, some of them equivalent to fractions of a degree. There are some instances where the data are not consistent, as for instance where he gets more change in 100 hours than in 200 hours, or where his curves cross over. I know when trying for such accuracy as this, that errors are apt to creep in, and there are two questions I would like to raise concerning his technic.

Asbestos wool was used to plug up the end of the test furnace. That has been known to cause errors if a reducing gas is driven off from the wool and into the furnace at a high enough temperature. The exact limitations of the use of asbestos wool are not known, so it should be used with caution.

The other point involves temperature gradients. With the test wires and the platinum couple all welded together it is possible to take perfectly good readings while the temperature is changing. However, the effect of the temperature gradient is such that plenty of time should be allowed for the temperature gradient to reach its equilibrium. For a given design of furnace there will be a very different temperature gradient for each temperature used, and it takes considerable time for this gradient to establish itself. Too rapid manipulation of the temperature of the furnace is suggested as a possible cause of some small discrepancies.

Possibly the accuracy of the potentiometer is not consistent with the accuracy of the control of conditions in the test and part of the data may be out of "accuracy balance."

It is quite evident that temperature gradient, a necessary evil, is one of the important considerations in the use of thermocouples. Very few people are familiar with what goes on in the "zone of uneven heating" or, the "temperature gradient," and I believe a more thorough discussion of the problem would be in order in this paper.

In discussions of this sort we use terms which we would be hard-put to define. For instance, inhomogeneity. Now we have a pretty good conception of its opposite, homogeneity, because a piece of wire is homogeneous if a temperature gradient does not set up local emfs or "parasitic emfs." It is pretty safe to say that such a wire is very uniform as to composition and physical state.

If a wire is such that parasitic emfs *are* set up by a temperature gradient, then we say that it is inhomogeneous without knowing wherein inhomogeneity lies. Maybe the hottest part of the wire has lost some small part of its chemical ingredients. Maybe some surface oxide has been reduced permanently or temporarily. Maybe the physical state or the crystal form (as in the case of nickel) has been temporarily or permanently disturbed so that a parasitic emf could "come and go," depending on the temperature at the moment.

These are mentioned just as possibilities, to show that inhomogeneity may be one or several things all at the same time. Whatever it may actually be, it is the temperature gradient acting on the non-uniform wire which causes parasitic emfs which add or detract from the total couple emf.

It is one thing to age a couple wire when we heat the whole wire to some high temperature, as for annealing or stabilizing purposes. But aside from that, each couple in use is submitted to an ageing process, not at one temperature but at many temperatures along its length. A couple must reach from the high-temperature zone out to room temperature and it must pass through a temperature gradient. Hence, the couple in use is not aged uniformly at all.

Notice that in Mr. Dahl's curves, Figs. 1 to 4 inclusive, where the ageing temperature only reaches 1400 °F, the changes are more or less uniform and proportional to time and temperature. Those in Figs. 5 to 8 inclusive are quite different with decided "humps" in the Alumel curves at 400 to 500 °F.

It must be borne in mind that a couple which is aged at 1400 °F must pass through a continuous gradient clear to room temperature just as does the couple which is aged at 1600 °F. And still the couple aged at 1600 °F will exhibit the "hump" at 400 to 500 °F while the one aged at 1400 °F will show no "hump."

It is hard to believe that a hot-end temperature of 1600 °F would *in itself* cause an effect different from 1400 °F. It is pretty certain that if two wires were completely aged (the whole length) at 1400 and 1600 °F they would behave in the same way as to the hump. Knowing the peculiarities of nickel at 400 to 500° F, and knowing that Alumel is 95 per cent nickel, we would expect that the hump in the Alumel curve must be caused by a temperature at around 400 to 500 °F, which can only occur in the temperature gradient.

Fig. 21 has been drawn to represent a possible temperature distribution in a test furnace. Curve A could be the temperature of a wire being aged at 2000 °F. It will have one end in a uniform zone, L_5, and the other end at room temperature L_1. The remaining part represented by L_2, L_3, and L_4 will be in the gradient zone. Now forget L_2 and L_4 for a moment and think of L_3 as representing the inhomogeneous wire which has been aged at many different temperatures along its length. One end could be at 1500 °F, and the other end could be at 500 °F. If L_3 is inhomogeneous then 1500° at one end and 500° at the other end would cause a parasitic emf, and it might add to or it might subtract from the emf of the whole wire against platinum.

Now after the aging at 2000 °F, suppose the temperature of L_5 is dropped to B, or to 500 °F. We know that the two ends of L_3 will also be lowered say to 400 and 200 °F, and any parasitic emf, if present, will be of different degree and might even be of different sign.

Isolating L_3 and making the foregoing assumptions, we can see that the temperatures involved could be those which would affect the Alumel. While this is all speculation and does not suggest any cure for the effect of a temperature gradient, it does suggest an experiment which might explain the hump.

A furnace could be made up with 3 controllable zones, one representing the section L_5 and the two others which could be controlled at lower temperatures and which would represent the two ends of L_3. Then a length of wire could be welded into the Alumel wire, an insert several inches long, and of material having a decidedly different emf from the Alumel wire. This insert would then represent L_3.

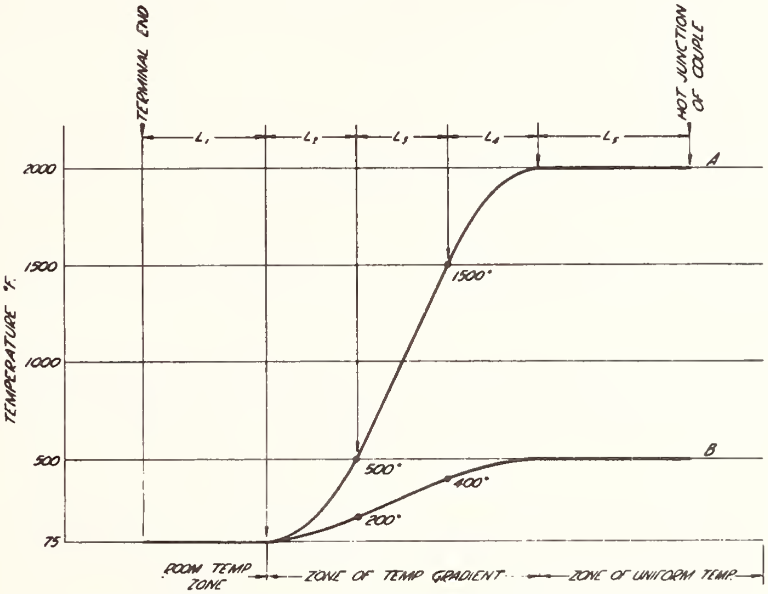


FIG. 21. Possible temperature distribution in test furnace.

Now a test could be run with selected temperatures for the ends of L_3 and a selected temperature for L_5. Then L_5 could be changed, but the difference in temperatures at the ends of L_3 could be kept the same, so that any parasitic emf in L_3 would be the same regardless of the temperature of L_5. This sort of experiment would contribute something to the explanation of the hump in the Alumel curves.

Time Rate of Change When a Chromel-Alumel Couple is Not Disturbed and is Held at One Temperature

When accurate temperatures must be measured over a long time, the couple should be checked periodically "in place," that is, not disturbed in any way. There are data in Figs. 1 to 8 inclusive which will tell what to expect in changes of emf with time. These data can be taken from Figs. 1 to 8 at the extreme right-hand end of the curves. Fig. 22 has been prepared in this manner. In some cases the curves cross over and it is not possible to identify all of them. When this occurs, the average of the group is used. It occurs only where the changes are very small, a degree or so.

Mr. Dahl's paper may at first be alarming to users of Chromel-Alumel couples. Many of them depend implicitly on check couples which are used at many temperatures and immersions.

In discussing the use of couples the expected accuracy should always be stated so that a user may decide just how he may operate his couples to attain the desired accuracy.

Mr. Dahl has carefully defined the conditions of his experiments as oxidizing. He has made some valuable suggestions in the use of Chromel-Alumel couples. However, it seems if he could combine his recommendations with his statements defining the accuracy expected, then his recommendations would have more practical use. If such accuracy cannot be conveniently defined, then he might head his list of recommendations with the statement that "extreme accuracy requires the following precautions." Such precautions selected from various paragraphs could then be summarized as follows.

(1) A couple which is used for measurements below 1000 °F should not be exposed to higher temperatures.

(2) A Chromel-Alumel couple which is used up to 1600 °F or higher should not be used for accurate measurements below 800 °F.

(3) The depth of immersion should not be changed from the original, and above all it should not be decreased.

(4) Any thermocouple should be checked if possible in place, *i.e.*, undisturbed in any way.

Reply

The asbestos wool used to close the ends of the furnace tube did not become heated to temperatures sufficiently high to disturb the oxidizing atmosphere within the tube. The wool was loosely placed against the ends of the tube. This permitted a relatively easy passage of air into the tube and if any foreign gases were liberated from the asbestos wool they would be so diluted with an excess of air that their effect would be negligible.

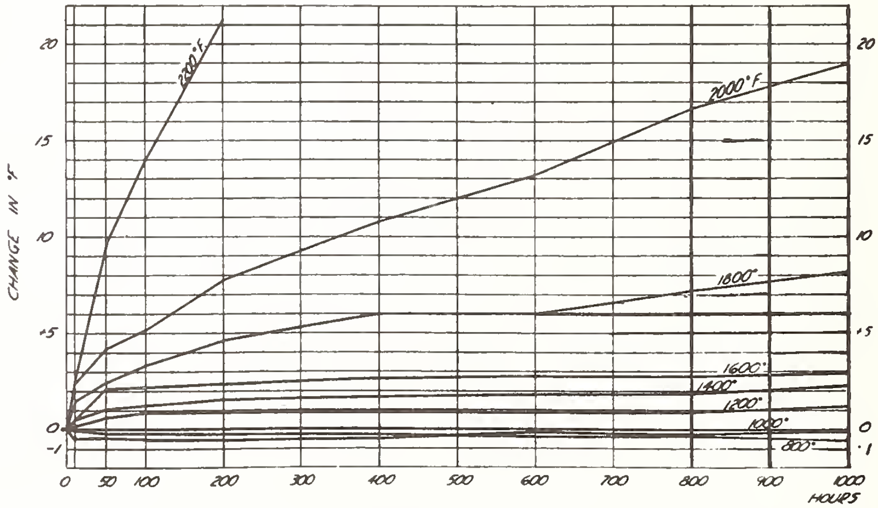


Fig. 22. Rate of change for Chromel-Alumel couples left undisturbed and aged at temperatures shown.

The time allowed for the temperature gradients in the test wires to become established after the furnace reached the desired steady temperature was about 15 minutes for temperatures up to 1200 °F and about 10 minutes for temperatures above 1200 °F. Moreover, the furnace temperature was changed slowly in passin from one point to the next. The emf of the test wires against platinum at the tim the observations were recorded showed no variation with time when the temperature was maintained constant. This would indicate that equilibrium conditions ha been reached.

The over-all accuracy of the measurements at any given temperature, includin the uncertainties in the potentiometers, the standard thermocouple, and the platinun reference wire, is estimated to be within 0.5 °F.

Discussion

A. H. Salerno, Hyatt Bearings Division, General Motors Corporation, Harrison, N. J.: Commenting on Mr. Dahl's paper from the viewpoint of the pyromete user, I wish to say that in the selection of the type of material to be used fo base-metal thermocouples in commercial application, it is necessary to know th conditions under which the wire will be used. Characteristics are influenced b type of atmosphere, whether oxidizing, neutral or reducing, and by time and temperature. Having decided upon the particular conditions, it is of extreme importance to consider the economies involved. It is well known that different types o couples will have a variable life depending upon the amosphere in which they ar used. The comparative cost per hour of service might justify the use of the les expensive of two wires, even though it is necessary to change couples more frequently. The fact that a couple must be taken out of service to avoid errors with continued use before failure occurs does not necessarily indicate an unsatisfactory type of material. Frequency of changing couples can be adjusted to avoid using them beyond the point of instability.

The atmospheric conditions encountered in the tests reported on by the author were undoubtedly quite strongly oxidizing. This condition is not always met with in practice.

In cases where difficulties might arise from using couples in a strongly oxidizing atmosphere, it is often advantageous to pack them so as to exclude as much oxygen as possible and thereby lengthen their service life.

Our practice in the use of iron-constantan thermocouples is to replace with new couples at regular stated intervals, regardless of their apparent condition. The length of time allowed in service depends on the temperature of operation. This is given below for I-C couples.

Temperature of Use	Period of Use
1700 °F	672 hours
1450–1550 °F	360 hours
300–800 °F	8760 hours

These periods are for 24 hours per day, 7 days per week. The 1700 °F-couples are packed with T.C. packing, while the others are in unpacked tubes. This accounts for the apparent discrepancy between the 1700 °F and the 1450-1550 °F time of use figures. The time of service does not indicate failure but has a large factor of safety, since the couples are inexpensive and the parts being heat-treated are valuable.

Since we have never made life tests on any thermocouple wire we are not in a position to offer comments on the stability under these conditions, other than the data given above.

G. C. Stauffer, Driver-Harris Co., Harrison, N. J.: The author of this paper should be complimented on the work done with the very desirable object of collecting information on the life of base-metal thermocouple materials.

Attention should be called to the fact that the results in this paper indicate the effect of definitely oxidizing conditions on base-metal thermocouple elements. It appears quite probable that the test conditions were considerably more strongly oxidizing than is met with in the industrial applications of base-metal thermocouples.

The results on constantan indicate what happens when it is exposed to an unknown concentration of oxygen at elevated temperatures for various periods of time. The heretofore unpublished data below indicates that the oxygen concentration in the atmosphere is more significant than the time factor. The life of any couple depends on the atmosphere. Strongly oxidizing atmospheres on an unprotected iron-constantan couple will cause rapid deterioration at temperatures over 1600 °F. It is well known that reducing atmospheres are equally destructive to some other types of base-metal couples.

In 1934 the National Bureau of Standards made some routine commercial calibrations against platinum of keyed samples submitted by the alloy manufacturer. Nine samples from one coil of No. 8 wire were taken. The coil had been given a commercial anneal at 1450 °F for 4½ hours in a closed pot. A neutral or slightly reducing atmosphere was maintained.

Of the nine pieces, one sample received no additional heat treatment. Four of the remaining samples were heated for three hours in pure hydrogen, the other four were placed in steel tubes packed with Aloxite and sealed on the ends with fireclay. This was termed an oxidizing anneal. The eight samples were then heated for three hours to the temperatures indicated.

Table 4. Heat Treatment.

Sample Number	Time (hrs)	Temp. (°F)	Atmosphere	Emf vs. Pt 27 at 1500 °F (mv)	Net Change from No. 1 (µv)
1	.	....	....	35.53	00
2	3	1400	Hydrogen	35.55	− 20
3	3	1600	Hydrogen	35.58	− 50
4	3	1800	Hydrogen	35.60	− 70
5	3	2000	Hydrogen	35.59	− 60
6	3	1400	Oxidizing	35.47	+ 60
7	3	1600	Oxidizing	35.52	+ 10
8	3	1800	Oxidizing	35.03	+500
9	3	2000	Oxidizing	34.97	+560

It would be expected that, if the oxidizing conditions were uniform for samples No. 6 and No. 9 inclusive, the change in microvolts would be consecutively greater with higher temperatures of treatment. It should be noted that this is not the case, which indicates that the oxidizing conditions were not uniform.

Comparing the tests in oxidizing atmospheres given in Table 4 with the figures given by Mr. Dahl, it will be seen that Sample No. 6, for example, shows a greater change than is given by Mr. Dahl in Fig. 14 for the same temperature but a longer period. The change on sample 7 for the oxidizing atmosphere at 1600 °F compares approximately with the data given by Mr. Dahl in Fig. 15.

A recent test to show the effect of exposure of constantan to severe oxidizing conditions for three hours at 1700 °F showed a change of 1650 microvolts when checked at a temperature of 1500 °F.

The results on the samples in the reducing atmospheres all having increased slightly, it is logical to assume that a strictly neutral atmosphere would have caused no change. Thus variations in atmospheric oxygen content will cause changes as high as 1650 microvolts at a 1500 °F test temperature when the wire is heated for only three hours. This indicates the necessity of knowing the condition of oxidation of the atmosphere in contact with the couple.

Commercial practice has indicated throughout the years that properly installed couples do not deteriorate at the rate shown by Mr. Dahl. Actual values fall between the ideal of no change, in the reducing atmosphere, and the rapid change shown under oxidizing conditions.

The amount of increase in emf after heating in reducing atmospheres has been determined to depend on the previous history of the sample. Properly melted and annealed samples show only slight changes. A piece which has been severely oxidized may be restored to its original value by heating in hydrogen at a temperature of 1850 °F for from 15 minutes to an hour or more. For example, the previously mentioned piece which changed 1650 microvolts after heating for 3 hours at 1700 °F in an oxidizing atmosphere and which had scaled off 0.005″ was fired for one hour at 1820 °F in an atmosphere of pure hydrogen.

Original value	35,500 μv vs Pt 27 at 1500 °F
After oxidizing at 1700 °F	33,850 μv vs Pt 27 at 1500 °F
After hydrogen heating at 1820 °F	35,575 μv vs Pt 27 at 1500 °F

The change is not due to the reduction of the surface oxide, since if the surface is completely removed by pickling or machining, the emf of the wire does not return to the original value until it has been fired in hydrogen.

It is apparent from this that the core of the metal in some way takes up oxygen, which definitely lower the emf of the wire. This effect on the emf is neutralized, and the oxygen is presumably removed when the wire is heated at high temperatures in an atmosphere of hydrogen.

It is obvious from the foregoing that when iron-constantan thermocouples are used it is desirable to use tight protection tubes and limit infiltration of air to the minimum.

Reply

I do not agree with Mr. Stauffer's statement that "the results on constantan indicate what happens when it is exposed to an unknown concentration of oxygen at elevated temperatures for various periods of time," because the atmosphere in which the materials were heated was that of clean air and therefore of known and constant oxygen content. The rate at which oxygen was consumed in the oxidation of the materials during heating was not great enough to change the oxygen concentration within the furnace appreciably since an excess of air was present at all times.

Bibliography

1. The thermoelectric reference standard maintained at the National Bureau of Standards.
2. Burgess, G. K., *Bur. Standards J. Research,* **1,** 635 (1928) (RP 22).

JOURNAL OF RESEARCH of the National Bureau of Standards—C. Engineering and Instrumentation
Vol. 70C, No. 2, April—June 1966

Reference Tables for the Pt-30 Percent Rh Versus Pt-6 Percent Rh Thermocouple

George W. Burns and John S. Gallagher

Institute for Basic Standards, National Bureau of Standards, Washington, D.C.

(December 9, 1965)

Reference tables for the platinum-30 percent rhodium versus platinum-6 percent rhodium thermocouple have been established for the range 0 to 1820 °C based upon the calibrations of thermocouples furnished by three manufacturers in the United States and by one European manufacturer. The thermocouples were calibrated by comparison with standard instruments such as platinum resistance thermometers, platinum-10 percent rhodium versus platinum thermocouples and optical pyrometers. The test procedures and facilities used for the calibrations are described and the accuracy of the measurements is discussed. The platinum-rhodium elements of the thermocouples were examined by a general qualitative spectrochemical method and the results of the analyses are given. Tables of emf of the individual elements of the thermocouple versus Pt-27 for the range 0 to 1500 °C are also presented. In addition, the effect of variations in the alloying percentages of platinum and rhodium on the temperature-emf relationships of the elements are shown. The results of calibrations for other Pt-30 percent Rh versus Pt-6 percent Rh thermocouples, which were received for routine calibration at NBS during the period from May 1963 to March 1965, are also shown.

Key Words: Accuracy, calibration, emf, platinum-rhodium elements, platinum-30 percent rhodium versus platinum-6 percent rhodium, reference tables, spectrochemical analyses, thermocouple.

1. Introduction

Studies by Ehringer [1][1] and by Walker, Ewing, and Miller [2, 3], have demonstrated that thermocouples in which both legs are platinum-rhodium alloys are capable of reliable temperature measurements at high temperatures. Such thermocouples have been shown to offer the following distinct advantages over the more familiar platinum-10 percent rhodium versus platinum and platinum-13 percent rhodium versus platinum thermocouples at high temperatures: (1) improved stability, (2) increased mechanical strength, and (3) higher operating temperature. The three most common platinum-rhodium combinations in use today are the platinum-20 percent rhodium versus platinum-5 percent rhodium, or 20–5 thermocouple; the platinum-30 percent rhodium versus platinum-6 percent rhodium, or 30–6 thermocouple; and the platinum-40 percent rhodium versus platinum-20 percent rhodium, or 40–20 thermocouple. The temperature-emf curves for these thermocouples and the more familiar Pt-10 percent Rh versus Pt and Pt-13 percent Rh versus Pt thermocouples are shown in figure 1.

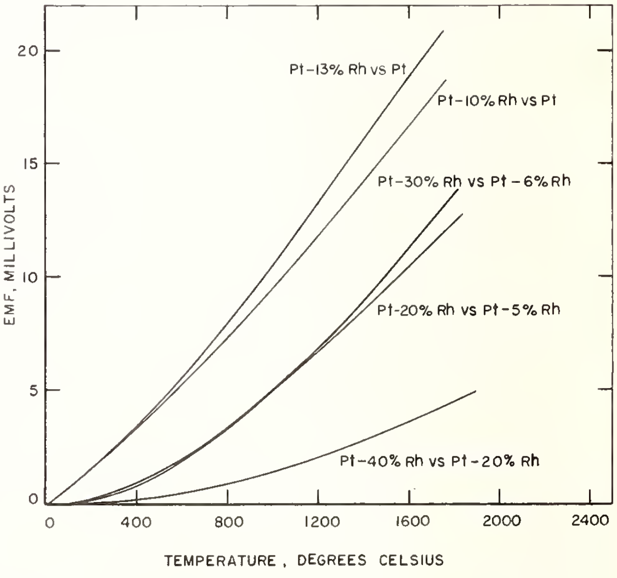


FIGURE 1. *Temperature-emf curves for platinum-rhodium thermocouples, reference junctions at 0 °C.*

---

[1] Figures in brackets indicate the literature references at the end of this paper.

Of the three platinum-rhodium combinations the 30–6 thermocouple offers the most favorable overall characteristics. Although the thermoelectric characteristics of the 30–6 thermocouple and the 20–5 thermocouple are similar, the 30–6 thermocouple does offer a slightly greater thermoelectric power at the higher temperatures and it also has a somewhat higher tensile strength than the 20–5 thermocouple. The 40–20 thermocouple is a special combination intended primarily for use in the 1700 to 1850 °C range [4]. Even though the 40–20 thermocouple may be used at slightly higher temperatures than the 30–6 thermocouple, its relatively low thermoelectric power limits its usefulness at lower temperatures.

Studies made with the 30–6 thermocouple have shown it can be used intermittently (for several hours) up to 1800 °C and continuously (for several hundred hours) at temperatures up to about 1750 °C with only small changes in calibration. The maximum temperature limit for the thermocouple is governed, primarily, by the liquidus of the Pt-6 percent Rh element which is estimated to be about 1820 °C [5]. The thermocouple is most reliable when used in a clean oxidizing atmosphere (air) but has also been used with some success in neutral atmospheres [2] and vacuum [3, 6]. The stability of the thermocouple at high temperatures has been shown [2] to depend, primarily, upon the quality of the materials used for protecting and insulating the thermocouple. High purity alumina with low iron-content appears to be the most suitable material available today for the purpose.

The 30–6 thermocouple was first introduced in Europe by Degussa, Hanau, Germany. Recently a reference curve for the thermocouple was published by Obrowski and Prinz [7] of the Degussa Laboratories. The curve, which is represented by a set of cubic equations, was developed by determining the emfs of numerous Degussa thermocouples at various thermometric fixed points. This curve is often referred to as the new Degussa curve since it replaces an older curve formerly used with the Degussa thermocouples. The emfs of the old and new Degussa reference curves [7] are given at 100 deg intervals in table 1 for the range 0 to 1800 °C.

Because of its favorable characteristics, the 30–6 thermocouple has rapidly gained acceptance and become more widely used in this country. Consequently, the National Bureau of Standards was requested by the American Society for Testing and Materials, Committee E–20, Subcommittee IV to prepare reference tables for the thermocouple to facilitate its use and calibration. A testing program was initiated by the Temperature Section at NBS for this purpose. In this program thermocouples were obtained from three manufacturers in the United States and from one European manufacturer and were calibrated by conventional methods of test. The methods included calibration by comparison with standard instruments, such as platinum-10 percent rhodium versus platinum thermocouples, platinum resistance thermometers, and optical pyrometers, and the determination of the emfs of the individual elements of the thermocouples against the platinum thermoelectric standard maintained at NBS known as Pt-27. These methods of test are discussed in NBS Circular 590. Reference tables for the 30–6 thermocouple were calculated from the results of the calibrations and the tables are presented in the appendix of this paper. The temperature-emf relationship given by the reference tables is believed to be representative of materials being produced by manufacturers in this country at the present time.

TABLE 1. *Emf of old and new Degussa reference curves for the 30–6 thermocouple*

Temperature	Emf	
(Int. 1948)	Old curve	New curve
°C	*mV*	*mV*
0	0.000	0.000
100	.056	.033
200	.162	.177
300	.419	.430
400	.790	.789
500	1.245	1.247
600	1.796	1.795
700	2.442	2.433
800	3.162	3.159
900	3.964	3.966
1000	4.839	4.847
1100	5.791	5.795
1200	6.811	6.806
1300	7.890	7.871
1400	9.000	8.977
1500	10.130	10.113
1600	11.260	11.267
1700	12.390	12.428
1800	13.520	13.583

Some of the preliminary work in the reference table program, concerned with the selection of thermocouple materials, was described in a previous paper [8]. The testing procedures and methods used in the program were also discussed in the previous paper but are described again in this paper in more detail.

2. Thermocouple Materials

2.1. Thermocouple Materials Used in the Preparation of the Reference Table

Thermocouple materials were supplied by three American manufacturers: (1) Engelhard Industries, Inc., (2) Sigmund Cohn Corporation, (3) J. Bishop and Company, and by one European manufacturer, Degussa, Hanau, Germany. A length of 0.020 in. (nominal) diameter wire, between 9 and 10 ft long, of both the Pt-6 percent Rh and the Pt-30 percent Rh alloy was furnished by each manufacturer. The alloy wires supplied by the American manufacturers were fabricated to have compositions of Pt-6.12 percent Rh and Pt-29.60 percent Rh [8]. The alloy wires submitted by Degussa were taken from stock and were reported to have nominal compositions of Pt-6.15 percent Rh and Pt-29.50 percent Rh.[2]

---

[2] For convenience in the ensuing discussion and presentation of the test results the platinum-rhodium wires submitted by Degussa will be referred to as Pt-6.12 percent Rh and Pt-29.60 percent Rh alloys.

Eleven thermocouples were prepared from the alloy wires supplied, three thermocouples from each of the American manufacturers and two thermocouples from Degussa. For purposes of this report, letter designations A, B, and C are assigned to the three American manufacturers (in an arbitrary way), and D is assigned to Degussa. The thermocouples of the various manufacturers are identified as shown in table 2.

TABLE 2. *Description of thermocouples used in preparation of reference table*

Manufacturer designation	Thermocouple identification	Material received
A	A1, A2, A3	Jan. 1963
B	B1, B2, B3	Dec. 1962
C	C1, C2, C3	Jan. 1963
D	D1, D2	Oct. 1962

Samples of the platinum-rhodium wires submitted by manufacturers A, B, C, and D were examined by a general qualitative spectrochemical method[3] and the results of the analyses are given in table 3. The results of an analysis for a thermocouple quality (reference grade) platinum wire are also shown for purposes of comparison.

TABLE 3. *Results of spectrochemical analyses of platinum-rhodium thermoelements*

Elements detected	Manufacturer A		Manufacturer B		Manufacturer C		Manufacturer D		Reference grade platinum
	Pt-6.12%Rh element	Pt-29.60%Rh element	Pt-6.12%Rh element	Pt-29.60%Rh element	Pt-6.12%Rh element	Pt-29.60%Rh element	Pt-6.12%Rh element	Pt-29.60%Rh element	
Ag	–?	–?	–?	–?	–?	–?	–?	–?	–?
Al	–	–	–	W	–	–	–	–	–
Au	–?	VW	–?	–?	–?	–?	–?	VW	–?
B	–	FT	–	–	–	FT	–	–	–
Ca	–	T	–	–	–	T	–	FT	–
Cu	FT	T	FT	FT	FT	FT	FT	T	T
Fe	VW	W	FT	VW	T	VW	T	W	–
Ir	–	W	–	VW	–	VW	–	W	–
Mg	–?	T	–	–	T	–	VW	T	–
Ni	–	–	–	–?	–	–	–	–	–
Pd	W	W	VW	VW	W	VW	W	W	–
Pt	VS	VS	VS	VS	VS	VS	VS	VS	VS
Rh	S	VS	S	VS	S	VS	S	VS	–
Si	W	VW	–?	VW	VW	VW	–?	–	–
Tl	–?	–	–?	–	–?	–	–?	–	–?

NOTE: In general, VS, greater than 10%; S, 1–10%; W, 0.01–0.1%; VW, 0.001–0.01%; T, 0.0001–0.001%; FT, less than 0.0001%;–, not detected; –?, probably not detected.

2.2. Other Thermocouples and Thermocouple Materials

In addition to the materials supplied specifically for purposes of preparing the reference tables, other thermocouples and thermocouple materials were also obtained and various other tests performed. Two groups of 0.020 in. diam platinum-rhodium wires were supplied by manufacturer B for study. The two groups consisted of one group of wires with rhodium percentages of 5.90, 5.95, 6.00, 6.05, and 6.10 and a second group of wires with rhodium percentages of 29.50, 29.75, 30.00, and 30.25. Also, during the period of test program, a number of 30–6 thermocouples were submitted by industrial users and thermocouple manufacturers for routine calibration. The results of the calibrations for some of the thermocouples submitted will be discussed in this paper. In most cases the manufacturers of these thermocouples were known. Some descriptive information about the thermocouples to be discussed is given in table 4.

TABLE 4. *Description of other thermocouples*

Manufacturer [a]	Approximate wire diameter	Thermocouple identification	Material received
	inches		
A	0.025	A11	Jan. 1964
A	.020	A22	Mar. 1965
B	.020	B11	Dec. 1963
B	.032	B22	May 1964
C	.020	C11	Oct. 1963
D	.020	D11	Oct. 1964
D	.020	D22	Oct. 1964
E [b]	.020	E11	May 1963
Unknown	.025	X11	Oct. 1963

[a] In cases where two thermocouples from the same manufacturer are listed, the thermocouples are from different lots.

[b] Manufacturer: Johnson Matthey and Company, London, England.

3. Apparatus

Four stirred liquid baths were used for calibrations in the range 0 to 450 °C. Each of the baths employed a different liquid medium and each was used to cover a separate portion of the temperature range. Temperatures in the stirred liquid baths were determined with a calibrated platinum resistance thermometer. The baths are described in more detail in section 5.1c

---

[3] Spectrochemical analysis performed by the Spectrochemistry Section of the National Bureau of Standards.

of NBS Monograph 90. Also in the range 0 to 450 °C and for temperatures up to 1100 °C a horizontal tube type furnace was used. The furnace has a nickel (80)-chromium (20) tube which serves as a heating element. The tube has an inside diameter of $^{13}/_{16}$ in., an outside diameter of $1^{5}/_{16}$ in. and is 24 in. long. The furnace is described in section 4.1 of NBS Circular 590. Temperatures in the tube furnace were determined with standard Pt-10 percent Rh versus Pt thermocouples. The Pt-10 percent Rh versus Pt thermocouples were calibrated by the fixed point method (see sections 3 and 5.1 of NBS Circular 590) and met the requirements of the International Practical Temperature Scale of 1948 for standard thermocouples (see NBS Monograph 37). The calibrations of the standard thermocouples above 1063 °C were extrapolated by the method described in section 5.1 of Circular 590.

Platinum reference wires were used in the calibrations performed in the stirred liquid baths and the tube furnace, and were also used in several other tests described in the paper. The emfs of the platinum reference wires were known relative to the platinum thermoelectic standard maintained at NBS, known as Standard Pt-27 (see section 7 of NBS Circ. 590).

The emf measurements for the calibrations in the stirred liquid baths in the 0 to 450 °C range were made with a six dial Rubicon thermal free potentiometer and the resistance measurements of the platinum resistance thermometer were made with a Leeds and Northrup Type G–2 resistance thermometer bridge. In all other tests, the emf measurements were made with Leeds and Northup Type K–3 potentiometers. The K–3 potentiometers were calibrated by comparison with a calibrated six dial precision potentiometer.

In the range 1063 to 1790 °C blackbodies were used for calibrations by direct comparison with an optical pyrometer. Two blackbodies were fabricated from 4 in. long, round, alumina rods, one with a diameter of $1^{3}/_{8}$ in. and one with a diameter of $1^{1}/_{2}$ in. In one end of each rod a $^{1}/_{8}$ in. diam axial sight hole was drilled to a depth of 2 in. and a $^{1}/_{4}$ in. diam axial hole was drilled in the opposite end of each rod to a depth of $1^{15}/_{16}$ in. The $^{1}/_{8}$ in. diam axial sight holes approximate a blackbody very closely when the walls of the holes are at a uniform temperature. The spectral emissivity of the sight holes at a wavelength of 0.65 μ was assumed to be 1 for measurements described in this paper which involve temperature determinations with an optical pyrometer (see sec. 7 for a discussion of the errors associated with the use of the blackbodies). For convenience, the alumina rods will, henceforth, be referred to as the alumina "blackbodies." A cross section of the $1^{1}/_{2}$ in. diam alumina "blackbody" is shown in figure 2.

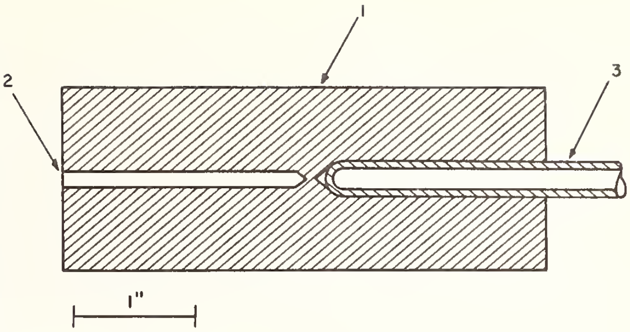


FIGURE 2. *Cross section of alumina "blackbody": (1) alumina rod; (2) blackbody cavity or sight hole; (3) alumina protecting tube.*

The $1^{3}/_{8}$ in. diam alumina "blackbody" was heated in a high temperature tube furnace. The heating element of the furnace was a silicon carbide tube with an inside diameter of about $1^{3}/_{8}$ in., and outside diameter of $2^{3}/_{8}$ in. and an overall length of 28 in. The alumina "blackbody" was located in the furnace at the center of the silicon carbide tube, and a series of alumina disks was positioned on either side of the rod. The disks served as radiation shields and reduced the power loses out the ends of the furnace. An alumina protecting tube with an o.d. of about $^{1}/_{4}$ in. was inserted through central holes in the series of alumina disks and into the $^{1}/_{4}$ in. hole in one end of the alumina "blackbody." A cross section of the furnace is shown in figure 3.

The $1^{1}/_{2}$-in. diam alumina "blackbody" was heated in a horizontal wire wound tube furnace. The furnace had three separate heater windings, two end windings, and a center winding of platinum-40 percent rhodium wire. The windings were wound on an alumina tube which had an inside diameter of about $1^{1}/_{2}$ in. and was 24 in. long. The inside of the alumina tube was lined with a Pt-10 percent Rh tube which was rolled from a piece of sheet stock 0.005 in. thick. The alumina "blackbody," alumina disks, and an alumina protecting tube were arranged in the furnace similar to the arrangement used in the silicon carbide tube furnace. A cross section of the wire wound tube furnace is shown in figure 4.

The temperatures of the alumina "blackbodies" were determined with a calibrated Leeds and Northrup Type 8636–C visual optical pyrometer. The optical pyrometer was calibrated by comparison with the NBS visual standard optical pyrometer[4] using a tungsten strip lamp as a transfer source. The calibration consisted of determining the relationship between the brightness or blackbody temperatures indicated by the instrument and the pyrometer lamp current. The calibration procedure is described in section 5.1 of NBS Monograph 41. In use the current through the pyrometer lamp was controlled with a rheostat and determined by measuring the voltage drop across a 1 Ω standard resistor in series with the lamp.

---

[4] This pyrometer is known as the Fairchild pyrometer and it is described in section 2.2 of NBS Monograph 41. The calibration and accuracy of the instrument are discussed in section 4 of the Monograph.

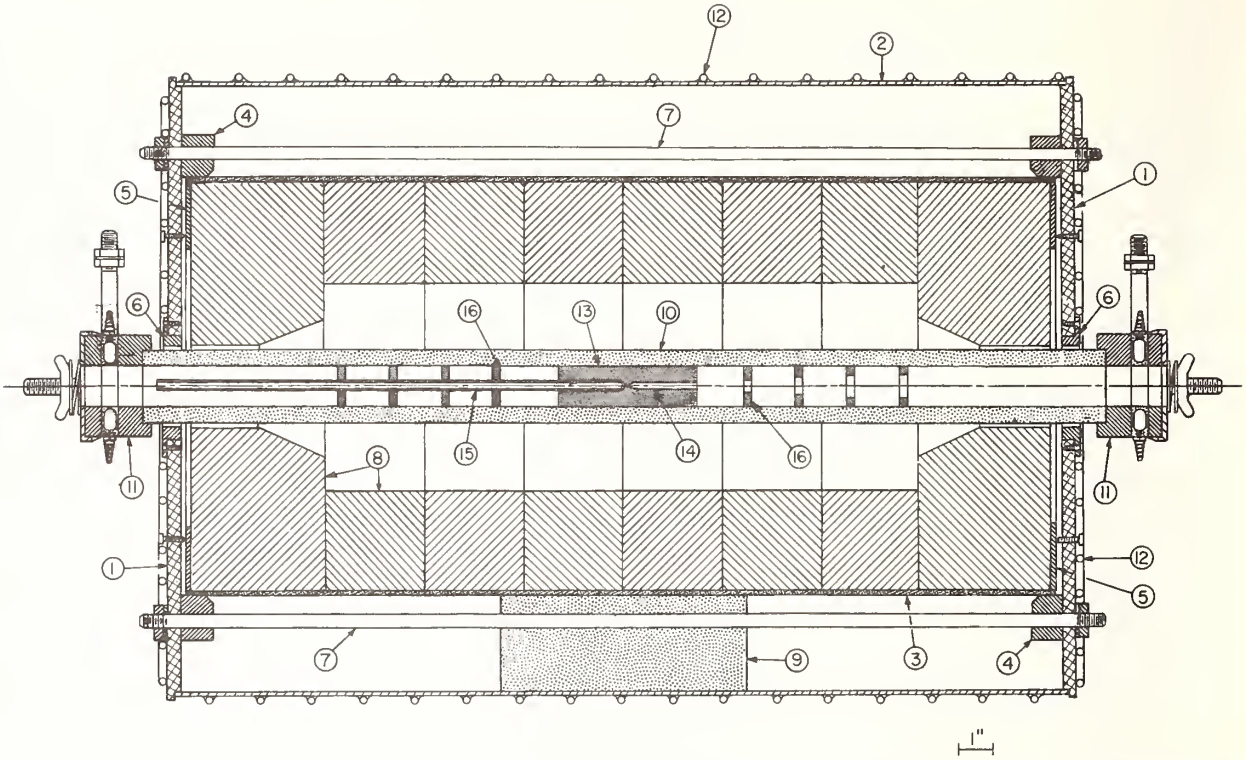


FIGURE 3. *Cross section of silicon carbide tube furnace:* (1) *brass end plate;* (2) *brass shell;* (3) *inconel liner;* (4) *stainless steel support ring;* (5) *stainless steel retaining disk;* (6) *transite insulator ring;* (7) *inconel tie rod;* (8) *refractory insulating liner;* (9) *refractory support;* (10) *silicon carbide heating tube;* (11) *terminal assembly;* (12) *copper tubing;* (13) *alumina "blackbody";* (14) *blackbody cavity or sight hole;* (15) *alumina protecting tube;* (16) *alumina disk.*

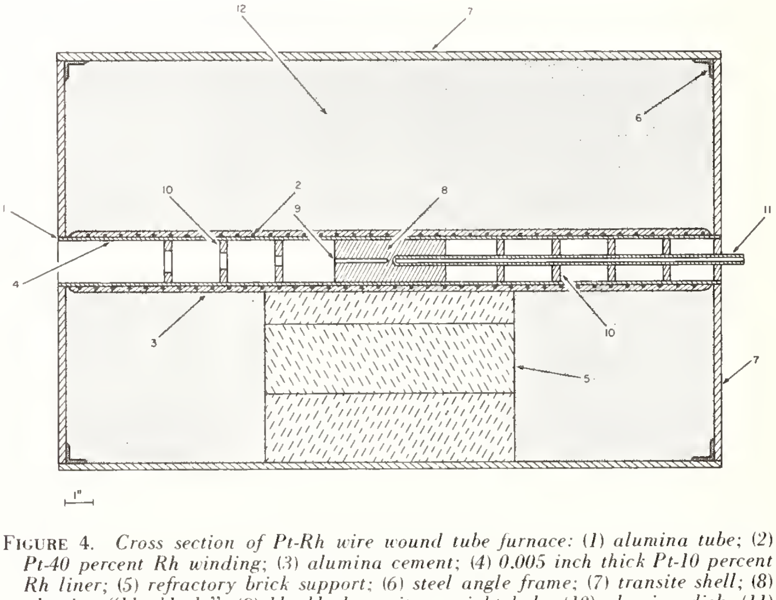


FIGURE 4. *Cross section of Pt-Rh wire wound tube furnace:* (1) *alumina tube;* (2) *Pt-40 percent Rh winding;* (3) *alumina cement;* (4) *0.005 inch thick Pt-10 percent Rh liner;* (5) *refractory brick support;* (6) *steel angle frame;* (7) *transite shell;* (8) *alumina "blackbody";* (9) *blackbody cavity or sight hole;* (10) *alumina disk;* (11) *alumina protecting tube;* (12) *bubbled alumina insulation.*

4. Experimental Procedure

4.1. Tests of Thermocouples in Table 2

The platinum-rhodium wires submitted by the four manufacturers were prepared for test by annealing them electrically in air for 1 hr at about 1450 °C. The annealing temperature of the wires was determined with an optical pyrometer, assuming the spectral emissivity of the wires was 0.3 at a wavelength of 0.65 μ. The wires were then cut and paired to form the 11 thermocouples listed in table 2. The measuring junctions of the thermocouples were welded with an oxygen-gas torch and the thermocouples were assembled in double bore alumina insulating tubes. The thermocouples were then tested as described in the following sections. The tests are described in the following sections in chronological order and are also summarized in table 5. All the tests were performed in air, and the reference junctions of the thermocouples and thermoelements were maintained at 0 °C in ice baths.

TABLE 5. *Summary of tests on the thermocouples in table 2*

Section	Thermocouple tested	Description of test	Temperature reference
4.1a	A1, A2, A3, B1, B2, B3, C1, C2, C3, D1 and D2	Calibration of thermoelements by comparison with platinum reference wires in chromel tube furnace in 0 to 1100 °C range.	Pt versus Pt-10 percent Rh thermocouple.
4.1b	A1, B3 and C2	Calibration of thermoelements by comparison with platinum reference wires in stirred liquid baths in 0 to 450 °C range.	Platinum resistance thermometer.
4.1c	A1, A2, B2, B3, C1, C2, D1 and D2	Calibration of thermocouples by direct comparison with optical pyrometer in range 1050 to 1600 °C (thermocouples heated in SiC tube furnace).	Optical pyrometer.
4.1d	A1, B2, C1 and D2	Calibration of thermoelements by comparison with platinum reference wires in range 1063 to 1500 °C.	Thermocouple B3.
4.1e	A1, A2, B2, B3, C1, C2, D1 and D2	Calibration of thermocouples by comparison with Pt versus Pt-10 percent Rh thermocouple in range 1063 to 1450 °C.	Pt versus Pt-10 percent Rh thermocouple.
4.1f	A2, A3, B1, B3, C2, C3, D1 and D2	Calibration of thermocouples by direct comparison with optical pyrometer in range 1063 to 1750 °C [a] (thermocouples heated in Pt-Rh wire wound tube furnace).	Optical pyrometer.

[a] Thermocouples A3, B1, and C3 calibrated to 1790 °C.

a. Tests in Nickel-Chromium Tube Furnace in Range 0 to 1100 °C

In these tests the emf of both thermoelements of each of the eleven thermocouples was determined against platinum reference wires in the horizontal nickel-chromium tube furnace. Determinations were made with decreasing furnace temperature at 50 deg intervals in the range 1100 to 50 °C, as well as at 1063 °C, 630.5, and 419.5 °C. These measurements were followed by a second set of determinations made with increasing furnace temperature at 50 deg intervals from 425 to 1075 °C and the determinations at 400, 419.5, 630.5, and 1063 °C were repeated. For these tests the measuring junctions of several 30–6 thermocouples, a platinum-10 percent rhodium versus platinum thermocouple and a platinum reference wire were welded into a common junction. The thermocouples and reference wire were placed in a closed end alumina protecting tube and inserted into the tube furnace until the common measuring junction was at the center of the furnace. The temperature of the furnace was regulated by the manual control of the power with an adjustable transformer. The emf of the platinum-rhodium thermoelement against the platinum reference wire and the emf of the platinum-10 percent rhodium versus platinum thermocouple were determined simultaneously by the two-potentiometer method. The two-potentiometer method is described in section 4.1 of NBS Circular 590.

b. Tests in Stirred Liquid Baths in Range 0 to 450 °C

Thermocouples A1, B3, and C2 were selected for testing in the stirred liquid baths in the range 0 to 450 °C. For these tests the Pt-6.12 percent Rh elements of the three thermocouples and a platinum reference wire were assembled in a four bore alumina insulating tube and the measuring junction of the wires welded together. The Pt-29.60 percent Rh elements and a platinum reference wire were assembled in the same manner. Each of the alumina insulating tubes was inserted into a closed end Pyrex protecting tube.

The assemblies were immersed in the stirred liquid bath along with a platinum resistance thermometer. The temperature of the bath was regulated by manually controlling the power input to the bath with an adjustable transformer. With the temperature of the bath held nearly constant the emfs of the Pt-6.12 percent Rh and Pt-29.60 percent Rh wires against the platinum reference wires were measured. The measurements were preceded and followed by determinations of the bath temperature with the platinum resistance thermometer. In this manner, measurements were made at 25 deg intervals from 25 to 450 °C. Four different stirred liquid baths were required for this purpose.

c. Calibration of Thermocouples by Direct Comparison With Optical Pyrometer in Range 1050 to 1600 °C (Thermocouples Heated in SiC Tube Furnace)

Thermocouples A1, A2, B2, B3, C1, C2, D1, and D2 were calibrated one at a time in the range 1050 to 1600 °C in the SiC tube furnace (see fig. 3). The thermocouple to be calibrated was inserted into the alumina protecting tube so that the measuring junction was in contact with the closed end of the tube. The temperature of the alumina "blackbody" was controlled near a desired calibration point by manually regulating the input power to the SiC tube with an adjustable transformer. An optical pyrometer was optically alined with the axis of the 1/8 in. diam sight hole in the alumina "blackbody" and focused on the hole near the surface. Brightness matches were made with the optical pyrometer by two experienced observers. With the temperature of the "alumina blackbody" held nearly constant (changing less than a few tenths of a deg per minute), a set of four independent brightness matches was made with the optical pyrometer by each observer. For every brightness match the pyrometer lamp current was determined and the emf of the thermocouple was measured simultaneously. A group of such readings was taken at about 1063 °C and then at approximately 50 deg intervals from 1050 to 1600 °C for each of the thermocouples. Some of the thermocouples were calibrated with increasing temperature, some with decreasing temperature, and others with both increasing and decreasing temperature. Approximately 6 to 8 hr was required to complete the calibration of each thermocouple in the range 1050 to 1600 °C.

Several problems were encountered with the measurements in the SiC tube furnace at the higher temperatures. Occasionally, the SiC tube would develop a "smoking condition" at the higher temperatures (usually above 1500 °C). When this occurred the furnace was cooled and the smoke was blown from the inside of the tube before attempting to make any further measurements with the optical pyrometer. Even so, a slight haze was sometimes noticeable inside the tube during the measurements. The effect of the haze on the optical pyrometer measurements was not known.

Also at temperatures above about 1500 °C a problem was experienced with the emf measurements which was attributed to electrical leakage between the thermocouple wires and the SiC heating element, through the alumina insulating parts and "blackbody." When the furnace power was turned off (briefly) at temperatures above about 1500 °C a difference in the emf of the thermocouple was usually observed. The magnitude and direction of the change in emf was unpredictable and would vary from thermocouple to thermocouple and from run to run. However, the change in emf was never observed to be more than 6 μV.

For measurements above 1500 °C the change in emf was determined after each set of readings and the appropriate correction was applied to the measured emfs. By this procedure it is estimated that the uncertainty in the emf measurements, because of the electrical leakage, was reduced to about 1μV or less.

Finally, a chemical reaction apparently occurred between the alumina "blackbody" and the SiC heating element at the higher temperatures. The electrical properties or characteristics of the SiC tube changed in the central region where the SiC tube and the alumina were in contact, and a "hot spot" developed in the tube. Consequently, the temperature distribution over the alumina "blackbody" became progressively less uniform and some additional uncertainty was introduced in the measurements. However, the temperature gradients were not severe and the error introduced by the nonuniform temperature probably did not exceed more than 1 or 2 deg at 1600 °C.

d. Calibration of Thermoelements by Comparison With Platinum Reference Wires in Range 1063 to 1500 °C

The emfs of the thermoelements of thermocouples A1, B2, C1, and D2 were determined against platinum reference wires at 1063 °C and then at 50 deg intervals with increasing temperature from 1100 to 1500 °C. The tests were made in the SiC tube furnace. For these tests another SiC heating tube was assembled in the furnace and a large diameter, closed end, alumina protecting tube (18 in. long with an inside diameter of 3/4 in.) was positioned inside the SiC heating tube. During the tests the thermocouples were located inside the alumina protecting tube and the tube was supported near the open end so as not to be in contact with the SiC heating tube. The test procedures were similar to those described in section 4.1a except that the temperature was determined with a 30–6 thermocouple (thermocouple B3), instead of a Pt-10 percent Rh versus Pt thermocouple.

e. Calibration of Thermocouples by Comparison With Pt-10 Percent Rh versus Pt Thermocouple in Range 1063 to 1450 °C

Thermocouples A1, A2, B2, B3, C1, C2, D1, and D2 were tested by comparing them directly with a Pt-10 percent Rh versus Pt thermocouple in the 1063 to 1450 °C range. The thermocouples were heated in the SiC tube furnace. The emf of each 30–6 thermocouple was determined at 1063 °C and then at 50 deg intervals with increasing temperature from 1100 to 1450 °C by using the two-potentiometer method.

f. Calibration of Thermocouples by Direct Comparison With Optical Pyrometer in Range 1063 to 1790 °C (Thermocouples Heated in Pt-Rh Wire Wound Tube Furnace)

Thermocouples A2, A3, B1, B3, C2, C3, D1, and D2 were calibrated by comparison with an optical pyrometer and the thermocouples were heated in the Pt-Rh wire wound tube furnace shown in figure 4. During these tests the Pt-Rh shield in the furnace was electrically grounded, and no difficulty was experienced with the emf measurements due to electrical leakage between the thermocouples and heater windings. The temperature control of the furnace was considerably more difficult than for the SiC tube furnace and rather tedious adjustments of the power to the various heater windings were required. The temperature profile in the region of the alumina "blackbody" was checked frequently with the 30–6 thermocouple being tested. The temperature was controlled and the temperature gradients minimized by manual regulation of the power to the various heater windings with variable transformers.

The calibration procedures for the thermocouples were similar to the procedures described in section 4.1c. Sets of brightness matches were taken by two different observers with the optical pyrometer and the emfs of the thermocouples were determined at about

1063 °C and then at approximately 50 deg intervals from 1100 to 1600 °C.

After completing the tests in the 1063 to 1600 °C range, each of the thermocouples was reassembled in double bore beryllium oxide insulating tube. The thermocouples were then calibrated at about 1600, 1650, 1700, and 1750 °C. Three of the thermocouples (A3, B1, C3) were also calibrated at about 1790 °C.

The calibrations described in this section were made with increasing furnace temperature. The thermocouples were removed from the furnace after taking the measurements at each calibration point and then reinserted after the temperature of the furnace was increased to the next calibration point. In general, the time required for checking the temperature gradients in the central portion of the furnace, for allowing the temperature of the furnace to stabilize, and for the two observers to take a set of observations with the optical pyrometer seldom exceeded 20 min at a calibration point for each thermocouple.

Several of the thermocouples were recalibrated at 1063 °C by the procedures described in section 4.1a following completion of the test to 1600 °C and then again following the tests to 1750 and 1790 °C.

4.2. Tests of Platinum-Rhodium Wires With Various Percentages of Rhodium

The platinum-rhodium wires were prepared for test by annealing them electrically in air for 1 hr at about 1450 °C. The wires were then assembled in alumina insulating tubes. The emfs of the platinum-rhodium wires with rhodium percentages of 5.90, 5.95, 6.00, 6.05, and 6.10 were determined against a Pt-6.12 percent Rh wire (negative leg of thermocouple B2). Similarly, the emf of the platinum-rhodium wires with rhodium percentages of 29.50, 29.75, 30.00, and 30.25 were determined against a Pt-29.60 percent Rh wire (positive leg of thermocouple B2). In the first set of measurements the measuring junctions of the various Pt-6 percent Rh wires and a Pt-10 percent Rh versus Pt thermocouple were welded into a common junction and the wires and the thermocouple were inserted into the nickel-chromium tube furnace. The emf of the Pt-Rh wires against the Pt-6.12 percent Rh wire and the emf of the Pt-10 percent Rh versus Pt thermocouple were measured simultaneously by the two-potentiometer method. Measurements were made at 100 deg intervals with decreasing furnace temperature from 1100 to 100 °C. The Pt-10 percent Rh versus thermocouple was then replaced with a 30–6 thermocouple (thermocouple B3) and measurements were made by the same method at 100 deg intervals from 1100 to 1600 °C in the SiC tube furnace. Measurements were also made at 100 deg intervals with the various Pt-30 percent Rh wires from 0 to 1600 °C by the same procedure.

4.3. Tests of Thermocouples in Table 4

Each of the thermocouples in table 4 was electrically annealed in air for 1 hr at about 1450 °C and then assembled in a double bore alumina insulating tube before testing. The thermocouples were calibrated by direct comparison with calibrated thermocouples using the two-potentiometer method. The thermocouples were heated in the nickel-chromium tube furnace and a Pt-10 percent Rh versus Pt thermocouple was used to determine the temperature in the range up to 1063 °C. Above 1063 °C the thermocouples were heated in the SiC tube furnace and one of the 30–6 thermocouples in table 2 was used to determine the temperature.

5. Computations

From the results of the tests described in sections 4.1a and 4.1b corresponding values of temperature and emf were calculated at 25 deg C intervals from 0 to 1050 °C and at 419.5, 630.5, and 1063 °C for each thermocouple. Similarly, from the tests described in section 4.1f corresponding values of temperature and emf were calculated at 1063 °C and at 50 deg intervals from 1100 to 1750 °C for each thermocouple. In the latter calculations the four readings of each observer with the optical pyrometer were averaged to obtain a single emf value for each thermocouple at about 1063 °C and at about 50 deg intervals from 1100 to 1750 °C. These values were adjusted to obtain values at exactly 1063 °C and at the nearest integral multiples of 50 °C and then the values of each observer for each thermocouple were averaged to obtain a single value of emf at each temperature. Since the measured values were nearly always within the equivalent of 5 deg of integral multiples of 50 deg, the adjustment could be made without introducing any significant error by using an approximate value for the thermoelectric power $\left(\frac{dE}{dT}\right)$ of the thermocouple at each temperature.

With the use of an IBM 7094 digital computer cubic equations were fitted by the method of least squares to the sets of emf and temperature values obtained for each thermocouple. One of the cubic equations was selected arbitrarily to serve as a rough "standard curve" with which to compare all the individual thermocouples. The deviations of the measured emf values for each thermocouple from the "standard curve" were plotted graphically and an "average deviation curve" was drawn by visually estimating the best fit. From the "average deviation curve" corresponding values of emf and temperature were calculated at 25 deg C intervals from 0 to 1825 °C.

This set of values was taken as the "principal points" upon which the reference table would be based. Several methods were considered for constructing an expanded set of temperature and emf values (the reference table) at 1 deg intervals from the "principal points." Hand calculation of the reference table using graphical interpolation and smoothing was a possible, but tedious solution. This method was not seriously considered, since a primary requirement was to adopt a method for representing the table that could be easily adapted to computer use. The method of second degree Lagrange interpolation applied to the "principal points" was given serious consideration, but was rejected in favor of using a single equation or several smoothly jointing equations.

The use of equations to represent the table instead of the Lagrange interpolation scheme seemed preferable for two reasons. First, equations require less storage space in the computer and their use is preferred by most people. Second, a set of "key values" can be generated from the equations and then the Lagrange interpolation scheme can be used for repsenting the table, if it is preferred. From preliminary curve fitting it was determined that a single polynomial equation of fairly low degree would not give an adequate representation of the temperature-emf relationship. Consequently, with the use of the IBM 7094 computer a series of polynomial equations was fitted to the "principal points" by the method of least squares. By trial, it was found that a good fit was obtained with a series of three quartic equations of the form: $E=a+bt+ct^2+dt^3+et^4$, where E is the emf in absolute millivolts and t is the temperature in degrees C (Int. 1948). The ranges of the three equations are 0 to 800 °C, 800 to 1175 °C, and 1175 to 1820 °C, and the coefficients of the equations were computed such that, at the crossover points of 800 and 1175 °C the emfs from each of the joining equations were equal and also the first derivatives $\left(\frac{dE}{dt}\right)$ of emf with respect to temperature were equal. The largest or maximum deviation of the equations from the "principal points" was 0.56 μV below 1175 °C and 0.88 μV in the region above 1175 °C, while the standard deviations for the fit of the three equations to the "principal points" were 0.31, 0.36, and 0.40 μV for the ranges 0 to 800, 800 to 1175, and 1175 to 1825, respectively.

By substituting for t in the equations the relationship 5/9 (t_f-32), where t_f is the temperature in degrees Fahrenheit, a set of three equations was calculated with the temperature expressed in degrees Fahrenheit. The coefficients and temperature ranges for the two sets of equations are given in table 6.

A method of successive approximations was developed for obtaining values of temperature from the equations at exact integral values of the emf. Sufficient accuracy was obtained with this inversion method by merely continuing the approximation until the required number of significant figures was achieved.

Using the results of the tests described in sections 4.1a, 4.1b, and 4.1d and curve fitting techniques similar to those described previously, smoothed emf values for Pt-6.12 percent Rh versus Pt-27 were determined at 50 °C intervals from 0 to 1500 °C. A set of emf values for Pt-29.60 percent Rh versus Pt-27 was then obtained by adding the set of emf values for Pt-6.12 percent Rh versus Pt-27 to the temperature-emf values given by the reference table for the thermocouple.

TABLE 6. *Coefficients and temperature ranges of equations for 30–6 thermocouple reference table*

Equations of the form $(E=a+bt+ct^2+dt^3+et^4)$* where E is given in abs. millivolts.

	*t expressed in degrees Celsius			*t expressed in degrees Fahrenheit		
Ranges / Coefficients	0–800 °C	800–1175 °C	1175–1820 °C	32–1472 °F	1472–2147 °F	2147–3308 °F
a	0	-1.5120133	6.5238699	0.60419×10^{-2}	-1.6253233	6.8443222
b	-2.37021×10^{-4}	6.286779×10^{-3}	-0.17621535×10^{-1}	$-.24594442\times10^{-3}$	0.35904493×10^{-2}	-0.10239859×10^{-1}
c	0.5767866×10^{-5}	-0.4764704×10^{-5}	$.2258695\times10^{-4}$	$.17906004\times10^{-5}$	$-.15858965\times10^{-5}$	$.70950713\times10^{-5}$
d	$-.6332156\times10^{-9}$	$.6930475\times10^{-8}$	$-.7488765\times10^{-8}$	$-.10798282\times10^{-9}$	$.12139161\times10^{-8}$	$-.12948876\times10^{-8}$
e	$-.48653\times10^{-13}$	$-.209649\times10^{-11}$	$.8862174\times10^{-12}$	$-.46346781\times10^{-14}$	$-.19971135\times10^{-12}$	$.84420950\times10^{-13}$

6. Results

6.1. Results of Tests on Thermocouple Materials Used in the Preparation of the Reference Table

Reference tables (tables 1A and 3A) for the 30–6 thermocouple for a reference junction temperature of 0 °C (32 °F) were generated from the polynomial equations (see table 6 for coefficients of the polynomial equations). In reference table 1A values of emf are given in absolute millivolts at 1 deg C intervals for the range 0 to 1820 °C. Similarly, table 3A gives values of emf at 1 degree F intervals for the range 32 to 3308 °F. Reference tables 2A and 4A are an inversion of tables 1A and 3A, respectively, and were developed by the computer technique described in the computation section. Table 2A gives values of the temperature in degrees C at 0.01 mV intervals, while table 4A gives values of temperature in degrees F at 0.01 mV intervals.

The thermoelectric power $\left(\frac{dE}{dt}\right)$ of the thermocouple was calculated from the polynomial equations and is plotted against temperature in figure 5. The thermo-

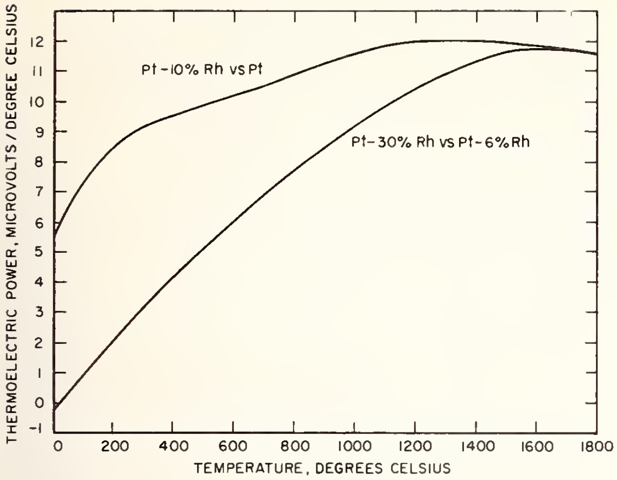


FIGURE 5. *Thermoelectric power* $\left(\frac{dE}{dt}\right)$ *of Pt-10 percent Rh versus Pt and Pt-30 percent Rh versus Pt-6 percent Rh thermocouples.*

electric power[5] of the more common Pt-10 percent Rh versus Pt thermocouple is also shown in figure 5 for purposes of comparison. The difference between the average calibration of the thermocouples from each manufacturer and the temperature-emf relationship given by the reference table are plotted in figure 6 for the range 0 to 1750 °C. The values shown in the figure in the range 0 to 1063 °C were calculated from the results of the tests described in sections 4.1a and 4.1b, and the values shown in the range 1063 to 1750 °C were calculated from tests described in section 4.1f. Since the elements of the thermocouples from each manufacturer were adjacent elements from the same wire lots, there was very little difference between the temperature-emf relationships of the thermocouples from the same manufacturer. For example, at 1063 °C the emf of each individual thermocouple from the same manufacturer (as determined in the

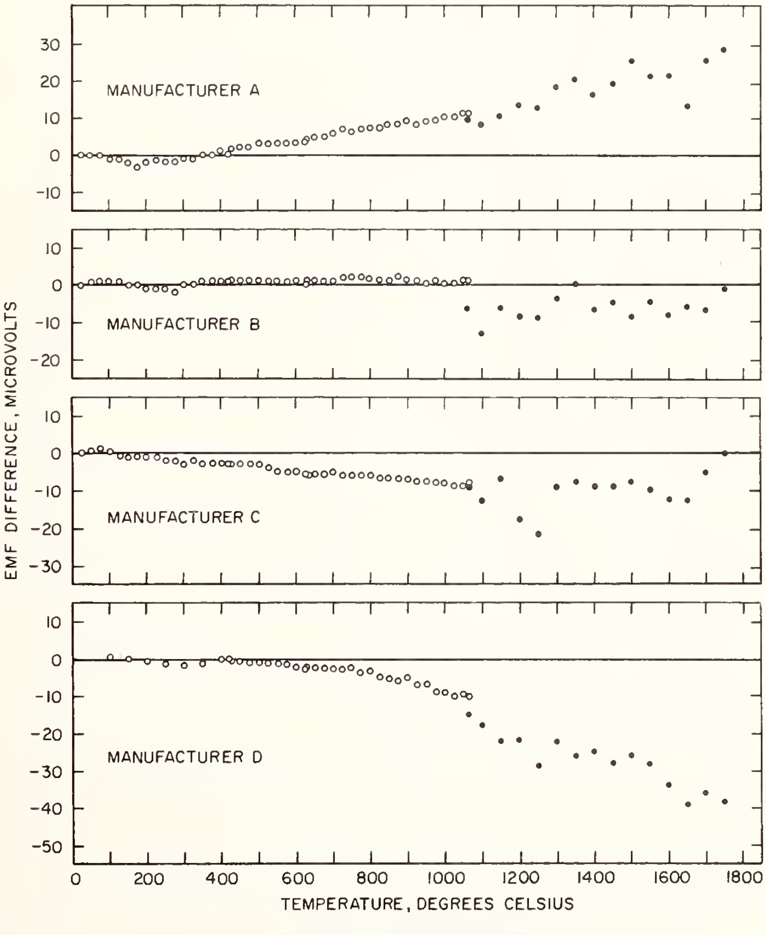


FIGURE 6. *Emf difference between average calibration of thermocouples from each manufacturer (see table 2) and the reference table (table 1A).*

Emf difference equals emf of thermocouple minus emf of reference table. Open symbols indicate temperature determined with standard thermocouples and resistance thermometers as described in sections 4.1a and 4.1b, respectively. Closed symbols indicate temperature determined with optical pyrometer as described in section 4.1f.

---

[5] Calculated from the Pt-10 percent Rh versus Pt thermocouple reference table given in NBS Circ. 561.

test described in section 4.1a), in no case differed by more than about 1 μV from the average emf of all the thermocouples from the manufacturer. For this reason, the individual calibrations of each of the thermocouples in table 2 are not shown but only the average calibration of the thermocouples of each manufacturer.

In table 7 the emf of the platinum-6.12 percent rhodium and the platinum 29.60 percent rhodium elements versus Pt-27 are given at 50 deg C intervals for the range 0 to 1500 °C. The difference between the temperature-emf values for the Pt-6.12 percent Rh elements of each manufacturer against Pt-27 and the temperature-emf values given in table 7 for the Pt-6.12 percent Rh versus Pt-27 are plotted in figure 7. Similarly, the difference between the temperature-emf values determined for the Pt-29.60 percent Rh elements against Pt-27 and the temperature-emf values given in table 7 for Pt-29.60 percent Rh versus Pt-27 are plotted in figure 8.

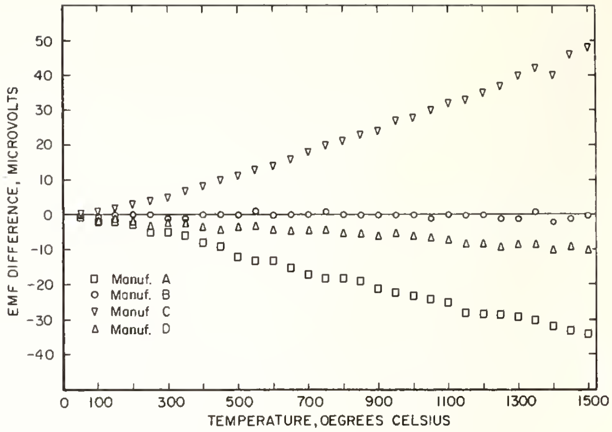


Figure 7. *Emf difference between Pt-6.12 percent Rh elements of each manufacturer and corresponding values in table 7 for emf of Pt-6.12 percent Rh versus Pt-27.*

Emf difference equals emf of element minus emf in table 7 at temperature indicated. Values shown determined in tests described in sections 4.1a, 4.1b, and 4.1d.

Table 7. *Emf of platinum-6.12 percent rhodium and platinum-29.60 percent rhodium versus Pt-27*

Temperature degrees C (Int. 1948)	Emf (abs. mV)	
	Pt-6.12% Rh	Pt-29.60% Rh
0	0.000	0.000
50	.276	.278
100	.586	.619
150	.920	1.012
200	1.272	1.450
250	1.636	1.927
300	2.007	2.438
350	2.384	2.980
400	2.765	3.551
450	3.148	4.150
500	3.534	4.775
550	3.922	5.427
600	4.313	6.104
650	4.708	6.808
700	5.106	7.537
750	5.508	8.292
800	5.914	9.072
850	6.323	9.874
900	6.737	10.700
950	7.154	11.549
1000	7.576	12.420
1050	8.003	13.314
1100	8.432	14.225
1150	8.863	15.153
1200	9.296	16.096
1250	9.732	17.058
1300	10.169	18.035
1350	10.608	19.026
1400	11.046	20.025
1450	11.480	21.029
1500	11.911	22.035

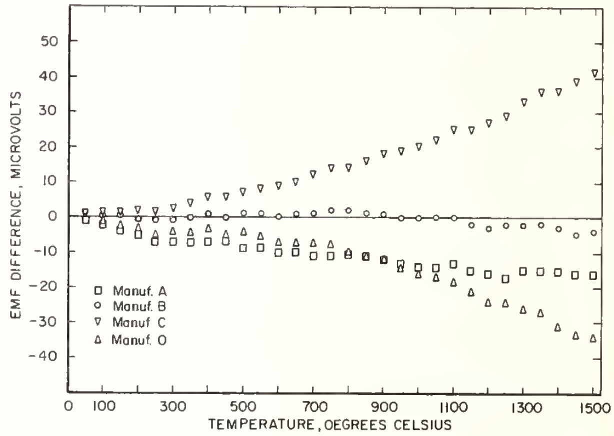


Figure 8. *Emf difference between Pt-29.60 percent Rh elements of each manufacturer and corresponding values in table 7 for emf of Pt-29.60 percent Rh versus Pt-27.*

Emf difference equals emf of element minus emf in table 7 at temperature indicated. Values shown determined in tests described in sections 4.1a, 4.1b, and 4.1d.

6.2. Results of Tests on Platinum-Rhodium Wires With Various Percentages of Rhodium

The emfs of the platinum-rhodium wires with compositions of Pt-5.90 percent Rh, Pt-5.95 percent Rh, Pt-6.00 percent Rh, Pt-6.05 percent Rh, Pt-6.10 percent Rh are shown versus a Pt-6.12 percent Rh wire (negative leg of thermocouple B2) in figure 9. In figure 10 the emfs of the platinum-rhodium wires with compositions of Pt-29.50 percent Rh, Pt-29.75 percent Rh, Pt-30.00 percent Rh, Pt-30.25 percent Rh are shown versus a Pt-29.60 percent Rh wire (positive leg of thermocouple B2) for the 0 to 1600 °C range.

6.3. Results of Testing for Other 30–6 Thermocouples

The deviations (expressed in microvolts) of the various thermocouples in table 4 from the reference table are shown in figure 11.

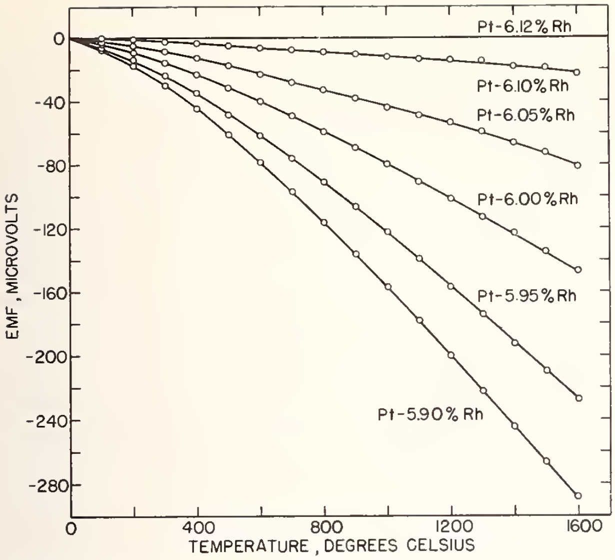


Figure 9. *Emf of platinum-rhodium wires with various percentages of rhodium versus a Pt-6.12 percent Rh wire (negative element of thermocouple B2).*

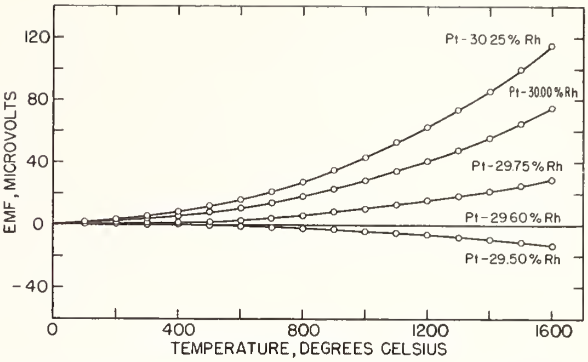


Figure 10. *Emf of platinum-rhodium wires with various percentages of rhodium versus a Pt-29.60 percent Rh wire (positive element of thermocouple B2).*

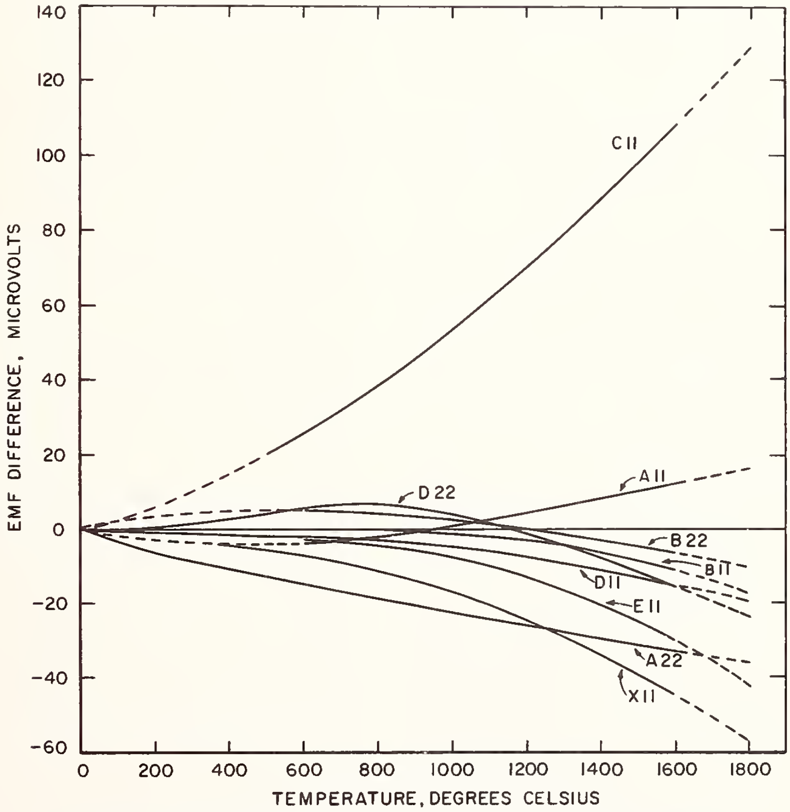


Figure 11. *Deviation of thermocouples in table 4 from reference table.*

Emf difference equals emf of thermocouple minus emf of reference table. Solid portion of curves indicate range of calibration data and dashed portions are extrapolated.

7. Discussion

As shown in figure 6 the differences between the average calibrations of the thermocouples from the different manufacturers and the temperature-emf relationship given by the reference table are quite small. The largest deviation for thermocouples from an American manufacturer occurs at 1750 °C for the thermocouples from manufacturer A and is only about 28 μV (about 2.4 °C). The differences between the temperature-emf relationships of the individual thermoelements of the thermocouples are somewhat larger than the difference between the temperature-emf relationships of the thermocouples themselves, as shown in figures 7 and 8. The spread between the temperature-emf relationships of the Pt-6.12 percent Rh thermoelements (fig. 7) is about the same as for the Pt-29.60 percent Rh thermoelements (fig. 8). The maximum spreads occur at the highest temperature measured, 1500 °C, and are about 80 μV and 75 μV for the Pt-6.12 percent Rh and Pt-29.60 percent Rh thermoelements, respectively.

It is interesting to note that the temperature-emf relationships of thermocouples from different manufacturers may agree quite closely, even though the temperature-emf relationship for the corresponding thermoelements of the thermocouples differ considerably. This is the case for the thermocouples from manufacturers B and C. It is also interesting that the spread between the temperature-emf relationships of the Pt-29.60 percent Rh elements from different manufacturers is about as large as the spread between the temperature-emf relationships of the Pt-6.12 percent Rh elements. This is a little surprising, since a small variation in rhodium content has a more pronounced effect on the temperature-emf relationship of the dilute alloy (Pt-6.12 % Rh).

The differences between the temperature-emf relationships of the various thermocouples and platinum-rhodium thermoelements are attributed to slight variations in the chemical compositions of the wires. In general, two platinum-rhodium wires of the same nominal type will differ slightly in chemical composition because of a variation in purity combined with a slight variation in the rhodium content.

It can be seen from the results of the spectrochemical analyses (table 3) that some significant differences in the purity of the platinum-rhodium thermoelements from the various manufacturers do exist. Appreciable amounts of Fe, Ir, Au, Pd, Si, and Al were detected in some of the platinum-rhodium wires as well as small traces of Ca, Mg, B, and Cu. A fairly large amount of aluminum was detected in the Pt-29.60 percent Rh wire submitted by manufacturer B, while none was detected in any of the other wires. However, the aluminum is probably present in oxide form and would be expected to have little or no effect on the thermoelectric characteristics of the wire. Of more importance is that the concentrations of Fe, Ir, Au, and Pd detected in the wires of manufacturers A and D were, in general, somewhat higher than the concentrations detected in the wires of manufacturers B and C. Another interesting point is that the wires of manufacturer D (Degussa) contained less Si than the wires submitted by the American manufacturers (A, B, and C). Also, the results of the analysis on the reference grade platinum wire shows that commercially available thermocouple platinum is considerably more pure than platinum-rhodium alloys. Consequently, the relative impurity of the platinum-rhodium alloys is attributed for the most part to impurities in the rhodium constituent.

The curves in figures 9 and 10 show the effect on the temperature-emf relationship of Pt-6 percent Rh and Pt-30 percent Rh thermoelements, respectively, caused by small variations in rhodium content. The differences between the curves are assumed to a first approximation to be entirely due to differences in rhodium. This assumption seems reasonable since the wires in each group were prepared by the same manufacturer from the same batch of platinum and rhodium. For example, the Pt-30.25 percent Rh wire should contain the same inpurities as the Pt-29.50 percent Rh wire and the concentrations would be expected to differ by a factor of only about $\frac{30.25}{29.50}$ (ratio of the rhodium percentages). It can be calculated from the curves that a 0.1 percent change in the rhodium content of a Pt-29.60 percent Rh wire will produce a corresponding change in the emf of about 15 μV at 1500 °C, while a change in the rhodium content of only about 0.01 percent will produce the same change in the emf of a Pt-6.12 percent Rh wire.

Efforts to determine the percentage of rhodium in the Pt-Rh elements from the different manufacturers to a few hundredths of a percent by chemical analysis were unsuccessful. Consequently, it is difficult, if not impossible, to establish whether the differences between the temperature-emf relationships of the thermoelements from different manufacturers are caused primarily by variation in purity or by variation in rhodium content. However, the variations of the impurities and their concentrations between thermoelements undoubtedly are large enough to be responsible for at least part of the differences. Also, slight variations in the rhodium content of thermoelements from different manufacturers are unavoidable and these variations combined with the variations in purity can easily account for the differences in emf shown in figures 7 and 8.

It has been suggested that slight differences in the alloying percentage of platinum and rhodium, and variations in purity can explain differences in the temperature-emf relationships of thermoelements and thermocouples from different manufacturers. For these same reasons differences between the temperature-emf relationships of thermocouples from the same manufacturer, but from different lots, will also occur. Comparison of the deviation curves in figure 11 with the deviation curves in figure 6, shows that the differences between the temperature-emf relationships of thermocouples from the same manufacturer do exist and can be rather large. For example, the difference between the average calibration of thermocouples C1, C2, and

C3 (shown by curve for manufacturer C in fig. 6) and the calibration of thermocouple C11 (see fig. 11) is about 130 μV at 1600 °C. The difference is larger than the differences between the temperature-emf relationships of any of the other thermocouples and probably represents a rather extreme case. For thermocouples tested from the other manufacturers differences in emf at 1600 °C ranging from a few microvolts up to about 60 μV were typical for lot to lot differences.

If thermocouple C11 is disregarded, the variations among the temperature-emf relationships of all the other thermocouples in tables 2 and 4 are surprisingly small considering that five different manufacturers and about 12 different lots of wire are represented. The maximum difference between the temperature-emf relationships of the various thermocouples at 1600 °C is about 70 μV (about 6 deg C), and the largest deviation of any thermocouple from the reference table is only about 45 μV (about 3.8 deg C). Consequently, it is estimated that nearly all the 30–6 thermocouples produced by manufacturers in this country will have temperature-emf relationships that agree with the temperature-emf relationship given by the reference table to within the equivalent of ± 0.5 percent of the temperature in the range 500 to 1800 °C and to within ± 15 μV for temperatures below 500 °C.

These values do not represent a standard manufacturing tolerance for the 30–6 thermocouple, nor are they a recommendation for one. The values are merely estimates, based upon the calibrations of a rather small sampling of thermocouples which have been tested at NBS. The values are intended to serve as a guide for prospective users of the thermocouple, since no standard manufacturing tolerances exist for the thermocouple at present. If the 30–6 thermocouple comes into common use in this country, technical societies and manufacturers will most likely agree upon and adopt standard manufacturing tolerances.

The difference between the Degussa reference curves (old and new) and the reference table presented with this paper are shown in figure 12. It can be seen that the differences between the new Degussa reference curve, established by Obrowski and Prinz [7], and the temperature-emf relationship given by the NBS table are less than the spread between the temperature-emf relationships of the thermocouples tested in this investigation. The difference at 1600 °C is 19 μV or about 1.6 deg C while the maximum difference occurs at 1800 °C and is only 33 μV or about 2.9 deg C. This indicates that the thermocouples used by Obrowski and Prinz in establishing the new Degussa reference curve had essentially the same characteristics as the Pt-29.60 percent Rh versus Pt-6.12 percent Rh thermocouples produced by American manufacturers.

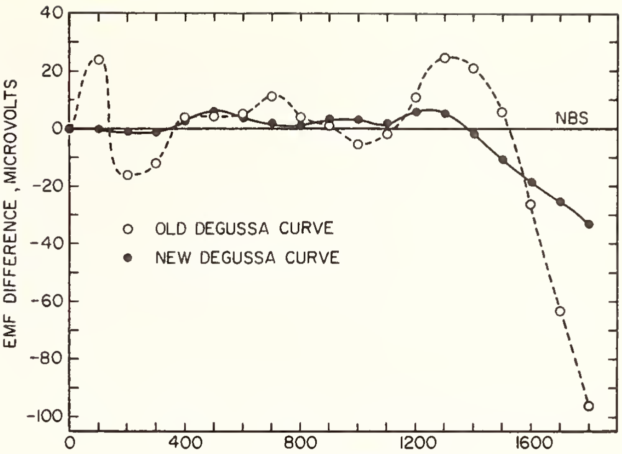


FIGURE 12. *Emf difference between Degussa reference curves (old and new) and NBS reference table for 30–6 thermocouple.*
Emf difference equals emf of Degussa curves minus emf of NBS reference table.

The fact that the emf developed by the 30–6 thermocouple is relatively small (about two-thirds the emf of the Pt-10 percent Rh versus Pt thermocouple at 1700 °C as shown in fig. 1) imposes no particular restrictions on the use of the thermocouple at high temperatures. The thermoelectric power or sensitivity of the thermocouple above 1100 °C, which is most important, is fairly high (> 9 μV/°C) and compares favorably with the thermoelectric power of the Pt-10 percent Rh versus Pt thermocouple as shown in figure 5. One advantage of the 30–6 thermocouple over most other types of thermocouples, is that the thermoelectric power and emf of the thermocouple are almost negligible in the normal room temperature range. Consequently, in most applications the reference junction temperature of the thermocouple does not need to be controlled or even known as long as it is between 0 and 50 °C. For example, as shown by the reference tables the emf developed by the thermocouple with the reference junctions at 0 °C undergoes a reversal in sign at about 41 °C, and between 0 and 50 °C varies from a minimum of about −2 μV at about 20 °C to a maximum of about +3 μV at 50 °C. Therefore, in use, if the reference junctions of the thermocouple are both at the same temperature and within the range 0 to 50 °C, then a 0 °C reference junction temperature can be assumed and the error introduced will not exceed 3 μV. At high temperatures (above 1100 °C) an additional error of 3 μV (about 0.3 deg) in the measurements would be insignificant in most instances.

The arbitrary nature of the reference tables reported in this paper should be emphasized. The tables are intended only to accurately represent the general shape of the temperature-emf curve for the 30–6 thermocouple, and should not be expected to represent the actual emf, even for a thermocouple having exactly the composition given (Pt-29.60 % Rh versus Pt-6.12 % Rh).

In general, the temperature-emf relationship of a particular 30–6 thermocouple will deviate somewhat from the relationship given by the reference table. The deviation can be expected to be rather small and vary smoothly as shown by the curves in figures 6 and 11. Consequently, a deviation curve from the reference table can be constructed that will yield a calibration sufficiently accurate for most purposes, by calibrating a particular thermocouple at relatively few temperatures. The uncertainties in interpolated emf values calculated for the thermocouple from the deviation curve will then depend upon the number and spacing of the calibration points used in constructing the deviation curve, the uncertainty in the calibration points, and the quality or "accuracy" of the reference table. Obviously, the quality or "accuracy" of the reference table will depend to a certain extent on the accuracy of the measurements upon which the table is based and upon the method employed for constructing the table from the measured data.

The inaccuracies introduced in the reference table for the 30–6 thermocouple by the method employed for interpolating between the measured data are not believed to be significant. Almost any interpolation scheme will give an adequate representation of the data since there is an abundance of data and the temperature intervals between the data points are small. Therefore, any inaccuracy in the shape of the temperature-emf relationship given by the table is attributed for the most part to uncertainties in the measurements.

At temperatures below 450 °C the thermoelectric power of the 30–6 thermocouple becomes quite small. Hence, the accuracy of the measurements is limited in this range by inhomogeneities in the thermocouple materials and by limitations in the testing facilities and measuring equipment, rather than by uncertainties in the calibration of the standard instrument (platinum resistance thermometer) used for measuring the temperature. In the range 450 to 1063 °C the accuracy is limited primarily by uncertainties in the calibration of the platinum-10 percent rhodium versus platinum thermocouples used in the measurements for determining the temperature. Similarly the accuracy of the measurements above 1063 °C is limited by uncertainties in the calibration of the optical pyrometer. In addition, factors such as electrical leakage through the insulating parts and changes in the chemical composition of the wires may contribute to the uncertainty in the measurements above 1063 °C. Changes in the chemical composition of the wires may result from chemical contamination, preferential loss of platinum or rhodium by oxidation and volatilization, and rhodium migration. Considering the thermocouple wire sizes used, the quality and sizes of the alumina insulating tubes used, and the rather short exposure times involved, none of the factors are believed to introduce any significant uncertainty in the measurements for temperature up to about 1600 °C. However, above about 1600 °C the factors become more serious.

In preliminary experiments, beryllia (BeO) insulating tubes were found to have higher electrical resistance in the 1600 to 1790 °C range than alumina tubes by a factor of two or more. Consequently, the thermocouples were insulated with BeO insulating tubes for measurements in the range above 1600 °C. Even so, electrical conduction through the BeO insulating tubes is believed to have produced a small error in the measurements. From determinations made on the insulation resistance of the BeO tubes, by measuring the resistance between the wires of thermocouples with their measuring junctions open, the magnitude of the error is estimated not to exceed 0.5 deg C for temperatures up to 1790 °C.

Some significant shifts in the thermoelectric characteristics of the thermocouples occurred as a result of testing in the 1600 to 1790 °C range. The shifts were detected by measuring the emf of the thermocouples at a lower temperature (1063 °C) before and after the measurements in the 1600 to 1790 °C range and were attributed to changes in the chemical composition of the thermocouple wires. Chemical contamination by impurities transferred from the insulating and protecting parts was believed to have been the principal cause of the compositional changes. The error introduced in the measurements above 1600 °C because of the compositional changes in the thermocouple wires is estimated to be not more than about 1 deg C.

Another source of error in the measurements above 1063 °C is introduced by the alumina "blackbodies." In all the measurements with the optical pyrometer the spectral emissivities of the alumina "blackbodies" at a wavelength of 0.65 μ were taken as 1. Consequently, any departure in the spectral emissivities from 1 will produce an error in the measurements. The spectral emissivity or quality of a blackbody depends upon the internal dimensions of the blackbody cavity, the nature of the internal reflections (diffuse or specular), the values of the reflection factor, and the temperature distribution over the cavity walls [9]. Assuming uniform temperature of the cavity walls and using the calculations described by DeVos [9] with an experimentally determined value for the partial reflectivity of alumina, the spectral emissivities at a wavelength of 0.65 μ of the alumina "blackbodies" are estimated to be about 0.999. A departure of 0.001 in the spectral emissivities of the alumina "blackbodies" from the assumed value of 1 produces an uncertainty of less than 0.2 °C in the measurements in the range 1063 to 1790 °C. However, the temperature distributions along the walls of the blackbody cavities or sight holes were not uniform during the measurements. The temperature gradient along the alumina "blackbody" which was heated in the Pt-Rh wire wound tube furnace seldom exceeded more than 1 deg per inch. This would have a negligible effect upon the spectral emissivity of the blackbody cavity, but would introduce an additional error in the measurements. When there was a temperature gradient along the alumina "blackbody" the measuring junction of the thermocouple being tested would not have been at the temperature of the back wall of the blackbody cavity, since it was located approximately 1/8 in. from the cavity wall. Errors introduced by temperature gradients in the alumina "blackbody" are estimated not to exceed more than 0.2 or 0.3 deg for measurements in the Pt-Rh wire wound tube furnace.

The quality of the alumina "blackbodies" is verified experimentally by the good agreement (about 0.5 deg) achieved at 1063 °C between the calibrations of the various 30–6 thermocouples determined by comparison with the standard thermocouple (sec. 4.1a and 4.1e) and by comparison with the optical pyrometer (sec. 4.1f). The agreement achieved between the two methods of calibration really reflects the accuracy of the entire system since the quality of the furnace, thermocouples, optical pyrometer calibration and blackbody influence the agreement.

The results of other tests described in this paper also give some experimental verification to the accuracy of the measurements above 1063 °C. The calibrations of thermocouples by direct comparison with the optical pyrometer which were performed in both the silicon carbide tube furnace (sec. 4.1c) and the Pt-Rh wire wound tube furnace (sec. 4.1f) were in agreement to within about 0.5 deg C at 1063 °C and to within about 2 deg C at temperatures up to 1600 °C. In general, the calibrations in the Pt-Rh wire wound tube furnace yielded slightly higher emfs for the thermocouples than the calibrations performed in the SiC tube furnace. The calibrations in the Pt-Rh wire wound tube furnace were considered more reliable since problems with electrical leakage, hazing and nonuniformity of temperature were experienced in the SiC tube furnace. For this reason, the data obtained in the calibrations performed in the SiC tube furnace were not used in the calculation of the reference table. Even though the measurements made in the SiC tube furnace may be questionable, the agreement between the calibrations made in the two different furnaces does give added confidence in the measurements. Further confidence in the measurements above 1063 °C is gained by the agreement achieved between calibrations of thermocouples determined by direct comparison with standard Pt-10 percent Rh versus Pt thermocouples (sec. 4.1e) and by direct comparison with the optical pyrometer (sec. 4.1f). Calibrations of the same thermocouples by the two different methods agree to within 1 deg C in the range 1063 to 1350 °C and to within about 2 deg C up to 1450 °C. This agreement is quite satisfactory, since the calibrations of the standard Pt-10 percent Rh versus Pt thermocouples were obtained by extrapolation above 1063 °C and are estimated to be uncertain by 2 deg C at 1450 °C.

Since the 30–6 thermocouple is primarily intended for use in the range above 1063 °C, particular emphasis is placed upon the accuracy of the measurements in this range. Other tests, which are not described in this paper, were performed in hope of gaining more insight into the accuracy of the measurements. For example several 30–6 thermocouples were calibrated at the melting points of palladium (1552 °C) and platinum (1769 °C) by the wire method [10], and these calibrations differed from calibrations based upon comparison with an optical pyrometer by no more than about 1 deg C at the melting point of palladium and by no more than 2 deg C at the melting point of platinum. These differences were not considered unreasonable since the measurements by the wire method were estimated to be uncertain by about 1.5 deg C at the melting point of palladium and 2 or 3 deg C at the melting point of platinum. Several 30–6 thermocouples were also calibrated in a vertical "blackbody" furnace [11] at temperatures up to 1600 °C in an helium atmosphere and a different calibrated optical pyrometer was used to determine the temperature. These calibrations were in agreement with calibrations of the thermocouples performed in air in the Pt-Rh wire wound tube furnace to within about 2 deg C up to 1600 °C. In another test, a 30–6 thermocouple was calibrated by direct comparison with a calibrated Leeds and Northrup type 8640 photoelectric pyrometer in the range 1063 to 1555 °C. The thermocouple was heated in the Pt-Rh wire wound furnace. The difference between this calibration and a calibration of the thermocouple in the same furnace, but using the visual optical pyrometer to determine the temperature, varied from about 0.5 deg C at 1063 °C to about 1.5 deg C at 1555 °C.

After considering the capabilities of the standard instruments and test facilities used, the quality and stability of the thermocouples tested, and the results of the various tests performed, the uncertainties in the measurements that were used in calculating the reference table are estimated not to exceed ±2 μV in the range 0 to 450 °C and about ±3 μV in the range 450 to 1063 °C. The uncertainties in the measurements increased above 1063 °C and are estimated not to exceed the equivalent of about ±2 deg C at 1400 °C, and about ±3 or 4 deg C at 1750 °C. Furthermore, it is estimated that determinations of the emf of a particular 30–6 thermocouple at about 600, 1063, and 1300 °C by comparison with a standard Pt-10 percent Rh versus Pt thermocouple and at the melting point of palladium (1552 °C) by the melting wire method will be sufficient to construct a deviation curve from the reference table such that the resulting calibration will be accurate to within ±6 μV up to 1063 °C, the equivalent of about ±3 deg C up to 1550 °C, and the equivalent of about ±5 deg C above.

Calibration of other 30–6 thermocouples can then be determined rather easily by directly comparing them with a calibrated 30–6 thermocouple. In any event, calibration of 30–6 thermocouples by direct comparison with an optical pyrometer will generally prove undesirable, since the method is tedious, time consuming, and requires rather elaborate facilities and techniques. Also, actual calibration of the thermocouples above about 1600 °C seems undesirable in most instances, since it is likely to introduce some instability in the thermocouple and render it less reliable in use. Calibration values above 1600 °C can be obtained accurately by extrapolating the deviation curve.

Based upon the experience gained at NBS with the 30–6 thermocouple during the present studies, the following information is summarized for the thermocouple.

(1) Nearly all 30–6 thermocouples produced by manufacturers in this country will have temperature-emf relationships that agree with the temperature-emf relationship given by the reference table to within the equivalent of ±0.5 percent of the temperature in the range 500 to 1800 °C and to within ±15 μV for temperatures below 500 °C.

(2) Calibration of a particular 30–6 thermocouple at four points (about 600, 1063, 1300, and 1552 °C) will be sufficient to construct a deviation curve from the reference table such that the resulting calibration will be accurate to within ±6 μV up to 1063 °C, the equivalent of about ±3 °C up to 1552 °C, and the equivalent of about ±5 °C above.

(3) Actual calibration of the thermocouple above about 1600 °C is not recommended, since some instability may result in the thermocouple. Values above 1600 °C may be accurately determined by extrapolation.

(4) High purity alumina is recommended for insulation and protection of the thermocouple but caution should be exercised at temperatures above about 1600 °C for errors introduced by the electrical conductance of the insulators.

(5) The use of large diameter wires (at least 0.020 in.) and larger size insulating tubes is recommended for operating temperatures above 1500 or 1600 °C, so as to give the thermocouple added strength and to minimize errors due to electrical leakage.

(6) In most instances the reference junction temperature need not be controlled since the emf and thermoelectric power of the thermocouple at normal room temperatures are very small.

JOURNAL OF RESEARCH of the National Bureau of Standards—C. Engineering and Instrumentation
Vol. 66C, No. 1, January–March 1962

Reference Tables for 40 Percent Iridium-60 Percent Rhodium Versus Iridium Thermocouples*

G. F. Blackburn and F. R. Caldwell

(June 6, 1961)

In a program to establish reference tables for several alloys of iridium and rhodium against iridium, the work has been completed on 40 percent iridium-60 percent rhodium. Tables have been prepared giving emfs for temperatures in degrees Fahrenheit from 32 °F to 3,800 °F and in degrees Celsius (centigrade) from 0 °C to 2,100 °C, and temperatures in these units with emf in millivolts as the argument.

The emf is 11.6 millivolts at 3,800 °F. The thermoelectric power averages 3.1 microvolts per °F, and is within 0.1 microvolt of this value between 500 °F and 3,000 °F. It increases somewhat at temperatures above 3,000 °F.

Measurements at temperatures 32 °F to 2,500 °F were made in a platinum-wound furnace of conventional design, using a Pt-10 percent Rh versus Pt thermocouple to measure temperature. From 1,950 °F to 3,800 °F (thus overlapping the upper end of the lower range), the furnace used was an iridium block heated by electric induction. Blackbody conditions prevailed in the cavity in which the test thermocouple was inserted, and enabled measurement of the temperature with an optical pyrometer.

Good agreement between the data obtained in the overlapping parts of the platinum and optical pyrometer ranges (1,950 °F to 2,500 °F) established confidence in the temperature measurements with the optical pyrometer above 2,500 °F.

In both furnaces, helium surrounded the thermocouple junctions. The gas was dried by passing it through a trap immersed in liquid nitrogen.

Thoria and beryllia were used as thermal and electrical insulation in the high temperature range. While the electrical resistivity of these materials becomes relatively low at high temperatures, it did not become so low as to cause appreciable error in emf measurements. More serious was the introduction into the measuring circuit of a spurious emf, associated with the strong rf field and believed to be due to a rectifying property possessed by the insulators at high temperature. It was present in varying degrees, sometimes not at all. Its magnitude was determined by observing the (instantaneous) change in emf when the rf power was turned off, and the appropriate correction was made in the thermocouple emf measured with the power on.

The accuracy of the measurements is largely that associated with the measurement of temperature using an optical pyrometer. For the present work the maximum uncertainties in the range 2,500 °F to 3,800 °F are believed to range from about 8 °F to 12 °F.

1. Introduction

One of the earliest investigations of thermocouples of alloys of iridium and rhodium versus iridium was that made by Feussner [1].[1] His studies led him to suggest the alloy 40 percent iridium-60 percent rhodium for use with iridium. The increasing need in recent years for thermocouples capable of measuring temperatures higher than those at which platinum-rhodium versus platinum thermocouples can be used has led to further work on this combination [2], along with improvements in the metallurgy of these metals. In turn, the gradually increasing use of this and other iridium-rhodium alloys as thermoelements has given rise to the need for reference tables of the type available for platinum-rhodium versus platinum and other thermocouples [3].

The work reported here evolved from a project at the National Bureau of Standards originally sponsored by the United States Air Force, to examine thermocouples of alloys of iridium with 10 percent to 90 percent rhodium versus iridium. The tables (Appendix, I–A to IV–A) give the temperature-electromotive force values for 40 percent iridium-60 percent rhodium versus iridium, the first of the series to be completed.

2. Apparatus

Calibration up to 2,500 °F is accomplished in a high-temperature porcelain tube furnace having a bifilar platinum heating coil. The temperature is measured with a platinum-10 percent rhodium versus platinum thermocouple, calibrated prior to each run.

A blackbody is used to calibrate at higher temperatures. It is an iridium cylinder 1⅞ in. in diameter and 4$\frac{5}{16}$ in. long, with cavities as shown in figure 1.

---

*This paper was presented at the Fourth Symposium on Temperature, Its Measurement and Control in Science and Industry, Columbus, Ohio, March 27–31, 1961, sponsored by the American Institute of Physics, the Instrument Society of America, and the National Bureau of Standards. The proceedings will be published in book form by the Reinhold Publishing Corporation, New York, N.Y.

[1] Figures in brackets indicate the literature references at the end of this paper.

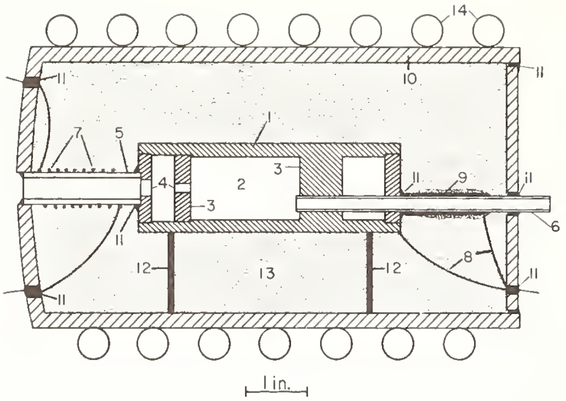


FIGURE 1. *Cross section of induction furnace.*

1, blackbody; 2, central cavity; 3, partitions; 4, sighting holes; 5, sighting tube; 6, thermocouple entrance tube; 7, heater winding; 8, ground wires; 9, iridium shield; 10, porcelain can; 11, thoria cement; 12, thoria supports; 13, thoria powder; 14, copper tubing.

Alined holes are provided in one end and the adjacent partition for inserting the thermocouple into the central cavity, and in the other end for sighting with the optical pyrometer which is used to measure the temperature. The area sighted upon is on the cavity wall opposite the ⅛-in. diameter hole in the partition at this end.

It is assumed that, owing to the design and method of heating the blackbody, the only departure from uniform temperature over the wall of the central cavity is that due to loss of heat by radiation through holes. This loss as calculated by a formula due to Gouffé [4] is about 0.2 percent, which is so small that it is unnecessary to correct observed temperatures on this account.

The blackbody is heated by electric induction with a 20 kw radiofrequency generator. A coil of iridium wire surrounds the sight tube and is connected externally to an rf ammeter and rheostat. The heat produced by rf current in the coil reduces the loss of heat from that end of the blackbody. A similar arrangement could be used at the thermocouple end; however, in an effort to provide shielding for the thermocouple wires and supporting tube, iridium wire was wound in a tight coil that formed a shield over the protection tube. Being heated by induction, this shield also serves to reduce the loss of heat by conduction along the thermocouple wires and supporting tube.

Preliminary experiments showed that it is necessary to ground the blackbody; this is done through an iridium wire welded to it. The shield just described is also grounded, but the thermocouple is not.

Thoria powder insulates the blackbody, which is supported centrally in a porcelain can 4 in. in diameter and 8 in. long by semicircular thoria disks. A coil of ⅜-in. copper tubing surrounding the porcelain can conducts the rf current and carries cooling water.

This assembly is placed with its axis horizontal on Pyrex glass supports in a box made of Transite and Plexiglas and having close fitting but not air tight joints. In use, helium flows into the box continuously at a rate judged sufficient to keep air out. The helium is cooled to the temperature of liquid nitrogen before it enters the furnace enclosure in order to remove water vapor and any other condensable impurities which may be present.

The emf is measured with Leeds and Northrop potentiometers, Models K2 and K3. An L. and N. No. 8622 optical pyrometer is used to measure temperature. Instead of using the temperature scale of the instrument, the temperature is obtained from calibration tables giving the temperature as a function of the current through the pyrometer lamp. A 2-ohm rheostat connected in series with the slide wire of the pyrometer increases the precision with which the lamp current can be adjusted to match the filament brightness with that of the blackbody. The lamp current is determined by measuring the voltage across a 1-ohm precision resistor in series with the lamp.

3. Thermocouples

The thermocouple wire was made by Sigmund Cohn Corporation. The first lot (A), obtained in 1955, was 0.035 in. in diameter. The second (B), obtained in 1959, consisted of 0.020- and 0.035-in. diam. wire. A third lot (D) of alloy wire only, acquired in 1960, consisted of wire sizes 0.020 in. and 0.030 in.

The data used in compiling the tables were obtained from a total of eight thermocouples—two from lot A, two from each wire size in lot B, and one from each size wire in lot D. The alloy wire of lot D was joined to iridium wire of lot B. The 0.030-in. alloy joined to 0.035-in. iridium wire formed one thermocouple, and the two 0.020-in. wires the other.

Each thermocouple was identified by a number indicating the lot of wire from which it was made, the percentage of rhodium in the alloy leg ("6," signifying 60 percent rhodium, is the only composition considered in this report), the wire diameter, and its order in a series of similar thermocouples. Thus A635a was thermocouple (a) from wire of lot A, 60 percent rhodium, 0.035 in. in diameter. Thermocouple (b) from the same coils of wire was A635b. The other six thermocouples were B620a, B620b, B635a, B635b, D620B, and D630B. In the last two, "B" signifies that the iridium leg was made from wire of lot B. In the remainder of this report, a particular thermocouple will be referred to by its number.

4. Experimental Procedure

In preparing a thermocouple the wires were annealed by heating them electrically in air. The manufacturer recommended annealing for about 1 min. at approximately 200 °C (360 °F) below the melting point. The temperature to be reached as observed with an optical pyrometer was estimated, taking the emissivity as 0.3, to be 3,460 °F for the iridium and 3,180 °F for the alloy wire [5]. In approaching these temperatures it was necessary to increase the current gradually, so that it was not unusual for several minutes to elapse while the temperature was being raised and pyrometric observations made. Measurement errors were comparatively large under these conditions, due in part to "smoke" that frequently appeared around the wires when they were heated to high temperature in air. For this and other reasons the actual temperature probably differred from those desired by as much as 100 °F.

The junction was welded in an oxyacetylene flame. Each thermocouple wire joined a copper wire in a bath of melting ice. The copper wires led to a potentiometer through a selector switch.

In working with the induction furnace an undesirably large rf voltage was induced on the thermocouple wires. Most of this was prevented from reaching the potentiometer by inserting a 1-mh choke in each lead between the reference junction and the potentiometer, and a 1-μf capacitor from the low potential end of each choke to ground.

Except for a few readings at intervals of 25 °F on lot A thermocouples at temperatures under 300 °F, the measurements were made at intervals of 50 °F.

The thermocouples were run first in the 2,500 °F furnace. They were supported in high-temperature porcelain tubes and immersed about 8 in. For these runs the test and the reference thermocouples were welded to form a common junction. This made it possible to compare one thermoelement with another, and the readings regularly included measurements of the emf between the iridium and platinum, and between the iridium-rhodium and platinum elements. Each reading consisted of two measurements of each desired emf, made in such sequence that the mean values were very nearly free from error due to the slight change in temperature which unavoidably occurred while the measurements were being made.

Thermocouples A635a and A635b were each run twice, both times at ascending temperatures. The others were each run once, readings being obtained first at ascending, then descending temperatures. The means of the two readings were taken as the experimentally determined temperature-emf relationship for the thermocouple. This applies also to measurements made in the induction furnace.

For calibrating in the induction furnace a thermocouple was supported in an insulating tube of thoria or beryllia. Experiments on the effect of depth of immersion showed that, to be free of error due to conduction of heat away from the junction, the thermocouple should extend not less than ¾ in. into the central cavity. The immersion was at least twice this distance.

In making a single observation, the heating rate was adjusted so as to maintain as nearly as possible constant temperature. Then one observer adjusted the current in the pyrometer lamp until the brightness of the filament was the same as that of the blackbody. Simultaneously another observer measured the thermocouple emf. A "reading" at a given temperature was taken as the mean of two observed values of filament current and corresponding emf.

Readings were made from 1,950 °F to 3,800 °F at intervals of 50 °F, and repeated in descending order.

5. Computations

The observed temperatures seldom differed more than 5 °F from the nearest integral multiple of 50 °F. For each observed temperature the emf was "normalized"—that is, it was computed for the nearest integral multiple of 50 °F. The rate of change of emf with temperature (dE/dT) required in normalizing was obtained either by direct calculation from observed differences or by plotting these differences and hand fitting a curve through the points.

The emf for lot A wire was taken as the mean of the normalized emfs for the two thermocouples made of that wire. Similarly, the emf for each of the two wire sizes in lot B was computed as the mean of the normalized emfs of the two thermocouples made from each of the two sizes of wires. To these emfs were added the normalized emfs obtained from lot D (one thermocouple from each of the two wire sizes). The average of these five sets of normalized emfs constituted the basic data for constructing temperature-emf tables.

These data, comprising 78 temperatures and the corresponding emfs, were processed by the Computation Section of the NBS Applied Mathematics Division using its IBM 704 Computer. It was found by trial that an equation of the fifth degree with coefficients computed to give a least-square fit to the data gave calculated emfs from which the experimental values differed by not more than 4 μv at temperatures up to 2,700 °F, and not more than 10 μv at temperatures between 2,800° F and 3,800 °F. These deviations were considered satisfactorily small; hence, using the equation so derived, the computer calculated emfs for temperatures in integral multiples of 10 °F from 40 °F to 3,800 °F. The machine-computed deviations were plotted and a smooth curve fitted to them by hand. From this curve the deviations for the 10 °F points were taken, and added to the emfs computed by machine to give table IV-A.

The table of emfs for temperature in integral multiples of 10 °C (table II-A) was interpolated by hand from the Fahrenheit table.

By hand interpolation the temperatures in degrees C and degrees F were obtained for emfs in steps of 0.1 mv from 0 to 11.6 mv. The computer interpolated within the 0.1-mv intervals to obtain temperatures at 0.01-mv intervals (tables I-A and III-A).

Thermal emfs for iridium versus platinum up to 2,500 °F were computed from measurements made in the course of the runs on the iridium-rhodium versus iridium thermocouples. The iridium came from three coils, viz, lot A and the two wire sizes of lot B. By applying corrections obtained from data on the emf of the platinum working standard versus platinum 27, the iridium versus platinum 27 values given in table V-A were obtained.

Thermal emfs for 40 percent iridium-60 percent rhodium versus copper and for copper versus iridium are given in table VI-A. This table may be used to correct for emfs generated at the junctions of the thermocouple legs with copper lead wires when these junctions are not at the same temperature.

6. Discussion

Not surprisingly, the emfs for a given temperature differed appreciably within the three lots of wire. One way of expressing the difference is to compare the individual emfs with the average, at a given temperature. For example, at 3,000 °F the emfs were as shown in table 1.

Table 1. *Deviation of the thermal emf of different lots of wire from the average, at 3000 °F*

Lot	Wire diam	emf E	Difference, $E-E_{av}$
	in.	*mv*	*μv*
A	0.035	8.830	—31
B	.020	8.909	48
B	.035	8.862	1
D	.020	8.864	3
D	.030	8.842	—19
Average		8.861	

Here the lowest emf was for lot A and the highest the 0.020-in. wire of lot B. The difference is 79 μv, which corresponds to about 24 °F.

Similar data are plotted for the entire range of temperatures in figure 2. Differences shown there are not wholly attributable to the different sources of wire involved, since there were naturally differences in emf between thermocouples made of wire from the same coil. In most cases these differences were only a few microvolts, but in one case, the 0.20-in. wire of lot B, the two thermocouples gave emfs differing by as much as 36 μv, corresponding to about 12 °F.

Figure 3 is a plot, for iridium wire from the three sources (lot A, and the two sizes in lot B) versus platinum 27, of the differences between individual values and the adjusted [6] average of the three. An emf on this graph is a measure of the contribution of the iridium in question to the analagous difference shown in figure 2 for the iridium-rhodium versus iridium thermocouple of which it is an element. For if, of two iridium wires making a common junction with an iridium-rhodium and a platinum wire, one has a higher emf to platinum than the other, its emf to the alloy wire must be lower by the same amount numerically. The reasoning can easily be extended to apply to the difference from the average (the ordinates of figs. 2 and 3). Thus it is evident that the lower emf of a thermocouple of lot A as compared with one from another lot is largely accounted for by the fact that the iridium wire of

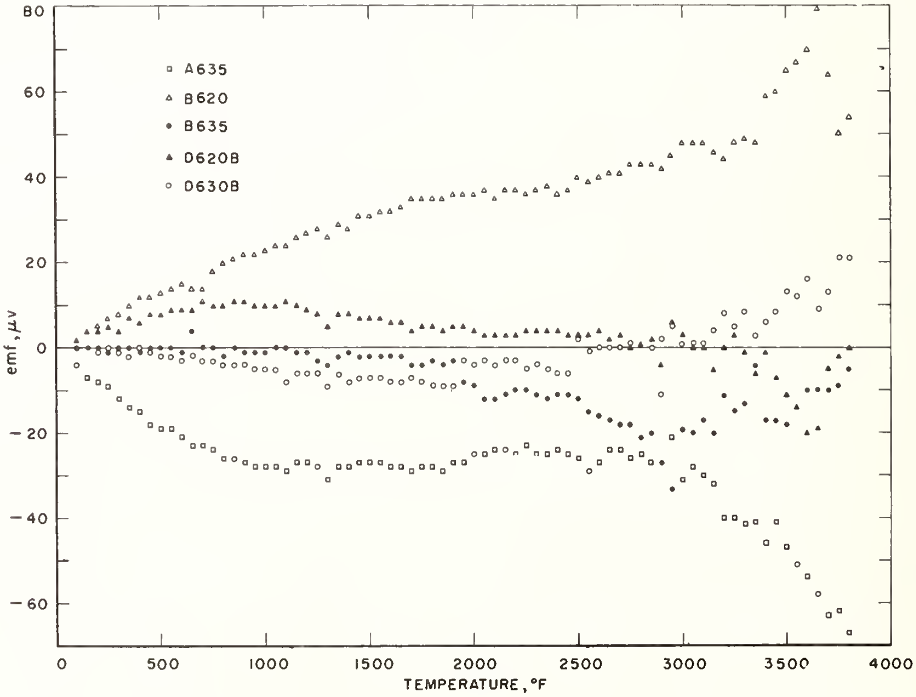


Figure 2. *Difference between the emf of each thermocouple and the average emf for 40% Ir 60% Rh versus Ir thermocouples.*

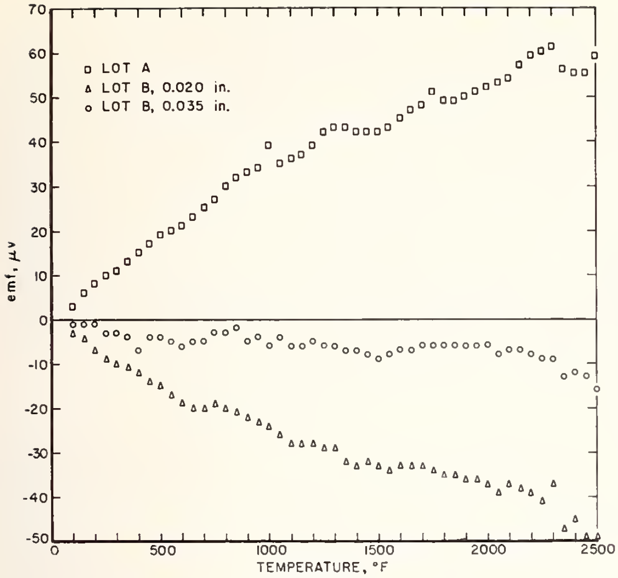


Figure 3. *Difference between the emf of each lot and size of Ir wire and the average emf for Ir versus Pt 27.*

this lot had a higher emf to platinum than did either of the other two coils of iridium wire. A similar situation prevails with respect to the 0.020-in. iridium wire of lot B. However, this wire was also used in D620B, and the differences between the emfs of figure 2 for thermocouples B620 and D620B are of course due to the differences between the two alloy wires used. These differences can be, and were, measured directly.

In the range 1,950 °F to 2,500 °F, where temperatures were measured both with the platinum-10 percent rhodium thermocouple (in the platinum-wound furnace) and with the optical pyrometer (in the induction furnace), the difference between emfs of the test thermocouples did not exceed 6 µv in most cases. This is little if any larger than the errors of observation, and gave added assurance that the measurements were free from significantly large systematic errors. The largest difference occurred on thermocouple B635b: The emfs with the optical pyrometer averaged 21 µv higher than with the platinum thermocouple. This corresponds to about 7 °F, and is larger than the reading error. The data yielded no clue as to what caused the difference.

The thermoelectric power is nearly constant over a wide range of temperature, having a value of 3.0 to 3.2 µv per degree from about 600 °F to 3,200 °F. Below 600 °F it decreases to about 2 µv per degree at 100 °F, and above 3,200 °F it increases to about 3.6 µv per degree at 3,800 °F.

The uncertainty in the temperature-emf values is partly that associated with measuring the temperature with a thermocouple and with an optical pyrometer. For the platinum-10 percent rhodium versus platinum thermocouple the uncertainty is about one degree at 2,000 °F and 3 degrees at 2,500 °F [7]. For the optical pyrometer the uncertainty was minimized by carefully calibrating the instrument in terms of lamp current and by adjusting this current precisely in the photometric matching. This procedure together with favorable blackbody conditions probably limited the uncertainty to 5 or 6 degrees at 3,800 ° F.

The increased electrical conductivity of insulators at high temperature contributes to the uncertainty of the emf measurements at temperatures above about 3,200 °F. When the thoria tubes which were used at first to support the wires in the induction furnace exhibited lowered resistance they were replaced with beryllia, which has higher resistivity than thoria [8]. Even so, the resistance between thermocouple wires (as determined in a test made with the wires unjoined) decreased to a few tens of ohms at 3,800 °F. The magnitude of error due to insulator conduction depends on the resistance of the insulator as compared with the resistance of the thermocouple wires between points where they effectively make electrical contact with the insulator. For example, for wire resistance 0.1 ohm between points of contact, an insulator resistance of 100 ohms would cause the observed emf of the thermocouple to be 0.1 percent lower than the actual emf. The available data yield an estimated uncertainty of this order, which at the highest temperature would amount to about 4 °F. Since this conductivity effect is believed to have occurred in a largely fortuitous manner, no correction has been made for it.

An effect was associated with the electrical conduction in the ceramic insulation which manifested itself in the superposition of a spurious emf on the thermal emf due to the presence of the strong rf field. This was thought to result from a rectifying process. It was not always present, but when it was, readings were obtained that were larger or smaller than the thermal emf by as much as 100 µv. Its magnitude was ascertained by turning off the power and observing the instantaneous change in galvanometer deflection, which occurred before an appreciable change due to cooling took place. The readings were corrected by the appropriate amount. We believe that loss in precision arising from this effect was held to a few microvolts by the means adopted to correct for it.

The combined uncertainties are believed not to exceed 12 °F.

The wires were discolored somewhat after a test. Although they were embrittled as a result of heating, and evidently had undergone considerable recrystallization, their thermoelectric properties were not changed appreciably. This was evidenced by good agreement of emfs measured in the low temperature range after a high temperature calibration.

The temperature-emf relationship for 40 percent iridium-60 percent rhodium versus iridium thermocouples is plotted in figure 4 for temperatures 2,000 °F to 3,800 °F, along with the thermal emfs of several other thermocouples useful in this range, all having

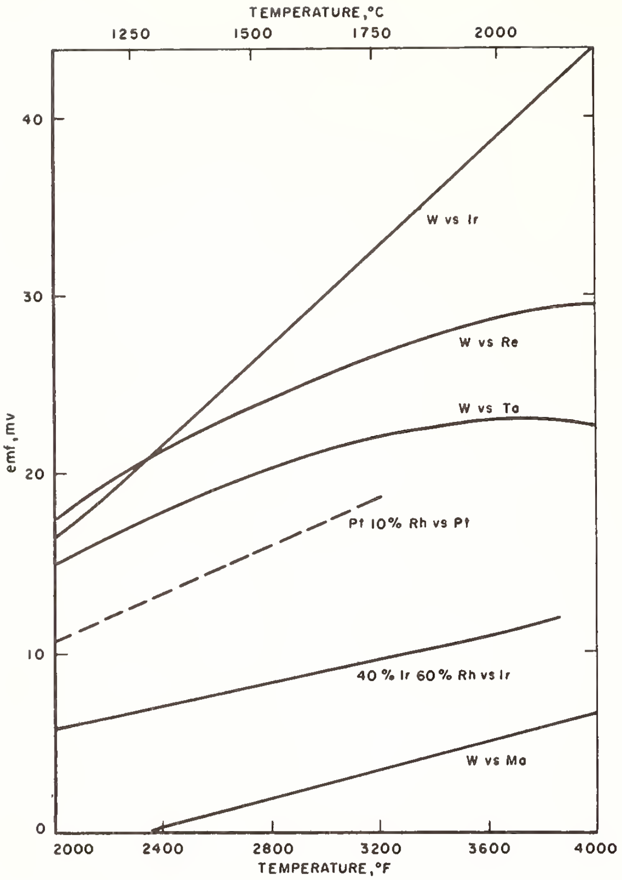


FIGURE 4. *Thermal emf of several thermocouples in the range 2,000 °F to 4,000 °F.*

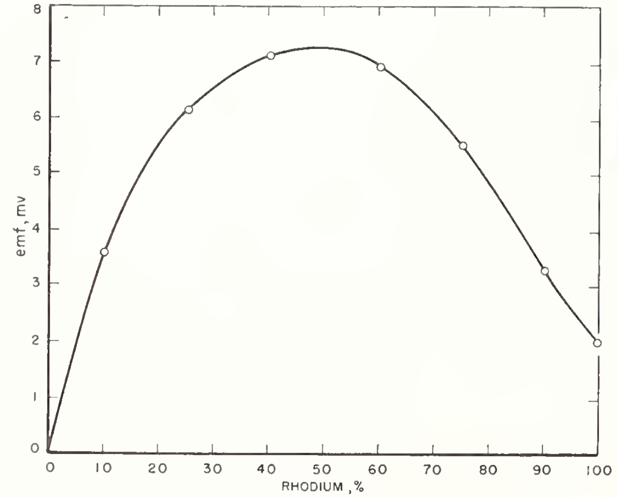


FIGURE 5. *Change of thermal emf of Ir-Rh versus Ir thermocouples with composition of the alloy, at 2,400 °F.*

tungsten as an element. The data on tungsten versus iridium are from Troy and Steven [9]. For tungsten versus rhenium the data were obtained from Lachman [10], for tungsten versus molybdenum from Potter and Grant [11], and tungsten versus tantalum from Sanders [12]. The emf is also plotted for platinum-10 percent rhodium versus platinum [3].

Some data have been obtained at NBS on the effect of varying the percent rhodium in the alloy leg. They have thus far been limited to temperatures at which a platimun-rhodium versus platimun thermocouple can be used to measure the temperature. These data are plotted for one temperature, 2,400 °F, in figure 5.

The authors thank J. F. Swindells and Henry Kostkowski for permission to use the facilities of the Temperature Physics Section of the NBS Heat Division, and for their helpful interest in the work; also, to Ronald C. Gordon and D. B. Thomas for calibrating, respectively, the optical pyrometer and platinum-rhodium versus platinum thermocouple used.

They are also indebted to G. M. Galler and B. S. Prush of the Computation Section of the NBS Applied Mathematics Division for their help in arranging the data for processing by the IBM 704 Computer.

7. References

[1] O. Feussner, New noble-metal thermoelements for very high temperatures (in German), Elektrotech. Z. **54**, 155 (1933).

[2] C. R. Droms and A. I. Dahl, Iridium vs iridium rhodium thermocouple for gas temperature measurements up to 3500 °F, General Electric Company Report No. R54GL314 (Nov. 19, 1954).

[3] Henry Shenker, John I. Lauritzen, Jr., Robert J. Corruccini, and S. T. Lonberger, Reference tables for thermocouples, Natl. Bur. Standards (U.S.) Circ. **561** (1955).

[4] A. Gouffé, Opening corrections of artificial blackbodies computed on the basis of multiple internal diffusion (in French), Rev. optique **24**, 1 (1945).

[5] Paul D. Foote, C. O. Fairchild, and T. R. Harrison, Pyrometric practice, Tech. Pap. BS **14** (1921).

[6] The averages as computed were adjusted by inspection to smooth the differences corresponding to 50 °F. The change did not exceed 3 microvolts in most cases.

[7] W. F. Roeser and S. T. Lonberger, Methods of testing thermocouples and thermocouple materials, Natl. Bur. Standards (U.S.) Circ. 590 (1958).

[8] I. E. Campbell, High temperature technology (Wiley, 1956), p. 58.

[9] W. C. Troy and Gary Steven, The tungsten iridium thermocouple for very high temperatures, Trans. Am. Soc. Metals **42**, 1131 (1950).

[10] J. C. Lachman, Calibration of rhenium molybdenum and rhenium tungsten thermocouples to 4000 °F, Report APEX 365, General Electric Company, Atomic Products Division (1958).

[11] R. D. Potter and N. J. Grant, Tungsten molybdenum thermocouples, Iron Age **163**, 65 (March 31, 1949).

[12] V. D. Sanders, Review of high-temperature immersion thermal sensing devices for in-flight engine control, Rev. Sci. Instr. **29**, 917 (1958).

JOURNAL OF RESEARCH of the National Bureau of Standards—C. Engineering and Instrumentation
Vol. 66C, No. 3, July–September 1962

A Furnace for Thermocouple Calibrations to 2,200 °C

Douglas B. Thomas

(February 26, 1962)

A tantalum-tube furnace has been constructed to calibrate and investigate the thermoelectric behavior of high-temperature thermocouples. The furnace and its associated equipment were designed with emphasis on features that would assure a high degree of accuracy in measurements that are made at high temperatures and also with emphasis on trouble-free performance. Data that were obtained during furnace operation showed that thermocouple depth of immersion into a properly designed blackbody is of considerable importance if good agreement is to be realized between a calibrated optical pyrometer and a calibrated thermocouple that has been placed in the hot zone of the furnace. High-purity helium gas can be used in the furnace to keep thermocouple contamination to a minimum.

1. Introduction

Furnaces consisting of a single metal tube which is heated to temperatures as high as 3,000 °C have been reported in the literature [1, 2, 3, 4, 5].[1] Although all of these furnaces have the same basic design, each has minor modifications that adapt it to a particular type of high-temperature work. Nadler, Runyan, and Kempter [1], for example, designed a furnace with emphasis on its ability to operate in a vacuum or in an inert or reducing gas up to a pressure of 100 atm. The furnaces described by Sims, Gaines, and Jaffee [4] and by Lachman and Kuether [5] were designed specifically for thermocouple calibrations.

Some of the features that are essential in the design of a high temperature[2] thermocouple calibrating furnace are, (1) The thermocouple should be freely suspended in the hot zone of the furnace. Any obstructions along the entrance path into the furnace would require undesirable bending of the thermocouple wires and could conduct heat away from the wires which might result in an erroneous calibration. Also, any materials that are placed in contact with the thermocouple at high temperatures could bring about solid state reactions between the thermoelements and these materials with resulting local diffusional contamination of the thermoelements. (2) The measuring junction of the thermocouple should be contained in a blackbody enclosure with provisions for viewing the radiation emanating from the enclosure. This arrangement is essential since the International Practical Temperature Scale of 1948 above 1,063 °C is defined in terms of blackbody radiation [6]. If this blackbody radiation is observed with a calibrated optical pyrometer [7], the temperature of the measuring junction of the thermocouple can be accurately determined. However, if the radiation in the vicinity of the thermocouple measuring junction is not blackbody radiation, an emissivity correction must be applied to the optical pyrometer readings. In many cases, emissivity corrections cannot be accurately determined. (3) The temperature profile along the thermocouple wires should be as follows: The measuring junction and a specific length[3] of the thermocouple wires leading directly from the junction should be in a region of uniform temperature. Without this temperature uniformity, it is likely that a significant amount of heat will be conducted away from the measuring junction along the thermocouple wires thus causing the thermocouple to indicate a temperature which is lower than its environment. From this uniform temperature region to the water cooled shell of the furnace, the temperature should decrease uniformly with no sharp temperature gradients existing at or near the thermocouple wires. Freeman [8] observed significantly large differences in the emf developed by thermocouples when the thermocouple wires were subjected to extreme gradients from the emf developed by the same thermocouples under normal gradient conditions. (4) At temperatures in the 2,000 °C region (and higher), a furnace should be designed to allow the thermocouple to be suspended free from any electrically insulating or supporting materials in the hot zone. The electrical resistivity of known available materials in this temperature range becomes quite low and can give rise to a short circuiting effect between the thermocouple wires. (5) The furnace design should be such that all internal parts can be easily out-gassed or baked out in order to maintain a high vacuum or clean atmosphere during calibration runs. If calibrations are performed in an inert atmosphere, the inert gas that is used should be of research grade quality. Some inert gases of "commercial grade" quality have relatively large percentages of impurities and these impurities can have a serious effect on the physical and chemical properties of a thermocouple at high temperatures. Refractory oxides should be eliminated from the interior of the furnace wherever possible since such materials usually continue to out-gas for long periods of time. (6) The thermal inertia of the furnace

---

[1] Figures in brackets indicate the literature references at the end of this paper.
[2] High temperature meaning between 1,000 and 3,000 °C.
[3] The length of the thermocouple wires that should be at a uniform temperature depends primarily upon the diameter of the wires. The length that is needed for 0.020 in. diam wires is discussed later in this paper.

should be such that any desired temperature can be reached in a relatively short time. When a desired temperature has been reached, thermal stability throughout the furnace should prevail shortly thereafter.

2. Furnace

A high temperature tantalum tube furnace has been built at the National Bureau of Standards to investigate and calibrate thermocouples and thermocouple materials at temperatures up to 2,200 °C. In constructing the furnace considerable emphasis was placed on a design that would entail all of the above mentioned features. The heater in the furnace is a seamless tantalum tube[4] with an outside diameter of 1.0 in., a wall thickness of 0.020 in. and an overall length of 18.25 in. Its electrical resistance is 0.0022 ohm at room temperature and 0.0126 ohm at 2,200 °C. A thermal expansion joint (15, fig. 1) was made in the upper section of the tube by cutting the tube lengthwise into six sections and then spreading the sections to form wedge-shaped "arms." Both the upper and lower tantalum rings (14 and 32, fig. 1) were "electron beam" welded to the ends of the tantalum tube. The lower tantalum ring is bolted to a water-cooled square copper plate (33, fig. 1) which contains an O-ring gasket on the underside. By removing the bottom plate bolt (34, fig. 1), the tantalum tube and top plate can be removed from the furnace shell.

In the initial design of the furnace, it was calculated that blackbody conditions would prevail inside of the tantalum tube at the level of the sighting hole (28, fig. 1) provided that a tantalum tube was selected with proper dimensions. In order to evaluate this calculation a calibrated Pt 6 percent Rh versus Pt 30 percent Rh thermocouple was placed inside of the tantalum tube with its measuring junction at the level of the sighting hole. A standard Pt versus Pt 10 percent Rh thermocouple was not used in this instance since the platinum element showed various degrees of instability which was probably due to tantalum or molybdenum vapor contamination. A considerable amount of data was taken at temperatures in the 1,000 to 1,200 °C range in which the calibrated thermocouple emf readings and the calibrated optical pyrometer[5] readings were made simultaneously. The data showed that the temperature indicated by the thermocouple was from 4 to 5 deg lower than the temperature indicated by the optical pyrometer. Comparisons between the calibrated thermocouple and the optical pyrometer at temperatures above 1,200 °C were not made since there was no readily available method for calibrating a thermocouple above this temperature to an accuracy better than ±1.0 deg C. A good agreement between the thermocouple and the optical pyrometer in a furnace of this type is extremely important at lower temperatures (1,000 to 1,200 °C) since a discrepancy of 4 or 5 deg C may increase to 10 or 15 deg C at temperatures in the 2,000 °C region.

To make certain that this 4 to 5 deg C discrepancy was not due to calibration errors in the optical pyrometer, a careful calibration check was made between the optical pyrometer in question and the Fairchild optical pyrometer[6] at NBS. About a half dozen observations were made by each of several experienced observers on both instruments and the average of their observations showed that the two optical pyrometers agreed within 0.2 deg at 1,170 °C. This eliminated the possibility of a sufficiently large calibration error in the optical pyrometer in question. In addition, the Pt 6 percent Rh versus Pt 30 percent Rh thermocouple that was used was recalibrated to determine whether the discrepancy could have resulted from a calibration change in the thermocouple. The second calibration indicated a thermocouple emf change of less than 0.3 deg at 1,100 °C. It was therefore concluded, contrary to initial calculations, that either blackbody conditions did not prevail inside of the tantalum tube or that the thermocouple indicated a lower temperature because of heat loss upward from the thermocouple measuring junction.

In order to resolve this discrepancy, it was felt that a separate blackbody cavity contained within the central portion of the tantalum tube might be a possible solution to the problem. This blackbody cavity would provide a longer isothermal region in the vicinity of the thermocouple measuring junction. Blackbody cavities of various shapes and dimensions were fabricated and placed inside of the tantalum tube for evaluation in the 1,000 to 1,200 °C range. A molybdenum blackbody (fig. 2) in the shape of a cylinder crucible containing a thorium oxide lid was found to bring about the best agreement between the thermocouple and the optical pyrometer. The thorium oxide lid serves to electrically insulate the thermocouple wires from the walls of the molybdenum blackbody at low furnace temperatures. As it was stated in the introduction, the resistivity of insulating materials becomes quite low at temperatures above 2,000 °C and thorium oxide is not an exception. However, if the thermocouple wires come in contact with the thorium oxide lid at temperatures above 2,000 °C, there is an immediate indication of a partially rectified a-c voltage[7] on the galvanometer in the emf measuring circuit. When this occurs the thermocouple wires can be manually repositioned (through the thermocouple wire seals) until the wires hang freely in the center hole of the thorium oxide lid. The molybdenum blackbody is supported inside of the tantalum tube by four tungsten wires (0.030 in. diam) that are attached to the top plate of the furnace. The uniqueness of this design is that as the

---

[4] The tube was obtained from the Fansteel Metallurgical Corporation, North Chicago, Ill.

[5] The optical pyrometer used in this work was a modified commercial optical pyrometer that was calibrated on a basis of temperature versus optical pyrometer lamp current. A higher accuracy can often be realized with an optical pyrometer calibrated and used in this manner [7].

[6] The NBS Fairchild optical pyrometer, also referred to in the literature [7] as "The NBS Optical Pyrometer" is a high precision instrument designed by C. O. Fairchild of NBS and is used at NBS for testing other optical pyrometers and pyrometer lamps submitted for calibration.

[7] The a-c voltage applied to the furnace heating element is partially rectified by the thorium oxide.

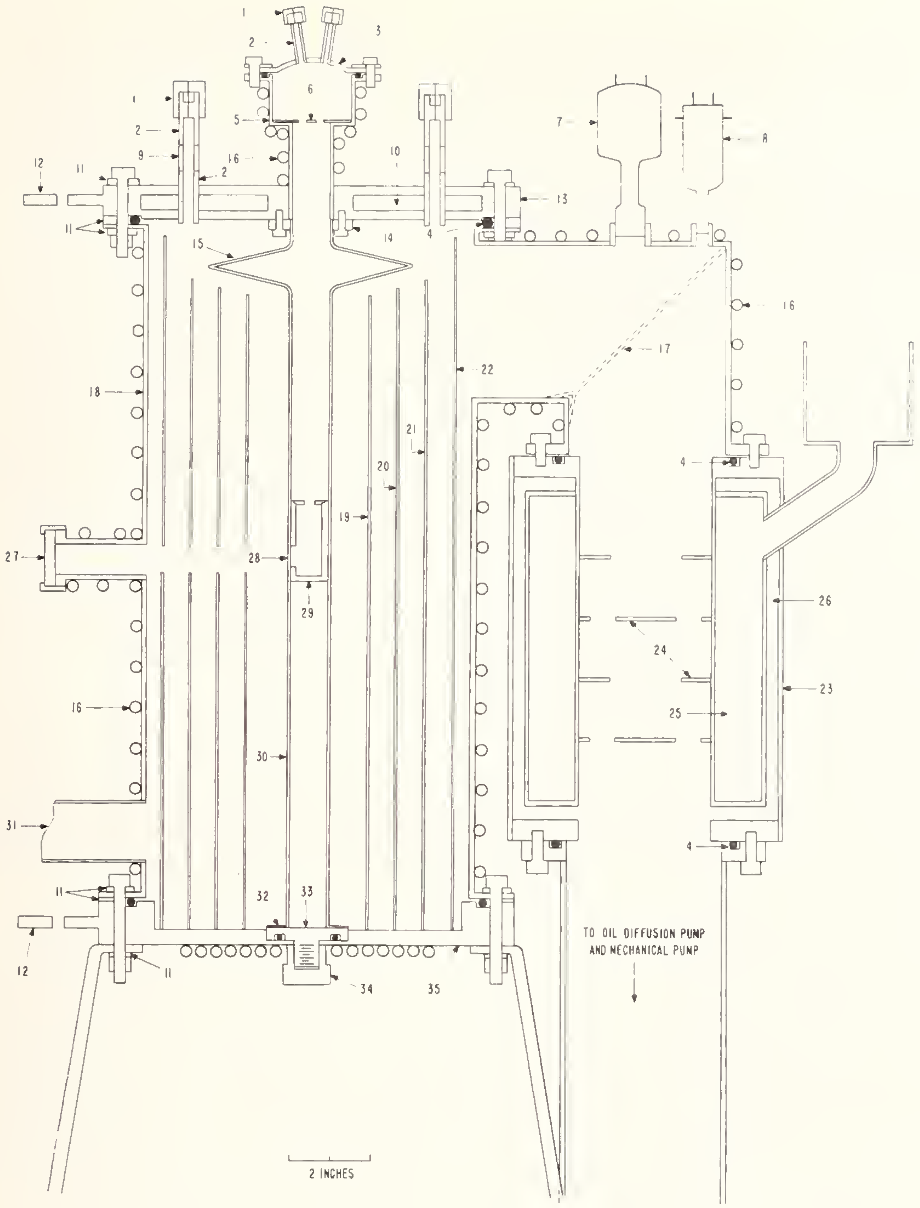


Figure 1. *Tantalum-tube furnace.*

1. Caps for making vacuum tight seals around thermocouple wires. A cylinder type neoprene gasket is compressed around thermocouple wires.
2. Kovar metal tube.
3. Dome made of #7052 glass providing electrical insulation for thermocouple elements.
4. Neoprene O-ring gasket.
5. Top plate extension (brass).
6. Aluminum oxide radiation shield.
7. Ionization vacuum gage.
8. Thermocouple vacuum gage.
9. 7052 glass tube providing electrical insulation for thermocouple elements.
10. Chamber for water flow during furnace operation.
11. Electrically insulating spacers.
12. Power supply terminal.
13. Removable top plate (brass).
14. Tantalum spacing ring providing electrical contact between top plate and tantalum tube.
15. Thermal expansion joint of tantalum tube.
16. Copper tubing for water cooling.
17. Auxiliary radiation shield.
18. Furnace shell (brass).
19. First radiation shield. 0.020 in. tantalum sheet rolled into a cylinder and secured with tantalum rivets.
20. Second radiation shield. (0.020 in. molybdenum.)
21. Third radiation shield. (0.020 in. molybdenum.)
22. Fourth radiation shield. (0.010 in. molybdenum.)
23. Liquid nitrogen trap.
24. Metal baffle plates at liquid nitrogen temperature.
25. Liquid nitrogen chamber.
26. Vacuum chamber.
27. Pyrex glass window.
28. Hole (0.045 in. diam) for sighting with optical pyrometer.
29. Molybdenum blackbody.
30. Tantalum tube.
31. Inert gas entrance.
32. Tantalum rings for electrical contact.
33. Removable copper plate for electrical contact.
34. Hex-head nut for tightening copper plate again O-ring gasket
35. Bottom plate (brass).

temperature of the furnace is increased or decreased, the thermal expansion or contraction of the tungsten support wires and of the thermocouple wires is nearly equal and thus the depth of immersion of the thermocouple into the blackbody remains nearly constant.

The data obtained with this molybdenum blackbody indicate that at least 2 in.[8] of the thermocouple at the measuring junction end must be contained within the blackbody to obtain good agreement with the optical pyrometer. With a thermocouple immersion of 2 in. into the molybdenum blackbody, the differences observed between the calibrated thermocouple and the optical pyrometer were 0.4 deg at 1,000 °C, 0.3 deg at 1,100 °C, and 0.3 deg at 1,200 °C. These figures represent an average of many observations made at the respective temperatures and are well within the combined estimated uncertainties of the thermocouple and the optical pyrometer.

A thermocouple that is to be calibrated in the furnace against the optical pyrometer is suspended from two thermocouple wire seals (1, fig. 1) directly above the tantalum tube. The thermocouple hangs freely inside of the tantalum tube with its measuring junction at the level of the sighting hole. The only material in contact with the thermocouple wires is an aluminum oxide disk (6, fig. 1) which serves as a radiation shield. The thermocouple wires are threaded through two holes in this disk. Since the aluminum oxide disk is small in size and remains relatively cool during furnace operation, its out-gassing or contaminating effects are negligible. Auxiliary thermocouple seals (1, fig. 1) are located in the top plate of the furnace. Thermocouples or thermoelements can be brought into the furnace through these seals and held mechanically on the outside of the tantalum tube near the level of the sighting hole. If thermocouples are placed outside of the tantalum tube, the three inner radiation shields (19, 20, and 21, fig. 1) are removed from the furnace and a different set of shields is used. The top plate contains a total of six auxiliary seals through which three thermocouples or six thermoelements can be brought into the furnace with all of the elements fused at one common junction. This arrangement of six auxiliary seals is useful if two test thermocouples are to be compared or calibrated against a standard thermocouple. The arrangement is also useful if six thermoelements of the same type are to be statistically compared one against another. In the latter example, the exact temperature of the junction of the thermoelements need not be known.

Thermocouples can be calibrated in the furnace either in a high vacuum or in a purified inert atmosphere. Once the internal parts of the furnace have been out-gassed and the liquid nitrogen trap is put to use, a vacuum in the order of 0.1 to 0.01 μ of mercury can be maintained when all parts of the furnace are at room temperature. When the furnace is operating at a high temperature, a vacuum of between 1 and 10 μ of mercury can be obtained by continually pumping on the system and by using the liquid nitrogen trap and oil diffusion pump. A purified inert gas can be released into the furnace chamber through the inert gas inlet (31, fig. 1).

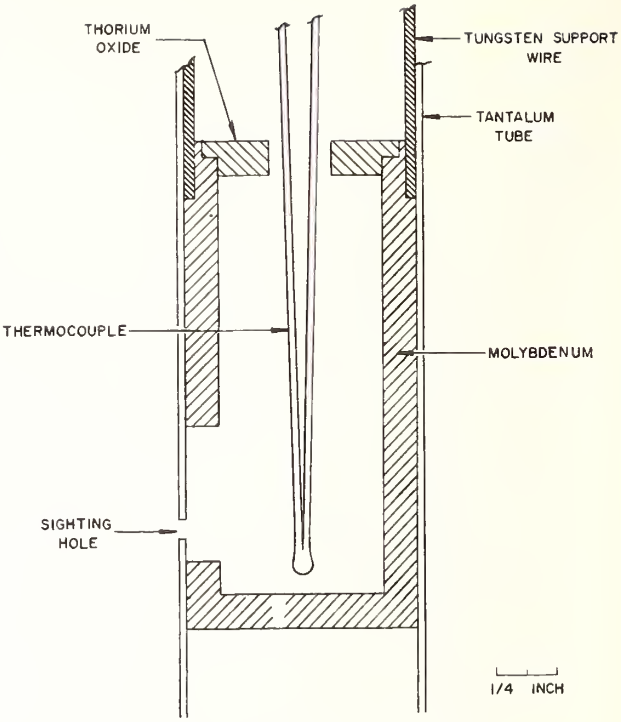


FIGURE 2. *Molybdenum blackbody.*

3. Inert Gas Purifiers

The emf developed by a thermocouple is directly related to the chemical composition and metallurgical structure of its elements. If an inert gas that is used in a thermocouple calibrating furnace contains impurities, the hot thermocouple elements may have an affinity for these impurities and consequently the chemical composition and metallurgical structure of the thermocouple may be affected. If the thermocouple is affected by these impurities, it will exhibit an asymptotic drift in emf as long as it remains in this environment. For this reason, two inert gas purifiers (fig. 3) are included as auxiliary equipment for the tantalum tube furnace. The major impurities in commercially obtained helium are oxygen, hydrogen, and nitrogen with perhaps small amounts of carbon dioxide and carbon monoxide. According to Richardson and Grant [9] large amounts of oxygen and nitrogen are absorbed by titanium metal between 800 and 1,000 °C. Likewise, zirconium metal between 300 and 400 °C will absorb large quantities of hydrogen and oxygen as reported by Gulbransen and Andrew [10]. Thus, one purifier containing titanium metal chips and one containing zirconium metal chips are used to purify the inert gas used in the furnace. The use of an inert gas of

---

[8] This is the case for a thermocouple wire diameter of 0.020 in.

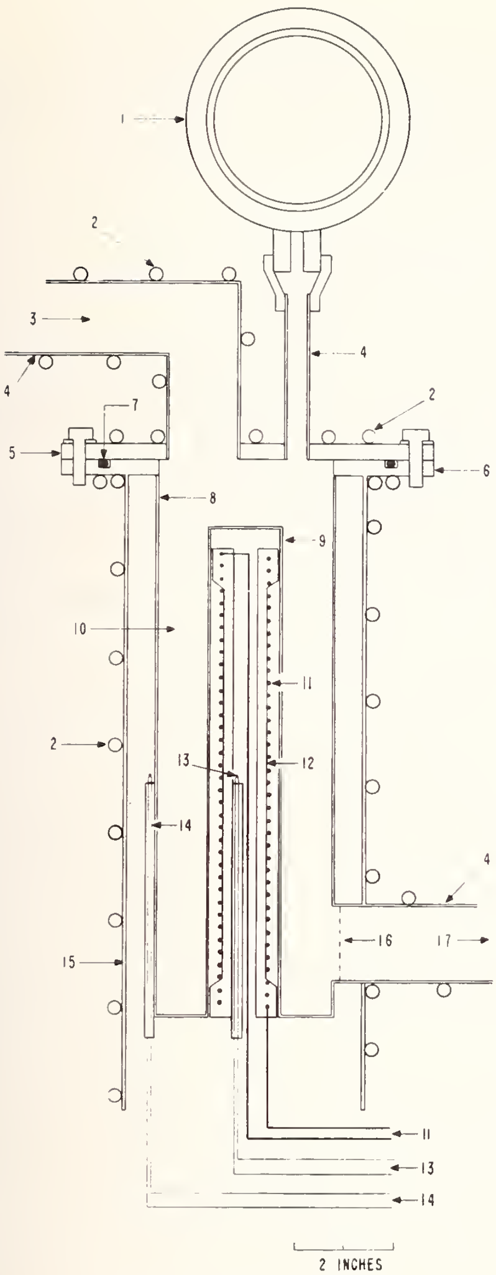


Figure 3. *Inert gas purifier*

1. Pressure-vacuum gage.
2. Copper water-cooling coils.
3. Inert gas entrance.
4. Stainless steel tubing.
5. Stainless steel top plate.
6. Stainless steel flange.
7. Neoprene O-ring gasket.
8. Outer wall of stainless steel tank.
9. Inner wall of stainless steel tank.
10. Chamber for titanium or zirconium chips.
11. Chromel-A 18 AWG heater winding.
12. Threaded aluminum oxide tube.

13, 14. Chromel-alumel or platinum-platinum 10 percent rhodium thermocouple.

15. Brass outer shell.
16. Stainless steel screen.
17. Inert gas exit.

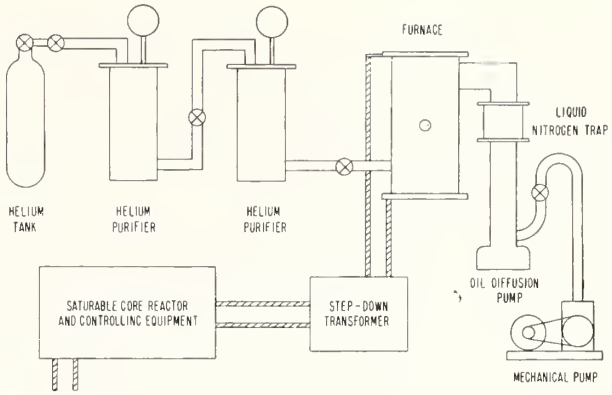


Figure 4. *Furnace and associated equipment.*

high purity also serves in maintaining a longer life for the tantalum heating element. For economic reasons helium was chosen to be used in this application. According to the manufacturer, the purity of the helium before it enters the two purifiers is 99.99 percent.

The two inert gas purifiers are connected in series (fig. 4) such that the gas entering the first purifier also passes through the second purifier before entering the furnace chamber. It can be seen that the inert gas is given a "double treatment" as far as oxygen removal is concerned. In most calibrations where the thermocouples are to be heated in a helium atmosphere, a quantity of helium is allowed to remain in each purifier from 3 to 6 min with the titanium and zirconium chips at optimum temperatures for the removal of impurities. In an application where high purity is not of the essence, the inert gas can flow through the purifiers at a slow rate.

4. Furnace Power Supply

Electrical power is supplied to the tantalum tube furnace through a 30 kva saturable core reactor and a step-down transformer of 12:1 ratio. Input voltage to the reactor is 200 v at 60 cycles, single phase. A modified commercial controller is used to manually select a voltage that is needed to maintain a specific furnace temperature. Once this voltage has been selected (by varying a 0 to 5 ma d-c current) the controller automatically maintains that voltage to within a close tolerance via a feedback signal from the transformer primary winding. With a stable supply voltage, the furnace temperature is held very nearly constant for reasonably long periods of time. However, since a thermal sensing device is not incorporated in this type of automatic control, it is necessary to maintain a steady flow of water to the furnace for cooling purposes. If the flow rate is not constant, noticeable temperature fluctuations may result.

During some of the initial test runs, the furnace was allowed to stabilize at a given temperature for 30 min and then the temperature fluctuations over a 10-min interval were observed with a thermocouple placed inside of the tantalum tube with the measuring junction in the molybdenum blackbody. The maximum fluctuations deduced from thermocouple readings during the 10-min interval were 0.2 deg at 1,140, 0.5 deg at 1,510, and 4.2 deg at 2,115 °C. The fluctuations at 2,115 °C were decreasing with respect to time at the end of the 10-min interval and were partly attributed to thermocouple instability resulting from inadequate annealing of the thermocouple. If the thermocouple had been allowed to anneal at the high temperature for a longer period of time, the fluctuations would have been less. Starting from room temperature, a furnace temperature of 2,200 °C can be obtained in less than 5 min. However, this fast heating rate is rarely brought about during thermocouple calibrations since a longer period of time is needed to bring about thermal stability. A power of approximately 17 kw is required to maintain a furnace temperature of 2,200 °C.

The author acknowledges the contributions made by R. J. Corruccini, National Bureau of Standards, Boulder, Colo., in the design of various parts of the furnace.

5. References

[1] M. R. Nadler, J. E. Runyan, and C. P. Kempter, Report LAMS-2393, Los Alamos Laboratory of the Univ. of California.

[2] K. B. Alherman, J. Sci. Instr. **27,** 280 (1950).

[3] F. H. McRitchie and N. N. Ault, J. Am. Ceram. Soc. **33,** 25 (1950).

[4] C. T. Sims, G. B. Gaines, and R. I. Jaffee, Refractory metal thermocouples containing rhenium, Battelle Memorial Inst., Columbus, Ohio.

[5] J. C. Lachman and F. W. Kuether, Stability of rhenium-tungsten thermocouples in a hydrogen atmosphere, Instr. Soc. Am. J. **7,** 3 (1960).

[6] H. F. Stimson, The International Practical Temperature Scale of 1948, J. Research NBS **65A,** 3 (1961).

[7] H. J. Kostkowski and R. D. Lee, Theory and methods of optical pyrometry, NBS Monograph No. 41 (1962).

[8] R. J. Freeman, Distributed Seebeck effect at high temperatures, Proc. High Temp. Thermometry Seminar. AEC Oak Ridge, October 1959.

[9] L. S. Richardson and N. J. Grant, Trans. Am. Inst. Min. Met. Engrs. **200,** 69 (1954).

[10] E. A. Gulbransen and K. F. Andrew, Kinetics of the reactions of zirconium with oxygen, nitrogen and hydrogen, Trans. Am. Inst. Min. Met. Engrs. **185,** 515 (1949).

(Paper 66C–101)

Reprinted from *Cryogenics* Volume 1, No. 3. Heywood & Company Ltd. 1961

Low Temperature Thermocouples—I. Gold-Cobalt or Constantan versus Copper or 'Normal' Silver

R. L. Powell, M. D. Bunch, and R. J. Corruccini
National Bureau of Standards, Boulder, Colorado

Received 1 September 1960

THE objectives of this research programme were twofold: first, to construct an apparatus for the study and calibration of thermocouples at low temperatures, and, second, to calibrate between 4° and 300° K those commercially available thermocouple wires best suited for low temperature use. In this first report the apparatus is described and data are given on the thermoelectric properties of three alloys, gold–cobalt (gold–2·1 atomic per cent cobalt), constantan, and 'normal' silver (silver–0·37 atomic per cent gold); the special silver–gold alloy is called 'normal' because it was used originally in the Kamerlingh Onnes Laboratory of Leiden University as a laboratory standard or 'normal'. Gold–cobalt was selected because of its large thermoelectric power relative to copper at low temperatures; constantan, because of its widespread use, especially above 90° K. 'Normal' silver is often used instead of copper in systems where heat flow along the thermocouple wires can be troublesome. It has about the same thermoelectric power as copper, but has a much lower thermal conductivity, especially in the liquid hydrogen temperature range. Future reports will contain information on commercial alloys less useful at low temperatures, e.g. chromel, alumel, and iron.

Data on the thermoelectric properties of all three alloys have been published previously. Borelius, Keesom, Johansson, and Linde[1] measured the thermoelectric power of gold–cobalt versus 'normal' silver between 18° and 103° K and at 293°K. More recently, Fuschillo[2] published a temperature scale for gold–cobalt versus copper from 4° to 300° K and discussed some of the characteristics of the system. A recent book on experimental techniques[3] includes graphs of the thermoelectric potential differences of gold–cobalt versus 'normal' silver that were obtained from an unpublished report by Basinski and Swenson. For constantan versus copper thermocouples there is a reference table[4] from about 670° K down to 85° K, based partly on the low temperature research of Scott.[5] Calibrations down to 14° K have also been published[6, 7] for special lots of constantan versus copper thermocouples used for secondary laboratory thermometers. Borelius, Keesom, Johansson, and Linde[8] measured the thermoelectric power of 'normal' silver versus copper between 17° and 293° K. They also determined the Thomson coefficient, and therefore the absolute thermoelectric power, of 'normal' silver between 20° and 293° K.[9] However, previous measurements and calibrations do not provide a satisfactory basis for thermometry at low temperatures because either the temperature range of measurements is not sufficient or the alloys do not correspond closely enough to commercially available alloys.

The low temperature thermal and electrical conductivities of the alloys have also been published; gold–cobalt by Powell, Bunch, and Gibson,[10] constantan by Estermann and Zimmerman[11] and others,[12] and 'normal' silver by Grüneisen and Reddemann.[13]

Apparatus

The cyrostat shown in Figure 1 consists of two chambers in an evacuated enclosure, the latter immersed in

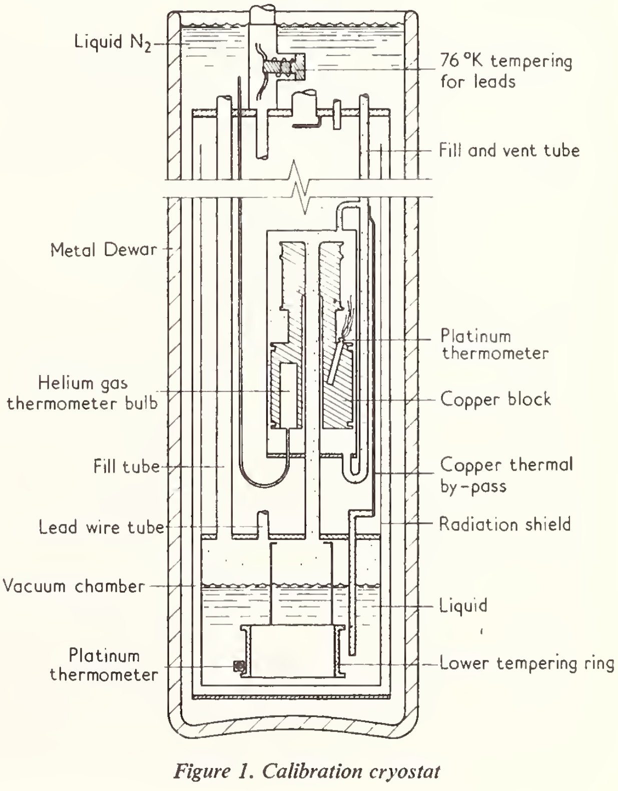


Figure 1. Calibration cryostat

liquid nitrogen. The gas-filled upper chamber contains the variable-temperature junctions of the thermocouples. The lower chamber contains the refrigerant liquid and the reference temperature junctions of the thermocouples.

The important unit in the upper chamber is the copper block. The lower part of the block contains a helium gas thermometer cavity, re-entrant wells for calibrated platinum resistance thermometers, and a groove for the variable-temperature junctions of thermocouples. The thermocouple junctions are soldered to a thin copper plate which is placed between mica sheets and clamped against a plane surface of the groove milled around the block. The upper part of the block has a surface for tempering thermocouple and thermometer wires and for wrapping a block heater. The whole chamber is cooled initially by the introduction of liquid nitrogen, followed by liquid hydrogen or helium when necessary. After evaporation of the last refrigerant, the temperature can be adjusted to any higher value by the electric heater on the uppermost part of the block.

The lower chamber has three functions: (1) it provides nearly constant temperatures for the reference junctions of the thermocouples; (2) it acts as a sink for heat from the warmer surroundings and for heat supplied to hold the upper chamber at elevated temperatures; (3) it is a source of cold vapour which can supply additional refrigeration to the upper chamber when needed. Whenever the two chambers are at nearly the same temperature vapour cooling is required for the upper chamber. The necessary cold vapour is generated by increasing the boiling rate of the refrigerant bath with an electric heater wrapped on the lower chamber. The tempering ring in the lower chamber has a surface for tempering all of the wires and also has holders for a platinum resistance thermometer and for the reference temperature junction of the thermocouples. There is a single reference junction formed by connection of all thermocouple wires to a common lead. The common lead consists of several copper wires in parallel to reduce the effects of local inhomogeneities in the lead wires.

It is important that the upper chamber be isothermal and also that it be thermally isolated from its surroundings, particularly from the warmer areas. To eliminate that heating caused by conduction along the lead wires, all electrical leads from the upper chamber pass through a stainless steel connecting tube to the lower chamber and the refrigerant liquid. From there the wires go up to a tempering rod in thermal contact with liquid nitrogen and then further up to the junction box at room temperature. Thus all heat flowing along the leads from higher temperatures is absorbed in the refrigerant without reaching the upper chamber. Similarly the heat flow down the fill and vent tube of the upper chamber is by-passed to the lower chamber by copper rods connected between the tube and the lower chamber. A large part of the thermal radiation from the walls of the vacuum enclosure is intercepted by a copper shield fastened to the lower chamber. The outside copper wall of the upper chamber is adjusted to the same temperature as the copper block by means of a heater and a six junction gold–cobalt versus copper differential thermocouple. Thermal gradients within the block are detected by a six junction gold–cobalt versus copper differential thermocouple placed on the upper and lower parts of the block.

Adequate tempering of all thermometer and thermocouple wires is also important for reproducible measurements. In the upper chamber about 1 m of each of the wires is wrapped on the upper part of the block and fastened down with electrical varnish. This brings the wires to the temperature of the block before reaching the thermocouple junctions or thermometer resistance coils. Similarly about 1 m of each wire is wrapped on the tempering ring in the lower chamber.

Because of the large range of temperatures in the upper and lower chambers, temperature measurements are not simple. With liquid helium in the lower chamber, its temperature is determined by reading the barometric pressure and converting to the equivalent temperature by means of the 1958 helium temperature scale.[14] It is not possible to employ this procedure with the nitrogen that we use because of the presence in it of unmeasured small concentrations of argon and oxygen. Therefore a platinum resistance thermometer is used to determine the temperature when the lower chamber contains liquid nitrogen. With liquid hydrogen either procedure can be used. However, it is more convenient to rely on the platinum thermometer because the use of the vapour pressure relations with hydrogen requires a simultaneous analysis of the *ortho–para* composition.[15] The latter method is occasionally used as a check on the platinum thermometer. The *ortho–para* composition, as determined by a gas thermal conductivity analyser, is usually between 88 and 98 per cent *para*-hydrogen.

The temperature of the copper block in the upper chamber is determined with the platinum resistance thermometer if it is between 15° and 300° K and with the constant volume helium gas thermometer if it is between 4° and 25° K. In order to determine the pressure within the gas thermometer, the cavity is connected to a mercury manometer by 580 cm of 0·015 in. i.d. capillary tubing. The glass tubing of the manometer has a diameter of 10 mm. The gas thermometer cavity of volume 50 cm^3 is initially filled with pure helium to a pressure of 20 cm Hg while the block is held at a temperature of about 20° K. The height of the mercury in the manometer is read to better than 0·1 mm (equivalent to 0·01° K) with a precision cathetometer.

The capsule type resistance thermometers, calibrated by the National Bureau of Standards at Washington,[16] are measured with a Mueller bridge. The precision of measurement is equivalent to about 0·001° K above 15° K. The thermocouple potentials are measured to about 0·01 μV with a six decade potentiometer. A breaker amplifier with phase sensitive detection and a filtered output meter serves as the null indicator for both the bridge and the potentiometer.

Samples

All of the thermocouple wires were calibrated in the condition in which they were received from the manufacturer. The gold–cobalt and 'normal' silver had been hard-drawn to a diameter of 0·005 in. from a bar of about 1 in. diameter. They were both covered with a woven glass fibre insulation, but were not varnished. The constantan wires were 36 A.w.g. (0·005 in. diameter), 'Teflon' covered, I.S.A. code TN. The gold–cobalt, labelled *Bar 5*, and 'normal' silver were obtained from Sigmund Cohn Corporation, Mt Vernon, New York; the constantan, from Thermo Electric Inc., Saddle Brook, New Jersey. The reference metal and extension wires were instrument grade copper obtained from Leeds and Northrup Co., Philadelphia, Pennsylvania.

The apparatus was designed to contain up to twelve thermocouples for concurrent testing. For this report there were eleven: four gold–cobalt, four constantan, and three 'normal' silver, numbered respectively 1–4, 5–8, and 9–11.

Performance

The apparatus requires 6 l. of liquid helium to cool it down from 20° to 4° K and to fill the lower chamber. The rate of use after that varies from 0·25 to 1·0 l./hr, depending on the temperature in the upper chamber. With liquid hydrogen or nitrogen the problem of boil-off is much less serious. Even with the largest gradients, liquid hydrogen will remain in the lower chamber for over 6 hr. The time required to change temperatures in the upper chamber and to re-establish equilibrium is about 1 hr.

Consideration of all sources of error, exclusive of those inherent in the thermocouple materials, suggests that temperatures can be realized and measured with an accuracy of about 0·02° K and that thermoelectric potentials can be measured with a reproducibility of about 0·01 μV below 1 mV and about 0·1 μV for higher values. Temperature differences between the top and bottom of the copper block in the upper chamber are always less than 0·01° K during an equilibrium period. The temperature of the outer wall of the upper chamber is regularly held to within 0·1° K of the copper block. Insufficient tempering of the thermocouple and thermometer wires would allow errors caused by heat conduction across the junctions. This would in turn cause inconsistencies in the readings for temperature ranges that overlap each other. There is no clear indication of a significant error caused by this possible difficulty.

The systematic and instrumentation errors mentioned above are normally outweighed by the inhomogeneity variations characteristic of thermocouple wires. This was especially true for the gold–cobalt material. In the first experiments with the calibration apparatus, the data for gold–cobalt versus copper had much greater scatter than that for constantan versus copper. This was caused by a varying liquid level in the lower chamber, which had the effect of altering the temperature gradients on the wires in regions having inhomogeneities. With gold–cobalt versus copper, there were thermoelectric potential variations of up to 5 μV with liquid hydrogen and of up to 20 μV with liquid nitrogen when the liquid level changed by several centimetres. The constantan versus copper thermocouples had almost negligible changes in the same experiments. Thereafter the liquid level was held constant to within about 0·5 cm in order to improve the consistency of the data. The effects of inhomogeneities are discussed further in the section on results.

Analysis of data

Numerous corrections to a manometer reading are necessary before the true gas thermometer temperature can be obtained. First, conventional corrections for temperature, gravitational field, and meniscus height of the mercury manometer must be made.[17] Then, corrections to the gas thermometer pressure must be calculated to account for nuisance volumes, density of the transmitting column of helium, thermo-molecular effect in the helium, and for the deviations from ideality of the helium gas.[18, 19] The corrections for the non-ideality of helium are by far the largest; as large as 0·05° K near 20° K. By contrast, the corrections to a platinum resistance thermometer reading are quite simple.

Treatment of the corrected data is complicated by the use of three different reference junction temperatures at approximately 4°, 20°, and 76° K. The procedure consists of (1) fitting by least squares of semi-empirical expressions to the data for each temperature range, (2) computing of smooth tables of values from the equations for a given thermocouple, and (3) adjusting by very small amounts the slopes at 20° and 76° K where different sets of computed values join.

For gold–cobalt versus copper between 4° and 25° K the reference junction was at about 4° K and the equation used for fitting was

$$E_T - E_4 = A + BT^2 + CT^3 \qquad \ldots (1)$$

Since

$$E_4 - E_0 = -A,$$

the values of thermoelectric potential differences for a reference temperature at 0° K could be calculated from

$$E_T - E_0 = BT^2 + CT^3 \qquad \ldots (2)$$

Measurements with a reference junction temperature at about 20° K were adjusted to a reference at 0° K by adding the quantity $E_{20} - E_0$, as calculated from equation (2). The adjusted values were fitted to the equation

$$\frac{T^2}{E_T - E_0} = D + ET + FT^2 \qquad \ldots (3)$$

The same procedure was repeated for measurements with a reference junction temperature at about 76° K.

The data for constantan versus copper were treated similarly except that values above 150° K were separately fitted by a cubic equation in temperature. The thermoelectric potential differences for 'normal' silver versus copper were small and therefore were smoothed and interpolated graphically.

The final representative reference table for a thermocouple combination was obtained by averaging the values for all of the separate thermocouples of the specified materials.

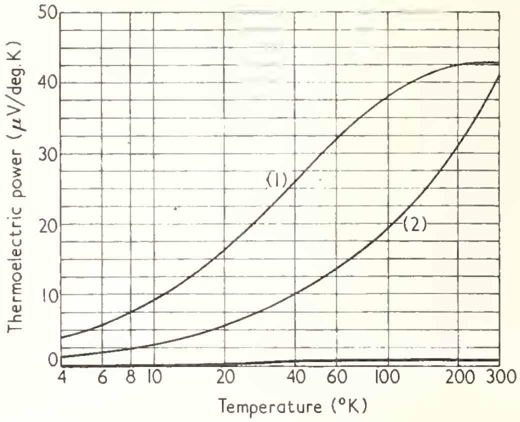
Results and discussion

Smoothed average data for the thermoelectric potential differences and powers of gold–cobalt, constantan, and 'normal' silver versus copper are given in Figure 2 and Tables 1, 2, and 3. Deviations of the thermoelectric potential differences for each thermocouple from the smoothed average values for all thermocouples of the same type are given in Figures 3, 4, and 5. The deviations plotted indicate the total differences to be expected between wires from the same lot.

The relative deviations of the thermoelectric powers for wires from a single lot of constantan are about 0·3 per cent up to 20° K, 0·03 per cent from 20° to 80° K, and 0·02 per cent from 80° to 300° K. With gold–cobalt the deviations are much larger for most of the temperature range: 0·5 per cent below 20° K, 0·3 per cent above. For both alloys the deviations between wires from the same lot could represent significant errors in temperature determinations if low temperature measurements were made with ice point reference junctions. This is especially true for gold–cobalt because of its large relative deviations at higher temperatures. 'Normal' silver has relative deviations of about 1 per cent over the entire temperature range. The absolute deviations of 'normal' silver are, however, very small, from 0·1 to 1 μV.

The deviations between wires from different lots are much greater than the deviations within one lot, especially for gold–cobalt. Earlier runs on gold–cobalt versus copper at this laboratory gave values up to 5 per cent lower than the ones given in Table 1.[20] More recent spot-checks on current lots of wire are up to 1 per cent lower than those values. The results of Fuschillo[2] are from 8 to 17 per cent lower than ours; those of Borelius et al.[1] are from 0·3 to 10 per cent higher. The relative deviations are greatest below 20° K and above 200° K; the intermediate range seems to be more reproducible. The results of Borelius et al.[8] on 'normal' silver versus copper are about the same as ours at lower temperatures, but up to 25 per cent lower near room temperatures.

The deviations between the constantan versus copper thermocouples reported in this paper and those given in *N.B.S. Circular* 561[4] are quite small, never more than 1 per cent above 80° K, the lower limit of the *N.B.S. Circular* tables. The results of Giauque, Buffington, and Schulze,[6] and Aston, Willihnganz, and Messerly,[7] differ considerably from those given here, from 3 to 7 per cent and 4 to 20 per cent respectively. The largest variations were at the higher temperatures. A lot of commercial thermocouple constantan tested here earlier differed from the present results by 0·5 to 3 per cent, with the largest variations being at the lower temperatures.



(1) Au-2·1% (at) Co versus Cu (2) Constantan versus Cu
(3) Ag-0·37% (at) Au versus Cu

Figure 2. Thermoelectric power of gold–cobalt, constantan, and 'normal' silver versus copper

Auxiliary measurements were also carried out on gold–cobalt to determine the effects of time variations (room temperature ageing or annealing) and of higher temperature anneals. Three thermocouples were tested over a period of 2·5 years. One of them had no significant decrease in thermoelectric power, one decreased 3 per cent, and one 5 per cent. For the latter two, approximately a 1 per cent change occurred in the first 6 months. The annealing tests showed that a 24 hr anneal did not change the thermoelectric power significantly if the annealing temperature was below 70° C. At 90° C a 24 hr anneal decreased the thermoelectric power about 1 per cent. The decrease in thermoelectric power caused by both the ageing at room temperature and the annealing at slightly elevated temperatures probably reflected changes in chemical composition within the crystallites.

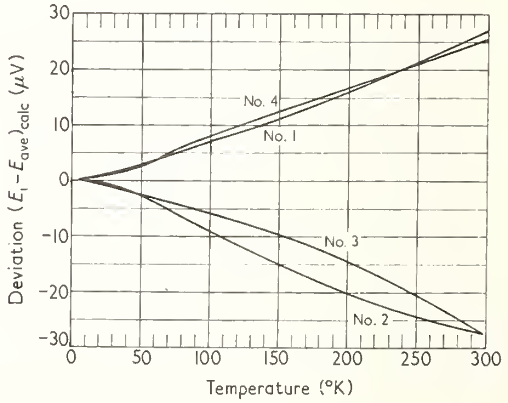


Figure 3. Deviations of individual gold–cobalt versus copper thermocouples from the group average

Table 1. Gold–2·1 Atomic Per Cent Cobalt versus Copper Thermocouples

T (°K)	E (μV)	ΔE (μV)	dE/dT ($\mu V/deg.K$)	T (°K)	E (μV)	ΔE (μV)	dE/dT ($\mu V/deg.K$)
1	0·53	0·53	1·047	56	1076·2	31·1	31·183
2	2·09	1·56	2·070	57	1107·5	31·3	31·430
3	4·66	2·57	3·069	58	1139·1	31·6	31·671
4	8·22	3·56	4·044	59	1170·9	31·8	31·905
5	12·74	4·52	4·994	60	1202·9	32·0	32·134
6	18·20	5·46	5·920	61	1235·1	32·2	32·356
7	24·57	6·37	6·822	62	1267·6	32·5	32·573
8	31·83	7·26	7·700	63	1300·3	32·7	32·784
9	39·96	8·13	8·554	64	1333·1	32·9	32·989
10	48·93	8·97	9·383	65	1366·2	33·1	33·189
11	58·72	9·79	10·188	66	1399·5	33·3	33·384
12	69·30	10·58	10·969	67	1433·0	33·5	33·574
13	80·65	11·35	11·726	68	1466·7	33·7	33·758
14	92·75	12·09	12·459	69	1500·5	33·8	33·938
15	105·6	12·8	13·167	70	1534·5	34·0	34·112
16	119·1	13·5	13·847	71	1568·7	34·2	34·282
17	133·2	14·2	14·513	72	1603·1	34·4	34·442
18	148·1	14·8	15·165	73	1637·6	34·5	34·599
19	163·5	15·5	15·803	74	1672·3	34·7	34·753
20	179·6	16·1	16·428	75	1707·1	34·8	34·906
21	196·4	16·7	17·038	76	1742·1	35·0	35·056
22	213·7	17·3	17·635	77	1777·2	35·1	35·205
23	231·6	17·9	18·218	78	1812·5	35·3	35·351
24	250·1	18·5	18·791	79	1847·9	35·4	35·497
25	269·1	19·1	19·349	80	1883·5	35·6	35·640
26	288·8	19·6	19·893	81	1919·2	35·7	35·783
27	308·9	20·2	20·424	82	1955·0	35·9	35·929
28	329·6	20·7	20·941	83	1991·0	36·0	36·072
29	350·8	21·2	21·446	84	2027·2	36·1	36·211
30	372·5	21·7	21·937	85	2063·4	36·3	36·349
31	394·7	22·2	22·417	86	2099·9	36·4	36·483
32	417·3	22·7	22·884	87	2136·4	36·5	36·615
33	440·4	23·1	23·340	88	2173·1	36·7	36·744
34	464·0	23·6	23·785	89	2209·9	36·8	36·871
35	488·0	24·0	24·218	90	2246·8	36·9	36·995
36	512·4	24·4	24·640	91	2283·9	37·1	37·117
37	537·3	24·8	25·052	92	2321·1	37·2	37·236
38	562·5	25·3	25·454	93	2358·4	37·3	37·353
39	588·2	25·7	25·846	94	2395·8	37·4	37·468
40	614·2	26·0	26·228	95	2433·3	37·5	37·581
41	640·6	26·4	26·600	96	2470·9	37·6	37·692
42	667·4	26·8	26·963	97	2508·7	37·7	37·800
43	694·6	27·1	27·317	98	2546·5	37·9	37·907
44	722·1	27·5	27·662	99	2584·5	38·0	38·011
45	749·9	27·8	27·998	100	2622·6	38·1	38·113
46	778·1	28·2	28·326	101	2660·7	38·2	38·214
47	806·5	28·5	28·646	102	2699·0	38·3	38·312
48	835·3	28·8	28·958	103	2737·3	38·4	38·409
49	864·5	29·1	29·261	104	2775·8	38·5	38·504
50	893·9	29·4	29·558	105	2814·4	38·6	38·597
51	923·6	29·7	29·846	106	2853·0	38·6	38·689
52	953·6	30·0	30·127	107	2891·7	38·7	38·778
53	983·8	30·3	30·402	108	2930·6	38·8	38·866
54	1014·4	30·5	30·669	109	2969·5	38·9	38·953
55	1045·2	30·8	30·929	110	3008·5	39·0	39·038

Table 1 (*continued*)

T (°K)	E (μV)	ΔE (μV)	dE/dT (μV/$deg.K$)
111	3047·5	39·1	39·121
112	3086·7	39·2	39·202
113	3125·9	39·2	39·283
114	3165·3	39·3	39·361
115	3204·7	39·4	39·439
116	3244·1	39·5	39·514
117	3283·7	39·6	39·589
118	3323·3	39·6	39·662
119	3363·0	39·7	39·733
120	3402·8	39·8	39·804
121	3442·6	39·8	39·873
122	3482·5	39·9	39·941
123	3522·5	40·0	40·007
124	3562·5	40·0	40·073
125	3602·6	40·1	40·137
126	3642·8	40·2	40·200
127	3683·0	40·2	40·262
128	3723·3	40·3	40·322
129	3763·7	40·4	40·382
130	3804·1	40·4	40·440
131	3844·6	40·5	40·498
132	3885·1	40·5	40·554
133	3925·7	40·6	40·609
134	3966·3	40·6	40·664
135	4007·0	40·7	40·717
136	4047·7	40·7	40·769
137	4088·5	40·8	40·821
138	4129·4	40·8	40·871
139	4170·3	40·9	40·921
140	4211·2	40·9	40·969
141	4252·2	41·0	41·017
142	4293·3	41·0	41·064
143	4334·3	41·1	41·110
144	4375·5	41·1	41·155
145	4416·7	41·2	41·199
146	4457·9	41·2	41·243
147	4499·1	41·3	41·285
148	4540·4	41·3	41·327
149	4581·8	41·3	41·368
150	4623·2	41·4	41·408
151	4664·6	41·4	41·448
152	4706·1	41·5	41·487
153	4747·6	41·5	41·525
154	4789·1	41·5	41·562
155	4830·7	41·6	41·599
156	4872·3	41·6	41·635
157	4914·0	41·7	41·670
158	4955·7	41·7	41·705
159	4997·4	41·7	41·739
160	5039·1	41·8	41·772
161	5080·9	41·8	41·805
162	5122·8	41·8	41·837
163	5164·6	41·9	41·868
164	5206·5	41·9	41·899
165	5248·4	41·9	41·929
166	5290·3	41·9	41·959
167	5332·3	42·0	41·988
168	5374·3	42·0	42·016
169	5416·4	42·0	42·044
170	5458·4	42·1	42·072
171	5500·5	42·1	42·099
172	5542·6	42·1	42·125
173	5584·7	42·1	42·151
174	5626·9	42·2	42·176
175	5669·1	42·2	42·201
176	5711·3	42·2	42·225
177	5753·5	42·2	42·249
178	5795·8	42·3	42·272
179	5838·1	42·3	42·295
180	5880·4	42·3	42·317
181	5922·7	42·3	42·339
182	5965·1	42·3	42·360
183	6007·4	42·4	42·381
184	6049·8	42·4	42·402
185	6092·2	42·4	42·422
186	6134·7	42·4	42·441
187	6177·1	42·5	42·460
188	6219·6	42·5	42·479
189	6262·1	42·5	42·497
190	6304·6	42·5	42·515
191	6347·1	42·5	42·533
192	6389·7	42·5	42·550
193	6432·2	42·6	42·567
194	6474·8	42·6	42·583
195	6517·4	42·6	42·599
196	6560·0	42·6	42·615
197	6602·6	42·6	42·630
198	6645·3	42·6	42·645
199	6687·9	42·7	42·660
200	6730·6	42·7	42·674
201	6773·3	42·7	42·688
202	6815·9	42·7	42·701
203	6858·7	42·7	42·714
204	6901·4	42·7	42·727
205	6944·1	42·7	42·740
206	6986·9	42·7	42·752
207	7029·6	42·8	42·764
208	7072·4	42·8	42·775
209	7115·2	42·8	42·786
210	7158·0	42·8	42·797
211	7200·8	42·8	42·808
212	7243·6	42·8	42·818
213	7286·4	42·8	42·828
214	7329·2	42·8	42·838
215	7372·1	42·8	42·848
216	7414·9	42·9	42·857
217	7457·8	42·9	42·866
218	7500·7	42·9	42·874
219	7543·5	42·9	42·883
220	7586·4	42·9	42·891

Table 1 (*continued*)

T (°K)	E (μV)	ΔE (μV)	dE/dT (μV/deg.K)
221	7629·3	42·9	42·899
222	7672·2	42·9	42·906
223	7715·1	42·9	42·913
224	7758·0	42·9	42·920
225	7801·0	42·9	42·927
226	7843·9	42·9	42·934
227	7886·8	42·9	42·940
228	7929·8	42·9	42·946
229	7972·7	42·9	42·952
230	8015·7	43·0	42·958
231	8058·6	43·0	42·963
232	8101·6	43·0	42·968
233	8144·6	43·0	42·973
234	8187·6	43·0	42·978
235	8230·5	43·0	42·982
236	8273·5	43·0	42·987
237	8316·5	43·0	42·991
238	8359·5	43·0	42·995
239	8402·5	43·0	42·998
240	8445·5	43·0	43·002
241	8488·5	43·0	43·005
242	8531·5	43·0	43·008
243	8574·5	43·0	43·011
244	8617·5	43·0	43·014
245	8660·5	43·0	43·016
246	8703·6	43·0	43·018
247	8746·6	43·0	43·020
248	8789·6	43·0	43·022
249	8832·6	43·0	43·024
250	8875·6	43·0	43·026
251	8918·7	43·0	43·027
252	8961·7	43·0	43·028
253	9004·7	43·0	43·029
254	9047·8	43·0	43·030
255	9090·8	43·0	43·031
256	9133·8	43·0	43·031
257	9176·9	43·0	43·031
258	9219·9	43·0	43·032
259	9262·9	43·0	43·032
260	9305·9	43·0	43·031
261	9349·0	43·0	43·031
262	9392·0	43·0	43·031
263	9435·0	43·0	43·030
264	9478·1	43·0	43·029
265	9521·1	43·0	43·028
266	9564·1	43·0	43·027
267	9607·2	43·0	43·026
268	9650·2	43·0	43·025
269	9693·2	43·0	43·023
270	9736·2	43·0	43·022
271	9779·2	43·0	43·020
272	9822·3	43·0	43·018
273	9865·3	43·0	43·016
274	9908·3	43·0	43·014
275	9951·3	43·0	43·011
276	9994·3	43·0	43·009
277	10037·3	43·0	43·006
278	10080·3	43·0	43·004
279	10123·3	43·0	43·001
280	10166·3	43·0	42·998
281	10209·3	43·0	42·995
282	10252·3	43·0	42·992
283	10295·3	43·0	42·988
284	10338·3	43·0	42·985
285	10381·3	43·0	42·981
286	10424·3	43·0	42·978
287	10467·2	43·0	42·974
288	10510·2	43·0	42·970
289	10553·2	43·0	42·966
290	10596·1	43·0	42·962
291	10639·1	43·0	42·958
292	10682·1	43·0	42·953
293	10725·0	43·0	42·949
294	10768·0	42·9	42·944
295	10810·9	42·9	42·940
296	10853·8	42·9	42·935
297	10896·8	42·9	42·930
298	10939·7	42·9	42·925
299	10982·6	42·9	42·920
300	11025·5	42·9	42·915

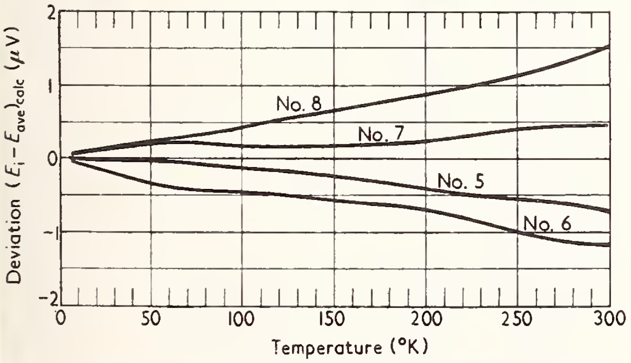


Figure 4. Deviations of individual constantan versus copper thermocouples from the group average

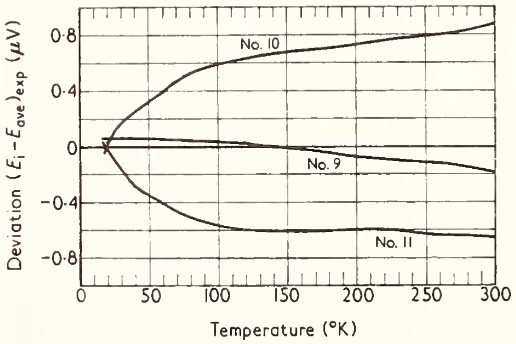


Figure 5. Deviations of individual 'normal' silver versus copper thermocouples from the group average

Table 2. Constantan versus Copper Thermocouples

T (°*K*)	*E* (μ*V*)	Δ*E* (μ*V*)	d*E*/d*T* (μ*V*/*deg.K*)
1	0·17	0·17	0·331
2	0·66	0·49	0·657
3	1·48	0·82	0·979
4	2·62	1·14	1·295
5	4·07	1·45	1·607
6	5·83	1·76	1·915
7	7·90	2·07	2·217
8	10·26	2·37	2·515
9	12·92	2·66	2·808
10	15·88	2·95	3·097
11	19·12	3·24	3·380
12	22·64	3·52	3·659
13	26·43	3·80	3·934
14	30·50	4·07	4·203
15	34·84	4·34	4·468
16	39·43	4·59	4·728
17	44·29	4·86	4·988
18	49·40	5·11	5·248
19	54·78	5·37	5·508
20	60·40	5·63	5·765
21	66·28	5·88	6·019
22	72·42	6·13	6·269
23	78·80	6·38	6·517
24	85·43	6·63	6·761
25	92·31	6·88	7·003
26	99·43	7·12	7·242
27	106·8	7·4	7·478
28	114·4	7·6	7·711
29	122·2	7·8	7·942
30	130·3	8·1	8·170
31	138·6	8·3	8·395
32	147·1	8·5	8·617
33	155·8	8·7	8·837
34	164·7	8·9	9·054
35	173·9	9·2	9·269
36	183·3	9·4	9·481
37	192·9	9·6	9·691
38	202·7	9·8	9·898
39	212·7	10·0	10·103
40	222·9	10·2	10·305
41	233·3	10·4	10·505
42	243·9	10·6	10·702
43	254·7	10·8	10·898
44	265·7	11·0	11·091
45	276·8	11·2	11·281
46	288·2	11·4	11·470
47	299·8	11·6	11·656
48	311·5	11·7	11·840
49	323·5	11·9	12·022
50	335·6	12·1	12·201
51	347·9	12·3	12·379
52	360·3	12·5	12·554
53	373·0	12·6	12·728
54	385·8	12·8	12·899
55	398·8	13·0	13·068
56	411·9	13·2	13·236
57	425·2	13·3	13·401
58	438·7	13·5	13·564
59	452·4	13·6	13·726
60	466·2	13·8	13·885
61	480·1	14·0	14·043
62	494·3	14·1	14·199
63	508·5	14·3	14·353
64	523·0	14·4	14·505
65	537·5	14·6	14·655
66	552·3	14·7	14·804
67	567·2	14·9	14·950
68	582·2	15·0	15·095
69	597·3	15·2	15·239
70	612·7	15·3	15·380
71	628·1	15·5	15·520
72	643·7	15·6	15·651
73	659·4	15·7	15·780
74	675·3	15·8	15·907
75	691·2	16·0	16·032
76	707·3	16·1	16·156
77	723·5	16·2	16·290
78	739·9	16·4	16·424
79	756·4	16·5	16·556
80	773·0	16·6	16·688
81	789·8	16·8	16·819
82	806·6	16·9	16·958
83	823·7	17·0	17·095
84	840·8	17·2	17·232
85	858·1	17·3	17·369
86	875·6	17·4	17·505
87	893·1	17·6	17·640
88	910·9	17·7	17·775
89	928·7	17·8	17·909
90	946·7	18·0	18·043
91	964·8	18·1	18·176
92	983·0	18·2	18·309
93	1001·4	18·4	18·441
94	1019·9	18·5	18·573
95	1038·5	18·6	18·705
96	1057·3	18·8	18·836
97	1076·2	18·9	18·967
98	1095·2	19·0	19·097
99	1114·4	19·2	19·227
100	1133·7	19·3	19·357
101	1153·1	19·4	19·486
102	1172·7	19·6	19·615
103	1192·4	19·7	19·744
104	1212·2	19·8	19·873
105	1232·1	19·9	20·001
106	1252·2	20·1	20·129
107	1272·4	20·2	20·257
108	1292·7	20·3	20·384
109	1313·1	20·4	20·511
110	1333·7	20·6	20·639

Table 2 (*continued*)

T (°K)	E (μV)	ΔE (μV)	dE/dT (μV/*deg.K*)
111	1354·4	20·7	20·765
112	1375·2	20·8	20·892
113	1396·2	21·0	21·019
114	1417·3	21·1	21·145
115	1438·5	21·2	21·272
116	1459·8	21·3	21·398
117	1481·3	21·5	21·524
118	1502·9	21·6	21·650
119	1524·6	21·7	21·775
120	1546·4	21·8	21·901
121	1568·4	22·0	22·027
122	1590·5	22·1	22·153
123	1612·7	22·2	22·278
124	1635·0	22·3	22·404
125	1657·5	22·5	22·529
126	1680·1	22·6	22·655
127	1702·8	22·7	22·780
128	1725·6	22·8	22·905
129	1748·6	23·0	23·031
130	1771·7	23·1	23·156
131	1794·9	23·2	23·282
132	1818·3	23·3	23·407
133	1841·7	23·5	23·533
134	1865·3	23·6	23·659
135	1889·1	23·7	23·784
136	1912·9	23·8	23·910
137	1936·9	24·0	24·036
138	1961·0	24·1	24·162
139	1985·2	24·2	24·288
140	2009·5	24·4	24·414
141	2034·0	24·5	24·541
142	2058·6	24·6	24·667
143	2083·4	24·7	24·793
144	2108·2	24·9	24·920
145	2133·2	25·0	25·047
146	2158·3	25·1	25·170
147	2183·6	25·2	25·293
148	2208·9	25·4	25·417
149	2234·4	25·5	25·540
150	2260·0	25·6	25·663
151	2285·7	25·7	25·786
152	2311·6	25·9	25·910
153	2337·6	26·0	26·033
154	2363·7	26·1	26·152
155	2389·9	26·2	26·270
156	2416·2	26·3	26·388
157	2442·7	26·4	26·507
158	2469·2	26·6	26·625
159	2495·9	26·7	26·742
160	2522·7	26·8	26·860
161	2549·6	26·9	26·977
162	2576·7	27·0	27·094
163	2603·8	27·2	27·211
164	2631·1	27·3	27·327
165	2658·5	27·4	27·443
166	2686·0	27·5	27·560
167	2713·6	27·6	27·675
168	2741·3	27·7	27·791
169	2769·2	27·8	27·906
170	2797·1	28·0	28·022
171	2825·2	28·1	28·137
172	2853·4	28·2	28·251
173	2881·7	28·3	28·366
174	2910·1	28·4	28·480
175	2938·7	28·5	28·594
176	2967·3	28·7	28·708
177	2996·1	28·8	28·822
178	3025·0	28·9	28·935
179	3054·0	29·0	29·048
180	3083·1	29·1	29·161
181	3112·3	29·2	29·274
182	3141·6	29·3	29·387
183	3171·1	29·4	29·499
184	3200·6	29·6	29·611
185	3230·3	29·7	29·723
186	3260·1	29·8	29·834
187	3290·0	29·9	29·946
188	3320·0	30·0	30·057
189	3350·1	30·1	30·168
190	3380·3	30·2	30·278
191	3410·6	30·3	30·389
192	3441·1	30·4	30·499
193	3471·6	30·6	30·609
194	3502·3	30·7	30·719
195	3533·1	30·8	30·829
196	3563·9	30·9	30·938
197	3594·9	31·0	31·047
198	3626·0	31·1	31·156
199	3657·3	31·2	31·265
200	3688·6	31·3	31·373
201	3720·0	31·4	31·481
202	3751·5	31·5	31·589
203	3783·2	31·6	31·697
204	3814·9	31·8	31·805
205	3846·8	31·9	31·912
206	3878·8	32·0	32·019
207	3910·8	32·1	32·126
208	3943·0	32·2	32·233
209	3975·3	32·3	32·339
210	4007·7	32·4	32·445
211	4040·2	32·5	32·551
212	4072·8	32·6	32·657
213	4105·5	32·7	32·763
214	4138·3	32·8	32·868
215	4171·2	32·9	32·973
216	4204·3	33·0	33·078
217	4237·4	33·1	33·183
218	4270·6	33·2	33·287
219	4304·0	33·3	33·391
220	4337·4	33·4	33·495

Table 2 (*continued*)

T (°K)	E (μV)	ΔE (μV)	dE/dT (μV/deg.K)
221	4371·0	33·5	33·599
222	4404·6	33·7	33·702
223	4438·4	33·8	33·806
224	4472·2	33·9	33·909
225	4506·2	34·0	34·012
226	4540·2	34·1	34·114
227	4574·4	34·2	34·217
228	4608·7	34·3	34·319
229	4643·0	34·4	34·421
230	4677·5	34·5	34·523
231	4712·1	34·6	34·624
232	4746·8	34·7	34·725
233	4781·5	34·8	34·826
234	4816·4	34·9	34·927
235	4851·4	35·0	35·028
236	4886·5	35·1	35·128
237	4921·6	35·2	35·228
238	4956·9	35·3	35·328
239	4992·3	35·4	35·428
240	5027·8	35·5	35·527
241	5063·4	35·6	35·627
242	5099·0	35·7	35·726
243	5134·8	35·8	35·824
244	5170·7	35·9	35·923
245	5206·7	36·0	36·021
246	5242·7	36·1	36·120
247	5278·9	36·2	36·217
248	5315·2	36·3	36·315
249	5351·5	36·4	36·413
250	5388·0	36·5	36·510
251	5424·5	36·6	36·607
252	5461·2	36·7	36·704
253	5497·9	36·8	36·800
254	5534·8	36·8	36·896
255	5571·7	36·9	36·993
256	5608·8	37·0	37·088
257	5645·9	37·1	37·184
258	5683·2	37·2	37·280
259	5720·5	37·3	37·375
260	5757·9	37·4	37·470
261	5795·4	37·5	37·565
262	5833·0	37·6	37·659
263	5870·7	37·7	37·753
264	5908·5	37·8	37·847
265	5946·4	37·9	37·941
266	5984·4	38·0	38·035
267	6022·5	38·1	38·128
268	6060·7	38·2	38·222
269	6098·9	38·3	38·315
270	6137·3	38·4	38·407
271	6175·8	38·5	38·500
272	6214·3	38·5	38·592
273	6252·9	38·6	38·684
274	6291·7	38·7	38·776
275	6330·5	38·8	38·868
276	6369·4	38·9	38·959
277	6408·4	39·0	39·050
278	6447·5	39·1	39·141
279	6486·7	39·2	39·232
280	6526·0	39·3	39·322
281	6565·3	39·4	39·413
282	6604·8	39·5	39·503
283	6644·3	39·5	39·592
284	6684·0	39·6	39·682
285	6723·7	39·7	39·771
286	6763·5	39·8	39·861
287	6803·4	39·9	39·949
288	6843·4	40·0	40·038
289	6883·5	40·1	40·127
290	6923·7	40·2	40·215
291	6963·9	40·3	40·303
292	7004·3	40·3	30·391
293	7044·7	40·4	40·478
294	7085·2	40·5	40·566
295	7125·8	40·6	40·653
296	7166·5	40·7	40·740
297	7207·3	40·8	40·826
298	7248·2	40·9	40·913
299	7289·2	41·0	40·999
300	7330·2	41·0	41·085

The given composition (2·1 atomic per cent cobalt) is an unstable solution[21] and the cobalt atoms will gradually diffuse to grain boundaries, with elevated temperatures accelerating the process.

As mentioned previously, in the section on apparatus the main errors of measurement are caused by the local inhomogeneities of the wires. Conversely, the deviations of the experimental calibration points for a given thermocouple from a smoothed curve should give an indication of the inhomogeneities of the wires. Typical deviation plots for gold–cobalt versus copper and constantan versus copper are given in Figures 6 and 7, respectively. An earlier run on constantan (from another source) versus copper gave deviations as large as 6 μV between 20° and 80° K. The newer material is clearly much more homogeneous.

Additional tests for local inhomogeneities are made by dipping a loop of the particular thermocouple wire into a refrigerant while the ends are connected to a potentiometer. The galvanometer deflections indicate the potential differences between different sections of the wire subjected to the same temperature gradient. The

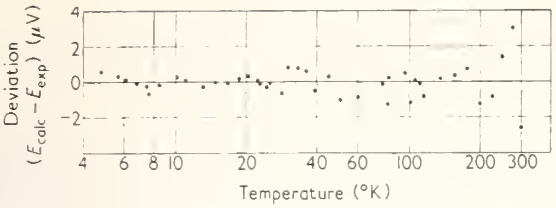


Figure 6. Typical deviations of experimental calibration points from a smoothed curve for a single gold–cobalt versus copper thermocouple

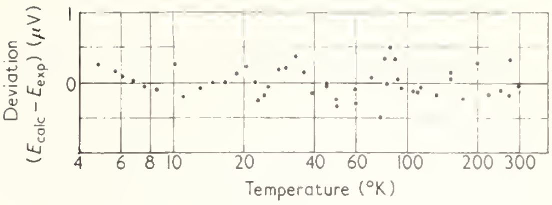


Figure 7. Typical deviations of experimental calibration points from a smoothed curve for a single constantan versus copper thermocouple

maximum and average inhomogeneity voltages for several copper, constantan, gold–cobalt, and 'normal' silver wires are given in Table 4. Indications of inhomogeneity obtained from dip tests are usually larger than those obtained in the calibration apparatus. This is caused by the much greater temperature gradients present in the dip tests.

Another test for homogeneity which is applicable to short samples (about 6 ft) arises as a by-product of a technique for making fixed point calibrations of thermocouples. It involves making up a symmetrical differential thermocouple of copper–test-wire–copper. The junctions are dipped into two baths of different temperatures, for example of melting ice or boiling cryogenic fluids. A change in the thermoelectric potential difference upon interchanging both the junctions in the baths and the junctions at the potentiometer terminals is an indication of inhomogeneity. Earlier lots of gold-cobalt gave differences on interchanging the junctions of about 30 μV between 4° and 76° K, and about 6 between 76° and 273° K. A recent lot, *Bar 9*, gave substantially lower differences, about 4 μV, at the higher temperatures. Constantan and 'normal' silver do not show variations greater than those given in Table 4. A test thermocouple system of instrument grade copper versus thermocouple grade copper gave total readings of about 4 μV between 4° and 76° K and about 3 μV between 76° and 300° K.

Summary and recommendations

Both gold–cobalt and constantan have a sufficiently large thermoelectric power against copper or 'normal' silver to allow their use in thermometry at temperatures down to 4° K. Gold–cobalt has a much larger sensitivity than constantan but this advantage is unfortunately offset by larger inhomogeneity voltages which therefore cause approximately the same relative error. For precise work two precautions are necessary to reduce the effects of inhomogeneities. First, a reference junction should be as close thermally to the variable junction as is possible. Second, alloy wires should not be taken through regions where the temperature is greatly different from either junction or where there are large temperature gradients. For example, it would be very poor practice to measure a temperature near 25° K using a reference junction at the ice point (273·15° K) if a bath at the hydrogen boiling

Table 3. Silver–0·37 Atomic Per Cent Gold versus Copper Thermocouples

T (°*K*)	*E* (μ*V*)	d*E*/d*T* (μ*V*/*deg.K*)
5	0·00	0·00
10	0·01	0·005
15	0·07	0·02
20	0·2	0·06
25	0·6	0·16
30	1·8	0·36
35	4·2	0·54
40	7·2	0·67
45	10·9	0·80
50	15·2	0·86
55	19·5	0·88
60	24·0	0·88
65	28·3	0·88
70	32·7	0·89
75	37·2	0·88
80	41·6	0·86
85	45·8	0·82
90	49·8	0·77
95	53·5	0·74
100	57·2	0·73
110	64·3	0·70
120	71·2	0·67
130	77·7	0·65
140	84·1	0·63
150	90·3	0·62
160	96·5	0·62
170	102·7	0·64
180	109·2	0·65
190	115·6	0·63
200	121·8	0·63
210	128·2	0·64
220	134·6	0·66
230	141·3	0·68
240	148·2	0·70
250	155·2	0·71
260	162·3	0·72
270	169·6	0·73
280	176·9	0·74
290	184·4	0·76
300	192·3	0·77

Table 4. Inhomogeneity of Thermoelectric Voltages Obtained from Dip Tests

Samples†	*Bath temperatures*			
	4–300° *K*		76–300° *K*	
	Voltage (μ*V*)		*Voltage* (μ*V*)	
	Maximum	*Average*	*Maximum*	*Average*
(1) Cu	4·5	2·5	2·0	0·8
(2) Cu	1·8	0·7	1·0	0·3
(3) Constantan	0·5	0·2	0·5	0·2
(4) Au–Co	5·0	3·0	4·0	2·5
(5) Au–Co	5·5	3·5	4·0	2·5
(6) Ag–Au	2·2	1·2	1·2	0·8

† Samples were: (1) Instrument grade copper, 32 A.w.g.; (2) Thermocouple grade copper, 36 A.w.g.; (3) Thermocouple grade constantan, 36 A.w.g.; (4) Gold–cobalt, *Bar 9*, 36 A.w.g. (1960); (5) Gold–cobalt, *Bar 5*, 36 A.w.g. (1958); (6) 'Normal' silver, 36 A.w.g.

point (20·4° K) were available. It would also be undesirable to use a 20° K reference junction with interconnecting gold–cobalt or constantan wires leading out to room temperatures and then back to a 25° K region.

Because of variations between different lots or continuous composition gradients within a single lot, it is important to spot-calibrate each sample of gold–cobalt. This precaution is also necessary for constantan for work below 80° K. Above that temperature, constantan is much more reliable thermometrically. The regularity of the deviation curves in Figures 3 and 4 indicates that it is acceptable to construct a complete recalibration table for any new thermocouple by calibration at a few fixed points, followed by a linear interpolation of the deviations from the appropriate reference table. The main problem for low temperature thermocouple thermometry is at present one of chemical metallurgy. Advances in precision can be made only after substantial improvements are made in sample homogeneity. In general, constantan is strongly preferred for work above 80° K; gold–cobalt is slightly better for the lower temperatures.

Copper and 'normal' silver have approximately the same absolute thermoelectric power; both are useful in conjunction with gold–cobalt or constantan. Thermocouple grade copper is slightly more homogeneous than 'normal' silver. However, 'normal' silver has a lower thermal conductivity than copper, particularly at low temperatures, and therefore better insulates the actual thermocouple junction from heat sinks or sources along the thermocouple lead wires. In general, copper is preferred above 80° K; 'normal' silver is preferable below 80° K where heat leaks along wires can be important.

We would like to thank J. L. Harden for assistance on some experimental runs, W. J. Hall for advice and assistance on computer programmes, and James Cohn of Sigmund Cohn Corporation for supplying some of the thermocouple wires.

REFERENCES

1. Borelius, G., Keesom, W. H., Johansson, C. H., and Linde, J. O. *Leiden Comm.* 217d (1932)
2. Fuschillo, N. *J. phys. Chem.* **61**, 644 (1957)
3. White, G. K. *Experimental Techniques in Low Temperature Physics* (Oxford University Press, London, 1959)
4. Shenker, H., Lauritzen, J. I., Corruccini, R. J., and Lonberger, S. T. 'Reference Tables for Thermocouples'. *N.B.S. Circ.* 561 (U.S. Govt. Printing Office, Washington, 1955)
5. Scott, R. B. *J. Res. nat. Bur. Stand.* **25**, 459 (1940); *Temperature, its Measurement and Control in Science and Industry*, Vol. 1, p. 206 (Reinhold, New York, 1941)
6. Giauque, W. F., Buffington, R. M., and Schulze, W. A. *J. Amer. chem. Soc.* **49**, 2343 (1927)
7. Aston, J. G., Willihnganz, E., and Messerly, G. H. *J. Amer. chem. Soc.* **57**, 1642 (1935); *Temperature, its Measurement and Control in Science and Industry*, Vol. 1, p. 219 (Reinhold, New York, 1941)
8. Borelius, G., Keesom, W. H., Johansson, C. H., and Linde, J. O. *Leiden Comm.* 206a (1930)
9. Borelius, G., Keesom, W. H., Johansson, C. H., and Linde, J. O. *Leiden Comm. Suppl.* 70a (1932)
10. Powell, R. L., Bunch, M. D., and Gibson, E. F. *J. appl. Phys.* **31**, 504 (1960)
11. Estermann, I., and Zimmerman, J. E. *J. appl. Phys.* **23**, 578 (1952)
12. *See* Powell, R. L., and Blanpied, W. A. 'Thermal Conductivity of Metals and Alloys at Low Temperatures'. *N.B.S. Circ.* 556 (U.S. Govt. Printing Office, Washington, 1954)
13. Grüneisen, E., and Reddemann, H. *Ann. Phys.* **20**, 843 (1934)
14. van Dijk, H. *Progress in Cryogenics 2*, p. 121 (Heywood, London, 1960)
15. Wooley, H. W., Scott, R. B., and Brickwedde, F. G. *J. Res. nat. Bur. Stand.* **41**, 379 (1948)
16. The platinum thermometers are calibrated on the temperature scale of Hoge, H. J., and Brickwedde, F. G. *J. Res. nat. Bur. Stand.* **22**, 351 (1939) between 10° and 90° K and on the International Temperature Scale above 90° K. *See* Stimson, H. F. *J. Res. nat. Bur. Stand.* **42**, 209 (1949)
17. Brombacher, W. G., Johnson, D. P., and Cross, J. L. *Mercury Barometers and Manometers*, N.B.S. Monograph 8 (U.S. Govt. Printing Office, Washington, 1960)
18. Kilpatrick, J. E., Keller, W. E., and Hammel, E. F. *Phys. Rev.* **97**, 9 (1955); Keller, W. E. *Phys. Rev.* **97**, 1 (1955)
19. Beattie, J. A. *Temperature, its Measurement and Control in Science and Industry*, Vol. 2, p. 63 (Reinhold, New York, 1955)
20. Powell, R. L., and Bunch, M. D. *Bull. Inst. Int. du Froid* Supplement. Annexe 1958–1, p. 129; Proceedings of the Commission I meeting, June 17–21, 1958, at Delft, Netherlands
21. Hansen, M. *Constitution of Binary Alloys*, p. 195 (McGraw-Hill, New York, 1958)

Liquid-in-Glass Thermometry

UNITED STATES DEPARTMENT OF COMMERCE • Luther H. Hodges, *Secretary*
NATIONAL BUREAU OF STANDARDS • A. V. Astin, *Director*

Calibration of Liquid-in-Glass Thermometers

James F. Swindells

National Bureau of Standards Monograph 90
Issued February 12, 1965

[Supersedes Circular 600]

333-I

Foreword

The liquid-in-glass thermometer is probably the most widely used temperature measuring device in both science and industry. In spite of its fragile nature, its relative simplicity makes this type of thermometer singularly attractive where reliable temperature measurements are required but where the highest attainable accuracy is not necessary.

The liquid-in-glass thermometer is not an entirely foolproof instrument, however. If the user is to realize the accuracy of which his thermometer is capable, and to recognize its inherent limitations as well, he must have, in additon to its calibration, some knowledge of the behavior to be expected of such a thermometer. It is the purpose of this Monograph to emphasize the important features of good practice in the design and use of liquid-in-glass thermometers, and to describe the techinques used by the National Bureau of Standards in their calibration. This information is intended to be of value not only to those who wish to submit thermometers to the Bureau for calibration, but also to manufacturers, to other standards laboratories, and to those who wish to calibrate their own instruments.

A. V. Astin, *Director.*

Library of Congress Catalog Card Number: 64–62825

Contents

Calibration and Use of Liquid-in-Glass Thermometers

James F. Swindells

This Monograph, which supersedes Circular 600, contains information of general interest to both manufacturers and users of liquid-in-glass thermometers, as well as those who wish to calibrate thermometers or submit them to the National Bureau of Standards for calibration. Instructions are provided for applicants requesting calibration services, and the techniques and equipment used in the calibration procedures are described. Important elements of thermometer design are discussed, and factors affecting the use of common types of liquid-in-glass thermometers are included together with tables of tolerances and reasonably attainable accuracies. The calculation of corrections for the temperature of the emergent stem is given in detail for various types of thermometers and conditions of use.

1. Introduction

It is the responsibility of the National Bureau of Standards to establish, maintain, and assume custody of the Nation's standards of physical measurement. One important activity under this responsibility is the accurate reproduction of the International Practical Temperature Scale as a basis for the uniform measurement of temperature throughout the scientific and industrial activities of the United States. To this end the Bureau accepts for calibration with reference to this scale selected types of temperature-measuring instruments [1] [1] for use as reference or working standards where precise-temperature measurements are required. Less precise types of instruments are not accepted, nor are the more routine calibrations performed in cases where such work can be done in qualified commercial testing laboratories. This Monograph describes the practices employed at the Bureau in the calibration of acceptable types of liquid-in-glass thermometers. The information is intended for those who wish to submit thermometers for calibration or who have occasion to use thermometers calibrated at the Bureau.

Important features of good practice in the use of liquid-in-glass thermometers are emphasized to assure realization of the accuracy of which thermometers are capable, as well as to point out their inherent limitations.

In this Monograph, the material presented in Circular 600 has been somewhat expanded and brought up to date. The rearrangement of the material is intended to inform the reader immediately of the Bureau's calibration services and how to make use of them, with the detailed description of calibration methods and discussions of topics in thermometry coming later.

2. Thermometer Calibration Services

The liquid-in-glass thermometer, discussed in this Monograph, is one of many types of precise instruments and standards for which calibration services are offered by the NBS. A complete listing is found in NBS Miscellaneous Publication 250.

As services are initiated or discontinued, or as fees are changed, announcements will appear in the Federal Register. Major changes in these will be noted in the Standards and Calibration column of the NBS Technical News Bulletin. The Bureau also plans to issue periodical listings of such changes. To be placed on a mailing list to receive these inserts as they are issued, a request should be addressed to The Office of Technical Information, National Bureau of Standards, Washington, D.C., 20234.

2.1. Kinds of Thermometers Accepted for Calibration

Liquid-in-glass thermometers include a wide variety of types, not all of which are accepted for test. In general, considerations of design, intended use, and probable stability of the thermometer indications are the principal factors governing acceptability for test. Thermometers belonging to the large and varied group which may be classed as laboratory or "chemical" thermometers are regularly accepted. These may be of the etched-stem or enclosed scale (Einschluss) type. Other acceptable types include such special-purpose thermometers as Beckmanns and calorimeter thermometers. Thermometers of the so-called industrial or mechanical types, with special mountings for their various intended uses, can be accepted for test only when their construction permits testing with the equipment available.

---

[1] Figures in brackets indicate the literature references at the end of this Monograph.

Ordinary household or meteorological thermometers will not, in general, be accepted unless the scale is graduated on the glass stem itself and the thermometer can be readily detached from its mounting for insertion in a testing bath.

Every thermometer submitted must be uniquely identified by a serial number and must pass a preliminary examination for details of construction before being finally accepted for test. The examination is made with optical aid (15 or 20 ×) for fineness and uniformity of graduation, cleanness of the mercury and capillary bore, and freedom from moisture, gas bubbles, and cracks in the glass. Among other possible defects detected in other ways, are omission of gas filling where needed, insufficient annealing and misnumbered graduations. A complete listing of all possible defects is not practicable. When serious defects are found the thermometer is returned untested.

2.2. Reports of Calibration

A Report of Calibration issued by the Bureau for a liquid-in-glass thermometer, in addition to giving the results of the calibration, may be taken as an indication that the thermometer is free from serious defects of design, material, or workmanship, as discussed in section 7. Except in special instances, a Report of Calibration is issued only when the thermometer has been calibrated at a sufficient number of points to provide reasonable assurance that the corrections obtained at the temperatures of calibration can be applied, with interpolation and extrapolation, throughout the whole scale (see sec. 5.2).

In addition to the scale corrections listed with the temperatures of calibration, the Report contains an estimate of the uncertainties associated with the corrections. The Report will also show the following information: the manufacturer's identification markings and numbers, the agency or firm for which the calibration was made, the NBS test number and date of test, and explanatory notes necessary to define the conditions under which the results of test are applicable. When necessary, the Report is accompanied by a sheet showing how to calculate the correction for emergent stem. If the thermometer is of the metastatic (Beckmann) type, the Report will be accompanied by a table of setting factors to enable the user to apply the calibration results when the thermometer is used with a setting other than that for which the corrections are given. Figure 1 shows the face of a sample Report and figure 2 shows the back of the same Report.

It should be emphasized that the estimates of error assigned to the scale corrections do not assure the user of this accuracy in a temperature measurement. Care must be taken that the thermometer bulb is at the temperature of the medium whose temperature is to be measured. This involves considerations of heat transfer from the medium to the bulb and heat conduction along the thermometer stem. Any departure from the conditions under which the corrections were obtained in calibration may significantly change the values of the corrections. Conditions of immersion are particularly important (see sec. 6), and even a change in the pressure to which the bulb is exposed may require an additional correction (sec. 8.2).

Some of the reasons why a thermometer may be denied a Report of Calibration are summarized as follows:

(a) Defective design or workmanship.

(b) Omission, where required, of ice point or other reference point.

(c) Part of graduated scale not usable.

(d) Defects in scale graduation or numbering.

(e) Omission of required marking on partial-immersion thermometers.

(f) Unsuitable bulb glass or inadequate annealing.

(g) Inadequate gas filling.

(h) Excessive scale error.

Details of good design and workmanship are discussed in section 7.

2.3. General Instructions to Applicants for Tests

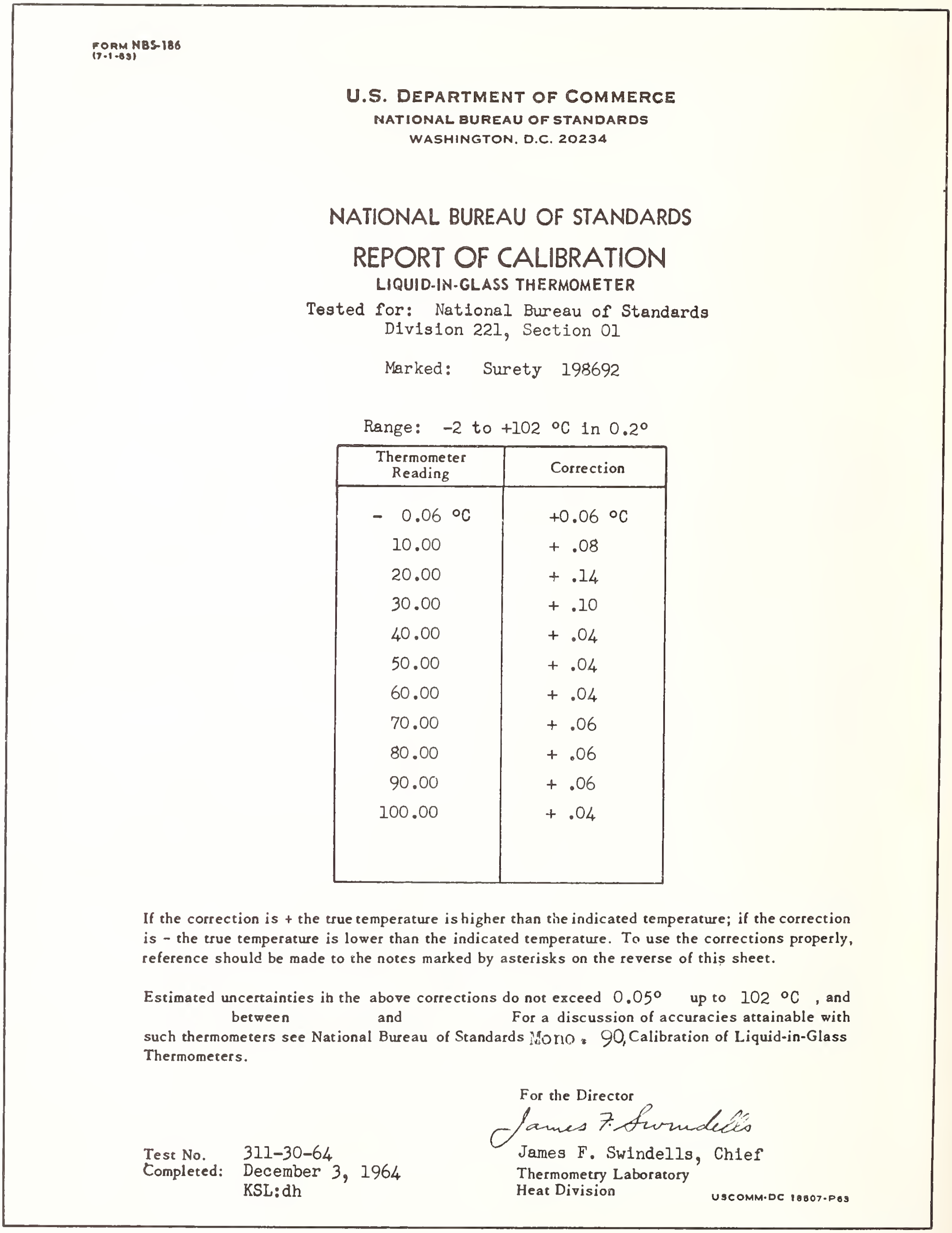
Tests in accord with the policies of the National Bureau of Standards, and of the types indicated in the fee schedules as published in the "Federal Register", will be undertaken. If need arises for a special test, not listed in the fee schedule but of a similar nature, the Bureau should be consulted. If the required measurements appear feasible, and, in the opinion of the Bureau, sufficiently important to justify the work, such tests will be undertaken for a special fee determined by the nature of the work. In all requests the following procedures and information are pertinent.

a. Initial Arrangements

A letter or purchase order, stating the tests desired and referring to the appropriate section and subsections of the fee schedule, should be sent to the Bureau prior to any shipment. The purpose of this requirement is to determine whether or not the Bureau will undertake the test and to insure correct procedure in reporting, shipping, and billing. In the case of routine or periodic tests, of a type made previously for the requester, this letter may be sent at the time shipment is made. In general, the purpose of the test and the manner in which the results are to be used should be stated. If the thermometer submitted has been previously calibrated by the Bureau, reference should be made to the former test number. A test number will be assigned by the Bureau to each project, and this test number must be referred to in all subsequent communications.

b. Shipping Instructions

Shipping charges, both to and from the Bureau, must be assumed by the applicant. Return shipments are made by the Bureau in accordance with



FORM NBS-186
(7-1-63)

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
WASHINGTON, D.C. 20234

NATIONAL BUREAU OF STANDARDS

REPORT OF CALIBRATION

LIQUID-IN-GLASS THERMOMETER

Tested for: National Bureau of Standards
Division 221, Section 01

Marked: Surety 198692

Range: -2 to +102 °C in 0.2°

Thermometer Reading	Correction
- 0.06 °C	+0.06 °C
10.00	+ .08
20.00	+ .14
30.00	+ .10
40.00	+ .04
50.00	+ .04
60.00	+ .04
70.00	+ .06
80.00	+ .06
90.00	+ .06
100.00	+ .04

If the correction is + the true temperature is higher than the indicated temperature; if the correction is - the true temperature is lower than the indicated temperature. To use the corrections properly, reference should be made to the notes marked by asterisks on the reverse of this sheet.

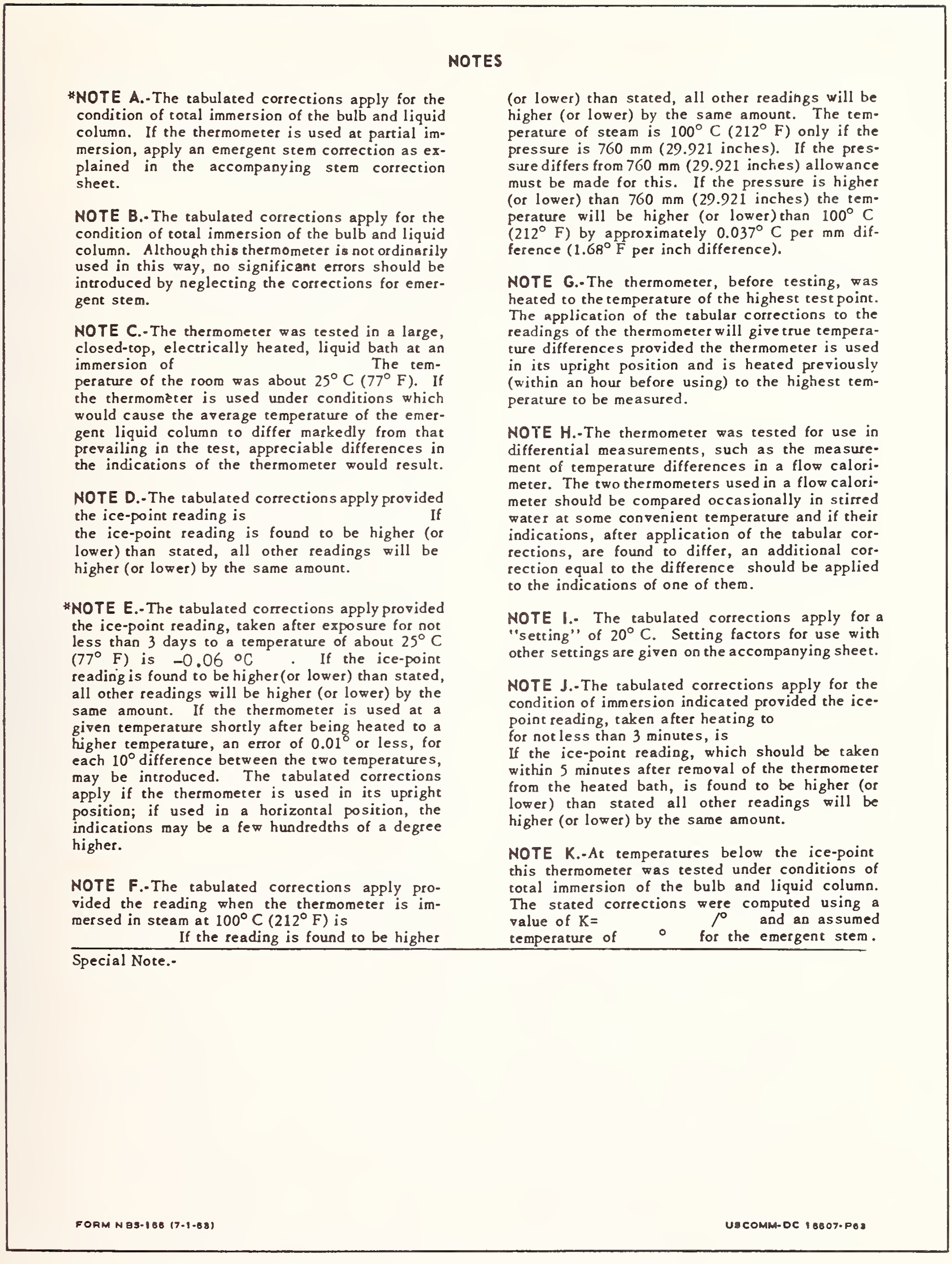
Estimated uncertainties in the above corrections do not exceed 0.05° up to 102 °C , and between and For a discussion of accuracies attainable with such thermometers see National Bureau of Standards Mono. 90, Calibration of Liquid-in-Glass Thermometers.

For the Director
James F. Swindells
James F. Swindells, Chief
Thermometry Laboratory
Heat Division

Test No. 311-30-64
Completed: December 3, 1964
KSL:dh

USCOMM-DC 18807-P63

FIGURE 1.—*Facsimile of face of a Report of Calibration.*



NOTES

*__NOTE A.__-The tabulated corrections apply for the condition of total immersion of the bulb and liquid column. If the thermometer is used at partial immersion, apply an emergent stem correction as explained in the accompanying stem correction sheet.

NOTE B.-The tabulated corrections apply for the condition of total immersion of the bulb and liquid column. Although this thermometer is not ordinarily used in this way, no significant errors should be introduced by neglecting the corrections for emergent stem.

NOTE C.-The thermometer was tested in a large, closed-top, electrically heated, liquid bath at an immersion of The temperature of the room was about 25° C (77° F). If the thermometer is used under conditions which would cause the average temperature of the emergent liquid column to differ markedly from that prevailing in the test, appreciable differences in the indications of the thermometer would result.

NOTE D.-The tabulated corrections apply provided the ice-point reading is If the ice-point reading is found to be higher (or lower) than stated, all other readings will be higher (or lower) by the same amount.

*__NOTE E.__-The tabulated corrections apply provided the ice-point reading, taken after exposure for not less than 3 days to a temperature of about 25° C (77° F) is -0.06 °C . If the ice-point reading is found to be higher (or lower) than stated, all other readings will be higher (or lower) by the same amount. If the thermometer is used at a given temperature shortly after being heated to a higher temperature, an error of 0.01° or less, for each 10° difference between the two temperatures, may be introduced. The tabulated corrections apply if the thermometer is used in its upright position; if used in a horizontal position, the indications may be a few hundredths of a degree higher.

NOTE F.-The tabulated corrections apply provided the reading when the thermometer is immersed in steam at 100° C (212° F) is If the reading is found to be higher (or lower) than stated, all other readings will be higher (or lower) by the same amount. The temperature of steam is 100° C (212° F) only if the pressure is 760 mm (29.921 inches). If the pressure differs from 760 mm (29.921 inches) allowance must be made for this. If the pressure is higher (or lower) than 760 mm (29.921 inches) the temperature will be higher (or lower) than 100° C (212° F) by approximately 0.037° C per mm difference (1.68° F per inch difference).

NOTE G.-The thermometer, before testing, was heated to the temperature of the highest test point. The application of the tabular corrections to the readings of the thermometer will give true temperature differences provided the thermometer is used in its upright position and is heated previously (within an hour before using) to the highest temperature to be measured.

NOTE H.-The thermometer was tested for use in differential measurements, such as the measurement of temperature differences in a flow calorimeter. The two thermometers used in a flow calorimeter should be compared occasionally in stirred water at some convenient temperature and if their indications, after application of the tabular corrections, are found to differ, an additional correction equal to the difference should be applied to the indications of one of them.

NOTE I.- The tabulated corrections apply for a "setting" of 20° C. Setting factors for use with other settings are given on the accompanying sheet.

NOTE J.-The tabulated corrections apply for the condition of immersion indicated provided the ice-point reading, taken after heating to
for not less than 3 minutes, is
If the ice-point reading, which should be taken within 5 minutes after removal of the thermometer from the heated bath, is found to be higher (or lower) than stated all other readings will be higher (or lower) by the same amount.

NOTE K.-At temperatures below the ice-point this thermometer was tested under conditions of total immersion of the bulb and liquid column. The stated corrections were computed using a value of K= /° and an assumed temperature of ° for the emergent stem.

Special Note.-

FORM NBS-166 (7-1-63)

USCOMM-DC 18807-P63

Figure 2.—*Facsimile of back of a Report of Calibration.*

its judgment of the best method of shipping unless specific instructions are received. Such instructions should be supplied at the time that arrangements are being made for the test. If a test number has been assigned prior to the shipment, this number should appear on the shipping container. If a test number has not been assigned at this time, a purchase order, or letter should be sent under separate cover. In either case the shipment should include a packing list.

All possible care will be taken in handling thermometers at the Bureau, but the risk of damage either in shipment or in testing must be assumed by the applicant. The applicant should consider the nature of the equipment he is shipping and pack it accordingly, with appropriate labeling. Attention is called to the availability of security express in shipping thermometers.

3. Definitions

The principal features of a solid-stem liquid-in-glass thermometer are shown in figure 3. Not all of the features shown would be necessarily be incorporated in any one thermometer.

Bulb: The liquid reservoir. The bulb of a thermometer will contain a volume equivalent to a specific number of degrees of the scale depending upon the coefficients of expansion of the thermometric liquid and bulb glass. For mercury in a "normal" glass bulb the volume is equivalent to about 6200 °C, or 11, 200 °F. For organic thermometric liquids with higher coefficients of expansion than mercury, the degree equivalents of the bulb volume are correspondingly lower.

Stem: The glass capillary tube through which the thermometric liquid advances or retreats with change in temperature.

Main Scale: The scale graduated in degrees or multiples or submultiples of degrees.

Auxiliary Scale: A short scale including a reference temperature such as the ice point, to provide a means for checking thermometer for change in calibration with time. (See sec. 7.4.) This scale is added when a suitable reference temperature is not included in the range of the main scale.

Expansion Chamber: An enlargement at the top end of the capillary bore having a volume equivalent to not less than 20 mm of unchanged capillary. Smaller chambers are not regarded as expansion chambers. The expansion chamber is provided to prevent the buildup of excessive pressures in gas-filled thermometers as the liquid filling advances toward the top of the scale.

Contraction Chamber: An enlargement of the capillary bore which serves to reduce a long length of capillary or to prevent contraction of the liquid column into the bulb. This chamber is introduced below the main scale or between the main scale and an auxiliary scale.

Reference Point: Some reference temperature, within the range of the main scale or an auxiliary scale, such as the ice point or steam point, at which the thermometer may be checked periodically for changes in scale calibration. (See sec. 7.4.)

Total Immersion Thermometer: A thermometer designed to indicate temperatures correctly when used with the bulb and the entire liquid column in the stem exposed to the temperature being measured.

Partial Immersion Thermometer: A thermometer designed to indicate temperatures correctly when used with the bulb and a specified part of the stem exposed to the temperature being measured. The remaining part of the stem will be at the ambient temperature, usually different from the temperature being measured. Such thermometers are marked with an *immersion line* to indicate the proper depth of immersion. The *emergent stem* refers to the length of liquid column and stem at the ambient temperature.

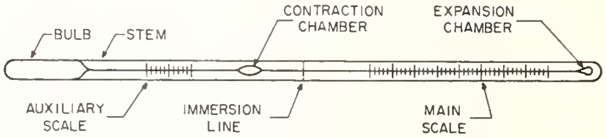


FIGURE 3.—*Principal features of a solid-stem liquid-in-glass thermometer.*

Complete Immersion Thermometer: A thermometer designed to indicate temperatures correctly when the whole thermometer, including the expansion chamber, is exposed to the temperature being measured. In gas-filled thermometers the reading will be different for complete, as compared to total immersion as a result of the effect of temperature on the gas pressure in the thermometer. (See sec. 8.2). The difference in readings under the two conditions is particularly significant at high temperatures.

Calibration Points are the temperatures at which corrections to the thermometer scale are determined.

Accuracy: The accuracy of a measurement refers to the closeness with which the result of the measurement approaches the true value of the quantity being measured. In this Monograph the accuracy expected of a given thermometer refers to the closeness of the observed indication of the thermometer to the true temperature on the International Practical Temperature Scale. The accuracy attainable is principally limited by the characteristics of the thermometer itself. Instability of the thermometer glass, capillary forces at the surface of the thermometric liquid, non-uniformity of capillary bore, and inaccuracies in scale graduation are among the important factors. With partial immersion thermometers, uncertainties in corrections for the emergent stem may greatly limit the accuracy. Observer errors are also involved, but with care these can usually be made relatively small.

Precision: The precision of measurement refers to the degree of agreement amongst repeated measurements of the same quantity. When a thermometer is held at constant temperature and it is read repeatedly at the same scale reading, one can be deceived in assuming that a corresponding accuracy is being achieved. For example, capillary forces may be holding the liquid column at the false level, or the bulb volume may have changed since the time of calibration.

4. Temperature Scales and Standards

The calibration of a thermometer consists of comparing its indications with known temperatures on a standard scale of temperature. By international agreement, the Kelvin Scale is now accepted as the absolute Thermodynamic scale. In 1954 the Tenth General Conference on Weights and Measures defined the Kelvin Scale by means of a single fixed point, the triple point of water, to which was assigned the temperature 273.16 °K, exactly. Because of the difficulties encountered in the practical realization of the Kelvin Scale, however, a practical working scale, the International Temperature Scale, was first adopted in 1927 and later revised in 1948. In 1960 the Eleventh General Conference changed the name of the scale to International Practical Temperature Scale of 1948 (IPTS) and adopted a revised text of the scale [2]. The Scale itself was not changed, however. The new text, therefore, does not change the value of any temperature on the 1948 scale by as much as the experimental error of measurement. This Scale is intended to have close correspondence with the Kelvin Scale and to provide scientific and industrial laboratories throughout the world with a common basis for stating temperatures. Calibrations of thermometers at the Bureau, therefore, are made with reference to temperatures on the IPTS.

In the range of temperatures normally covered by liquid-in-glass thermometry, the IPTS is defined by four fixed points, the normal boiling point of oxygen at −182.97 °C, the triple point of water at +0.01 °C, the normal boiling point of water at 100 °C, and the normal boiling point of sulfur at 444.6 °C. In place of the sulfur point, however, the text of the Scale recommends the use of the temperature of equilibrium between solid zinc and liquid zinc (zinc point) with the value of 419.505 °C. Experience has shown the zinc point to be more reproducible than the sulfur point. Temperatures in the range −182.97 to 630.5 °C, at other than these fixed points, are defined in terms of a standard platinum resistance thermometer calibrated at the four fixed points and using a specified equation for interpolation.

Temperatures on the IPTS are expressed in degrees Celsius (centigrade). Thermometers graduated on the Fahrenheit Scale are calibrated with reference to the IPTS using the conversion formula,

$$\text{temperature in } ^\circ\text{F} = \frac{9}{5}\,(\text{temperature in } ^\circ\text{C}) + 32.$$

When the highest accuracy is required in a calibration, the thermometer indications are compared directly with temperatures obtained with a standard resistance thermometer. If lesser accuracy is adequate, one of a series of mercury-in-glass standards is used, except below 0 °C and above 300 °C, where the calibration is made directly with a resistance thermometer regardless of the accuracy required. The series of mercury-in-glass thermometers which serve as standards for total-immersion comparisons is shown below.

Range	Smallest graduation	Auxiliary scale
°C	*°C*	*°C*
0 to 50	0.1	
0 to 100	0.2	
50 to 100	0.1	at 0
100 to 200	0.2	at 0
200 to 300	0.5	at 0

These standards are calibrated with reference to the IPTS through comparisons with a standard resistance thermometer.

Partial-immersion standards, known as "like standards", are maintained for the calibration of accepted designs of partial-immersion thermometers. These standards are calibrated for stem-temperature conditions expected to prevail during the calibration of similar thermometers. This use of like standards eliminates the need for many of the precautions necessary when dissimilar thermometers are compared. The procedure permits the direct comparison of the indications of similar thermometers as long as the bulbs are at the same temperature and the stem temperatures are essentially the same for all of the thermometers under comparison.

For those who may want to use reproducible fixed points in their own laboratories, the Bureau sells triple-point-of-benzoic-acid cells, 122 °C (252 °F); and freezing point cells of phenol, 41 °C (106 °F), naphthalene, 80 °C (176 °F), and phthalic anhydride, 131 °C (268 °F). At higher temperatures freezing point standards of tin, 232 °C (450 °F); lead, 327 °C (621 °F); and zinc, 419 °C (786 °F) are available. (All of the above temperatures are approximate, but precise values are supplied with the standards.) Detailed information on these cells and standards and their procurement is given in NBS Miscellaneous Publication 241.

5. Calibration Procedures

All liquid-in-glass thermometers are calibrated in terms of the IPTS as defined by the standard platinum resistance thermometer. The readings may be compared directly with a standard resistance thermometer, or indirectly using a mercury-in-glass standard. Ice and steam baths, together with a series of stirred liquid baths, provide controlled temperature media for the comparisons.

5.1. Equipment

a. Ice Bath

Through the use of an ice bath, the ice point may be realized conveniently to better than 0.01 °C. A Dewar flask serves as a container for the ice, the melting of the ice being retarded by the insulating properties of the vessel. Ice shaved from clear cakes is mixed with distilled water to form a slush. Enough water is used to afford good contact with the thermometers, but not so much as to float the ice. From time to time excess water is syphoned from the bath. Care is taken to prevent contamination of the ice and water. A small reading telescope with a magnification of 10 diameters aids in reading the thermometer indication and reduces parallax errors. Gently tapping the thermometer just before reading may prevent the sticking of a falling meniscus. On the other hand too vigorous a tap will occasionally cause the mercury to rebound to an erroneously high reading.

b. Steam Bath

The steam point may be realized in a steam-point apparatus either by comparing the thermometers with standards or by the determination of the temperature of the steam from a measurement of the prevailing atmospheric pressure.

The steam bath, shown in figure 4, consists of a double-walled steam jacket in which steam from a boiler circulates. The thermometers are suspended in such a manner as to insure free circulation of steam around them. Provision is made for either relieving any excess pressure in the space surrounding the thermometers, or for determining the excess by means of a small differential manometer.

When the steam bath is used as a fixed-point apparatus a barometer is a necessary accessory since the true temperature of the steam is dependent upon the prevailing atmospheric pressure. The usual corrections are applied to the barometer reading including any corrections necessary for the value of local acceleration of gravity, for the difference in height of the steam bath and the barometer, and for any excess pressure above atmospheric in the steam jacket. The steam temperature may then be found from the pressure-temperature values given in table 1. With a good barometer, accurate to 0.1 mm Hg, this procedure is capable of an accuracy of 0.002 to 0.003 deg C (0.004 to 0.005 deg F). The Fortin type barometer will usually serve for all but the most exacting measurements.

The steam bath is also used as comparison bath, in which case the temperature of the steam is determined at the time of test by means of a previously standardized thermometer. This method is simpler than determining the steam temperature from a barometer reading, and may be preferable, particularly when a resistance thermometer can be used as the standard.

c. Comparison Liquid Baths

Stirred liquid baths of two designs are used at the Bureau as comparators in which thermometers are calibrated in the range −40 to +500 °C. (−40 to +930 °F). This equipment permits stirring adequate for uniform temperature distribution, and provides controlled heat input for temperature regulation.

A type suitable for use with media liquid at room temperature is shown in figure 5. This bath is constructed with two tubes of different diameters having connecting passages at the top and bottom. The heating coil, cooling coil for circulating cold water for comparisons below room

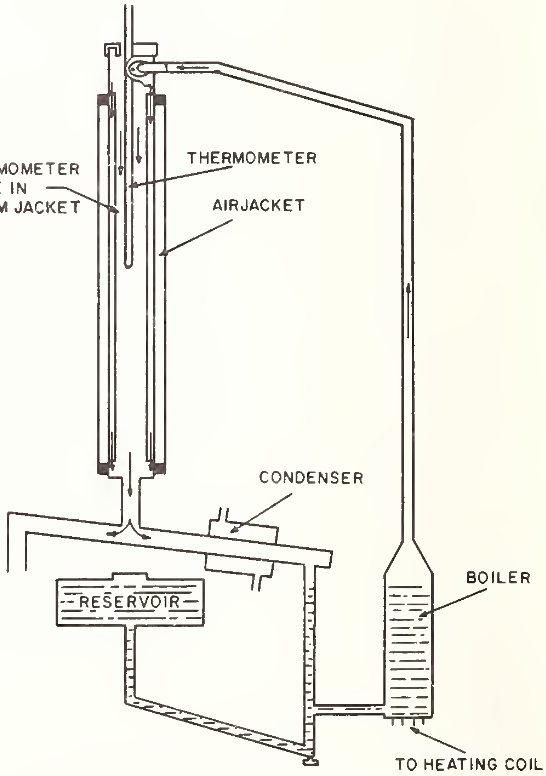


Figure 4.—*Schematic drawing of steam bath.*

Table 1.—(*Thermometric*) *condensation temperature of steam* [*3*]

[Astrisk (*) indicates change in integer]

	Pressure in mm mercury (standard)									
P	0	1	2	3	4	5	6	7	8	9
	Temperature in degrees of International Scale									
500	88. 678	0. 730	0. 782	0. 834	0. 886	0. 938	0. 990	*0. 042	*0. 093	*0. 144
510	89. 196	. 247	. 298	. 350	. 401	. 452	. 502	. 553	. 604	. 655
520	0. 705	. 756	. 806	. 856	. 907	. 957	*. 007	*. 057	*. 107	*. 157
530	90. 206	. 256	. 306	. 355	. 405	. 454	. 503	. 553	. 602	. 651
540	0. 700	. 749	. 798	. 846	. 895	. 944	. 992	*. 041	*. 089	*. 138
550	91. 186	. 234	. 282	. 330	. 378	. 426	. 474	. 521	. 569	. 617
560	0. 664	. 712	. 759	. 806	. 854	. 901	. 948	. 995	*. 042	*. 089
570	92. 136	. 182	. 229	. 276	. 322	. 369	. 415	. 462	. 508	. 554
580	0. 600	. 646	. 692	. 738	. 784	. 830	. 876	. 922	. 967	*. 013
590	93. 058	. 104	. 149	. 195	. 240	. 285	. 330	. 375	. 420	. 465
600	0. 5100	. 5548	. 5996	. 6443	. 6889	. 7335	. 7780	. 8224	. 8668	. 9112
610	. 9554	. 9996	*. 0438	*. 0879	*. 1319	*. 1759	*. 2198	*. 2636	*. 3074	*. 3511
620	94. 3948	. 4384	. 4820	. 5255	. 5689	. 6123	. 6556	. 6989	. 7421	. 7852
630	0. 8283	. 8713	. 9143	. 9572	*. 0001	*. 0429	*. 0857	*. 1284	*. 1710	*. 2136
640	95. 2562	. 2987	. 3411	. 3834	. 4257	. 4680	. 5102	. 5523	. 5944	. 6365
650	95. 6785	. 7204	. 7623	. 8041	. 8459	. 8876	. 9293	. 9709	*. 0125	*. 0539
660	96. 0954	. 1368	. 1782	. 2195	. 2607	. 3019	. 3431	. 3842	. 4252	. 4662
670	0. 5072	. 5480	. 5889	. 6297	. 6704	. 7111	. 7517	. 7923	. 8329	. 8734
680	. 9138	. 9542	. 9946	*. 0349	*. 0751	*. 1153	*. 1555	*. 1956	*. 2356	*. 2756
690	97. 3156	. 3555	. 3954	. 4352	. 4749	. 5146	. 5543	. 5939	. 6335	. 6730
700	0. 7125	. 7519	. 7913	. 8307	. 8700	. 9092	. 9484	. 9876	*. 0267	*. 0657
710	98. 1048	. 1437	. 1827	. 2216	. 2604	. 2992	. 3379	. 3766	. 4153	. 4539
720	0. 4925	. 5310	. 5695	. 6079	. 6463	. 6846	. 7229	. 7612	. 7994	. 8376
730	. 8757	. 9138	. 9519	. 9899	*. 0278	*. 0657	*. 1036	*. 1414	*. 1792	*. 2110
740	99. 2547	. 2924	. 3300	. 3675	. 4051	. 4426	. 4800	. 5174	. 5548	. 5921
750	0. 6294	. 6667	. 7039	. 7410	. 7781	. 8152	. 8523	. 8893	. 9262	. 9631
760	100. 0000	. 0368	. 0736	. 1104	. 1471	. 1838	. 2204	. 2570	. 2936	. 3301
770	0. 3666	. 4030	. 4394	. 4758	. 5121	. 5484	. 5846	. 6208	. 6570	. 6932
780	. 7293	. 7653	. 8013	. 8373	. 8733	. 9092	. 9450	. 9808	*. 0166	*. 0524
790	101. 0881	. 1238	. 1594	. 1950	. 2306	. 2661	. 3016	. 3371	. 3725	. 4079

temperature, and stirrer are located in the smaller tube, the larger tube being left clear for immersion of the thermometers.

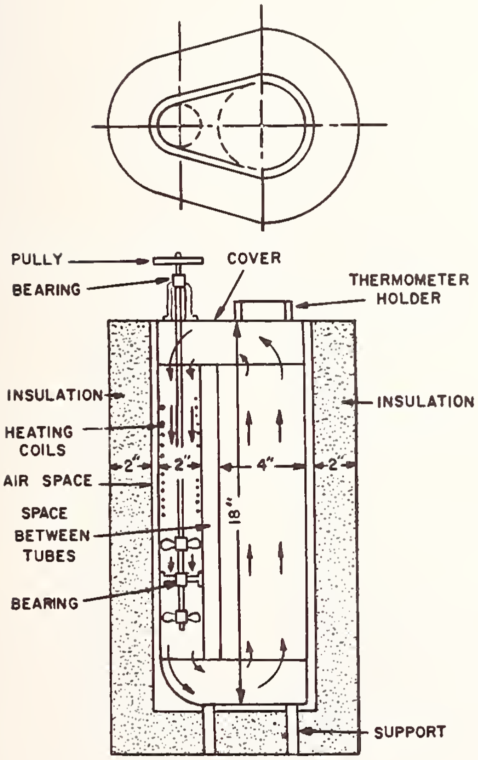


Figure 5.—*Stirred liquid bath.*

The type shown in figure 6 is designed for use at high temperatures with molten tin as the bath liquid. The bath is made with two coaxial tubes of which the inner tube is open at both ends. The stirring propeller is mounted near the bottom of the inner tube leaving the space above the propeller free to receive thermometers which are inserted in reentrant tubes. Heat is supplied by heater coils wound on the outside tube. As is also the case with the bath shown in figure 5, the thermometers are shielded from direct radiation from the hotter parts of the bath.

In each type of bath a 2- or 3-in. thickness of insulation reduces heat loss and thus aids in maintaining a uniform temperature distribution throughout the bath liquid. Each bath is provided with an insulated cover carrying a thermometer holder which can be rotated to bring successive thermometers into the field of a vertically adjustable reading telescope.

For calibrations in the range 5 to 99 °C (40 to 210 °F) water is used as the bath liquid. One grade of petroleum oil is used between 99 and 200 °C (210 and 392 °F) and a second between 200 and 315 °C (392 and 599 °F). The oils are chosen with properties such that they are not too viscous for adequate stirring at the lower temperature but at the same time have flash points which

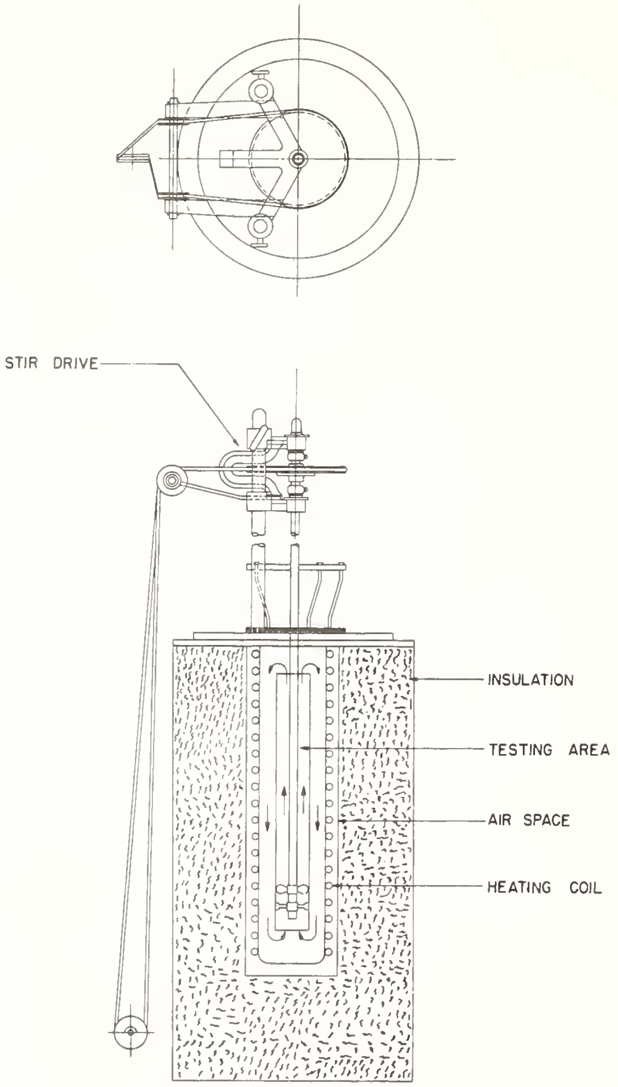


FIGURE 6.—*Stirred high-temperature bath using liquid having freezing point above room temperature.*

are not exceeded at the higher temperatures. The tin bath is used from 315 °C up to about 540 °C (599 to 1004 °F).

Calibrations from 0 to −110 °C (32 to −166 °F) are made in a cryostat similar in essentials to that described by Scott and Brickwedde [4]. The cryostat, shown in figure 7, consists of an inner Dewar flask, D, which contains the bath liquid, surrounded by liquid nitrogen in the outer Dewar flask, C. The rate of heat transfer between the bath liquid and the liquid nitrogen is controlled by varying the gas pressure between the walls of the inner Dewar flask, which is connected to a vacuum system through the side tube, M. Vigorous stirring of the bath liquid is maintained by the propeller, I, which circulates liquid upwards through the inside of the stirrer tube, P, and down the outside. Excess refrigeration is compensated by thermostatically controlled heat supplied by a heater coil, J, wound outside the stirrer tube.

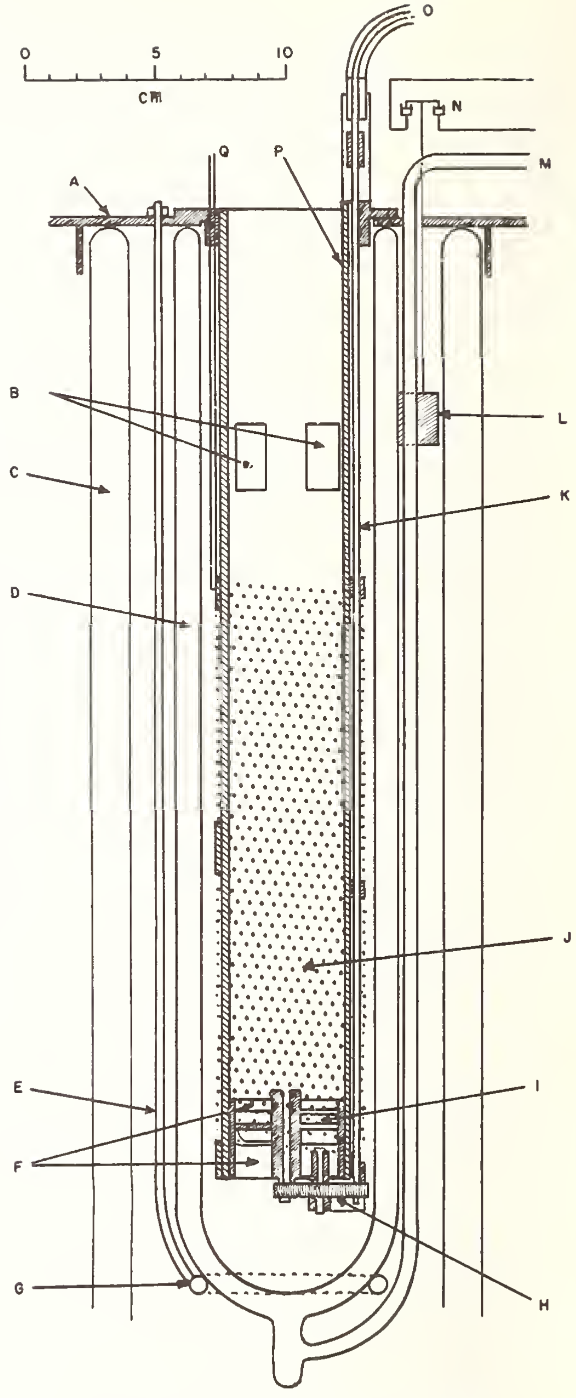


FIGURE 7.—*Vertical section of cryostat.*

For temperatures down to −75 °C (−103 °F) the bath liquid used is the eutectic mixture of carbon tetrachloride and chloroform (49.4 percent, by weight, of CCl_4, and 50 6 percent of $CHCl_3$), which freezes at about −81 °C (−114 °F). For temperatures between −75 and −110 °C (−103 and −166 °F) a five-component mixture is used containing 14.5 percent of chloroform, 25.3 percent of methylene chloride, 33.4 percent of ethyl bromide, 10.4 percent of transdichloroethylene, and 16.4 percent of trichloroethylene. This mixture freezes at about −150 °C (238 °F), but absorbs moisture readily and becomes cloudy at somewhat higher temperatures.

5.2. Number and Choice of Test Points

Usually corrections to a thermometer scale are measured at uniformly spaced calibration points covering the whole range of the main scale. The length of scale between calibration points should be chosen with regard to the accuracy expected of the thermometer in use. The points should not be chosen unnecessarily close together, nor should they be spaced so far apart as to destroy confidence in interpolated corrections at temperatures between the calibration points. For many years the predecessors of this Monograph have contained the statement: "In general, if the readings of a thermometer are to be trusted to one or two-tenths of the smallest scale division, the interval between test points should not exceed 100 divisions and usually need not be less than 40." Recent studies of calibration data for over 50 thermometers purchased during the years 1930 through 1956 for use as laboratory standards showed that, while there was considerable variation between individual thermometers, the above statement was usually applicable only to thermometers not graduated above about 200 °C. For the thermometers not graduated above 200 °C, calibrations every 40 to 50 divisions were required for interpolation to one or two-tenths of a division. In nearly all cases, interpolation between calibrations 100 divisions apart could be relied upon only to one-half of a division. For most of the thermometers graduated above 200 °C, the data showed that interpolations between calibrations 40 to 50 divisions apart were reliable to only one-half division, and that the spacing had to be reduced to 20 to 25 divisions if interpolation to one or two-tenths division was to be expected. It was found also that an examination of scale corrections obtained a given number of divisions apart for a particular thermometer was not sufficient to predict whether or not more calibration points were required for reliable interpolation. The above studies were made with only a few of the many types of thermometers submitted to the Bureau for calibration, and, therefore, conclusions may not necessarily be applicable to other types. Experience with a particular type of thermometer seems to be the most reliable guide in the choice of calibration points.

When a thermometer is to be calibrated without reference to any special use, the choice of calibration points should be left to the calibration laboratory. In some cases the number and distribution of test points can be decided only after a careful inspection of the thermometer. If the thermometer is to be used for a special purpose, this fact should be clearly stated before calibration. The Bureau will not make calibrations at more, or fewer, points than are necessary, although this judgment may be influenced by considerations given to special requests. In any case, no fewer than two points are taken on the main scale. At least one reference point is included as a calibration point when such a point (or points) is included in the scale.

5.3. Determination of Scale Corrections

Through considerations of accuracy, Beckmann thermometers, calorimeter thermometers, and thermometers graduated in tenths of a degree Fahrenheit are calibrated using a platinum resistance thermometer. A platinum thermometer is also used for all calibrations made below 0 °C (32 °F) or above 300 °C (572 °F). Other calibrations are generally made using mercury-in-glass standards (listed in sec. 4) which have been calibrated with a platinum thermometer.

When comparing thermometers with liquid-in-glass standards two standards are always used. In this way reading errors are more readily detected and cross checks of the standards are maintained. The comparison procedures are described in simplified form in the following hypothetical test of four thermometers, T1 through T4.

Table 2 shows the observations taken in obtaining the corrections applicable to the thermometers at 20 °C. For simplification, all of the entries in the table reflect perfect thermometer performance and no observer error.

TABLE 2.—*Comparison of test thermometers with liquid-in-glass standards*

Ice-point readings of test thermometers	S1	T1	T2	T3	T4	S2
Observer A		+0.02	−0.02	+0.02	0.00	
Observer B		+.02	−.02	+.02	0.00	
Mean ice points		+.02	−.02	+.02	.00	
Thermometer comparisons						
Observer A reading left to right	19.87	19.98	19.96	20.02	20.03	19.89
Observer A reading right to left	19.88	19.99	19.97	20.03	20.04	19.89
Observer B reading left to right	19.88	19.99	19.97	20.04	20.05	19.90
Observer B reading right to left	19.89	20.00	19.98	20.04	20.05	19.90
Means	19.88	19.99	19.97	20.03	20.04	19.89_5
Ice-point readings of standards						
Observer A	−0.01					−0.08
Observer B	−.01					−.08
Mean ice points	−.01					−.08
Calculations of corrections						
Correction to standards	+0.12					+0.04
Mean temperature, each standard	20.01					20.01_5
Mean temperature of all readings			20.01			
Corrections to test thermometers		+0.02	+0.04	−0.02	−0.03	

The first observations are the ice points of the thermometers under test. These are entered in the upper part of the table. The thermometers are then mounted in the comparison bath between the two standards, and the power to the bath is so adjusted that its temperature is slowly increasing at a steady rate. The data shown in the table are for a temperature rise of 0.001° between each observation. Two observers (A and B) are used, first with one observer reading and the other recording, and next with the observers interchanged. Observer A reads in the order left to right as the thermometers appear in the table and then repeats the observations in the order right to left. Observer B then immediately reads in the same manner. The observations are spaced uniformly in time so that, with the bath temperature increasing linearly with time, the mean of the observations with any one thermometer will correspond to the mean temperature of the comparison bath during the observations of all of the thermometers. Immediately after the comparison observations, ice points are taken of the two standards. Using these ice point data, together with the known scale corrections for the standards, the temperatures indicated by the standards are calculated and an overall mean temperature for the observations is obtained. This overall mean temperature is compared with the mean of the observations for each thermometer to obtain a correction to the scale of the thermometer at this point. The thermometer comparisons are then repeated at the next higher test point and so on until corrections are obtained at a sufficient number of points to calibrate the complete scale, as specified in section 5.2.

When a resistance thermometer standard is used, the sequence of observations is the same except that only one standard is used, the same resistance thermometer being read four times in place of the separate observations of two liquid-in-glass standards.

Ice-point readings are not usually taken with each test point on the scale. For thermometers not graduated above 300 °C or 600 °F, ice points taken before the first test point on the scale and after the last point will usually suffice. With high-temperature thermometers, however, it is the practice to take an ice point and then test immediately at the highest test point on the scale. After a rest period of 3 days at room temperature a second ice point is taken. If a change in ice point is found that is greater than the expected accuracy of the thermometer, the thermometer is deemed unsuitable for calibration and further tests are unnecessary.

The corrections obtained in this manner apply as long as the ice point remains the same as that observed during calibration. Subsequent changes in the ice point will be a result of small changes in the glass which affect the volume of the thermometer bulb. The volume of the capillary stem also changes, but the volume of mercury contained in the stem is so small in comparison to that in the bulb that changes in the stem volume can usually be ignored. As a result, changes in the ice-point reading will be duplicated by similar changes in readings at each point along the scale. Thus, when during use the correction at the ice point is found to be higher (or lower) than that observed at the time of calibration, the other reported corrections to the scale can confidently be taken to be higher (or lower) by the same amount.

5.4. Corrections for Emergent Stem

The proper application of scale corrections as reported in NBS Reports presents no difficulties in cases where thermometers are calibrated and used under conditions of total immersion. In such cases the temperature of the thermometer, including the stem up to the top of the mercury thread, is definitely specified and the corrections as given apply when the thermometer is used at total immersion. Instances frequently occur, however, where some part of the mercury column is emergent from the region whose temperature is being measured. In these cases the emergent part of the stem may be in an environment, not only in which the temperature is markedly different from that of the thermometer bulb, but in which pronounced temperature gradients may be present. If such a situation exists in the use of a thermometer which has been calibrated at total immersion, a correction may be calculated to account for the difference in temperature between the bulb and the emergent stem. The calculation of this correction requires a reliable estimate of the mean temperature of the emergent stem, which, for the best work, will be made from measurements. But if the stem temperature measurements are not repeated each time the thermometer is used, the accuracy of the correction will depend upon the constancy of the stem temperature over periods of time. For example, if the emergent stem is exposed to the air above a liquid bath, variations in ambient temperature and air circulation can cause significant variations in the temperature of the emergent stem.

The same situation occurs in the case of partial-immersion thermometers. For this type of thermometer, the reported scale corrections apply only for the indicated depth of immersion and a particular stem temperature. If the thermometer is then used under conditions where the mean stem temperature is different, the reported scale corrections are not applicable, and a stem temperature correction is required.

The following paragraphs describe methods for determining stem temperatures and calculating corrections. For a known or assumed condition, the use of these formulas will indicate the importance of the stem correction in relation to a desired accuracy, and the corrections can then be applied as necessary.

a. Measurement of Emergent-Stem Temperature

The mean temperature of the emergent stem may be measured approximately by means of one or more small auxiliary thermometers suspended near the emergent stem, or more accurately by exposing a similar stem and capillary mercury column beside the emergent stem and thus measuring its mean temperature [5, 6]. This is conveniently carried out with a faden thermometer ("thread thermometer") in which the expansion of the mercury in a capillary tube (bulb) is measured in a still finer capillary stem.

The methods used at the NBS in calibration work are based upon the use of faden thermometers whenever possible. These thermometers have very long bulbs (5 to 20 cm) with wall thicknesses and bore sizes nearly the same as the stem of an ordinary thermometer. If a faden thermometer is placed beside a thermometer to be observed, at such a height that the top of the faden thermometer bulb is at the same level as the top of the mercury column in the thermometer, the faden thermometer reading will give approximately the mean temperature of the adjacent portion of the thermometer stem and mercury thread. For example, a faden thermometer with a 10-cm bulb will give the mean temperature of the adjacent 10 cm of the thermometer stem. This method of using the faden thermometer is convenient for correcting the readings of a total-immersion thermometer when being used at partial immersion. The use of a faden thermometer in this manner is illustrated in figure 8(a) for the case where the mercury column in a total immersion thermometer extends a short distance above the surface of the bath to permit reading. In this case a correction must be calculated for the emergent part of the mercury column. If the stem temperature of a partial-immersion thermometer is to be measured, one or more faden thermometers are mounted so as to indicate the mean stem temperature between the immersion mark and the top of the mercury column, as shown in figure 8(b). If faden thermometers are not available, an estimate of the stem temperature can be made with auxiliary thermometers as in figure 8(c).

In calculating the correction for the emergent stem, it is convenient to express the length of thermometer stem adjacent to the faden bulb in terms of degrees on the thermometer scale. Thus, for a 10-cm faden thermometer, the number of degrees corresponding to 10 cm must be found by measurement of a portion of the thermometer scale. This measurement should be made over the portion of the graduated scale which was adjacent to the faden bulb. This is particularly important with high-temperature thermometers where the length of a degree is generally not the same at all parts of the scale.

b. Formula for Total-Immersion Thermometers

When a thermometer, which has been graduated and calibrated for use at total immersion is actually used at partial immersion, the correction for the emergent stem may be calculated by the general formula,

$$\text{stem correction} = Kn\ (T-t),$$

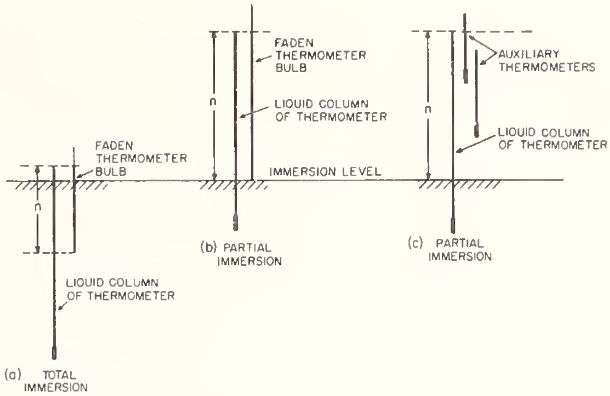


FIGURE 8.—*Schemes for measurement of emergent stem temperature.*

where

K = differential expansion coefficient of mercury (or other thermometric liquid) in the particular kind of glass which the thermometer is made (see table 3),

n = number of thermometer scale degrees adjacent to the faden thermometer,

t = average temperature of n degrees of the thermometer stem (faden thermometer reading),

T = temperature of the thermometer bulb.

The coefficient K is different for different kinds of glass, and even for the same glass, it differs for different temperature intervals, i.e., different values of $(T-t)$. Since most of the change results from the varying coefficient of the mercury, the change in K with temperature for one glass may reasonably be inferred from the change for another glass.

Calculation of the stem correction may be illustrated by the following example:

A total-immersion thermometer reads 90° C in a bath when immersed to the 80 °C graduation mark on the scale, and a 10-cm faden thermometer

TABLE 3.—*Values of* K *for mercury-in-glass thermometers*

Mean temp. $\frac{T^\circ + t^\circ}{2}$	K for "normal" glass	K for "borosilicate" glass
For Celsius thermometers		
0°	0.000158	0.000164
100	.000158	.000164
150	.000158	.000165
200	.000159	.000167
250	.000161	.000170
300	.000164	.000174
350	--------	.000178
400	--------	.000183
450	--------	.000188
For Fahrenheit thermometers		
0°	0.000088	0.000091
200	.000088	.000091
300	.000088	.000092
400	.000089	.000093
500	.000090	.000095
600	.000092	.000097
700	--------	.000100
800	--------	.000103

placed alongside the thermometer is adjacent to the scale between 60 and 90 °C. For this case $n=90-60=30$. If the faden thermometer indicates 80 °C, then the stem correction$=0.00016\times 30(90-80)=+0.048$, or $+0.05$ °C. Note that when the temperature of the emergent stem is lower than the bath temperature, the sign of the correction is +.

If a faden thermometer were not available in the above example, the emergent-stem temperature could be estimated by suspending a small auxiliary thermometer above the bath adjacent to the main thermometer and with its bulb centered at about the level of the 85° graduation. The reading of the auxiliary thermometer will then approximate the mean temperature of the 10 deg C (80° to 90 °C) emergent from the bath. For this condition $n=10$. If the auxiliary thermometre reads 60 °C, the stem correction $=0.00016\times 10(90-60)=+0.048$ or $+0.05$ °C. This method will usually not be as reliable as the method using a faden thermometer [6].

c. Formula for Partial-Immersion Thermometers

The scale corrections for partial-immersion thermometers calibrated at the Bureau are reported for the conditions of immersion to the depth of the immersion mark on the thermometer and, unless otherwise requested, for the unspecified stem temperatures resulting from the particular environments prevailing over the comparison baths in the course of the calibration. Frequently, however, thermometers are submitted for calibration with a request for scale corrections which are applicable to a specified mean temperature of the emergent stem. In such cases the emergent stem temperatures are measured during the process of calibration. The calibration observations are then corrected as necessary to account for any differences found between the stem temperatures observed during test and the specified stem temperature for which the scale corrections are to apply. In this case, the magnitude of the stem correction is proportional to the difference between the specified and observed stem temperatures and may be calculated for Celsius mercurial thermometers by means of the relation,

$$\text{stem correction}=0.00016n(t_{\text{sp}}-t_{\text{obs}}),$$

where

t_{sp} = specified mean temperature of emergent stem (for which reported scale corrections apply),
t_{obs} = observed mean temperature of emergent stem,
n = number of scale degrees equivalent to the length of emergent stem.

The above relation, of course, may also be used to correct the indications of a partial-immersion thermometer when used under stem-temperature conditions other than specified ones for which the scale corrections apply. In using the formula it should be noted that n applies to the whole length of emergent stem, i.e., from the immersion mark to the top of the mercury column. The ungraduated length between the immersion mark and the first graduation on the scale must therefore be evaluated in terms of scale degrees and included in the value of n.

For purposes of computing the emergent-stem correction, the value of K may be considered as depending on the average of T and t, that is $(T+t)/2$. Values of K as a function of $(T+t)/2$ for two widely used thermometer glasses are given in table 3. If the kind of glass is not known, K may be taken as 0.00016 for Celsius mercury thermometers and 0.00009 for Fahrenheit thermometers.

d. Formula for Calorimeter Thermometers

The stem correction is often important when thermometers are used for differential temperature measurements, as in calorimetry. In this case, provided the mean temperature of the stem remains constant, the correction may be computed from the following formula, involving the difference of the initial and final readings:

$$\text{stem correction}=Kd(T_1+T_2-S-t),$$

where

K=factor for relative expansion of glass and mercury,
T_1 and T_2=the initial and final readings, respectively,
$d=T_2-T_1$,
S=scale reading to which the thermometer is immersed,
and t=mean temperature of the emergent stem.

This correction must be applied (added if +, subtracted if −) to the difference of the readings to give the true difference of temperature.

Example: Suppose the thermometer was immersed to its 20° mark; its initial reading, T_1, was 25 °C; its final reading, T_2, was 30 °C; and the stem temperature was 20 °C. Then the correction is $0.00016\times 5\ (25+30-20-20)=+0.012$ °C. The difference between T_1 and T_2 is 5°. The true difference between the initial and final temperatures was $T_2-T_1+\text{correction}=5.012$ °C.

e. Formula for Beckmann Thermometers

For a Beckmann thermometer the correction may be readily computed from the following formula, differing only slightly from that for calorimeter thermometers, provided the thermometer is immersed to near the zero on its scale and that the temperature of the stem remains constant:

$$\text{stem correction}=Kd(S+T_1+T_2-t),$$

where

S=setting of the thermometer (sec. 6.4), and the other symbols have the same meanings as for calorimeter thermometers.

A Beckmann thermometer of the ordinary type should not be used with any part of the lower portion of the stem exposed, as this part may contain 5 to 10 times as much mercury per centimeter as the graduated portion and, if exposed, introduces a large and uncertain error. If it is unavoidable, however, to use such a thermometer with some of the lower portion of the stem emergent from the bath, the necessary correction may be computed from the above formula, provided S in the formula is replaced by $S+m$, where m is the number of degrees the temperature of the thermometer must be lowered to bring the meniscus from the zero mark on its scale to the point of immersion.

If the thermometer is immersed to some point other than its zero mark, as would ordinarily be the case with thermometers having the zero graduation at the top of the scale, the differential stem correction may be calculated from the above formula if S is replaced by $S+m$. The formula is applicable whether the point of immersion is on the scale or below it, provided the points at which readings are made are above the point to which the thermometer is immersed.

6. Common Thermometers and Factors Affecting Their Use

In this section common types of high-grade thermometers are mentioned with a discussion of some of the factors affecting their use.

Tolerances allowed by the Bureau in issuing Reports of Calibration are given in tables 4 through 11 for individual types of thermometers. The values of these tolerances are the same as those given in the first edition of Circular 600 (1959). The accuracy bounds shown in the tables may seem broad in some instances, but the definite limitations of liquid-in-glass thermometry become apparent when all factors are considered. For example, if one keeps expanding the scale for more precise reading by reducing the capillary-bore diameter, a practical limit is reached beyond which capillary forces, in combination with the elasticity of the thermometer bulb, will prevent a smooth advance or retreat of the mercury column. Particularly with a slowly falling temperature, the movement of the mercury meniscus may be found to occur erratically in steps appreciably large in comparison to the graduation interval. Large "meniscus jumps" are associated with less rigid bulbs (relatively large diameters and/or thin walls) as well as small capillary-bore diameters. Excessively elliptical or flattened bores are not recommended. Thus increasing the length of a degree on the scale, for practical bulb sizes, improves thermometric performance to a certain point only, beyond which the precision of reading may readily be mistaken for accuracy in temperature measurement. A study of the effects of bulb and capillary dimensions on thermometer performance, made by Hall and Leaver [7], provides valuable guidelines for design purposes.

Other factors such as ice-point changes, unless exactly accounted for, and differences in external pressure may also account for inaccuracies much greater than the imprecision with which a scale having 0.1- or 0.2-deg graduations may be read.

6.1. Total-Immersion Thermometers

Thermometers pointed and graduated by the manufacturer to read correct temperatures when the bulb and entire liquid column in the stem are exposed to the temperature to be measured are known as "total-immersion" thermometers. While these thermometers are designed for immersion of all the mercury, it is not necessary, and in some cases not desirable, that the portion of the stem above the meniscus be immersed. The heating of this portion to high temperatures might cause excessive gas pressures resulting in erroneous readings if not permanent damage to the bulb.

In practice a short length of the mercury column often must be left emergent from the bath (or region) so that the meniscus will be visible when the temperature is being measured. If a large enough temperature difference exists between the bath and its surroundings, an appreciable temperature gradient may be found in the thermometer stem near the surface of the bath for which a correction to the thermometer reading may be required. The condition becomes more serious when a thermometer designed and calibrated for total immersion is intentionally used at partial immersion, that is with a significant portion of the liquid column at a temperature different from that of the bath. The reading will be too low or too high depending upon whether the surrounding temperature is lower or higher than that of the bath. For a total-immersion thermometer so used, an emergent stem correction must be determined and applied in addition to the calibration corrections. The correction may be as large as 20 Celsius degrees (36 Fahrenheit degrees) if the length of emergent liquid column and the difference in temperature between the bath and the space above it are large.

A method for determining this correction is given in section 5.4.b.

The scale tolerances shown in tables 4 and 5 are chosen to be indicative of good manufacturing practice. These tolerances are based on the fact that in the manufacture of thermometers certain small errors in pointing and graduation are inevitable, and also that the indications of thermometers are subject to variations due to the inherent properties of the glass. The tolerances

Table 4.—*Tolerances for Celsius total-immersion mercury thermometers*

Temperature range in degrees	Graduation interval in degrees	Tolerance in degrees	Accuracy in degrees	Corrections stated to
Thermometer graduated under 150 °C				
°C				
0 up to 150	1.0 or 0.5	0.5	0.1 to 0.2	0.1
0 up to 150	.2	.4	.02 to .05	.02
0 up to 100	.1	.3	.01 to .03	.01
Thermometers graduated under 300 °C				
0 up to 100	1.0 or 0.5	0.5	0.1 to 0.2	0.1
Above 100 up to 300		1.0	.2 to .3	.1
0 up to 100	.2	0.4	.02 to .05	.02
Above 100 up to 200		.5	.05 to .1	.02
Thermometers graduated above 300 °C				
0 up to 300	2.0	2.0	0.2 to 0.5	0.2
Above 300 up to 500		4.0	.5 to 1.0	.2
0 up to 300	1.0 or 0.5	2.0	.1 to 0.5	.1
Above 300 up to 500		4.0	.2 to .5	.1

Table 5.—*Tolerances for Fahrenheit total-immersion mercury thermometers*

Temperature range in degrees	Graduation interval in degrees	Tolerance in degrees	Accuracy in degrees	Corrections stated to
Thermometers graduated under 300 °F				
32 up to 300	2.0	1.0	0.2 to 0.5	0.2
32 up to 300	1.0 or 0.5	1.0	.1 to .2	.1
32 up to 212	.2 or .1	0.5	.02 to .05	.02
Thermometers graduated under 600 °F				
32 up to 212	2 or 1	1.0	0.2 to 0.5	0.2
Above 212 up to 600		2.0	.5	.2
Thermometers graduated above 600 °F				
32 up to 600	5	4.0	0.5 to 1.0	0.5
Above 600 up to 950		7.0	1. to 2.0	.5
32 up to 600	2 or 1	3.0	0.2 to 1.0	.2
Above 600 up to 950		6.0	.5 to 1.0	.2

must be sufficiently restrictive to insure to the user a satisfactory high-grade thermometer but at the same time must not cause undue manufacturing difficulties.

In addition to the above requirements, the error in any temperature interval must not exceed 5 percent of the nominal value of the interval. The intent of this requirement is to eliminate thermometers having large corrections of alternating signs, which would lead to uncertainties in the interpolation of scale corrections between calibration points.

Tables 4 and 5 also give suitable values for the subdivisions and the accuracy which may be expected. The word "*accuracy*" used in these tables refers to the best values attainable in the use of the thermometer when all corrections are applied. The final columns state the decimal figures to which the corrections are given for thermometers calibrated by the Bureau. They are stated to somewhat higher precision than can be attained with certainty in calibrating the thermometers. They are so-stated to avoid the possibility of an additional uncertainty due to rounding off.

6.2. Partial-Immersion Thermometers

In many instances it is required to measure temperatures under conditions where it is inconvenient or impossible to use a liquid-in-glass thermometer at total immersion. For such uses partial-immersion thermometers are designed with scales graduated to indicate true temperatures when the thermometers are immersed to specified depths. No stem temperature correction is necessary, therefore, when these thermometers are used with the same depth of immersion and emergent-stem temperature for which they are calibrated. Unless otherwise stated, each Report of Calibration issued by the Bureau gives corrections that apply for the temperatures prevailing above the comparison baths. When such a thermometer is to be used with a different stem temperature, the necessary emergent stem correction must be calculated as shown in section 5.4.c.

The accuracy attained with this type of thermometer will usually be significantly less than that possible with total-immersion thermometers. This is particularly the case when partial-immersion thermometers are used with stem temperatures greatly different than the temperature being measured. An unsteady or irreproducible environment surrounding the emergent stem, together with the inherent difficulty of estimating or measuring the emergent-stem temperature with sufficient accuracy, can contribute markedly to the uncertainty of a given thermometer indication. For this reason tables 6 and 7 show that accuracies expected of partial-immersion thermometers are not so high as those for total-immersion thermometers nor are the calibration corrections stated so precisely.

6.3. Low-Temperature Thermometers

The lowest temperature to which a mercury-filled thermometer can be used is limited by the freezing point of mercury at −38.9 °C (−38.0 °F). This limit may be extended to considerably lower temperatures by alloying thallium with the mercury. The eutectic alloy of 8.7 percent of thallium by weight has a freezing point of −59 °C (−74 °F) and is used successfully in thermometers for temperatures down to about −56 °C (−69 °F). The freezing temperature of the alloy is critically affected in the neighborhood of the eutectic by the amount of thallium present. Small differences in composition, resulting in either too much or too little thallium, have the effect of markedly raising the freezing point of the alloy. It is therefore difficult to achieve the lowest freezing temperature in practice. In addition, some thermometers with this filling have been found to behave erratically in the range of about two degrees above the freezing point. Consequently, thermometers of this type should not be used below −56 °C.

Table 6.—*Tolerances for Celsius partial-immersion mercury thermometers*

Temperature range in degrees	Graduation interval in degrees [a]	Tolerance in degrees	Accuracy [b] in degrees	Corrections stated to
Thermometers not graduated above 150 °C				
0 up to 100	1.0 or 0.5	1.0	0.1 to 0.3	0.1
0 up to 150	1.0 or 0.5	1.0	0.1 to 0.5	0.1
Thermometers not graduated above 300 °C				
0 up to 100	1.0	1.0	0.1 to 0.3	0.1
Above 100 up to 300	1.0	1.5	.5 to 1.0	.2
Thermometers graduated above 300 °C				
0 up to 300	2.0 or 1.0	2.5	0.5 to 1.0	0.5
Above 300 up to 500		5.0	1.0 to 2.0	.5

Table 7.—*Tolerances for Fahrenheit partial-immersion mercury thermometers*

Temperature range in degrees	Graduation interval in degrees [a]	Tolerance in degrees	Accuracy [b] in degrees	Corrections stated to
Thermometers not graduated above 300 °F				
32 up to 212	2.0 or 1.0	2.0	0.2 to 0.5	0.2
32 up to 300	2.0 or 1.0	2.0	0.2 to 1.0	0.2
Thermometers not graduated above 600 °F				
32 up to 212	2.0 or 1.0	2.0	0.2 to 0.5	0.2
Above 212 up to 600	2.0 or 1.0	3.0	1.0 to 2.0	.5
Thermometers graduated above 600 °F				
32 up to 600	5.0 or 2.0	5.0	1.0 to 2.0	1.0
Above 600 up to 950		10.0	2.0 to 3.0	1.0

[a] Partial-immersion thermometers are sometimes graduated in smaller intervals than shown in these tables, but this in no way improves the performance of the thermometers, and the listed tolerances and accuracies still apply.

[b] The accuracies shown are attainable only if emergent stem temperatures are closely known and accounted for.

Other low-temperature thermometers are commonly filled with organic liquids. While not considered to be as reliable as mercury-thallium-filled thermometers, they serve to extend the range below −56 °C. Some of these liquids are used as low as −200 °C (−328 °F).

Alcohol, toluene, and pentane have all been used as fluids for low-temperature thermometers. All of these fluids, however, have limitations of one kind or another. Other organic liquids, alone or in mixtures, have been found by some manufacturers to show better characteristics for particular applications.

All of these organic liquids have the disadvantage of wetting the bore of the thermometer tubing which may lead to significant error in the indications of such thermometers if sufficient precautions are not taken. Any liquid that wets the tube will leave a film on the wall as the meniscus falls, the thickness of the film being dependent among other things on the viscosity of the liquid, the interfacial action between the liquid and glass, and the rate at which the thermometer is cooled. Where possible the rate of cooling should be slow with the bulb cooled first. In this way the viscosity of the filling fluid in the thermometer bore is kept as low as possible until the final temperature is reached, thus minimizing the amount of liquid left behind on the wall. Even so, sufficient time should be allowed for drainage from the wall to be essentially completed. Under adverse conditions it may take an hour or more before the effect of drainage ends.

In addition to good drainage characteristics, a satisfactory low-temperature fluid should be free of water, dirt, or other foreign material which will separate out at temperatures for which the thermometer is graduated. Furthermore, low-temperature thermometers are frequently designed for use up to room temperature or above. In these cases the vapor pressure of the filling liquid becomes important. A low vapor pressure is necessary to prevent distillation of the liquid at the higher temperatures. Any dye added to improve the visibility of the thermometer liquid should be chosen for good color fastness with respect to light exposure or chemical action with the thermometer liquid.

Tolerances applicable to low-temperature thermometers are given in tables 8 and 9.

6.4. Beckmann Thermometers

A metastatic, or Beckmann thermometer is usually of the enclosed-scale type, so constructed that portions of the mercury may be removed from, or added to, the bulb permitting the same thermometer to be used for differential measurements in various temperature ranges. The scales are kept short, usually to 5 or 6 deg C, although some micro types have a scale of only 3 deg C. The "setting" of such a thermometer refers to the temperature of the bulb when the reading is 0° on the scale. When the setting is changed to allow for use at a higher or lower temperature, the quantity of mercury affected by a temperature change is different. It follows that two equal changes in temperature at different settings cause different indications on the scale. Therefore a "setting factor" must always be used to convert reading differences into true temperature differences whenever the thermometer is used at any setting different from the one at which its scale was calibrated. These setting factors combine corrections for the different changes in volume of different quantities of mercury during equal temperature changes, and the difference between the mercury-in-glass scale and the International Practical Temperature Scale.

Table 10 lists setting factors calculated for thermometers of Jena 16^{III} glass, or its American equivalent, Corning normal. The scale calibrations for Beckmann thermometers as reported by the Bureau are applicable to a setting of 20 °C, and the factor is consequently 1.0000 at this temperature. For a setting of any other temperature the observed temperature difference must be multi-

TABLE 8.—*Tolerances for low-temperature total-immersion thermometers*

Temperature range in degrees	Type of thermometer	Graduation interval in degrees	Tolerance in degrees	Accuracy in degrees	Corrections stated to
		Celsius thermometers			
−35 to 0	Mercury	1 or 0.5	0.5	0.1 to 0.2	0.1
−35 to 0	do	.2	.4	.02 to .05	.02
−56 to 0	Mercury-thallium.	.5	.5	.1 to .2	.1
−56 to 0	do	.2	.4	.02 to .05	.02
−200 to 0	Organic liquid.	1.0	2.0	.2 to .5	.1
		Fahrenheit thermometers			
−35 to 32	Mercury	1 or 0.5	1.0	0.1 to 0.2	0.1
−35 to 32	do	.2	0.5	.05	.02
−69 to 32	Mercury-thallium.	1 or .5	1.0	.1 to .2	.1
−69 to 32	do	.2	0.5	.05	.02
−328 to 32	Organic liquid.	2 or 1.0	3.0	.3 to .5	.2

TABLE 9.—*Tolerances for low-temperature partial-immersion thermometers*

Temperature range in degrees	Type of thermometer	Graduation interval in degrees	Tolerance in degrees	Accuracy in degrees	Corrections stated to
		Celsius thermometers			
−35 to 0	Mercury	1.0 or 0.5	0.5	0.2 to 0.3	0.1
−56 to 0	Mercury-thallium.	1.0 or .5	.5	.2 to .3	.1
−90 to 0	Organic liquid.	1.0	3.0	.4 to 1.0	.2
		Fahrenheit thermometers			
−35 to 32	Mercury	1.0 or 0.5	1	0.3 to 0.5	0.1
−69 to 32	Mercury-thallium.	1.0 or .5	1	.3 to .5	.1
−130 to 32	Organic liquid.	2 or 1	5	.8 to 2.0	.5

TABLE 10.—*Setting factors for Beckmann thermometers*

Setting	Factor	Setting	Factor
°C		*°C*	
0	0.9934	55	1.0096
5	.9952	60	1.0107
10	.9969	65	1.0118
15	.9985	70	1.0129
20	1.0000	75	1.0139
25	1.0015	80	1.0148
30	1.0030	85	1.0157
35	1.0044	90	1.0165
40	1.0058	95	1.0172
45	1.0071	100	1.0179
50	1.0084		

As an illustration, suppose the following observations were made:

Setting=25°C. Lower reading=2.058°
Stem temperature=24° Upper reading=5.127°

	Lower	*Upper*
Observed reading	=2.058	5.127
Correction from certificate	=+0.005	−0.008
Corrected upper reading		5.119
Corrected lower reading		2.063
Difference		= 3.056
Difference multiplied by setting factor (1.0015)		= 3.061
Emergent stem correction (see accompanying-stem correction sheet)		=+.004
Corrected difference		= 3.065

TABLE 11.—*Tolerances for Beckmann and calorimeter thermometers*

Type of thermometer	Graduation interval in degrees	Allowable change in correction in degrees	Accuracy of interval in degrees	Corrections stated to
Beckmann	0.01 °C	0.01 over 0.5° interval for setting of 20 °C	0.002 to 0.005	0.001
Bomb calorimeter	.01 °C	0.02 over 1.5° interval	.005 to .01	.002
Do	.02 °C	0.02 over 1.5° interval	.005 to .01	.002
Do	.05 °F	0.04 over 2.5° interval	.01 to .02	.005
Gas calorimeter	.1 °F	0.15 over a 5° interval	.02 to .05	.02

plied by the appropriate factor from the table. An example is given below the table.

In a common design of the Beckmann thermometer the large bulb is joined to the fine capillary, backed by the milk-glass scale, by a capillary of much larger diameter. When such an instrument is used at partial immersion this large capillary is a source of some uncertainty, since the temperature of this relatively large quantity of mercury, enclosed in the glass case, cannot be actually measured. When an estimate can be made of the temperature of the emergent stem, however, a correction may be calculated as described in section 5.4.e.

Tolerance requirements for Beckmann thermometers are given in table 11.

Under the heading "Accuracy of interval in degrees" is given the estimated accuracy attainable in the measurement of any interval within the limits of the scale.

No tolerances for scale error are given although it is desirable that the scale error be no greater than 0.02 °C over a 1.0 °C interval.

6.5. Calorimeter Thermometers

Calorimeter thermometers include a specialized group of etched-stem mercury-in-glass thermometers which are used for accurate differential measurements. Since the accuracy of these thermometers at any one temperature is of less importance than the accuracy of the temperature intervals, no reference point is required.

Table 11 gives the scale tolerances required of some typical calorimeter thermometers. No tolerances for scale error are given although it is desirable that the scale corrections be no larger than about five graduation intervals.

7. Thermometer Design

To be eligible for calibration the thermometer shall be of good design, material, and workmanship and shall be permanently marked with a serial number which will uniquely identify the thermometer with its Report of Calibration. No attempt is made to list specifically all possible defects of design and workmanship, since some latitude for judgment must be reserved for individual cases as they arise. Certain important requirements of general applicability can be singled out, however, and these are described below.

7.1. Materials of Construction

While the cleanliness of the thermometer bulb, bore, and liquid filling have a pronounced effect upon the performance of a finished thermometer, of equal importance is the proper choice of the glass from which the thermometer is manufactured. Particularly, the thermometer bulb must be made of glass suitable for use in the temperature range for which the thermometer is graduated. In addition, the thermometer must be adequately annealed so that continued use will not greatly change its indications. This is especially important for a thermometer graduated above 300 °C or 600 °F. The quality of the thermometer glass and the adequacy of the annealing process may be judged in part by the stability of reference-point readings (such as ice points).

A method of test for bulb stability is described in The American Society for Testing and Materials' Method E77.

Table 12 lists some types of glasses commonly used in the manufacture of thermometer bulbs with reasonable upper temperature limits of their use. These estimates by Thompson [8] are based upon the work of Liberatore and Whitcomb [9], whose results show that significant changes in bulb volume may occur if the bulb is heated for long periods of time at a temperature higher than 130 °C (234 °F) below the strain point of the glass. Thermometers may be used intermittently, however, up to within 70 °C (126 °F) of the strain point of the bulb glass. The strain point of a glass is defined as that temperature at which the glass has a viscosity of $10^{14.5}$ poises [10].

It should be noted that the use of glass with a high strain point, such as that of borosilicate glass or higher, result in better thermometer performance and stability even in thermometers used at temperatures much lower than the exposure limits given in table 12.

TABLE 12.—*Temperature exposure limits for various thermometer glasses*[a]

	Strain point	Exposure limits			
		Continuous		Intermittent	
	°*C*	°*C*	°*F*	°*C*	°*F*
Corning normal 7560	500	370	700	[b]430*	[b]805*
Kimble R 6	490	360	680	420	790
Jena 16 III	495	365	690	425	795
Corning borosilicate 8800	529	400	750	460	860
Jena borosilicate 2954	548	420	790	480	900
Corning 1720	668	540	1005	600	1110
Jena Supremax 2955	665	535	995	595	1100

[a] From reference [8].

[b] *405 °C or 760 °F if Corning Standard Thermometer 0041 glass is used for the stem.

All high-temperature thermometers should be filled with a dry inert gas under sufficient pressure to prevent separation of the mercury at any temperature for which the scale is graduated. Total-immersion thermometers graduated above 150 °C or 300 °F must be gas filled to minimize the distillation of mercury from the top of the column. Gas filling for lower temperatures is optional, but is strongly recommended.

7.2. Scale Design and Workmanship

Thermometers of the solid-stem type shall have the graduation marks etched directly on the stem and so located as to be opposite the enamel back. In thermometers of the enclosed-scale type, the graduated scale must be securely fastened to prevent relative displacement between scale and and capillary (for example, by fusing the scale to the enclosing tube) or, if this is not done, a mark should be placed on the outer tube to locate the scale and indicate at any time whether the scale is in its original position. The graduation marks shall be clear cut, straight, of uniform width, and in a plane perpendicular to the axis of the thermometer.

The scale shall be graduated either in 1.0-, 0.5-, 0.2-, or 0.1-deg intervals, or in decimal multiples of such intervals. The divisions shall be numbered in such a way that the identification of any graduation is not unnecessarily difficult. Thermometers with scales graduated in 0.25-deg intervals, or in 0.25-deg intervals further subdivided, are sometimes difficult to read and their elimination is desirable. Thermometers graduated in 0.1- or 0.2-deg intervals, or decimal multiples of these, should have every fifth mark longer than the intermediate ones and should be numbered at every tenth mark. Thermometers graduated in 0.5-deg intervals, or in decimal multiples of 0.5 deg, require three lengths of graduation marks consisting of alternating short and intermediate marks, with every tenth mark distinctly longer the others, and numbering at every 10th or 20th mark.

The scale must not be extended to temperatures for which the particular thermometer glass is unsuited. For example, a thermometer of borosilicate glass graduated to 500 °C (932 °F) would be ruined in a short time if used at that temperature.

7.3. Scale Dimensions

Coarse graduation marks do not represent good design. Optimum line width, however, depends in some measure upon the use for which a particular thermometer is intended. If the thermometer indications are to be observed precisely, for example to 0.1 division, the width of the graduation marks in the extreme case should not be more than 0.2 of the interval between center lines of the graduations. In cases where the thermometer must be read quickly or in poor light, and less precision is expected, somewhat wider lines may be acceptable.

In addition, the graduation marks must not be too closely spaced. The closest permissible spacing depends upon the fineness and clearness of the marks. In no case should the distance between center lines of adjacent graduation marks on an etched-stem thermometer be less than 0.4 mm. The minimum permissible interval between graduation marks for an enclosed-scale thermometer is 0.3 mm if the lines are ruled on a milk-glass scale; for other scales the minimum is 0.4 mm. The minimum in no case represents good design, and well-designed thermometers will have graduation intervals considerably larger than the specified minimum.

In order that a thermometer scale be usable over its entire range, graduation marks must not be placed too close to any enlargement in the capillary. Insufficient immersion of the mercury in the main bulb or a capillary enlargement, graduation marks placed over parts of the capillary that have been changed by manufacturing operations, or graduations so close to the top of the thermometer that excessive gas pressure results when the mercury is raised to this level, may lead to appreciable errors. The following distances between graduations and the bulb and between graduations and enlargements in the bore are considered as minimum limits commensurate with good thermometer design:

(a) A 13-mm length of unchanged capillary between the bulb and the lowest graduation, if the graduation is not above 100 °C (212 °F); a 30-mm length if the graduation is above 100 °C (212 °F).

(b) A 5-mm length of unchanged capillary between an enlargement and the graduation next below, except at the top of the thermometer.

(c) A 10-mm length of unchanged capillary between an enlargement, other than the bulb, and the graduation next above, if the graduation is not above 100 °C (212 °F); a 30-mm length if the graduation is above 100 °C (212 °F).

(d) A 10-mm length of unchanged capillary above the highest graduation, if there is an expansion chamber at the top of the thermometer; a 30-mm length if there is no expansion chamber. For the purposes of this requirement, "an expansion chamber" is interpreted as an enlargement at the top end of the capillary bore which shall have a capacity equivalent to not less than 20 mm of unchanged capillary.

7.4. Reference Point on Scale

Thermometers graduated above 150 °C or 300 °F, or precision thermometers expected to be used with an accuracy better than 0.1 °C or 0.2 °F, when calibrated for the measurement of actual temperatures rather than temperature differences, must have a reference point at which the thermometer can be conveniently retested from time to time. From these reference-point tests, the effects of changes in bulb volume on the thermometer indications may be followed throughout the life of the thermometer and the proper corrections applied at any time. If no suitable reference point such as the ice or steam point is included in the range of the main scale, a short auxiliary scale including a fixed point shall be provided. To avoid making the thermometer unduly long, a contraction chamber may be introduced between the auxiliary scale and the main scale. The graduations on an auxiliary scale must extend for a short interval both above and below the reference point. Similarly, when the main scale ends near a temperature to be used as a reference point, the graduations must be continued for a short interval above or below the reference point as the case may be.

Any auxiliary scale must have graduations identical to those of the main scale, both dimensionally and in terms of temperature.

Reference points are not needed on thermometers intended for differential measurements (such as calorimeter thermometers) nor on thermometers not graduated above 150 °C or 300 °F if these are not to be calibrated to an accuracy better than 0.1 °C or 0.2 °F.

7.5. Marking of Partial-Immersion Thermometers

Partial-immersion thermometers will not be calibrated unless plainly marked "partial immersion", or its equivalent (for example, "76-mm immersion"), and unless a conspicuous line is engraved on the stem to indicate the depth to which the thermometer is to be immersed. This mark must not be less than 13 mm above the top of the bulb. Special partial-immersion thermometers adapted to instruments which fix definitely the manner for use (for example, viscometers and flash-point testers in which the thermometer is held in a ferrule or other mounting fitting the instrument) need not be marked, although it is always desirable that the thermometers be marked "partial-immersion"

8. Special Notes

The following brief notes on the characteristic behavior of mercury-in-glass thermometers are added to aid the user in understanding the behavior of such thermometers and in a better utilization of the information contained in the Reports of Calibration.

8.1. Glass Changes

The changes which occur in thermometer bulb glass on heating to a temperature, high but still within its intended range of use, and subsequent cooling to ambient are an involved function of time and temperature and will depend upon the thermal history of the glass, both during manufacture and previous use, the time of exposure to the high temperature, and the rate of cooling. Evidence from many investigations [9, 11, 12] seems to show that when a glass is held indefinitely at some fixed temperature, density (and volume) changes proceed more or less slowly toward a preferred density corresponding to a quasi equilibrium condition characteristic of the particular kind of glass and the temperature. Since these changes involve molecular rearrangements, they proceed more rapidly at high temperatures where the viscosity of the glass is lower and the molecular mobility consequently higher. Thus a close approach to quasi equilibrium may be reached in the order of hours at annealing temperatures, while infinite time may be required at much lower temperatures. As a consequence, when a glass is cooled in the order of minutes from some high temperature, equilibrium is not reached at lower temperatures on the way down, and an equilibrium density more nearly corresponding to the high temperature is "frozen" into the glass. This characteristic behavior of glass has a lasting effect on the performance of liquid-in-glass thermometers. For its entire lifetime, a thermometer may retain a "memory" of its thermal history at the higher temperatures experienced during manufacture. The techniques of good manufacture, therefore, are designed to produce in the thermometer glass a state which will result in maximum stability at the temperature of use. The achievement of perfect stability for all conditions of use, however, is not possible in thermometer manufacture so that changes in ice point readings with time and use are observed. The changes observed in scale readings at the ice point reflect changes of the same magnitude and sign at all points on the scale since they are the result of changes in bulb volume; changes in the stem have very little effect.

The changes in bulb volume are of two kinds resulting naturally from the behavior of glass as discussed above.

a. Temporary Changes

Upon heating to high temperature the bulb expands from its initial state and, after a short period of time, appears to reach an equilibrium condition corresponding to that particular high temperature If the thermometer is then cooled sufficiently slowly through critical temperature regions, the glass will return to close to its initial state, and the ice point reading will show no change on this account. If, on the other hand, the thermometer is cooled rapidly as, for example, cooling naturally in still air, the bulb will retain a portion of its expanded condition, and the ice point reading will be *lower* than its reading before the heating. This phenomenon is known as "zero, or ice-point depression". Thermometers which have been heated to high temperatures recover from this ice-point depression in an unpredictable way, and frequently there will be no significant recovery after a year's time at room temperature. The ice-point depression has a reproducible value, however, for a thermometer cooled in still air, so that the ice point, taken from time-to-time immediately (within about 1 hour) following cooling in this manner, may be used reliably to show changes in thermometer bulb volume with time and use.

On the other hand, thermometers used only up to about 100 °C will usually exhibit a relatively rapid recovery from the ice-point depression, and the original bulb volume will be recovered within the equivalent of 0.01 or 0.02 deg C in about 3 days. This phenomenon has an important bearing on the precision attainable with mercury thermometers and most be taken into consideration in precision thermometry, especially in the interval 0 to 100 deg C. Thus, if a thermometer is used to measure a given temperature, it will read lower than it otherwise would if it has a short time previously been exposed to a higher temperature. With the better grades of thermometric glasses the error resulting from this hysteresis will not exceed (in the interval 0 to 100 deg) 0.01 of a degree for each 10-deg difference between the temperature being measured and the higher temperature to which the thermometer has recently been exposed and with the best glasses only a few thousandths of a degree for each 10-deg difference. The errors due to this hysteresis become somewhat erratic at temperatures much above 100 °C. For the reasons briefly set forth above it is customary, in precision thermometry, to apply a scale correction based upon an ice point reading taken immediately after the temperature measurement.

b. Permanent Changes

A second type of change in thermometer glasses, known as the "secular change," results in a non-recoverable decrease in bulb volume which may progress with time even at room temperature, but which is markedly accelerated at high temperatures. This type of change is evidenced by an *increase* in the ice point reading. At low to moderate temperatures there may be a gradual change which will continue for years. With better grades of thermometer glasses the change will not exceed 0.1 °C in many years, provided the thermometer has not been heated to temperatures above about 150 °C. In addition, permanent changes in bulb volumes have sometimes been observed with thermometers which have been repeatedly cycled at low temperatures, for example between −30 and +25 °C [13]. At high temperatures the secular change usually progresses more rapidly at first, but, with continued heating, tends toward lower rate of change with time. The rate of secular change will be dependent upon the kind of glass used in the thermometer bulb and the particular heat treatment given the thermometer in manufacture. Thermometers manufactured according to good practices will evidence only small secular changes, but thermometers made of glass unsuitable for the use temperature, or improperly annealed, may show changes as large as 20 °C (36 °F). after continued heating at high temperature [14].

In the use of high-temperature thermometers care must be taken to avoid overheating. In only a few minutes of heating at a temperature higher than the intended range of the thermometer, the built up gas pressure above the liquid column may cause a permanent distortion of the bulb resulting in lower thermometer indications.

8.2. Pressure Effects

Since glass exhibits elastic properties, the volume of a thermometer bulb will change with change of pressure, either internal or external. Therefore, at the same temperature, the reading of a thermometer in a horizontal position will be different than its reading in a vertical position. Thermometer readings will change also with altitude or when the external pressure is changed in some other way. Changes of about 0.1 °C (0.2 °F) per atmosphere have been found for many thermometers with bulb diameters between 5 and 7 mm. This value can be used with some confidence for estimating the probable effect of an external pressure change. The effect of change of internal pressure is about 10 percent greater. Formulas for both external and internal pressure coefficients have been derived by Guillaume [15].

If the external pressure coefficient β is defined as the change in scale reading in degrees resulting from a change of 1 mm Hg in external pressure, Guillaume found the relation,

$$\beta_e = k\frac{R_e^2}{R_e^2 - R_i^2},$$

where R_e and R_i are external and internal radii of the bulb, and k is a constant containing elastic properties of the glass and a conversion factor for expressing the volume change in terms of change of thermometer reading in degrees. For Celsius thermometers, Guillaume found a value of 5.2×10^{-5} degrees C/mm Hg for k, but Hall and Lever [7], by experiment, found a value about 25 percent lower for their thermometers.

In cases where an accurate correction is necessary, β_e should be determined experimentally. A simple apparatus for the determination is shown in figure 9.

The internal pressure coefficient β_i is more difficult to determine accurately but may be calculated from β_e by means of the relation,

$$\beta_i = \beta_e + 1.5\times10^{-5},$$

for thermometers in Celsius degrees, or

$$\beta_i = \beta_e + 2.7\times10^{-5}$$

for Fahrenheit thermometers.

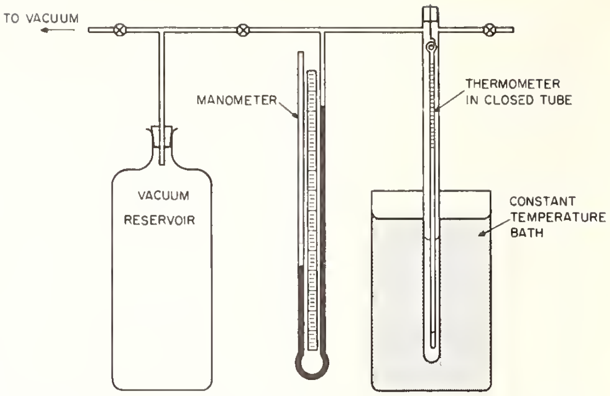


Figure 9.—*Apparatus for measurement of the external pressure coefficient.*

8.3. Lag

Practically all theoretical treatments of the question of thermometer lag are based on the assumption that Newton's law of cooling (i.e., that the rate of change in the reading of the thermometer is proportional to the difference between thermometer temperature and bath temperature) holds for the thermometer. It is an immediate consequence of this law that when a thermometer is immersed in any medium it does not take up the temperature immediately, but approaches it asymptotically. A certain time must elapse before the thermometer reading agrees with the temperature of the medium to 0.1 deg, still longer to 0.01 deg, the temperature remaining constant. If the temperature is varying, the thermometer always indicates, not the true temperature, but what the temperature of the medium was at some previous time. The thermometer readings are thus said to "lag" behind the temperature by an amount which may or may not be negligible, depending upon the rapidity of temperature variation and the physical characteristics of the thermometer. A more complete treatment of this subject has been given by Harper [16].

For a thermometer immersed in a bath, the temperature of which is changing uniformly, the lag may be defined as the interval in seconds between the time when the bath reaches a given temperature and the time when the thermometer indicates that temperature. This lag λ is dependent upon the dimensions and material of the thermometer bulb, the medium in which it is immersed, and the rate at which this medium is stirred. For instance, the lag when in the still air of a room would be perhaps 50 times that of the same thermometer when immersed in a well-stirred water bath.

Since the value of λ for mercurial thermometers is not large, being from 2 to 10 sec on a well-stirred water bath, it is not generally necessary to correct for it. For example, if two thermometers, one having a lag of 3 and another of 8 sec, are read simultaneously in a bath whose temperature is rising at the rate of 0.001 degree in 5 sec, the

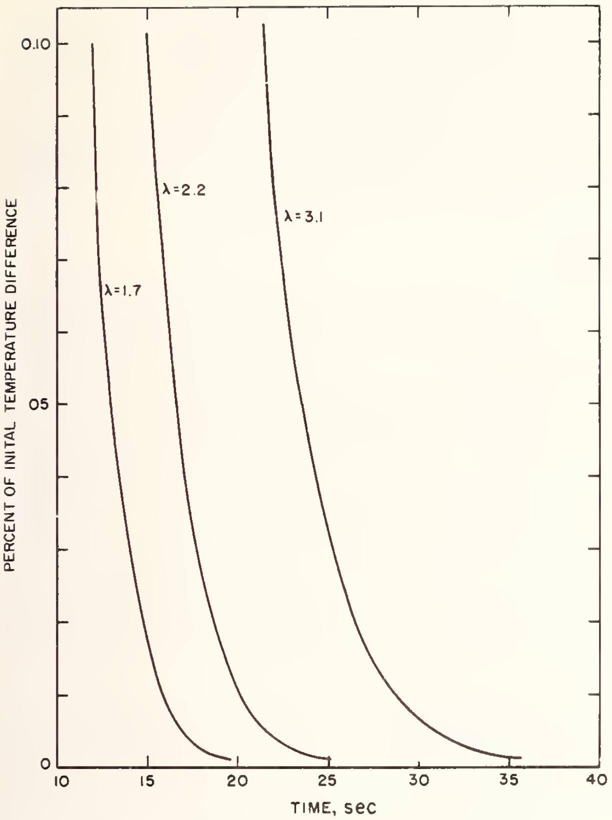


FIGURE 10.—*The approach to temperature in a stirred water bath for three thermometers with typical lag constants.*

former will read 0.001 degree higher than the latter, due to the lag. In the intercomparison of thermometers the rate of temperature rise may nearly always be kept so small that this lag correction is negligible.

If a thermometer at a given initial temperature is plunged into a bath at a different temperature, the lag, λ, is the time required for the original difference in temperature between thermometer and bath to be reduced to 1/*e* (that is 1/2.7) of itself. In a length of time 4 λ the difference will have become about 1.5 percent and in a length of time 7 λ about 0.1 percent of the original difference. Determinations of λ for solid stem laboratory thermometers representative of American manufacture have yielded values of about 2 to 3 seconds in a well-stirred water bath. Figure 10 shows the approach of thermometer readings to the water bath temperature for 3 selected thermometers having different values of λ. For example, if the thermometer for which λ=2.2 sec is initially at 25 °C and then is immersed in a bath at 75 °C, the thermometer reading will be within 0.05 °C (0.1 percent of 50 °C) of the bath temperature in 15 sec and within 0.01 °C in 19 sec. The curve for λ=3.1 was obtained for an American Society for Testing and Materials (ASTM) specification 56C calorimeter thermometer with a bulb diameter (outside) of 7.9 mm and bulb length of 44 mm. The value of λ=2.2 was found for an ASTM 7C thermometer having bulb dimensions of 5.4 by 12 mm. The third curve, for λ=1.7, was obtained for a bulb with dimensions of 5.4 by 34 mm. It is probable that most solid stem thermometers of American manufacture will have values of λ lying within the range covered by the 3 curves shown.

According to Harper [16] the value of λ for a given thermometer in a well stirred oil bath will be about twice its value for a water bath.

When a thermometer is used to measure changes of temperature, as in calorimetry, it has been shown by White [17] that the lag enters into the observations in such a way as to be eliminated from the results in applying the usual radiation corrections. Therefore the lag need not be considered, provided only that the initial and final readings are made when the temperature is varying uniformly. This is not strictly true, however, in the case of some Beckmann thermometers that have no true value of λ, as has been explained in the paper referred to above.

8.4. Separated Columns

Many inquiries are received concerning separated mercury columns, particularly after shipment. Since no means of avoiding such occurrences has yet been found, some directions for joining the mercury may be helpful. The mercury may separate somewhat more readily in thermometers which are not pressure-filled, but it can be more easily joined since there is little gas to separate the liquid. The process of joining broken columns consists of one or a series of manipulations which may be effective, and these are briefly described here.

(a) The bulb of the thermometer may be cooled in a solution of common salt, ice, and water (or other cooling agent) to bring the mercury down into the bulb. Moderate tapping of the bulb on a paper pad or equally firm object or the application of centrifugal force usually serves to unite the mercury in the bulb. If the salt solution does not provide sufficient cooling, carbon dioxide snow (dry ice) may be used. Since the temperature of dry ice is about −78 °C (−108 °F) and mercury freezes at about −40 °C (−40 °F) it will cause the mercury to solidify. Care must be taken to warm the top of the bulb first so that pressures in the bulb due to the expanding mercury may be relieved.

(b) If there is a contraction chamber above the bulb or an expansion chamber at the top of the thermometer the mercury can sometines be united by warming the bulb until the column reaches the separated portions in either enlargement. Great care is necessary to avoid filling the expansion chamber completely with mercury, which might produce pressures large enough to burst the bulb. Joining the mercury is more readily accomplished if the quantity in either cavity has first been shattered into droplets by tapping the thermometer laterally against the hand.

(c) As a last resort, especially for thermometers having no expansion chambers, small separated portions of the column can sometimes be dispersed by warming into droplets tiny enough to leave space for the gas to by-pass, and then droplets can then be collected by a rising mercury column.

The procedure for thermometers in which organic liquids are used is similar. Liquids in the stem can more readily be vaporized and may then be drained down the bore. The latter process is aided by cooling the bulb. All of these manipulations require patience, and experience is helpful, but they will yield results if care is used. A convenient method of ascertaining that all the liquid has been joined is a check of the ice point, or some other point on the scale.

9. References

[1] Federal Register, Title 15, Chapter II, Part 203 (copies available from NBS on request).

[2] H. F. Stimson, The International Practical Temperature Scale of 1948, J. Res. NBS **65A,** 1939 (1961).

[3] N. S. Osborne and C. H. Meyers, A formula an tables for the pressure of saturated water vapor in the range 0 to 374 C, J. Res. NBS **13,** 1 (1934) RP691.

[4] R. B. Scott and F. G. Brickwedde, A precision cryostat with automatic temperature regulation, BS J. Res. **6,** 401 (1931) RP284.

[5] E. Buckingham, The correction for emergent stem of the mercurial thermometer, Bul. BS **8,** 239 (1912) S170.

[6] L. H. Pemberton, Further consideration of emergent column correction in mercury thermometry, J. Sci. Instr. **41,** 234 (1964).

[7] J. A. Hall and V. M. Leaver, The design of mercury thermometers for calorimetry, J. Sci. Instr. **36,** 183 (1959).

[8] R. D. Thompson, Recent developments in liquid-in-glass thermometry, Temperature, Its Measurement and Control in Science and Industry **3,** Part 1 (Reinhold Publishing Corp., New York, 1962) p. 201.

[9] L. C. Liberatore and H. J. Whitcomb, Density changes in thermometer glasses, J. Am. Ceram. Soc. **35,** 67 (1952).

[10] American Society for Testing and Materials Designation C162–56, Standard Definitions of Terms Relating to Glass and Glass Products.

[11] H. R. Lillie and W. W. Shaver, Method of tempering glass, U.S. Patent No. 2,148,630 (Feb. 28, 1939).

[12] L. C. Liberatore, Method of stabilizing the molecular arrangement of glass thermometers, U.S. Patent No. 2,610,445 (Sept. 16, 1952).

[13] W. I. Martin and S. S. Grossman, Calibration drift with thermometers repeatedly cooled to −30 C, ASTM Bul. No. 231, 62 (July 1958).

[14] E. L. Ruh and G. E. Conklin, Thermal stability in ASTM thermometers, ASTM Bul. No. 233, 35 (Oct. 1958).

[15] C. E. Guillaume, Traité Practique de la Thermométrie, Gauthier-Villars et Fils, Paris (1889) p. 99.

[16] D. R. Harper 3d, Thermometric lag, Bul. BS **8,** 659 (1912) S185.

[17] W. P. White, Lag effects and other errors in calorimetry, Phys. Rev. **31,** 562 (1910).

Optical Pyrometry

UNITED STATES DEPARTMENT OF COMMERCE • Luther H. Hodges, *Secretary*
NATIONAL BUREAU OF STANDARDS • A. V. Astin, *Director*

Theory and Methods of Optical Pyrometry

H. J. Kostkowski and R. D. Lee

National Bureau of Standards Monograph 41

Issued March 1, 1962

Reprinted with Corrections September 1962

361-I

Contents

Theory and Methods of Optical Pyrometry*

H. J. Kostkowski and R. D. Lee

A detailed review of the theoretical methods of optical pyrometry and the application of these methods at the National Bureau of Standards in realizing, maintaining and distributing the International Practical Temperature Scale above 1063 °C is presented. In the theoretical presentation, the concepts of effective and mean effective wavelengths are introduced, and various equations relating these parameters to each other and other physical quantities are derived. The important features of precision visual optical pyrometers are discussed and a number of blackbody sources and tungsten strip lamps described. Detailed experimental procedures and results of primary and secondary calibrations of optical pyrometers at NBS are given. Finally, recommendations for achieving high precision and accuracy and the fundamental limitations in visual optical pyrometry are presented.

Introduction

The quantity and quality of technical and scientific investigations using optical pyrometry have been increasing steadily during the past 5 years. This has resulted in the need for an improvement in the efficiency and accuracy of optical pyrometer measurements. The National Bureau of Standards (NBS) has tried to meet its responsibilities in this area by developing new instruments such as the photoelectric pyrometer [1] [1] and by re-evaluating the theory and methods of optical pyrometry.

The current paper is an attempt to make the theory of optical pyrometry and the application of this theory at NBS readily accessible. Most of the theory presented is not new or original with the authors. However, much of it is scattered throughout the technical literature, and to the best of our knowledge, a detailed review of the theory in English does not exist. In addition to the general theory of optical pyrometry, the current paper presents the instrumentation and methods currently used at NBS to realize the International Practical Temperature Scale [2] above 1063 °C and to transfer this scale to instruments submitted for calibration.

No attempt has been made to present a complete bibliography on optical pyrometry. References to other papers are given only when a more detailed account than is given here is thought to be helpful to the reader.

1. Theory

1.1. The Planck Radiation Equation

The measurement of temperature utilizing optical pyrometry is based on the fact that the spectral radiance [3] from an incandescent body is a function of temperature. In particular, if the body is black, i.e. can absorb all the radiation that might be incident on it, the Planck radiation equation

$$N_{b\lambda}=\frac{C_1\lambda^{-5}/\pi}{e^{C_2/\lambda T}-1} \qquad (1\text{–}1)$$

relates the spectral radiance to the temperature. In eq (1–1) $N_{b\lambda}$ is the spectral radiance at the wavelength λ of a blackbody at a thermodynamic temperature T, and C_1 and C_2 are the first and second radiation constants. Thus it is possible to determine the thermodynamic temperature of a blackbody through the measurement of $N_{b\lambda}$ provided the other parameters in eq (1–1) are known. Absolute measurements of radiation, however, are very tedious and usually not very precise. To overcome these obstacles one could measure $N_{b\lambda}$ relative to some standard spectral radiance; thus defining a temperature scale based on the ratio of two spectral radiances, one of which is selected as a standard. This is the procedure adopted in the International Practical Temperature Scale (IPTS).

1.2. The International Practical Temperature Scale

The International Practical Temperature Scale of 1948 [2] defines the temperature, t, above the temperature of equilibrium between solid and liquid gold (gold point), t_{Au}, by the equation

$$\frac{N_{b\lambda}(t)}{N_{b\lambda}(t_{\mathrm{Au}})}=\frac{e^{\frac{C_2}{\lambda(t_{\mathrm{Au}}+T_0)}}-1}{e^{\frac{C_2}{\lambda(t+T_0)}}-1} \qquad (1\text{–}2)$$

where C_2 and the gold point, t_{Au}, are defined to be 1.438 centimeter degrees and 1063 °C, respectively,

---

*This paper was presented at the Fourth Symposium on Temperature, Its Measurement and Control in Science and Industry; Columbus, Ohio; March 27-31, 1961; sponsored by the American Institute of Physics, the Instrument Society of America, and the National Bureau of Standards. The proceedings will be published in book form by the Reinhold Publishing Corporation, New York, N.Y.

[1] Figures in brackets indicate the literature references at the end of this Monograph.

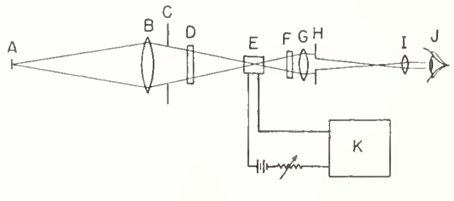
[2] Prior to 1960, this scale was called the International Temperature Scale. The new name, International Practical Temperature Scale, was adopted in October 1960 by the Eleventh General Conference on Weights and Measures.

[3] Spectral radiance is defined as the energy radiated by a body in a particular direction per unit time, per unit wavelength, per unit projected area of the body and per unit solid angle. Radiance is the integral with respect to wavelength of the spectral radiance. The American Standards Association has adopted the symbol, N_λ, for spectral radiance and this notation will be adhered to in this paper. The text of the International Practical Temperature Scale, however, utilizes the symbol J.

and T_0 is 273.15 degrees. Temperature-measuring instruments calibrated at the National Bureau of Standards are calibrated in terms of the IPTS, and therefore, temperature calibrations above the gold point are based on eq (1–2).

If it were possible to use eq (1–2) directly, little more would be required concerning the basic theory of optical pyrometry. However, this cannot be done because any observable radiation consists of a finite spectral band, and the question arises as to the wavelength to use in eq (1–2). In fact, most instruments used for this purpose at the present time use the eye as a detector and require a large spectral bandwidth [4] in order to have sufficient energy for the eye to see. Thus a major part of the theory to be presented is concerned with determining the wavelength to be used in eq (1–2). Since it is simpler to discuss this in terms of a particular instrument, the main features of the instrument commonly used will be given at this time. Nevertheless, the presentation will be sufficiently general to apply with minor modification to any such instrument, visual or photoelectric.

The instrument that is usually used to realize the IPTS above the gold point is the disappearing filament optical pyrometer. A schematic diagram of this instrument is shown in figure 1. The instrument is operated by imaging the blackbody or source whose temperature is to be determined onto the filament of the small pyrometer lamp and varying the current in this lamp until its filament disappears into the background of the source. At this time the photometric brightness [5] of the body and the pyrometer lamp filament as seen through the optical pyrometer are the same.



A SOURCE
B. OBJECTIVE LENS
C. OBJECTIVE APERTURE
D. ABSORPTION FILTER (Used for temp. above 1300 °C)
E. PYROMETER LAMP
F RED FILTER
G. MICROSCOPE OBJECTIVE LENS
H. MICROSCOPE APERTURE STOP
I. MICROSCOPE OCULAR
J. EYE
K. CURRENT MEASURING INSTRUMENT

FIGURE 1. *Schematic diagram of an optical pyrometer.*

If the instrument has been calibrated and the source is a blackbody, this brightness match will result in a temperature determination on the IPTS. The calibration of an optical pyrometer in which an attempt is made to realize the IPTS directly rather than from a calibrated pyrometer or source is termed a primary calibration. The remainder of this section will describe the theory required in order to perform a primary calibration on an optical pyrometer.

1.3. The Primary Calibration at the Gold Point

The first step in the primary calibration of an optical pyrometer is a brightness match of a blackbody at the gold point. A mathematical description of this match, i.e., the brightness of the blackbody being equal to the brightness of the pyrometer lamp, as seen through the instrument, is given by

$$\int_0^\infty N_{b\lambda}(t_{\mathrm{Au}})\tau'_\lambda\tau_{r\lambda}\tau''_\lambda V_\lambda d\lambda=\int_0^\infty N_\lambda(t_1)\tau_{r\lambda}\tau''_\lambda V_\lambda d\lambda \quad (1\text{–}3)$$

where $N_{b\lambda}(t_{\mathrm{Au}})$ is the spectral radiance of the blackbody at the temperature t_{Au}, the gold point, τ'_λ is the spectral transmittance of all the optical components preceding the pyrometer filament, $\tau_{r\lambda}$ that of the red filter, τ''_λ that of all optical components following the pyrometer filament except the red glass, V_λ the relative luminosity factor of the observer [6,7] and $N_\lambda(t_1)$ [8] is the spectral radiance of the pyrometer lamp filament at temperature t_1. $N_{b\lambda}(t_{\mathrm{Au}})$ as well as typical curves for V_λ and $\tau_{r\lambda}$ are shown in figure 2. The transmittances τ'_λ and τ''_λ are usually constant and equal to about 0.8 and 0.7, respectively, in the wavelength range of interest. The spectral brightness of a gold-point blackbody, $\beta_\lambda(t_{\mathrm{Au}})$, as seen through such a typical optical pyrometer, is also shown in figure 2. The area under β_λ is equal to the brightness and to the integrals in eq (1–3). When the brightness match is made, measurement of the current in the pyrometer lamp realizes the primary calibration at the gold point. It should be emphasized that the temperature of the pyrometer lamp t_1 or the lamp current at the match depends on the particular transmittances and the observer's relative luminosity factor. Changing any of these will, in general, change the calibration.

1.4. The Primary Calibration Above the Gold Point

To perform a primary calibration above the gold point, a procedure similar to that at the gold

---

[4] Photoelectric instruments which are now being developed have smaller bandwidths but still sufficiently large for the wavelength question to be significant.

[5] Photometric brightness of a surface is the radiance of the surface evaluated according to its capacity to produce visual sensation. In this paper, as elsewhere, the adjective photometric will often be omitted. The term luminance is also used sometimes in place of the term photometric brightness.

[6] The relative luminosity factor at a particular wavelength or relative visibility function, as it is sometimes called, is the ratio of the luminous flux at that wavelength to the maximum luminous flux, maximum with respect to wavelength.

[7] K. S. Gibson and E. P. T. Tyndall, Visibility of radiant energy, BS Sci. Pap., No. 475 (1923).

[8] Since $N_\lambda(t_1)$ is, in general, a function of direction or angle with respect to the tungsten filament surface, $N_\lambda(t_1)$ in eq (1–3) is an average over the range of angles involved. However, it will be seen later that only $N_{b\lambda}$ will be used quantitatively, and this is independent of direction.

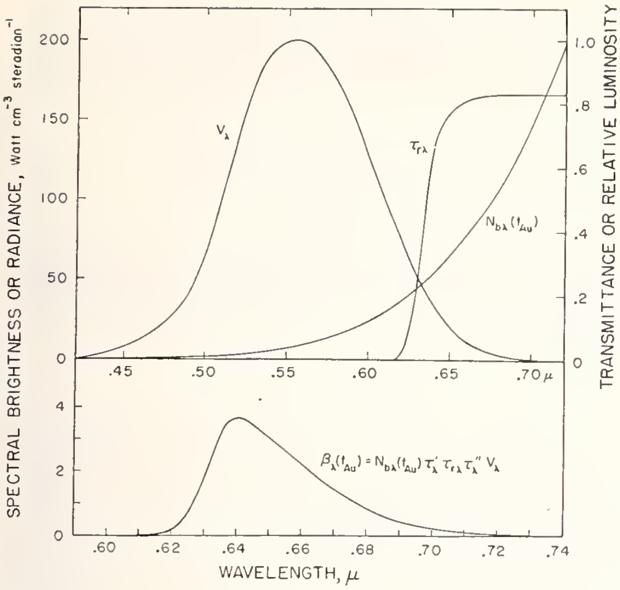


FIGURE 2. *The spectral brightness of a gold-point blackbody $\beta_\lambda(t_{Au})$ as observed by an observer with a relative luminosity function V_λ through an optical pyrometer having spectral transmittances $\tau_{r\lambda}$ for the red glass and $\tau_\lambda'=0.8$ and $\tau_\lambda''=0.7$ for all the optical elements preceding and following the pyrometer lamp filament respectively, excluding the red glass.*

point is followed except that the higher temperature, say t, must be determined. To obtain the temperature t a brightness match is made on the blackbody as seen through a device whose transmittance is constant with wavelength and of such value as to require the same pyrometer filament current as that used in the gold point blackbody match. Mathematically,

$$\int_0^\infty RN_{b\lambda}(t)\tau_\lambda'\tau_{r\lambda}\tau_\lambda''V_\lambda\,d\lambda=\int_0^\infty R\beta_\lambda(t)d\lambda$$

$$=\int_0^\infty N_\lambda(t_1)\tau_{r\lambda}\tau_\lambda''V_\lambda\,d\lambda=\int_0^\infty N_{b\lambda}(t_{\mathrm{Au}})\tau_\lambda'\tau_{r\lambda}\tau_\lambda''V_\lambda\,d\lambda$$

$$=\int_0^\infty \beta_\lambda(t_{\mathrm{Au}})d\lambda \qquad (1\text{–}4)$$

where R is the constant transmittance as a function of wavelength of the device, say a sectored disk. From the nature of the various functions in the integrands, a plot of the spectral brightnesses $\beta_\lambda(t)$ and $\beta_\lambda(t_{\mathrm{Au}})$ together with $R\beta_\lambda(t)$ as a function of wavelength would result in curves similar to those shown in figure 3. The wavelength at which $\beta_\lambda(t_{\mathrm{Au}})$ and $R\beta_\lambda(t)$ are equal is called the mean effective wavelength between the temperature t_{Au} and t and is denoted by $\lambda_{t_{\mathrm{Au}}-t}$. At this wavelength

$$RN_{b\lambda\,t_{\mathrm{Au}}-t}(t)=N_{b\lambda\,t_{\mathrm{Au}}-t}(t_{\mathrm{Au}}). \qquad (1\text{–}5)$$

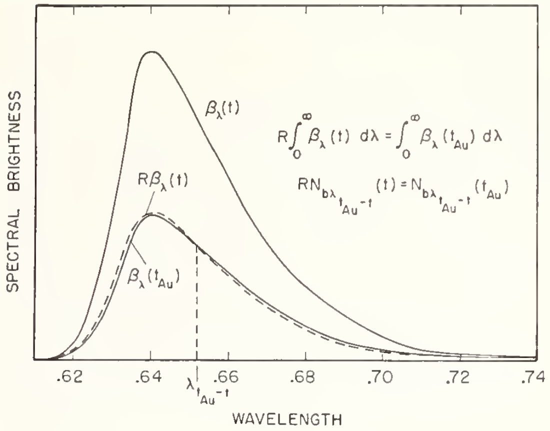


FIGURE 3. *Approximate spectral brightness as observed through an optical pyrometer of a blackbody at the temperature t_{Au} and a blackbody of temperature t such that the brightness of the t_{Au} blackbody equals that of the t blackbody when the latter is observed through a sectored disk of transmittance R.*

$\lambda_{t_{\mathrm{Au}}-t}$ is the mean effective wavelength between the temperature t_{Au} and t.

Thus the desired blackbody temperature t satisfies the defining equation for the IPTS and can be obtained by solving (usually numerical solutions are necessary) the integral equation represented by the first and fourth integrals in eq (1–4), provided all the transmittances and the relative luminosity function are known. In this manner a primary calibration could be performed at a temperature t greater than the gold point and repeated (with different sectored disks) for as many temperatures as necessary in order to obtain a smooth curve of blackbody temperature versus pyrometer-lamp current.

1.5. Absorbing Glasses

In order to have a very stable pyrometer lamp a vacuum lamp is usually used.[9] However, to assure long-term stability, a tungsten vacuum lamp is usually not used above a brightness temperature[10] of about 1350 °C. Thus, using the method just described, an optical pyrometer could only be calibrated to about 1350 °C. Higher temperature calibrations could be attained, however, by using the sectored disks as part of the calibrated instrument. For example, a 2280 °C blackbody appears, as seen through a sectored disk having a transmittance of 0.7 percent, to have the brightness at 6500 A of a 1350 °C blackbody. Therefore an optical pyrometer calibrated from

---

[9] This is discussed in detail in section 2 of this paper.

[10] The brightness temperature of a source is defined as the temperature of a blackbody which has the same spectral radiance at a particular wavelength as the source. Mathematically if $N_{\lambda'}(t)=N_{b\lambda'}(t')$, t' is the brightness temperature of the source at the wavelength λ'. Generally, the brightness temperature is different for different wavelengths.

1063 to 1350 °C together with sectored disks can be used to measure temperatures higher than 1350 °C. Equation (1–4) would be used to determine this higher temperature t where t_{Au} in eq (1–4) is replaced with a temperature below 1350 °C already realized. There are two disadvantages, however, in doing this. One is the inconvenience of using sectored disks routinely. The other is that one cannot realize temperatures much higher than the 2280 °C without incurring large errors from the uncertainty of the sectored disk transmittance. Though it might be possible to design and construct sectored disks for which the angular opening of the disk can be determined to better than 1 min of arc, this has not yet been done. For a 0.007 transmittance which is necessary to achieve 2280 °C an uncertainty of 1 min of arc amounts to an uncertainty of 2.0 deg C.

A means out of this dilemma is the use of a filter rather than a sectored disk to reduce the brightness of the source. Such a filter is called an absorbing glass and is usually inserted between the objective lens and the pyrometer lamp. The primary calibration of the pyrometer for temperature ranges using an absorbing glass would proceed as follows. The temperature t of a blackbody above 1350 °C but below 2280 °C would be determined as described in the last paragraph. Next the sectored disk would be removed, the absorbing glass inserted, and a brightness match made. The current in the pyrometer lamp at the match together with the absorbing glass constitutes a calibration point at the temperature t. Now one is able to proceed to even higher temperatures than 2280 °C because with each absorbing glass one can again use a sectored disk and need not use a disk with a very small transmittance.

There are other advantages in using an absorbing glass, particularly if its spectral transmittance is given by

$$\tau_{a\lambda}=e^{-k/\lambda} \tag{1–6}$$

where k is a constant with respect to wavelength. Suppose t_3 is a blackbody temperature above 1350 °C obtained by using eq (1–4). Looking at such a blackbody without a sectored disk but through an absorbing glass, and using Wien's radiation equation [11] rather than Planck's equation, we have for the integrated brightness

$$\int_0^\infty C_1\lambda^{-5}e^{-C_2/\lambda T_3}e^{-k/\lambda}\tau'_\lambda\tau_{r\lambda}\tau''_\lambda V_\lambda d\lambda$$
$$=\int_0^\infty C_1\lambda^{-5}e^{-\frac{C_2}{\lambda}\left(\frac{1}{T_3}+\frac{k}{C_2}\right)}\tau'_\lambda\tau_{r\lambda}\tau''_\lambda V_\lambda d\lambda \tag{1–7}$$

where $T_3=t_3+273.15$.[12] Thus a blackbody at the temperature T_3 appears through the absorbing glass as another blackbody at a temperature T_2 where

$$\frac{1}{T_2}=\frac{1}{T_3}+\frac{k}{C_2}=\frac{1}{T_3}+A. \tag{1–8}$$

Since k/C_2, the so-called "A" value of the absorbing glass, is a constant, any blackbody whose temperature is T_i will appear through the absorbing glass as another blackbody at a lower temperature T_j where

$$\frac{1}{T_j}=\frac{1}{T_i}+A. \tag{1–9}$$

The apparent temperature T_j can always be made less than 1350 °C by making the A value sufficiently large. Thus with an absorbing glass with this type transmittance, the A value is a constant and once obtained can be used together with eq (1–9) and a lower range calibration to calibrate the upper range. In addition, such an absorbing glass insures a close color match between the pyrometer lamp and the source. This is helpful for precise brightness matching. Furthermore, from eqs (1–7) and (1–8), the A value of two or more absorbing glasses used together is the sum of the individual A values. Therefore, since the A values are also independent of the blackbody temperature, a high-temperature calibration can be obtained without actually making observations at the high temperature but simply by determining the individual A values at some low temperature and adding them together for the high temperature.

1.6. The Relation Between Effective and Mean Effective Wavelengths

The basic principles involved in the primary calibration of an optical pyrometer at any temperature above the gold point have been described. In this method, sectored disks and absorption filters are used, and eq (1–4) is solved numerically for any pair of temperatures represented by t and t_{Au}. However, the amount of tedious calculation can be greatly reduced by introducing and utilizing the concept of effective wavelength.

If Wien's radiation equation rather than Planck's equation is used and t_{Au} and t are generalized to any two temperatures t_1 and t_2, one obtains by using eqs (1–4) and (1–5)

$$\frac{\int_0^\infty \lambda^{-5}e^{-C_2/\lambda T_1}\tau'_\lambda\tau_{r\lambda}\tau''_\lambda V_\lambda d\lambda}{\int_0^\infty \lambda^{-5}e^{-C_2/\lambda T_2}\tau'_\lambda\tau_{r\lambda}\tau''_\lambda V_\lambda d\lambda}=e^{-\frac{C_2}{\lambda_{T_1-T_2}}\left(\frac{1}{T_1}-\frac{1}{T_2}\right)} \tag{1–10}$$

---

[11] Wien's radiation equation states $N_{b\lambda}=(C_1\lambda^{-5}/\pi)\exp(-C_2/\lambda T)$ and for a temperature of 5000 °K and a wavelength of 7500 A (approximately the longest wavelength required in eq (1–4)) it is about 2 percent smaller than the Planck equation, while at 2500 °K and 7500 A it is only 0.05 percent smaller.

[12] $T_i=t_i+273.15$ °C is called the International Practical Kelvin temperature

Designating the integrals in the numerator and denominator of eq (1–10) as B_1 and B_2, respectively, and taking the natural logarithm of both sides of eq (1–10) leads to

$$\frac{1}{\lambda_{T_1-T_2}}=\frac{\ln B_1-\ln B_2}{C_2\left(\frac{1}{T_2}-\frac{1}{T_1}\right)}. \tag{1–11}$$

The effective wavelength λ_T[13] at $T_1=T$ is defined as

$$\frac{1}{\lambda_T}=\lim_{T_2\to T}\frac{1}{\lambda_{T-T_2}}. \tag{1–12}$$

Through the use of this definition and eq (1–11) one obtains

$$\frac{1}{\lambda_T}=\frac{1}{C_2}\frac{d(\ln B)}{d\left(\frac{1}{T}\right)} \tag{1–13}$$

or

$$\int_{\frac{1}{T_1}}^{\frac{1}{T_2}}\frac{1}{\lambda_T}\,d\left(\frac{1}{T}\right)=\frac{\ln B_2-\ln B_1}{C_2} \tag{1–14}$$

and if eq (1–11) is substituted into eq (1–14)

$$\frac{1}{\lambda_{T_1-T_2}}=\frac{1}{\frac{1}{T_1}-\frac{1}{T_2}}\int_{\frac{1}{T_1}}^{\frac{1}{T_2}}\frac{1}{\lambda_T}\,d\left(\frac{1}{T}\right). \tag{1–15}$$

Hence the reciprocal of the mean effective wavelength between two temperatures is the center of gravity of the reciprocal of the effective wavelength with respect to and between the reciprocal temperatures

An expression useful for computing the reciprocal effective wavelength can be derived as follows. From eq (1–10) and the definition of β and mean effective wavelength, one obtains

$$\frac{B_2}{B}=\left(\frac{\beta_2}{\beta}\right)_{\lambda_{T-T_2}}. \tag{1–16}$$

Then

$$\left(\frac{B-B_2}{T-T_2}\right)\frac{1}{B}=\left[\left(\frac{\beta-\beta_2}{T-T_2}\right)\frac{1}{\beta}\right]_{\lambda_{T-T_2}} \tag{1–17}$$

and

$$\lim_{T_2\to T}\left(\frac{B-B_2}{T-T_2}\right)\frac{1}{B}=\lim_{T_2\to T}\left[\left(\frac{\beta-\beta_2}{T-T_2}\right)\frac{1}{\beta}\right]_{\lambda_{T-T_2}} \tag{1–18}$$

or

$$\frac{1}{B}\frac{dB}{dT}=\left(\frac{1}{\beta}\frac{d\beta}{dT}\right)_{\lambda_T}. \tag{1–19}$$

Substituting for β and B, differentiating and solving for $1/\lambda_T$ leads to

$$\frac{1}{\lambda_T}=\frac{\int_0^\infty\frac{N_{\lambda b}(T)\tau'_\lambda\tau_{r\lambda}\tau''_\lambda V_\lambda}{\lambda}\,d\lambda}{\int_0^\infty N_{\lambda b}(T)\tau'_\lambda\tau_{r\lambda}\tau''_\lambda V_\lambda d\lambda}. \tag{1–20}$$

By numerical integration of eq (1–20), the effective wavelength can be determined for any temperature T. Doing this for 5 or 6 temperatures in a particular range of a pyrometer is usually sufficient to enable one to plot an accurate curve of λ_T versus T for that range. Moreover, it turns out that $1/\lambda_T$ is, to a good approximation, a linear function of $1/T$ and therefore

$$\frac{1}{\lambda_{T_1-T_2}}\cong\frac{1}{2}\left(\frac{1}{\lambda_{T_1}}+\frac{1}{\lambda_{T_2}}\right). \tag{1–21}$$

This approximation is usually correct to about five significant figures. Therefore from the λ_T versus T or $1/\lambda_T$ versus $1/T$ curves and eq (1–21), the mean effective wavelength between any two temperatures can be obtained. When one of the temperatures is not known initially, such as in a primary calibration, the mean effective wavelength is assumed to be 0.65 μ and the unknown temperature computed from eq (1–5). Using this first approximation of the temperature, a second approximation of the mean effective wavelength can be determined from the effective wavelength curve and eq (1–21) and a second approximation of the temperature obtained from eq (1–5). One or two such successive approximations are usually sufficient. Hence, through the use of effective wavelengths, integral equations need be solved only when initially determining the effective wavelength versus temperature curves.

1.7. The Use of Non-blackbody Sources in a Primary Calibration

All that has been presented so far has required a blackbody source, not only at the gold point but at higher temperatures. However, it is possible to use any stable source (excluding, of course, the gold-point blackbody) without error, when absorbing glasses are not used, and a tungsten strip lamp with only small errors ($<1°$), when absorbing glasses are used. This is easily verified from the integrated brightness equations. For example, suppose instead of looking at a blackbody of temperature t_1 through a sectored disk of such transmittance that the blackbody's integrated brightness appeared to be equal to that of a gold-point blackbody, a tungsten strip lamp was used and adjusted until through the

---

[13] In some references, the effective wavelength is called the limiting effective wavelength and the mean effective wavelength is called the effective wavelength.

same sectored disk, it matched the gold point. Mathematically,

$$\int_0^\infty N_{b\lambda}(t_{\mathrm{Au}})\tau'_\lambda \tau_{r\lambda}\tau''_\lambda V_\lambda d\lambda$$

$$=R\int_0^\infty N_{b\lambda}(t_1)\tau'_\lambda \tau_{r\lambda}\tau''_\lambda V_\lambda d\lambda$$

$$=R\int_0^\infty \epsilon_\lambda(t_2)N_{b\lambda}(t_2)\tau_\lambda\tau'_\lambda \tau_{r\lambda}\tau''_\lambda V_\lambda d\lambda$$

$$=R\epsilon_c(t_2)\tau_e\int_0^\infty N_{b\lambda}(t_2^c)\tau'_\lambda \tau_{r\lambda}\tau''_\lambda V_\lambda d\lambda \qquad (1\text{–}22)$$

where t_2 is the temperature of the tungsten, $\epsilon_\lambda(t_2)$ its spectral emittance, τ_λ and τ_e the spectral and effective transmittance of the glass envelope of the tungsten lamp, $\epsilon_c(t_2)$ is the color emissivity [14] and t_2^c is the color temperature [14] for tungsten at a temperature t_2. From the second and fourth integrals in eq (1–22) and the definition of mean effective wavelength, one notes that the tungsten as seen through the lamp envelope has a brightness temperature [10] t_1 at the mean effective wavelength $\lambda_{t_1-t_2^c}$. If an absorbing glass is inserted in the optical path of the pyrometer when the sectored disk is removed, this mean effective wavelength changes. Mathematically,

$$\int_0^\infty \epsilon_\lambda(t_2)\, N_{b\lambda}(t_2)\tau_\lambda\tau_{a\lambda}\tau'_\lambda \tau_{r\lambda}\tau''_\lambda\, V_\lambda d\lambda$$

$$=\epsilon_c(t_2)\tau_e\int_0^\infty N_{b\lambda}(t_2^c)\tau_{a\lambda}\tau'_\lambda \tau_{r\lambda}\tau''_\lambda\, V_\lambda d\lambda$$

$$=\int_0^\infty N_{b\lambda}(t'_1)\tau_{a\lambda}\tau'_\lambda \tau_{r\lambda}\tau''_\lambda V_\lambda d\lambda. \qquad (1\text{–}23)$$

In addition as seen from eq (1–23) the brightness temperature will, in general, also change from t_1 to some temperature t'_1. A relationship between t'_1 and t_1 can be obtained as follows. From eqs (1–22) and (1–23) and the definition of mean effective wavelength, one obtains

$$\left[\frac{N_{b\lambda}(t_1)}{N_{b\lambda}(t_2^c)}\right]_{\lambda_{t_1-t_2^c}}=\epsilon_c(t_2)\tau_e=\left[\frac{N_{b\lambda}(t'_1)}{N_{b\lambda}(t_2^c)}\right]_{\lambda_{t'_1-t_2^c}} \qquad (1\text{–}24)$$

Then, using Wien's equation

$$e^{-\frac{c_2}{\lambda_{t_1-t_2^c}}\left(\frac{1}{T_1}-\frac{1}{T_2^c}\right)}=e^{-\frac{c_2}{\lambda_{t'_1-t_2^c}}\left(\frac{1}{T'_1}-\frac{1}{T_2^c}\right)} \qquad (1\text{–}25)$$

and

$$\frac{1}{\lambda_{t_1-t_2^c}}\left(\frac{1}{T_1}-\frac{1}{T_2^c}\right)=\frac{1}{\lambda_{t'_1-t_2^c}}\left(\frac{1}{T'_1}-\frac{1}{T_2^c}\right). \qquad (1\text{–}26)$$

Rearranging and subtracting $1/T_1\lambda_{t'_1-t_2^c}$ from each side of eq (1–26) gives

$$\frac{1}{T_1}\left(\frac{1}{\lambda_{t_1-t_2^c}}-\frac{1}{\lambda_{t'_1-t_2^c}}\right)=\frac{1}{T_2^c}\left(\frac{1}{\lambda_{t_1-t_2^c}}-\frac{1}{\lambda_{t'_1-t_2^c}}\right)$$

$$+\frac{1}{\lambda_{t'_1-t_2^c}}\left(\frac{1}{T'_1}-\frac{1}{T_1}\right). \qquad (1\text{–}27)$$

Combining the term on the left of eq (1–27) and the first term on the right, multiplying through by $\lambda_{t'_1-t_2^c}$, and solving for $1/T'_1$ results in

$$\frac{1}{T'_1}=\frac{\lambda_{t'_1-t_2^c}-\lambda_{t_1-t_2^c}}{\lambda_{t_1-t_2^c}}\left(\frac{1}{T_1}-\frac{1}{T_2^c}\right)+\frac{1}{T_1}. \qquad (1\text{–}28)$$

In practice T'_1, the brightness temperature with the absorbing glass inserted, is only a degree or two different from T_1 and very insensitive to T_2^c. The correction of a degree or two can usually be made sufficiently accurate so that the resulting error is less than one degree.

It has been shown that a blackbody source is not needed for a primary calibration above the gold point of an optical pyrometer. When absorbing glasses are used, however, a source for which a color temperature exists, at least in the spectral bandwidth of the pyrometer, and which is approximately known as a function of brightness temperature is required.

The basic theory of optical pyrometry has been developed. The application of this theory at NBS to actual calibrations of optical pyrometers is given in sections 4 and 5. The basic characteristics of optical pyrometers and the sources of radiation commonly used in optical pyrometry will be presented in sections 2 and 3.

2. Optical Pyrometers

In this section, some of the more important general characteristics of optical pyrometers as well as a detailed description of the NBS pyrometer will be presented. Detailed accounts of the commercially available instruments are given in instruction manuals issued by the manufacturers or, for the noncommercial instruments, in published research papers [3–6].

2.1. General Characteristics of Optical Pyrometers

The visual optical pyrometer, the schematic diagram of which is shown in figure 1, is an instrument of surprisingly high precision and accuracy. This is mainly the result of the high stability of the pyrometer lamp and the proper selection of apertures and filters.

---

[14] The color temperature of a source in a particular wavelength region is here defined as that temperature at which a blackbody has in this spectral region the same relative spectral radiance as the source. Mathematically, $\epsilon_\lambda(t)N_{b\lambda}(t)=\epsilon_c(t)N_{b\lambda}(t^c)$ for all wavelengths where ϵ_c is the color emissivity and a constant with respect to wavelength.

a. The Pyrometer Lamp

The pyrometer lamp is probably the most important element in the optical pyrometer. It serves as the instrument's reference standard for radiance. Most pyrometer lamps used today consist of a round or flat highly pure tungsten filament in an evacuated small (dimensions of a few centimeters) glass envelope. The envelope has plane windows of good optical quality which are sometimes oriented so as to avoid troublesome reflections. A vacuum rather than gas lamp is preferred because the elimination of convective and reduction of conductive heat transfer make the lamp's radiance less dependent on its orientation or ambient temperature [5].

Typical dimensions of lamp filaments are 0.03 to 0.05 mm diameter for round filaments and 0.05 to 0.1 mm by 0.005 mm for ribbon filaments. Lengths vary from 20 to about 40 mm. The small cross-sectional area and relatively long length keep the current and voltage requirements low (30 to 200 ma, which is obtained with less than 6 v) and reduce the heat losses through lead conduction, thus further reducing the effect of ambient temperature on lamp radiance. These filament dimensions also make the time constant of the lamp short. For example, pyrometer lamps of the type described reach within 2 deg C of their final temperature within 5 to 60 sec from the initial turn-on time, the exact time depending on the particular filament dimensions and the final temperature.

Pyrometer lamps are usually calibrated using electrical current as the parameter to which the brightness temperature is related. Current is a more convenient parameter to use than lamp resistance or power input and appears to be a sufficiently stable function of brightness temperature, at least to the extent of requirements in visual optical pyrometry. Direct current is used so that a potentiometer may be utilized for determining the current. It is important that the direction of current in the filament during use be the same as that for which the lamp was calibrated. Due to the Thompson effect, a reversal of the current will modify the temperature distribution along the filament and therefore change the radiance at the sighting area. Most commercial pyrometer lamps have a rate of change of current with brightness temperature varying from about 0.05 ma per degree at 800 °C to 0.1 ma per degree at 1350 °C. Corresponding figures for higher source temperatures when using absorbing glasses can be determined by using eq (1–9).

New pyrometer lamps are extensively annealed or aged before being calibrated. The purpose of the annealing is to complete the recrystallization of the tungsten which occurs when the metal is subjected to high temperature. Since the recrystallization modifies the resistivity and emittance of the tungsten, the calibration of the pyrometer lamp will change during this time. Usually, the lamps in commercial pyrometers are annealed by the manufacturer. For lamps made at NBS, an anneal of several thousand hours at about 1800 °K (approximately 1400 °C brightness temperature at 0.65 μ) has been adequate for visual optical pyrometry. However, recently, using the new NBS photoelectric pyrometer [1] several NBS and commercial lamps were observed to change in brightness temperature (for a fixed current) from ½ to 1 °C in 300 hr in the vicinity of 1063 °C after having been annealed for 2000 hr at 1800 °K. On the other hand, one NBS constructed pyrometer lamp has been used for about 4000 hr without changing this much. At the present time, the difference in the two results is not understood. Thus, unless the stability of a particular pyrometer lamp has been established, it is recommended that for accurate work a lamp be compared with other lamps or recalibrated after being used for 200 hr. As a corollary to this, an optical pyrometer lamp after being calibrated should be left off except when brightness matches are actually being made, keeping in mind of course the time required for the lamp to reach equilibrium.

b. Apertures and Filters

In addition to the stability of the pyrometer lamp, two characteristics which are required for an accurate optical pyrometer are that the ratio of the brightness of the pyrometer filament to that of the source be independent of the source distance and that there be a highly reproducible means for realizing this ratio.

The first characteristic is largely achieved through the microscope and objective apertures. The microscope aperture is the aperture stop for the entire optical system, and from a geometrical optics viewpoint is adequate to maintain the ratio of the source to the filament brightness independent of source distance. However, due to the diffraction pattern of the source being partially obscured by the filament, the radiance of the source image, particularly in the vicinity of the pyrometer filament, depends on the angular size of the cone of radiation incident on the pyrometer filament. By adding the objective aperture, this cone is kept constant regardless of source distance.

In most optical pyrometers, the test that the observer uses to determine the existence of the brightness ratio or match is the disappearance of the pyrometer filament into the source image. For this to occur the color of the incandescent filament must be (visually) the same as that of the source image. For temperatures below which absorbing glasses are used, this is achieved fairly well by using a sharp cut-off red filter with a transmittance curve such as that shown in figure 2. This filter, cutting off the shorter wavelengths, and the visibility function of the eye, cutting off the longer wavelengths, produce a sufficiently narrow spectral bandwidth so that an adequate color match exists for most sources. However, Lovejoy has shown [7] that greater precision can be obtained for brightness temperatures below 850 °C by removing the red glass. This is a consequence of increasing the apparent brightness of the source and the pyrometer filament and therefore decreasing the eye's threshold contrast or contrast limen.[15]

Where sector disks or neutral absorbing glasses are used or where a non-blackbody source has a much higher color temperature than its brightness temperature, a noticeable color mismatch may exist. The spectral distribution of the source is characteristic of a high temperature while that of the filament of a low temperature, giving the source image a more orange like color relative to the filament. An observer will probably be aware of a difficulty in brightness matching or disappearance before he is aware of the color mismatch. This effect is minimized, at least for blackbody and tungsten sources, by the use of absorbing glasses which have the previously described exponential transmittance. Most high-precision optical pyrometers use such absorbing glasses.

c. Fairchild's Criterion

Even when a color match exists, a complete visual disappearance is not possible in some optical pyrometers. As a brightness match or disappearance is approached, a thin dark line appears outside the edge of the filament, and/or a bright line appears inside the edge. The origin of these lines has not been definitely established. However, Cunnold [8] develops a rather strong case that the bright line is caused by deviations from Lambert's cosine law, particularly for round filaments, and that the dark line is caused by diffraction effects at the edge of the pyrometer filament. Fairchild and Hoover [3] experimentally determined how to avoid the appearance of these effects and obtain complete visual disappearance. They found that if the ratio of the exit angle to the entrance angle at the pyrometer filament, α/β, as shown in figure 4 is sufficiently small, the dark or bright lines are not observed. The required ratio for disappearance is a function of the width and shape (round or flat) of the pyrometer filament [3] and has become known as Fairchild's criterion. It should be pointed out, however, that Cunnold [8] contends that complete disappearance is not the most precise condition for determining a brightness match and that the apertures can be selected such that the resulting enhanced variation of brightness across a round filament permits a more precise match than can be obtained by disappearance. Moreover, under these conditions, the exit angle may be made considerably larger and since the pyrometer's transmittance is greater, lower brightness temperatures can be measured or a narrower spectral bandwidth can be used. The latter would allow a more accurate determination of mean effective wavelength. In spite of Cunnold's convincing arguments, little effort has been made in this direction, and complete disappearance is still used to determine a brightness match in most visual optical pyrometers.

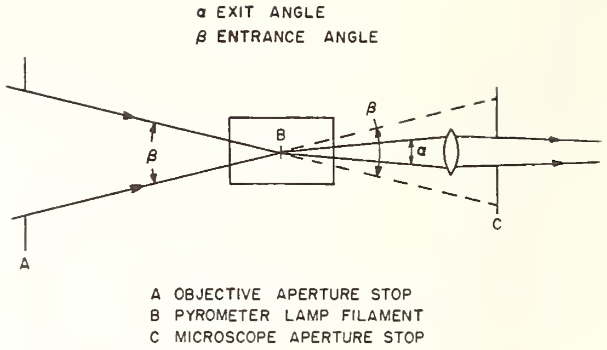


FIGURE 4. *Schematic diagram showing the entrance and exit angles at the optical pyrometer filament.*

Optical pyrometer design has not been carried to its ultimate but only to the extent that the major limitation in precision and accuracy is the observer. The more important general characteristics and requirements of this design have been presented. Their integration into an actual instrument will be illustrated through a detailed description of the NBS optical pyrometer.

2.2. The NBS Optical Pyrometer

The National Bureau of Standards maintains a specially designed visual optical pyrometer for realizing the International Practical Temperature Scale above 1063 °C and for distributing this scale throughout the United States by the calibration of pyrometers and tungsten strip lamps. The NBS pyrometer is based on the design of Fairchild and Hoover [3] and, to the best of our knowledge, has been in use since about 1923. It is described here in order to clarify the pyrometer design characteristics already discussed and to prepare the reader for sections 4 and 5 on calibrations.

a. Objective Lens Assembly

Figure 5 is a cross section of the NBS optical pyrometer. The objective lens is a plano-convex achromatic doublet with a clear aperture of 4.3 cm and a focal length of about 13.6 cm. The source is generally positioned about 65 cm from the pyrometer filament and the objective lens adjusted through a rack and pinion gear assembly until the source image is at the filament. At this position the objective lens is about 45 cm from the source and 20 cm from the source image. The objective aperture is 1 cm in diameter and 10.8 cm from the filament, forming a fixed entrance angle of about 0.093 radian, independent of the position of the objective lens.

---

[15] Contrast limen is defined as $|(B_t-B_s)/B_s|$ where B_s is the brightness of a background reference source and B_t is the brightness of a test area for which there is a 50 percent probability of an observers detecting it from the background. The contrast limen is a function of B_s and increases rapidly for brightnesses lower than those associated with optical pyrometer observations below about 1000 °C.

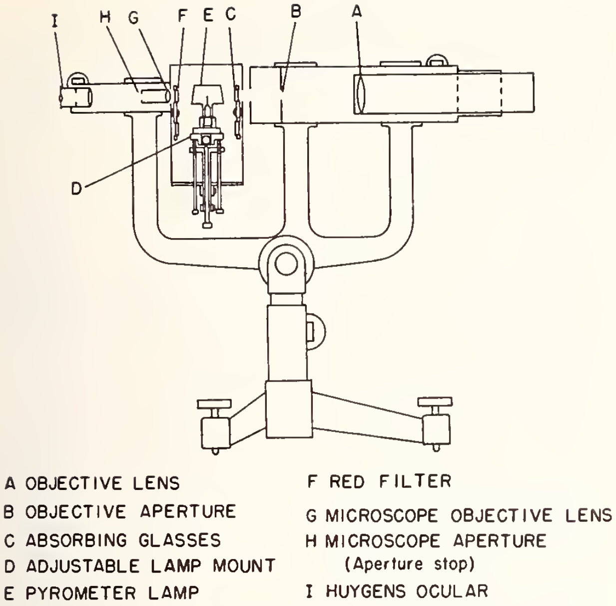


Figure 5. *Sketch of the NBS visual optical pyrometer.*

In the construction of the NBS pyrometer, provision was made for inserting sectored disks between the objective aperture and the pyrometer lamp. Though this position is still used occasionally for routine work, it is no longer used in primary calibrations because of vibrations being set up in the pyrometer filament and because of the sectored disks of low transmittance acting as objective apertures. The alternate position for the sectored disks that is usually used is at the source. This is accomplished by forming with an auxiliary lens an image of the source at the distance from the filament that the source itself is normally positioned and placing the sectored disk there.

b. Absorbing Glasses, Pyrometer Lamp and Red Filter

The absorbing glasses, pyrometer lamp, and red filter are contained in a box in which the temperature can be accurately controlled. Thermostating this box, however, was found unnecessary and has not been done for years. Nevertheless, as a precautionary measure, the temperature of the room in which the pyrometer is used is controlled to within ±1.5 deg C.

The absorbing glasses are mounted on a disk which can be rotated into any of four positions representing four of the instrument's five ranges. These are designated as Ag 0 (no absorbing glass), AG 1, AG 2, and AG 3, and are used for temperatures from 800 to 1350 °C, 1300 to 1750 °C, 1700 to 2050 °C, and 2000 to 2400 °C, respectively. Their spectral transmittances are given in table 1. The fifth range is selected by placing another absorption glass called the extension glass in front of the objective lens and using it in series with AG 3. The instrument can be used up to 4000 °C in this manner. AG 1 and the extension glass are Corning pyrometer brown glasses and have a constant A value at least within the precision of the measurements. Ag 2 and 3 are composite glasses. Before the advent of the Corning pyrometer brown glass, a constant A value was achieved by combining two or more glass filters. Only the red portion of the spectrum needed to be considered, and these glasses appear magenta to the unaided eye.

The pyrometer lamp is mechanically mounted with sufficient degrees of freedom to permit precise alinement. The lamp, now in use, is designated L1 and has been used in the pyrometer since 1953. It is a vacuum lamp with a round filament 0.035 mm in diameter and about 40 mm long. The filament contains a number of small coils which increase the length of the filament possible and decrease the effect of ambient temperature. The coils also reduce temperature gradients by radiation exchange. The central part of the filament is horizontal except for a slight dip at the center which serves to indicate the portion used in brightness matches. The lamp envelope is Pyrex and has plane windows inclined about 10 deg from the normal to the optical axis as shown in figure 5.

The previous gold-point primary calibrations of L1 indicate that it has not changed by more than 1.5 deg C at 1063 °C since 1953 and has not changed at all within the experimental error since 1957.

Following the pyrometer lamp in the optical train is the red glass whose spectral transmittance is given in table 1. It is located 4.0 cm from the pyrometer filament and is mounted on a rotatable disk similar to that containing the absorbing glasses. The disk has open areas in which red glasses from optical pyrometers being calibrated may be mounted and compared to the NBS red glass.

Table 1. *Spectral transmittances of the absorbing glasses and the red filter in the NBS visual optical pyrometer and the CIE standard relative luminosity factors*

Wave-length	Spectra ltransmittances				Luminosity factors (CIE)
	Ag 1	Ag 2	Ag 3	Red filter	
mμ					
600	0.043	0.009	0.003	0.000	0.631
610	.048	.010	.003	.001	.503
620	.052	.011	.004	.019	.381
630	.056	.011	.004	.292	.265
640	.059	.012	.005	.678	.175
650	.062	.014	.005	.800	.107
660	.065	.015	.006	.830	.061
670	.067	.017	.006	.841	.032
680	.069	.019	.007	.847	.017
690	.070	.022	.009	.850	.0082
700	.070	.025	.010	.850	.0041
710	.070	.028	.011	.849	.0021
720	.070	.031	.012	.846	.00105
730	.069	.034	.014	.844	.00052
740	.068	.037	.015	.839	.00025
750	.066	.040	.017	.836	.00012
760	.065	.044	.018	.830	.00006
770	.063	.048	.020	.826	.00003
780	.060	.051	.022	.821	.000015

c. Microscope Assembly

Beyond the red glass is a lens assembly similar in design to a low-power microscope. The objective lens of the microscope is 0.7 cm in diameter, has a focal length of about 4.0 cm and is mounted about 6.3 cm from the pyrometer filament. At a distance of 4.0 cm from the microscope objective is the microscope aperture which is the aperture stop for the entire pyrometer. For brightness temperatures above 1050 °C, the aperture stop is 0.16 cm in diameter, producing an exit angle at the pyrometer lamp of about 0.04 radian. This, in conjunction with the 0.093-radian entrance angle, satisfies Fairchild's criterion for visual disappearance for the round filament used. At brightness temperatures between 950 and 1050 °C an aperture stop of 0.24 cm is used, from 850 to 950 °C an aperture stop of 0.32 cm is used and below 850 °C a stop of 0.40 cm is used. With these larger stops Fairchild's criterion is not satisfied, being sacrificed in order to increase the apparent brightness[16] and reduce the contrast limen. However, the apparent brightness is now low enough so that the edge effects are not visible to the eye, i.e., disappearance still exists.

A 10-power Huygens ocular completes the microscope assembly and the optics of the optical pyrometer. The microscope assembly thus magnifies the pyrometer filament by a factor of about 17, and since the source observed by the pyrometer objective is magnified by 0.5, the overall magnification of the source by the pyrometer is about 8.5. With the 0.16 cm aperture stop, the exit pupil, which is the image of the aperture stop formed by the ocular, is about 0.07 cm. When compared to the eye pupil diameter of 0.3 to 0.5 cm for the brightness encountered with this aperture stop, one is led to postulate that disappearance of the pyrometer filament is achieved to some extent by insufficient resolving power, fine details at the edge of the filament being washed out.

d. The Electrical Circuit

The electrical current measuring apparatus used with the NBS pyrometer is rather straightforward. The pyrometer lamp is connected in series with a resistance box, a multiturn rheostat, a 6v lead storage battery, a milliammeter, and a 0.1-ohm standard resistor. A high-precision potentiometer, standardized by a temperature stabilized saturated electrical cell, determines the filament current by measuring the voltage drop across the 0.1-ohm standard resistor.

The L1 current ranging from 65 to 160 ma is usually determined to the nearest 0.01 ma. Values of current corresponding to 1 deg C change in brightness temperature are 0.12 ma at 800 °C, 0.17 ma at 1063 °C, and 0.20 ma at 1350 °C. It has been a relatively simple matter, using the above described electrical equipment, to attain a long-term reproducibility in pyrometer lamp current measurements of better than 1 part in 10,000 which is more than adequate for visual optical pyrometry.

3. Sources

The two major types of sources used in optical pyrometry are blackbodies and tungsten strip lamps. The blackbody is the most fundamental source of radiation because it is generally accepted that the Planck radiation equation exactly describes the spectral radiation from a blackbody as a function of temperature and wavelength. However, highly stable blackbodies are not convenient to use, particularly at high temperatures. Moreover, blackbodies for temperatures much higher than 1000 °C are not readily available commercially (as of 1961). On the other hand, tungsten strip lamps are highly stable, easy to use, and commercially available. As a result, when very accurate knowledge of the spectral distribution of radiation from a source is not as important as high stability and convenience, tungsten strip lamps are used.

In this section some of the general principles of the design and use of blackbodies, tungsten strip lamps, and other sources will be presented, with particular emphasis on those used at NBS.

3.1. Blackbodies

A blackbody is a substance or object which completely absorbs any radiation that is incident on it. If such a substance or object has a uniform temperature, it will emit radiation as determined by its temperature and by Planck's radiation equation. Lampblack is an example of a substance that approaches a blackbody, at least in the visible spectral region,[17] to within about 1 percent, i.e., it absorbs about 99 percent of the visible radiation falling on it.

A hollow, opaque body containing a small hole can be made to approximate a blackbody extremely well, and sources used as blackbodies are usually of this type. In such bodies, the smaller the area of the hole relative to the area of the walls of the cavity, the higher the emittance or blacker the body. For a particular geometry, the blackness of a hollow body also depends on the reflectivity of the inner surface of the cavity, including how diffuse or specular it is. As an

---

[16] The apparent brightness is proportional to the retinal illumination and the exit pupil of the pyrometer is generally smaller than the pupil of the eye. Therefore by increasing the aperture stop diameter, the illumination and the apparent brightness can be increased

[17] It is possible for a substance or object to have an absorptance of unity in some wavelength region or regions but not in all. Such a body is not, strictly speaking, a blackbody; but radiates as a blackbody in the regions where its absorptance is unity. From Kirchoff's law, which states that the ratio of the spectral radiance of a body at a uniform temperature to its spectral absorptance is equal to the spectral radiance of a blackbody, and from the definition of spectral emittance given in section 1, the spectral absorptance of a body is equal to its spectral emittance.

example, the radiation emitted from the bottom of a hollow cylinder of which one end is closed and the other open and whose inner walls are at a uniform temperature is about 0.99 that of a blackbody provided the ratio of the depth of the cylinder to its radius is 10, its normal reflectivity is 0.2, and it is diffuse [9]. If the same conditions existed except for the reflectivity being largely specular, the effective emittance of the cylinder would be about 0.90 [9]. Calculations of the effective emittance of hollow bodies of various shapes, sizes, and reflectivities can be found in the literature [9–11].

a. Gold-Point Blackbodies

The hollow bodies used as gold-point blackbodies for realizing the IPTS are probably the closest approximation to blackbody radiators currently in existence. Figures 6 and 7 show two such "blackbodies,"[18] with vertical and horizontal axes respectively, which were designed and constructed at NBS. The gold used to surround the cavities is 0.99999 pure. In both cases the sighting tubes and the crucibles for the gold are made of the highest purity graphite available so that

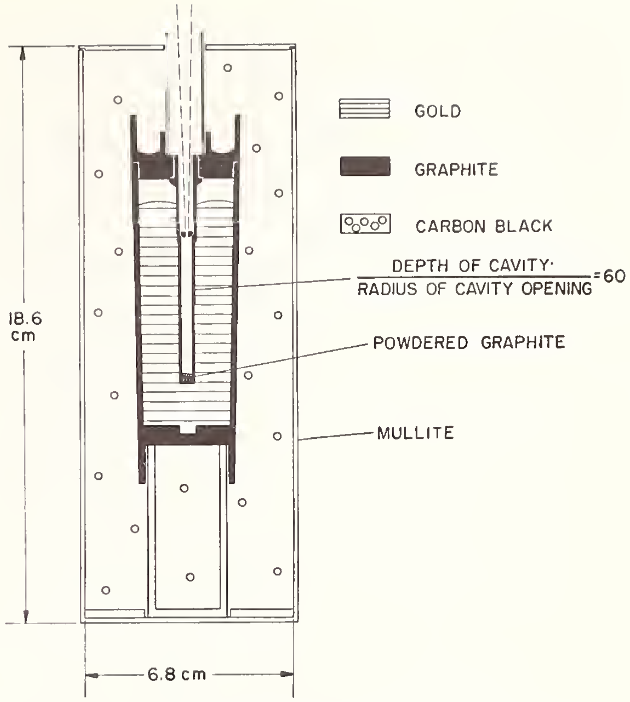


Figure 6. *Cross section of the NBS vertical gold-point "blackbody".*

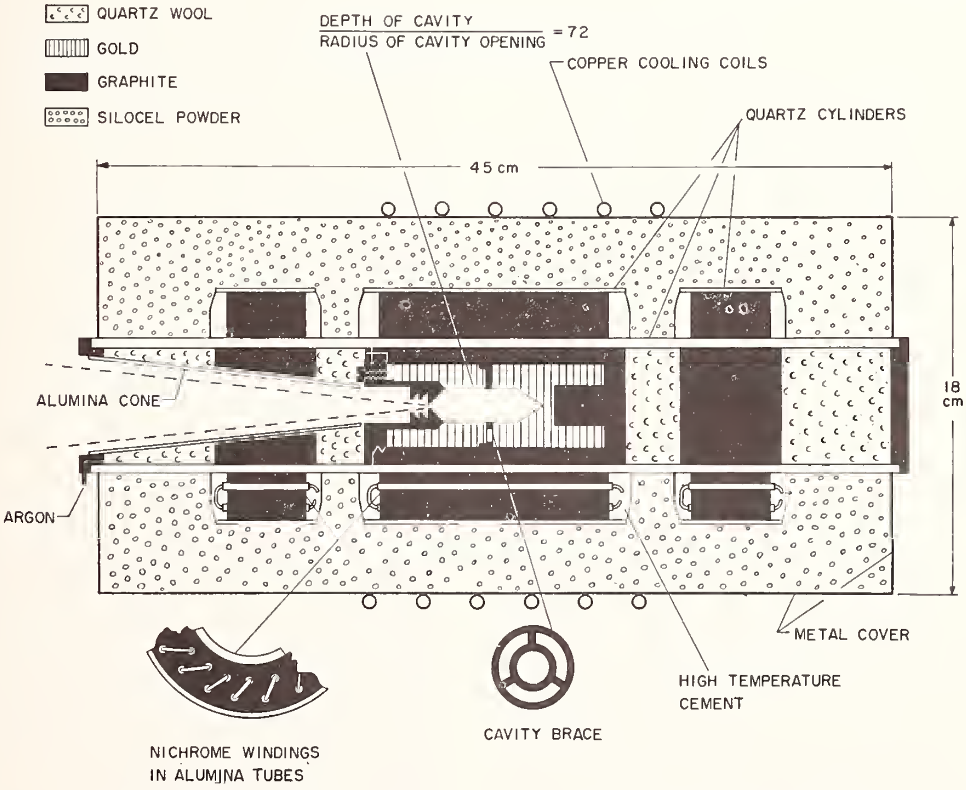


Figure 7. *Cross section of the NBS horizontal gold-point "blackbody" and furnace.*

---

[18] For convenience, a hollow body used to approximate a blackbody will be referred to as a "blackbody."

the gold remains uncontaminated. The graphite used is reported by the manufacturer to contain impurities not exceeding 20 parts per million. In addition, the graphite has a high emittance, a fairly high thermal conductivity, and is easy to machine. The latter factor has made possible the construction of sight tubes of ¼-mm wall thickness for the vertical "blackbody" and ½ mm for the horizontal type. The thinner the walls and the higher their thermal conductivity, the closer the inside temperature of the walls will be to that of the freezing gold.

The vertical "blackbody" assembly is heated in a wire-wound muffle furnace or in the coils of an RF generator. It is estimated, using the calculations of Gouffé [11] that the emittance of the vertical "blackbody," assuming the walls are at a uniform temperature, is 0.999. A partial confirmation of this emittance was obtained experimentally in the following manner. The region above the diaphragm in the sight tube (see fig. 6) itself approximates a blackbody, but of lesser quality than the main "blackbody." The depth of this "blackbody" is somewhat greater than the height of the gold above the diaphragm and its base is the diaphragm of the primary enclosure. Optical pyrometer measurements made on this base during a gold-point freeze resulted in a brightness temperature 0.6 °C less than that obtained from the primary enclosure. A calculation of the relative emittance of these two "blackbodies" is compatible with the 0.6 °C observed, and increases one's confidence in the estimate of the emittance of the main sight tube.

Though the vertical "blackbody" is easier to construct, its use required that the axis of the optical pyrometer be vertical or that a reflector be used in conjunction with the "blackbody." For many years, a 45-degree prism was used at NBS for this purpose. Its *A* value was determined sufficiently well so that it introduced an uncertainty of the gold-point radiance of no more than the equivalent of 0.1 or 0.2 °C. However, in order to avoid this additional uncertainty and in order to have as black a "blackbody" as possible to be used with the recently developed NBS photoelectric pyrometer, the horizontal "blackbody" and furnace shown in figure 7 were developed.

In the design of the horizontal "blackbody" and furnace, attention was placed on achieving a uniform temperature over the inner walls of the sight tube. The crucible containing the gold is shaped so that the mass of gold per unit length of the crucible is about constant for the crucible's entire length. The furnace has three independently controlled heater windings which are embedded longitudinally in cylindrical graphite muffles. The graphite, having a high thermal conductivity, tends to reduce longitudinal temperature gradients. The power inputs to the two end windings are adjusted to maintain the two end sections at 1063 °C as determined by two thermocouples positioned near the inner surface of these sections. The center winding is used to control the rate of heat loss by the gold during a freeze. With this design, it is expected that the gold will freeze more uniformly over the entire sight tube than in the vertical blackbody.

It has not been possible to detect in gold-point freezes differences between the vertical and horizontal "blackbodies" using a visual optical pyrometer. Such differences that may exist are so small they will require the photoelectric pyrometer for detection. The detailed results of using these gold point "blackbodies" will be given in the Primary Calibration section.

b. Lesser Quality "Blackbodies"

Lesser quality "blackbodies," particularly at temperatures much higher than the gold point, are required occasionally in optical pyrometer calibrations.[19] In addition, they are preferred for accurate spectral calibrations of monochromators and spectrographs. One such "blackbody" that has been used at NBS up to temperatures of 3000 °C consists of a graphite cylindrical tube resistively heated in an argon atmosphere and surrounded by a number of graphite radiation shields. The tube is about 200 mm long, has a wall thickness of about 3 mm, and an inside diameter of about 9 mm. A small hole in the center of the tube and correspondingly larger holes in the shields permit the radiation to exit. A current of about 800 amp is required to reach a temperature of 2800 °C. The tube can be used for about 50 hr at this temperature and the radiance stabilized for several hours to better than 1 percent by automatically controlling the current in the tube. The effective emittance of this "blackbody" is currently (1961) being investigated.

"Blackbodies" are sometimes built into an experimental apparatus so that the temperature in an experiment can be determined with an optical pyrometer. For example, to determine the surface temperature of an incandescent material whose spectral emittance at 0.65 μ is not known, a small hole could be made in the material and optical pyrometer observations made on this "blackbody." The depth to diameter ratio of the hole will usually be a compromise between that required for an adequate absorptance and that insuring a uniform temperature throughout the hole which is equal to the temperature at the surface. In general, even when blackbody conditions cannot be met well, temperature measurements on a poor "blackbody" with estimated corrections often may be more accurate than utilizing the brightness temperature of the surface and a poor estimate of the emittance.

---

[19] Tungsten strip lamps usually are adequate for this purpose, as discussed in section 1, Theory.

3.2. Tungsten Strip Lamps

The most stable lamp currently available is the small vacuum pyrometer lamp described in the Optical Pyrometer section. Though excellent as a reference standard in optical pyrometers, its smallness makes this lamp unsuitable for use in checking or calibrating optical pyrometers, or for spectral-radiance calibrations of monochromators or spectrographs. For these purposes a larger type tungsten lamp called a strip or ribbon filament lamp is often used. A variety of these lamps is commercially available from the General Electric Company in the United States (to the best of our knowledge the sole supplier in the U.S.), General Electric Co., Ltd., in England, and Phillips' Lamp works in the Netherlands.

a. Types of Strip Lamps

In the United States, the tungsten strip lamp most commonly used for optical pyrometer applications is the General Electric Company type 30A/6V/T24 ribbon filament lamp. The first two numbers in the type designation mean that if 6 v is applied to the lamp, the resulting current is about 30 amp. This lamp has a glass envelope about 75 mm in diameter and 300 mm long and a tungsten ribbon filament about 0.075 mm thick, 3 mm wide, and 50 mm long. In order to increase the reproducibility of observing the same point or area of the filament, the filament is notched on one edge at about the midpoint of its length. A V bend toward one end of the ribbon allows it to expand or contract without twisting or bending when its temperature is changed. The envelope contains, according to the manufacturer, argon at a pressure of about ⅓ atm at room temperature. The filament is approximately parallel to the axis of the envelope. Its exact position varies, but it is preferable that the filament be situated off the axis of the envelope and that it be oriented so that the normal to its surface is not on a radius of the cylindrical envelope.[20] There is sufficient volume in the envelope above the filament to allow convective gas currents to flow smoothly upward from the filament and thus allow any tungsten vapor to condense on the upper portion of the relatively cool envelope.

The 30A/6V/T24 lamp requires a current of about 14 amp for a brightness temperature of 1000 °C and about 45 amp for 2300 °C. The change of current per degree change in brightness temperature varies from about 0.010 to 0.030 amp per degree from 800 to 2300 °C, respectively. Direct current is usually used so that standard potentiometric measurement methods can be employed. When a sufficiently high-current source is not available, some of the lower current lamps should be considered. However, their narrower filament makes brightness matching more difficult with optical pyrometers having a low magnification.

A strip lamp that is especially useful when a higher brightness temperature is required is the the General Electric 75A/T24. The filament and filament supports for this lamp are designed to permit the lamp to be used up to a brightness temperature of about 2800 °K. In addition, the lamp may be obtained with a plane quartz window so that it can be used in the ultraviolet spectral region. However. these lamps require about twice the current of the 30A/6V/T24 lamp and have no notch.

The General Electric Co., Ltd., in England manufactures a vacuum tungsten strip lamp which is highly recommended for use below 1400 °C. It is called a secondary standard tungsten strip vacuum pyrometer lamp and requires only about 7 amp to achieve a 1400 °C brightness temperature. This lamp has been used at NBS up to 1750 °C, but if high stability is required, it is recommended that the lamp not be used above about 1400 °C.

The High Temperature Measurements Laboratory at NBS has had very little experience with Phillips' tungsten lamps made in the Netherlands. Lamps made in this country have usually been adequate. However, with the increased stability required of tungsten sources in photoelectric pyrometry, this will probably not continue to be the case and tungsten strip lamps from essentially every source will have to be investigated in the near future.

b. Factors Affecting the Reproducibility of Strip Lamps

There are a number of factors which must be considered in order to obtain the optimum reproducibility and stability with tungsten strip lamps. Many of these have been investigated by Barber [5], DeVos [6], and by the High Temperature Measurements Laboratory at NBS. The following is a brief summary of the factors considered to be of major importance.

Tungsten strip lamps possess a temperature gradient along the length of the strip with a maximum temperature at or near the notch. In T24 type lamps the brightness temperature gradient at the notch may vary from zero to 5 deg C per millimeter, depending on the particular lamp, its temperature, and orientation. The direction of the current also has an effect. The current direction is important because when direct current exists in a region of a temperature gradient, heat is absorbed or generated (in addition to the "Joule heating") depending on the direction of the current relative to the gradient. This is called the Thompson effect; and in tungsten, if the current direction is from hot to cold, heat is absorbed. When the direction is from cold to hot, heat is generated. Thus in order to obtain reproducible brightness temperatures from a strip lamp, care must be taken to sight at the same point or region. This is usually the notch.

---

[20] Reasons for this will be given later in this section.

Another factor important in obtaining reproducibility with a strip lamp is the room or ambient temperature, particularly for brightness temperatures below 1500 °C for gas-filled lamps and 900 °C for vacuum lamps. The convective and conductive heat losses depend on the ambient temperature, and if the ambient temperature changes, the resulting temperature at the notch will change. For example, Barber [5] observed a variation of brightness temperature of 0.3 deg C per 1 deg C change of ambient temperature for a gas-filled lamp at a brightness temperature of 1050 °C. At the very high filament temperatures, the energy loss from a filament is largely radiative, and the room temperature has much less effect.

The temperature at the notch for gas lamps is also a function of the lamp orientation. This is caused by gas convection currents in the lamps, and Barber [5] shows the effect to be about ½ deg C for a forward tilt of the filament of an angle of 1 deg. At NBS, gas lamp strip filaments are adjusted with the aid of a plumb line to be vertical at the notch.

In general, the radiance or brightness temperature of a tungsten strip lamp depends on the direction of observation. This is due to the fact that the emittance of tungsten is a function of the angle of emission. It is also caused by reflections. Radiation from the filament may be reflected by the envelope onto the tungsten strip and then into the pyrometer's field of view. The emittance variation as a function of angle of emission is very small near normal emission and can usually be neglected. This is not the case for the reflection effect, and it is desirable to orient the lamp with respect to the optical pyrometer to avoid these reflections. Figure 8 shows several examples of the reflection under discussion. It can be seen that the nature of the reflection depends on the position of the filament relative to the axis of the envelope and on the orientation of the plane of the filament. Case *c* is the preferred positioning and orientation of the filament. In this case the filament may be observed normally without any contribution from reflections. It is desirable to view a filament normally because of the small emittance variation stated above, and because at normal emission the radiation will not be polarized. In case *a* when the filament is on the axis of the lamp, it is impossible to avoid reflections. In case *b*, reflections can be avoided but observations must be made off the normal. In using lamps in position *b*, one should keep in mind that the radiation is partially polarized.[21] When lamps are used or calibrated at NBS, the best direction of sighting is decided on, and an arrow is etched on the glass envelope such that a line extending from the head of the arrow through the notch defines the desired direction.

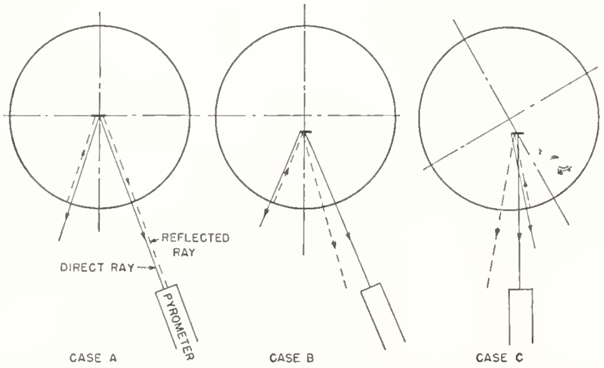


FIGURE 8. *Examples of reflections in a cylindrical envelope tungsten strip lamp for three different positions and orientations of the strip.*

In order to achieve stability, a tungsten strip lamp should be extensively aged or annealed. Some of the details concerning annealing were discussed previously in connection with the small pyrometer lamps. DeVos [6] claims that after annealing a tungsten strip for 100 hr at 2400 °K, 20 hr at 2600 °K, or 2 hr at 2800 °K, no further change in its radiance (at constant current) was observed.[22] At NBS, gas-filled strip lamps are annealed at between 2325 and 2350 °C brightness temperature (a tungsten temperature of about 2625 °C) for 2 hr. After such an annealing and after taking the necessary precautions with the various factors discussed in this section, 30A/6V/T24 gas lamps have been used as high as 2200 °C brightness temperature for 50 hr and as high as 2380 °C for 20 hr without any change in their radiance being detectable. The precision of these measurements was about 2 deg C. It should be emphasized, however, that all gas-filled strip lamps may not possess this kind of stability; and at present, very little statistical information on their stability is available.

3.3. Other Sources

a. The Carbon Arc

At brightness temperatures higher than about 3000 °C, no convenient, stable sources are at present (1961) available. The positive crater of a carbon arc has been recommended and used as a radiation standard [12–14] at the sublimation temperature of carbon. At this temperature the brightness temperature of the crater corresponds to about 3527 °C at 0.65 μ. However, the carbon arc is not as convenient to use as a lamp and is highly stable only at the one temperature.

b. High-Pressure Arc

At brightness temperatures above 3000 °C, gaseous sources probably are the greatest hope for the future. Xenon high pressure arcs have been

---

[21] This is probably important only in using strip lamps to calibrate an optical system containing mirrors. Such a system may have a transmittance which depends strongly on the polarization of the radiation.

[22] This presumably means no change within the long-term precision of his measurements which appears to be about 1 percent in spectral radiance.

studied extensively [15] and are available commercially. Their usefulness in optical pyrometry, however, has not yet been established.

4. Primary Calibration

The temperature scale above 1063 °C that is maintained at the National Bureau of Standards is the result of attempting to realize the International Practical Temperature Scale using the methods of optical pyrometry. The experimental attempt to realize any portion of this scale without comparison with previously calibrated pyrometers or sources is called a primary calibration. In the previous sections of this paper, the IPTS above 1063 °C was defined and the theory and instruments used in optical pyrometry described. This section presents the results of the 1958 primary calibration of the NBS visual optical pyrometer.

4.1. Calibration at the Gold Point

The initial step in the primary calibration at the gold point was the optical alinement of the "blackbody" and the pyrometer. The optical axis of the NBS pyrometer was positioned on the axis of the vertical "blackbody," and the pyrometer focused on the "blackbody" diaphragm. The "blackbody" was slowly heated until the gold was melted and brought to a temperature estimated at 5 to 10 deg C above the melting point. It was then allowed to cool, and brightness matches were made as a function of time. The pyrometer lamp current, corresponding to these brightness matches, plotted against time constituted the gold-point "blackbody" cooling curve. As the "blackbody" cooled, its brightness decreased rather rapidly, and then increased slightly. This dip, seen on the typical cooling curve in figure 9, is called the undercool. After the undercool, the brightness remained constant within the reproducibility of the determinations, and matches were made about every 15 sec alternating between a bright pyrometer filament to disappearance and a dark filament to disappearance. The average of two such matches was considered one observation. The brightness remained constant from 5 to 8 min, allowing 10 to 16 observations. This plateau represented the freezing-point temperature of the gold.

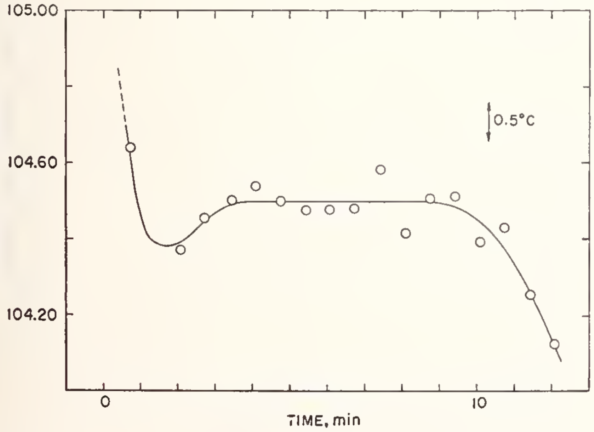


FIGURE 9. *A typical cooling curve obtained during a gold-point calibration with the NBS visual optical pyrometer and the vertical gold-point "blackbody."*

In the primary calibration of 1958, about 50 such plateaus were taken on the vertical "blackbody" over a 2-month period by 3 experienced observers using both an RF generator and a muffle furnace for heating. Though the muffle furnace system had a larger heat capacity and freezes lasted 2 to 3 times longer, the lamp currents corresponding to the plateaus of the cooling curves were the same to better than the standard deviation of an observer's brightness matches, or the equivalent of about 0.2 deg C.

Heating or melting curves were also obtained. When inductively heating, the brightness matches corresponding to the melts were almost 1 deg higher than those obtained during the freezes; but in the muffle furnace, they were only a few tenths of a degree higher.[23] The large difference in the case of the RF melt is attributed to a less uniform heat input and to the background conditions in the pyrometer field of view affecting one's judgment of the match. In the case of freezes, the cooling is more uniform and the brightness of the region which surrounds the small sighting hole or diaphragm is negligibly different from the brightness of the sighting hole. Only the freezes were used for the actual calculation of the gold-point calibration.

The results of the 1958 gold-point determination are given in table 2. In addition, data obtained in 1957 and 1960 are included. The observations in 1957 were made using a vertical "blackbody" similar to that in 1958, but the horizontal "blackbody" of figure 7 was used in 1960. The 1957 and 1958 results include the effect of a 45° right-angle prism and represent a temperature lower than the gold point due to the prism absorption and reflection. This apparent gold-point temperature was calculated from eq (1—9) where $T_i=T_0+1063=1336.15$ °K and $A=6.92$ mireds[24] resulting in $T_j=T_{\mathrm{app}}=1323.9$ °K. The A value of the prism was determined independently using a strip lamp and data from the previous primary calibration. The standard deviation of the A value of each of three observers about their grand mean was equivalent to about 0.1 deg C. Since only relatively small differences of temperature near the gold point were required to determine A, use of the

---

[23] Observations made in 1960 on the horizontal "blackbody" resulted in melts only 0.1 deg C higher than the freezes.

[24] The unit in which A values are usually reported is the mired. One mired is equal to 10^{-6} (°K)$^{-1}$.

TABLE 2. *NBS primary optical pyrometer calibrations at the gold point using a glass prism and an apparent temperature of 1323.9 °K*

Observer	1957				1958				1960[a]			
	L1 Pyrometer lamp current[b]	Number of freezes	Standard deviation[c]		L1 Pyrometer lamp current[b]	Number of freezes	Standard deviation[c]		L1 Pyrometer lamp current[b]	Number of freezes	Standard deviation[c]	
			S_1	S_2			S_1	S_2			S_1	S_2
	ma		*ma*	*ma*	*ma*		*ma*	*ma*	*ma*		*ma*	*ma*
RDL	104.465	9	0.023		104.450	17	0.019		104.484	3	0.029	
RCH									104.457	1		
RCG					104.426	16	.036		104.427	2	.028	
HJK									104.410	1		
EL									104.573	2	.018	
ATH					104.522	12	.042					
Mean of all observers	104.465				104.466			0.049	104.470			0.059

[a] The 1960 data were obtained using a horizontal "blackbody," and therefore the glass prism used with the vertical "blackbody" was not required. As a result, for comparison purposes, the 1960 data were normalized to 1323.9 °K.
[b] 0.05 ma is equivalent to 0.3 °C.
[c] S_1 is the sample standard deviation of an individual's freezing point determinations about his own mean. S_2 is the sample standard deviation of individual observers' mean determinations about the mean of the determinations of all observers.

former calibration data did not significantly affect the accuracy of *A*. If no previous calibration had existed, a sectored disk and strip lamp would have been used to determine the *A* value of the prism. The horizontal "blackbody" constructed after 1958 and used in 1960 did not require the use of a prism. For comparison in table 2, the 1960 data were adjusted to the apparent temperature of 1323.9 °K or 1050.7 °C using the completed calibration.

Table 2 shows that the standard deviation of an individual's single freeze varied from about 0.1 to 0.25 deg C about his own mean. The difference between observers was as large as 1 deg when only a few freezes were taken. Even the means of 16 freezes of RCG and 12 freezes of ATH differed by 0.6 deg C, though the sum of the standard deviation of the two means was about 0.13 deg C. These differences can not be accounted for by relative luminosity factor differences. The differences in the measured relative luminosity factors would account for only about 0.1 deg C. Moreover, the observer differences would be less when using a tungsten strip lamp; but the observers maintained the same differences in this case. When observations were made on tungsten strip lamps through sectored disks with an apparent temperature near the gold point, the same differences still remained. These differences between observers at the gold point were attributed to their matching technique and to psychological factors, and the only way of reducing their effect on the accuracy is to use a number of observers. The observer effect may be indicated quantitatively by the standard deviation of an observer about the mean of all observers. In the 1960 data, where five observers were used, this standard deviation was estimated to be 0.4 deg C.

4.2. Calibration Above the Gold Point

To extend the calibration to temperatures above and below[25] the gold point, tungsten strip lamps were matched through sectored disks and eq (1–5) used to calculate the new temperature *t*. Then the sectored disk was removed and the strip lamp matched to obtain the pyrometer current corresponding to the new temperature. The transmittances, *R*, of the sectored disks were determined in the Metrology Division of NBS and the mean effective wavelength, $\lambda_{t_{Au}-t}$, were obtained from eq (1–21) using the effective wavelengths shown in figure 10. The latter were calculated with eq (1–20) using spectral transmittance functions of the pyrometer elements determined at NBS and the CIE[26] standard relative luminosity factors.[27] However, it was found from independent measurements that the relative luminosity factors of the observers were slightly different from the CIE factors. This produced an average change in the

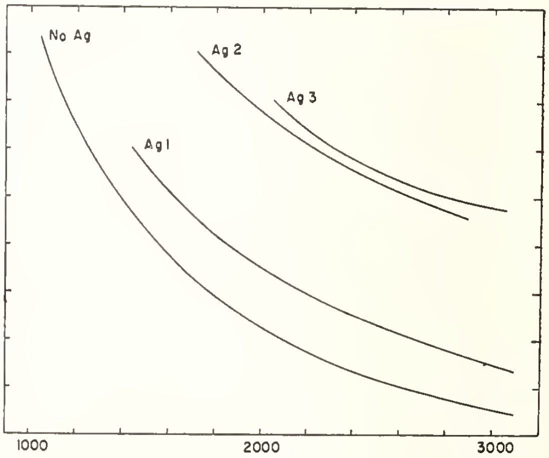


FIGURE 10. *Effective wavelengths for the NBS visual optical pyrometer using the CIE standard relative luminosity factors.*

---

[25] Even though the International Practical Temperature Scale is defined by Planck's radiation equation only above 1063 °C, optical pyrometers are frequently required at lower temperatures.

[26] Commission Internationale de l'Eclairage.

[27] I.E.S. General Guide to Photometry, Illuminating Engineering Society, New York, N.Y. (1954).

mean effective wavelengths of about 7 A, and required a correction from about −0.2 deg C at 800 °C to about +3.2 deg C at 2400 °C.

For observations using sectored disks, the disks were positioned at the tungsten-strip image which was produced by a lens corrected for spherical aberration and coma. The strip-lamp current was continually monitored to insure constancy of lamp brightness. Using 7 sectored disks ranging in transmittance from 0.35 to 0.007, three observers made 50 sets of observations for the low range from 800 to 1300 °C, 42 for the range 1300 to 1750 °C using absorbing glass number one (AG 1), and 30 sets each for AG 2 and AG 3 covering 1750 to 2050 °C and 2050 to 2400 °C, respectively. Each set of observations consisted of 4 brightness matches with the sector, 6 without, and 4 more with the sector. Again, matches were made by approaching the disappearance alternately from the dark and bright side. Each observer used his own gold-point or low-range calibration to obtain the apparent temperature.

In the low-range calibration above 1051 °C, the lamp brightness through the sectored disks was maintained close to that of the gold "blackbody" as seen through the glass prism, i.e., 1051 °C. For temperatures less than 1051 °C, the lamp brightness was adjusted to about 1051 °C when not looking through the sector. Figure 11 shows the results of the low-range calibration for the three observers. I_{table} in figure 11 was obtained from the original (1952) calibration for this pyrometer lamp. If a previous calibration had not been available, a 3d- or 4th-order polynomial approximately fitting the new calibration could have been used to obtain an I_{table} as a function of temperature. For the low-range calibration the standard deviation of an observer about his own mean was approximately 0.35 °C.

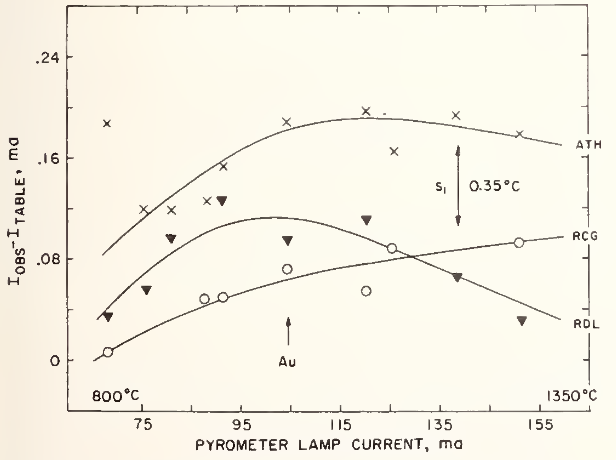


Figure 11. *The 1958 primary calibration of the low range of the NBS visual optical pyrometer.*

For the higher ranges where AG 1, 2, and 3 are used, brightness temperatures of the source as seen through the sectored disks were not maintained at the gold point alone, but also at other points already calibrated in the low range. *A* values were calculated from eq (1–9) for each set of observations where T_t was the apparent temperature as seen through the absorbing glass and T_j the brightness temperature of the strip lamp obtained from a sectored disk calculation. It should be emphasized that the brightness temperature of the tungsten strip lamp T_j must correspond to the mean effective wavelength for the absorbing glass used. Figures 12, 13, and 14 show the *A* values obtained for each of the absorbing glasses. The standard deviation of an observer's *A* value about his own mean varied by an equivalent of 1.0 to 2.0 deg C.

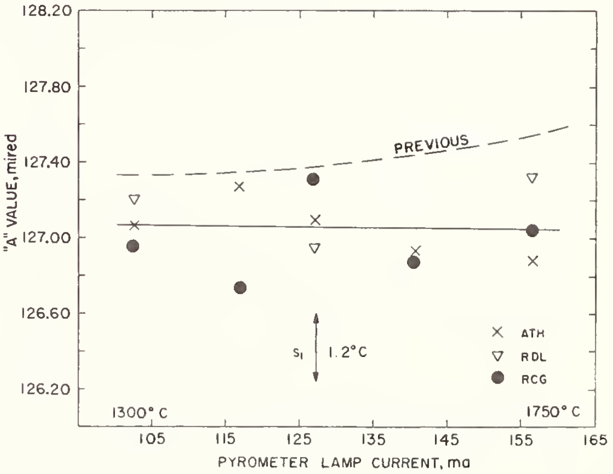


Figure 12. *The 1958 determination of the A value of absorbing glass 1 of the NBS visual optical pyrometer.*

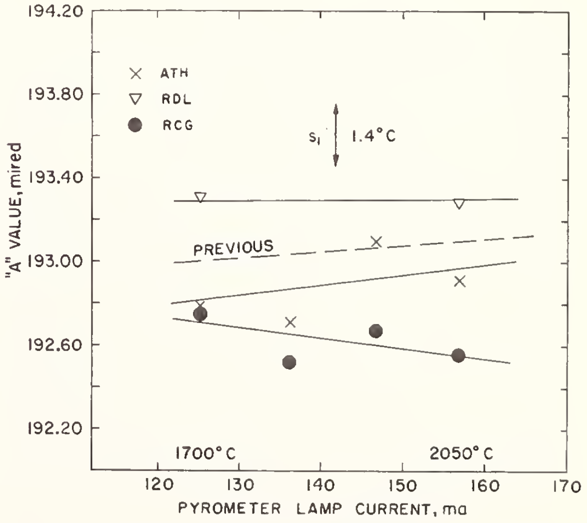


Figure 13. *The 1958 determination of the A value of absorbing glass 2 of the NBS visual optical pyrometer.*

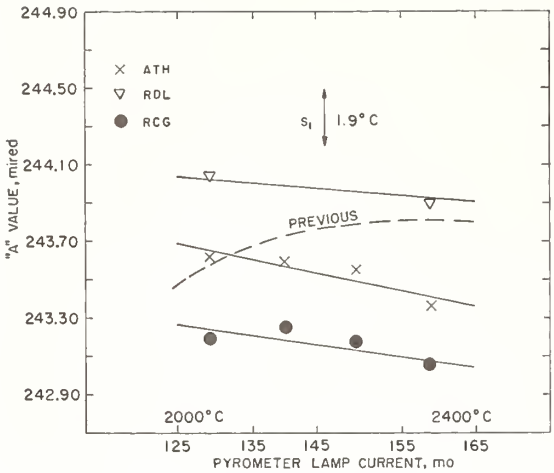


FIGURE 14. *The 1958 determination of the A value of absorbing glass 3 of the NBS visual optical pyrometer.*

An analysis of the data obtained for the low-range calibration reveals that the observers continue to read strip lamps with about the same difference throughout the low range, except for a slight trend of observer RDL indicated by the crossover of his calibration with that of observer RCG. Thus the observer differences throughout the low range also appear to be the result of judgment or psychological factors. Therefore it was decided to take the mean of three observers and apply an average relative luminosity factor correction to the mean. The 1958 low-range calibration, including luminosity corrections, is 0.8 deg C lower than the 1956 calibration at 800 °C and 0.9 deg C higher at 1350 °C.

The *A* values for all the absorbing glasses are, within the experimental error, constant with source temperature, thus supporting an $\exp[-k/\lambda]$ transmittance. Except for AG 1, differences continue to exist between observers that have no adequate explanation. In analyzing the data, it is seen that ATH and RCG have the same differences in temperature when matching with or without sectors, and this is independent of current. However, ATH and RDL match differently through sectors when the apparent temperature is changed. When matching through absorbing glasses, ATH and RDL maintain the same difference that exists between them at the gold point but ATH and RCG change by 0.6 deg C. The mean of the *A* value curves for the three observers was corrected for the average relative luminosity factor of the three observers and used in conjunction with the average low-range calibration to obtain calibrations for the high ranges. The 1958 calibration of the upper ranges is about equal to the 1956 calibration at 1400° C, 0.6 deg higher than the 1956 calibration at 1700 °C, and 2.4 deg C higher at 2000 and 2400 °C. Part of these differences is attributed to the relative luminosity factor corrections which were made in 1958 but not in 1956.

4.3. Estimated Accuracy

An estimate of the accuracy of this primary calibration can be made by comparing it with the mean of similar calibrations from other national laboratories throughout the world. In fact, to the best of our knowledge, this is the only way of quantitatively estimating the accuracy. Fortunately this can be done through the international comparison of strip lamps completed in 1958. Figure 15 shows the difference as a function of temperature between the strip lamp calibration at NBS using six observers and using the 1958 primary calibration and the mean of the strip-lamp calibrations of three other national laboratories. These are the Deutsches Amt für Mass und Gewicht, German Democratic Republic, the National Research Council, Canada, and the Physikalisch-Technische Bundesanstalt, Federal Republic of Germany. The standard deviation of all four national laboratories about their grand mean is also given in figure 15. This serves as an indication of how well the IPTS above 1063 °C has been realized.

It is felt that the results of the 1958 primary calibration at NBS is about the best one can expect from visual optical pyrometry. The major limitations are the sensitivity of the eye to differences in brightness and the knowledge of the mean effective wavelengths.

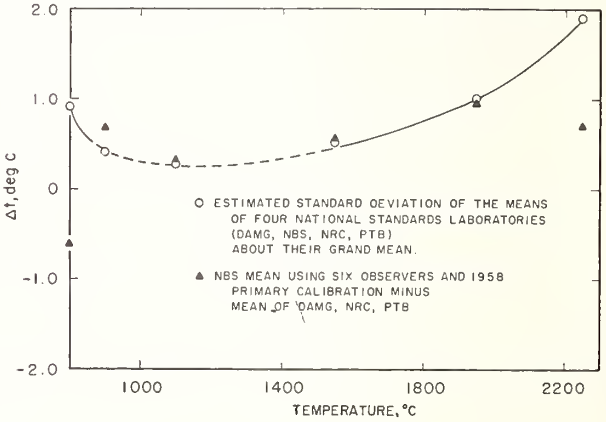


FIGURE 15. *The international comparison of strip lamp calibrations completed in 1958 between Deutsches Amt für Mass und Gewicht (DAMG) of the German Democratic Republic, NBS of the United States, National Research Council (NRC) of Canada, and Physikalisch-Technische Bundesanstalt (PTB) of the Federal Republic of Germany.*

The dashed curve represents a region in which the estimated standard deviations are somewhat less reliable due to the fact that the laboratories rounded off their data to the nearest degree.

5. Secondary Calibrations

The International Practical Temperature Scale that is realized and maintained at the National Bureau of Standards is distributed throughout the United States through the NBS calibration and test services. The fees and instructions for utilizing these services are listed in the Federal Register. The present section describes in detail the procedures used in calibrating optical pyrometers and tungsten strip lamps.

5.1. Optical Pyrometers

a. Inspection and Cleaning

The initial step after receiving an optical pyrometer submitted for calibration is the general inspection of the instrument to confirm that it is in good operating condition. If it passes this test, the optical elements of the instrument are cleaned, using lens tissue and distilled water. The surfaces of the objective lens, absorbing glasses, and the window of the pyrometer lamp, which is located between the source and the pyrometer lamp filament, are the most important surfaces to clean. A reminder is given on optical pyrometer certificates that the optical surfaces should be kept clean in order for the calibration to be applicable.

b. Determination of the Effective Wavelengths

Since optical pyrometers are usually calibrated by comparison with the NBS pyrometer using a tungsten strip lamp and not a blackbody as a transfer source,[28] differences between the mean effective wavelengths of the test and the NBS instrument are required. These differences are used to calculate from eq (1–28) the brightness temperature T_1' that the test pyrometer should indicate when the NBS pyrometer indicates T_1. Even though both instruments are observing the same tungsten lamp, the brightness temperature obtained by the two should be different if their effective wavelengths are different. If a blackbody were used, this would not be the case. Thus $T_1'-T_1$ must be determined as a function of temperature and added as a correction to each brightness temperature determined by the NBS pyrometer during the calibration.

The differences in mean effective wavelengths required for the above temperature corrections are obtained by either of two methods. The first method is to determine the spectral transmittances of the red filter and the absorbing glasses of the test pyrometer and to calculate the effective and mean effective wavelengths as outlined in sections 1 and 4. Effective wavelengths have been determined for the NBS pyrometer for the primary calibration, and therefore differences between mean effective wavelengths for the NBS instrument and the test instrument can be computed. The second method, though simpler to use when established is not quite so straightforward, and therefore a detailed description will be given.

The second method consists of determining the brightness temperatures with the NBS pyrometer using its own red filter and the test pyrometer red filter for a series of sources for which the brightness temperatures are the same when using the NBS red filter but for which the color temperatures vary from values very large compared to the brightness temperature to values close to it. Such sources can be obtained by using a strip lamp in conjunction with a number of sectored disks. With each of the sectored disks the lamp brightness is adjusted so that when observed through the disk, the lamp has the same brightness temperature. Using eq (1–28), the differences between the mean effective wavelengths are calculated. The limit of the mean effective wavelengths for the test red filter as the disks are changed and the color temperature approaches the brightness temperature is the effective wavelength for that red filter at the limiting brightness temperature. This is repeated for a sufficient number of brightness temperatures in the low range, in order to determine by curve fitting the effective wavelength as a function of temperature for the entire range. The resulting wavelengths, however, represent only a first approximation to the effective wavelengths required. The reason is that the calibration of the NBS pyrometer using the test red filter is slightly different from that using its own red filter. A closer approximation can be obtained by correcting the primary calibration of the NBS pyrometer with the first approximation of the effective wavelength for the test red glass. The improved calibration for the NBS pyrometer when using the test red filter will usually modify the temperature differences determined initially for the series of sources by about 25 percent and permit a second approximation to the determination of the test instrument effective wavelength. This second approximation is usually adequate.

Since the spectral transmittance curves of most red filters used in optical pyrometers have the same general shape, their effective wavelength versus temperature curves are approximately parallel. Therefore, usually one effective wavelength determination is sufficient. Moreover, at NBS the actual temperature corrections to be applied to the test pyrometer have been determined as a function of the temperature difference observed using a particular strip-lamp brightness and sectored disk and the uncorrected NBS primary calibration. Such a set of curves need be computed only once and, thereafter, a single observation through each of the two red filters, using one lamp brightness and sectored disk, is

---

[28] However, a resistively heated graphite tube "blackbody" similar to that described in section 3.2 is being investigated at NBS for use as a transfer source in the calibration of optical pyrometers up to 2800 °C. Using a blackbody would eliminate the need for determining the differences in effective wavelength.

sufficient to determine the correction to be applied at every temperature of the calibration.

For optical pyrometers which have absorbing glasses with a constant A value, the effective wavelengths of the higher ranges are approximately equal to the effective wavelengths of the low range for corresponding pyrometer lamp currents. In these cases the effective wavelengths determined for the low range also suffice for the higher ranges. When the type of absorbing glass used is not of the constant A value type or is not known, effective wavelengths for the higher ranges are calculated from experimentally determined transmittances.

Most of the visual optical pyrometers received for calibration that have been manufactured since about 1959 appear to have mean effective wavelengths negligibly [29] different from those of the NBS instrument. However, this is not the case for the older instruments. Some of these have had differences as large as 0.01μ, corresponding to about a 5 deg C correction at a tungsten brightness temperature of 2400 °C and to about a 1 deg C correction at 1063 °C.

c. Calibration Procedure

After determining the effective wavelength and/or corresponding tungsten brightness temperature correction as a function of temperature for the test optical pyrometer, the test pyrometer is carefully mounted alongside the NBS instrument so that their optical axes are parallel and in the same horizontal plane. A GE tungsten strip lamp, 30A/6V/T24, is oriented as described in section 3, on a large lathe serving as an optical bench so that it can be easily and accurately translated in a direction perpendicular to the optical axes of the pyrometers. Surplus lathes have been found quite adequate for such purposes. For convenience, micro-switches are positioned on the lathe bed so that the lamp may be stopped exactly on the optical axis of each pyrometer.

The tungsten strip lamp is specially selected to have its filament positioned off the lamp axis, and therefore the filament plane can be made perpendicular to the pyrometer axis without detrimental reflection effects. The brightness temperature of the lamp as a function of distance from the pyrometer is also determined; and, if large, the lamp is not used. As a result of this careful arrangement of the pyrometer and lamp, the orientation of the lamp with respect to each pyrometer is the same within the experimental errors of the alinement.

The test optical pyrometer could be compared to the NBS instrument in the same manner in which it is used; that is, a brightness match made with the test instrument and the scale on this instrument read. However, a different procedure has been found to be more accurate and convenient. The calibration is performed in two parts, the first being a lamp calibration where the brightness temperature indicated by the instrument is determined as a function of the test pyrometer lamp current. The second part is a scale calibration where the instrument scale is calibrated as a function of pyrometer lamp current. When combined, these two parts result in the calibration of the instrument scale as a function of the brightness or blackbody temperature of the source being observed.

In order to perform the calibration as described, the pyrometer lamp current must be measured to at least 1 part in 1 thousand and preferably to 1 part in 10 thousand. A potentiometer and standard resistor are used for this purpose. An electrical series circuit is set up containing the test pyrometer lamp, resistors or meters normally in the test pyrometer lamp circuit, a continuously variable resistor, a standard resistor, and a lead storage battery. The pyrometer lamp current is controlled with the variable resistor and determined with the potentiometer by measuring the voltage drop across the standard resistor.

Two observers perform the first part or lamp calibration of the test instrument; one observer makes the brightness match while the other determines the lamp current with the potentiometer. One point on the brightness calibration is obtained as follows. The strip-lamp current is determined. Then one observer makes two brightness matches on the strip lamp using the NBS instrument, the first approaching the match with the filament initially darker than the strip and the second with the filament initially brighter. These matches will be designated as dark to bright and bright to dark respectively. After each match, the current in the pyrometer filament is determined. Next the observer shifts himself and the strip lamp to the test instrument and makes 4 matches, dark to bright, bright to dark, bright to dark, and dark to bright. Returning to the NBS instrument, two more matches, bright to dark and then dark to bright, are made; and the strip-lamp current is again determined. Bracketing the eight brightness matches with two strip-current determinations serves as a check on any drift of the strip-lamp current and therefore the brightness temperature. The drift is usually negligible. The data for this one calibration point for the pyrometer lamp are completed after the observers switch roles (brightness matching and current measuring) and the process repeated. In summary, the brightness comparison of the test and NBS pyrometer at a given temperature consists of four matches on the NBS instrument and four on the test instrument by each of two individuals.

The data obtained by the two individuals are separately averaged, each of the average NBS pyrometer lamp currents are converted to brightness temperatures through the primary calibration, and finally these temperatures are corrected for any mean effective wavelength differences

---

[29] By negligible is meant an effective wavelength for which the temperature correction when observing strip lamps is about 1/10 or less of the other uncertainties in a calibration.

between the NBS and test instruments. Thus a lamp-calibration point consists of two test pyrometer lamp currents and corresponding brightness temperatures of the tungsten strip lamp determined by two observers at the mean effective wavelength of the test instrument.

d. Low-Range Calibration

The brightness calibrations are performed range by range. The low range is calibrated first, because its calibration is used in the calibration of the other ranges. Six calibration points similar to that described in section 5.1.c are obtained for the low range, about 800 to 1250 °C. Other points in the low range are obtained by interpolation. For one class of optical pyrometers, calibrated at NBS for a number of years, a table of current versus temperature representing an average smoothed low-range calibration has been obtained. Temperature differences between this table and the six calibrated points are plotted as a function of current, and a curve best fitting these points is drawn. This is similar to the Δt curve obtained for the low range of the NBS primary calibration. A typical example is shown in figure 16. For instruments for which an average calibration does not exist, eight calibration points are obtained at equal current intervals in the low range and a 4th- or 5th-degree equation is fitted to the eight points by the method of orthogonal polynomials [16, 17].

The low-range calibration is completed by determining the current corresponding to the cardinal readings on the pyrometer scale or meter for which a temperature is to be reported. This, together with the Δt curve and the table or the 4th- or 5th-degree equation, permits a blackbody temperature to be obtained for each of these cardinal points.

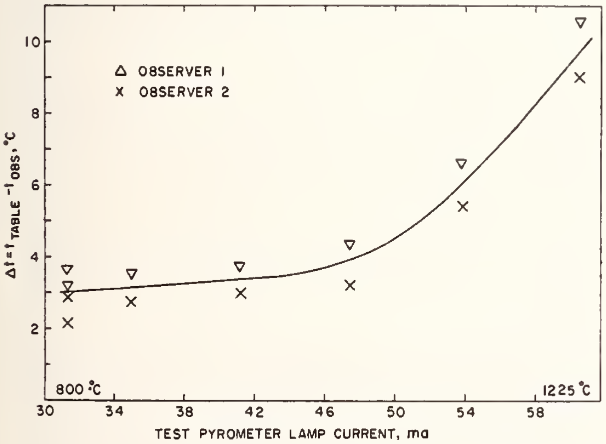


FIGURE 16. *A typical low-range Δt calibration curve for a commercial optical pyrometer.*

e. High-Range Calibrations

The high ranges of an optical pyrometer are calibrated by determining the A value for each of the absorbing glasses as a function of blackbody temperature. The A value is calculated using eq (1–9) in which T_j is the apparent temperature determined from the low-range calibration using the current corresponding to a brightness match, through the absorbing glass, of a source having a brightness temperature T_t. The temperature T_t is determined by the NBS instrument and must be corrected for the mean effective wavelength of the test pyrometer.

Observations at a particular temperature are taken in a manner similar to that described for the low range. Since A values are usually linear functions of temperature, observations are limited to three temperatures in a range. However, each observer takes two sets of observations at each point to improve the precision of the mean.

A values for each range are plotted as a function of pyrometer lamp current or source temperature. As in the low-range calibration, pyrometer lamp currents corresponding to the cardinal points to be reported are determined. Apparent temperatures are obtained for these currents using the low range Δt curve. The T_{app} together with the corresponding A values are then used in eq (1–9) to obtain a temperature calibration. Mathematically

$$\frac{1}{T}=\frac{1}{T_{\text{app}}}-A=\frac{1}{T_{\text{app}}}-\left(\frac{1}{T'_{\text{app}}}-\frac{1}{T_t}\right) \qquad (5\text{–}1)$$

where the apparent temperature associated with the A value is primed to emphasize that its value depends on how the A value curve is drawn and may be different from T_{app}. Since unexplainable observer differences exist in brightness matches, a compromise is made when drawing the A value curve—a compromise between completely smoothing the data with the theoretically predicted curve and exactly following the experimentally determined A values. Figure 17 is a typical example of an A value curve.

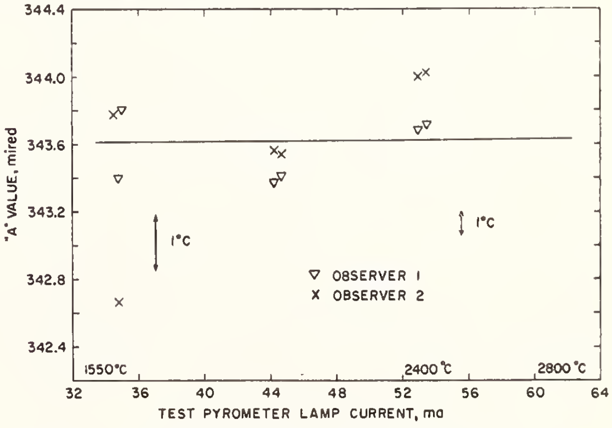


FIGURE 17. *A typical A value determination for an upper range of a commercial optical pyrometer.*

Optical pyrometers are calibrated up to 2400 °C (as of May 1961) using tungsten strip lamp sources.[28] Usually for instruments used to 2800 or 3200 °C actual observations are not made above 2400 °C. The A value is extrapolated above 2400 °C using the theoretically predicted shape, which is usually a constant. For ranges which extend to about 4200 °C, in addition to using a tungsten strip lamp up to 2400 °C, the positive crater of a carbon arc, at a brightness temperature of about 3530 °C with spectrographically pure graphite electrodes, or between about 3630 and 3800 °C with projector pregraphited carbons, is also used to obtain the A value. Since the carbon arc is not as stable as a strip lamp, observations are often made simultaneously with two observers making brightness matches with the NBS pyrometer and the test pyrometer simultaneously.

Changes in the brightness temperature with wavelength in the case of carbon arcs are sufficiently small so that effective wavelength corrections can be neglected. This is because the positive crater of a carbon arc is very close to a gray body with a spectral emittance of about 0.77 in the visible spectral region [14]. Thus the color temperature in this case is the temperature; and for a brightness temperature of 3800 °C, the temperature would be about 4000 °C. Such a range of brightness to color temperature is not sufficient to produce a significant change in brightness temperature for a 0.01 μ wavelength shift, the maximum normally observed.

In some optical pyrometers the range to 4200 °C is reached by using two absorbing glasses in series. These may be calibrated at lower temperatures and the A values added. When this is possible the uncertainty of the calibration is often less.

5.2. Tungsten Strip Lamps

a. Calibration Range

Gas-filled tungsten strip lamps are normally calibrated at NBS at brightness temperatures from 800 to 2300 °C. The lower limit is set by the fact that very few calibrations are ever requested below this temperature and because the eye's contrast limen[15] is already quite high at 800 °C. However, Lovejoy [7], by removing the red glass, has used a conventional laboratory optical pyrometer to brightness temperatures as low as 590 °C with a standard deviation of about 7 deg C. The upper brightness temperature limit of 2300 °C has evolved from years of experience of how well the lamps withstand deterioration at high temperatures. Obviously, the limit is somewhat arbitrary. One can operate a lamp above a 2400 °C brightness temperature; but on the other hand, one should not leave a lamp at even a 2300 °C brightness temperature needlessly. Though lamps are usually calibrated at intervals of 100 deg C, a calibration at any temperatures from 800 to 2300 °C will be supplied if requested.

b. Mounting and Orientation

The first step in the calibration of a tungsten strip lamp of the T24 type at NBS is to determine the orientation for which the lamp is to be calibrated. The lamp is mounted on the optical axis of the NBS pyrometer about 60 cm from the pyrometer lamp with the tungsten strip approximately vertical. With the strip at a brightness temperature of about 1600 °C, the lamp is rotated about the axis of its envelope so that radiation reflected from the lamp envelope onto the tungsten strip and then reflected by the strip does not enter the pyrometer. This condition is determined in the following manner. The reflection of the strip from the glass envelope is observed from the side of the cylindrical envelope away from the pyrometer and the eye moved until the image appears to be in line with the filament. This determines the direction of the rays which are reflected from the envelope and then reflected from the strip. The direction of the secondary reflection from the strip is obtained by looking down from above the strip. If possible, the lamp is oriented so that the pyrometer axis is normal to the strip. If it is found that a reflection into the pyrometer occurs when the pyrometer optical axis is normal to the filament, a suitable position of the lamp close to this normal is selected. Finally the lamp is adjusted so that the tungsten strip at the notch is vertical as determined by a plumb line.

With the optical pyrometer axis horizontal and aimed at the filament notch, a small ink mark is made on the envelope of the lamp at the position where the optic axis strikes the envelope on the side away from the pyrometer. The lamp is taken down and a small arrow etched on the glass such that the head of the arrow just touches the ink spot.

The etching is performed using hydrofluoric acid (48 percent) and a wax protective coating commonly referred to as a resist. Resist formula P–1 described in NBS Circular 565 [18] is used. A large needle is used to inscribe the arrow on the resist and beeswax is placed on and around the resist in the form of a small cup to keep the hydrofluoric acid from coming in contact with any glass not protected with the resist. A 3 min etch appears to be quite satisfactory. After this period of time, the acid is washed off with water, the lamp is cleaned with xylene, then soap and water, and finally dried with a nonabrasive tissue paper.

The lamp is now remounted for final adjustment prior to the actual calibration. With the strip incandescent and some background illumination on the arrow, the latter can be seen in the field of view of the pyrometer; and the lamp is oriented so that the arrowhead appears at the notch. This orientation is checked and maintained throughout the entire calibration.

---

[28] See footnote on p. 19.

[15] See footnote on p. 8.

At the normal distance at which lamps are calibrated, the angle subtended at the strip by the entrance pupil of the pyrometer varies from about 0.02 radian in the range 1100 to 2300 °C to about 0.05 radian at 800 °C. A detailed description of the lamp orientation, direction of sighting, entrance angle, and room temperature is given in each certificate of calibration so that these conditions can be duplicated by the lamp user.

c. The Electrical System

The source of electric current for the lamps is a bank of storage batteries having a 1600 amp-hr capacity and an emf of 120 v. Coarse control of the lamp current is obtained with an NBS-constructed air-ventilated resistor made of coils of chromel A and nichrome wire connected in parallel through knife switches. In parallel with this arrangement are two slide-wire reostats for fine control permitting changes of a few parts in 10,000. The polarity of the electrical connection to the lamp is identified on the certificate. Depending on the lamp, currents from a few amperes to 75 amp are required. These are determined to an accuracy of about 1 part in 10,000 with a potentiometer by measuring the potential difference across a 0.001-ohm calibrated shunt resistor placed in series with the lamp. The current drift during the time required to make a set of 4 brightness matches is usually less than the equivalent of 1 deg C.

d. Calibration

Gas-filled lamps are annealed at a brightness temperature between 2325 and 2350 °C for 2 hr just prior to the calibration. The first temperature calibrated is the highest point requested. Observations are made using a procedure similar to that used in calibrating optical pyrometers. Two observers each make four matches (bright to dark, two dark to bright, bright to dark) at each of the temperatures to be reported. In the usual case of calibrating at 100 deg C intervals, the observers wait 10 min between points (after the initial 2 hr anneal) to allow the lamp to reach equilibrium after each temperature change. However, at 1000 and 900 °C, a 15 min wait is employed and at 800 °C, 20 min. For temperature changes greater than 100 °C even longer waiting periods are used.

The brightness temperatures of tungsten strip lamps calibrated at NBS are reported to correspond to a wavelength of 0.653 μ. The actual wavelength for the observations between 800 and 2300 °C varies from 0.657 to 0.653 μ with abrupt changes in wavelength whenever the range of the pyrometer is changed. However the greatest difference in the actual wavelength and that reported only amounts to an error in brightness temperature of about one-seventh the uncertainty stated.

5.3. Precision and Accuracy[30]

a. Definition of Precision and Accuracy

By the precision of a measurement, one usually means how well the measurement is reproduced. More specifically, if NBS calibrates an optical pyrometer a number of times and if the pyrometer is stable, a measure of the precision of the calibration or calibrations is the standard deviation of the entire population comprising the calibrations. If the entire population is not available, the standard deviation of the population is estimated by the standard deviation of a sample of the population, and it should be kept in mind that such estimates are subject to considerable variation from sample to sample when the size of the sample is small [19].

The concept of accuracy refers to how well a particular value agrees with the correct value. However, except in a situation where a material standard defines a unit of measurement, such as the meter bar previous to 1960, the correct value is not known and the accuracy of a particular result can never be exactly determined. An experimenter can make an estimate of the constant or systematic errors of a measurement, and this information is certainly useful. However, since such estimates are a matter of judgment they vary greatly from one individual to another, and an objective interpretation on the meaning of the errors is even more difficult if not impossible to make.

There is a manner of obtaining an estimate of accuracy, at least for temperature calibrations on the IPTS, which does not possess these limitations. The various national standards laboratories throughout the world independently attempt to experimentally realize the IPTS. Moreover, many of these laboratories are continually trying to improve their realization of the scale, and differences among the laboratories are probably the best indication available of how well the scale is being realized. Therefore, a very useful measure of the accuracy of a temperature calibration relative to the IPTS is the standard deviation of the population consisting of the means of the population of the temperature calibrations performed in each of the national laboratories. In practice numerical results are usually not available from all the national laboratories, and therefore only a sample or estimated standard deviation can be determined. Of course, any constant systematic error that exists in all the national laboratories is not revealed in this manner. But under these circumstances neither would it be accounted for in any other way. Thus it is believed that the above standard or sample standard deviation is the best available estimate of the accuracy of realizing the IPTS.

---

[30] The authors thank C. Eisenhart, H. H. Ku, and J. Mandel of the National Bureau of Standards for their interest and helpful discussions concerning this section.

b. A Statistical Model for Calibration Errors

There are a number of sources contributing to the lack of precision and accuracy in optical pyrometer and tungsten strip lamp calibrations. These have already been discussed in various parts of the paper and are summarized in the following statistical model.

$$t^l_{ijk}=t_{\text{Int}}+e^l+a_i+b_j+c_k+d \qquad (5\text{–}2)$$

where t^l_{ijk} represents the temperature obtained from a single set of observations [31] by a single individual with a particular apparatus in a particular national laboratory. In eq (5–2) t_{Int} is the correct temperature on the IPTS, e^l is the (random) error of the lth set of observations of an observer,[32] a_i is the systematic error of the ith observer, b_j is the systematic error of the jth apparatus, c_k the systematic error of the kth national standards laboratory and d is the constant systematic error common to all the laboratories. All the errors except d are assumed to be normally and independently distributed [19] with mean or expected value zero and variances $V(e)$, $V(a)$, $V(b)$, and $V(c)$. From theory of statistics, then, the variance of t is equal to the sum of the variances of the errors or

$$V(t)=V(e)+V(a)+V(b)+V(c). \qquad (5\text{–}3)$$

No statistical (or other type) information can be obtained for d until it is discovered in one or more laboratories, and then it becomes part of the c_k's of the remaining laboratories.

Estimates of the variances in eq (5–3) or their square roots, i.e., the standard deviations, can be obtained from the results of experiments by the components of variance technique [20]. For example, if one observer performs many calibrations at one temperature on the same instrument using the same apparatus in the same standards laboratory, all the parameters on the right hand side of eq (5–2) remain constant except e^l. Therefore the variance of these individual temperature determinations is an estimate of $V(e)$. With $V(e)$ determined, a large number of observers can be used to obtain an estimate of $V(a)$. Similarly estimates of $V(b)$ and $V(c)$ can be obtained. This involves a tremendous amount of work and in addition is complicated by the fact that any changes or drifts in the instruments must also be taken into account. Nevertheless, an attempt has been made at NBS to begin to determine the variances in this model. Preliminary estimates for the standard deviations of these errors are listed in table 3 for calibrations of optical pyrometers and tungsten strip lamps at 1063 and 2300 °C. Only an upper limit for the estimate of the standard deviation of c could be determined because of the incompleteness of the data from the 1957–58 international comparison of strip lamps discussed in section 4.

TABLE 3. *Preliminary estimates for the standard deviations in deg C of various errors associated with optical pyrometer and strip lamp calibrations on the IPTS*

e is the random error of a set of observations by a single observer and a, b, and c are systematic errors associated with the observers, the apparatus, and the national standards laboratory, respectively.

	Strip lamps		Pyrometers	
	1063 °C	2300 °C	1063 °C	2300 °C
s(e)	0.3	0.9	0.3	1.4
s(a)	0.5	0.8	0.5	1.8
s(b)	0.3	0.6	0.3	1.4
s(c)	<0.5	<2.0	<0.5	<2.0

It is interesting to note that the estimated standard deviations of the errors associated with the calibration of pyrometers at 1063 °C turned out to be the same as that for strip lamps. At first this is surprising because twice as many brightness matches are necessary for a pyrometer calibration than for a strip-lamp calibration. Analyzing the brightness matches more carefully, however, one notes that when observers match high or low with the NBS pyrometer, they also match high or low respectively with the test pyrometer. At 2300 °C the correlation does not appear to exist, probably due to different pyrometer-lamp brightness temperatures in the test (~1050 °C) and NBS instrument (~1300 °C).

c. Uncertainties on Certificates

Ideally, the uncertainties stated on certificates of calibrations should be related to the estimated standard deviation of t. Unfortunately, adequate information has not yet been obtained to make this sufficiently quantitative to be meaningful. Thus, until sufficient data are obtained, preliminary estimates of the type given in table 3 together with the available data on the stability of strip lamps and pyrometers have been used to make "judgement type" estimates of the sum of the errors in eq (5–2), assuming the signs associated with the errors are the same. These are called maximum uncertainties on the calibration certificates. For optical pyrometers they are usually given as ±4 deg C at 800 °C, ±3 deg C at 1063 °C, ±8 deg C at 2800 °C, and about ±40 deg C at 4000 °C. For strip lamps they are ±5 deg C at 800 °C, ±3 deg C at 1000 and 1100 °C, and ±7 deg C at 2300 °C. It is presently (1961) felt that these errors are more conservative at the lower temperatures than at the high temperatures. It should be emphasized that these uncertainties as stated on the certificates do not represent a

---

[31] For strip-lamp calibrations, a single set of observations means the 4 brightness matches (dark to bright, 2 bright to dark, dark to bright) and the associated electrical current measurements. For optical pyrometer calibrations, a single set of observations means the 8 brightness matches of the NBS and test pyrometers and associated electrical current measurements described in section 5.3.

[32] For simplicity it has been assumed that the random error population for each observer is the same. This is only approximately true in practice.

standard deviation or some multiple of a standard deviation. It is hoped, however, that something more statistically meaningful can be incorporated in the certificates in the near future.

d. Differences Between the IPTS and TTS

When it is necessary for someone to obtain a temperature on the Thermodynamic Temperature Scale (TTS) [21] with an instrument calibrated at NBS on the IPTS, the estimated difference between the two scales is required. Above 1063 °C this is relatively easy to obtain because the IPTS would also be the TTS if the second radiation constant C_2 and the freezing point of gold t_{Au} were correct. Thus, estimates of the correct values for C_2 and t_{Au} are sufficient to calculate estimated differences between the two scales.

DuMond and Cohen [22] have reported a value of 1.43884 ± 0.00008 cm deg for C_2, obtained from their adjusted values of the atomic constants. The freezing point of gold on the Thermodynamic Scale has been redetermined in a number of laboratories during the past 6 years and three independent groups have confirmed the value 1064.5 °C (therm.) [23]. Using these values for C_2 and t_{Au}, estimated differences between the TTS and IPTS have been calculated and are presented in figure 18. Also included in figure 18 is the error incurred in using the Wien equation at 0.65 μ as an approximation for the Planck equation in the IPTS.

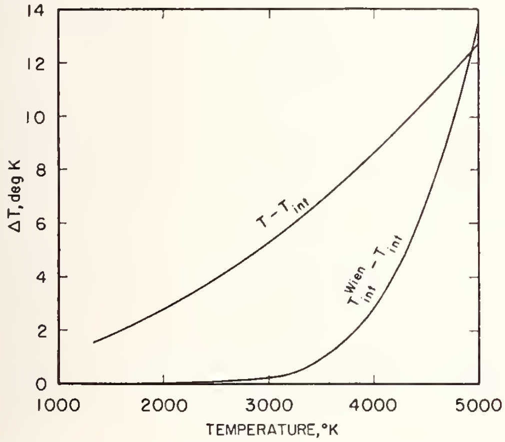


FIGURE 18. *Estimated difference between the Thermodynamic Temperature Scale and the International Practical Temperature Scale, and the error incurred when using the Wien equation (at 0.65 μ) as an approximation for the Planck equation in the IPTS.*

6. Applications

6.1. Temperature Measurements

An optical pyrometer determines the brightness temperature of an incandescent body at the mean effective wavelength between the brightness temperature and the color temperature of the body. If the spectral emittance of the particular part of the body sighted on is known, the temperature of the body may be determined from the following equation

$$\epsilon_{\lambda_{T_B-T_C}}(T)\,N_{b\lambda_{T_B-T_C}}(T)=N_{b\lambda_{T_B-T_C}}(T_B) \qquad (6\text{–}1)$$

or

$$\epsilon_{\lambda_{T_B-T_C}}(T)\left[e^{\frac{C_2}{\lambda_{T_B-T_C}T}}-1\right]^{-1}=\left[e^{\frac{C_2}{\lambda_{T_B-T_C}T_B}}-1\right]^{-1} \qquad (6\text{–}2)$$

where $\epsilon_{\lambda T_B-T_C}(T)$ is the spectral emittance at the mean effective wavelength $\lambda_{T_B-T_C}$, T_B is the brightness temperature of the body at this wavelength, T_C the color temperature, and T the temperature. When Wien's equation is an adequate approximation, eq (6–2) can be reduced to the simpler form

$$\frac{1}{T}=\frac{1}{T_B}+\frac{\lambda_{T_B-T_C}}{C_2}\ln \epsilon_{\lambda_{T_B-T_C}}(T). \qquad (6\text{–}3)$$

Spectral emittances are accurately known for only a few substances and surface conditions. Probably the most accurately known spectral emittances are those for tungsten [6, 24, 25]. An illuminating review of the principles, methods of measurement and the results of investigations on spectral emittances prior to 1939 has been given by Worthing [26]. More recent contributions can be found in the proceedings [27] of the Fourth Symposium on Temperature, Columbus, Ohio (1961).

In the vicinity of the gold point and a wavelength of 6500 A an error of 1 percent in spectral emittance results in an error of only 0.065 percent in temperature. More generally, using Wien's approximation, assuming that the small variation of spectral emittance with temperature may be neglected, and differentiating the equation

$$N_\lambda(T)=\epsilon_\lambda(T)\,C_1\lambda^{-5}e^{-C_2/\lambda T}, \qquad (6\text{–}4)$$

one obtains

$$\frac{dT}{T}=\frac{\lambda T}{C_2}\,\frac{dN}{N}. \qquad (6\text{–}5)$$

For the most accurate temperature determination with an optical pyrometer, it is recommended that a blackbody be built into the experimental setup. Then, of course, the spectral emittance is unity and the temperature is equal to the brightness temperature. Often blackbody conditions can be approximated sufficiently well by simply drilling a small hole into a solid or by inserting a small cavity in a molten substance.

6.2. Spectral Radiance Calibrations Using Strip Lamps

Tungsten strip lamps are often used to calibrate the response of spectrographs and spectrometers from about 2500 to 25,000 A. For this purpose the brightness temperature or spectral radiance of the lamp as a function of wavelength is required. Such a calibration is performed in the Radiometry Section at NBS and is available to the public. At present (1961) the maximum uncertainties reported vary from 3 percent at 25000 A to 8 percent at 2500 A.

Another way of obtaining the spectral calibration of a strip lamp is to calculate it using the brightness temperature from an optical pyrometer determination and published values for the spectral emittance of tungsten. The spectral radiance of a tungsten lamp is given by

$$N_\lambda(T)=C_1\lambda^{-5}[e^{C_2/\lambda T_B}-1]^{-1}$$

$$=\epsilon_\lambda(T)\,\tau_\lambda C_1\lambda^{-5}[e^{C_2/\lambda T}-1]^{-1} \quad (6\text{–}6)$$

where T_B is the brightness temperature of the lamp at wavelength λ, $\epsilon_\lambda(T)$ is the spectral emittance of the tungsten, τ_λ the spectral transmittance of the lamp window or envelope, and T the strip temperature. The procedure for determining $N_\lambda(T)$ at any wavelength is to first solve for T in eq (6–6) using the calibrated value of T_B and the measured or assumed value for τ_λ and published value of ϵ_λ, all at the mean effective wavelength associated with T_B. Then $N_\lambda(T)$ can be calculated for any wavelength for which ϵ_λ and τ_λ are available. For the visible spectral region and infrared to about 25000 A, it is usually adequate to assume τ_λ is constant. If a quartz envelope is used rather than glass, the constancy can be extended down to about 2800 A or less, depending on the type of quartz. Several papers have reported experimental determinations of ϵ_λ for tungsten during the past 10 years [6, 24, 25]. One of the major limitations of this technique is the question of whether the emittance of the tungsten in the lamp being used is the same as that reported in the literature. In addition, the effect of internal reflections and knowledge of the transmittance of the window will be somewhat uncertain. On the other hand, all of these parameters are used in a relative manner, i.e., the spectral radiance is known at about 0.65 μ, and one merely has to compute values at other wavelengths relative to it. As a result, the calculated spectral radiances at wavelengths other than 0.65 μ are usually only a few percent more uncertain than the spectral radiance at 0.65 μ which is obtained directly from the brightness temperature.

In using the tungsten lamp for spectral calibrations one should take the same precautions of orientation and alinement described in sections 3 and 5. In particular, one should try to use the strip lamp at the same entrance angle at which it was calibrated, especially when this angle is small and the lamp envelope appears to be inhomogeneous in the region where the beam exits.

6.3. Secondary Standards

A laboratory or industrial group that requires high accuracy in their optical pyrometry work or that requires only moderate accuracy but uses many strip lamps or optical pyrometers should consider maintaining their own secondary standards. It is often asked which is preferable, a strip lamp or optical pyrometer as a secondary standard to maintain the IPTS above 1063 °C. There is no unique answer to this question. It will depend on some factors that only the user himself is aware of, factors such as the manner and frequency with which the secondary standards are used and the money and personnel available for this work. Some of the factors that should be considered are listed in table 4.

6.4. Recommendations for Achieving High Accuracy and Precision

When high accuracy is the primary consideration in maintaining or making measurements on the IPTS, a few procedures should be emphasized. Both optical pyrometers and tungsten strip lamps change with use. Therefore, in order to obtain high accuracy, a laboratory should use one calibrated strip lamp or optical pyrometer infrequently and compare the strip lamps or pyrometers used regularly to it. As emphasized previously, great care should be taken concerning the orientation and alinement of the strip lamps, and vacuum lamps should be used whenever possible

Table 4. *Relative merits of strip lamps and optical pyrometers as secondary standards for the IPTS*

	Strip lamps	Optical pyrometers	Section discussed
Stability		Somewhat better	2.1, 3.4
NBS calibration uncertainty	At present (1961) about the same		5.12
Brightness temperature range	800–2300 °C	800–4000 °C, and higher	5.6
Care necessary for orientation and ambient temperature control.	Considerable	Very little	3.4
Time to reach equilibrium	Minutes to an hour	Seconds to a minute	2.1, 5.9
Cost of instrument	Considerably less		
Cost of NBS calibration	Less		
Cost of additional apparatus for most accurate use.		Somewhat less.	

For optimum precision and accuracy in the use of pyrometers, laboratories should request NBS to calibrate their pyrometer as a function of pyrometer filament current. The laboratory should then use a standard resistor and a sufficiently accurate potentiometer to determine this current. A multiturn smooth turning rheostat is highly desirable for varying the filament current while making the brightness matches. The precision of matches can often be improved greatly by having the pyrometer mounted rigidly in a comfortable position for a sitting observer. A black cloth thrown over the observer's head and part of the optical pyrometer to shield the observer from any distracting or annoying light is helpful. Observations should always be made from both a dark and a bright filament to a match or disappearance and the two results averaged. If one or two individuals primarily use the pyrometer, make sure that their technique of matching does not give results very different from the average of 5 or 6 observers. In addition, if nonblackbodies are often used, it is well to use 5 or 6 observers to determine if any observer has a very unusual relative luminosity curve. The standard deviation of the mean effective wavelength due to luminosity factor differences has been reported [28] to be about 8 A, which in reading a strip lamp at 2300 °C with a pyrometer having a constant *A* value absorbing glass, amounts to about 0.4 deg C.[33] Of greater relative importance than the relative luminosity factors for affecting the effective wavelengths are differences in spectral transmittance of the red glasses in pyrometers. Methods for determining the effective wavelengths of optical pyrometers were described in section 5. For convenience, table 5 summarizes the various recommendations for the practice of precise and accurate optical pyrometry.

TABLE 5. *Recommendations for the precise and accurate use of optical pyrometers and tungsten strip lamps*

Recommendation	Section discussed
Use the instrument infrequently	2.1, 6.4
Take the necessary precautions in orienting and alining strip lamps	3.4, 5.3, 5.7
Use a source whose image is large compared to that of the pyrometer filament	3.3
Use several observers	5.11, 6.4
The observer should be in a comfortable position, have a hood, and have the pyrometer rigidly mounted	6.4
Determine the effective wavelength of the pyrometer when observing non-black sources	1.6, 1.7, 5.2, 6.4
Use the pyrometer lamp current as the parameter to relate the brightness match	5.3, 6.4
Use a vacuum strip lamp for brightness temperatures below 1400 °C	3.3

6.5. Fundamental Limitations

The fundamental limitation in visual optical pyrometry is the sensitivity of the human eye. Lovejoy [7], using the results of an investigation of contrast thresholds or limens (see footnote 15) reported by Blackwell [29], calculated the expected observer standard deviation temperatures for the mean of a set of matches consisting of a bright filament to disappearance and a dark filament to disappearance for a pyrometer having a 0.05 radian exit angle, a 0.7 mm exit pupil, and a 0.038 mm actual and 10 min apparent angular filament width. The standard deviations ranged from 0.2 deg C at 1400 °C to 0.3 deg C at 1063 °C and increased to 1.6 deg C at 800 °C,[34] and agreed well with his experimental values.

Another basic limitation in visual pyrometry is the uncertainty of the observer's relative luminosity function. This function is required in a primary calibration of optical pyrometers at temperatures above the gold point, and its uncertainty corresponds to an equivalent uncertainty of about 1 to 1½ deg C in the primary calibration at 2400 °C. The effect of the uncertainty in the relative luminosity factors could be reduced by using a narrower spectral bandwidth in optical pyrometers. However, then one would begin to be even more limited by the eye's contrast sensitivity. Most optical pyrometers appear to be designed so that the two limitations are about equal at 2400 °C.

6.6. Photoelectric Optical Pyrometers

During the past 5 years, optical pyrometers which employ a photomultiplier tube rather than the eye as a detector have come into existence. Such instruments have been developed in the national standards laboratories of the U.S.S.R. [30], Australia [31], and the United States [1]. They have considerably greater sensitivity and precision (~0.01 deg) than the visual instruments and can use a much smaller spectral bandwidth. It is expected that photoelectric pyrometers will make possible at least an order of magnitude greater accuracy in optical pyrometry. However, in order to achieve this a number of difficult problems will have to be solved. Two of these are obtaining a "blackbody" with an emittance approaching 0.9999 and determining the ratio of two beams of radiant energy with an accuracy of 0.01 percent. These and other challenging problems, and the promising increase in the accuracy of high-temperature measurement if they are solved, have stimulated a new and exciting activity in the field of optical pyrometry.

---

[33] However, in a primary calibration an error of 8 A in the mean effective wavelength between 1063 and 2300 °C is equivalent to an error of about 3½ deg C at 2300 °C.

[34] Corresponding standard deviations for higher temperatures can be obtained from the relation between two temperature differentials obtained from Wien's equation. This relation is $dT=(T/T_A)^2dT_A$ where T represents the higher range temperature and T_A its corresponding apparent temperature as seen through the absorbing glass. At 2400 °C the resulting standard deviation is about 1 deg C.

7. References

[1] R. D. Lee, The NBS photoelectric pyrometer of 1961, Temperature, Its Measurement and Control in Science and Industry (to be published by Reinhold Publishing Corp., New York, N.Y.).

[2] H. F. Stimson, The International Practical Temperature Scale of 1948, J. Research NBS **65A,** 139 (1961); The International Temperature Scale of 1948, J. Research NBS **42,** 209 (1949).

[3] C. O. Fairchild and W. H. Hoover, Disappearqnce of the filament and diffraction effects in improved forms of an optical pyrometer, J. Opt. Soc. Am. **7,** 543 (1923).

[4] W. E. Forsythe, Optical pyrometry, Temperature, Its Measurement and Control in Science and Industry (Reinhold Publishing Corp., New York, 1941) p. 1115.

[5] C. R. Barber, Factors affecting the reproducibility of brightness of tungsten strip lamps for pyrometer standardization, J. Sci. Instr. **23,** 238 (1946).

[6] J. C. DeVos, A new determination of the emissivity of tungsten ribbon, Physica **20,** 690 (1954).

[7] D. R. Lovejoy, Photometry of the optical pyrometer and its use below 800°C, J. Opt. Soc. Am. **49,** 249 (1959).

[8] F. A. Cunnold, The optical system of the disappearing filament pyrometer, Proc. Roy. Soc. (London) **152A,** 64 (1935).

[9] J. C. DeVos, Evaluation of the quality of a blackbody, Physica **20,** 669 (1954).

[10] J. Vollmer, Study of the effective thermal emittance of cylindrical cavities, J. Opt. Soc. Am. **47,** 926 (1957).

[11] A. Gouffé, Corrections d'ouverture des corps-noirs artificiels compte tenu des diffusions multiples internes, Revue d'optique **24,** 1 (1945).

[12] H. G. MacPherson, The carbon arc as a radiation standard, Temperature, Its Measurement and Control in Science and Industry (Reinhold Publishing Corp., New York (1941) p. 1141.

[13] M. R. Null and W. W. Lozier, The carbon arc as a radiation standard, Temperature, Its Measurement and Control in Science and Industry (to be published by Reinhold Publishing Corp., New York, N.Y.).

[14] J. Euler, The graphite carbon arc as a standard source of intense radiation, Sitzber. Heidelberg Akad. Wiss. **4,** 418 (1956–57).

15] A. Bauer and P. Schultz, Eingeengte Xenon-Hochdruckentladungen höher Stromdichte, Z. Physik **155,** 614 (1959)

[16] R. A. Fisher, Statistical Methods for Research Workers (Hafner Publishing Co., New York, 1954) 12th ed., p 147.

[17] R. L. Anderson and E. E. Houseman, Tables of orthogonal polynomial values extended to $N=104$, Iowa Agr. Exp. Sta. Research Bul. 297 (1942).

[18] R. Davis and C. I. Pope, Techniques for ruling and etching precise scales in glass and their reproduction by photoetching with a new light-sensitive resist, NBS Circ. 565 (1955) p. 10.

[19] For definitions and further discussions see J. M. Cameron, Statistics, Fundamental Formulas of Physics, edited by D. H. Menzel (Dover Publications, Inc., New York, 1960) p. 107.

[20] F. A. Graybill, An Introduction to Linear Statistical Models (McGraw-Hill Book Company, Inc., New York, 1961), vol. I, ch. 6.

[21] H. F. Stimson, Heat units and temperature scales for calorimetry, Am. J. Phys. **23,** 615 (1955).

[22] J. W. DuMond and E. R. Cohen, Least squares adjustment of the atomic constants, 1952, Revs. Modern Phys. **25,** 691 (1953).

[23] H. Moser, Review of recent determinations of thermodynamic temperatures of fixed points above 419°C, Temperature, Its Measurement and Control in Science and Industry (to be published by Reinhold Publishing Corp., New York, N.Y.).

[24] R. D. Larrabee, The spectral emissivity and optical properties of tungsten, J. Opt. Soc. Am. **49, 619** (1959).

[25] C. Tingwaldt, New optical methods for the determination of thermodynamic temperatures of glowing metals, Temperature, Its Measurement and Control in Science and Industry (to be published by Reinhold Publishing Corp., New York, N.Y.).

[26] A. G. Worthing, Temperature radiation emissivities and emittances, Temperature, Its Measurement and Control in Science and Industry (Reinhold Publishing Corp., New York, 1941) p. 1164.

[27] Temperature, Its Measurement and Control in Science and Industry (to be published by Reinhold Publishing Corp., New York, N.Y.).

[28] D. R. Lovejoy, Accuracy of optical pyrometry in the range 800°C to 4000°C, Can. J. Phys. **36,** 1397 (1958).

[29] H. R. Blackwell, Contrast thresholds of the human eye, J. Opt. Soc. Am. **36,** 624 (1946).

[30] V. V. Kandyba and V. A. Kovalevskii, A photoelectric spectropyrometer of high precision, Doklady Akad. Nauk S.S.S.R. **108,** 633 (1956).

[31] J. Middlehurst and T. P. Jones, A precision photoelectric optical pyrometer, Temperature, Its Measurement and Control in Science and Industry (to be published by Reinhold Publishing Corp., New York, N.Y.).

Offprint from „Metrologia"
Journal International de Métrologie scientifique — International Journal of scientific Metrology
Internationale Zeitschrift für wissenschaftliche Metrologie. Vol. 2, No. 4, October 1966, Pages 150—162
Springer-Verlag, Berlin · Heidelberg · New York

The NBS Photoelectric Pyrometer and its Use in realizing the International Practical Temperature Scale above 1063 °C

R. D. Lee

National Bureau of Standards, Washington, D. C.

Received June 1, 1966

Abstract

A photoelectric pyrometer has been developed with which the International Practical Temperature Scale (IPTS) above the gold point, 1063 °C, is realized about 5 times more accurately than with the prevalently used disappearing filament visual pyrometer. Estimated standard deviation uncertainties of realizing the IPTS with the photoelectric instrument are 0.06 deg C at 1063 °C, 0.12 deg C at 1256 °C, 0.27 deg C at 1650 °C, 0.7 deg C at 2330 °C, and 2 deg C at 3525 °C. The design, evaluation, and calibration to realize the IPTS are discussed.

1. Introduction

The International Practical Temperature Scale (IPTS) [1] above 1063 °C is usually realized with a disappearing filament optical pyrometer [2]. The reproducibility and accuracy of the optical pyrometer is primarily limited by the contrast sensitivity of the human eye [3]. Photoelectric means of detecting the equality of spectral radiance along the same principles as those of the visual instrument have been demonstrated to be considerably more precise, and this increased precision has been accomplished with a narrower spectral passband.

During the past few years, photoelectric pyrometers have been developed at the National Bureau of Standards (NBS) and at other national standards laboratories [4, 5]. Progress toward evaluating the NBS instrument has been previously reported [6, 7]. This instrument has been calibrated relative to the IPTS four different times during the past two years, and has been used for about 735 hours in calibrating strip lamps and pyrometers. The present paper is a comprehensive description of the NBS photoelectric pyrometer and of the results in realizing and maintaining the IPTS.

2. Description

The optical system of the photoelectric pyrometer is shown in Fig. 1. The major differences of this optical system from that of the visual pyrometer are the 1.3 mm diameter field stop*, the passband filters in addition to a red glass, and a specularly reflecting disk with a slit. The image reflected at the disk provides for alignment and focusing. For this purpose the 1.3 mm field stop is temporarily removed. Small (0.2 mm) vertical displacements of the pyrometer lamp alternate its image on the slit with that of the external radiant source. This can be accomplished manually or automatically at intervals of 30 secs. The equality of the multiplier phototube response as it is irradiated alternately by the two images constitutes a photoelectric match.

The optical system is largely corrected for spherical aberration and coma. Lenses at IA are telescope objectives and are used in the pyrometer at the object and image distances for which they are corrected. The remaining lenses were designed specifically for the photoelectric pyrometer. According to the manufactures report, lenses IIA and IIB together have a longitudinal spherical aberration of less than 0.15 mm for 6563 Å (Hydrogen C line), 5893 Å (Sodium D line), and 5461 Å (Mercury E line). The lens system IIIA and IIIB, treated as one optical component, is reported to have a longitudinal spherical aberration of only 1.5 mm for the C line and less for the D and E lines. The resulting image quality appears to be adequate. Some defocusing (as a way to represent a poorer image) is possible without a detectable change in photoelectric response, thus indicating that the response is independent of the residual aberrations.

The absorbing glasses are made of Jena NG-3 filter glass, and are inserted into the optical path to extend the temperature range above 1256 °C. Corning Pyrometer Brown glass is often used for this purpose; however, this glass was not available in small quan-

---

* Lenses at IA and the field stop were not in the original version of the instrument described in Ref. [6].

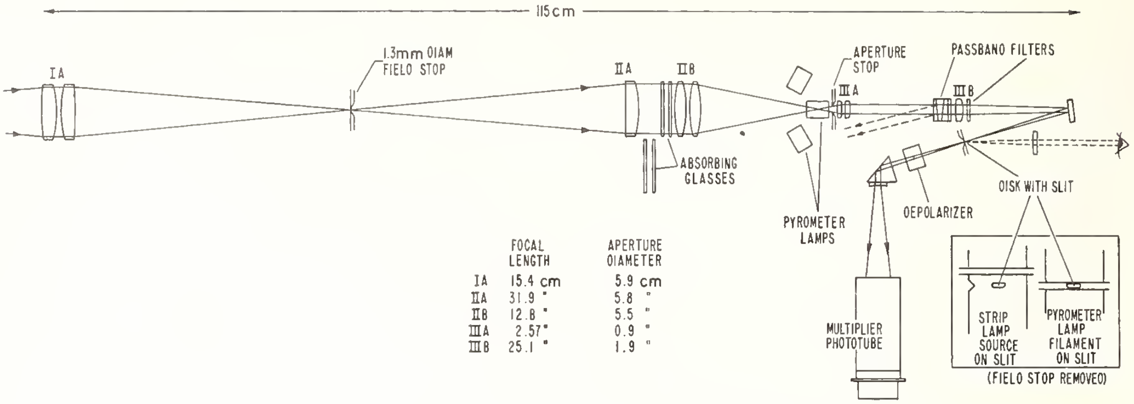


Fig. 1. Optical system of the NBS photoelectric pyrometer. The plane of the source is fixed 30.4 cm from the first lens, IA

tities at the time of construction of the pyrometer. The Jena NG-3 was selected for its similarity to the Corning Brown in its relative spectral transmittance within the spectral passband of the pyrometer. Both of these glasses have "*A*" values [2] that vary only slightly with source temperature. This characteristic facilitates a more reliable determination of the "*A*" value at all temperatures. The 4 glasses are nearly equal in "*A*" value (approximately 135 mireds) and are used in tandem for the high temperature ranges. They are positioned in a parallel beam so that the image formed by the inter-reflected rays is superimposed on the primary image. An accurate correction can be made for this additional radiation using the experimentally determined reflectance of each glass surface.

The photoelectric pyrometer has three vacuum pyrometer lamps that are mounted so that they can be quickly and precisely interchanged. Thus the lamps may be accurately intercompared by using an external source which need be stable only for times of the order of 5 or 10 mins. The lamps have small tungsten ribbon filaments up to 0.1 mm wide. The flat filament provides a more uniform radiance than a round filament, and this makes positioning of the image over the slit less critical.

The aperture stop before the lenses at IIIA is not in the proper ratio to the objective aperture to fulfill Fairchild and Hoover's criterion [8]. This criterion was concerned with conditions for reducing diffraction at the edge of a pyrometer lamp filament, in order to provide good visual disappearance. The criterion is not applicable to the photoelectric pyrometer, since the slit is covered only by the central 0.8 of the filament image, and the edges are avoided. Both the entrance aperture and exit aperture are considerably larger than those of a conventional visual pyrometer, with the ratio, entrance to exit, being 1.23.

The multi-element filter in front of lens IIIB plus an additional filter behind this lens isolates a spectral passband centered on 6545 Å with a width at half the transmittance of 125 Å*. The multi-element filter consists of a multi-layer dielectric interference filter, a sideband suppression interference filter, and a red glass, all of which are cemented together. The remaining filter is another side-band suppression interference filter, added to suppress some radiation detected at 7700 Å. Fig. 2 compares the passband of the photoelectric pyrometer with that of the NBS laboratory visual pyrometer [2], which is typical, in this respect, of present day optical pyrometers.

Two mechanically interchangeable specular disks are provided. One contains a slit about 0.8 mm by 2.4 mm and the other a circular aperture 0.8 mm in diameter. The conjugate target dimensions are 0.2 mm by 0.6 mm, and 0.2 mm diameter. The slit is used for regular work, while the smaller circular aperture is used for determining the temperature gradient of a source.

The optical system, chiefly the interference filters, polarize the radiation about 5%. This is probably due to the orientation of the interference surfaces at 7 degrees to the optic axis (to direct the reflected radiation out of the optical train). This polarization, if not corrected, would cause errors in radiance temperature measurements of polarized or partially polarized sources. A tungsten strip lamp, which is frequently used as a secondary standard source, is an example of a partially polarized source when it is viewed at an angle away from the normal of the strip surface. The most general solution to the problem was to depolarize the instrument, and this was done rather simply by inserting a parallel plane glass plate in the optical path and adjusting its orientation until the photoelectric

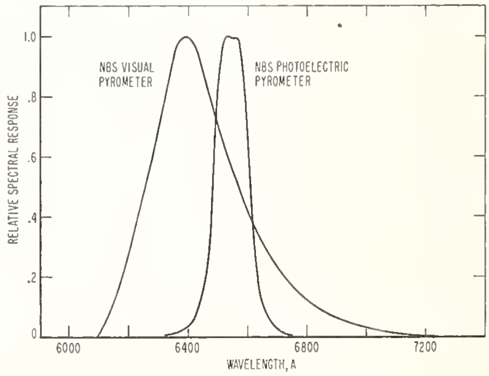


Fig. 2. Spectral passbands of the NBS visual and photoelectric pyrometer. The visual pyrometer curve is determined by a red glass and the visibility function of the observer, while the photoelectric curve is determined mainly by an interference filter

---

* Previously reported as 110 Å from manufacturer's data.

response to polarized radiation was constant regardless of the direction of the polarization.

A block diagram of the electrical system of the photoelectric pyrometer is shown in Fig. 3. The system detects, amplifies, and records a dc signal. The potential developed across the load resistor in the output of the multiplier phototube is largely canceled by an adjustable bias voltage in order to reduce the linearity and stability requirements of the amplifier and to increase the sensitivity of the recorder trace. Rather than to attempt to match completely the source and pyrometer lamp it is less time consuming to leave small differences in their recorder traces and interpolate to a match. These differences are usually less than the equivalent of 0.2 deg C, and the interpolation does not add any additional significant uncertainty.

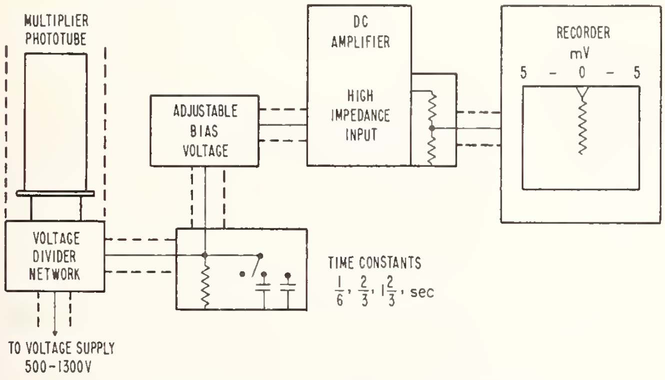


Fig. 3. Electrical system of the NBS photoelectric pyrometer

The multiplier phototube is an RCA 7265, 14-stage, end-on-illumination type with an S-20 spectral response. The tube data show a sensitivity at 6545 Å of 35% of the maximum sensitivity at 4200 Å. The quantum efficiency at 6545 Å is reported to be about 6%. At present the multiplier phototube is operated at room temperature, but, if required, it can be cooled with a minor modification of the pyrometer. A voltage supply, reported by the manufacturer to regulate to 0.1% for an ac line change of 25 volts, supplies up to 1300 volts across a voltage divider resistance network for the phototube dynodes. Carbon resistors of 5% tolerance and 1 watt rating are used in the network. A battery supply has also been used with the individual batteries connected between the dynodes. Comparison of the performance of the phototube with the two voltage supplies has shown that the resistance network does not add a significant amount of noise to the signal.

Typical electrical parameters, used with a blackbody source of 1063 °C, are as follows. With 1150 volts on the multiplier phototube the tube has an output current of 0.058 μA (with dark current <0.0002 μA), which developes 192 millivolts across the 3.3 megohm resistance. With this signal biased, and the amplifier plus attenuator at a gain of about 2, the recorder has a 10 inch deflection for a change of signal of about 2.5%. This change corresponds to about a 2 deg C change in the temperature of the 1063 °C source, or 0.02 deg C per chart division of 0.1 inch.

3. Reproducibility

3.1 Precision of a radiance match

The precision attainable in making a radiance match is limited by the fluctuations appearing on the recorder trace. Fig. 4 shows these in comparison to a 0.2 deg C change in radiance temperature of a source at 1063 °C, using various electrical time responses.

When recorder traces 30 secs long are obtained, as has been the practice, the higher frequency fluctuations or noise can be averaged fairly well by a straight line through the trace. The effect of longer period fluctuations is reduced by averaging 4 to 8 consecutive radiance matches. As a measure of the obtainable precision of a single radiance match, the sample standard deviation of a series of successive determinations of the radiance temperature of a vacuum tungsten strip lamp at a radiance temperature of about 1063 °C was determined. A standard deviation of 0.02 deg C, largely independent of the electrical time response used, was obtained.

Since the dark current trace of Fig. 4 shows no significant noise, the noise appearing on the recorder trace under conditions of illumination must be due primarily to the statistical fluctuations of the electrons released at the cathode surface of the multiplier phototube. In accord with theoretical considerations the expected rms value of this noise is proportional to the square root of the signal [9], and therefore the signal-to-noise ratio is also proportional to the square root of the signal. The characteristics which determine the signal-to-noise ratio are listed in Tab. 1. The entrance angle is the angle subtended at the source by the entrance pupil of the pyrometer. The target dimensions given are those of the conjugate image of the slit in the plane of the source. An improved signal-to-noise ratio does not rapidly improve the precision of the radiance match over and above that obtainable

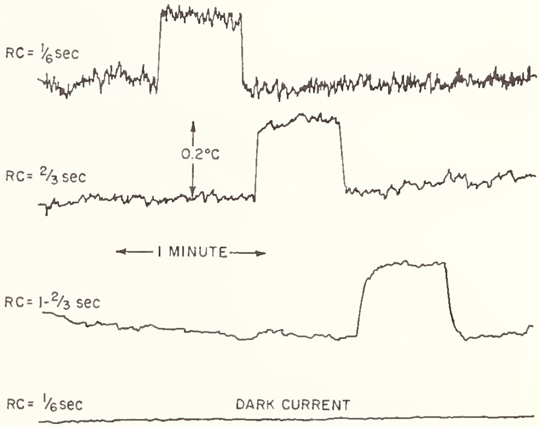


Fig. 4. Recorder traces showing the noise in comparison to 0.2 deg C change in radiance temperature of a source at 1063 °C, for various RC time constants of the electrical system

Table 1. *Characteristics which determine the signal to noise ratio of the* NBS *photoelectric pyrometer*

(1) Optical
Entrance angle: 8 degrees
Target dimensions: 0.2 mm × 0.6 mm
Passband: 125 Angstroms at 6545 Å
Transmittance: 35%

(2) Electrical
Multiplier phototube: Quantum efficiency, 6% at 6545 Å
Time constants: 1/6, 2/3, 1 2/3 sec.

already from integrating 30 sec traces. At the upper end of the low range, 1256 °C, the signal-to-noise ratio is greater by a factor of about three; however, the precision of the match is only slightly improved. Therefore, considerable change in the characteristics listed in Tab. 1 would be necessary to produce a significant improvement in the pyrometer.

3.2 Stability of pyrometer lamps

The frequency of recalibration and the accuracy to which the IPTS is maintained between calibrations depend in large measure on the reproducibility of the radiance of the pyrometer lamps for any given electric current. New pyrometer lamps are aged before being calibrated in order to obtain a stable radiance vs current relationship. Eight lamps have been investigated for reproducibility during or after various schedules of ageing. However the results have not shown a significant correlation between manner of ageing and stability. The instability of the pyrometer lamps is probably the major limitation in maintaining the IPTS.

The lamps tested have been labeled ph 1 to ph 8. Lamps ph 1, 2, 7 and 8 are NBS designed lamps having tungsten filaments of 99.9% purity. The filaments are 0.1 mm wide, 0.01 mm thick, and 32 mm long. Lamps ph 3, 4, 5, and 6 are commercial lamps with flat tungsten filaments about 0.05 mm wide and of 99.9+ % purity. All the lamps are vacuum type with an estimated bulb pressure of 10^{-5} torr.

Results of the stability tests are given in Figs. 5 to 9. Differences occurring as a function of time between pyrometer lamps left on continuously and a pyrometer lamp inoperative (except for the periodic comparison) are plotted. The comparisons were made by using an external vacuum strip lamp as a transfer source.

Lamps ph 1 and ph 3 of Fig. 5 were aged prior to testing for 2000 hours at 1500 °C (tungsten temperature) and 1000 hours at 1450 °C, respectively, while ph 4 was used as purchased.

Fig. 6 shows the behavior of a lamp which, because of its rapid decrease in radiance temperature (∼ 1063 °C) for a constant current, was given additional treatment. After three hours at 1950 °C its radiance temperature at the initial current was about 8 deg C higher than just before the ageing, and was increasing rapidly. During 500 hours ageing at 1900 °C the radiance temperature decreased about 2 deg C but was found to increase with time on a subsequent run at 1063 °C radiance temperature. The transmittance of the windows of the lamp ph 2 was measured before and after the last ageing treatment in order to check the possible coating of the inner surfaces of the glass envelope. A decrease in the transmittance of about 1% (for two windows) was observed. This accounts for only 20% of the change observed after the 500 hour ageing treatment.

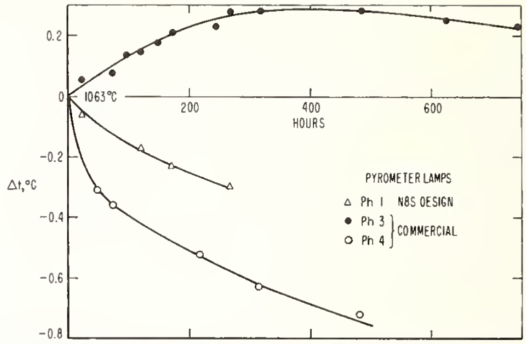


Fig. 5. Change in radiance temperature of pyrometer lamps initially at 1063 °C radiance temperature, versus hours at a constant lamp current

Fig. 7b shows the results of two commercial lamps which were not given prior ageing at NBS. After 500 hours at lamp currents for a 1063 °C radiance temperature, the lamps were run at 1250 °C radiance temperature for an additional 300 hours, then finally set back to 1063 °C for the remainder of the test. The reproducibility of the radiance of the lamps was checked at 1063 °C throughout. Also shown (Fig. 7a) are the periodic comparisons between the pyrometer lamp used as a reference and the vacuum strip lamp used as the transfer source. These latter results show continual long term agreement between these infrequently used lamps.

Two new NBS lamps, ph 7 and ph 8, were checked during the process of ageing by periodic comparisons at 1063 °C radiance temperature with a little used reference lamp. After 900 hours both lamps had become reasonably stable while they were kept on at 1550 °C, Fig. 8. The stability was not maintained when the lamps were aged further at a lower temperature of 1130 °C (1063 °C radiance temperature), as Fig. 8 shows.

English vacuum tungsten strip lamps with strips 1.3 mm wide have been tested for stability with a spectroradiometer in another laboratory of the NBS Radiation Thermometry Section, and with a sensitivity within a factor of 2 or 3 of that of the photoelectric pyrometer. Some of these lamps, compared with a little-used reference lamp (another strip lamp), showed results similar to those pyrometer lamps of

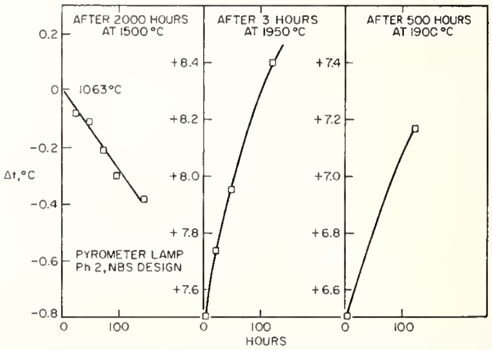


Fig. 6. Changes in radiance temperature of a pyrometer lamp versus hours at a constant lamp cturren, as a result of ageing the lamp

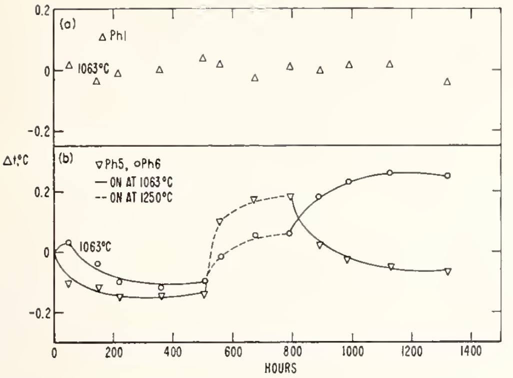


Fig. 7. (a) Comparisons of a pyrometer lamp and a 1.3 mm vacuum strip lamp both left off except for the brief comparisons. The pyrometer and strip lamps were used to check lamps in b below. (b) Changes in radiance temperature 1063 °C versus hours at constant lamp currents for 1063 °C or 1250 °C radiance temperatures

Fig. 7. Others behaved better while a few were substantially worse.

The photoelectric pyrometer was given a primary calibration, using the pyrometer lamp designated ph 1. This lamp, whose early history is shown in Fig. 5, had been frequently used thereafter, and therefore received additional ageing. After the calibration, comparisons were made at 1063 °C with the gold point furnace, as the most reliable way of ascertaining drifts and correcting the IPTS. Fig. 9 shows the results of these comparisons. After the first one-hundred hours the trend has become fairly predictable.

Short term instabilities of pyrometer lamps were investigated by first matching to a strip lamp at 1063 °C radiance temperature, then turning the pyrometer lamps up to 1256 °C (highest temperature used) for an hour, and immediately thereafter rechecking at 1063 °C to see if the original matches were reproduced. Early in its history ph 1 showed a significant inertia, taking an hour to recover [6] in this treatment. After several years of use at various temperatures the lamp has improved and recent cycling tests show recovery within two minutes at 1063 °C after an hour at 1256 °C.

Our experience with vacuum tungsten pyrometer lamps has not led to any conclusion as to the causes of observed instabilities. A new lamp may either increase or decrease in radiance with time and at an unpredictable rate. Lamps achieving good long term stability have, on occasion, begun to change more rapidly. Our present practice is to choose a lamp with a suitable history and check or recalibrate is after fifty to a hundred hours of use. In addition, a more comprehensive investigation of pyrometer lamps is being initiated.

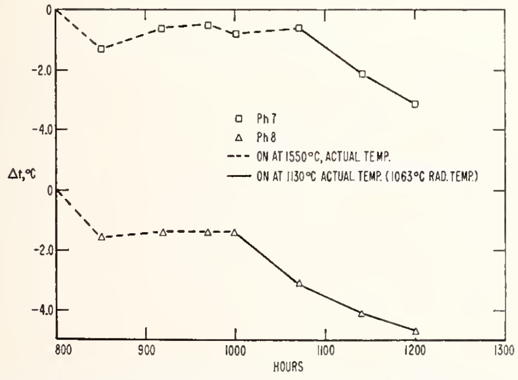


Fig. 8. Pyrometer lamps checked at 1063 °C for final stability while on after the indicated period of ageing at 1550 °C, then checked for stability during the additional indicated ageing at 1063 °C radiance temperature

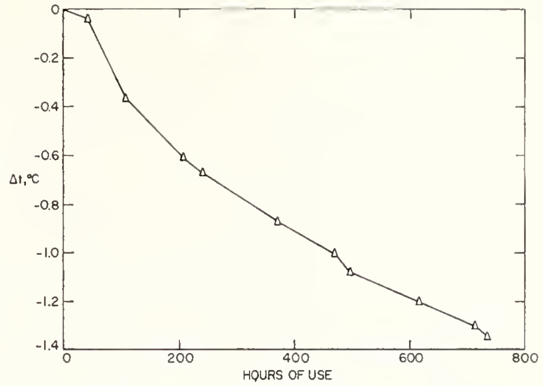


Fig. 9. Changes at 1063 °C radiance temperature of pyrometer lamp, ph 1, with hours of use in the calibrated pyrometer. The lamp becomes less radiant at a given current with continued use

4. Effect of the size of the radiant source on accuracy

Three different factors that could affect the accuracy of realizing the IPTS were related to the size of the radiant source. In the initial design of the pyrometer there were adverse effects caused by scattering of radiation in the optical system and heating of the pyrometer lamp filament by the incident image. In addition, there was heating of the absorbing glasses by the incident radiation, which was dependent on the source size (as well as its temperature); this heating was found to cause a change in absorptance. The effect on performance of all three factors has been considerably reduced by the addition of lenses IA and the 1.3 mm field stop (Fig. 1). Nevertheless, prior investigation of these factors with lenses IIA and IIB as the objective had revealed several characteristics of interest.

4.1 Radiation scatter in the optical system

It had been observed that a significant amount of the radiation originating in the object plane (the conjugate image of the slit) outside the target area was detected by the pyrometer. Radiation from these areas on the source could arrive at the slit through diffraction, interreflections in the optical components, and scattering by dust or imperfections in the components. In the absence of detailed analysis of the causes and to simplify discussion, the combined effects will be referred to as a scattering of the radiation.

The effect of scatter on the radiance match with sources of the same radiance but differing in size was investigated. In the process of a primary calibration, a gold point furnace, which is a radiant source approximately 50 mm in diameter, and 1.3 mm wide tungsten strip lamps are used. An experimental source made of a 50 mm diameter disk coated with MgO paint was irradiated by a number of conventional incandescent lamps to represent the furnace. The flat disk at room temperature provided a convenient way to represent, also, a 1.3 mm by 50 mm strip source by positioning black velvet paper with a cut out of these dimensions in front of the disk. Upon comparing these two different sized and shaped surfaces at 1063 °C simulated temperature, the 50 mm disk. matched 0.1 deg C higher than the 1.3 mm strip.

There was some concern that the partial coherence of the reflected radiation from the MgO may not properly simulate a self-radiating source. Therefore, besides the MgO disk, a self-radiating 50 mm disk of 60% platinum, 40% rhodium alloy was used, with 1.3 mm graphite cut outs. Tests with both disks gave similar results, and indicated that the more convenient MgO source is suitable for additional work of this nature.

The amount of radiation detected from outside the target area is considerably more than that equivalent to the 0.1 deg C radiance temperature. Fig. 10 shows the relative photoelectric response in an experiment which reveals the total amount of scattered radiation. The figure first represents a match (a and b) between the pyrometer lamp and the 1.3 mm strip. The drop in response at c occurs when the source is blocked off from the pyrometer. This shows that about 4% of the radiation (difference between a and c) arrived at the slit through scatter from the 1.3 mm strip source. Over 7% is scattered from the 50 mm disk (difference between d and c).

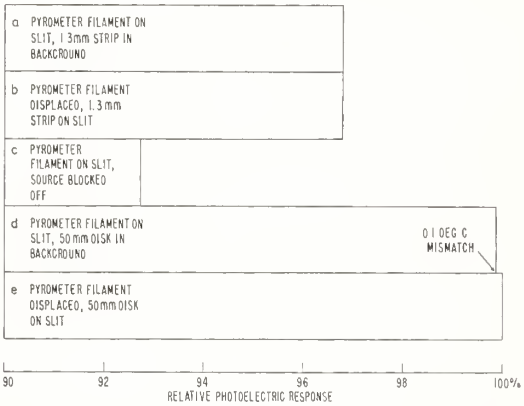


Fig. 10. Drop in photoelectric response to the pyrometer lamp filament when the 1.3 mm by 50 mm and the 50 mm disk sources are blocked off. The pyrometer lamp current was constant throughout. Only the 0.1 deg C mismatch is of significance to accuracy

For further explorations of scatter, an MgO disk was made with a 1 mm diameter hole through the center. In use the photoelectric pyrometer is sighted at the center of the dark hole. Thus, any photoelectric response under these conditions is that due to scatter alone.

By using this source it was determined that the interference filters were largely responsible for the radiation scatter. When the photoelectric pyrometer was tested without the filters the percentage scattered was reduced by a factor of three. The interference layers of the filters, when examined with oblique illumination, appear somewhat spotty.

By adding the 1.3 mm field stop and lenses IA to image the source at the stop, the effective size of the source was made invariant for the remainder of the pyrometer. The scattering under these conditions was about 3.5% of the radiation detected. The matching discrepancy between a 50 mm disk and a 1.3 mm strip was reduced from 0.1 dec C to 0.03 deg C. This correction was made when comparing the gold point furnace and a 1.3 mm strip lamp.

4.2 Heating of the pyrometer filament by incident radiation

The heating of the pyrometer filament by the incident radiation could lead to errors in radiance temperature measurements. The filament is horizontal, and of two sources of the same radiance the wider source gave rise to more heating of the filament, which would then require less lamp current for a match.

The heating of the filament was first noticed by a slight increase in pyrometer lamp current when a source was blocked off. This change indicated a decrease in the resistance of the lamp filament brought about by its decrease in temperature. To check this further, an infrared transmitting filter with essentially complete absorption at 7500 Å and shorter wavelengths was positioned between the source and the pyrometer. This filter eliminated any effects of the radiation scatter by absorbing most of the radiation which the photomultiplier could detect. Pyrometer lamp radiance changes were observed as the front lens (of the initial photoelectric pyrometer) was covered with a shutter. With a 1.3 mm strip lamp as a 1063 °C source the decrease in radiance temperature of the filament was about 0.05 deg C. Before similar observations could be made with the gold point furnace, the pyrometer was modified with the additional lenses and field stop. It was estimated, that with the initial pyrometer design the gold point would have raised the pyrometer filament about 1 deg C.

With the modification, as with the radiation scatter effect, the size (and width) of the source was made invariant, and there should be no unequal heating by different sources. Experiments, however, with the infra-red filter and the gold point furnace as well as the strip lamp showed a 0.03 deg C difference in temperature. This is believed to be caused by the greater infra-red content of the furnace radiation. The 0.03 deg C correction was made in the calibration process, where the gold blackbody and strip lamps were compared.

4.3 Change of absorptance of the absorbing glasses through heating

The change in the absorptance of the absorbing glasses due to heating by the incident radiation was indicated by matching a 1.3 mm strip lamp at 1350 °C, through an absorbing glass, before and immediately after sighting on a 3 mm by 45 mm strip lamp at 2400 °C for one hour. The difference in absorptance before and after heating by the high temperature lamp was observed as an erroneous change in the radiance temperature of the 1350 °C lamp of a little more than one deg C. Both the Jena NG-3 and the Corning Brown were tested in this manner. The Jena NG-3 glass decreased in absorptance with heating and the Corning glass increased by about the same amount.

Because the Jena and Corning glasses showed opposite temperature effects, a laminated absorbing glass of Jena NG-3 and Corning Brown was constructed in order to neutralize the heating effect. Tests on the laminated glass showed this to be a satisfactory solution. However, the addition of the 1.3 mm field stop, which was desirable for other reasons also, cut down the radiant energy incident on the glasses from a 3 mm strip lamp by a factor of about 100. Further tests showed this to be an adequate solution to eliminating undue heating by radiant sources, and the Jena NG-3 glasses were continued in use.

The pyrometer is used in a laboratory where the temperature is known to vary over a range of 2 deg C. To test the effect of the temperature of the glass as it changes with ambient temperature, a 6 deg C change in ambient temperature was induced while the pyrometer was matched to a 1256 °C strip lamp using an absorbing glass. Comparison of temperature measurements with the glass and without (i.e. on the low range) showed there was about 0.1% change in transmittance per deg C change in glass temperature for the Jena NG-3. In terms of errors in radiant temperatures measurement at 1256 °C, 0.1% amounts to about 0.1 deg C. This effect is accounted for by noting the ambient temperature when the absorbing glasses are calibrated and correcting this calibration for any other ambient temperature during use.

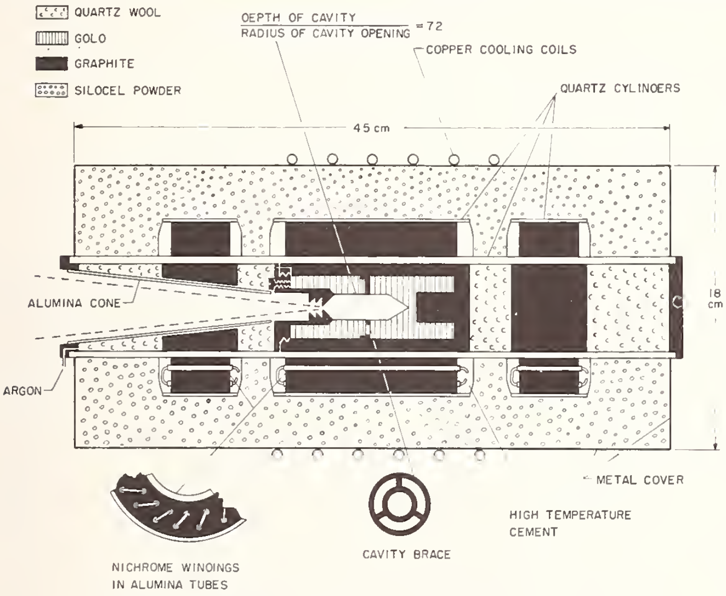


Fig. 11. Cross section of the NBS horizontal gold point blackbody and furnace

5. Calibration of the photoelectric pyrometer

The principles involved in calibrating a visual optical pyrometer [2], that is, in realizing the IPTS, also apply to the photoelectric pyrometer. The definition of the IPTS above the gold point is as follows [1].

$$\frac{N_{b\lambda}(t)}{N_{b\lambda}(t_{au})} = \frac{e^{\frac{C_2}{\lambda(t_{au}+T_o)}}-1}{e^{\frac{C_2}{\lambda(t+T_o)}}-1} \qquad (1)$$

$N_{b\lambda}(t)$ and $N_{b\lambda}(t_{au})$ are the spectral radiances of blackbodies at temperatures t and t_{au}. t_{au} is defined as 1063 °C, C_2 as 1.438 centimeter degrees, and T_0 as 273.15 degrees. λ is the wavelength in centimeters. The realization of the IPTS above 1063 °C can be divided into four parts. These consist of (1), a calibration at the gold point, (2), a low range calibration obtained by measuring ratios of radiances of sources at higher temperature, to the gold point radiance, (3), determination of the mean effective wavelengths of the pyrometer, and finally, (4), determination of the "A" values of the absorbing glasses used for the higher temperature ranges. The "A" value is defined as

$$\text{“}A\text{”} = \frac{1}{T_a} - \frac{1}{T} \qquad (2)$$

where T is the source temperature in °K and T_a is the lower apparent temperature (°K) of the source as seen through the glass.

5.1 Calibration at the gold point, 1063 °C

A gold stabilized blackbody cavity and furnace that would be reliable enough to meet the demands of the increased sensitivity of the photoelectric pyrometer were designed and constructed. Fig. 11 illustrates this design. Particular attention was devoted to achieving a uniform temperature over the inner walls of the cavity. The crucible containing 1800 grams of gold is shaped so that the mass of gold per unit length is about constant for the crucible's entire inner length. The furnace has three independently controlled heater windings which are imbedded in cylindrical graphite muffles. The power inputs to the two end windings are adjusted to maintain the two end sections to within 5 deg C of 1063 °C as determined by embedded thermocouples (not shown). The center winding is used for controlling the rate of heat loss by the gold during a freeze, as well as for heating during a melt.

Gold with a purity of 0.99999 as determined by the Analytical Chemistry Division at NBS is used. The cavity and crucible for the gold are made of the highest purity graphite available. The manufacturer claims that the impurities do not exceed 20 parts per million. In addition, the graphite has a high emissivity, a fairly high thermal conductivity, and is easy to machine. The latter characteristic has made possible the construction of cavities of 0.5 mm wall thickness.

Sightings were made on the diaphragm at the edge of the cavity opening as a check for temperature uniformity. The radiance temperature was about 0.2 deg C lower than that of the hole. Since the effective emissivity of the diaphragm is expected to be less than that of the hole, the temperature difference between the cavity and the diaphragm is less than 0.2 deg C. Nevertheless, if the inner surface of the diaphragm were 0.2 deg C lower than 1063 °C the emissivity of the cavity would be reduced by only 0.000001.

The effective emissivity of the cavity was calculated by using the equations derived by De Vos [10]. The partial reflectance used was determined at room temperature on a piece of graphite with a surface condition similar to that in the cavity. De Vos' first approximation to the emissivity was calculated to be 0.99999.

By the time the first full calibration was completed, the gold point furnace had been used a number of times over a two-year span. In particular, comparisons of two different gold point blackbodies, of melts and freezes, of the constancy of the melting and freezing plateaus, and trends during a day's operation had been obtained. One of the crucibles contained a cavity of 0.5 mm wall thickness and the other a cavity of 1.0 mm wall. Tab. 2 summarizes these results. From these comparisons the gold blackbody appears to be as reproducible as the precision available (0.02 deg C), and has not deteriorated in use. In addition, the negligible difference between the two crucibles indicates that the correction for temperature gradients across the cavity wall is negligible.

With the main heater power off, the duration of a freeze is about 15 to 17 mins. This time is largely dependent on the degree of furnace insulation and the amount of gold used. Fig. 12 is a reproduction of an approach to and departure from a freezing plateau. With some power on, the duration of a freeze has been prolonged to an hour, and there is no significant difference in radiance from that of a 17 min freeze. For the melts the power input is adjusted for approximately 17 mins duration of melting.

There was a question of whether there may be some absorption of the exit radiation by the furnace gases, which probably consist of C, CO, and CO_2. Argon is fed in from the front of the furnace but it cannot be relied on to completely clear away other gases from the optical path. To check whether there may be absorption within the spectral pass band of the pyrometer, the crucible and back section were removed and the crucible was replaced with a graphite cylinder. The cylinder was hollowed out to allow an image of a strip lamp to be formed within the furnace and sighted upon by the pyrometer. Matches were made with the strip lamp image through the hot (1063 °C) furnace and with the furnace removed. A diaphragm was placed in front of the lamp envelope so that radiation from the furnace did not reach the strip lamp and raise its temperature. Ray tracing from the hot furnace parts through the lens to the diaphragm showed that the radiation was properly blocked. This was realized by making a larger opening in the graphite at the image plane than was otherwise necessary.

A difference in matches with and without the furnace had to be corrected for the extra radiation known to be scattered in from the furnace, and also for radiation reflected from the lenses forming the strip image. To find this correction, the strip lamp was turned off, and the photoelectric response with the furnace in place was obtained while the pyrometer was focused on the image of the dark strip.

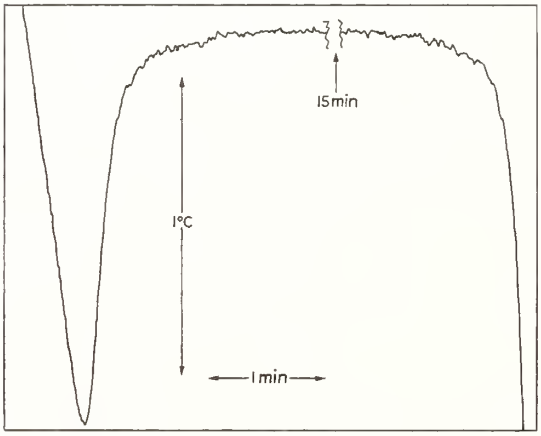


Fig. 12. Chart recording of approach to and termination of a gold point freeze plateau

The corrected comparisons of radiance matches with and without the furnace should show whether furnace gases absorb a significant amount of the radiation. A number of comparisons averaged to a 0.002 deg C difference with the standard deviation of the result being 0.015 deg C*. Under the conditions of the experiment there was considerably more graphite surface exposed than with the gold-filled crucible. Also, there was no discernible difference in the results with argon either flowing in or turned off. It was concluded that to within the experimental error of these measurements there was no absorption by the furnace gases in the spectral passband of the pyrometer.

A calibration of the photoelectric pyrometer at the gold point consists of radiance matches with three melts and freezes.

Table 2. *Analysis of the Gold Point Reproducibility*

Nature of Comparison	Average of Measurements	Number of Measurements	S. D. of a single Measurement
0.5 mm Wall vs 1.0 mm Wall Cavity			
[Melts and Freezes], 0.5 mm − 1.0 mm	+0.009 deg C	14	0.015 deg C
Freezes vs. Melts			
[Freezes] — [Melts]	+0.010 deg C	48	0.010 deg C
Trend of a Plateau			
[Freeze] — [Freeze] 1st half 2nd half	−0.001 deg C	46	0.008 deg C
[Melt] — [Melt] 1st half 2nd half	+0.001 deg C	41	0.008 deg C
Trend during a Day			
[Freezes] — [Freezes] 1st half 2nd half	−0.012 deg C	23	0.015 deg C
[Melts] — [Melts] 1st half 2nd half	−0.009 deg C	21	0.015 deg C

Two measurements are obtained for each plateau with each measurement consisting of an average of eight matches. The standard deviation of a measurement is 0.023 deg C. A correction of 0.03 deg C is made when the gold point radiance is transferred to a 1.3 mm strip lamp, to compensate for the effect of the difference in source size. An additional correction of 0.03 deg C is made for the difference in heating of the pyrometer lamps with the blackbody and strip lamp.

As far as it can be determined, the uncertainty in maintaining the IPTS at the gold point is preponderantly due to lack of sufficient stability of the pyrometer lamps rather than to the gold point apparatus or the calibration procedure. After each hundred hours of use the photoelectric pyrometer is recalibrated at the gold point to correct for the pyrometer lamp drift, which is shown in Fig. 9. Between gold point calibrations the amount of drift is predicted from an extrapolation in Fig. 9, and the necessary correction is made. The prediction is estimated to be uncertain by 0.05 deg C by the end of a hundred hours. Taking this into account, along with the precision of the matches and the uncertainties of corrections made for transferrals to a strip lamp, the overall uncertainty of the gold point after a hundred hours was calculated to be 0.06 deg C (standard deviation). In the calculation, the various individual uncertainties are treated as independent standard deviations and are combined in quadrature.

5.2 *Realizing ratios of radiance*

Sectored disks are used in visual pyrometry to obtain radiance ratios required to realize the IPTS above the gold point [2]. They are feasible in visual work due to the persistence of vision of the observer. It did not appear desirable to use sectored disks with the photoelectric pyrometer, because with their use a comparison would be made between a high, intermittent irradiance from the source and a low steady irradiance from the pyrometer lamp. Experience has indicated that the gain of the photomultiplier would not be constant with the accuracy desired for these two irradiances. Initially, a double beam splitter was used [7, 11] to obtain ratios relative to the gold point radiance. Ratios of 2^n where n is an integer could be obtained by this device. Erminy of NBS conceived a scheme for obtaining more numerous ratios and also fractional ratios [12] with a device for conjoining beams from three radiant sources. The method was implemented as shown in Fig. 13. Ratios of 1.5, 2, 3, 4, 6, and 8 were used above the gold point to 1256 °C. A calibration was also made to 794 °C

---

* This number with other standard deviations yet to be discussed is listed in Table 3.

using ratios of 0.67, .5, .25, etc., with successive ratios of a factor of one half. This latter extension is needed in some of the work in calibrating commercial optical pyrometers. In all, 14 determinations of radiance temperature versus lamp current from 794 °C to 1256 °C were obtained.

The sources used in the conjoiner were 1.3 mm tungsten strip vacuum lamps. The lamp currents were well regulated and essentially no lamp instability was detected over the thirty minutes that it took to obtain a calibration point. Typically, the lamps were matched individually 4 times each, then matched in combination 8 times, and finally rechecked individually with 4 matches each. Some calibration points were taken with the three lamps set in different combinations of radiance ratios. For instance, the calibration at 1256 °C was obtained with lamps set at previously achieved ratios of 3, 2, and 3 and then at ratios of 4, 2, and 2.

A calibration at a given temperature was repeated two or three times, usually within a two hour period. Above 1063 °C the individual results differed by no more than 0.03 deg C, and below 1063 °C, except for 794 °C, there was a maximum of 0.04 deg C difference. At 794 °C the calibration had a range of 0.15 deg C. This was expected due to the poorer sensitivity at the low temperatures.

In order to provide adequate interpolation between the calibrated points, least squares fits to various equations were calculated. Following Kostkowski, Erminy, and Hattenburg [13], the equation

$$\frac{1}{I} = \frac{A}{T_r^2} + \frac{B}{T_r} + C + DT_r + ET_r^2 + FT_r^3 + \frac{G}{T_r^3} \qquad (3)$$

was derived by assuming that conduction losses in the pyrometer lamp filament, to a first approximation, were proportional to the temperature. Tables were made using this equation. However, as found by Kostkowski, et al., a polynomial of the form $I = P(T_r)$ fitted as well and required one less term. In both equations the least squares deviation of the points was less than 0.02 deg C, and the standard deviation of the points along the curve was, on the average, less than 0.02 deg C.

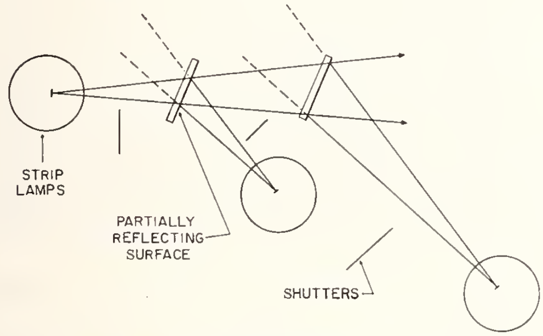


Fig. 13. Optical design of a beam conjoiner for providing radiance ratios relative to the gold point

Whenever a gold point calibration was made to check the pyrometer lamp drift, the low range was either recalculated on the basis of the new gold point and certain other assumptions discussed below, or (at alternate times) given a more complete calibration with the beam conjoiner. Ten-point calibrations were performed rather then fourteen-point calibrations as initially performed. The ten-point calibrations are less time consuming and are adequate to correct established tables.

Fig. 14 compares conjoiner calibrations performed after 260, 495, and 735 hours of pyrometer use with the initial conjoiner calibration. Each calibration is normalized to the original calibration by adding Δt_t to the radiance temperature t in the new calibration where

$$\Delta t_t = \Delta t_{\mathrm{au}} \left(\frac{t + 273.15}{1336.15} \right)^2 \qquad (4)$$

and Δt_t and Δt_{au} are radiance temperature differences between the new calibration and the original calibration at the radiance temperature t and the gold point, respectively. This normalization implies that the spectral radiance of the lamp has changed by the same percentage at all radiance temperatures. Fig. 14 shows that this has not been the case, at least in the earlier calibrations. The radiences corresponding to calibration points above the gold point appear to have changed less than the percent change at 1063 °C and vice versa below the gold point. However, departures from this simple model have decreased with time as have changes in the gold point calibration. For example, the gold point changed by 0.7, 0.4 and 0.25 deg C between successive calibrations at 0, 260, 495, and 735 hours. At 1256 °C, the change in terms of a departure from the above model has been 0.14, 0.06, and 0.05 deg. These departures are in a direction to suggest using a model in which the radiance temperature changes are constant at all points. The various calibrations agree with this latter model somewhat better but with an opposite sign. Thus the correct model is somewhere between the two simple ones discussed. However, the changes between the last two calibrations (0.25 deg C at the gold point and 0.28 deg C at 1256 °C) are sufficiently small that either simple model agrees with the experimental results within the short term reproducibility of the low range calibration.

Calibrations will be performed every 200 hours of pyrometer operation, using the beam conjoiner, meanwhile retaking the gold point at 100 hour intervals. In addition to predicting trends in the lamp at 1063 °C, trends in the low range at temperatures away from 1063 °C are to be predicted, using the results in Fig. 14 as a guide.

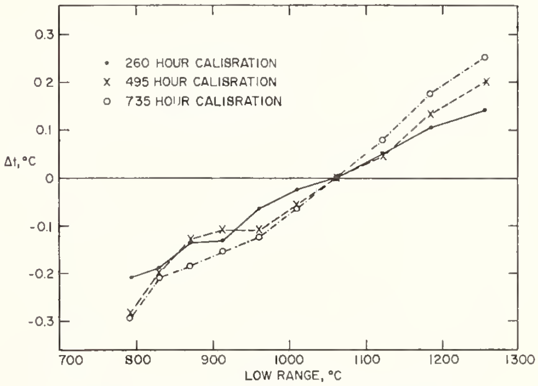


Fig. 14. Differences of three calibrations from the initial calibration after normalization to the initial gold point calibration

In estimating uncertainties at 1256 °C, a correction of 0.06 deg C is first to be made (in addition to one made for gold point changes) by the end of 200 hours. This extra correction is assessed as uncertain by 0.06 deg C, thus recognizing the possibility the correction may not be needed, or, on the other hand, that a 0.12 deg C difference may occur, corresponding (approximately) to the once observed difference of 0.14 deg C in 260 hours. Other sources of uncertainty at 1256 °C are the uncertainty of the gold point, 0.06 deg C, which increases to 0.08 deg C at 1256 °C, statistical variations of the beam conjoiner process of 0.046 deg C (standard deviation), and an estimated uncertainty of 0.03 deg C due to short-term pyrometer lamp instabilities during the calibration process. In addition, there is a contribution due to the uncertainty of the mean effective wavelength, which is discussed later.

5.3 Mean effective wavelength determination

The mean effective wavelengths were derived from experimentally determined curves of effective wavelength versus temperature [2]. The equation

$$\frac{1}{\lambda_e} = \frac{\int_0^\infty \frac{N_{b\lambda} R_\lambda \, d\lambda}{\lambda}}{\int_0^\infty N_{b\lambda} R_\lambda \, d\lambda} \qquad (5)$$

was used to obtain the effective wavelengths. $N_{b\lambda}$ is the Planck radiation function, λ the wavelength, λ_e the effective wavelength, and R_λ is the relative spectral response of the photoelectric pyrometer.

In the process of finding R_λ, a small grating monochromator with an Ebert optical system was set up on its side to make the exit slit suitably horizontal for sighting with the pyrometer. The monochromator entrance optics were arranged so that a quick and brief exchange of the image of the regular source with that of a neon discharge source could be made. The monochromator has a scanning drive, and the recorder and the monochromator were run simultaneously. Thus a profile of photoelectric response versus wavelength was traced. When a chosen neon spectral line was approached, it was recorded to provide a wavelength calibration on the recorder chart.

Chart measurements were taken at 5 Å intervals from 6000 to 6945 Å, at which wavelengths the response was less than 0.02% of the peak response. Corrections were made for the relative spectral transmittance of the monochromator and the relative spectral radiance of the source in order to obtain R_λ of Eq. (5).

To find the relative transmittance of the monochromator (including its external optics), sensitive vacuum thermopiles coated with gold black were used as approximately neutral detectors. A graphite arc was used as a source of sufficiently known spectral radiance [14] within the spectral passband. The optical beam was chopped at 11 cycles per second and the output of a thermopile was fed to a tuned amplifier. The spectral transmittance of the monochromator did not vary rapidly. Therefore it was possible to use a relatively wide passband of 30 Å which permitted a sufficient signal to noise ratio with the thermopile.

Twenty to thirty spectral transmittance curves were obtained with each of three thermopiles. The average curve from each thermopile was normalized to 1.00 at 6500 Å so that the three curves could be directly compared at other wavelengths. At 6800 Å the transmittance was about 0.9 of that at 6500 Å, and the range of the three values was 0.0035. At 6300 Å the relative transmittance was 0.95 and the range, 0.0075. If these ranges were treated as errors, the range of 0.0075 would lead to an error in the effective wavelength of about 0.12 Å. This is not a significant error, and at any rate the average of the three curves should be in error less than the range, provide there are no systematic errors.

One thermopile was checked for its constancy of spectral absorptance by measuring the reflectance at several random spots on the gold black surface. There was a slight specular component, and measurements were taken at the specular angle as well as other angles. The absorptance (relative spectral) was calculated and was found to be independent of wavelength within the standard deviation of the measurement. This uncertainty had negligible effect on the effective wavelength.

Radiation is detectable at a low level at wavelengths well away from the main spectral passband of the pyrometer. It is of some significance to the accuracy of the effective wavelength to determine whether the wavelength of this radiation is that identified by the spectral setting, or otherwise scattered by the monochromator. While the amount scattered may be relatively insignificant, any scattered radiation at wavelengths of the main passband is preferentially detected by up to several orders of magnitude.

To test for spectral scatter, the spectral response of the photoelectric pyrometer was determined at monochromator settings of 6311 Å, 6412 Å, and 6848 Å, with a strip lamp as a source. These are wavelengths away from the main passband, where the response is low, in the same order, 0.6%, 4.3%, and 0.3% of the peak response. Three interference filters peaked at the given wavelengths were interposed in the optical path in turn as the monochromator was set at the peak. The filters were spectrally narrow enough to reject the pyrometer's main passband and therefore any spectral scatter therefrom. A drop in response when a filter was interposed was corrected for the reduction of radiation at its peak transmittance. Any further drop would be attributed to scatter. However, less than 2% of the response at the tested wavelengths was accounted for in this way, and therefore scatter did not contribute to a significant error.

In determining the effective wavelengths several variations in experimental procedure were tried. A graphite arc (3800 °K) and a blackbody furnace at 1250 °C were used as sources. Different sets of neon spectral lines were used. Wavelength scans were made in opposite spectral directions. The monochromator was fitted with different width slits although no greater than a 4 Å passband was used. Various multiplier phototube voltage settings were used.

Of the different procedures only one gave cause for concern. A persistent difference of 0.6 Å was found between scanning in the increasing and decreasing wavelength directions. The difference was opposite to that expected if the multiplier phototube were fatiguing, which was primarily the factor the opposite scans were intended to check. The difference would be explained if the electronic response times (1/6 sec) were not brief enough to record a spectral line faithfully. Slower scans were limited by the burning time of the arc and drifts of the 1250 °C furnace. No reason could be found for a scan in one direction to result in a systematic error of 0.6 Å while an opposite scan would contain no error. It was concluded that there was a systematic error in both cases of 0.3 Å, and that the average of opposite scans was the most probably correct value.

The relative spectral response as found by the graphite arc and the 1250 °C blackbody resulted in a difference in effective wavelength of 0.24 Å at 1250 °C. This could be a statistical variation. Other variations in procedure did not reveal any systematic differences in results.

Effective wavelengths were taken a year apart to ascertain the stability of the spectral response. The photoelectric pyrometer was used frequently during this time. Initially 24 scans had been made and a year later 12 more. The averages of the two sets of values differed by 0.52 Å. The uncertainty of each average was estimated to be about that amount. Since it is not readily discernible whether there was an actual change, the mean of both sets was used. In taking into account the uncertainties of the methods and also that there may be some change with time, an uncertainty of 0.8 Å was assigned to the effective wavelength. This leads to an uncertainty of 0 026 deg C in the calibration at 1256 °C.

The effective (and mean effective) wavelength of the pyrometer changes when absorbing glasses are used. To find the additional effective wavelength curves, the spectral transmittances of the glasses were determined, and the product of them and the previously found low range spectral response was taken as the overall spectral response with the glasses. The mean effective wavelengths of the pyrometer with absorbing glasses were not used in the calibration process. However, uncertainties of the relative transmittance of the glasses figure in the calculations of "*A*" values of the glasses.

5.4 Determination of the "A" values of the absorbing glasses

Of the four Jena NG-3 absorbing glasses one is used singly to extend the temperature range from 1256 °C to 1650 °C. The remaining glasses are successively added to provide temperature ranges of 1650 °C to 2330 °C, 2330 °C to 3730 °C and, with all four glasses, 3730 °C to 8570 °C. This procedure of achieving the higher ranges with a series of glasses is used because the "*A*" value of each glass, about 135 mireds, can be found separately and at the relatively low temperature of 1256 °C. In addition to this determination, however, the variation of the "*A*" value with source temperature must be found. With the type glass used this variation should be small.

The "*A*" values at 1256 °C were obtained with a strip lamp source utilizing the low range calibration. The glasses were inserted in turn and an apparent temperature of about 994 °C was measured. When a strip lamp rather than a blackbody radiator is used, its radiance temperature at the mean effective wavelength on the low range must be corrected for the mean effective wavelength on the higher range where the absorbing glass is used [2]. This correction is small, being only 0.04 deg C at 1256 °C.

The beam conjoiner was used to extend the calibration to 1383 °C and 1533 °C in an attempt to obtain the "*A*" values at these temperatures, and therefore determine the variation of "*A*" with temperature (trend). However, the "*A*" value trend with temperature was too small to determine in this way. To establish the trend the equation,

$$\int_0^\infty N_{b\lambda}(T)\, R_\lambda\, T_{ag,\lambda}\, d\lambda = \int_0^\infty N_{b\lambda}(T_a)\, R_\lambda\, d\lambda \qquad (6)$$

was used. This equation expresses the radiance match between a blackbody source at the Kelvin temperature T, through an absorbing glass, and one at the resulting apparent temperature, T_a. $T_{ag,\lambda}$ is the spectral transmittance of the glass. Values of T were chosen and the equation was solved for T_a. From T and T_a the "*A*" values were found. The increase of "*A*" at 1650 °C, 2330 °C, and 3730 °C over that at 1256 °C, is in equivalent temperature, 0.05 deg C, 0.3 deg C, and 0.7 deg C, respectively. The uncertainties of the values found are estimated to be 0.02 deg C, 0.07 deg C, and 0.26 deg C in the same order.

Shortly after calibrations with the beam conjoiner the "*A*" values were redetermined at 1256 °C. The results from the first three calibrations, taken over a period of 14 months, show a linear increase of the "*A*" values of about 0.035 mireds per year, or, in equivalent temperature at 1256 °C, about 0.08 deg C per year. The absorbing glasses were cleaned before the initial calibration, but they had not been cleaned thereafter, and the drift of the "*A*" values indicated a need for recleaning. This was done but with variable results. Two absorbing glasses changed back to the original "*A*" value and two did not. In cleaning glasses five months later for the fourth calibration, the "*A*" values of the glasses changed significantly, about 0.2 deg C 1256 °C, from the previous calibration, and in the direction of greater transmittance. The changes of the glasses and change between glasses upon cleaning indicate our cleaning of them is not consistent. As a result, their "*A*" values are more reproducible if they do not undergo the cleaning process. A slow drift of the glasses is tolerable when the drift is determined by recalibrations every 200 hours, and the correction predicted as a function of time. In the immediate future the "*A*" values will be redetermined more often till a drift is discerned. It is expected that the glasses may be cleaned at two year intervals, if the drift is no more than that previously observed.

The uncertainty of the "*A*" values determined at 1256 °C is largely composed of uncertainties in the low range at 1256 °C and at the resulting apparent temperature of 994 °C. (However, errors at these temperatures which are due to an error in the gold point determination cancel, and this is taken into account). When two or more glasses are used, errors in the "*A*" values add. Inasmuch as the "*A*" values are determined at 1256 °C, when this temperature becomes the apparent temperature in a measurement, its error is additive to the errors in the "*A*" values, i.e., they are not independent. The errors in other apparent temperatures are also likely to lack this independence, inasmuch as errors in the low range away from the gold point are probably in the same direction. Uncertainties are quoted for those high temperatures for which the apparent temperature is 1256 °C or near this temperature. The standard deviations of the non-independent uncertainties are 0.208 deg C at 1650 °C, 0.600 deg C at 2330 °C, and 1.755 deg C at 3525 °C (which is in the vicinity of the graphite arc radiance temperature). These and other (independent) standard deviations are listed in Tab. 3. It can be seen that the above given deviations are preponderant in affecting the accuracy of the IPTS at temperatures needing one or more absorbing glasses.

When two or more glasses are in position, interreflections add radiation to the image of the source. The reflected radiation superimposes an image upon the primary image. Thus a correction can be made which is good to the uncertainty of measuring the reflectance of the glass surfaces. Reflectance measurements were made to a precision of 0.4% (standard deviation of a measurement), and this uncertainty is incorporated in the uncertainties of the high range temperatures.

6. Estimated uncertainty in realizing and maintaining in IPTS.

In developing the photoelectric pyrometer, a significant amount of time was spent on the investigation and elimination of possible systematic errors. The remaining errors, as far as can be determined, are the random errors in the various experimental processes in the calibration and the uncertainties of corrections for drifts of the pyrometer lamp.

In many cases the individual processes that contribute to the IPTS were repeated often enough to yield a representative standard deviation. In other cases in which a process was not sufficiently repeated, standard deviations are estimated. In the case of trends, the

Table 3. *Statistical errors and estimates of uncertainty in realizing and maintaining the* IPTS

	Standard deviations (S.D.), deg C				
Temperature on the IPTS	1063 °C	1256 °C	1650 °C	2330 °C	3525 °C[a]
Gold point					
Emmissivity of cavity	negl.				
Cavity temp. non-uniformity	negl.				
Temp. gradient through cavity wall	negl.				
Absorption by furnace gas	0.015				
Radiant source size correction	.012				
Unequal heating of lamp filament	.015				
Precision of match	.023				
Lamp drift correction, 100 hours	.050[b]				
S.D. of gold point	0.060	0.078[c]	0.124	0.227	0.485
Calibration at 1256 °C					
Precision of compound matches		0.046			
Mean effective wavelength		.026			
Lamp instability during calib.		.030[b]			
Lamp drift correction, 200 hours		.060[b]			
S.D. at 1256 °C		0.086			
Calibration at higher temperatures					
Precision in determining "*A*" value			0.032	0.082	0.214
"*A*" value (uncertainty of temps. used), and apparent temp. uncer. } one entry			.208	.600	1.755
Correction of drift of "*A*" with time			.043[b]	.155[b]	.490[b]
Trend of "*A*" with radiance temp.			.020[b]	.102[b]	.435[b]
Ambient temp. correction of "*A*"			.032[b]	.115[b]	.371[b]
Correction for interreflections				.010	.025
Lamp drift correction, 200 hours			.095[b]	.173[b]	.370[b]
S.D. at 1650—3525 °C			0.238	.666	1.96
Total standard deviation uncertainty of realizing and maintaining (200 hours) the IPTS	0.06	0.12	0.27	0.7	2.

---

[a] This temperature is in the vicinity of the graphite arc radiance temperature.

[b] Estimated values.

[c] This entry and the following to the right are the gold point S.D. reflected at the higher temperatures.

corrections for the trends are assigned estimates of standard deviations. It is our endeavor to combine in quadrature deviations of all the processes, to obtain overall standard deviations at chosen temperatures that are reasonably valid. Tab. 3 has been constructed to summarize all the processes or elements that contribute to the IPTS, along with their standard deviations (calculated or estimated). Some of the entries are recognizable as related to a familiar process. Other entries originate when results are corrected for errors which were experimentally determined. The corrections have statistical uncertainties which are passed on to the corrected result. The radiant source size correction in transferring a gold point calibration to a strip lamp is an example.

The final values at the end of Tab. 3 are the estimated standard deviation uncertainties of the IPTS at NBS after being maintained for 200 hours (photoelectric pyrometer use), with a gold point calibration at 100 hours. Immediately after a complete calibration the uncertainty up to 1256 °C is reduced by about 40%. At higher temperatures, where absorbing glasses are used, the improvement is not significant.

A spectroradiometer in the NBS Radiation Thermometry Section of which the photoelectric pyrometry project is a part, also requires the realization of the IPTS above 1063 °C [13]. The spectroradiometer provides a largely independent realization of the Scale, and with a temperature resolution of about 0.04 deg C. In IPTS calibrations with both instruments the same gold point furnace has been used, but from there on the instrumentation was significantly different. It was worthwhile to both projects to compare results as a measure of the uncertainties involved.

Comparisons were made on occasions about a year apart. On the first occasion a vacuum strip lamp on which the IPTS was newly realized in conjunction with the spectroradiometer was in turn checked with the recently calibrated photoelectric pyrometer. There was agreement at 1063 °C within the precision of the pyrometer's radiance match, 0.02 deg C. Of greater interest, the vacuum strip lamp was used with the spectroradiometer to calibrate a gas-filled strip lamp at 2337 °C. This lamp was then calibrated with the photoelectric pyrometer and the two calibrations agreed to about 0.5 deg C.

Recently, comparisons were made at 1040 °C, 1063 °C and 1256 °C and differences were 0.03 deg C, 0.06 deg C, and 0.10 deg C, respectively. A comparison at 3525 °C using a graphite arc resulted in a difference of 0.2 deg C. However, the reproducibility of the arc itself was only 3 deg C.

In the course of making these comparisons, corrections of the strip lamp radiance temperatures were made for slightly different mean effective wavelengths, for different target areas over which temperature gradients existed, and for a partial polarization of the lamp. The spectroradiometer could not be completely depolarized at all wavelengths and there was a correction due to polarization at the mean effective wavelength of the pyrometer. The corrections were small, being about the same magnitude as the final differences observed.

The uncertainty inherent in the corrections made makes the comparisons less certain. But in allowing for this, the overall results, which reflect combined inaccuracies of both instruments, are viewed as supporting the uncertainty estimates of Tab. 3. A more regular schedule of comparisons is planned as a continuing check on the IPTS as realized with the two different instruments.

The NBS laboratory visual pyrometer, which has been in service in calibrating strip lamps and visual optical pyrometers for many years, was compared with the photoelectric pyrometer through a simultaneous calibration of strip lamps. Up to 1300 °C a vacuum strip lamp was calibrated, and on up to 2300 °C a gas-filled lamp was calibrated. Further, at about 2730 °C and 3525 °C a graphite arc was used with both instruments. To attain 2730 °C the arc was used with an absorbing glass.

Differences in the calibrations are given in Fig. 15. Part of the differences may be real, but the results are of the same order of magnitude as the precision of the visual observations in performing the calibrations. The agreement is good considering the accuracy to which a visual pyrometer can be calibrated. The uncertainty (standard deviation) of the IPTS on the visual instrument has been estimated [15] to be 0.4 deg C at 1063 °C, 3 deg C at 2300 °C, and 7 deg C at 3525 °C. Incidentally, the radiance temperature of the graphite arc positive electrode measured with the photoelectric pyrometer was very close to 3525 °C or 3798 °K. However, differences between graphite electrodes up to as much as 12 deg K above or below 3798 °K have been observed.

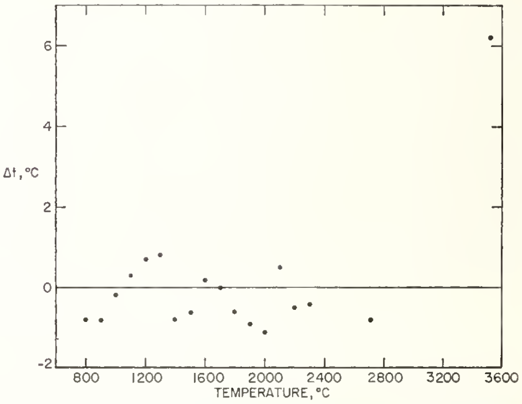


Fig. 15. Difference in the IPTS as maintained on the NBS photoelectric pyrometer and the NBS laboratory visual pyrometer

7. Present status and future work

In order to maintain the IPTS with an accuracy approaching that with which it can be realized, the photoelectric pyrometer must undergo frequent calibrations. A major limitation to the accuracy lies in the observed instabilities of the pyrometer lamps, unless they are frequently checked and corrected. Both the internal pyrometer lamps and the larger strip lamps, used as secondary temperature standards, lack the desired stability. There is a need for more reproducible temperature sources if the IPTS is to be transferred with a certainty approaching that attainable with the photoelectric pyrometer. As a result, an intensive investigation of lamps has been initiated.

8. Acknowledgments

The author was privileged to complete the development of a photoelectric pyrometer at NBS that was based on preliminary studies and experimental work of C. P. Johnson, G. Ziegler and D. E. Erminy. The photoelectric pyrometer was completed in the Radiation Thermometry Section under the direction of H. J. Kostkowski, Section Chief. The innumerable discussions with him were of great value to the author. Most of the instrument was constructed by A. N. Graef and W. Grote. Finally, the author wishes to thank E. Lewis for his assistance in pyrometer calibrations and other work.

References: [1] Stimson, H. F.: The international practical temperature scale of 1948. J. Research Nat. Bur. Standards **65**A, No. 3, 139 (1961). — [2] Kostkowski, H. J., and R. D. Lee: Theory and methods of optical pyrometry. Temperature, its measurement and control in sciences and industry, Vol. 3, Part 1, p. 449. New York: Reinhold Publishing Corporation 1961. — [3] Lovejoy, D. R.: Photometry of the optical pyrometer and its use below 800 °C. J. Opt. Soc. Am. **49**, 249 (1959). — [4] Kandyba, V. V., and V. A. Kovalevskii: A photoelectric spectropyrometer of high precision. Doklady Akad. Nauk. S.S.S.R. **108**, 633 (1956). — [5] Middlehurst, J., and T. P. Jones: A precision photoelectric optical pyrometer. Temperature, its measurement and control in science and industry, Vol. 3, Part 1, p. 517. New York: Reinhold Publishing Corporation 1961. — [6] Lee, R. D.: The NBS photoelectric pyrometer of 1961. Temperature, its measurement and control in science and industry, Vol. 3, part 1, p. 507. New York: Reinhold Publishing Corporation 1961. — [7] Lee, R. D.: Some results and problems in calibrating the NBS photoelectric pyrometer of 1961. Comite Consultatif de Thermometrie, 6- Session (1962). — [8] Fairchild, C. O., and W. H. Hoover: Disappearance of the filament and diffraction effects in improved forms of an optical pyrometer. J. Opt. Soc. Am. **7**, 543 (1923). — [9] Engstrom, R. W.: Multiplier phototube characteristics: Application to low light levels. J. Opt. Soc. Am. **37**, 420 (1947). — [10] De Vos, J. C.: Evaluation of the quality of a blackbody. Physica **20**, 669 (1954). — [11] Bojarski, L. A.: The use of the photoelectric method for precise measurements in the domain of the optical pyrometer. Procès-Verbaux des Séances du Comité International des Poids et Mesures **26A** (1959). — [12] Erminy, D. E.: Scheme for obtaining integral and fractional multiples of a given radiance. J. Opt. Soc. Am. **53**, 1448 (1963). — [13] Kostkowski, H. J., D. E. Erminy, and A. T. Hattenburg: A high accuracy spectroradiometer, to be submitted to the Journal of the Optical Society of America. — [14] Null, M. R., and W. W. Lozier: Measurement of reflectance and emissivity at high temperatures with a carbon arc image furnace. Measurement of thermal radiation properties of solids. NASA SP-31 (1963). — [15] Kostkowski, H. J., and G. W. Burns: Thermocouple and radiation thermometry above 900 °K. Measurement of thermal radiation properties of solids. NASA SP-31 (1963).

Reprinted from **APPLIED OPTICS,** Vol. 5, page 1858, November 1966

Radiance Temperature at 6550 Å of the Graphite Arc

R. D. Lee and E. Lewis

National Bureau of Standards, Washington, D.C. 20234.

Received 1 August 1966.

Low current graphite arcs are frequently used as spectral radiance or radiance temperature standards, particularly in the vicinity of 6500–6600 Å, the spectral domain of the optical pyrometer. This letter reports on the results of a large number of radiance temperature measurements at 6550 Å of the positive crater of a graphite arc. The measurements were made with the National Bureau of Standards photoelectric pyrometer[1], which is estimated to realize the International Practical Temperature Scale (IPTS)[2] with a standard deviation uncertainty of 2°K at 3800°K, the approximate crater radiance temperature. The sensitivity of the pyrometer at 3800°K is 0.2°K.

Spectroscopically pure graphite rods were used for the positive and negative electrodes (National Carbon grade SPK $\frac{1}{4}$ inch and AGKS $\frac{1}{8}$ inch, respectively). The negative electrode was inclined $-120°$ to the positive electrode, which was mounted in a horizontal position, and the pyrometer sighting of the crater of the positive electrode was made along the axis of that electrode. The arc current (about 12.5 A) was normally kept to within 0.2 A of the overload or *hissing* point. Occasionally, readings were made at 0.5 A below overload, and these showed a drop of less than 2°K in radiance temperature.

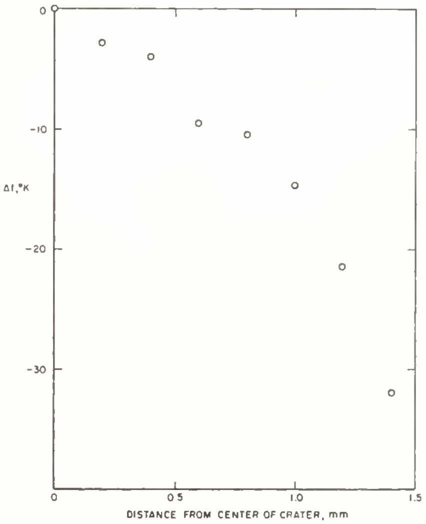


Fig. 1. Radial gradient in a graphite arc crater.

Two different lots of positive electrodes were used over a period of a year and a half. Out of one lot ten electrodes were burned, and the mean radiance temperature was found to be 3800°K. The standard deviation of the radiance temperatures of the ten electrodes was 4°K, the lowest and highest values being 3795°K and 3808°K. Seven electrodes were burned from the other lot, with a resulting mean of 3793°K and a standard deviation of 7°K. The range was from 3786°K to 3805°K. Recently, one electrode was obtained from each of four additional lots. The radiance temperature of these four electrodes ranged from 3787°K to 3794°K. Each of the radiance temperatures of the twenty-one electrodes was an average of several measurements over an interval of about 6 min, beginning well after burn-in time. The atmospheric pressure was taken at the time of the measurements, and temperatures were corrected to the expected radiance temperature at a pressure of 760 mm Hg.[3] The largest correction necessary was 1.6°C for a barometric pressure of 752 mm Hg.

The temperatures given are for a target area 0.2 mm in diam. and at the center of the crater. The temperature profile of a typical positive crater is shown in Fig. 1. The profile was obtained with an areal resolution of 0.2 mm.

Additional studies have shown that a 30.5-cm long SPK rod may vary in temperature over its useful burning length by an average of 7°K, and occasionally by as much as 10°K. Short term variations, fluctuations of a period of a few seconds, were about 3°K standard deviation from the mean. The fluctuations were recorded with an electronic time constant of $\frac{1}{6}$ sec.

From the present observations of twenty-one positive electrodes out of six different lots, the lowest observed radiance temperature was 3786°K and the highest was 3808°K. All the observed radiance temperatures fall within ±11°K of the nominal value of 3797°K. This result agrees with Null and Lozier's[4] radiance temperature of 3800°K, ±20°K. The low current graphite arc as presently used, though useful as a radiometric fixed point, is significantly less reproducible than the accuracy with which the IPTS can be realized.

References

1. R. D. Lee, Metrologia (October 1966).
2. H. F. Stimson, J. Res. Natl. Bur. Std. **65A,** 139 (1961).
3. N. K. Chaney, V. C. Hamister, and S. W. Glass, Trans. Am. Electrochem. Soc. **67,** 107 (1935).
4. M. R. Null and W. W. Lozier, J. Opt. Soc. Am. **52,** 1156 (1962).

Spectroscopic Thermometry

Reprinted from JOURNAL OF THE OPTICAL SOCIETY OF AMERICA, Vol. 46, No. 4, 246–254, April, 1956
Printed in U. S. A.

Spectral Absorption Method for Determining Population "Temperatures" in Hot Gases*†

HENRY J. KOSTKOWSKI AND HERBERT P. BROIDA
National Bureau of Standards, Washington, D. C.

(Received September 26, 1955)

A spectroscopic method, useful for strongly absorbed lines, has been investigated for measuring temperatures of hot gases. The minimum transmission of discrete spectral lines in gases at equilibrium has a simple dependence upon the absolute temperature and this relation is used to measure temperature from a straight line plot. An experimental study has been made of the absorption due to the rotational lines of OH ($^2\Sigma\leftarrow{}^2\Pi$) between 3067 and 3090 A in an oxygen-acetylene flame. It is shown that temperatures measured by this method are less affected than the conventional one by lack of sufficient resolving power, flame thickness, and various light sources (either continuous or line).

I. INTRODUCTION

INTEREST in nonequilibrium phenomena, combustion kinetics and control in the development of jet engines has provided a stimulus for investigating new methods of measuring high gas temperatures. Temperatures in flames and hot gases often are determined from spectra by measuring the distribution of intensities among the lines or bands.‡ These spectral measurements usually have been made in emission. However, if the self-absorption is great, the measured "temperature" may be considerably larger than the actual temperature. Furthermore, if the temperature of the system is low, the radiation emitted generally is small, making measurements very difficult. In such cases it would be desirable to make the measurements in absorption. Unfortunately, the conventional method for determining population "temperatures" in absorption requires that the peak absorption of the lines be small, thus limiting the applicability and accuracy of such measurements. In addition very high resolving power is needed to measure a weak absorption line. Because of these experimental difficulties, little use has been made of line absorption for "temperature" determinations. We have investigated a method by which "temperatures" may be determined in absorption when the peak absorption is as great as 98%. This paper reports on the method and compares it with the conventional one under a variety of conditions. Recently Huldt and Knall[1a] reported one such comparison.

II. THEORY

A. Conventional Method

The integrated absorption, $\mathcal{A}$, of a spectral line as measured by a spectrometer is given by the expression

$$\mathcal{A}=\int_{\text{line}} A(\nu)d\nu=\int_{\text{line}} \times\left[\frac{\int_{\nu-\Delta x}^{\nu+\Delta x} I_0(x)\sigma(\nu,x)(1-e^{-K(x)u})dx}{\int_{\nu-\Delta x}^{\nu+\Delta x} I_0(x)\sigma(\nu,x)dx}\right]d\nu \quad (1)$$

where $A(\nu)$ is the fractional absorption measured with the spectrometer when it is set on frequency ν and Δx is the spectral slit width of the spectrometer whose slit function is $\sigma(\nu,x)$. $I_0(x)$ is the intensity of radiation at the frequency x incident on the absorber, $K(x)$ the absorption coefficient and u the optical path length of the absorber.§ Equation (1) usually[1b] can be reduced to

$$\mathcal{A}=\int_{\text{line}}(1-e^{-K(\nu)u})d\nu. \quad (2)$$

If the maximum value of $K(\nu)$ is sufficiently small

$$\frac{\mathcal{A}}{u}=\int_{\text{line}}K(\nu)d\nu. \quad (3)$$

Equation (3) is correct to within two percent if the peak absorption is 5% or less.

Quantum electrodynamics[2] shows that for gases in thermal equilibrium

$$\int_{\text{line}}K(\nu)d\nu=\frac{8\pi^3}{3hc}\nu_0\frac{(1-e^{-h\nu_0/kT})|R|^2e^{-E''/kT}}{Q}=S \quad (4)$$

where S is the intensity per molecule per unit volume of the absorption line, ν_0 is the frequency of the line, k is the Boltzmann constant, T is the absolute temperature of the absorber, $|R|^2$ is the sum of the squares of

---

* This research was supported by the United States Air Force through the Office of Scientific Research of the Air Research and Development Command.

† This paper was presented in part at the April, 1955 meeting of the Optical Society of America.

‡ Since such temperatures are determined from the relative populations of energy levels, they are called population "temperatures." Quotation marks are used unless thermal equilibrium is clearly indicated.

[1] (a) L. Huldt and E. Knall, Naturwiss. 41, 421 (1954); (b) E. Bright Wilson, Jr., and A. J. Wells, J. Chem. Phys. 14, 578 (1946).

§ The optical path length is defined here as the product of the geometrical path length and the number of molecules per unit volume of the gas. Frequently, other quantities are used, e.g., the product of the geometrical path length and pressure of the gas in atmospheres at 0°C.

[2] B. L. Crawford, Jr., and H. L. Dinsmore, J. Chem. Phys. 18, 983 (1950); 18, 1682 (1950).

the matrix elements of all the transitions producing the line, E'' is the energy of the lower level of the transition, Q is the state sum or partition function, h is Planck's constant, and c the velocity of light. In many circumstances, $h\nu_0$ is very large compared to kT and $1-e^{-h\nu_0/kT}$ may be set equal to one. For example, if $T\leqslant 3000°\text{K}$ and $\nu_0 \geqslant 9700\ \text{cm}^{-1}$ ($\lambda \leqslant 10309$ A), $e^{-h\nu_0/kT}$ is less than 0.01. Thus from Eqs. (3) and (4) and for $h\nu_0 \gg kT$

$$\mathcal{A}=C_1\nu_0|R|^2e^{-E''/kT} \tag{5}$$

where the quantity $C_1=8\pi^3u/3Qhc$ is constant for our purposes. The conventional equation with which population "temperatures" in absorption have been determined is obtained directly from Eq. (5). It is

$$\log\frac{\mathcal{A}}{\nu_0|R|^2}=\log C_1-\frac{\log e}{kT}E''. \tag{6}$$

The significant assumption used in deriving Eq. (6) is that the maximum value of Ku (or if one prefers, the peak absorption of the line) is sufficiently small so that in the expansion of the exponential in Eq. (2), no terms beyond the linear one need be retained. An equation similar to Eq. (6) can be obtained using the peak rather than the integrated absorption.[3] Though such a relation depends on the functional form of the absorption coefficient,‖ differences obtained using a Doppler and a Lorentz shaped line usually are negligible for "temperature" determinations.

B. Method Using Minimum Transmission

From the defining equation for the absorption coefficient, the minimum transmission of a spectral line, $\tau_{\min}$, in terms of the maximum value of the absorption coefficient, $K_{\max}$, is given by

$$\tau_{\min}=e^{-K_{\max}u}. \tag{7}$$

If the line has a Doppler shape

$$K_{\max}=\frac{Sc}{\nu_0}\left(\frac{m}{2\pi kT}\right)^{\frac{1}{2}} \tag{8}$$

and if the line has a Lorentz (pressure-broadened) shape

$$K_{\max}=\frac{S}{\pi\alpha} \tag{9}$$

where m is the mass of the absorbing molecule and α is the half-width of the absorption coefficient at half its maximum value. α is usually called the line half-width. Using Eqs. (4) and (7) in conjunction with (8) and (9) one may obtain, again assuming that $h\nu_0 \gg kT$, for a line with a Doppler shape

$$\log\left(\frac{\ln 1/\tau_{\min}}{|R|^2}\right)=C_2-\frac{\log e}{kT}E'' \tag{10}$$

and for a Lorentz shape

$$\log\left(\frac{\ln 1/\tau_{\min}}{|R|^2\nu_0}\right)=C_3-\log\alpha-\frac{\log e}{kT}E'' \tag{11}$$

where all the constants have been incorporated into

$$C_2=\log\left[\frac{u}{3hQ}\left(\frac{32\pi^5 m}{kT}\right)^{\frac{1}{2}}\right]$$

and

$$C_3=\log\frac{8\pi^2u}{3hcQ}.$$

Equations (10) and (11) represent the extended method by which population "temperatures" in absorption may be obtained. Usually ν_0, the frequency of each line in Eq. (11), varies only slightly over the band and can be considered as constant. Thus if, in addition, α, the line half-width does not vary from line to line, Eqs. (10) and (11) become identical for temperature measurements. For the present paper this will be assumed and Eq. (10) used even though the spectral lines have a combination of Doppler and pressure-broadened shape.

The method of Eq. (10) is not restricted to the case of only small absorption and, therefore, can be used in many more situations. However, it does require measuring the minimum transmission of the absorption lines which usually requires far better resolution than is available. This is probably the reason why the method has not been applied extensively. If a suitable discrete line source rather than a continuous source is used, however, the minimum transmission of an absorption line may be determined even with poor resolution.

Such a discrete line source exists for measuring OH lines in a flame at atmospheric pressure. Therefore the method was tried by measuring the minimum transmission of the rotational lines of the 0,0 band in the $^2\Sigma \leftarrow {}^2\Pi$ electronic transition of OH in an oxygen-acetylene flame. The results were so encouraging that a detailed study of the method under a variety of experimental conditions was made. Effects of resolution, amount of absorption and types of sources were compared with the results obtained from the conventional method [Eq. (6)].

III. EXPERIMENTAL

A. Instrumentation

Figure 1 is a schematic diagram of the experimental setup. "Temperature" measurements were made of a premixed oxygen-acetylene flame burning in air on a

---

[3] S. S. Penner, J. Chem. Phys. 20, 507 (1952).

‖ This is usually called the line shape.

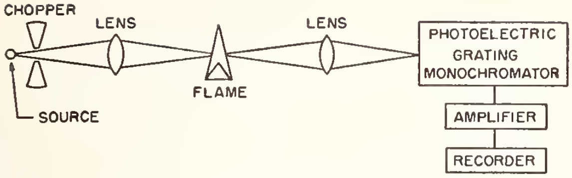


FIG. 1. Schematic diagram of arrangement of apparatus.

0.075 mm×50 mm water-cooled slot burner (Fig. 2). The flow rates, determined to within 5% by float type flowmeters, were 49 cc/sec for acetylene and 122.5 cc/sec for oxygen. Observations were made well into the hot gases above the reaction zone about 25 mm above the top of the burner.

Two discrete line sources and one continuum source were used in the experiments. One of the discrete line sources was an electrodeless discharge through water vapor. Figure 3 is a sketch of this apparatus, which is a simplification of a discharge system used previously.[4] It consists of a section of quartz tubing connected through ball and sphere joints to a glass system containing a supply of distilled water, a pressure gauge and a mechanical pump and trap. The discharge is excited by a 2450 megacycle signal from a continuous wave 125 watt magnetron source which is coupled to the quartz tubing through the modified wave-guide resonator shown in Fig. 3. This method of coupling produces an intense and stable discharge. The OH emission from this discharge is greater than that from the usual oxygen-acetylene welding torch. A stability of the order of 1% was possible for several hours. The water flow rate was adjusted to give maximum brightness of the OH emission by regulating the stopcock above the water supply. The pressure in the discharge was about 0.6 mm Hg. The "temperature" of the discharge was approximately 650°K[5] or, as will be seen, about $\frac{1}{4}$ that observed for the oxygen-acetylene flame.

Oldenberg and Rieke[6] have observed that the half-widths of OH lines are about 0.29 cm^{-1} at atmospheric pressure and 1473°K; pressure broadening contributes 0.19 cm^{-1} to this width. From this information, in a flame at one atmosphere and 2550°K, the half-width is computed to be 0.28 cm^{-1}. In a low-pressure discharge at 650°K, the half-width is computed to be 0.07 cm^{-1}. Therefore the half-widths of OH lines in the flame are four times those in the discharge. Thus the electrodeless discharge through water vapor is a bright, stable discrete line source of OH lines which are considerably narrower than those in the flame.

FIG. 2. Photograph of flame on slot burner. The reaction zone is the small bright line just above the burner. The remainder of the luminous zone is due to the hot gases in which there is little chemical reaction.

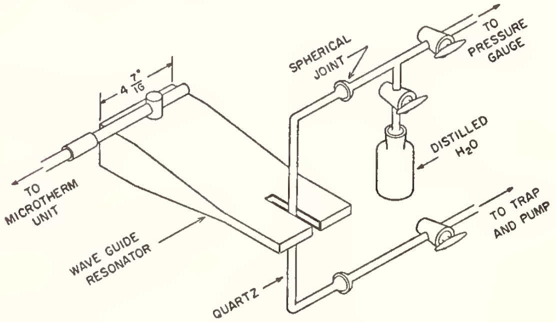


FIG. 3. Sketch of the discharge line source.

The other discrete line source was a premixed oxygen-acetylene flame at atmospheric pressure on a small burner whose bore diameter was 0.575 mm. The gas flow rates were 12.5 cc/sec of acetylene and 20 cc/sec of oxygen. The width of the OH lines in this source should be approximately the same as those in the slot burner.

The continuum source was a 1000 watt high pressure xenon lamp similar to those described by Baum and Dunkleman[7] operating with a direct current of 30 amperes.

The spectroscopic measurements were made with a scanning, grating monochromator¶ with photomultiplier detection.[8] The grating was a 75 mm×75 mm replica with 90 000 lines blazed for the first order at 6000 A.

---

[4] Broida, Morowitz, and Selgin, J. Research Natl. Bur. Standard **52**, 293 (1954).

[5] A. M. Bass and H. P. Broida, "A spectrophotometric atlas of the $^2\Sigma^+-^2\Pi$ transition of OH", National Bureau of Standards Circular 541 (1953).

[6] O. Oldenberg and F. F. Rieke, J. Chem. Phys. **6**, 439 (1938); R. J. Dwyer and O. Oldenberg, J. Chem. Phys. **12**, 351 (1944).

[7] W. A. Baum and L. Dunkelman, J. Opt. Soc. Am. **40**, 782 (1950).

¶ This instrument was constructed by the Research Department of Leeds and Northrup Company and loaned to the Heat and Power Division at the National Bureau of Standards on a field trial basis.

[8] William G. Fastie, J. Opt. Soc. Am. **42**, 641 (1952).

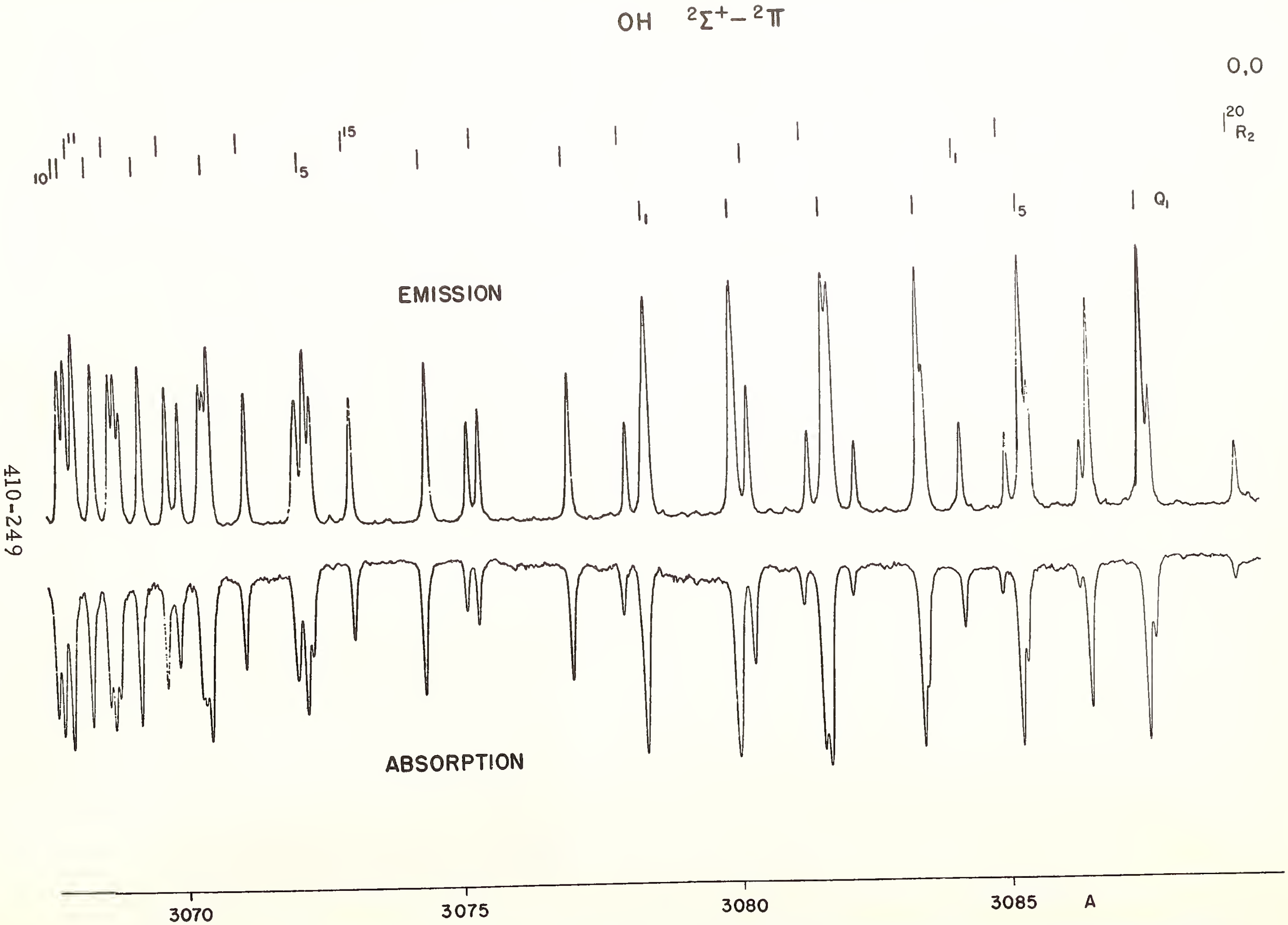


FIG. 4. Recorded spectra of OH in emission (top) and absorption (bottom) of an oxygen-acetylene flame. A high pressure xenon lamp was the continuum source.

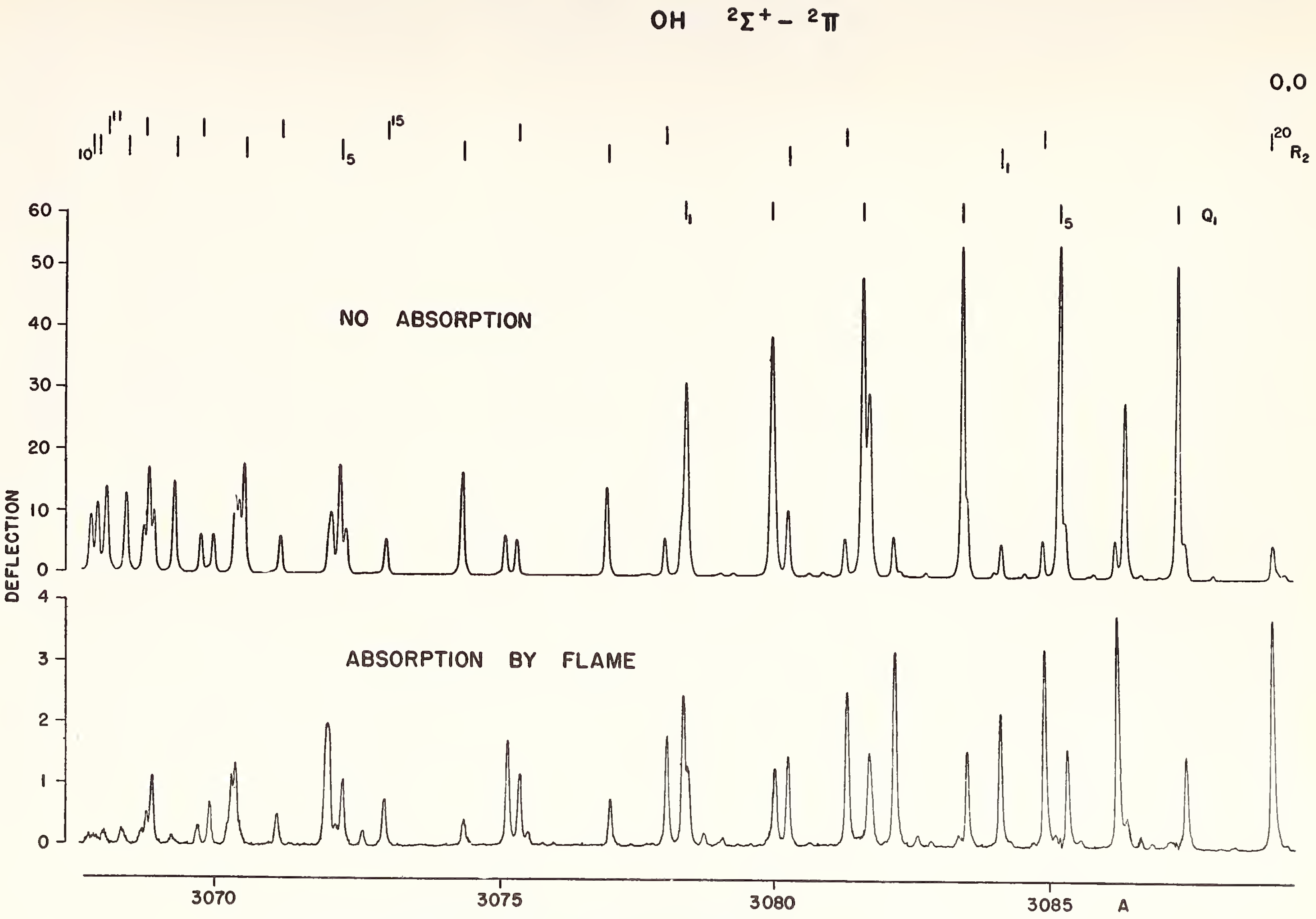


FIG. 5. Recorded spectra of OH from an electrodeless discharge through water vapor as seen with no absorption (top) and through a strongly absorbing oxygen-acetylene flame (bottom).

Two sets of entrance and exit slit widths of 6 (approximately) and 50 microns were used to determine the effect of resolving power on the measured absorption "temperature." These widths are equivalent to 0.03 A and 0.25 A in the second order. With a slit height of 0.5 mm, lines of OH in the second order near 3100 A whose centers were separated by 0.07 A and 0.45 A could be clearly resolved in the two cases. The detector was a 1P28 RCA photomultiplier. Radiation from the source was modulated at a frequency of 60 cycles per second by a metal chopper placed between the source and the flame. Thus, since the detected signal was amplified by a narrow band synchronous ac amplifier, radiation from the source alone is "seen" regardless of the relative intensities of the emission lines in the source and absorber. The spectra were recorded on a pen recorder.

B. Spectra

Absorption spectra of the R_2 branch of the 0,0 band in the $^2\Sigma \leftarrow {}^2\Pi$ electronic transition of OH between 3067 A and 3090 A were obtained (see Figs. 4 and 5) with high and low resolution using the three sources mentioned previously. This branch, as pointed out by Dieke and Crosswhite,[9] is particularly suitable for temperature measurements because the first 20 lines occur in a wavelength region of 20 A and the branch is relatively free of overlapping lines. For each source, successive spectra were obtained for the source alone, the source and absorber, source alone, source and absorber and a final check on the source stability by recording the first few lines. In general the recorder deflections for the lines of the repeated spectra agreed with one another to within a few percent.

Figures 4 and 5 are examples of the spectra obtained under high resolution. Height above the base lines is proportional to the radiation intensity. Satellite lines, lines of the R_1 and P_1 branches and Rowland "ghosts" are not identified in the figures. The upper spectrum of Fig. 4 is an emission spectrum for the oxygen-acetylene flame on the slot burner. The lower spectrum is the absorption of this flame using the continuum source.

Figure 5 shows the spectrum of the discharge through water vapor with and without absorption by the flame. Since the OH discharge lines are considerably narrower than those in the flame, the ratio of the observed deflections of the absorbed to the nonabsorbed lines in Fig. 5 should be nearly equal to the minimum transmission of the respective lines. Thus a close look at Fig. 5 shows that the Q_1 lines have a transmission of only a fraction of one percent, i.e., they are almost completely absorbed. This large absorption produces an interesting effect on the weak lines. For example, the satellites close to the strong Q_1 lines can be seen only as shoulders on the $Q_1(1)$ to $Q_1(6)$ lines in the nonabsorbed spectrum. However in the lower spectrum of Fig. 5, the strong lines are almost completely absorbed leaving the six satellites of the Q_1 lines clearly visible. In addition satellites of the weaker R_1 lines also are observable. This, incidentally, illustrates a way in which the wavelengths of weak lines near very strong lines could be obtained more accurately.

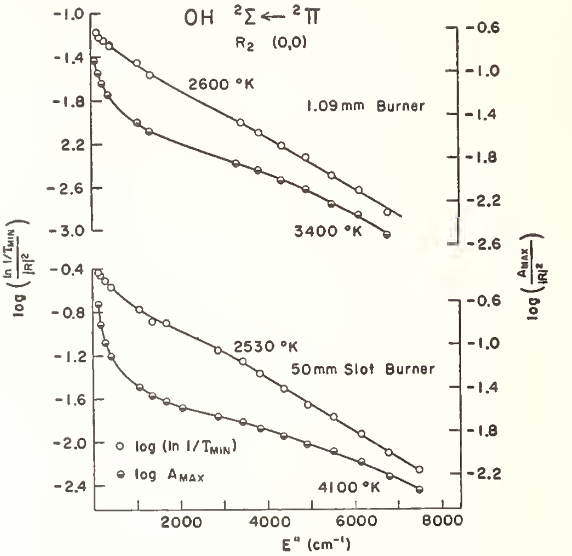


FIG. 6. Log and log ln plots of OH absorption in two thicknesses of an oxygen-acetylene flame. "Temperatures" are measured from the slopes of the curves between 4000 and 7500 cm^{-1}.

Minimum transmission (i.e., at the peak of the observed line) for all useable lines in the R_2 branch for each of the various runs were measured and averaged. Other quantities required in order to use Eq. (10) were obtained from the compilation of Dieke and Crosswhite.[9]

IV. RESULTS

"Temperature" plots were constructed for all the spectra obtained using both Eqs. (6)** and (10). Figure 6 compares the two methods for the case of high resolution and a discharge source.†† In order to observe the effect of changing the amount of absorption, a small welding torch with a port diameter of 1.09 mm was used as well as the slot burner.

Peak absorption in each flame for the R_2 lines is given in Table I. Except for slight dips in the vicinity of the stronger lines of the branch, the log ln plots give fairly straight lines in both flames. The slopes of these lines and therefore the respective "temperatures" are nearly equal. The temperature of the flame on the slot burner is expected to be somewhat lower than that

---

[9] G. H. Dieke and H. M. Crosswhite, Bumblebee Series Report No. 87 (November, 1948) (unclassified).

** For the sake of convenience, the peak absorption rather than the integrated absorption was measured.

†† We shall call the conventional method a log method or plot and the method using minimum transmission, log ln; this nomenclature follows from Eqs. (6) and (10).

Table I. Peak absorption of the R_2 branch of OH in an oxygen-acetylene flame as measured using a narrow discrete line source

K''	Peak absorption 1.09 mm burner	 50 mm slot burner
1	0.34	0.62
2	0.54	0.85
3	0.69	0.93
4	0.78	0.97
5		
6		
7	0.86	0.98
8	0.84	0.98
9		0.98
10		0.97
11		0.95
12		
13	0.68	0.93
14	0.63	0.90
15	0.55	0.83
16	0.49	0.74
17	0.38	0.67
18	0.32	0.56
19	0.32	0.44
20	0.22	0.35

on the small burner because in the former case measurements were made a greater distance above the inner cone. Moreover, the experimental error estimated from the scatter of slopes is about 3% (75°K at 2500°K). While greater accuracy and closer comparison might be obtained, there would be no additional advantage since large differences and trends were the primary interest of this study.

The log plots in Fig. 6 deviate considerably from straight lines. In order that quantitative comparisons might be made, however, the straight line best fitting the higher energy transitions was used for obtaining a "temperature." These "temperatures", as seen in Fig. 6, are not only very high but differ greatly for the two flames. Thus the usual log method is greatly dependent upon the amount of absorption in the flame while the log ln method using a discrete, narrow line source is not.

The slight dip at the most intense lines in the log ln plot was unexpected and the cause of this is not definitely known. A greater half-width for the more highly populated transitions as is obtained in resonance type pressure broadening[10] would produce such an effect [see Eq. (11)]. However, the partial pressure of OH was only of the order of 16 mm Hg‡‡; this was calculated using our data on the integrated absorption of the $R_2(1)$ line corrected for lack of sufficient resolution, Oldenburg and Rieke's[6] absolute intensity for this line and Eqs. (3) and (4). This is probably too small for resonance broadening to have an effect. Another possible cause of the dip could be the amplifier passing a small signal from the slot burner itself, i.e., some of the unchopped radiation. A careful test definitely showed this not to be the case.

A slight dip probably is due to the finite width of the OH lines in the discharge and the lack of sufficient resolving power. Even though the discharge lines are $\frac{1}{4}$ as wide as those in the flame, a small amount of absorption due to the wings is present in the measured peak absorption. This is so small, however, that its effect is only observed in the strongly absorbed lines. For example, if the peak fractional absorption for a line is 0.99 but due to a small wing contribution we obtain 0.98 at the peak of an observed discharge line, the reciprocal of the transmission should be 100 but is measured as 50. However, when the peak absorption is 0.50, even if the measured value were 0.40, the reciprocal of the transmission would change only from 2 to 1.7. This tentative explanation is consistent with the explanation given below of the effects of resolving power and source line width on the measured "temperature." The dip, whatever its cause, does not appear to affect seriously the "temperatures" obtained.

Figure 7 presents log ln plots for the slot burner under the various experimental conditions. For the low resolution case, fewer lines in the R_2 branch were free of overlapping from neighboring lines, resulting in fewer points. "Temperatures" obtained from these plots together with those from log plots and isointensity plots (Fig. 8) are listed in Table II.

Another method of using spectral data for determining temperature has been called the isointensity method.[9] It is most useful for branches of molecular bands which form a band head and is particularly well

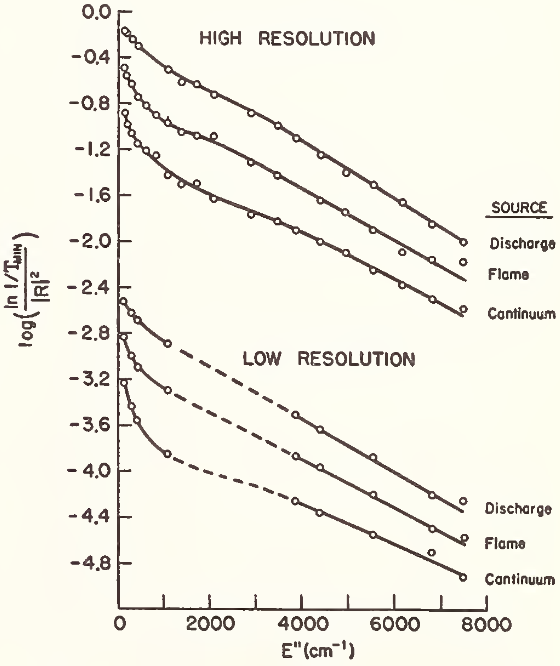


Fig. 7. Effect of resolving power on log ln plots of OH absorption with different light sources.

---

[10] H. M. Foley, Phys. Rev. 69, 616 (1946); P. W. Anderson, Phys. Rev. 76, 647 (1949).

‡‡ 14.5 mm Hg is the calculated equilibrium pressure of OH in the combustion products at this temperature.

suited for the R_2 branch of OH.[11,12] Heretofore this method has not been used for absorption. The isointensity method is based on the intensities of two lines being equal. For example, setting expressions for respective intensities of two lines equal to each other, e.g., in absorption Eq. (4), and assuming that their frequencies are the same, the temperature is found to depend only upon the difference in the energy levels and the ratio of the transition probabilities, $|R|^2$, of the two lines. Figure 8 compares isointensity plots of the same spectrum for the slot burner using the logarithm of the reciprocal transmission and the maximum absorption. Although the curve of the maximum absorption *versus* the rotational quantum number is considerably flatter than the corresponding transmission curve, both curves give the same isointensity "temperatures" for the first three lines. The lower curve is so flat that the precision for other pairs of lines is very low. These "temperatures" also agree with those obtained in the infrared in OH emission[13] for the same electronic and vibrational state. The isointensity method in absorption thus gives reasonable "temperatures" even when the absorption is large. However, one disadvantage of the method is that it provides no simple way of detecting nonequilibrium, i.e., the nonexistence of a temperature. When this possibility exists it is more desirable to use the log or log ln plot where a straight line indicates equilibrium.

The isointensity "temperatures" in Table II are approximately the same and with greater care would be closer. It is quite possible that the low "temperature" measured with the flame source at the higher resolving power is caused by a slight difference in the position of the slot burner flame. From the infrared and these present measurements, it appears that the rotational energy in the (0,0) band of the ground electronic state of the OH about 25 mm above the inner cone of an acetylene-oxygen flame with a mixture ratio of 2 to 5 is distributed as though the average "temperature" were 2550°±100°K.

TABLE II. Measured OH rotational "temperatures."

Resolution	Source	Method of determination log (ln 1/τ)	Log A_{max}	Iso-intens.
0.03 A	Discharge	2530°K	4100°K	2570°K
	Flame	2800	3750	2400
	Continuum	3000	3200	2520
0.25 A	Discharge	2650	4300	2480
	Flame	3000	4100	2490
	Continuum	3600	3600	2700

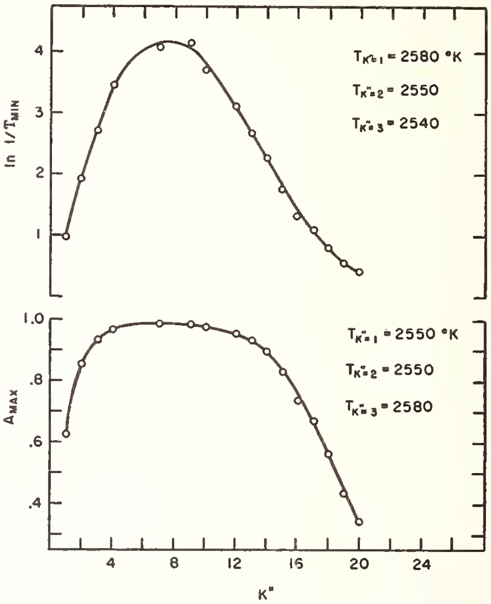


FIG. 8. The logarithm of the reciprocal transmission and the maximum fractional absorption plotted against the rotational quantum number, K'', of the initial state. Measured isointensity "temperatures" from the first three pairs of lines are listed.

Table II emphasizes two points in comparing the log and log ln methods of measuring "temperature." The first is that the log ln method with the discharge source gives correct "temperatures" independent of the resolution whereas the "temperatures" obtained from the log method are as much as 70% high. Second, regardless of the source or the resolution, the log ln "temperatures" are not in error by as much as the log "temperatures."

The trends exhibited by the different methods of "temperature" measurement and the different experimental conditions as shown in Table II can be explained in a rather simple manner. Consider first the group of "temperatures" obtained using the log ln method under high resolution. The "temperature" of 2530°K using the discharge source was shown to be correct. When a flame source is used the "temperature" is increased about 10%. Since the straight line portion of the plots from $K''=14$ to $K''=20$ ($E''=4000$ to $7500\ \mathrm{cm}^{-1}$) were used in the nonlinear cases to obtain a "temperature," the relative changes in the reciprocal of the minimum transmission (or maximum absorption for log plots) for lines near $E''=4000\ \mathrm{cm}^{-1}$ as compared to those at $E''=7500\ \mathrm{cm}^{-1}$ will show how the slope of the plot or the "temperature" will vary. Lines near $E''=4000\ \mathrm{cm}^{-1}$ have a peak fractional absorption of approximately 0.9 while those at $E''=7500\ \mathrm{cm}^{-1}$ are about 0.4 (from discharge source). These values will decrease using a flame source since now source radiation is present not only at the center but also in the wings of the OH lines where absorption is less. The source lines are thus absorbed less in the wings than in the center and since the spectrometer "sees" more than just the center of the line when set on this wavelength (i.e., $\Delta x_{\mathrm{spectrometer}} \sim \alpha_{\mathrm{flame}}$), the observed absorption is less.

---

[11] K. E. Shuler, J. Chem. Phys. 18, 1466 (1950).
[12] H. P. Broida, J. Chem. Phys. 21, 1165 (1953).
[13] Benedict, Plyler, and Humphreys, J. Chem. Phys. 21, 398 (1953).

The decrease is probably somewhat less for the strongly absorbed lines since these transmitted lines (not the absorption coefficient) are broader. Even so, if the peak absorption changed from 0.9 to 0.8 and from 0.4 to 0.2, respectively, the corresponding change in reciprocal transmission would be from 10 to 5 and 1.66 to 1.25. This would cause the point at $E''=4000\ \text{cm}^{-1}$ to drop more than that at $7500\ \text{cm}^{-1}$ resulting in a reduced slope and a greater "temperature." In going to a continuous source the same effect is present but since the source radiation in the wings of the OH lines is now the same as that at the peak, the transmitted energy in the wings is greater resulting in even less observed absorption and a still higher "temperature." The somewhat higher "temperatures" obtained when using the log ln method under poorer resolution is expected since the spectrometer now passes more of the wing transmission when set on the peak of the line (i.e., much broader slit function).

The very high "temperature" measured using the log method with the discharge source is to be expected since Eq. (6) is valid only for small absorption. For the spectral lines near $E''=7500\ \text{cm}^{-1}$ where the peak absorption is about 0.4, the intensity of the absorbed line is still roughly (15% error) proportional to the peak absorption. However, when the fractional peak absorption is 0.9, the absorption has increased far less than the intensity simply because the intensity is in the exponent. Thus the plotted points near $E''=4000\ \text{cm}^{-1}$ are much lower than they should be, producing a very high "temperature" measurement. This effect, which might be called saturation, is analogous to self-absorption in the case of emission measurements.

It is interesting to note that the "temperatures" obtained using the log method decrease in changing from a discharge to a continuous source—the opposite of that for the log ln method. This is simply due to the fact that we are plotting a function of absorption rather than reciprocal transmission. Since the relative absorption decreases more, as mentioned before, when it is weak, i.e., near $E''=7500\ \text{cm}^{-1}$, these points are lowered when using the flame and continuum source more than those at $E''=4000\ \text{cm}^{-1}$. This increases the slope of the log plot and therefore reduces the measured "temperatures."

Thus it is seen that the various trends in "temperature" can be explained by a combination of effects: plotting a function of absorption rather than reciprocal transmission, measurement of absorption in the wings as well as at the peak, and finally the spectral slit width of the spectrometer.

V. CONCLUSION

The log ln method based on Eq. (10) provides a more accurate means of measuring population "temperatures" in absorption in flames and hot gases. If a line source of radiation is available whose line widths are less than one-fourth those in the absorber, accurate "temperatures" may be determined, even when the peak line absorption is as great as 98%. Even with broader line sources or with a continuum, the "temperatures" will be more accurate than those obtained using the conventional method based on Eq. (6).

Reprinted from TEMPERATURE—ITS MEASUREMENT AND CONTROL IN SCIENCE AND INDUSTRY, Vol. 3, Part 1
1962 Reinhold Publishing Corp., New York, N. Y.

57. Measurement of Electron Density and Temperature in Dense Plasmas by Application of Line Broadening Theory

J. B. SHUMAKER, JR., AND W. L. WIESE

National Bureau of Standards, Washington, D. C.

For the determination of electron density and temperature in dense plasmas a number of spectroscopic methods are available.[1] One of these is based upon the relationship between the electron density and the widths of spectral lines broadened by the interatomic electric fields of the electrons and ions. The application of this method was heretofore hampered by the lack of an adequate theory, but recent improvements in the theory of statistical Stark broadening and its application to the line profiles of the Balmer lines of hydrogen in plasmas[2] indicate that electron densities accurate to 10% should now be attainable. In view of these developments it seemed desirable to reexamine this method.

In the work reported here, line profile measurements are applied to the diagnostics of arc plasmas into which a trace of hydrogen is added for that purpose. The electron density is obtained directly from the line profile theory, but the temperature must be calculated from the electron density in cases of local thermodynamic equilibrium (LTE) by solution of the plasma conservation and equilibrium equations.[3, 4] The set of plasma equations leaves undetermined as many unknowns including the temperature as there are chemical elements present in the plasma (for known total pressure). The relative gas composition, when available, furnishes all but one of the necessary supplementary relationships, and a single additional measurement then suffices to evaluate the temperature. In arcs, however, a "demixing" or local nonstoichiometry of the components of a gas mixture often results from the high-temperature gradients present so that relative compositions measured in the cold gas are unreliable values for the discharge.[5, 6] Consequently, the introduction of hydrogen (if not already present) is of advantage in measuring the temperature only if it provides two or more independent measurements or relationships. If the concentration of the added hydrogen is very small, even a rough estimate of its concentration will generally be sufficiently accurate, and this, together with a line profile measurement of the electron density, provides an additional piece of information for the solution of the plasma equations. This becomes particularly useful in the cases studied here of a single element other than the hydrogen trace since the hydrogen line profile measurement together with the concentration estimate is then sufficient to determine the temperature as well as, of course, the electron density.

APPARATUS AND PROCEDURE

The plasmas studied in these experiments were generated in an arc chamber of the wall-stabilized or cascade arc type,[7, 8] which produces an extremely stable arc in an atmosphere of arbitrary composition. The arc was operated at currents between 50 and 100 amperes. Since these chambers require a continuous small flow of gas, the hydrogen fraction was introduced either by directly mixing hydrogen with the gas to be studied in a constant ratio controlled by flow meters and needle valves, or (in the case of the oxygen arc) by saturating the gas with water vapor at room temperature as it passed into the arc chamber. In either case periodic samples were taken and analyzed to insure the constancy of the mixture during an experiment.

416-575

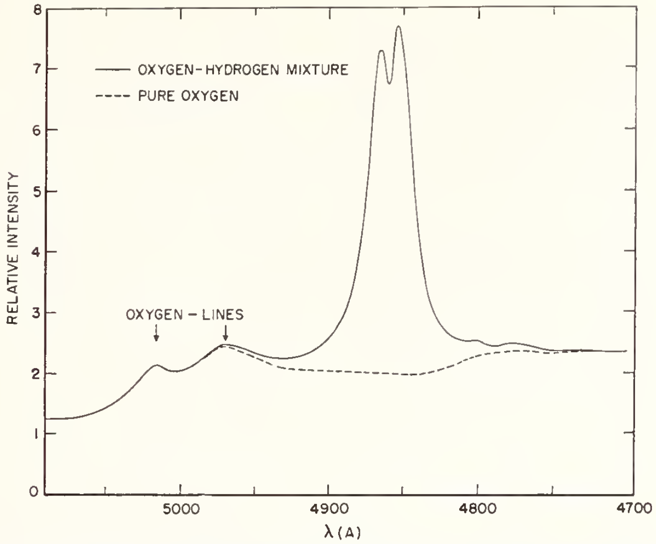


FIG. 1. Spectrometer recordings in the region of H_β illustrating the determination of the shape of the background under H_β. The spectra were taken side-on at the axial position of a 50 ampere arc. The Stark broadened H_β profile shows characteristically a dip in the center because of the absence of an unshifted component.

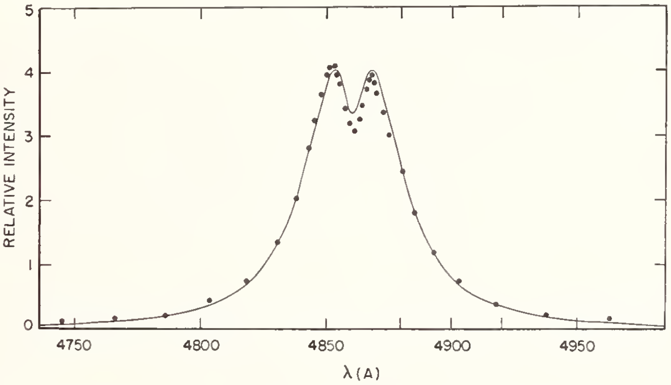


FIG. 2. Theoretical H_β profile for $n_e = 9.2 \times 10^{16}$ cm^{-3} and experimental points measured at the axis of a 100-ampere oxygen arc. The curve is normalized in intensity to give approximate agreement at the maximum.

An enlarged image of the cylindrically symmetric arc column as seen from the side was focused on the 150-micron wide slit of a scanning photoelectric spectrometer (3.4-meter JACO Ebert) and the spectrum in the neighborhood of an appropriate hydrogen line recorded as shown in Fig. 1. For this investigation the Balmer line H_β was chosen because it was sufficiently broadened to permit an accurate measurement of the profile, and its wings did not overlap with the neighboring Balmer lines. This spectrum was repeated at each of more than 20 points across the width of the arc, and again for the same arc in the absence of the hydrogen. The spectra with and without hydrogen were then matched, as in Fig. 1, to locate the hydrogen line background, which is important for the measurement of profiles of broad lines since changes in the underlying continuum may not be negligible and the wings of neighboring lines may overlap, as illustrated by the oxygen lines in Fig. 1. The difference—the hydrogen line itself—was then subjected to an Abel integral transform to obtain the true line profile as a function of radial distance from the axis of the arc. The Abel inversion, which has been described in detail elsewhere,[9, 4] must be done numerically. It was carried out for a number of discrete wavelengths across the line leading to profiles such as those shown in Fig. 2.

The profile of H_β was measured for the two element systems: oxygen-hydrogen, nitrogen-hydrogen, and argon-hydrogen. For comparison purposes also the absolute intensity of an oxygen, nitrogen, or argon line was determined, with a calibrated tungsten strip-lamp serving as radiation standard.

DETERMINATION OF THE ELECTRON DENSITY

The electric microfields of the ions and electrons are the dominant cause for the broadening of spectral lines in dense, partially ionized plasmas. This broadening is especially pronounced for hydrogen, which is subject to a linear Stark effect. A generalized theory of Stark broadening which includes broadening due to electrons as well as ions has recently been developed by Kolb and Griem. The same authors have subsequently published detailed numerical calculations on the Balmer lines for a wide range of electron densities and temperatures. It turns out that for the temperature range in which high current arcs operate, i.e., 8000 to 40,000°K, the line profiles depend practically only on the electron density. The intensity distribution in the lines is presented in tables which give the relative intensity $S(\alpha)$ for a number of positions α across the line. $S(\alpha)$ is normalized so that the area of the line is unity, i.e.,

$$\int S(\alpha)\, d\alpha = 1,$$

and α, a reduced wavelength, is defined by $\alpha = \Delta\lambda / F_0$, where $\Delta\lambda$ is the distance from the center of the line in angstrom units and $F_0 = 1.25 \times 10^{-9} n_e^{2/3}$ is the Holtsmark field strength (n_e is the number of electrons per cm³).

The experimental determination of the electron density consists of measuring a complete hydrogen line profile and fitting it to a theoretical one. But since generally good agreement of the measured shapes with the theory may be expected, the measurement of only one characteristic of the experimental profile such as its half-width is usually sufficient. The dependence of the H_β half-width on the electron density as derived from the tables of Griem, Kolb, and Shen[2] for 10,000°K is shown in Fig. 3. In spite of the precautions described above for obtaining the background by taking spectra with and without the trace of hydrogen, some uncertainty in the vertical positioning of the background—though not in its shape—may remain. In addition, in many cases it is not expedient to obtain a hydrogen-free spectrum or to carry the measurements far into the line wings. For the estimation of the error involved and its correction under these circumstances, curves are shown in Fig. 3 for arbitrary background levels which cut the H_β profile at two points W_0 angstroms apart and symmetrical about the line center. Then the electron density corresponding to the measured width $W_{1/2}$ at ½ the apparent maximum intensity depends upon the parameter $W_0/W_{1/2}$. The apparent maximum intensity is measured from the arbitrarily positioned background to the average of the two slightly different maxima of H_β since the theoretical profiles do not distinguish between the left and right wings. Curves are shown for $W_0/W_{1/2} = 2, 3,$ and ∞. For values of $W_0/W_{1/2} \geq 5$ the curves practically coincide with the curve for true half-widths $W_0/W_{1/2} = \infty$. The explicit dependence of these curves upon temperature is very weak; similar curves for 5000 and 20,000° differ from the set at 10,000° by less than 7% in electron density.

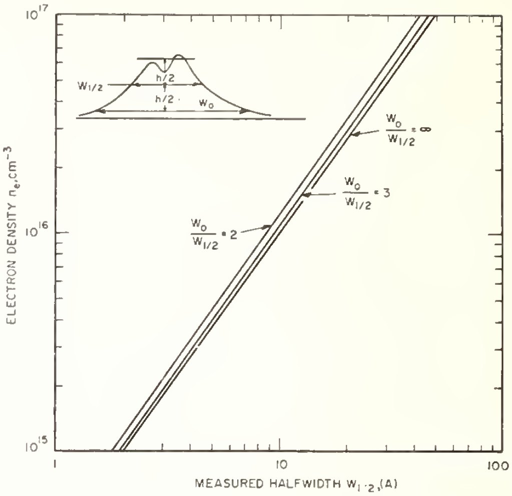


FIG. 3. Electron density as a function of the H_β half-width from line broadening theory for $T =$ 10,000°K. The parameter $W_0/W_{1/2}$, the relative spectral range of the measurements, is a measure of the extent to which the apparent line background approaches the true background.

DETERMINATION OF THE TEMPERATURE

While the electron density can be measured with this method even when the existence of LTE is doubtful, the temperature can be calculated only in cases of LTE by solving the plasma equations[3, 4, 10] for the measured electron density n_e. For a many element mixture, n_e will be a function of the mole fractions of the elements as well as of the temperature T, and is generally obtained by tedious numerical processes. In simple systems, however, n_e can be calculated as an explicit function of T, and a graphical presentation of this relationship then permits the determination of the temperature associated with a measured electron density. For example, in a two-element system when only a trace of hydrogen is present and when the major constituent has a comparable or lower ionization potential than the hydrogen, it is convenient to expand the solution of the plasma equations in a power series in the hydrogen concentration. In the temperature range where only neutral and singly ionized atoms and electrons are present in significant amounts this power series solution takes the form:[11]

$$n_e = n_e^\circ \left[1 + \gamma \frac{n_e^\circ (F_H - F_A)}{2F_A(n_e^\circ + F_H)} + 0(\gamma^2) \right] \quad (1)$$

with

$$n_e^\circ = F_A \left[\left(1 + \frac{P}{kTF_A} \right)^{1/2} - 1 \right]$$

$$\gamma = \frac{n_H + n_{H^+}}{n_A + n_{A^+}}$$

$$F_A = 2 \left(\frac{2\pi mkT}{h^2} \right)^{3/2} \frac{u_{A^+}}{u_A} \exp\,(E_A/kT)$$

$$F_H = 2 \left(\frac{2\pi mkT}{h^2} \right)^{3/2} \frac{u_{H^+}}{u_H} \exp\,(E_H/kT)$$

where n_A, n_{A^+}, etc., are number densities of atoms A, ions A^+, etc., u_A, u_{A^+}, etc., are the internal partition functions (which can often be approximated by the statistical weights of the ground states) of the species A, A^+, etc., E_A and E_H are the ionization energies for atoms A and H, P is the total pressure, k is the Boltzmann constant, and h is the Planck constant. The quantity γ is the ratio of number densities of total hydrogen to total gas A.

The value of the electron density approaches n_e°, the electron density for pure gas A, as the hydrogen concentration is reduced. For many systems this zero-order approximation, neglecting the hydrogen trace entirely, produces a very small error in the temperature. In the present experiments, for instance, the difference between the zero-order solution and the solution actually used retaining the term in γ[Eq. (1)], corresponded to less than 0.2% in temperature.

RESULTS AND DISCUSSION

From Eq. (1) it can be seen that for $\gamma \ll 1$ even large relative errors in γ will generally have only a negligible effect on the calculated temperature. Consequently, the problems associated with "demixing" or nonstoichiometry in this arc were circumvented by ensuring that the hydrogen concentration was small. In the experiments, γ was about 2% which had the added advantage of avoiding the complications of self-absorption in matching line shapes. Self-absorption was less than 1% at the center of H_α and even less for the other Balmer lines.

In Table 1 are presented the temperatures corresponding to the electron densities determined from the measured H_β line shape and those calculated from simultaneously measured absolute intensities of spectral lines of the major gaseous constituent using transition probabilities obtained from the Coulomb approximation[12] and solving the plasma equations. The over-all error in the measurement of the electron density is estimated to be about 15%, the main error re-

TABLE 1. AXIAL TEMPERATURES IN WALL-STABILIZED ARCS BURNING IN GASES CONTAINING ~2% HYDROGEN

	Gas			
	Oxygen	Oxygen	Argon	Nitrogen
Current, amp	50	100	70	50
Electron density from H_β, n_e, cm^{-3}	7.35×10^{16}	9.2×10^{16}	9.0×10^{16}	8.2×10^{16}
Temperature from n_e, °K	12 330	12 830	12 290	12 120
Comparison line	OI 6157 A	OI 6157 A	AII 4806 A	NI 4935 A
Transition prob. sec^{-1}	7.45×10^6	7.45×10^6	63.4×10^6	1.30×10^6
Temp. from comparison line °K	12 320	12 710	12 650	12 590

sulting from theoretical approximations.[2] The corresponding error in the temperature measurement depends upon the particular gas and upon the electron density, being large for constant pressure processes in the region of the maximum of n_e versus T. For these runs the error is estimated to be about 3%. For temperatures determined from transition probabilities the experimental errors of measuring the absolute line intensities are likely to be only slightly less than the over-all estimated error in the measurement of electron densities by line shapes. Thus when the additional uncertainties in the values of most transition probabilities are considered, it is evident that temperatures derived from them will generally be less reliable than those obtained from line shape measurements.

The useful range of this method for measuring electron densities is limited to electron densities between about 10^{14} and 10^{18} cm^{-3}. At low electron densities, other broadening mechanisms, especially Doppler broadening, become increasingly important, and at high electron densities the Balmer lines overlap. H_α is the most useful line at high electron densities because of minimum overlap with other Balmer lines, whereas the higher members of the Balmer series are best utilized at low electron densities because of their relatively strong broadening. Where LTE prevails the method is limited at atmospheric pressure to temperatures between about 7000 and 30,000°K by the intensities of the hydrogen lines. The temperature range increases with increasing hydrogen partial pressure. The upper limits of temperature and electron density may be extended considerably by substituting helium or ionized helium (for which line profile calculations have also been carried out[13, 14]) for hydrogen.

The complication of self-absorption and many difficulties in the calculation of temperature from the electron density are minimized by low hydrogen concentrations. However, the accompanying low line intensities produce correspondingly large errors and difficulties of profile fitting. A practical compromise seems to be to use hydrogen concentrations of 0.5% to 5%.

CONCLUSIONS

The results of this investigation indicate that electron densities accurate to 10 or 15% can easily be obtained from the measurement of line profiles of hydrogen using the new theory by Kolb and Griem. No knowledge of the amount of hydrogen present is required, and the application of the technique is independent of the presence of LTE. The determination of the temperature from the electron density requires, of course, LTE and a rather detailed knowledge of the energy levels and amounts of the elements present. This method is of particular advantage in those cases where the hydrogen negligibly affects the plasma and is present in small concentrations. The hydrogen then behaves as a true thermometer.

References

1. W. Finkelnburg and H. Maecker, *Handbuch der Physik* (Springer-Verlag, Berlin, 1956), Vol. XXII.
2. H. R. Griem, A. C. Kolb, and K. Y. Shen, NRL Rept 5455 (1960), and to be published.
3. W. Lochte-Holtgreven, Repts. Progr. in Phys. **21**, 312 (1958).
4. W. L. Wiese and J. B. Shumaker J. Opt. Soc. Am. *51*, 937 (1961).
5. H. Maecker, Ann. Physik **18**, 441 (1956).
6. F. Mastrup and W. Wiese, Z. Astrophys. **44**, 259 (1958).
7. H. Maecker, Z. Physik **158**, 392 (1960).
8. J. B. Shumaker, Rev. Sci. Instr. **32**, 65 (1961)
9. O. H. Nestor and H. N. Olsen, SIAM Rev. **2**, 200 (1960).
10. H. N. Olsen, Physics of Fluids **2**, 614 (1959).
11. Equation (1) is not yet strictly free of the necessity for some iteration since the ionization potentials entering into the Saha functions F_A and F_H depend weakly upon n_e [G. Ecker and W. Weizel, Ann. Physik 17, 126 (1956)]. However, the effect is not large and can often be ignored at low electron densities.
12. D. R. Bates and A. Damgaard, Phil. Trans. Roy. Soc. London **A242**, 101 (1949).
13. H. R. Griem and K. Y. Shen.
14. H. R. Griem, M. Baranger, A. C. Kolb, and G. Oertel, Phys. Rev. **125**, 177 (1962).

Reprinted from THE REVIEW OF SCIENTIFIC INSTRUMENTS, Vol. 32, No. 1, 65–67, January, 1961

Arc Source for High Temperature Gas Studies

JOHN B. SHUMAKER, JR.
National Bureau of Standards, Washington 25, D. C.

(Received August 22, 1960)

A wall-stabilized water-cooled copper ring type arc source is described which operates stably in apparently any gas for periods of an hour or more at currents up to 100 amp. Arc temperatures obtained spectroscopically by absolute line intensity and line profile methods are given for the arc in nitrogen at 92 amp.

AS part of a larger program of plasma thermometry an arc chamber has been developed which is based upon the wall-stabilized, water-cooled, copper disk arc device described by Maecker.[1] The essential difference is that, in addition to introducing the gas under study, a second inert gas is deliberately used to blanket the electrodes. This procedure retards erosion of the electrodes and enhances the stability of the arc. Such an arc has been operated in a number of gases at currents up to 100 amp for periods of hours with unchanging electrical properties, thus permitting leisurely detailed spectroscopic studies.

A photograph of the arc is shown in Fig. 1 and its essentials are indicated schematically in Fig. 2. It consists of a series of $\frac{5}{16}$-in. thick water-cooled copper rings separated from one another by insulating Bakelite rings. Gases may be introduced tangentially and permitted to escape through the openings indicated in the Bakelite rings. Carbon electrodes, as shown, and water-cooled metal electrodes have both been used. In either case, an argon atmosphere is maintained around the electrodes to retard their consumption and improve the stability of the arc. The gas to be studied (designated X in Fig. 2) is introduced in the central region between the electrode chambers where it can be viewed from the side through windows in the Bakelite rings or from the end by means of axial holes drilled through the electrodes. The arc is confined to the $\frac{3}{16}$-in. channel defined by the water-cooled rings. It burns quietly for hours in any orientation at currents up to over 100 amp and appears motionless in all gases tested.

The water flow rate is about 5 liters/min per copper ring. This generally results in an average water temperature rise of only a few degrees. Gas flow rates are of the order of a few liters per minute at each gas entry point indicated in

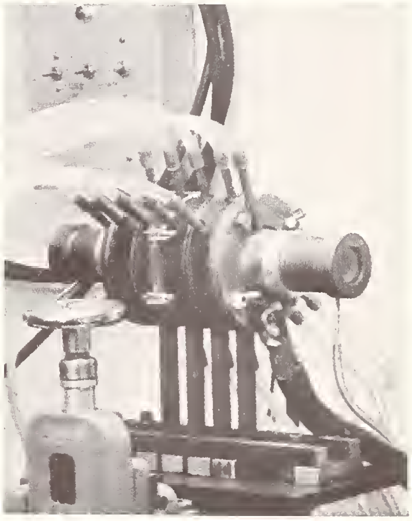


FIG. 1. Photograph of arc chamber with water, gas, and electrical connections.

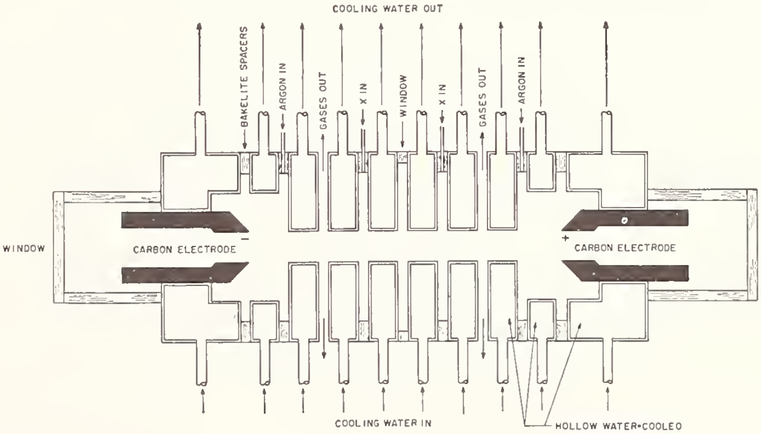


FIG. 2. Schematic cross-section view of arc chamber.

---

[1] H. Maecker, Z. Naturforsch. 11a, 457 (1956).

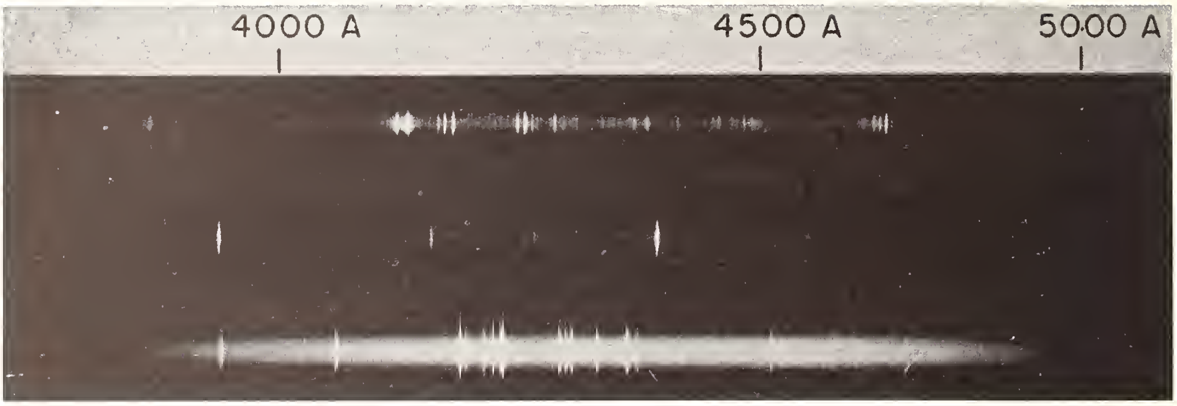


Fig. 3. Spectra of nitrogen (upper), oxygen (middle), and argon (lower) obtained side-on at 50 amp.

Fig. 2. The gas exhausts to the atmosphere at the large ports indicated, so the gas pressure within the arc is only a few millimeters of mercury above the atmospheric pressure.

Because the arc length may be as great as 10 cm with this device a relatively high voltage power supply is necessary for stable arc operation. A 400-v bank of storage batteries has proved valuable although frequently 230 v from a motor generator set is adequate. The variable ballast resistor which generally absorbs half or more of the energy has been described elsewhere.[2] It consists simply of a large electrolytic cell with the opposed electrode areas varied by controlling the electrolyte (city water) level.

On using the 400-v battery power supply, the current fluctuations are normally very small. At 100 amp and with a 150-v drop across the arc with nitrogen in the center, for instance, peak-to-peak current variations do not exceed 1 amp when measured with time constants in the range 0.0001 sec to 5 min. With the batteries a small current drift can generally be discerned over a period of 5 or 10 min due to their limited capacity (about 50 amp hr at the 100-amp rate). Under the same conditions 3% maximum peak-to-peak fluctuations in the intensity of the 4935 A N I line at the center of the arc are observed. The use of shorter resolving times was not warranted because with a resolving time of 0.0001 sec the shot noise due to statistical fluctuations in the number of photons measured by the optical and detection system was calculated to be of the same order of magnitude as the observed noise.

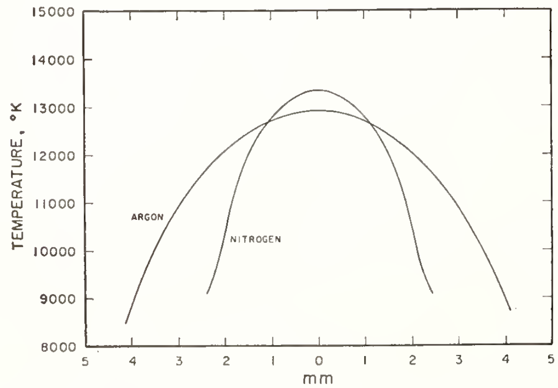


Fig. 4. Radial temperature distributions in argon and nitrogen arcs at 92 amp and atmospheric pressure.

The gases which have been used so far in this arc device are argon, nitrogen, oxygen, hydrogen, and helium. Spectrograms of argon, oxygen, and nitrogen taken from the side perpendicular to the axis of a 50-amp arc are shown in Fig. 3. The spectrograms show no trace of carbon from the electrodes and, in the oxygen and nitrogen arcs where the electrodes are surrounded by argon, they also show no trace of argon. Figure 4 shows the radial temperature distributions also obtained side-on from photoelectric absolute intensity measurements of the 4935 A N I line in a 92-amp nitrogen arc and the 7635 A Ar I line in a 92-amp argon arc. The standard light source used for the absolute intensity measurements was a tungsten strip lamp calibrated for brightness temperature at 6530 A at the National Bureau of Standards and operated with a filament temperature of about 3000°K (Int. 1948). Emissivities for tungsten were extrapolated from the measurements of Larrabee.[3] The transition probability for nitrogen was taken from Motschmann's[4] values and that for argon from Olsen's[5] values. The calculations of radial intensities from the side-on observations were performed on a desk calculator by the method outlined by Olsen.[6]

By means of end-on optical measurements radial distributions can be obtained directly, but in this arc their usefulness is limited because the length of arc containing the gas of interest (the X component shown in Fig. 2)

---

[2] C. R. Yokley and J. B. Shumaker, Rev. Sci.

[3] R. D. Larrabee, J. Opt. Soc. Am. **49**, 619 (1959).

[4] H. Motschmann, Z. Physik **143**, 77 (1955).

[5] H. N. Olsen, Bull. Am. Phys. Soc. 4, 262 (1959).

[6] H. N. Olsen, Phys. Fluids **2**, 614 (1959).

is not well defined. Auxiliary spectroscopic observations from the side can be used to help define the arc length in some cases. In other cases where only relative intensities are required end-on measurements are adequate provided that the temperature along the line of observation parallel to the arc axis is uniform wherever the X gas is present. Such a case is presented in the study of line profiles, and the data of Fig. 4 suggest that measurements on nitrogen lines should be reliable near the center of the arc.

A strip chart recording of the profile of the 4935 A N I line is shown in Fig. 5. The measurement was made end-on with a 92-amp arc assembled as illustrated in Fig. 2 containing nitrogen in the middle part. The spectrograph viewed only the region lying within about 0.1 mm of the axis of the arc. Griem[7] has calculated the dependence of the shape of this line on the temperature and electron density using the line broadening theory of Kolb and Griem.[8] The line is seen to fit very well the shape predicted (a dispersion profile) for a temperature of 15 500°K.

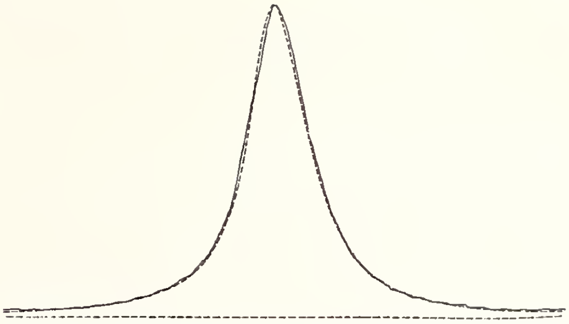


FIG. 5. Line profile of 4935 A N I line (solid curve) measured end-on on axis of a 92-amp nitrogen arc and superimposed theoretical profile with background (dotted curve) for 15 500°K. Linewidth at one-half maximum intensity is 3.30 A.

The reason for the discrepancies between the line shape axial temperature measurement of 15 500°K and the line intensity measurement of 13 300° and between these values and that of Burhorn[9] who obtains an axial temperature of about 13 000° in a nitrogen arc at 100 amp is not completely known. A discussion of the errors involved in making high temperature measurements will be the subject of future communications.

---

[7] H. R. Griem (private communication).

[8] A. C. Kolb and H. R. Griem, Phys. Rev. **111**, 514 (1958).

[9] F. Burhorn, Z. Physik **155**, 42 (1959).

JOURNAL OF RESEARCH of the National Bureau of Standards—A. Physics and Chemistry
Vol. 69A, No. 6, November–December 1965

Arc Measurement of Some Argon Transition Probabilities

C. H. Popenoe and J. B. Shumaker, Jr.

(July 29, 1965)

Transition probabilities and line shape parameters for three argon lines have been measured in a wall-stablilized argon arc containing a trace of hydrogen. The H_β line shape measurement and the assumption of local thermodynamic equilibrium provided the determination of the argon level populations. From these three lines ten other argon line transition probabilities have been obtained by relative measurements in a pure argon arc. The results are compared with those of other investigators and sources of error are discussed.

Key Words: Arc, argon, linewidth, plasma, spectroscopy, stark broadening, transition probability.

1. Introduction

The importance of argon transition probabilities for plasma diagnostics is reflected in the large amount of recent experimental work on the measurement of these quantities [1, 2, 3, 4].[1] The most fruitful source of these measurements has been the high current thermal arc, but unfortunately even here in similar sources the results of different investigators may differ by factors of two, well outside the error estimates attributed to the measurements by their authors. Consequently an additional attempt to measure argon transition probabilities in a thermal arc source was undertaken. The particular technique employed was one which has previously been used in these laboratories [5]. It consists of operating a wall-stabilized arc with a gas mixture containing a trace of hydrogen in the gas whose transition probability is to be measured, and then deducing the arc plasma temperature and composition from the spectral line shape of the 4861 Å hydrogen Balmer β line. From the plasma composition and absolute line intensity measurements the transition probabilities can be derived.

Absolute transition probabilities were determined in this manner for the two AI lines at 4300 and 6965 Å and for the AII line at 4806 Å. These lines were selected for their prominence, isolation from their neighbors, symmetry, relative freedom from self absorption, and location in wavelength regions favorable for photoelectric detection. Some additional transition probabilities were measured relative to one or another of these three reference lines in pure argon arcs. However, measurements on these lines are less satisfactory either because the lines are weak or because of ambiguity in the location of the background. Most of the prominent blue argon lines in this source are afflicted with this background problem due to the closeness of strong neighbors or asymmetric line shapes (see fig. 1) either of which can result in an uncertainty in the total intensity to be ascribed to the lines.

All of the data recording, handling, and calculations including the graphical presentation of the results were done by automatic machine methods to eliminate as many sources of error as possible. With the statistically large samples made possible by these methods along with elimination of subjective measurements and increased precision, it becomes possible to attempt a more thorough analysis of the errors and uncertainties involved in these measurements.

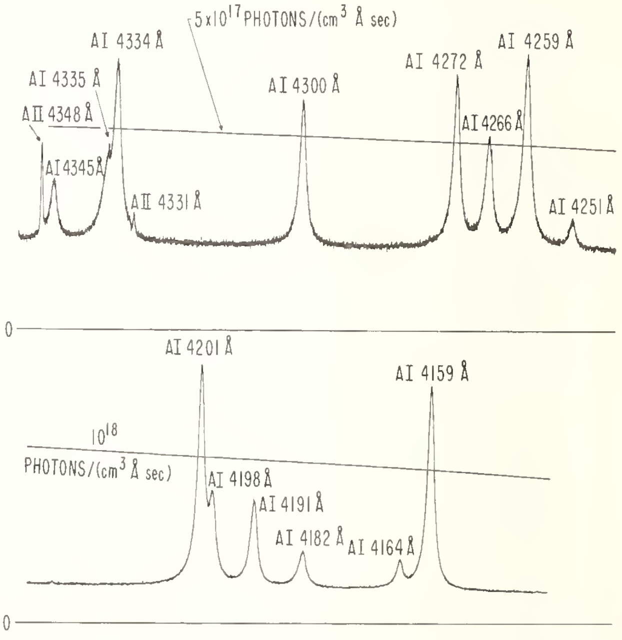


FIGURE 1. *Atmospheric pressure argon arc spectra after Abel inversion [ref. 19].*

The total intensity of AI 4300 Å yields an electron density of 6.9×10^{16} cm^{-3} and temperature of 12 060 °K assuming the transition probability value of table 3.

---

[1] Figures in brackets indicate the literature references at the end of this paper.

2. Experimental Details

2.1. Light Source

The radiation source is a wall-stabilized or cascade d-c arc of about 10 cm length and 5 mm diam. The arc chamber is similar to that described in reference [6] with the exception of improved water cooling for higher current operation. The graphite electrodes are surrounded by a separate flow of argon, preventing rapid electrode erosion and contamination of the test gas in the observation section. After passing through the arc the gases are exhausted to the atmosphere through large diameter ports. The arc characteristically operates stably for long periods of time for most test gases. For the experiments reported here arc currents of 40, 60, and 90 A were used.

The arc chamber is mounted on a carriage movable by means of a lead screw in a direction transverse to the optic axis of the monochromator. An electrically actuated single-revolution clutch couples an electric motor to the leadscrew drive providing for either continuous or incremental movement of the arc carriage. Variation in rate of scan or increment size is accomplished by a set of quick-change gears in the drive train.

Electrical power is supplied to the arc by either a bank of 100 6 V storage batteries, or a rotary converter of 500 kVA capacity and 650 V output as shown schematically in figure 2. Both power sources were used during this series of experiments with no observable difference in results. The voltage drop across the arc is typically 102 V in argon at 60 A, and 112 V with 1 percent hydrogen added to the test gas. The bulk of the power is dissipated in a large variable water resistor [7] in series with the arc supply.

The current is automatically regulated by a solid-state series current regulator (see fig. 2) consisting of 30 power transistors in parallel, with the current error signal being derived from a 0.2 Ω oil-cooled manganin shunt. The arc current is initially set and later monitored with a potentiometer and galvanometer by which variations in total arc current as small as 1 mA may be observed. A carbon pile rheostat is used to provide vernier adjustment of the ballast resistance.

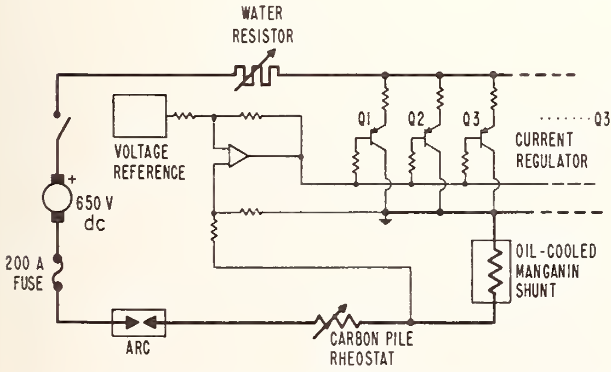


FIGURE 2. *Arc circuit schematic including some details of the transistorized automatic current regulator.*

2.2. Optical and Spectrographic Arrangement

The arc was viewed in a plane perpendicular to the arc axis with the image focused slightly enlarged on the monochromator entrance slit. A rectangular diaphragm opening at the lens formed the aperture stop of the system and limited the solid angle from the arc to 0.002 sr. The dispersing element was an 0.8 m Ebert-Fastie plane grating monochromator having a nominal dispersion of 10 Å/mm in the first order. Entrance and exit slits of 15 μ width were used in most of the experiments. The entrance slit height was masked to 1.2 mm to eliminate reflections from the copper plates adjacent to the observation section of the arc chamber and to minimize the effect of any slight variations of the arc column along its length. During the course of the experiments, RCA 931A (S–4 response), Hamamatsu R–136 and RCA 7265 (S–20 response), and ITT FW–118 (S–1 response) photomultiplier tubes were employed to detect the spectral intensity.

The monochromator grating drive is fitted with a single channel paper tape reader attached directly to the wavelength counter to allow direct digital control of the wavelength setting. An electrical signal causes the monochromator to scan in wavelength until a punched hole in the paper tape is sensed by the reader. A program paper tape may therefore be punched to direct the monochromator through a prescribed, not necessarily evenly spaced sequence of wavelengths in the spectrum. The resolution of the tape reader is 0.05 Å and the precision of the wavelength setting better than 0.01 Å.

2.3. Data Recording and Control System

The large quantity of data encountered in spectrometric studies involving spacial resolution of plasma characteristics invites the use of automatic digital techniques for data collection and reduction [8]. To facilitate data handling the response of the monochromator was recorded digitally on punched paper tape in a form compatible with electronic data processing equipment. In addition, the monochromator wavelength drive and arc carriage positioning mechanism were automatically actuated and coordinated so as to perform the proper variable changes during an experiment in the minimum time.

In essence, the data recorder consists of amplifying, digitizing and tape punching equipment. The small current output of the photomultiplier is amplified and converted to a voltage signal of the order of 1 V which in turn is converted to a pulse train whose frequency is proportional to this voltage. An electronic counter sums the pulses for a precise interval of time, resulting in a digitized integral of the applied voltage over the counting interval. Upon command, six digits of information from the counter are loaded simultaneously into a shift register from which they may be shifted out serially into a code-conversion matrix and punched on paper tape in binary-coded-decimal form.

Movement of the arc carriage, changes in the monochromator wavelength and recording of photomultiplier current are all directed and coordinated automatically during a run by a central programmer. The heart of the programmer is a 25-step, 11 level stepping switch, wired in a closed-loop mode; i.e., a signal from the preceding operation verifying its successful completion is necessary to initiate a succeeding operation. With the above system the rate of data recording is limited by the tape punch to about two 8-character data points per second.

The possibility of erroneous recordings is greatly diminished by various self-checks incorporated into the system. The analog section of the system (current amplifier and voltage-to-frequency converter) is subject to the small errors inherent in analog devices and is therefore checked and calibrated several times during an experiment. The calibration is transferred directly to punched tape to preclude errors in recording. The nature of the digital section, and indeed of digital systems in general is such that the occurrence of small errors in transferring digits through the system is highly improbable. To ensure that such errors, if they occur, will be detected, an odd-bit parity check is made at the tape punch, and the recording process is automatically stopped if an added or dropped bit is detected on the tape. A second and independent parity check is made during the process of converting the tape to punched cards.

2.4. Experimental Method

A representative spectral line measurement consisted of the photoelectric recording of the arc intensity at each of perhaps 30 equally spaced positions across the width of the arc. This set of measurements was then repeated at each of usually 27 wavelengths spaced nonuniformly across the spectral line—spanning altogether about 10 times the maximum full halfwidth of the line. Finally, without turning off the electronics, recordings were made of the intensity of a calibrated tungsten strip pyrometer lamp at the same 27 wavelengths.

An intermittent arc traversing technique was used in which the motion of the arc carriage was momentarily stopped for an interval of time sufficient to overcome photomultiplier delay effects and to record the intensity at that point before resuming motion and proceeding to the next point. This eliminates the distortion of the arc profile which results from continuous movement of the arc carriage during the counting interval. Also, since the traverses always begin at precisely the same point (±0.001 cm), each recorded point corresponds to a given point in space referenced to a laboratory coordinate system, not a function of time or scanning rate. The recording positions are therefore repeatable and the recorded intensities directly comparable from traverse to traverse.

The effect of integrating the intensity at a point for a finite interval of time is a temporal smoothing of noise at that point on the arc profile. Some further spacial smoothing occurs because of the necessity of observing a finite "slice" of the arc column. However, the additional loss of spacial resolution which would result from a continuous traversing or "scanning" of the arc image is effectively avoided by the intermittent traversing technique. In these experiments an integrating period of 0.1 sec was used. The width of the observed "slice" was determined by the slit width and in most experiments amounted to about 0.001 cm while the distance between samples was typically 0.03 cm.

The test gas—either pure argon or premixed mixture of argon and 1 percent hydrogen—was injected tangentially into the arc on both sides of the observation chamber at a rate of 1.2 liter/min and a differential pressure of a few millimeters of water. Gas flow rates were monitored by flowmeters and adjusted to minimize flow in the observation chamber. Separate flows of pure argon at about 0.2 liter/min were injected tangentially at the electrodes. The difference in flow rates insured a net gas flow away from the observation section, further precluding electrode vapor contamination by diffusion.

The intensity measurements are calibrated with a tungsten strip lamp at a brightness temperature at 6530 Å of 2340.3 °K (IPTS 1948). The lamp was periodically calibrated by the Temperature Physics Section of the National Bureau of Standards. At the conclusion of each arc experiment it was placed at the arc position with the quartz window from the arc placed in the optic path to eliminate the necessity for determination of window transmission. A well-regulated d-c power supply maintained the strip lamp current at a constant level within 0.01 percent. The same punched program tape used to direct the monochromator through the sequence of wavelengths for the experiment was then used to record the calibrated strip lamp intensity at the same wavelengths as those of the experiment.

3. Treatment of Data

3.1. Abel Inversion

In order to obtain the radial distribution of volume emission in the arc from side-on measurements it is necessary to solve the appropriate Abel integral equation [9] for each traverse across the arc. The technique employed is based upon one described by Freeman and Katz [10] in which the distribution of measured side-on intensities is fitted by a polynomial in the positional coordinate with origin at the center of symmetry. The solution of the integral equation is then obtained analytically for this polynomial and the volume emission at any desired point in the arc is calculated from this solution. By including odd powers in the fitting polynomial some minimal allowance is made for source asymmetry and for errors in locating the position of the arc "center of symmetry" [11].

The polynomial fitting was accomplished by the use of the orthogonal properties of the Jacobi [12] polynomials $P_n^{(a,a)}(x/R)$ whose inverse Abel transform is expressible in terms of $P_m^{(a-1/2,0)}(2[r/R]^2-1)$ with odd n terms treated in the approximation of Freeman and Katz [11]. R is the distance from the arc center beyond which the intensity is considered negligible. This technique results in the weighting of the data points by $(1-[x/R]^2)^a$. In the experiments reported here uniform weighting ($a=0$) was arbitrarily used after experiments revealed no appreciable difference in the results obtained using $a=0$ (corresponding essentially to the Freeman and Katz method) and $a=\frac{1}{2}$ (corresponding, except for the odd n terms, to a method described by Herlitz [13]). Individual arc traverses contained from 20 to 41 measurements at equally spaced x points and the resulting intensity profiles were fitted by the Jacobi polynomial expansions with 8 to 12 terms.

3.2. Line Shape Parameters

The volume emission intensities calculated from the Abel inversions were reassembled as a function of wavelength at each radial point and a suitable theoretical spectral line shape was fitted by an iterative least squares technique. In the case of the argon lines a dispersion (Lorentz) shape superimposed upon a linear background was used as the fitting function:

$$\mathrm{I}=A+B(\lambda-\lambda_0)+\frac{C}{1+[(\lambda-\lambda_0)/\Delta]^2}$$

with A, B, C, λ_0, and Δ being adjusted to minimize the sum of the squares of the residuals. In the case of the hydrogen β lines the line shape fitting was preceded by subtracting from each experimental Abel inverted wavelength scan the corresponding pure argon arc spectrum at the same radial point. This pure argon background spectrum was obtained as a part of each experiment in the same manner and under the same arc conditions as was the argon-hydrogen mixture data. The red and blue wings of the resulting difference spectrum were then averaged and this line shape was fitted to an appropriate theoretical H_β line shape:

$$\mathrm{I}=A+BS(\alpha)$$

where $\alpha=1.25\times10^{-9}|\lambda-\lambda_0|(N_e)^{-2/3}$, $S(\alpha)$ is a theoretical line shape [14], and A, B, and the electron density $N_e(\mathrm{cm}^{-3})$ are adjusted to minimize the residual function. The Griem, Kolb, and Shen tabulations of $S(\alpha)$ were fitted piecewise by cubics in all the tabulated intervals except the first where a parabola was used with the condition $\frac{dS}{d\alpha}=0$ at $\alpha=0$. The asymptotic wing formulas [15] were used beyond the range of the tables. In this manner piecewise analytic approximations to $S(\alpha)$ were constructed for H_β. In addition to the dependence of the H_β line shapes upon N_e implied by the definition of α, there is a further weak dependence upon N_e and T. This dependence was included in these calculations by the actual use of different piecewise line shapes calculated for $N_e=10^{17}$ and $T=13\,000$ °K, $N_e=10^{16}$ and $T=10\,000$ °K, and for $N_e=10^{15}$ and $T=7500$ °K – the first and last being obtained by interpolation in the Griem, Kolb, and Shen tables.

All of the above calculations as well as division by the strip lamp calibration data and conversion to absolute intensities are programmed to be performed in one pass through the IBM 7094 digital computer. At each radial point the computer plots the experimental radially-resolved wavelength scans and tabulates all of the line fitting parameters; in particular the argon line centers λ_0, $\frac{1}{2}$-halfwidths Δ, and total intensities $\pi C\Delta$, the hydrogen line total intensity $B\int S(\alpha)d\alpha$, and the electron density N_e.

No slit width corrections were necessary for the hydrogen lines because of their relatively great width. However, for the argon lines slit or apparatus function corrections were required. For this purpose the program for dispersion line shape fitting was systematically calibrated using various ratios of apparatus function width to dispersion line width and using various distributions of wavelength points of measurement across the line. The calibration was done for both Gaussian and triangular apparatus functions and resulted in the application of small slit width dependent corrections to the computed line widths and, for very wide slits, to the line intensities. This procedure should be quite reliable for lines which have nearly a dispersion shape.

The apparatus functions observed with the 15 μ entrance and exit slits used in most of these experiments were approximately Gaussian with $\frac{1}{2}$-halfwidths (one-half of the full width at the half maximum intensity level) of 0.1 Å. One experiment was performed with 150 μ slits in which the apparatus function was nearly triangular with a $\frac{1}{2}$-halfwidth of 0.75 Å.

Examples of the line shape fitting are given in figures 3 and 4. The AI 4300 Å line can be seen to exhibit some skewness. This skewness together with the unsymmetric disposition of the wavelength points [2] causes the dispersion shape fitting routine to produce a line shape which in this example is about 3 percent narrower than a good eye-fit would probably yield. The apparatus function for both lines in this example was the Gaussian shape with $\frac{1}{2}$-halfwidth of 0.1 Å. In figure 3 the computer-fitted $\frac{1}{2}$-halfwidth of 0.771 Å required a correction of 0.013 Å for apparatus function resulting in an estimate of 0.758 Å for the $\frac{1}{2}$-halfwidth of the spectral line itself. In figure 4 the intensity scale for H_β is displaced vertically by an amount which has no particular physical significance being determined by the subtracted hydrogen-free background spectrum.

Beyond a radial distance of 0.2–.25 cm, the line shape fitting procedure was considered unreliable due to the sharpness of the lines and the attendent small

---

[2] The asymmetric distribution of wavelength points apparent in figure 3 is, to some extent, unavoidable unless an excessive number of uniformly spaced wavelengths is used because of the dependence of the line shift upon the radial position of the observation.

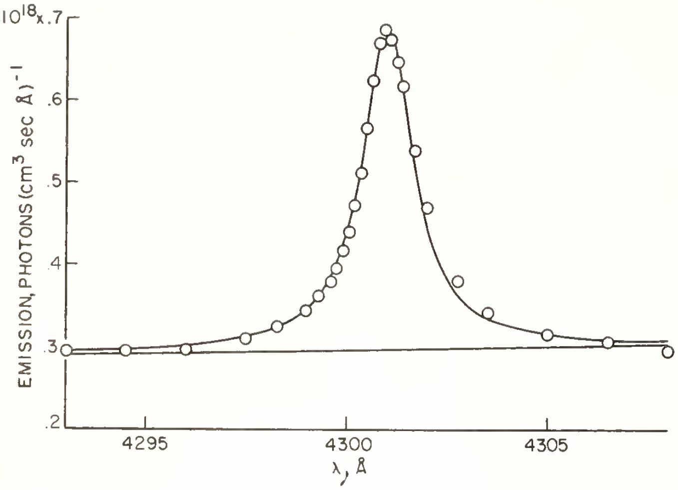


FIGURE 3. *Experimental intensity points in the neighborhood of Al 4300 Å after Abel inversion (0.13 cm from axis of 90 ampere arc in argon with ~1% H_2) showing computer fitted background and dispersion shape: ½-halfwidth = 0.771 Å, total line emission = 9.44×10^{17} photons cm^{-3} sec^{-1}*

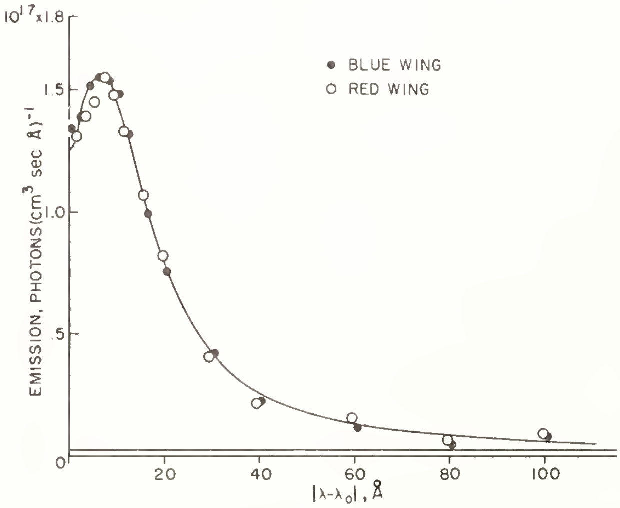


FIGURE 4. *Experimental intensity points in the neighborhood of H_β 4861 Å after Abel inversion (same conditions as fig. 3) showing computer fitted background level and theoretical line shape: electron density = 7.45×10^{16} cm^{-3}, total line emission = 8.10×10^{18} photons cm^{-3} sec^{-1}.*

number of points defining their shapes. At these distances, the low number density of the emitting species causes a reduction in the signal/noise ratio with the effect that the determination of the true line shape from a statistically small sample of noisy data is improbable. For these reasons, the data from regions lying beyond an arbitrarily chosen radial distance of 0.2 cm (0.16 cm for ionic lines) is not reported here.

Argon line shifts and ½-halfwidths corrected for the 0.1 Å Gaussian apparatus function are plotted in

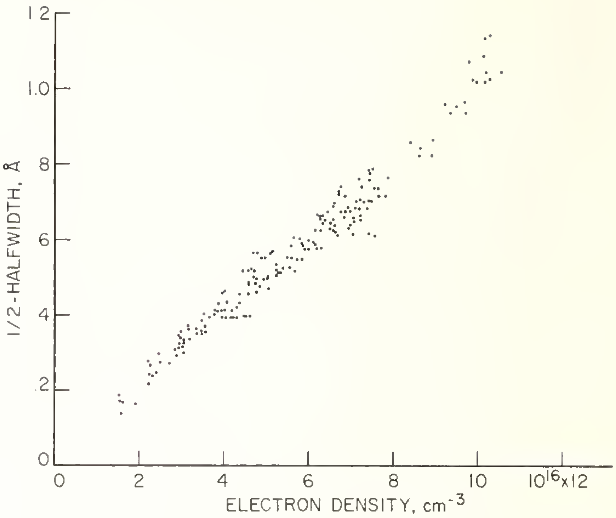


FIGURE 5. *Dependence of ½-halfwidth upon electron density for Al 4300 Å.*

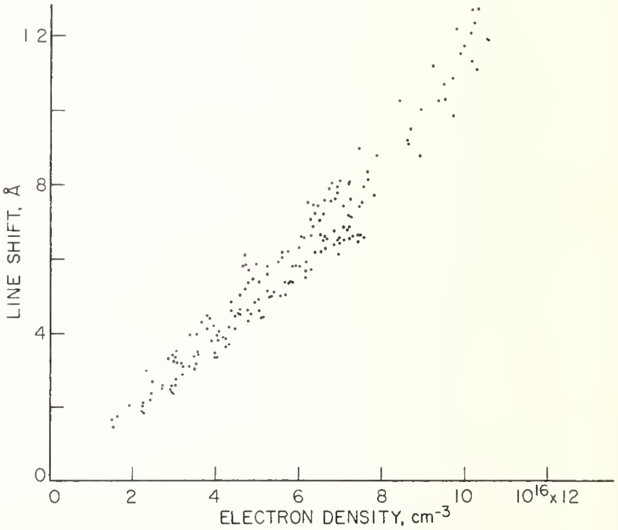


FIGURE 6. *Dependence of the red shift of the Al 4300 Å line upon electron density.*

figures 5 to 10 against the electron density as determined from the H_β line shapes. The wavelengths for the unshifted lines were obtained by extrapolation to $N_e = 0$. Both the widths and shifts are seen to be approximately proportional to the electron density in rough agreement with theory [9]. The proportionality constants obtained by least squares fitting of this data are shown in table 1.

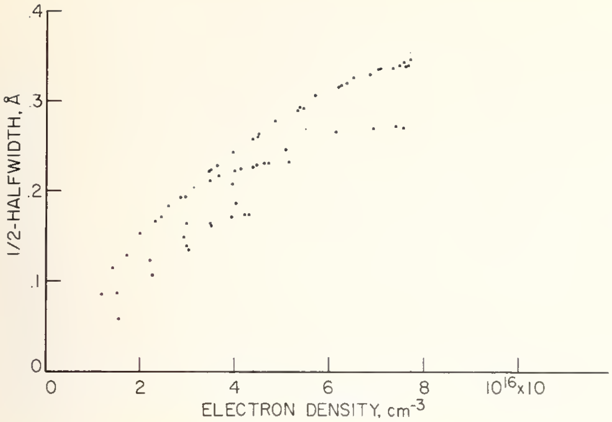


Figure 7. *Dependence of $\frac{1}{2}$-halfwidth upon electron density for AI 6965 Å*

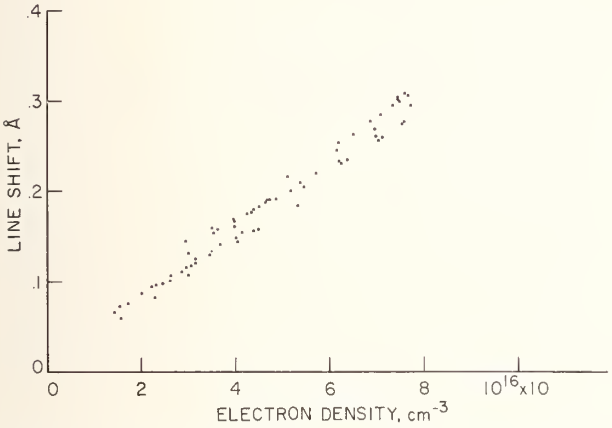


Figure 8. *Dependence of the red shift of the AI 6965 Å line upon electron density.*

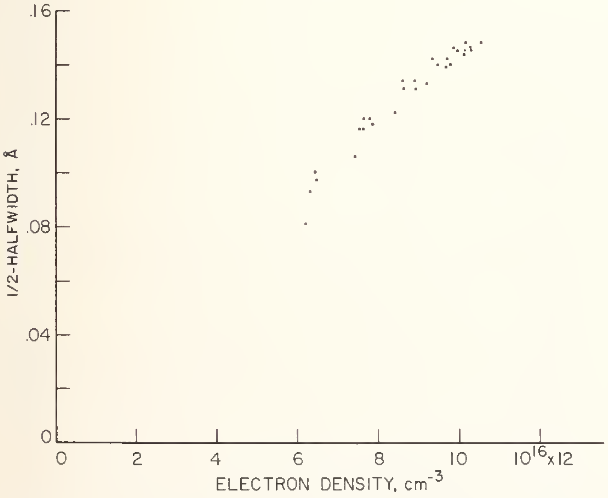


Figure 9. *Dependence of $\frac{1}{2}$-halfwidth upon electron density for AII 4806 Å.*

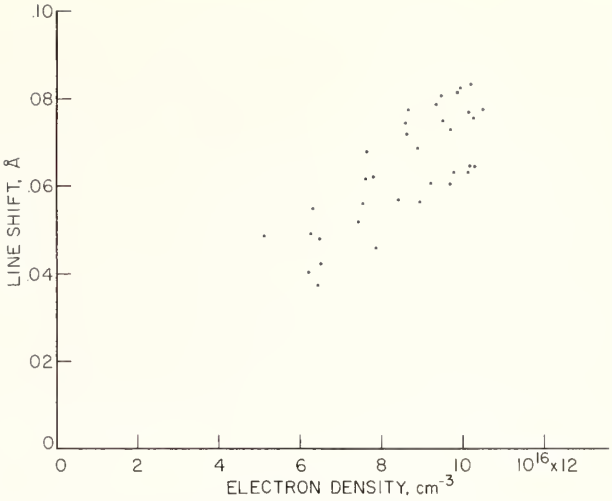


Figure 10. *Dependence of the blue shift of the AII 4806 Å line upon electron density.*

Table 1. *Stark 1/2-half widths,* w, *and shifts,* d, *for argon lines*

Line	$\frac{w}{N_e} \times 10^{16}$ [Å cm^3]		$\frac{d}{N_e} \times 10^{16}$ [Å cm^3] *	
	Expt.	Theor.	Expt.	Theor.
AI 4300 Å	0.100	0.124	0.103	0.132
AI 6965 Å	.048	.061	.039	.079
AII 4806 Å	.0148	.0058	−.0073	(−.0022)

*Shifts to the red are taken as positive.

3.3. Transition Probabilities

The calculation of the argon transition probabilities requires a knowledge of the plasma composition at each arc data point. For conditions of local thermodynamic equilibrium this can be computed in principle from the total pressure (1 atm), measured electron density, and total H_β line intensity assuming that only hydrogen and argon are present and using the theoretical H_β transition probability, Dalton's law, the condition for quasi-neutrality and the appropropariate mass action laws (Saha equations) for the possible ionization and dissociation reactions. The fact that the hydrogen was present in trace amounts permitted some simplification of the calculations as has been discussed previously [5, 16]. This simplified calculation requires a table of the composition of a pure argon plasma at atmospheric pressure and employs small corrections computed iteratively from the observed H_β line intensity.

The pure argon plasma composition was machine computed by a method similar to that of Drellishak, Knopp, and Cambel [17] including first order Debye corrections. The partition functions as functions of the cutoff energy were analytically smoothed and made to assume the asymptotic hydrogenlike form at the ionization energy limit (9). The number density of triply ionized argon atoms was assumed negligible thus limiting the calculations to temperatures below about 20 000 °K. The computed composition table including upper level populations pertinent to the present experiments is presented as table 2. Griem's treatment [18] of high density corrections to plasma composition calculations suggests that table 2 should be accurate to approximately 1 percent.

Finally the electron density and H_β line intensity obtained from the H_β line shape fitting are used iteratively in conjunction with this table to determine the total hydrogen content and the number density of excited argon atoms at the radial points considered. The argon transition probabilities are then found by division of the total line intensities (in photons per cubic centimeter per second) by these number densities at corresponding radii. The individual values of the transition probabilities obtained in this manner are presented in figures 11, 12, and 13. The averages of these experimental transition probabilities are given in table 3.

The transition probabilities of the lines other than 6965, 4300, and 4806 were determined relative to one or another of these three reference lines. The lines lying in the red and infrared were measured using the digital apparatus described above with full Abel inversion but with wider slits and with an abbreviated wavelength scan. The plasma composition was

TABLE 2. *Argon plasma composition at 1.00 atm pressure**

T	Z_0	Z_1	Z_2	U_0	U_1	U_2	N_e	N_0	N_1	N_2
5000	1.0000	5.3246	7.904	127106	222812	329954	1.322E 12	1.468E 18	1.322E 12	3.642E-07
5500	1.0000	5.3752	8.034	127101	222803	329940	7.174E 12	1.335E 18	7.174E 12	1.441E-04
6000	1.0000	5.4188	8.158	127093	222787	329916	2.944E 13	1.223E 18	2.944E 13	2.135E-02
6500	1.0000	5.4567	8.278	127081	222762	329879	9.746E 13	1.129E 18	9.746E 13	1.485E 00
7000	1.0000	5.4901	8.393	127063	222726	329825	2.724E 14	1.048E 18	2.724E 14	5.702E 01
7500	1.0000	5.5196	8.506	127039	222678	329753	6.648E 14	9.775E 17	6.648E 14	1.361E 03
8000	1.0000	5.5459	8.615	127009	222617	329662	1.453E 15	9.147E 17	1.453E 15	2.205E 04
8500	1.0000	5.5695	8.722	126971	222542	329549	2.898E 15	8.579E 17	2.898E 15	2.599E 05
9000	1.0001	5.5908	8.827	126926	222453	329415	5.352E 15	8.050E 17	5.352E 15	2.347E 06
9500	1.0001	5.6101	8.929	126875	222350	329261	9.254E 15	7.543E 17	9.254E 15	1.693E 07
10000	1.0003	5.6276	9.029	126818	222235	329089	1.511E 16	7.041E 17	1.511E 16	1.009E 08
10500	1.0005	5.6437	9.126	126755	222109	328900	2.342E 16	6.527E 17	2.342E 16	5.104E 08
11000	1.0009	5.6584	9.221	126688	221975	328699	3.466E 16	5.987E 17	3.466E 16	2.239E 09
11500	1.0015	5.6720	9.314	126618	221836	328491	4.910E 16	5.412E 17	4.910E 16	8.668E 09
12000	1.0025	5.6845	9.405	126549	221698	328283	6.672E 16	4.798E 17	6.672E 16	3.008E 10
12500	1.0039	5.6961	9.493	126482	221564	328082	8.705E 16	4.153E 17	8.705E 16	9.473E 10
13000	1.0061	5.7069	9.579	126421	221441	327898	1.091E 17	3.492E 17	1.091E 17	2.735E 11
13500	1.0093	5.7170	9.663	126367	221334	327738	1.315E 17	2.843E 17	1.315E 17	7.307E 11
14000	1.0140	5.7264	9.745	126325	221249	327610	1.525E 17	2.235E 17	1.525E 17	1.820E 12
14500	1.0208	5.7353	9.825	126294	221188	327517	1.705E 17	1.698E 17	1.705E 17	4.255E 12
15000	1.0304	5.7436	9.902	126275	221150	327462	1.846E 17	1.252E 17	1.845E 17	9.396E 12
15500	1.0441	5.7515	9.978	126268	221135	327439	1.942E 17	9.030E 16	1.942E 17	1.971E 13
16000	1.0630	5.7590	10.052	126269	221138	327443	1.998E 17	6.426E 16	1.997E 17	3.949E 13
16500	1.0890	5.7662	10.124	126277	221154	327467	2.022E 17	4.557E 16	2.020E 17	7.586E 13
17000	1.1241	5.7731	10.195	126289	221178	327504	2.021E 17	3.248E 16	2.018E 17	1.403E 14
17500	1.1706	5.7799	10.263	126304	221208	327549	2.004E 17	2.344E 16	1.999E 17	2.506E 14
18000	1.2315	5.7865	10.330	126321	221241	327598	1.976E 17	1.720E 16	1.967E 17	4.336E 14
18500	1.3099	5.7932	10.395	126337	221275	327648	1.943E 17	1.288E 16	1.928E 17	7.283E 14
19000	1.4093	5.7999	10.459	126354	221307	327697	1.907E 17	9.856E 15	1.883E 17	1.189E 15
19500	1.5334	5.8068	10.522	126369	221338	327744	1.870E 17	7.704E 15	1.833E 17	1.890E 15

T	N_e	4044 AI	4159 AI	4259 AI	4272 AI	4300 AI	4348 AII	4806 AII
5000	1.322E 12	1.153E 04	1.669E 04	2.054E 03	1.011E 04	1.760E 04	4.465E-08	6.290E-08
5500	7.174E 12	2.324E 05	3.252E 05	4.184E 04	1.968E 05	3.414E 05	1.467E-05	1.952E-05
6000	2.944E 13	2.818E 06	3.835E 06	5.118E 05	2.319E 06	4.009E 06	1.840E-03	2.333E-03
6500	9.746E 13	2.313E 07	3.073E 07	4.231E 06	1.858E 07	3.202E 07	1.099E-01	1.339E-01
7000	2.724E 14	1.397E 08	1.819E 08	2.572E 07	1.099E 08	1.890E 08	3.667E 00	4.314E 00
7500	6.648E 14	6.604E 08	8.450E 08	1.223E 08	5.102E 08	8.755E 08	7.675E 01	8.764E 01
8000	1.453E 15	2.557E 09	3.222E 09	4.758E 08	1.945E 09	3.331E 09	1.100E 03	1.223E 03
8500	2.898E 15	8.398E 09	1.044E 10	1.569E 09	6.298E 09	1.077E 10	1.153E 04	1.252E 04
9000	5.352E 15	2.401E 10	2.948E 10	4.503E 09	1.778E 10	3.037E 10	9.301E 04	9.901E 04
9500	9.254E 15	6.094E 10	7.404E 10	1.147E 10	4.464E 10	7.614E 10	6.016E 05	6.288E 05
10000	1.511E 16	1.395E 11	1.678E 11	2.633E 10	1.012E 11	1.723E 11	3.220E 06	3.310E 06
10500	2.342E 16	2.910E 11	3.471E 11	5.509E 10	2.092E 11	3.560E 11	1.462E 07	1.480E 07
11000	3.466E 16	5.581E 11	6.603E 11	1.059E 11	3.979E 11	6.764E 11	5.745E 07	5.738E 07
11500	4.910E 16	9.889E 11	1.161E 12	1.881E 11	6.997E 11	1.189E 12	1.985E 08	1.958E 08
12000	6.672E 16	1.624E 12	1.895E 12	3.096E 11	1.141E 12	1.937E 12	6.108E 08	5.957E 08
12500	8.705E 16	2.478E 12	2.873E 12	4.731E 11	1.730E 12	2.934E 12	1.690E 09	1.631E 09
13000	1.091E 17	3.513E 12	4.049E 12	6.719E 11	2.438E 12	4.133E 12	4.242E 09	4.055E 09
13500	1.315E 17	4.631E 12	5.311E 12	8.874E 11	3.198E 12	5.417E 12	9.722E 09	9.209E 09
14000	1.525E 17	5.689E 12	6.492E 12	1.092E 12	3.908E 12	6.616E 12	2.048E 10	1.924E 10
14500	1.705E 17	6.534E 12	7.423E 12	1.256E 12	4.468E 12	7.560E 12	3.991E 10	3.720E 10
15000	1.846E 17	7.063E 12	7.990E 12	1.359E 12	4.809E 12	8.133E 12	7.254E 10	6.713E 10
15500	1.942E 17	7.252E 12	8.171E 12	1.397E 12	4.918E 12	8.312E 12	1.240E 11	1.140E 11
16000	1.998E 17	7.147E 12	8.023E 12	1.379E 12	4.828E 12	8.157E 12	2.010E 11	1.836E 11
16500	2.022E 17	6.832E 12	7.642E 12	1.319E 12	4.599E 12	7.767E 12	3.116E 11	2.829E 11
17000	2.021E 17	6.394E 12	7.128E 12	1.236E 12	4.289E 12	7.241E 12	4.653E 11	4.201E 11
17500	2.004E 17	5.899E 12	6.557E 12	1.141E 12	3.945E 12	6.657E 12	6.732E 11	6.046E 11
18000	1.976E 17	5.394E 12	5.978E 12	1.045E 12	3.596E 12	6.067E 12	9.479E 11	8.470E 11
18500	1.943E 17	4.905E 12	5.421E 12	9.508E 11	3.261E 12	5.499E 12	1.303E 12	1.159E 12
19000	1.907E 17	4.445E 12	4.899E 12	8.624E 11	2.947E 12	4.968E 12	1.754E 12	1.553E 12
19500	1.870E 17	4.019E 12	4.419E 12	7.804E 11	2.658E 12	4.480E 12	2.313E 12	2.039E 12

T	N_e	6753 AI	6871 AI	6965 AI	7030 AI	9195 AI	9292 AI
5000	1.322E 12	1.016E 04	6.565E 03	1.626E 05	8.131E 03	1.891E 04	6.510E 03
5500	7.174E 12	2.072E 05	1.330E 05	2.460E 06	1.692E 05	3.478E 05	1.194E 05
6000	2.944E 13	2.537E 06	1.619E 06	2.348E 07	2.106E 06	3.908E 06	1.338E 06
6500	9.746E 13	2.099E 07	1.333E 07	1.574E 08	1.768E 07	3.007E 07	1.028E 07
7000	2.724E 14	1.277E 08	8.074E 07	7.994E 08	1.088E 08	1.719E 08	5.863E 07
7500	6.648E 14	6.072E 08	3.826E 08	3.251E 09	5.232E 08	7.745E 08	2.638E 08
8000	1.453E 15	2.364E 09	1.485E 09	1.104E 10	2.056E 09	2.876E 09	9.785E 08
8500	2.898E 15	7.798E 09	4.886E 09	3.228E 10	6.838E 09	9.103E 09	3.093E 09
9000	5.352E 15	2.238E 10	1.399E 10	8.323E 10	1.977E 10	2.518E 10	8.546E 09
9500	9.254E 15	5.703E 10	3.557E 10	1.926E 11	5.071E 10	6.207E 10	2.105E 10
10000	1.511E 16	1.310E 11	8.153E 10	4.058E 11	1.171E 11	1.384E 11	4.687E 10
10500	2.342E 16	2.741E 11	1.703E 11	7.853E 11	2.464E 11	2.819E 11	9.542E 10
11000	3.466E 16	5.270E 11	3.270E 11	1.407E 12	4.762E 11	5.289E 11	1.789E 11
11500	4.910E 16	9.362E 11	5.800E 11	2.341E 12	8.496E 11	9.186E 11	3.106E 11
12000	6.672E 16	1.541E 12	9.536E 11	3.632E 12	1.404E 12	1.482E 12	5.006E 11
12500	8.705E 16	2.356E 12	1.456E 12	5.256E 12	2.155E 12	2.223E 12	7.505E 11
13000	1.091E 17	3.346E 12	2.066E 12	7.098E 12	3.071E 12	3.102E 12	1.047E 12
13500	1.315E 17	4.420E 12	2.725E 12	8.948E 12	4.069E 12	4.032E 12	1.360E 12
14000	1.525E 17	5.438E 12	3.350E 12	1.054E 13	5.022E 12	4.888E 12	1.648E 12
14500	1.705E 17	6.256E 12	3.850E 12	1.165E 13	5.793E 12	5.545E 12	1.869E 12
15000	1.846E 17	6.773E 12	4.165E 12	1.214E 13	6.287E 12	5.925E 12	1.997E 12
15500	1.942E 17	6.963E 12	4.278E 12	1.205E 13	6.479E 12	6.018E 12	2.027E 12
16000	1.998E 17	6.871E 12	4.219E 12	1.150E 13	6.408E 12	5.871E 12	1.977E 12
16500	2.022E 17	6.576E 12	4.035E 12	1.067E 13	6.146E 12	5.559E 12	1.872E 12
17000	2.021E 17	6.161E 12	3.778E 12	9.710E 12	5.770E 12	5.156E 12	1.735E 12
17500	2.004E 17	5.691E 12	3.487E 12	8.724E 12	5.339E 12	4.717E 12	1.587E 12
18000	1.976E 17	5.209E 12	3.190E 12	7.780E 12	4.895E 12	4.279E 12	1.439E 12
18500	1.943E 17	4.741E 12	2.902E 12	6.909E 12	4.463E 12	3.862E 12	1.299E 12
19000	1.907E 17	4.300E 12	2.631E 12	6.122E 12	4.055E 12	3.475E 12	1.168E 12
19500	1.870E 17	3.891E 12	2.379E 12	5.419E 12	3.675E 12	3.121E 12	1.049E 12

*Z_0, Z_1, and Z_2 are internal partition functions for neutral, singly ionized, and doubly ionized argon atoms respectively.
U_0, U_1, and U_2 are effective ionization energies [cm^{-1}].
N_e, N_0, N_1, and N_2 are number densities of electrons, neutral, singly ionized, and doubly ionized argon atoms [cm^{-3}].
Columns headed by a wavelength contain number densities in the upper state of the line: e.g., under 4300 AI is tabulated $N_0 g_u \exp(-E_u/kT)/Z_0$ with $g_u=5$, $E_u=116999$ cm^{-1}.

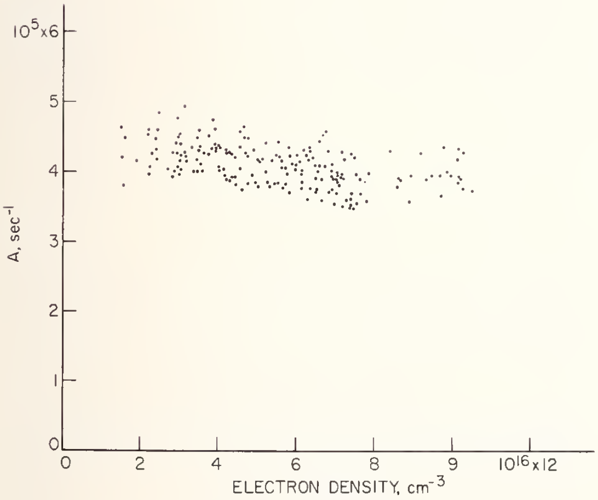


FIGURE 11. *AI 4300 Å transition probability values.*
Ave. = 4.11 × 10^5 sec^{-1}. Std. dev. = 0.29 × 10^5 sec^{-1}.

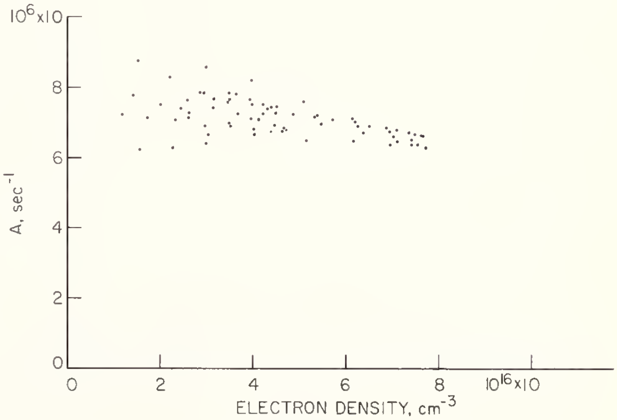


FIGURE 12. *AI 6965 Å transition probability values.*
Ave. = 7.10 × 10^6 sec^{-1}. Std. dev. = 0.55 × 10^6 sec^{-1}.

obtained from measurements of the AI 6965 Å intensity using a transition probability of 7.10 × 10^6 sec^{-1}. The lines in the blue were measured using an analog computer [19] for the direct recording of the Abel inverted spectra. In this way it was felt that the separation of overlapping lines (see fig. 1) could be better accomplished—although somewhat subjectively. The line intensities were determined by planimeter integration and the plasma composition was derived from the measured AI 4300 Å intensity (using $A = 4.11 \times 10^5$ sec^{-1}) for the neutral lines and from the AII 4806 Å intensity (using $A = 1.31 \times 10^8$ sec^{-1}) for the AII 4348 Å line. Because of the less satisfactory estimates of the line wing corrections, the limited number of experiments, and the uncertainty in the reference transition probabilities the A values for these lines are slightly less accurate than those for the 4300, 6965, and 4806 lines.

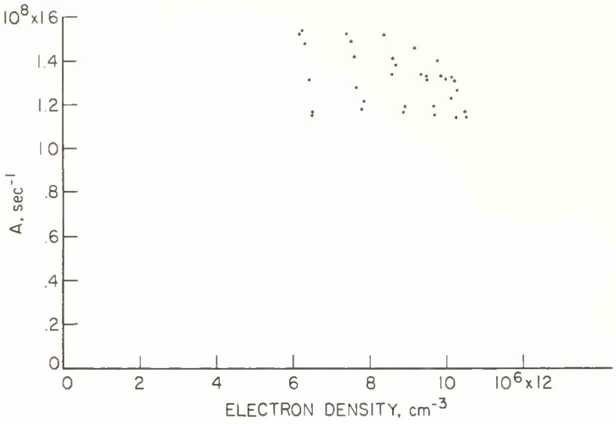


FIGURE 13. *All 4806 Å transition probability values.*
Ave. = 1.31×10^8 sec^{-1}. Std. dev. = 0.21×10^8 sec.$^{-1}$.

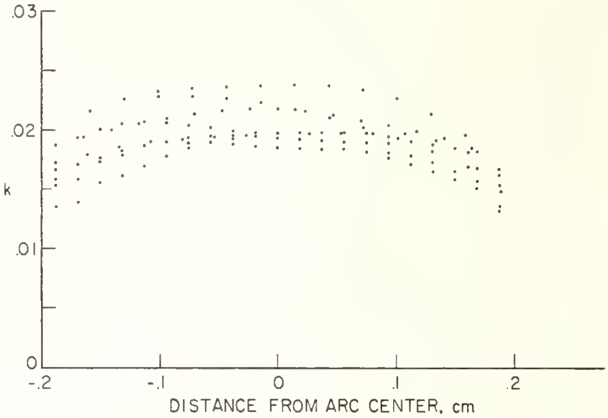


FIGURE 14. *The hydrogen/argon atomic ratio,* k, *as a function of radius for some 60 ampere experiments.*

TABLE 3. *Argon transition probabilities*

Wavelength	Transition	$A\times10^{-6}$ [sec^{-1}]						
		This expt.	Drawin	Gericke	Olsen	Richter	Pery-Thorne	Garstang
Å								
4044 I	$1s_4-3p_3$	0.45 ± 13%	0.37			0.35		
4159 I	$1s_5-3p_6$	1.60 ± 13%	1.7	1.2	0.66			
4259 I	$1s_2-3p_1$	4.4 ± 14%	4.0	3.3	2.5			
4272 I	$1s_4-3p_7$	0.94 ± 14%	0.76	0.69	0.37			
4300 I	$1s_4-3p_8$	0.411 ± 11%	.36	.32				
4348 II	$4s^4P-4p^4D^\circ$	240 ± 27%			115			128
4806 II	$4s^4P-4p^4P^\circ$	131 ± 23%			79			79
6753 I	$2p_{10}-4d_3$	2.9 ± 12%						
6871 I	$2p_{10}-4d_5$	4.0 ± 13%						
6965 I	$1s_5-2p_2$	7.10 ± 11%			5.3		8.7	
7030 I	$2p_9-3s_5$	4.0 ± 12%						
9195 I	$2p_{10}-2s_2$	2.2 ± 12%						
9292 I	$2p_{10}-2s_3$	4.5 ± 12%						

3.4. Hydrogen-Argon Ratio

The ratio of the total hydrogen content to the total argon content as determined from the H_β shape and intensity measurements alone is shown in figure 14 as a function of radial position for some 60 A experiments. This ratio is defined as

$$k=(2N_{H_2}+N_H+N_{H+})/(N_A+N_{A+}+N_{A++}+\ .\ .\ .)$$

where N_{H_2}, N_H, etc., are number densities of the species H_2, H, etc. All of the experiments in figure 14 utilized a premixed tank of the hydrogen-argon mixture with a value for this ratio of about 0.02 as determined by a mass spectrometric analysis. This figure illustrates the "demixing" effect [9] which precludes the use of cold gas composition data in determining the plasma composition in arcs containing gas mixtures.

4. Discussion of Errors

The recent appearance of a detailed and self-consistent theoretical treatment [9] of the problems of laboratory plasma sources and of spectroscopic plasma diagnostics together with the relatively large data sample sizes that can be accumulated with automatic recording and computing techniques makes possible a much more thorough error analysis than has heretofore been attempted. A discussion of several sources of error follows. In general it is found that the expected experimental and theoretical errors are of roughly comparable magnitudes.

4.1. Electronic

The maximum imprecision of the recorded intensities due to instrumental uncertainties was determined to be of the order of 0.15 percent. This figure results from the treatment as independent errors of the maximum effects of instrument nonlinearities and zero drift over a period of 1 hr with the combined effects of ambient temperature variations of plus or minus 5 °C and ± 10 percent line voltage fluctuations, and includes the contributions from the photomultiplier high-voltage power supply, the current amplifier, the voltage-to-frequency converter and the electronic counter.

An additional variation has been observed in the photomultiplier dark current on the higher gain range settings of the amplifier. This effect became noticeable after the dark current had been suppressed and appeared to consist of a long-term drift of the dark current of as much as 1 percent of full scale accompanied by short-term random noise of a similar magnitude.

The effects of photomultiplier fatigue on the photocurrent measurements were made negligible by restricting anode currents in the photomultiplier to less than 10^{-7} A, a value which previous investigations had shown to be below the threshold of fatigue effects for these tubes.

A certain amount of delay in the response of the photomultipliers to step inputs was observed. A rise time of about 0.2 sec was measured for the phototubes with S–20 response, while the delay was unmeasureable for the S–4 phototubes, implying some dependence on photocathode material. To ensure sufficient time for any effects of photomultiplier delay, mechanical relaxation or transient vibrations to decay, the recording of the photocurrent was postponed until 0.25 seconds after the arc chamber had completed its shift to a new position.

4.2. Calibration

The absolute calibration of the source intensities with a tungsten strip lamp is subject to a maximum uncertainty of about ± 5 percent. The brightness temperature calibration of the strip lamp at NBS is qualified by a certificated uncertainty of ± 7 °C relative to the IPTS which would produce uncertainties of about ± 3 percent in the transition probabilities of both neutral and ionic lines. For the calculation of the strip lamp emission at wavelengths other than the calibration wavelength (6530 Å) the tungsten emissivities given by DeVos [20] were used. These are estimated to be accurate to within ± 2 percent. The maximum uncertainty due to this cause would therefore presumably be ± 2 percent in the blue and infrared spectrum and would decrease to zero at the calibration wavelength.

The errors in intensity due to uncertainties in determination of the correct strip lamp current are around ±0.07 percent, almost two orders of magnitude below the errors discussed above and therefore negligible. The combined expected uncertainties are therefore ±5 percent for blue and infrared lines decreasing to ±3 percent for lines in the red.

4.3. Arc Source

The argon used in these experiments was technical grade argon with typically a purity of 99.996 percent containing mainly nitrogen and oxygen as contaminants. The gas flow system in the arc chamber is designed to prevent atmospheric and electrode contaminants from entering the observation chamber and indeed no impurities were observed spectroscopically during the experiments. From this observation the impurity upper limit and corresponding transition probability error of the order of 1 percent can be set based upon a minimum detectable signal and estimated transition probabilities for lines of the likely impurities, C, N, and O.

The arc current regulator maintains the arc current constant to within 0.05 percent for periods of 1/4 or 1/2 hr. Effects of a long-term drift presumably due to ohmic heating of the oil-cooled regulator shunt were minimized by monitoring the arc current at intervals with a potentiometer and precision shunt and making small manual corrections. Oscilloscopic observation of the arc current reveals a 0.3 percent 360 cycle ripple when the rotary converter power supply is used. Assuming the totally unrealistic worst possible case—that the averaging over the 0.1 sec counting time results in a measurement of the electron density at one current extremum and of the line intensity at the other—then the ensuing error in the transition probabilities would be of the order of 0.5 percent and 1 percent for the AI and AII lines respectively.

The arc positioning mechanism is capable of locating the arc chamber to within 0.002 cm, with a repeatability an order of magnitude better. Since these positioning errors are attributed to the lead screw and are therefore noncumulative, they will appear on the recorded profile of the traverse as noise amounting at most to about 0.4 percent rms of the maximum signal.

The assumed total arc pressure of 1 atm is clearly an approximation. No record was kept of the prevailing atmospheric pressure during the experiments so that day-to-day pressure fluctuations of 2 or 3 percent must be expected. The over-pressure of the argon in the arc required to maintain the steady gas flow was 0.0003 atm. The arc column over-pressures due to magnetic self-compression and due to the momentum transport accompanying the heat transport can be estimated [9] for the 90 A arc as 0.0003 atm and 0.02 atm respectively. Thus the actual pressure at all points in the arc was at all times probably within 5 percent of the 1 atm assumed for the calculations. By repeating the plasma composition calculations (table 2) at other pressures the effect of this pressure uncertainty upon the transition probabilities can be evaluated. The result is that a ±5 percent error in pressure produces a ∓ 1 percent error in the neutral line transition probabilities and a ±8 percent error in the ionic line values.

4.4. Optical

Any nonuniformity of the arc in the axial direction within the observation chamber will result in transition probability errors due to the finite height of the spectrometer slit which collects light from a region 0.05 cm long in the axial direction and because of the resulting signal averaging which will be different for line widths, neutral line intensities, and ion line intensities. Estimates of the maximum errors from this source based upon measurements taken during a crude scan along the arc axis are 0.5 percent and 4 percent for neutral and ionic line transition probabilities respectively. Similar errors arise in the steep gradient regions of the arc because of imaging errors of the optical system and the finite width of the entrance slit. The combined lateral image smearing was determined to be less than 0.005 cm for the 15 μ slit by moving the edge of a tungsten strip filament lamp across the optic axis at the arc position and observing the "halfwidth" of the signal step. The corresponding maximum transition probability errors in this case are also 0.5 percent and 4 percent respectively at the edges of the arc. In all cases the experimental values should be too high. Turbulence, if present in the arc, would lead to similar errors. However, estimates of the Reynolds number for the conditions of these experiments lie well within the laminar flow region suggesting that this should not be a problem. Optical refractivity gradients in the arc are expected to cause a negligible distortion of the arc intensity profile even in the vicinity of strong lines [9]. This expectation was partially confirmed experimentally by the failure to detect a significant displacement of the apparent position of the edge of a tungsten strip lamp filament imaged into the arc plasma at any observing wavelength near the AI 6965 Å line.

Scattering of light by the optical elements and arc chamber windows would cause an increase in the apparent transition probabilities at the higher radii, i.e., at the edges of the luminous arc column. Since a slight variation of this type was indeed observed, several experiments were performed with no window in the arc chamber. These failed to show a significant difference at the arc edges from those in which the window was included in the optical path. Direct rough measurements of the light scattered by the optical elements showed this amount to be less than 0.3 percent of the maximum source intensity, which could not possibly account for the observed radial variation of the A-values.

The shot noise arising from statistical fluctuation in the arrival of photons at the photomultiplier can be estimated from the source intensity and the geometry of the optical train. It is estimated to be always less than 0.5 percent for the strip lamp calibration and less than 0.1 percent for the arc, except at the extreme edges.

For some experiments the limiting aperture of the optical system was reduced to one-half its original size. Any observed difference in the results of these experiments would have pointed out errors and misalinements of the optical system. No such differences were observed, indicating that the optical system was properly alined and that the original aperture was indeed limiting.

The degree of self-absorption can be estimated by calculating the optical depth $\tau=2\int_0^R \kappa' dr$

where $$\kappa'=\epsilon/B(T)$$

and $$B(T)=2hc^2\lambda^{-5}(e^{hc/\lambda kT}-1)^{-1}$$

κ' is the effective absorption coefficient (cm^{-1}), and ϵ is the observed radially resolved emission coefficient per steradian (erg sec^{-1} cm^{-3} sr^{-1} cm^{-1}). The results of such calculations at the centers of the three lines at 4300, 6965, and 4806 Å are respectively 0.002, 0.11, and 0.002 for the optical depths, τ, in the worst cases encountered. Since the Abel inversion is most unstable near the center due to the infinite kernel at that point it is to be expected that the consequences of errors in the side-on intensity measurements due to self-absorption will normally be most severe in the radially inverted values near the center of the arc. This is borne out by exact analytic calculations of simple models and by the approximate Freeman and Katz [10] treatment of more realistic models. These calculations indicate that for small degrees of self-absorption and for bell-shaped profiles the relative error in the radially resolved emission coefficient is of the order of $\kappa_0'R$ at the arc center where κ_0' is the effective absorption coefficient at the center and R is, as before, the nominal arc radius. Thus only in the case of the AI 6965 Å line will self-absorption play a role leading to transition probabilities that are too low by about 5 percent ($\kappa_0'R$ averaged over the line shape) at the arc center and increasing to the correct value at the edge. To some extent this conclusion appears to be supported by the data of figures 11 and 12 which show for the 6965 Å line a more pronounced depression of the transition probabilities at high electron densities near the arc center.

4.5. Analytical and Theoretical

In general, the accuracy of an Abel inversion based on curve fitting techniques is dependent upon the form of the intensity profile of the arc traverse and the fitting function, the number of polynomials used in the fitting function, the number of increments examined during each arc traverse, and the noise present on the intensity profile. To assess the effects of these variables on the accuracy of the inversion, analytical test functions were constructed with varying amounts of superimposed noise drawn from a table of random normal deviates. These test functions, which are of the same general shape as the observed profile of the arc traverse, were then inverted by the machine program used in processing the experimental results. As expected, for data with a relatively high noise level a small number of polynomials in the fitting function produces the best inversion in terms of accuracy of fit and minimum noise amplification. Conversely, no significant improvement in accuracy results from using large numbers of increments and terms unless the signal/noise ratio of the data is quite high. The accuracy of the inversion is, however, relatively insensitive to variations in number of increments for noise levels greater than 0.3 percent due to the smoothing inherent in the curve fitting process and in this range the relative noise level of the inverted profile is almost identical to that on the original recorded intensity profile.

The results of tests on analytical functions were borne out by further tests of the inversion on actual experimental profiles. The number of data points of representative many-point arc traverses was halved and quartered by systematically discarding alternate data points, and the resulting "thinned" traverses inverted and compared to the originals. These tests also showed that, at least for the data encountered here, no further accuracy could be attained by taking more than 20 or 30 measurements per arc traverse. Similarly, the use of more than 8 or 10 terms in the polynomial expansion was again not warranted and, in fact, increased the noise level in the results.

Numerical tests of the dispersion shape fitting program carried out by superimposing noise upon calculated dispersion shapes reveals that the relative rms noise on the computed line intensity and halfwidth is roughly equal to the relative noise in the input intensity data at the half maximum intensity level. Thus, little smoothing of the noise is accomplished in this step. This is due mainly to the influence of the noise upon the background or continuum level determination by the program. In these experiments this determination was dependent upon a comparatively small effective number of points due to the wavelength point distribution employed.

The use of the area of the fitted dispersion shape as the spectral line intensity obviates the necessity for correcting measured line intensities for that portion of the line lying below and beyond the end points of the wavelength scan. This is a significant correction amounting to 13 percent for scans of only ten halfwidths and may account for part of the difference between the transition probabilities observed here and the lower values of other workers. Since the experimental line shapes even after correction for apparatus functions are not expected to be quite dispersion shapes [9] it was necessary to ascertain the effect of departures from the dispersion shape upon the linewidth, shift, and intensity values as measured in these experiments. For this purpose the dispersion shape fitting program was applied to a theoretical complete asymmetric line shape [21] which appears to be reasonably representative of the experimental line shapes encountered here. The computed intensities and halfwidths were consistently low by 3 percent and 2 percent respectively. The line shifts were consistently overestimated by a magnitude approximately equal to the error in the $\frac{1}{2}$-halfwidth. No attempt was made to calibrate the dispersion shape fitting program for these theoretical line shapes because of the unavailability of sufficiently extensive tables of the necessary line shapes. Consequently, systematic errors can be expected in the results amounting to perhaps 5 percent and probably always in the direction indicated by this example.

At the heart of these measurements is the determination of the electron density by the H_β line shape measurement. Unfortunately a significant uncertainty in the results is associated with this step. For example, Griem [9] estimates that the electron densities obtained from H_β line shapes are probably reliable only to about 5 percent based upon an analysis of the theoretical approximations. In addition, as indicated in figure 4, some error is involved in the fitting of a theoretical line shape to the experimental data. Typically the rms deviation of the experimental points from the fitted curve is 2 or 3 percent of the maximum H_β intensity. (This is somewhat better than the dispersion shape fitting to the argon lines which typically has an rms deviation of 3 to 5 percent. However, in part this greater error is explained by the influence of the apparatus or slit function which is not taken into account in the fitting and by the approximation of the true theoretical shapes by the dispersion shape.) The subtraction of the pure argon spectrum from the argon + hydrogen spectrum removes the major part of any uncertainties in the H_β shape measurement due to irregularities in the argon continuum underlying the hydrogen line. Any errors in this step due to small changes in the radial temperature profile caused by the addition of the trace of hydrogen are expected to be negligible but presumably are included in this 2 or 3 percent deviation. As a partial check of these H_β measurements in two of the 60 A experiments H_α line shapes were also recorded. From the electron density, temperature, and hydrogen to argon ratio as determined from the H_β measurements the theoretical intensity and shape of the H_α lines were computed using the Griem, Kolb, and Shen tabulations. Figure 15 shows a comparison of an experimental H_α line shape (after the Abel inversion and subtraction of the pure argon spectrum) with the theoretical shape based upon the H_β measurements at the same radial point. The agreement is seen to be satisfactory in the wings and at the center but the halfwidth of the theoretical shape is 10 percent or so smaller than the experimental one. This difference appears to be in accord both in magnitude and direction with the correction to the theoretical H_α shapes which Griem et al., [14] estimate would accrue by taking into account the improved ion field strength distribution functions of Mozer and Baranger. Thus, in conclusion, it is reasonable to assume that the electron densities obtained in these experiments from the H_β line shapes should not be in error by much more than about 5 percent. This results in 8 and 20 percent uncertainties respectively in the AI and AII transition probabilities.

Griem [22] has discussed in detail the validity of the local thermodynamic equilibrium (L.T.E.) assumption in laboratory plasmas. Using his criteria one finds

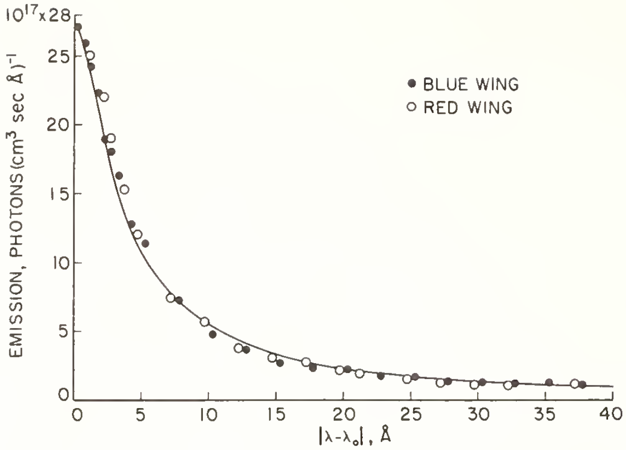


FIGURE 15. *Experimental intensity points in the neighborhood of* H_α *6563 Å after Abel inversion (on axis of 60 ampere arc in argon with* $\sim 1\%$ H_2*) with theoretical* H_α *line shape computed from parameters obtained by* H_β *measurements:* $N_e = 7.35 \times 10^{16}$ cm^{-3}, $k = 0.0197$.

that for homogeneous plasmas of the dimensions of the arcs of these experiments complete L.T.E. would be probable down to the lowest electron densities actually utilized in the measurements—2×10^{16} for neutral species and 5×10^{16} for ionic species. Again following Griem's treatment one finds that the greatest average distance traveled by any species in the arc between equilibrating collisions is that of the ground state neutrals of the order of 10^{-2} cm at the axis. Thus, the measured electron density and line intensities at a particular point in the arc are not to be interpreted as corresponding exactly to L.T.E. conditions at the local electron temperature at that point but rather as appropriate to some kind of averaging of near-equilibrium distributions which exist over a distance of the order of 10^{-2} cm. The use of this distance, then, permits some estimate of the effects of the temperature and composition gradients present in the arc upon the accuracy of the transition probability determinations. Clearly an over-estimate of the errors is obtained by coupling line intensity measurements at one point with equilibrium calculations based upon electron density measurements 10^{-2} cm away. Such a procedure results in error estimates of 1 percent for the neutral lines and 2 percent for the ionic lines at the center of the 90 A arc. Away from the center this equilibrating collision distance is not a proper measure of the L.T.E. smearing because of the additional equilibrating influences of the diffusion of ions and excited atoms from the hot core and the absorption of resonance radiation from the core. The fact that the measured transition probabilities show no strong dependence upon the electron density, however, suggests that if departures from L.T.E. are not serious at the arc center they are probably also not serious at least out to 0.2 cm where the lowest electron density measurements were taken.

5. Discussion of Results

The estimated transition probability uncertainties resulting from this error analysis assuming the errors are independent are included in table 3 together with transition probability values obtained by other investigators. Most of the errors which have been discussed are systematic. However, a few—the electronic noise, the numerical curve fitting errors, the day-to-day pressure variation, and the dark current drift errors—are not and will tend to be reduced in magnitude by the averaging over the many experiments or radii. In arriving at the uncertainty estimates in table 3 due allowance for this kind of error was taken, where appropriate, by division by the square root of the sample number. A similar calculation applied to the neutral line width and shift measurements gives an estimated 6 percent uncertainty.

The three dominating errors in the average transition probability values determined here are the absolute intensity calibration errors, the systematic errors in the argon line shape fitting due to apparatus functions and asymmetry, and the estimated uncertainty in the hydrogen line broadening theory. It is now possible to reduce the effect of calibration uncertainties from the 3 to 5 percent estimated in these experiments to about 1 to 2 percent, by means of new NBS radiometric calibration services which have become available on a limited basis [24] since these experiments were undertaken. Also, with some effort, the argon line shape fitting can be improved by the calculation and use of more extensive theoretical line shape tables including asymmetry and possibly with apparatus and Doppler broadening properly folded in. Thus the experimental errors can probably be reduced by a factor of two without excessive effort. However, without a concomitant improvement in the accuracy of the electron density determination these experimental improvements would only marginally reduce the estimated overall errors. The uncertainty in this step is the major contribution to the error estimates in table 3. Griem's estimate of the accuracy of the hydrogen line shape calculation is not significantly changed by consideration of the small amount of relatively contradictory experimental evidence [9]. Further experimental or theoretical studies should permit a better assessment of the accuracy of this extremely useful plasma diagnostic technique.

The origin of the apparent decrease of the transition probabilities with increasing electron density (see e.g., fig. 11) is unknown. Of the error sources described above, the only pertinent ones estimated to be of sufficient magnitude to encompass this effect are hydrogen line broadening theory errors, line shape fitting errors, and possibly departures from L.T.E. This deviation from a constant transition probability agrees qualitatively with the discrepancies observed by Wiese et al. [25] in pure hydrogen arcs.

The scatter of the transition probability values (figs. 4 to 13) is in agreement with the noise level estimates described above. These were mainly electronic and amounted to 1 or 2 percent of the maximum signals. When expressed in terms of the half-intensity of a line this relative noise level is higher by a factor of two or more, and, consequently, since neither the Abel inversion nor the dispersion line fitting seems to modify the noise level, the line intensities should exhibit a scatter of several percent. When combined with a similar noise in the electron density values a resultant scatter of the transition probability values of the order of 5 to 10 percent is to be expected.

The theoretical transition probabilities of Garstang [23], the "hook" method values of Pery-Thorne and Chamberlain [1], and the arc measurements of Drawin [4] appear to agree generally with the present values in the sense that the error ranges assigned by the investigators overlap the present ones. (The theoretical values are good to perhaps a factor of two, Pery-Thorne and Chamberlain estimate an accuracy of 20 to 30 percent for their values, and Drawin assigns error limits ranging from 10 percent for AI 4044 Å to 20 percent for AI 4300 Å.) Drawin's measurements were carried out in an arc containing a hydrogen-argon mixture. However, since his diagnostics were based upon hydrogen line intensity measurements and the use of the cold gas composition there is a possibility of a systematic error due to demixing.

Gericke's argon transition probabilities [3] are based upon an argon arc temperature profile derived from measurements of the AII 4348 Å line intensity using a transition probability value of 68×10^6 sec^{-1}. The value obtained in the present work for this transition probability is 240×10^6 sec^{-1}. If this is correct then Gericke's transition probability values should be increased by about 35 percent[3] and would agree well with the present values. These same comments apply to Richter's value for the AI 4044 A line (27) which was evidently obtained similarly. The corresponding adjustments to Gericke's electron density values result, in the case of the AI 4300 Å line, in values (in Å) for the $\frac{1}{2}$-halfwidth and shift both approximated by $0.12 \times 10^{-16}[N_e]$ where N_e is the number of electrons per cm^3. This compares reasonably well with the present values (table 1) of $0.10 \times 10^{-16}[N_e]$. Thus the measurements reported here are evidently well in accord with Gericke's on a relative basis but the absolute results differ through the use of the H_β line shape for the arc diagnostics rather than the AII 4348 Å transition probability used by Gericke.

In the case of Olsen's results an estimate of the degree of self-absorption at the center of the AII 4806 Å line[4] under his arc conditions leads to values for the optical depth, τ, of 0.7 or 0.3 depending upon whether the line halfwidth is estimated from Griem's theoretical calculations [9] or is extrapolated from the experimental data of figure 9. In either case the magnitude is sufficient to cause a serious error in the radially resolved emission coefficient and to raise doubts about whether Olsen's observed apparent off-axis maximum was not in fact a consequence of this absorption rather than a manifestation of the Larenz and Bartels [28] "normal" temperature effect. In this event Olsen's temperature determinations and transition probabilities are open to radical reinterpretation.

Table 1 compares the measured values of the line widths and shifts (averaged assuming they are proportional to the electron density) with theoretical values computed from Griem's tables [9] for a temperature of 12 000 °K. Fortunately the theoretical values of the reduced widths and shifts are not strongly temperature dependent so that the difference between 12 000° and whatever effective temperature is introduced by the averaging of the experimental values will cause a difference of only a few percent in the tabular entries. For the neutral argon lines the agreement of theory and experiment is roughly within the expected accuracy of 8 percent for the experiments and 20 percent for the theory. The ion line results, however, are in very poor agreement with theory. For the line shift this is understandable since the theoretical Stark shift for the line does not include the plasma polarization blue shift [9] which rough calculations indicate will be larger than the Stark shift. For the width of the AII 4806 Å line errors due to both Doppler broadening and the slit width correction procedure are important but do not appear to be sufficient to resolve the discrepancy between theory and experiment. The consequences of neglecting the Doppler broadening were estimated by folding the Doppler line shape (Gaussian with $\frac{1}{2}$-halfwidth of approximately 0.03 Å) into the apparatus function to give a broadened effective apparatus function. The use of this modified apparatus function (which significantly affects only the narrow ionic line) reduces the widths of figure 9 by approximately 0.005 Å and decreases the proportionality constant in table 1 by about 5 percent. The error in this proportionality constant stemming from the application of the slit width correction procedure to the AII 4806 Å line where the line and apparatus function widths are comparable (line width: 0.08 Å to 0.15 Å: apparatus width: 0.1 Å) is estimated at 10 or 20 percent. This figure is based upon the results of the 150 μ slit width experiment in which the apparatus function was wider than the AI 4300 Å line at all radii. In this case application of the slit width correction procedure to the computer fitted line widths resulted in an average value for $\frac{w}{N_e} \times 10^{16}$ of 0.089 compared to the average 0.100 for all the narrow slit experiments.

6. References

[1] A. Pery-Thorne and J. E. Chamberlain. Proc. Phys. Soc. (London) **82,** 133 (1963).

[2] H. N. Olsen, J. Quant. Spectr. Radiative Transfer **3,** 59 (1963).

[3] W. E. Gericke, Z. Astrophysik **53,** 68 (1961).

[4] H. W. Drawin, Z. Physik **146,** 295 (1956).

[5] W. L. Wiese and J. B. Shumaker, Jr., J. Opt. Soc. Am. **51,** 937 (1961).

---

[3] This includes a correction discussed by Griem (26) to the ionization potential lowering.

[4] There appears to be an error in the equation for self-absorption in reference 2 (eq (6)). g_n should probably be replaced by $\frac{1}{2}\pi$.

[6] J. B. Shumaker, Jr., Rev. Sci. Instr. **32**, 65 (1961).

[7] C. R. Yokley and J. B. Shumaker, Jr., Rev. Sci. Instr. **32**, 6 (1961).

[8] D. R. Paquette and W. L. Wiese, Applied Optics **3**, 291 (1964).

[9] H. R. Griem, Plasma Spectroscopy (McGraw-Hill Book Co., New York, N.Y., 1964).

[10] M. P. Freeman and S. Katz, J. Opt. Soc. Am. **50**, 826 (1960).

[11] M. P. Freeman and S. Katz, J. Opt. Soc. Am. **53**, 1172 (1963).

[12] A. Erdélyi, Higher Transcendental Functions, Vol. **2** (McGraw-Hill Book Co., New York, N.Y., 1953).

[13] S. I. Herlitz, Arkiv för Fysik, **23**, 571 (1963).

[14] H. R. Griem, A. C. Kolb, and K. Y. Shen, Astrophys. J. **135**, 272 (1962).

[15] H. R. Griem, Astrophys. J. **136**, 422 (1962).

[16] J. B. Shumaker, Jr., and W. L. Wiese, Temperature—Its Measurement and Control in Science and Industry, Vol. **3**, Pt. 1, pp. 575–579, (Reinhold Pub. Corp., New York, N.Y., 1962).

[17] K. S. Drellishak, C. F. Knopp, and A. B. Cambel, Arnold Engineering Development Center Tech. Documentary Report AEDC–TDR–63–146 (1962).

[18] H. R. Griem, Phys. Rev. **128**, 997 (1962).

[19] C. R. Yokley and J. B. Shumaker, Rev. Sci., Instr. **34**, 551 (1963).

[20] J. C. DeVos, Physica **20**, 690 (1954).

[21] O. Roder and A. Stampa, Z. Physik **178**, 348 (1964).

[22] H. R. Griem, Phys. Rev. **131**, 1170 (1963).

[23] R. H. Garstang, Mon. Not. R. Astr. Soc **114**, 118 (1954).

[23] N.B.S. Tech. News Bull. **49**, 14 (1965).

[25] W. L. Wiese, D. R. Paquette, and J. E. Solarski, Phys. Rev. **129**, 1225 (1963).

[26] H. R. Griem, Phys. Rev. **128**, 515 (1962).

[27] J. Richter, Z. Astrophysik **53**, 262 (1961).

[28] R. W. Larenz and H. Bartels, Naturwiss. **37**, 164 (1950).

(Paper 69A6–370)

Reprinted from **APPLIED OPTICS**, Vol. 3, page 83, January 1964

The Use of an Analog Computer in Side-On Arc Spectroscopy

J. B. Shumaker, Jr., and C. R. Yokley

An analog computer which solves Abel's integral equation is described and its application to the side-on spectroscopic study of high-current arcs is illustrated. By its use radially resolved spectra of cylindrically symmetric inhomogeneous sources are obtained with the same speed and simplicity as are spectra of homogeneous sources. Comparison of N I transition probability measurements using this computer with those using conventional numerical radial resolution techniques indicates that the computer errors are negligible.

Introduction

In the spectroscopic study of cylindrically symmetric arcs and flames spectroscopic observations are often carried out on a small cross-section of the light source in a direction perpendicular to its axis. Such "side-on" measurements include contributions from the outer, cooler regions of the source as well as from the hot core. In order to separate the contributions of the different radial zones and to obtain the true radial characteristics of the source, one of numerous graphical or numerical procedures for solving Abel's integral equation[1–8] is resorted to. The purpose of the present paper is to present the results of some high current arc spectroscopic experiments in which a specialized analog computer[9] has been applied to the Abel integral problem and to estimate the computer accuracy by comparison with the results of experiments in which numerical inversion procedures were employed.

The analog computer has been designed to produce true radially resolved spectra in a continuous instantaneous manner while the spectrum is being scanned in wavelength. The operating principle involves causing an image of the light source to be driven repeatedly across the entrance slit of a scanning spectrometer by means of a rapidly rotating prism. The waveform of the resulting train of photomultiplier pulses is then Fourier-analyzed by the computer and the Fourier amplitudes continuously weighted and summed to produce a recorder trace of the spectrum appropriate to the desired radial position.

For optically thin sources the equation relating the observed side-on arc profile, $F(x)$, and the true radial distribution of intensity, $G(r)$, is the familiar Abel integral equation

$$F(x) = 2\int_x^R \frac{G(r)\,rdr}{\sqrt{r^2 - x^2}}, \tag{1}$$

with the solution

$$G(r) = -\frac{1}{\pi}\int_r^R \frac{\frac{dF(x)}{dx}\,dx}{\sqrt{x^2 - r^2}}, \tag{2}$$

where R is any point beyond the edge of the arc such that $F(R) = G(R) = 0$. The computer approximates $F(x)$ by a six-term Fourier expansion

$$F(x) \approx F_0 + \sum_1^6 F_n \cos\frac{n\pi x}{R}, \tag{3}$$

using only cosine functions because the arc is symmetric about its center. With this substitution (2) becomes

$$\begin{aligned} G(r) &\approx \frac{1}{R}\sum_1^6 nF_nA_n(\rho), \\ A_n(\rho) &= \int_\rho^1 \frac{\sin n\pi t}{\sqrt{t^2 - \rho^2}}\,dt. \\ \rho &= r/R \end{aligned} \tag{4}$$

The integrals $A_n(\rho)$ have been evaluated numerically[9] for values of ρ at intervals of 0.05 between 0 and 1.

Computer Description

A simplified block diagram of the computer is shown in Fig. 1. The image of the arc is moved across the slit of the spectrometer 100 times per second by means of a rotating prism. The resulting photomultiplier current wave train is amplified by the current amplifier and applied to a bank of T-section filters tuned to

---

The authors are with the National Bureau of Standards, Washington, D.C.

Received 1 November 1962.

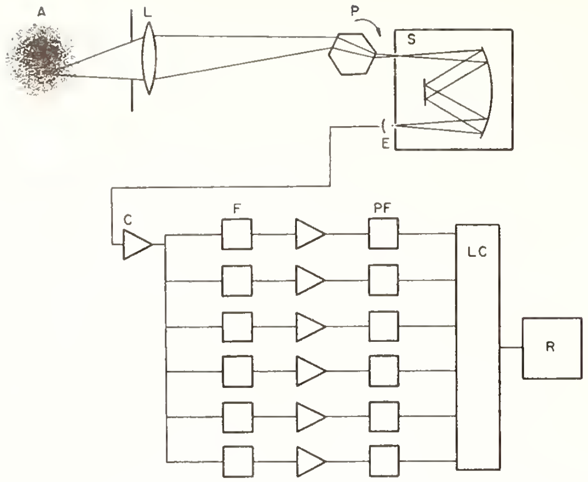


Fig. 1. Block diagram of essential elements of computer. A—cylindrically symmetric light source. L—varifocal lens. P—rotating prism. S—spectrometer. E—exit slit photomultiplier. C—current amplifier. F—filters and amplitude and phase correcting amplifiers. PF—peak followers. LC—linear combiner. R—recorder.

100, 200, ..., 600 cps. Following each of the six filters is an amplifier which corrects for filter losses and phase shifts and multiplies the signal by $n = \nu/100$, where ν is the channel frequency. A peak follower in each channel then furnishes a dc voltage equal to the maximum positive excursion of the sinusoidal signal over the previous few cycles. These dc voltages are the absolute values of the Fourier amplitudes F_n of Eq. (3) multiplied by n. The products nF_n are rendered positive or negative by means of toggle switches, with the proper signs being determined by visual comparison of the corrected filtered sinusoidal signals with the 100-cps component by means of an oscilloscope.* The only purpose of the phase correction of the filtered signals is to facilitate this comparison. The dc voltages representing the nF_n are then multiplied by the coefficients $A_n(\rho)$ and added [or subtracted according to the product of the signs of F_n and $A_n(\rho)$] in the final linear combiner to give

$$\sum_{1}^{6} nF_nA_n(\rho) \approx RG(\rho R). \tag{5}$$

The coefficients $A_n(\rho)$ are introduced into the linear combiner by means of a set of input resistors which are assembled as plug-in units for the different values of ρ. The time constants of the circuit elements involved were chosen to be less than the 0.2-sec time constant of the recorder employed.

The factor R in Eq. (5) is the distance in the arc represented by one-half the distance between centers of successive arc images passing across the entrance slit of the spectrometer. It is calculated from the magnification of the optical imaging system and the maximum displacement caused by the rotating prism. This displacement, in turn, is calculated from the geometry and index of refraction of the prism.

The accuracy with which a particular side-on arc profile can be fitted with six Fourier terms depends upon the value of R used. By means of a varifocal lens the magnification of the optical system is adjusted to provide a near optimum value of R for each set of experimental conditions. Fortunately, this is ordinarily not very critical, and a suitable magnification can quickly be found by inspection of the current amplifier output signal on an oscilloscope. The only important criterion appears to be that successive arc images not be permitted to overlap.

The intensity calibration of the spectra on an absolute basis is accomplished in two steps. First, with the prism held stationary, the optics and photomultiplier are calibrated by replacing the arc source by a calibrated standard tungsten strip lamp and measuring the dc photomultiplier current at each wavelength of interest. Then by means of a sine wave generator tuned to the operating frequency (100 cps) in series with a precision resistor (10^8 Ω) a known sinusoidal current is applied to the computer in lieu of the photomultiplier input, and the recorder output then provides the necessary calibration of the electronics.

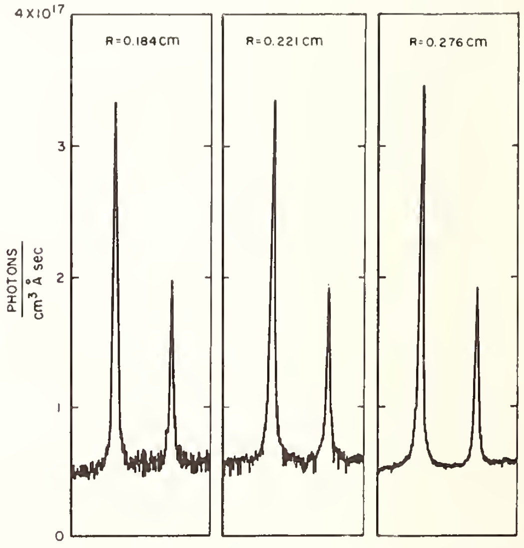


Fig. 2. Nitrogen spectrum in the neighborhood of the 4935–4915 Å NI multiplet obtained at $r = 0.055$ cm in a 50-A atmospheric pressure nitrogen arc for three different values of the Fourier period $2R$.

---

* Additional circuits by means of which this sign sensing and switching can be performed automatically are described in ref. 9. In the experiments described here the Fourier signs did not change during the wavelength scans, so the toggle switches, once set, never needed to be changed.

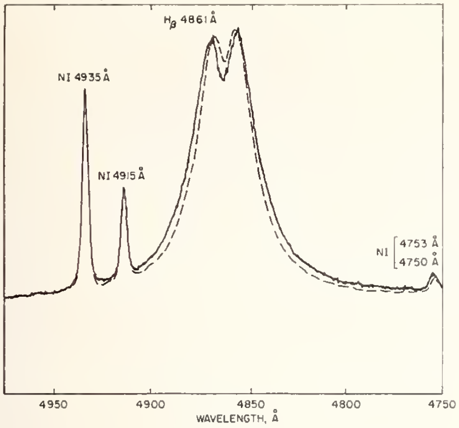


Fig. 3. Comparison of radially resolved spectrum at $r = 0$ (solid curve) with unresolved spectrum at $x = 0$ (dashed curve).

Experimental

Because of the difficulty of producing a test light source with a known spatial variation suitable for an absolute test of over-all computer performance it was decided to make an operational test of the computer by comparing spectroscopic measurements made by this method with those using conventional numerical computational methods. For this purpose a remeasurement of the transition probability of the NI 4935Å–4915 Å multiplet was chosen since this should be a constant independent of arc current, radial point of measurement, and any other day-to-day arc variations. The method of transition probability measurement employed was that described earlier[10] in which a trace of hydrogen is introduced into the arc for diagnostic purposes.

High-current wall stabilized arcs[11,12] were used to excite the spectra studied here. The channel diameter was 4.76 mm, and the working gas was nitrogen and mixtures of nitrogen with about 1% ammonia at a total pressure of 1 atm. Argon blanketed the electrodes but as no trace of argon (or other contaminants) was observed spectroscopically the maximum argon impurity level is estimated to be well below 1%.

A simple preliminary test of the computer was made to determine how critical the value of R is for a good six-term Fourier fit of an actual arc profile. The result of such a test is shown in Fig. 2 where the satisfying invariance of the results of the computer inversion to the choice of the distance R is clear. In this case the value of R below which some overlapping of successive signals appears to begin was about 0.15 cm. The noise in this experiment appears to be radiation noise in the low level signals which resulted from the use of small slits (50 μ by 2 mm high) and a small solid angle (1.8×10^{-5} sterad) for collecting the light emitted by the arc. The dependence of the radiation noise level upon R in Fig. 2 is due to the fact that the amount of light entering the spectrometer is inversely proportional to the square of the linear magnification of the optical system.

Figures 3–5 show the same spectral region of similar arcs burning at 50 A with 1.2% NH_3 added to the nitrogen. The slit-widths used were 500 μ ($\approx$2.5 Å) which accounts for the noise level being generally lower than in Fig. 2 and for the shapes of the NI lines, which are determined largely by the slit function. Figure 3 compares the inverted spectrum obtained from the computer for $r = 0$ with that given by a simple side-on view directly across the center of the arc. No vertical scale is given since the two curves are dimensionally different. The distortion of the line shape of H_β by the outer regions of the arc can clearly be seen in the case of the untreated profile. This effect is not seen in the NI lines because of the dominant instrumental broadening. Figure 4 shows the computed spectrum at several different radii.

The experiment was repeated without the NH_3 to obtain background levels for careful H_β line-shape measurements. Figure 5 shows an example of the superposition of the spectra obtained in this way. Spectrum pairs similar to Fig. 5 were obtained for the spectra of Fig. 4* as well as for six other cases on two additional separate occasions (each with an independent intensity calibration) at currents of 50 and 100 A, radial points 0.41 mm and 0.49 mm and with 500-μ and 150-μ slits. Electron densities were obtained by matching the Griem *et al.*[13] theoretical H_β profiles to the differences between the spectra with and without

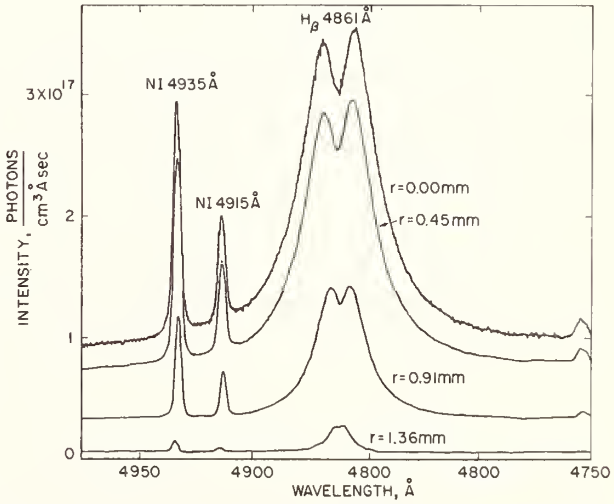


Fig. 4. Comparison of spectra obtained under identical arc conditions at different radii.

---

* The spectrum pair at $r = 1.36$ mm was not used because the H_β line profile was too much distorted by the slit function to permit a reliable electron density estimate.

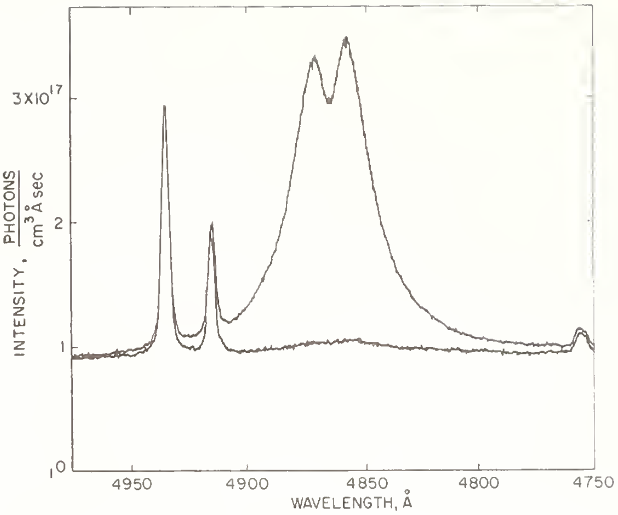


Fig. 5. Upper curve: Spectrum of nitrogen arc containing 1.2% NH_3 at $r = 0$. Lower curve: Same spectrum a few minutes later with the NH_3 flow shut off.

the added ammonia as described previously.[14] In Fig. 6 the difference between the spectra of Fig. 5 is compared with the fitted theoretical profile. The intensities of the 4935 Å and 4915 Å N I lines were determined by integration and their transition probabilities calculated using the electron densities derived from the H_β-width measurements and the assumption of local thermodynamic equilibrium.[10] In these calculations the lowering of the ionization potential was estimated by the Debye approximation as recommended by Griem.[15]

Results

Table I presents the average values of the two transition probabilities obtained in this way together with the standard deviation of the individual values of the nine determinations. In the last column of Table I are given comparison values obtained from 5 separate experiments with a total of 41 determinations covering the same range of radii and arc currents. The same technique of using a trace of hydrogen was employed but the Abel inversion was carried out numerically using in one experiment a method similar to that of Barr[8] and in the other four a modification of the method of Freeman and Katz.[5]

Table I. $3s\,^2P - 4p\,^2S^\circ$ **N I Transition Probabilities (sec^{-1})**

Å	Analog Abel inversion	Numerical Abel inversion
4935	1.66×10^6 (s.d. 12%)	1.73×10^6 (s.d. 12%)
4915	0.75×10^6 (s.d. 13%)	0.77×10^6 (s.d. 8%)

There appear not only to be no significant dependence of the measurement upon the means of solving the Abel integral problem but also no significant dependence upon arc current or upon the radial position of the measurement—at least out to about 1 mm from the axis which is the range covered by the data. These transition probabilities are in good agreement with those recently reported by Richter,[16] *viz.* 1.61×10^6 sec^{-1} for N I 4935 Å and 0.63×10^6 sec^{-1} for N I 4915 Å. In addition to the scatter of the measurements indicated in Table I there are doubtless systematic errors in the absolute intensity measurements, in the theoretical H_β profiles, and in the assumption and treatment of thermodynamic equilibrium. The maximum uncertainty from these sources has been estimated as 30%.[10]

Conclusion

By means of Fourier curve fitting using analog computer techniques it is now possible to produce directly "homogeneous layer" recordings from a spectrometer viewing a cylindrically symmetric inhomogeneous arc or flame from the side. A comparison of the results of spectroscopic measurements using this computer with those using numerical techniques for inverting side-on observations shows no significant deterioration of accuracy through its use. The indicated difference between the two methods is about 4% with a standard error of about 5%. Consequently, where additional errors approaching this magnitude are tolerable the computer offers an extremely attractive solution to the time-consuming data handling and manipulation drawbacks of quantitative side-on arc and flame spectroscopy. A particularly promising area for its application is in the study of spectral line shapes which are obtained at best only with great labor using numerical side-on resolution procedures.

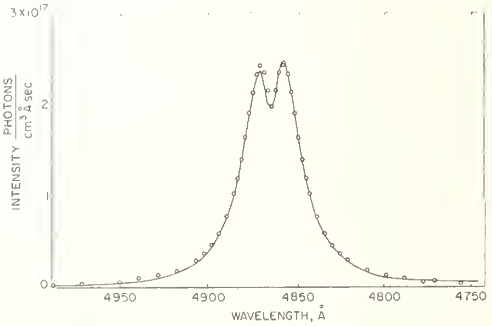


Fig. 6. Experimental H_β profile (curve) obtained by subtraction of the two spectra of Fig. 5 and theoretical points calculated for electron density = 7.3×10^{16} cm^{-3}, temperature = 12,130°K, and a hydrogen to nitrogen atomic ratio of 0.037.

References

1. H. Hörmann, Z. Physik **97**, 539 (1935).
2. R. N. Bracewell, Australian J. Phys. **9**, 198 (1956).
3. J. Friedrich, Ann. Physik **3**, (7), 327 (1959).
4. O. H. Nestor and H. N. Olsen, SIAM Rev. **2**, 200 (1960).
5. M. P. Freeman and S. Katz, J. Opt. Soc. Am. **50**, 826 (1960).
6. K. Bockasten, J. Opt. Soc. Am. **51**, 943 (1961).
7. S. I. Herlitz, Tech. Note No. 5, Inst. Phys. Univ. Upsala (1961).
8. W. L. Barr, J. Opt. Soc. Am. **52**, 885 (1962).
9. C. R. Yokley and J- B. Shumaker, Rev. Sci. Instr. **34**, 551 (1963).
10. W. L. Wiese and J. B. Shumaker, J. Opt. Soc. Am. **51**, 937 (1961).
11. H. Maecker, Z. Physik **158**, 392 (1960).
12. J. B. Shumaker, Rev. Sci. Instr. **23**, 65 (1961).
13. H. R. Griem, A. C. Kolb, and K. Y. Shen, Astrophys. J. **135**, 272 (1962).
14. J. B. Shumaker and W. L. Wiese, *Temperature, Its Measurement and Control in Science and Industry, Vol. III* (Reinhold, New York, 1962).
15. H. R. Griem, Phys. Rev. **128**, 997 (1962).
16. J. Richter, Z. Astrophysik **51**, 177 (1961).

Bibliography

Selected Bibliography January 1953 to December 1965

UNITED STATES DEPARTMENT OF COMMERCE • Luther H. Hodges, *Secretary*
NATIONAL BUREAU OF STANDARDS • A. V. Astin, *Director*

Bibliography of Temperature Measurement

January 1953 to June 1960

Compiled in Cooperation with
AE–2 Committee, Physical Measurement Sensing,
Society of Automotive Engineers

Carl Halpern and Robert J. Moffat

National Bureau of Standards Monograph 27

Issued April 6, 1961

447-I

Contents

Bibliography of Temperature Measurement

January 1953 to June 1960

Carl Halpern and Robert J. Moffat*

There are presented more than 500 references to the field of temperature measurement. These references were collected from two general sources: Scientific and technical literature and government reports. The period covered is from 1953 to June 1960, with some from earlier dates. For convenience of the user, the references are divided into a number of categories based on the type of instrument used. Some references to calibration of instruments and to scientific theories, on which temperature measurement is based, are also presented.

Introduction

The original version of this bibliography was compiled in 1957 by Robert J. Moffat of the Research Laboratories, General Motors Corporation, for the AE-2 Committee, Physical Measurement Sensing, of the Society of Automotive Engineers. Later, a Bibliography Subcommittee was formed to keep abreast of the current literature, and supplements have been compiled by Carl Halpern of the National Bureau of Standards. George E. Glawe of the Lewis Research Center, National Aeronautics and Space Administration; and John W. Fulton, Wright Air Development Division, U.S. Air Force, have also assisted in furnishing references. Because of the favorable response to and the continued demand for copies of the bibliography and its supplements, it was decided to issue it in a more permanent form for wider circulation.

The material contained herein was collected from two general sources: Scientific and technical journals, and reports of investigations sponsored or conducted by various governmental agencies. These latter are mostly distinguished as ASTIA or PB reports. ASTIA reports may be obtained from the Armed Services Technical Information Agency, Arlington Hall Station, Arlington 12, Va. PB reports designated as OTS may be obtained from Office of Technical Services, U.S. Department of Commerce, Washington 25, D.C.; those designated as LC may be obtained from the Library of Congress, Washington 25, D.C. Some agencies such as the National Advisory Committee for Aeronautics and its successor the National Aeronautical and Space Administration, Washington 25, D.C., issue their own reports.

The topical subdivisions are shown in the table of contents. Each subdivision is arranged chronologically and within the chronological sections, alphabetically by author. "Anonymous" articles appear at the end of each section. The period covered is from January 1953 to June 1960 with some earlier entries.

The journal abbreviations used are those employed in Chemical Abstracts. Volume numbers are in bold-faced type and the date of issue is given where page numbers do not run consecutively throughout a given volume. Since the year of issue appears at the head of each chronological section, this is not repeated in the individual references unless publication was in more than one year. References made to unpublished papers presented before various societies are designated by the abbreviation M.P.

---

*Research Laboratories, General Motors Corporation, Warren, Mich.

1. Thermoelectric Theory and Calibration

1948

Cullitz, B. D., The thermoelectric properties and electrical conductivity of bismuth-selenium alloys, Metals Technol. **15,** No. 1 (Jan.).

1952

Eatherly, W. P., and N. S. Rasor, Thermoelectric power of graphite, dependence on temperature type and neutron irradiation, U.S. Atomic Energy Comm. NAA–SR–196 (Nov.).

Tyler, W. W., and A. C. Wilson, Thermal conductivity, electrical resistivity, and thermoelectric power of titanium alloy RC–130–B, U.S. Atomic Energy Comm. KAPL 803 (Sept.).

1953

Corruccini, R. J., and H. Shenker, Modified 1917 reference table for iron/constantan thermocouples, J. Research Nat. Bur. Standards **50,** 229.

Domenicali, C. A., Irreversible thermodynamics of thermoelectric effects in inhomogeneous, anisotropic media, Phys. Rev. **92,** 877 (Nov. 15).

Holtan, H., Jr., P. Mazur, and S. R. De Groot, On the theory of thermocouples and thermocells, Physica **19,** 1109.

MacDonald, D. K. C., and S. K. Roy, Thermoelectric power of univalent metals at high temperature, Phil. Mag. **44,** 1364.

McSherry, P. B., Method for modifying the thermal emf/temperature characteristics of a constantan thermocouple, Iron Age **172,** 100 (Oct. 29).

Middleton, A. E., and W. W. Scanlon, Measurement of the thermoelectric power of germanium at temperatures above 78°R, Phys. Rev. **92,** 219 (Oct. 15).

Mortlock, A. J., The effect of tension on the thermoelectric properties of metals, Australian J. Phys. **6,** No. 4, 410 (Dec.).

Shoens, C. J., and J. W. Shortall, Thermoelectric calibration of zirconium-constantan and zirconium-Alumel thermocouples, U.S. Atomic Energy Comm. LRL 62 (Dec.).

1954

Domenicali, C. A., and F. A. Otter, Thermoelectric power and electron scattering in metal alloys, Phys. Rev. **95,** 1134 (Sept. 1).

Fuschillo, N., Inhomogeneity emfs in thermoelectric thermometers, J. Sci. Instr. **31,** No. 4, 133 (Apr.).

Herring, C., Theory of the thermoelectric power of semiconductors, Phys. Rev. **96,** 1163 (Dec. 1).

Mazur, P., Thermopotentials in thermocells, J. Chem. Phys. **58,** 700 (Sept.).

Patrick, L., and A. W. Lawson, Thermoelectric power of pure and doped AgBr, J. Chem. Phys. **22,** 1492 (Sept.).

Potter, R. D., Calibration of nickel-molybdenum thermocouples, J. Appl. Phys. **25,** No. 11, 1383 (Nov.).

Tauc, J., Theory of thermoelectric power in semi-conductors, Phys. Rev. **95,** 1394 (Sept. 15).

1955

Domenicali, C. A., and F. A. Otter, Thermoelectric power and electrical resistivity of dilute alloys of silicon in copper, nickel, and iron, J. Appl. Phys. **26,** 377 (Apr.).

Droms, C. R., and A. I. Dahl, Iridium versus iridium-rhodium thermocouples for gas-temperature measurements up to 3500° F, Proc. Joint Conf. Combustion (1955), p. 330.

Frederikse, H. P. R., and E. V. Mielczarerek, Thermoelectric power of indium antimonide, Phys. Rev. **99,** 1889 (Sept. 15).

Mooser, E., and S. B. Woods, Thermoelectric power of germanium at low temperature, Phys. Rev. **97,** 1721 (Mar. 15).

Parravano, G., Thermoelectric behavior of nickel oxide, J. Chem. Phys. **23,** 5 (Jan.).

Pearse, D. J., Electrical parasites hamper temperature measurement, Steel Processing **41,** No. 1, 22 (Jan.).

Rasor, N. S., Low temperature thermal and electrical conductivity and thermoelectric power of graphite, U.S. Atomic Energy Comm. NAA–SR–1061 (Jan.).

1956

Benel, H., Study of the thermoelectromotive force of unimetallic (thin Ag/thick Ag) and bimetallic (thin Ag/thick Cu or thick Ag/thin copper) couples as a function of the thickness of the thick branches, Rev. fac. sci. univ. Istanbul **21C,** 216.

Bodine, J. H., Jr., Hall coefficient and thermoelectric power of thorium metal, Phys. Rev. **102,** 1459 (June 15).

Cooper, H., et al., Thermoelectric power of AuCu in non-equilibrium states, J. Appl. Phys. **27,** 516 (May).

Goland, A. N., and A. W. Ewald, Thermoelectric power of gray tin, Phys. Rev. **104,** 948 (Nov. 15).

Kammer, E. W., Changes in thermoelectric power of copper with cold work at liquid nitrogen temperatures, Phys. Rev. **104,** 265 (Oct. 1).

Lepontre, G., and J. F. Dewald, Thermoelectric properties of metal-ammonia solutions, J. Am. Chem. Soc. **78,** 2953 (July 5).

Loebner, E. E., Thermoelectric power, electrical resistance and crystalline structure of carbons, Phys. Rev. **102,** 46 (Apr. 1).

Otter, F. A., Jr., Thermoelectric power and electrical resistivity of dilute alloys of Mn, Pd, Pt in Cu, Ag, Au, J. Appl. Phys. **27,** 197 (Mar.).

Price, P. J., Theory of transport effects in semi-conductors: thermoelectricity, Phys. Rev. **104,** 1223 (Dec. 1).

Price, P. J., Theory of transport effects in semi-conductors; the Nernst coefficient and its relation to thermoelectric power, Phys. Rev. **102,** 1245 (June 1).

Rudnitskii, A. A., and I. I. Tyurin, Study and selection of alloys for high-temperature thermocouples, Zhur. Neorg. Khim. **1,** 1074.

Taylor, J. C., and B. R.Coles, Thermoelectric powers in palladium-silver and palladium-rhodium alloys, Phys. Rev. **102,** No. 1, 27 (Apr. 1).

1957

Allen, L., Thermocouple reference voltage supply, Directorate of flight and all-weather testing, Wright-Patterson Air Force Base, Ohio, U.S. Air Force Wright Air Development Center, Tech. Note 57–364 (Oct.), PB 133211.

Bunch, M. D., and R. L. Powell, Calibration of thermocouples at low temperatures, Proc. Cryogenic Eng. Conf., Boulder **1957,** p. 269.

Domenicali, C. A., Thermoelectric power and resistivity of solid and liquid germanium in the vicinity of its melting point, J. Appl. Phys. **28,** 749.

Fisher, R. V., A typical problem in engineering—find the resistance values of a thermocouple-potentiometer circuit, Gen. Motors Eng. J. **5,** 58 (Apr.).

Ioffee, A., Thermoelectric and thermal properties of semiconductors, J. phys. radium **18,** 209 (Apr.).

Johnson, N. R., A. S. Weinstein, and F. Osterle, Influence of gradient temperature field on thermocouple measurement, PB 132585 (LC).

Kanclir, E., Calibration of thermocouple for differential thermal analysis, Chem. zvesti **11,**, 566.

Parravano, G., and C. A. Domenicali, Thermoelectric behavior of solid particulate systems; nickel oxide, J. Chem. Phys. **26,** 359 (Feb.).

Ubbelohde, A. R., and J. Orr, Anisotropic thermoelectric effects in graphite, Nature **179,** 193.

1958

Hatsopoulas, G. N., and J. H. Keenan, Thermoelectric effects and irreversible thermodynamics, J. Appl. Mech. **25,** 428.

Jan, J. P., W. P. Pearson, and I. M. Templeton, Thermoelectricity at low temperature, Can. J. Phys. **36,** 627.

Joffe, A. F., The revival of thermoelectricity, Sci. American **199,** 31 (Nov.).

Kammerer, E. W., Changes in thermoelectric power of silver and gold with cold work at liquid-nitrogen temperature, J. Appl. Phys. **29,** 1122.

Lachman, J. C., Calibration of rhenium-molybdenum and rhenium-tungsten thermocouples to 4000° F, U.S. Atomic Energy Comm. APEX–365.

Levin, G. M., and V. I. Vol'mir, Characteristic thermal inertia curves of conventional thermocouples and resistance thermometers, Measurement Techniques No. 6, 686.

Mortlock, A. J., Error in temperature measurement due to the interdiffusion at the hot junction of a thermocouple, J. Sci. Instr. **35,** 283 (Aug.).

Tsuji, M., Thermoelectric, galvanomagnetic, and thermomagnetic effects of univalent metals, J. Phys. Soc. Japan **13,** 133.

1959

Benedict, R. P., The calibration of thermocouples by freezing-point baths and empirical equations, Trans. Am. Soc. Mech. Engrs. (J. Eng. for Power) **81A,** 177.

Boerdijk, A. H., Contribution to a general theory of thermocouples, J. Appl. Phys. **30,** 1080 (July).

Donaldson, I. G., Temperature errors introduced by temperature measuring probes, Brit. J. Appl. Phys. **10,** 225 (June).

Lachman, J. C., Calibration of thermocouples to 4000° F, Instruments and Control Systems **32,** 1032 (July).

Timo, D. P., Thermocouple errors during temperature transients, Ind. Labs. **10,** 6 (June); 110 (Oct.).

1960

Almond, R. J., Errors in thermocouple circuits, Instruments and Control Systems **33,** 80 (Jan.).

Caldwell, F. R., L. O. Olsen, and P. D. Freeze, Intercomparison of thermocouple response data, S.A.E. M.P. 158F.

Scadron, M. D., Time response characteristics of temperature sensors, S.A.E. M.P. 158H.

Stauss, H. E., Thermoelectricity, PB 145603 (LC).

Wormser, A. F., Experimental determination of thermocouple time constants with use of variable turbulence, variable density wind tunnel, and analytic evaluation of conductance, radiation, and other secondary effects, S.A.E. M.P. 158D.

2. Thermoelectric Devices

1948

Wilhelm, H. A., et al., High temperature thermocouples, U.S. Atomic Energy Comm. AECD 3275 (June; reprint 1955).

1951

Boelter, L. M. K., and R. W. Lockhart, An investigation of aircraft heaters XXXV—thermocouple conduction error observed in measuring surface temperatures, Natl. Advisory Comm. Aeronaut. Tech. Note 2427.

1952

Miller, Edward S., and Paul L. Munter, Temperature probe recovery factor for B–1 free air temperature bulb on B–47 aircraft, ASTIA AD–7225 (Dec.).

Steven, G., and W. C. Troy, Development of temperature-sensing elements for jet engines, PB 122122 (LC); ASTIA AD–3562 (Apr.).

1953

Andrews, C. R., Capacitance welding technique for the installation of thermocouples, U.S. Air Force Wright Air Development Center Tech. Rept. 53–289, PB 134778 (LC).

Barnum, J. R., O. E. Buxton, J. M. Nau, and W. Robinson, Device for measurement of rotor hot-spot temperatures of aircraft generators by means of thermocouples, PB 128526 (LC); ASTIA AD–29 975 (Nov.).

Benedict, R. P., Thermocouples—their use and limitations, ASTIA AD–5672 (Jan.).

Clement, J. R., et al., Carbon-composition thermometers at very low temperatures, Rev. Sci. Instr. **24,** 545 (July).

Dallow, Thomas P., and John M. Davis, Flight tests to determine the temperature recovery factor and thermal response of several free air temperature probes, ASTIA AD–8246 (Mar.).

Fiock, Ernest F., and Andrew I. Dahl, Temperature measurements in high-velocity stream of hot gas, Proc. Iowa Thermodynamics Symposium (Apr.), State Univ. Iowa, Iowa City, Iowa, p. 190; ASTIA AD–70 705.

Fiock, Ernest F., and Andrew I. Dahl, The measurement of gas temperature by immersion-type instruments, J. Am. Rocket Soc. **23,** 155.

Potter, R. D., Open circuit thermocouples, Metal Progr. **64,** No. 5, 80 (Nov.).

Shepard, C. E., and I. Warshawsky, Electrical techniques for time lag compensation of thermocouples used in jet engines, Instruments **26,** 1725 (Nov.).

Simons, J. P., C. G. Hamstead, and E. J. Burton, Tungsten/molybdenum thermocouple for immersion pyrometry, J. Iron Steel Inst. (London) **175,** Part 4, 402 (Dec.).

Slater, C. H. W., Improvements in fine wire thermocouples, J. Sci. Instr. **30,** 293 (Aug.).

Sucher, Max, Leonard Sweet, and Herbert J. Carlin, The operation of bolometers under pulsed power conditions, ASTIA AD–16 893 (May).

Torgerson, Frederick A., Investigation of a thermocouple rake for measuring ramjet fuel/air distribution (Model Bomarc), ASTIA AD–66 221 (Oct.).

Werner, Frank D., Robert K. Keppel, and M. A. Bernards, Design and performance studies for improved multiple-shielded total temperature probes, ASTIA AD–27 727 (Apr.).

West, W. E., Jr., and J. W. Westwater, Radiation-conduction correction for temperature measurements in hot gases, Ind. Eng. Chem. **45,** No. 10, 2152 (Oct.).

1954

Benedict, R. P., Thermistors vs thermocouples for temperature measurements, Elec. Mfg. **54,** No. 2 (Aug.).

Chamberlain, H. H., Jet engine thermocouple averaging systems, Aero Dig. **69,** No. 6, 47 (Dec.).

Clayton, William H., Temperature measurements at Caplen Pier, ASTIA AD–47 740 (Aug.).

Ehringer, H., The life of Pt/Rh thermocouples, Metall **8,** 596 (Aug.).

Fiock, Ernest F., and Paul D. Freeze, Evaluation of exhaust-gas thermocouples and harness from a MIG–15 airplane, U.S. Air Force Wright Air Development Center Tech. Rept. 54–552 (July); ASTIA AD–59 641.

Glawe, G. E., and C. E. Shepard, Some effects of exposure to exhaust gas streams on emittance and thermoelectric power of bare-wire platinum rhodium-platinum thermocouples, Natl. Advisory Comm. Aeronaut. Tech. Note 3253.

Humphreys, J. D., Probe recovery factor, Instr. and Automation **27,** No. 2 (Feb.).

Krag, J., Improved needle thermocouple for subcutaneous and intramuscular temperature measurements in animals and man, Rev. Sci. Instr. **25,** No. 8, 799 (Aug.).

Kruithof, A. M., Some remarks on measurement of furnace temperatures by thermocouples, Philip's Gloeilampenfabrieken, Separaat 2209 (paper before Third Int. Congress on Glass).

Murphy, E. A., Theory and application of thermocouples, Heating Ventilating Mag. **51,** No. 2, 104 (Feb.).

Pearson, W. B., Thermocouples for use at low temperatures, J. Sci. Instr. **31,** No. 12, 444 (Dec.).

Rauch, W. E., Design and construction of needle thermocouples, Metal Progr. **65,** No. 3, 71 (Mar.).

Simmons, F. S., Recovery corrections for butt welded straight-wire thermocouples in high velocity, high temperature gas streams, Natl. Advisory Comm. Aeronaut. Research Mem. E54G22a.

Sims, L. G. A., Measurement of temperature by thermocouple and galvanometer, Engineering **177,** 180 (Feb. 5).

Sturm, W. J., and R. J. Jones, Applications of thermocouples to target temperature measurement in the internal beam of a cyclotron, Rev. Sci. Instr. **25,** 292 (Apr.).

Upton, D. E., Design for embedded thermocouple, Engineering **177,** No. 4603, 489 (Apr. 16).

Winkler, Eva M., Design and calibration of stagnation temperature probes for use at high supersonic speeds and elevated temperatures, J. Appl. Phys. **25,** 231 (Feb.).

Unique thermocouple, Mech. Eng. **76,** 518 (June).

1955

Barber, C. R., and L. H. Pemberton, Silver-palladium thermocouples, J. Sci. Instr. **32,** 486 (Dec.).

Benseman, R. F., and H. R. Hart, Thermocouple anemometer, J. Sci. Instr. **32,** 145 (Apr.).

Bollenger, L. E., Thermocouple measurements in R.F. field, J. Instr. Soc. Am. **2,** No. 9, 338 (Sept.).

Clark, J. A., Response of temperature measuring elements to thermal transients, Am. Soc. Mech. Engrs. M.P. 55SA18.

Dike, P. H., Thermoelectric thermometry 2d ed., Leeds and Northrup Co., Philadelphia, Pa.

Gordon, C. K., Jr., Comparison between air temperatures as measured by various shielded test thermocouples and a reference double-shielded aspirated thermocouple, ASTIA AD–80 593 (Aug.).

Huber, W. R., and L. G. Ekholm, Benefits derived from use of bath thermocouple, Proc. Am. Inst. Mining Eng. **38,** 57 (Apr.).

Jewell, R. C., E. G. Knowles, and T. Land, High temperature thermocouple, Metal Ind. (London) **87,** No. 11, 217, 221 (Sept. 9).

Kaufman, A. B., and P. R. Mitchell, How accurate are your reference temperature baths, Instr. and Automation **28,** No. 3, 450 (Mar.).

Kiernan, E. F., Preparation of copper-constantan thermocouples, J. Sci. Instr. **32,** 321 (Aug.).

Koletsky, Harold, A temperature indication system for exhaust gas, turbine-inlet and other engine temperatures, ASTIA AD–75 051 (July).

Ladt, M. A., Let's install thermocouple to measure tube temperature, Power **99,** No. 12, 118 (Dec.).

Lowell, Herman H., and Norman Patton, Response of homogeneous and two-material laminated cylinders to sinusoidal environmental temperature change, with applications to hot-wire anemometry and thermocouple pyrometry, Natl. Advisory Comm. Aeronaut. Tech. Note 3514 (Sept.); ASTIA AD–71 186.

Schenker, H., et al., Reference tables for thermocouples, Nat. Bur. Standards (U.S.) Circ. 561 (Apr.).

Spooner, N. F., and J. M. Thomas, Longer life for Chromel-Alumel thermocouples, Metal Progr. **68,** No. 5, 81 (Nov.).

Srikantiah, G., and A. Ramachandran, Temperature measurements in low velocity high temperature gas streams, J. Indian Inst. Sci., Sec. B **37,** No. 1, 41 (Jan.).

Stickney, T. M., Recovery and time response characteristics of 6 thermocouple probes in subsonic and supersonic flow, Natl. Advisory Comm. Aeronaut. Tech. Note 3455.

Wisely, H. R., Thermocouples for measurement of high temperatures, Ceram. Age **66,** No. 1, 15 (July).

Attaching thermocouples by capacitance welding, Naval Gun Factory Tech. Rept. NGF–T–21–55; PB 121901 (OTS).

Wire, electrical, Chromel and/or Alumel thermocouple, Notice 1, MIL–W–5846A, U.S. Department of Defense (Dec. 1).

Wire, electrical, copper and constantan thermocouple, Notice 1, MIL–W–5908B, U.S. Department of Defense (Dec. 14).

Wire, electrical, iron and constantan, thermocouple, Notice 1, MIL–W–5845A, U.S. Department of Defense (Dec. 1).

1956

Atkinson, P. G., Measurement of gas stream temperatures in industrial appliances, Gas Council (London), Research Comm. GC 33 (Nov.).

Benel, H., Thermoelectric couples made of several chemically different layers, Rev. fac. sci. univ. Istanbul **21C,** 272.

Betzenhowser, R. J., Thermocouples—these industrial watchdogs need testing and protecting, Plant Eng. **10,** No. 3, 116 (Mar.).

Corey, R. C., Measurement of gas temperature with thermocouples, Combustion **28,** No. 4, 47 (Oct.).

Engardt, N. N., Platinorhodium-platinum thermocouples made from purer materials, Izmer, Tekh. No. 2, 20.

Freeze, P. D., and F. R. Caldwell, Performance tests of jet engine thermocouples, U.S. Air Force Wright Air Development Center Tech. Rept. 56–476 (Aug.).

Glawe, G. E., F. S. Simmons, and T. M. Stickney, Radiation and recovery corrections and time constants of several Chromel-Alumel thermocouple probes in high temperature, high velocity gas streams, Natl. Advisory Comm. Aeronaut. Tech. Note 3766.

Guettel, C. L., New thermocouple for service in reducing atmospheres, Bull. Am. Soc. Testing Materials 64 (Sept.); Metal Progr. **69,** 89 (Apr.).

Haase, G., and G. Schneider, Investigation of thermocouples of the system iridium/rhenium, Z. Physik **144,** 256.

Hall, J. L., Temperature measurements in kilns, Calif. J. Min. **52,** 207.

Lacroix, R., Use of platinum metals in thermometry, Rev. met. **53,** 48.

Palmer, J. F., Jr., and R. S. Barnes, Modified thermocouple for peak exotherm measurement, Anal. Chem. **28,** 427 (Mar.).

Perrot, M., and G. Peri, On certain thermocouples, J. phys. radium **17,** 355 (June).

Reishaus, M., Temperature measurements in ceramic kilns, Sprechsaal **89,** 158 (Sept.).

Samal, E., The accuracy of temperature measurements with thermocouples in practice, Elektrotech. Z. **8B,** 199 (May).

Sawada, F. H., P. D. Freeze, C. J. Carter, and E. F. Fiock, Development and evaluation of ceramic coatings for thermocouples, U.S. Air Force Wright Air Development Center Tech. Rept. 56–135 (Mar.); ASTIA AD–97 495.

Shepard, R. L., H. S. Patten, and R. D. Westbrook, High-temperature boron-graphite thermocouple, Bull. Am. Phys. Soc. **1,** 119.

Stepka, F. S., and R. O. Hickel, Methods of measuring temperatures of thin walled gas turbine blades, Natl. Advisory Comm. Aeronaut. Research Mem. E56G17.

Wedell, T., Flue gas temperature measurements, Tek. Tidskr. **86,** 777.

Weise, E. K., and A. C. Hershberger, Simple thermocouple needle thermometer with high sensitivity, PB 119554 (LC) (Apr.).

Molten-metal pyrometer, Engineering **182,** 182 (Aug. 10).

Preparation and use of Chromel Alumel thermocouples for turbojet engines, Soc. Automotive Engrs. AIR #46.

Simple changes eliminate temperature errors, Elec. World **146,** 99 (Aug. 6).

Thermocouples, contact, aircraft engine spark plug gasket-type, MIL–T–5494A, U.S. Department of Defense (Nov. 28).

1957

Alexander, G. L., Development of subsonic and supersonic total temperature probes for a blow-down type wind tunnel, Texas U.D.R.L. Rept. 399 (AFOSR TN 57–(164), ASTIA AD–126 456 (June).

Bitler, W. R., Ling Yang, and G. Derge, Measurement of the thermoelectric power of a molten FeS-solid tungsten thermocouple, J. Appl. Phys. **28,** 514.

Chaston, J. C., Thermocouple for high temperatures. Advantages of the "Five-Twenty" couple, Platinum Metals Rev. **1,** 20 (Jan.).

Fuschillo, N., Low temperature scale from 4 to 300° K in terms of a gold-cobalt versus copper thermocouple, J. Phys. Chem. **61,** 644.

Glawe, G. E., and R. C. Johnson, Experimental study of heat transfer to small cylinders in a subsonic, high-temperature gas stream, Natl. Advisory Comm. Aeronaut. Tech. Note 3934.

Hett, J. H., Wedge thermocouples, NYU–TM3, PB 131862 (OTS).

Johnson, N. R., A. S. Weinstein, and F. Osterle, The influence of gradient temperature fields on thermocouple measurements, Abstract, Mech. Eng. **79,** 960; Am. Soc. Mech. Engrs.-Am. Inst. Chem. Engrs. Heat Transfer Conf. Paper No. 57–HT 18.

Kessler, R., The behavior of thermocouples in intermittent radiation under the influence of internally generated heat waves, Z. Angew. Phys. **9,** 408.

Kilpatrick, P. W., Accuracy of thermocouples in parallel, Instr. and Automation **30,** 1706 (Sept.).

Lodding, W., and E. Sturn, A new method of differential thermal analysis employing multiple thermocouples, Am. Mineralogist **42,** 78 (Jan.).

Moffat, R. J., How to specify thermocouple response, ISA Journal (June).

Murphy, A. H., and G. Stevens, Fast-response thermocouple using tubular hot-junction elements, Abstract, Mech. Eng. **79,** 879; Am. Soc. Mech. Engrs. Semi-Annual M.P. 57–SA–1.

Paludan, C. T. N., Thermocouple application for ballistic missiles, Missiles and Rockets **2,** 185 (Oct.).

Parize and Pignon, Measurement of temperatures by thermocouples in aeroplanes during flight, Tech. Sci. Aeronaut. No. 1, 15.

Reid, R. J., Fast response thermocouple, Electronic Design Mag. (July 1).

Tugarinow, N. I., G. S. Moskvichev, and A. A. Eremin, New design of tungsten-graphite thermocouple, Zavod. Lab. **23,** 92.

Vlasov, K. P., and N. V. Kokushkin, Temperature measurement of flowing gases in flames by means of thermocouples, Izvest. Akad. Nauk, S.S.S.R., Otdel-Tekh. Nauk, No. 8, p. 137.

Thermocouples for reducing atmospheres, Petrol. Engr. **29,** C34 (Aug.).

1958

Bennett, H. E., Noble metal thermocouples, 2d ed, Johnson, Matthey and Co., London.

Doyle, R. T., Metering gas with a heated thermopile, Instruments **30,** 2276.

Fischer, W. A., and G. Lorenz, Development of an oxide thermocouple, Arch. Eisenhüttenw. **29,** 293.

Gaylord, E. W., W. F. Hughes, F. C. Appl, and E. F. Ling, On the theoretical analysis of a dynamic thermocouple, Trans. Am. Soc. Mech. Engr. **80,** 307.

Haase, R., Thermocouples, Z. physik. Chem. (Frankfurt) **14,** 292.

Hunsinger, W., Temperature measurements with thermocouples, Arch. Tech. Messen **266,** 57.

Le May, J. L., More accurate thermocouples with percussion welding, ISA Journal **5,** 42 (Mar.).

Moffat, R. J., Designing thermocouples for response rate, Trans. Am. Soc. Mech. Engrs. **80,** 257.

Monteith, J. L., and P. C. Owen, Thermocouple method for measuring relative humidity in the range 95–100 percent, J. Sci. Instr. **35,** 443 (Dec.).

Seiner, J. A., Level measurement in frothing liquids with multiple thermocouple, Chem. Eng. **65,** 178 (May 19).

Shpigelman, E. S., Surface thermocouples, Measurement Techniques No. 6, 685.

Sitnik, G. F., Tungsten-tantalum thermocouple, Vestnik Moskov. Univ., Ser. Mat., Mekh., Astron., Fiz., Khim. **13,** No. 1, 86.

Solet, I. S., Elimination of cold-junction error in thermocouple measurements in electron tubes, Rev. Sci. Instr. **29,** 73 (Jan.).

Thomas, A. R., B. Schuren, and J. C. Morris, Temperature error associated with imbedded thermocouples, Rev. Sci. Instr. **29,** 1045 (Nov.).

Thermoelectric circuits and the performance of several current jet engine thermocouples, Soc. Automotive Engrs., AIR #65 (Aug. 1).

1959

Bennett, H. E., Care of platinum thermocouples, Glass Ind. **40,** 190 (Apr.).

Brühl, R., Measurements of temperature in wire drawing with a wire drawing die thermocouple using hard metal ball core, Wire and Wire Prod. **34,** 573 (May).

Carlson, J. F., Low-temperature-emf characteristics of Chromel-Alumel thermocouples, Ind. Heating **26,** 688.

Colclough, C. D., and J. Smillie, Welding fine thermocouple wires to large metal bodies, Engineer **208,** 696.

Deissinger, W. W., Accuracies of thermocouples on direct-fired heater tubes, ISA Journal **6,** 94 (Sept.).

Dutton, R., and E. C. Lee, Surface-temperature measurement of current carrying thermocouple circuit, ISA Journal **6,** 49 (Dec.).

Grover, G., Direct A-power electricity without using steam turbine; plasma thermocouple, Elec. Eng. **78,** 717 (June).

Grover, G. M., Los Alamos plasma thermocouple, Nucleonics **17,** 54 (July).

Lever, R. C., Better thermocouple alloys make 1800 C measurement feasible, S.A.E. Journal **67,** 48 (Oct.).

Lewis, H. W., and J. R. Reitz, Open-circuit voltages in the plasma thermocouple, J. Appl. Phys. **30,** 1833.

Moeller, C. E., Special thermocouple solves surface-temperature problem, ISA Journal **6,** 47 (June).

Moser, H., and P. Rahles, The Pt/Pt-Rh thermocouple in the international temperature scale, Procès-verbaux séances, Comité intern. poids et mesures, Ser. 2, **26A,** T78.

O'Conner, H., Thermocouple practice in ferrous foundry temperature control, Foundry **87,** 98 (July).

Okada, K., and H. Satone, Annealing of wires of standardized thermocouples, Procès-verbaux séances, Comité intern. poids et mesures, Ser. 2, **26A,** T211.

Penney, R. W., Developing a nomogram for differential temperatures in a thermocouple system, ISA Journal **6,** 75 (May).

Pidd, R. W., et al., Characteristics of a plasma thermocouple, J. Appl. Phys. **30,** 1861.

Pidd, R. W., Plasma thermocouple converts energy directly, Elec. Eng. **78,** 878 (Aug.).

Schubert, H. V., Immersion thermocouple practice, Iron Steel Eng. **36,** 91 (Jan.)

Shirakawa, Y., T. Ohara, and D. Amemiya, Thermocouples with nonlinear characteristics composed of iron-aluminum-chromium and copper-nickel alloys, Sci. Repts. Research Insts., Tohoku Univ., Ser. **A11,** 190.

Sims, C. T., G. B. Gaines, and R. I. Jaffee, Refractory metal thermocouples containing rhenium, Rev. Sci. Instr. **30,** 112 (Feb.).

Stoneburner, D. F., L. Yang, and G. Derge, Measurement of the thermoelectric power of several molten sulfide-solid-tungsten thermocouples, Trans. Am. Inst. Mining, Met. Petrol. Engrs. **215,** 879.

Terrell, O. D., Reduce errors in your temperature measurements, Power **103,** 190 (Aug.).

Ubbelohde, A. R., L. C. F. Blackman, and P. H. Dundas, A graphite/graphite thermocouple for high temperature, Chem. and Ind. (London) No. 19, 595 (May 9).

Mineral insulated thermocouples, Engineer **207,** 927 (June 12); Engineering **187,** 717 (May 29).

1960

Anderson, A. R., and D. J. MacKenzie, Materials for high (2500–4000 F) gas engine temperature measurements, S.A.E. M.P. 158B.

Carlson, J. F., Low temperature characteristics of Chromel-Alumel thermocouples, Instruments and Control Systems **33,** 98 (Jan.).

Clem, J. D., Jr., Development of a special thermocouple for measuring transient temperatures within a solid body, Rev. Sci. Instr. **31,** 334 (Mar.).

Davies, D. A., Two thermocouples suitable for measurement of temperatures up to 2800° C, J. Sci. Instr. **37,** 15 (Jan.).

Haig, L. B., Design procedure for thermocouple probes, S.A.E. M.P. 158C.

Hunt, M. H., Design and use of fine wire thermocouples for research, PB 144481 (LC).

Ihnat, M. E., and W. C. Hagel, A thermocouple system for measuring turbine-inlet temperatures, Trans. Am. Soc. Mech. Engrs. (J. Basic Eng.) **82D,** 81.

Kane, M. V., Thermocouple current indicators, Instr. and Control Systems **33,** 600 (Apr.).

Kaufman, A. B., Using thermocouples with non-standard reference temperatures, Instruments and Control Systems **33,** 106 (Jan.).

Kelly, D., Thermocouple temperature measurement without special instruments, Instruments and Control Systems **33,** 76 (Jan.).

Lachman, J. C., and F. W. Kuether, Stability of rhenium/tungsten thermocouples in hydrogen atmospheres, ISA Journal **7,** 67 (Mar.).

Meador, J. D., Dynamic testing of gas sampling thermocouples, S.A.E. M.P. 158G.

Potts, J. F., Jr., and D. L. McElroy, Basic studies on base-metal thermocouples, S.A.E. M.P. 158A.

Shaw, V. G., High temperature measurement—thermocouples, total radiation, brightness (optical) pyrometer and two-color pyrometer, Instruments and Control Systems **33,** 58 (Jan.).

Steven, G., and W. C. Troy, The mechanical protection of the W/Ir thermocouple, PB 138319, 138452, and 138456 (LC).

Wood, R. D., An experimental investigation of hypersonic stagnation temperature probes. Rept. on hypersonic research project, PB 144167 (LC).

Zysk, E. D., Developments on high temperature thermocouples using noble metals, Englehard Inds. Tech. Bull. **1,** 8 (June).

Metallic thermocouples for the measurement of temperatures above 1600° C, Metallurgia **61,** 141 (Mar.).

Still hotter horizons for thermocouples, Engineering **189,** 806.

Thermocouples for temperatures up to 2800° C, Engineering **189,** 122.

3. Resistance Devices

1950

Dahl, A. I., Kearfott temperature-sensing bulbs, PB 113066 (LC) (July).

1953

Muller, R. H., and H. J. Stolten, Use of thermistors in precise measurements of small temperature differences, Anal. Chem. **25,** 1103 (July).

Wright, G. M., Direct reading thermistor thermometer for aircraft use, PB 112649 (LC); ASTIA AD–21 947 (June).

1954

Benedict, R. P., Thermistors vs thermocouples for temperature measurements, Elec. Mfg. **54,** No. 2 (Aug.).

Dauphinee, T. M., and H. Preston-Thomas, Copper resistance temperature scale, Rev. Sci. Instr. **25,** 884 (Sept.).

Hutchinson, W. P., et al., Temperature control of a large water bath using a resistance thermometer, J. Sci. Instr. **31,** 420 (Nov.).

LeMar, R. L., Procedure for the use of the platinum resistance thermometer as a temperature standard, U.S. Arsenal, Rock Island, Ill. (June); PB 126455 (LC); ASTIA AD–39 464.

McLean, J. A., Method for constructing direct reading thermistor thermometers, J. Sci. Instr. **31,** No. 12, 455 (Dec.).

Piccard, J., H. Larsen, and J. Blomstrand, Thin wire thermometer for radiosondes, Rev. Sci. Instr. **25,** 959 (Oct.).

Sias, F. R., et al., Tungsten resistance thermometer, Elec. Eng. **73,** 442 (May).

Sims, L. G. A., Measuring fine temperature changes, Engineering **177,** 15 (Jan. 1).

Tellerman, J., Measuring transistor temperature rise, Electronics **27,** 185 (Apr.).

Wisely, H. R., P. D. Freeze, and E. F. Fiock, Study of thermistor materials for use as temperature-sensing elements in the high-velocity exhaust gases of jet-type engines, U.S. Air Force Wright Air Development Center Tech. Rept. 54388 (Nov.); PB 122463 (LC).

Woods, R. W., Thermistor electronic thermometer, Science **121,** 337 (Mar. 4).

1955

Barber, C. R., Platinum resistance thermometer for use at low temperatures, J. Sci. Instr. **32,** 416 (Nov.).

Muller, R. H., Resistance thermometer, instrument for determining freezing point, Anal. Chem. **27,** S 33A (Dec.).

Rounthwaite, C., Double wire method of resistance thermometry in gaseous explosions, Fuel **34,** S 59 (Apr.).

White, A. G., Transistor as a thermometer, J. Sci. Instr. **32,** 451 (Nov.).

Winding, C. C., L. Topper, and B. V. Baus, Metal film resistance thermometers for measuring surface temperatures, Ind. Eng. Chem. **47,** 386 (Mar.).

1956

Beck, A., Stability of thermistors, J. Sci. Instr. **33,** 16 (Jan.).

Benson, G. W., The use of thermistors in precision thermometry, Nat. Research Council Can. Rept. MI–817 (Oct. 22).

Blackburn, G. F., P. D. Freeze, and F. R. Caldwell, A study of thermistor materials for use as temperature sensing elements in the high velocity exhaust gases of jet-type engines, U.S. Air Force Wright Air Development Center Tech. Rept. 54–388, Supplement No. 1 (Apr.).

Cole, G. H., Transistorized indicator measures jet exhaust, Electronics **29,** 143 (Dec.).

Cole, G. H., Transistors are now measuring heat of exhaust in jet engines, Midwest Engr. **8,** 14 (Apr.).

Parkinson, D. H., and L. M. Roberts, A resistance thermometer for use at helium temperatures, Proc. Phys. Soc. (London) **B68,** 386.

Rabinowicz, J., and others, Resistance thermometer for transient high temperature studies, J. Appl. Phys. **27,** 97 (Jan.).

Simpson, T. B., and C. C. Winding, Properties of evaporated metal films related to their use for surface temperature measurement, A.I.Ch.E. Journal **2,** No. 1 (Mar.).

Bulbs, electrical resistance type thermometry −70° to +150° C, Notice 1, MIL–B–5495, U.S. Department of Defense (Oct. 15).

1957

Badgley, F. I., Response of radiosonde thermistors, Rev. Sci. Instr. **28,** 1079.

Belfield, W., and R. W. Johnson, Thermistor probe, J. Sci. Instr. **34,** 209.

Cole, Kenneth S., Thermistor thermometer bridge: Linearity and sensitivity for a range of temperature, Rev. Sci. Instr. **28,** No. 5 (May).

Kunzler, J. E., et al., Germanium resistance thermometers suitable for low-temperature calorimetry, Rev. Sci. Instr. **28,** 96 (Feb.).

Markham, A. H., R. G. Nitzel, and J. R. Dillinger, Carbon resistor thermometry below 1° K, Rev. Sci. Instr. **28,** No. 5, 382 (May).

Mason, G. L., A fast-response resistance thermometer system for simultaneous recording of air temperature at a number of separated points, Bull. Am. Meteorol. Soc. **38,** 391.

Sachse, B., Missile research points to low resistance thermistors as ultra-cold thermometers, Electronic Inds. Tele-Tech. **16,** 55 (Jan.).

Seiden, P. E., Wide-range thermistor vacuum gage, Rev. Sci. Instr. **28,** 657.

Trey, F., Resistance thermometers from semi-conductors, Radex Rundschau, No. 2, 519.

White, G. K., and S. B. Woods, Indium resistance thermometer, 4 to 300° K, Rev. Sci. Instr. **28,** 638 (Aug.).

Wisely, H. R., An exhaust gas temperature thermistor body for the range 1500° F to 3500° F, U.S. Air Force Wright Air Development Center Tech. Rept. 57–27 (Jan.); ASTIA AD–110 722.

Types and applications of thermistors, Machine Design **29,** 178 (Dec. 12).

1958

Anderson, J. C., Temperature measurement with thermistors, Electronic and Radio Eng. **35,** 80 (Mar.).

Blake, C., et al., Resistance thermometer bridge for measurement of temperatures in the liquid helium range, Rev. Sci. Instr. **29,** 715 (Aug.).

Broom, R. F., Low-temperature resistance thermometer using p-type gallium arsenide, J. Sci. Instr. **35,** 467 (Dec.).

Goodwin, R. D., Design of simple resistance thermometer bridges for wide-range control of low temperatures, Rev. Sci. Instr. **29,** 497 (June).

Loffler, H. J., and H. Henrici, Measurement of surface temperatures with vapor-deposited resistance thermometer, Chem. Ingr. Tech. **30,** 708.

Melville, A. W., High stability mains-operated recording thermistor thermometer, J. Sci. Instr. **35,** 179 (May).

Senin, V. S., Experience in measuring the temperature of liquids by means of thermistors, Measurement Techniques No. 6, 683.

Soble, A. B., Thermistors for linear temperature readings, Electronic Ind. **17,** 66 (Nov.).

White, G. K., S. B. Woods, and F. Anglin, Indium resistance thermometer, Rev. Sci. Instr. **29,** 181.

Zima, G. E., Introduction to a resistance thermometric method and qualitative metallic probe technique for rocket motor combustion analysis, CIT JPL 9–18; PB 130851 (LC).

Germanium resistance thermometer, Bell Labs. Record **36,** 261 (July).

Germanium resistance thermometer, Elec. Eng. **77,** 660 (July).

Germanium resistance thermometer, Mech. Eng. **80,** 92 (June).

Low temperature resistance thermometer, Elec. Mfg. **61,** 9 (May).

Temperature measurements at absolute zero, germanium resistance thermometer, Electronics **31,** 84 (Apr. 25).

Tiny resistance thermometer made of germanium crystal, Machine Design **30,** 14 (May 15).

1959

Jason, A. C., and A. Lees, Resistance thermometer spear for field measurement, J. Sci. Instr. **36,** 272 (June).

Marrone, P. V., and R. A. Hartunian, Thin-film thermometer measurements in partially ionized shock tube flows, Phys. Fluids **2,** 719.

Paterson, W. L., Chart gives thermal changes of thermistors, Electronics **32,** 128 (Oct. 23).

Pies, J. R., New semiconductor for temperature measuring sensistor resistors, ISA Journal **6,** 50 (Aug.).

Plumb, H. H., and M. H. Edow, Constant temperature liquid helium bath and reproducibility of resistance thermometers, Rev. Sci. Instr. **30,** 376 (May).

Price, R., The platinum resistance thermometer, J. Am. Soc. Naval Engrs. **71,** 729.

Sachse, H. B., Thermistors—10–600° K, Electronic Ind. **18,** 81 (Oct.).

Stewart, J. W., Application of indium resistance thermometry, Rev. Sci. Instr. **30,** 949 (Oct.).

High-temperature resistance thermometry, Metal Progr. **76,** 205A (Dec.).

Thermistor thermometer picks out hot spots in drill holes, Eng. Mining J. **160,** 120 (Oct.).

1960

Atkins, R. M., Temperature measurements with thermistors, Inst. Control Systems **33,** 86 (Jan.).

Rabinowicz, J., and M. E. Jessey, Resistance thermometer for heat transfer measurements in a shock tube, PB 128006 (LC).

Weise, E. K., Alignment chart for the resistance-temperature characteristics of thermistors, PB 133644 (LC).

4. Radiation Devices

1953

Brown, D. A. H., et al., Construction of radiation thermocouple using semi-conducting thermoelectric materials, J. Sci. Instr. **30,** 195 (June).

Burton, E. J., Recent advances in radiation and immersion pyrometry, Instruments **26,** 1524 (Oct.).

Dike, P. H., Temperature measurements with rayotubes, Leeds and Northrup Co., Philadelphia, Pa.

Heidman, M. F., and R. J. Priem, Application of an electro-optical two color pyrometer to measurement of flame temperature for liquid oxygen-hydrocarbon propellant combination, Nat. Advisory Comm. Aeronaut. Tech. Note 3033; PB 112259.

Herne, H., Theoretical characteristics of bichromatic pyrometers, Brit. J. Appl. Phys. **4,** No. 12, 374 (Dec.).

Johnson, I., High temperature radiation galvanometer, PB 114558 (LC) (Aug.).

Millar, G. H., et al., Fast, electro-optical, hot gas pyrometer, J. Opt. Soc. Am. **43,** 609 (July).

Radiamatic pyrometers, Mech. Eng. **75,** 729 (Sept.).

1954

Carte, A. E., Standard optical pyrometer, S. African J. Sci. **51,** No. 5, 136 (Dec.).

Londeree, J. W., Jr., Photographic pyrometry, J. Am. Ceram. Soc. **37,** 354 (Aug. 1).

Probene, M. C., and S. Bertaud, Notes on selection of observers for primary standard optical pyrometry, Brit. J. Appl. Phys. **5,** No. 6, 227 (June).

Pyatt, E. C., Some considerations of errors of brightness and two color types of spectral radiation pyrometer, Brit. J. Appl. Phys. **5,** No. 7, 254 (July).

Sims, R. B., and J. A. Place, Surface scanning pyrometer, J. Sci. Instr. **31,** No. 8, 293 (Aug.).

Stoll, A. M., Wide range thermistor radiometer for the measurement of skin temperature and environmental radiant temperature, Rev. Sci. Instr. **25,** 184 (Feb.).

Strong, H. M., and F. P. Bundy, Measurement of temperatures in flames of complex structure by resonance line radiation, J. Appl. Sci. **25,** No. 12, 1521 (Dec.).

Trout, H. E., Jr., Optical pyrometers, their functioning and maintenance, Steel Processing **40,** No. 4, 237 (Apr.).

Optical measurement of temperature, Can. Chem. Processing **38,** 66 (Jan.).

1955

Bond, T. E., and C. F. Kelly, Globe thermometer in agricultural research, Agr. Eng. **36,** No. 4, 251 (Apr.).

Bracewell, R. A., Infrared radiation pyrometer, Electronic Eng. **27,** No. 328, 238 (June).

Elonka, S., Now you can measure heat quickly—at a safe distance, Power **99**, No. 12, 116 (Dec.).

Garrison, J. L., Direct measurement of induction heat temperatures with L and N rayotube detector, Metal Treating **6**, No. 4, 28 (July-Aug.).

Harmer, J. D., and B. N. Watts, Infrared radiation pyrometer, J. Sci. Instr. **32**, 167 (May).

Hett, J. H., and J. B. Gilstein, Indicated instantaneous temperatures of liquid rocket exhausts and combustion chambers, Jet Propulsion **25**, No. 2, 119 (Feb.).

Kratz, J. H., Radiation pyrometer, J. Franklin Inst. **259**, 362 (Apr.).

Land surface pyrometer, Instr. and Automation **28**, 1952 (Nov.).

Milliscope pyrometer, Automobile Engr. **45**, No. 10, 437 (Oct.).

New infrared pyrometers determine temperatures at a distance, Ind. Eng. Chem. **47**, S 7A (Aug.).

Portable pyrometer, Mech. Eng. **77**, 900 (Oct.).

Pyrometer aids jet engine control, Aviation Week **63**, 80 (Aug. 8).

1956

Buchele, D., Self-balancing line-reversal pyrometer, Natl. Advisory Comm. Aeronaut. Tech. Note 3656; PB 123515.

Chion, R., Radiation pyrometers for the measurement of transient temperatures, Metaux-Corrosion-Inds. **31**, 23 (Jan.).

Derganc, W., and S. N. Howell, Two new total radiation pyrometers, Elec. Eng. **75**, 697 (Aug.).

Gergen, J. L., Black ball: A device for measuring atmospheric infrared radiation, Rev. Sci. Instr. **27**, 453 (July).

Godridge, A. M., Photoconductive cells for use in radiation pyrometry, Bull. Brit. Coal Utilisation Research Assoc. **20**, 349 (Sept.).

Kostkowski, H. J., and H. P. Broida, Spectral absorbtion method for determining population temperatures in hot gases, J. Opt. Soc. Am. **46**, 246 (Apr.).

Meyers, V. W., W. D. Walker, and H. S. Stewart, Theory of the behavior of bolometers cooled by gaseous conduction, PB 122757 (LC) (Sept.).

Naeser, G., Improved two color pyrometer and its use, Stahl u. Eisen **76**, 968.

Shpiegelman, E. S., Novyi metod posroeniia shkaly opticheskikh pirometrov v oblasti temperaturi vishe 3000° C, Izmer. Tekh. **1**, 37 (Nov.).

Smit, R., Influence of humidity on measurements with radiation pyrometers, Appl. Sci. Research, Sec. B, **5**, No. 6, 428.

Vollmer, J., et al., High speed radiation pyrometer, J. Opt. Soc. Am. **46**, 77 (Feb.).

Mapping surface temperatures; Baird Associates Evaporograph gives a direct thermal picture, Chem. Eng. News **34**, 1022 (Feb. 27).

1957

Benarie, M. M., Optical pyrometry below red heat, J. Opt. Soc. Am. **47**, 1005.

Ricker, C. W., et al., Development of radiation pryometry techniques for measurement of temperature during rolling of uranium, Metal Progr. **71**, 148 (Apr.).

Snelleman, W., and J. A. Smit, Photoelectric measurement of flame temperatures by line reversal, Spectrochim. Acta **11**, 44.

Sobelov, N. N., and F. S. Faizullov, Photoelectric pyrometer for the measurements of color temperature of flames, Optika i. Spektroskopiya **3**, 162.

1958

Birnstingle, D. W., Transitor operated self-balancing radiation pyrometer, Electronic Eng. **30**, 189 (Apr.).

Brenden, B. B., and H. W. Newkirk, Multicolor pyrometer, U.S. atomic Energy Comm. HW-57162 Rev.

Brombeck, W. M., R. E. Clemensen, and W. E. Voreck, A recording sodium-line reversal pyrometer, Jet Propulsion 28, 249.

Clouston, J. G., A. G. Gaydon, and I. I. Glass, Temperature measurements of shock waves by spectrum-line reversal method, Proc. Roy. Soc. (London) **A252**, 429 (Dec. 9).

Crabol, J., and J. Van Kote, Infrared pyrometer for measuring temperatures of turbine blades, Recherche Aeronaut. No. 66 (Sept.).

Davies, M. G., and H. Kronberger, Full radiation pyrometer suitable for temperature measurements in the range 0° to 100° C, AERE GP/R 272, PB 135020.

Euler, J., Higher adjusting accuracy with filament pyrometers with contrast plates, Optik **15**, 372.

Hariharan, P., and M. S. Bhalla, Precision, direct-reading color temperature meter, J. Sci. Instr. **35**, 499 (Dec.).

Kovalerskii, V. A., and L. A. Boiarskii, Objective spectropyrometer SPK-2, Measurement Techniques No. 6, 680.

Lovejoy, D. R., Accuracy of optical pyrometry in the range 800° to 4000°, Can. J. Phys. **36**, 1397.

Mullaney, G. J., Temperature determination in flames by X-ray absorption using a radioactive source, Rev. Sci. Instr. **29**, 87 (Feb.).

Murray, T. P., and V. G. Shaw, Two-color pyrometry in in the steel industry, ISA Journal **5**, 36 (Dec.).

Ritchey, B. B., Measure fabric temperature with a radiation pyrometer, Textile World **108**, 89 (June).

Tingwaldt, C., and H. Kuz, The attainment of black-body radiation at the gold and silver points for pyrometric temperature measurements, Optik **15**, 333.

Tourin, R. H., and M. Grossman, Note on monochromatic radiation pyrometer for measuring flame and exhaust gas temperature, Combustion and Flame **2**, 330.

1959

Blum, N. A., Recording optical pyrometer, Rev. Sci. Instr. **30**, 251 (Apr.).

Brenden, B. B., and H. W. Newkirk, Improved recording multicolor pyrometer, U.S. Atomic Energy Comm. HW-60678.

Clouston, J. B., A. G. Gaydon, and I. R. Hurtle, Temperature measurements of shock waves by spectrum-line reversal, Proc. Roy. Soc. (London) **A253**, 143 (Sept.).

Enslie, A. G., and H. H. Blau, Jr., Measurement of the temperatures of unenclosed objects by radiation methods, J. Electrochem. Soc. **106**, 877 (Oct.).

Finkelshtein, V. E., and V. V. Kandyba, Standardization of optical pyrometers, Procès-verbaux séances, Comité intern. poids et measures, Ser. 2, **26A**, T142.

Gillham, E. J., Measurement of optical radiation, Research **12**, 404 (Oct.).

Glaser, P. E., and H. H. Blau, Jr., A new technique for measuring the spectral emissivity of solids at high temperatures, Trans. Am. Soc. Mech. Engrs. (J. Heat Transfer) **81C**, 92.

Gluiberzon, M. E., Fast-acting photoelectric pyrometer, Metallurg. **4**, No. 5, 25.

Kirenkov, I. I., Metrological features of color pyrometry, Measurement Techniques No. 1, 33.

Moutet, A., C. Veret, and L. Nadaud, Optical method of measuring the instantaneous temperature of flames, Recherche Aeronaut. No. 68, 9 (Jan.).

Wagenbreth, H., Temperature of a black-body radiator at the Au point, Procès-verbaux séances, Comité intern. poids et mesures, Ser. 2, **26A**, T123.

Auto-optic recording pyrometer, J. Franklin Inst. **267**, 464 (May).

New radiation pyrometer: temperature measurement in induction hardening, Metallurgia **59**, 86 (Feb.).

Radiation pyrometer for foundry measurements, Engineer **207**, 189 (Jan. 30).

1960

Harrison, T. R., Radiation pyrometry and its underlying principles of radiant heat transfer, John Wiley & Sons, Inc., New York, N.Y.

Rossler, F., Measurements of flame temperatures, Z. Erzbergbau u. Metallhüttenw. **13**, 74.

Tingwaldt, C., A simple optical-pyrometric method for the direct measurement of the true temperature of incandescent metals, Z. Metallk. **51,** 116.

Infrared pyrometer reads engine gas temperature to ±20 deg R, S.A.E. Journal **68,** 76 (June).

5. Expansion Devices

1953

Ackman, A. R., J. McMillan, and A. W. Morrison, Static and dynamic performance of sheathed industrial thermometers, Trans. Soc. Instr. Tech. **5,** No. 4, 138 (Dec.).

1954

Faust, F. A., Selection of filled system thermometers, Oil Gas J. **53,** 131 (May 17).

Freeze, P. D., and E. F. Fiock, Evaluation of a differential-expansion temperature sensing device based on critical flow through a variable orifice, U.S. Air Force Wright Air Development Center Tech. Rept. 54–567 (June); PB 119204 (LC).

Muller-Girard, O., Dynamics of filled temperature measuring systems, Am. Soc. Mech. Engrs. M.P. 54–SA–29.

Smith, L. E., Operation of filled system thermometer, Refrig. Eng. **62,** No. 11, 40 (Nov.).

Stokes, K. H., and R. C. Whitehead, Ambient temperature errors in gas-filled thermal system for pneumatic-balance instruments, Am. Soc. Mech. Engrs. M.P. 54–A–159.

Industrial filled system thermometers, Mech. World **134,** No. 3420, 306 (July).

1955

Linahan, T. C., Dynamic response of industrial thermometers in walls, Am. Soc. Mech. Engrs. M.P. 55–SA–52.

1957

Moser, H., J. Otto, and W. Thomas, High temperature with gas thermometer. I. New gas thermometer method, Z. Physik **147,** 59.

1958

Hall, J. A., and V. M. Leaver, Emergent column correction in mercury thermometry, J. Sci. Instr. **35,** 93 (Mar.).

Martin, W. I., S. S. Grossman, and J. J. McGovern, Calibration drift of mercury thermometers repeatedly cooled to −30°, Am. Soc. Testing Materials Bull. No. 231, 62.

Van Dijk, S., et al., Influence of rate of cooling on the zeros of mercury-in-glass thermometers, J. Sci. Instr. **35,** 334 (Sept.).

1960

Solomons, C., and G. J. Janz, A recording Beckman thermometer and differential potentiometer, AFOSR Tech. Note 57–497, ASTIA AD–136 487; PB 129942 (LC).

6. Aspirated Devices

1951

Lalos, George T., A sonic-flow pyrometer for measuring gas temperatures, J. Research Natl. Bur. Standards **47,** No. 3, 179 (Sept.).

1952

Ruskin, R. E., R. M. Schecter, and others, Development of the NRL Axial-flow vortex thermometer, ASTIA AD–16 694 (Sept.).

Scadron, Marvin D., Analysis of a pneumatic probe for measuring exhaust gas temperature with some preliminary experimental results, Nat. Advisory Comm. Aeronaut. Research Mem. E52A11.

Skelly, E. T., Study to determine characteristics of a vortex type temperature probe, ASTIA AD–625.

1953

Packer, L. S., and Harold C. Box, Vortex free air thermometer, ASTIA AD–38 659.

1954

Cochran, Roy J., Flight tests of two experimental vortex true free air temperature systems, ASTIA AD–29 357 (Mar.).

Land, T., and R. Barber, Design of suction pyrometers, Trans. Soc. Instr. Tech. **6,** No. 3, 112 (Sept.).

1955

Beneke, Jack, Development of a miniature vortex free-air thermometer, ASTIA AD–84 572 (Nov.).

Godridge, A. M., R. Jackson, and G. G. Thurlow, Small pneumatic pyrometer, J. Sci. Instr. **32,** No. 7, 279 (July).

Owens, G. V., Cloud physics research, investigation of the characteristics of a tangential flow vortex thermometer housing, PB 119443 (LC) (Aug.).

Willshire, D. W., An investigation of the time response of the N.G.T.E. sonic pyrometer, ASTIA AD–91 926 (Nov.).

The vortex tube as a true free air thermometer. Symposium held May 24, 1955 at Armour Research Foundation, Chicago, Illinois, ASTIA AD–90 398 (May).

1956

Glawe, G. E., and F. S. Simmons, Theory and design of a pneumatic temperature probe and experimental results obtained in a high temperature gas stream, Natl. Advisory Comm. Aeronaut. Tech. Note 3893 (Oct.).

Havill, C. D., and L. S. Rolls, A sonic-flow orifice probe for the in-flight measurement of temperature profiles of a jet engine exhaust with afterburning, Natl. Advisory Comm. Aeronaut. Tech. Note 3714; ASTIA AD–93 401.

Land, T., Suction pyrometry, Instr. and Automation **29,** 1314 (July).

Land, T., and R Barber, Suction pyrometers in theory and practice, J. Iron Steel Inst. **184,** Part 3, 269 (Nov.).

Maulard, J., Standardizing equipment for sonic suction pyrometer, Recherche Aeronaut. No. 49, 27 (Jan.–Feb.).

1957

Barber, R., et al., Suction pyrometer for open-hearth furnace uptakes, J. Iron Steel Inst. **185,** 343 (Mar.).

Coldren, C. L., and E. W. Comings, Pneumatic thermometer and hygrometer, Chem. Eng. Progr. **53,** 403.

Engstrom, R., An air cooled suction pyrometer, Tek. Tidskr. **87,** 531.

Glawe, G. E., A high-temperature combination sonic aspirated thermocouple and total-pressure probe, Jet Propulsion **27,** 543 (May).

Kuhns, P. W., Effects of thermal relaxation and specific-heat changes on measurements with a pneumatic-probe pyrometer, Natl. Advisory Comm. Aeronaut. Tech. Note 4026.

Riviere, M., G. Urbain, and R. Kissel, Suction pyrometers, Chaleur et Ind. **38,** 318.

Thurlow, G. G., Venturi pneumatic pyrometer, Coke and Gas **19,** 201.

Urbain, G., and R. Kissel, Aspiration pyrometers, Chaleur et Ind. **38,** 389 (Dec.).

1958

Godridge, A. M., et al., Venturi pneumatic pyrometer, J. Sci. Instr. **35,** 81 (Mar.).

The measurement of gas stream temperatures in industrial appliances. II. A suction pyrometer for temperatures above 1100° C, Gas Council (Gt. Brit.), Research Commun. GC 57.

1960

Holland, R. E., R. Jackson, and G. C. Thurlow, Behavior of the venturi pyrometer in industrial furnaces, J. Inst. Fuel **33,** 180.

7. Other Methods, Descriptive Articles

1953

Ambrosio, A., and B. Bussell, Temp-tapes: improved design, construction, and calibration, U.S. Air Force Wright Air Development Center Tech. Rept. 53–211; PB 134779 (LC); ASTIA AD–27 589.

Cowling, J. E., P. King, and A. L. Alexander, Temperature indicating paints, Ind. Eng. Chem. **45**, No. 10, 2317 (Oct.).

Hanes, F. S., Jr., Measurement of temperature in explosives, PB 114023 (LC), (Aug.).

Harris, Franklin S., Jr., The measurement of temperature in explosives, ASTIA AD–19 028 (Aug.).

Miller, Paul, Method of measuring surface temperatures in vacuo, ASTIA AD–14 711(b).

Monroe, A. G., and H. A. S. Bristow, Method of measuring the temperature at the surface of a metal tube, J. Sci. Instr. **30**, 385 (Oct.).

Potter, Richard D., Phase equilibria studies, a modified method of temperature measurement, ASTIA AD–13 186 (Apr.).

1954

Eastman, Lester F., Measurement of cathode temperature using a retarding potential device, ASTIA AD–57 888(b) (Oct.).

Hoffman, Charles W., Investigations of temperature-distributions on rocket motors and launchers: Some phosphor methods, ASTIA AD–41 518.

Hogue, E. Walters, Factors affecting the precision and accuracy of an absolute noise thermometer, ASTIA AD–46 864 (July).

Kuhns, P. W., Determination of flame temperatures from 2000 to 3000° R by microwave absorption, Natl. Advisory Comm. Aeronaut. Tech. Note 3254.

Livengood, J. C., T. P. Rona, and J. J. Baruch, Ultrasonic temperature measurement in internal combustion engine chamber, J. Acoust. Soc. Am. **26**, No. 5, 824 (Sept.).

Lucier, John J., Measurement of peak temperatures with thermal sensitive indicators, ASTIA AD–47 530 (June).

Schweitzer, T. J., R. Kadesch and others, Measurement of compression temperatures in spark-ignition engines, ASTIA AD–52 637 (Aug.).

Tell-tale colors make temperature visible, Steel **135**, No. 19, 105 (Nov. 8).

1955

Tyroler, Jesse F., Bibliography of methods of measuring the temperature of pyrotechnic flames, ASTIA AD–68 346 (July).

Instantaneous temperature measurements: the development of methods for measuring end-gas temperatures in internal combustion engines, ASTIA AD–78 600.

Yes, you can now use paper thermometers, Safety Maintenance and Production **110**, 534 (July).

1956

Dehn, R., new method for measurement of rapid fluctuations of temperature, Brit. J. Appl. Phys. **7**, No. 4, 144 (Apr.).

Wolten, G. M., Power engineering handbook; temperature by chemical signal, Power Eng. **60**, 96 (May).

First report, high pressure research (Noise thermometer), PB 120667 (LC) (June).

Second report, high pressure research (Noise thermometer), PB 120668 (LC) (June).

1957

Edels, H., and D. Whittaker, The determination of arc temperatures from shock velocities, Proc. Roy. Soc. (London) **A240**, 54.

1958

Gibson, F. C., M. L. Bowser, et al., Use of an electro-optical method to determine detonation temperatures in high explosives, J. Appl. Phys. **29**, 628.

Hoenig, S. A., Use of a constant current hot wire for the measurement of extreme temperatures, Rev. Sci. Instr. **29**, 704 (Aug.).

Koch, W., and D. Kaplan, Rhodium-plated katathermometer for measuring true air velocity, J. Sci. Instr. **38**, 8 (Jan.).

Livengood, J. C., C. F. Taylor, and P. C. Wu, Measurement of gas temperature in an engine by the velocity of sound method, S.A.E. Trans. **66**, 683.

Savet, P. H., On a stationary temperature separating device used as a measuring and cooling/heating apparatus, Abstract, Mech. Eng. **80**, 110 (June).

Scott, D. S., Measure gas temperature with a flow meter, Chem. Eng. **65**, 161 (Nov.).

Simmons, F. S., and A. G. De Bell, Photographic technique for measuring temperatures in luminous rocket exhaust flames, J. Opt. Soc. Am. **48**, 717.

Stow, R. W., Rapid high-sensitivity recording thermometer, Rev. Sci. Instr. **29**, 774 (Sept.).

Film tells flame temperature, Chem. Eng. **65**, 64 (Jan.).

1959

Cammerer, J. S., Measurement of temperatures and heat quantities by electronic counters, Allgem. Wärmtech. **9**, 49.

Fink, H. J., A new absolute noise thermometer at low temperatures, Can. J. Phys. **37**, 1397.

Mouly, R. J., Impedance bridge for surface temperature measurement, Commun. and Electronics, 388 (Summer).

Patrones, E. T., Jr., et al., Low-temperature thermal noise thermometer, Rev. Sci. Instr. **30**, 578 (July).

Pursey, H., and E. C. Pyatt, Measurement of equivalent noise resistance of a noise thermometer amplifier, J. Sci. Instr. **36**, 260 (June).

Simmons, F. S., and A. G. De Bell, Photographic pyrometry of rocket exhaust jets, Aircraft Eng. **31**, 144.

Thureau, P., A method of measuring temperature utilizing the thermal sensibility of fluorescent colors, Publs. sci. et tech. ministere air (France) No. 349.

Townsend, A. A., The analysis of temperature fluctuations by pulse-counting techniques, J. Fluid Mechanics, 261 (Aug.).

I have found a better paint thermometer, Ind. Finishing (Indianapolis) **35**, 67 (Feb.).

1960

Burk, D. L., Ratio pyrometer, Instr. Control Systems **33**, 64 (Jan.).

Lucier, J. G., Measurement of peak temperatures with thermal-sensitive indicators, PB 130397 (LC).

Moen, W. K., Surface temperature measurements, Instr. Control Systems **33**, 70 (Jan.).

Scanlon, W. W., L. G. Mundie, and P. W. Shadle, Temperature measurement with lead sulfide cells, PB 145030 (LC).

8. Special Applications, Method Not Specified in Title

1953

Brownlee, A. L., and H. E. Brown, Generator stator copper temperature indicator, Trans. Am. Inst. Elec. Engrs. **72**, Part 1, No. 9, 676 (Nov.).

Chenoweth, J. M., et al., Gun barrel measurements involve rapidly fluctuating temperatures, Instruments **26**, 1714 (Nov.).

Grunfeld, C., Jr., Instruments for the measurement of local flame temperatures in high velocity streams, PB 122972 (LC); ASTIA AD–17 396.

Pleuthner, Richard L., and James P. Welsh, Manual of standard temperature measuring techniques, units, and terminology for miniaturized electronic equipment, ASTIA AD–49 485 (June).

Potter, J. H., and R. B. Dillaway, Investigation of flame temperatures in a single cylinder spark ignition engine, Trans. Am. Soc. Mech. Engrs. **75,** 1311 (Oct.).

Samberts, K., Temperature measurements in a dielectric field, Abhandl. braunschweig. wiss. Ges. **5,** 187.

Werner, F. D., R. E. Keppel, and M. A. Bernards, Design and performance studies for improved multiple-shielded total temperature probes, U.S. Air Force Wright Air Development Center Tech. Rept. 53–194, PB 133014.

1954

Bauserman, G. W., C. H. Prien, and T. Zandstra, Determination of transient flame termperatures, Rev. Sci. Instr. **25,** No. 7, 640 (July).

Biancheria, A., and G. Kegeles, Thermodynamic measurements of ultracentrifuge rotor temperature, J. Am. Chem. Soc. **76,** No. 14, 3737 (July 20).

Booth, A., Improved methods of temperature indication for a–c generators, Metropolitan-Vickers Gaz. **25,** No. 418, 257 (May).

Decker, G. E., and R. D. Stiehler, Temperature measurements in Mooney viscosemeter, Am. Soc. Testing Materials Bull. No. 195, 45 (Jan.).

Freedman, R., and E. Burke, Measurement of temperature distribution in a low pressure flat flame, J. Chem. Phys. **22,** 824 (May).

Hildenbrand, D. L., A. G. Wittaker, and C. B. Euston, Burning rate studies. Measurement of the temperature distribution in burning liquid strands, ASTIA AD–71 582.

Hudson, D. C., and W. T. Sweeney, Temperatures developed in rotating dental cutting tool, PB 116920 (LC) (Oct.).

Lewis, D. M., Techniques for investigation of thermal conditions in continuous casting, J. Inst. Metals **82,** Part 8, 395 (Apr.).

Oriani, R. A., and T. S. Jones, Apparatus for determining solidus temperatures of high melting alloys, Rev. Sci. Instr. **25,** No. 3, 248 (Mar.).

Reingold, I. and K. Garoff, Measurement of the gas temperature of a low-pressure rf discharge, J. Appl. Phys. **25,** 15 (Apr.).

Roberts, L. D., and J. W. T. Dobbs, Production and measurement of temperature below 1K, J. Instr. Soc. Am. **1,** No. 10, 25 (Oct.).

Schwartz, Herman, Three temperature probes for measuring ambient air temperatures in clear air and clouds, ASTIA AD–59 679 (Sept.).

Spencer, N. W., et al., Rocket instrumentation for reliable upper-atmosphere temperature determinations, Proc. IRE. **42,** 1104 (July).

Tretethers, L., Measurement of mean fluid temperatures, Am. Soc. Mech. Engrs. M.P. 54–A–135.

National Bureau of Standards whirling thermometer takes turbine's temperature, Machine Design **26,** 41 (Dec.).

Remote indication of turbine blade temperature, Automotive Inds. **111,** 71 (Dec. 15).

Turbine-blade temperature telemeter, Instr. and Automation **27,** No. 12, 1958 (Dec.).

1955

Baker, D. I., Mixture ratio and temperature survey of ammonia-oxygen rocket motor combustion chambers, Jet Propulsion **25,** No. 5, 217 (May).

Dahl, A. I., Probe for steam temperature measurements, J. Instr. Soc. Am. **2,** No. 4, 108 (Apr.).

Evans, J. C., It takes rugged instruments to measure 325 degrees below zero, Oil Gas J. **53,** No. 47, 123 (Mar. 28).

Garvitch, Z. S., Field instrument for measuring temperature of natural boiling pools, J. Sci. Instr. **32,** No. 7, 261 (July).

Gerbitz, D. D., and J. S. Ewing, Correlation of temperature measurements on d–c armatures, Trans. Am. Inst. Elec. Engrs. **74,** Part 3, No. 18 (June).

Giedt, W. H., Determination of transient temperatures and heat transfer at gas-metal interface applied to 40 mm gun barrel, Jet Propulsion **25,** No. 4, 158 (Apr.).

Goodall, A., Open-hearth immersion pyrometers, J. Iron Steel Inst. **180,** Part 3, 247 (July).

Greene, C. R., Temperature profiles throughout cigarettes, cigars, and pipes, Science **122,** 5145 (Sept. 16).

Koletsky, H., Temperature indicator for aircraft engines, Electronics **28,** 129 (Nov.).

Pease, R. S., Measurement of specimen temperatures in a high temperature X-ray powder camera, J. Sci Instr. **32,** 476 (Dec.).

Swenson, C. A., R. H. Stahl, and others, Measurement and control of low temperatures, ASTIA AD–82 757.

Willman, B. T., J. E. Brock, W. L. Sibbitt, and G. A. Hawkins, Measurement of gun barrel temperatures, Instr. and Automation **28,** No. 1, 106 (Jan.).

Best way to measure tube temperature? Power **99,** 138 (Apr.).

Steam temperature measurements, Elec. J. **155,** 2089 (Dec. 23).

1956

Belansky, A. M., and C. F. Peck, Jr., Roll temperature study on hot strip mill, Iron Steel Engr. **33,** 62 (Mar.).

Cushman, R., Cornell instruments for shock tubes, Aviation Week **65,** 255 (Oct. 29).

Fink, R., Checking and recording metal temperatures, Foundry **84,** No. 6, 142 (June).

Grosh, R. J., and E. A. Trabant, Arc welding temperatures, Welding J. (N.Y.) **35,** S396 (Aug).

Lucas, D. H., and M. E. Peplow, Measurement of steam temperatures in power stations, Proc. Inst. Elec. Engrs. (London) **103,** Part A (Apr.).

Pavlides, P. K., In-service temperature measurement of the amortisseur windings of large frequency changers, Elec. Eng. **75,** 1091 (Dec.).

Rickey, G. G., et al., Temperature studies of the air in a truck tire, Rubber Age **79,** 273 (May).

Device measures 400,000° F, J. Franklin Inst. **261,** 682 (June).

1957

Gill, T. P., Some problem in low-temperature pyrometry, J. Opt. Soc. Am. **47,** 1000.

Halsall, J. R., Some aspects of process control instrumentation, J. Brit. Inst. Radio Engrs. **17,** 551.

Sachse, H. B., Temperature measurements near absolute zero, Electronic Inds. Tele-Tech **16,** 58 (Sept.).

West, W. C., Jr., Ways to control temperature accurately and economically, Precision Metal Molding **15,** 79 (Nov.).

1958

Clark, D. D., Thermometer for high-speed aircraft, J. Sci. Instr. **35,** 433 (Dec.).

Flanigan, F. M., and J. O. Gonzales, Transient temperature sensing equipment, PB 132106 (LC).

Giedt, W. H., Temperature measurements in solids, Product Eng. **29,** 65 (July 21).

Hall, J. G., and A Hertzberg, Recent advances in transient surface temperature thermometry, Jet Propulsion **28,** 719.

Henshaw, D. H., and D. F. Daw, Design of total temperature probes, PB 126980 (LC).

Hett. J. H., Measurement of temperatures of pulsating burning gases, PB 131861 (OTS).

Krause, L. N., R. C. Johnson, and G. E. Glawe, A cooled-gas pyrometer for use in high temperature gas streams, Natl. Advisory Comm. Aeronaut. Tech. Note 4383.

Neher, I. E., Determination of temperature in high-temperature, high velocity gases, Arch. tech. Messen Lfg. **270,** 133.

Rothe, C. F., Simple surface thermometer, Rev. Sci. Instr. **29,** 436 (May).

Sanders, V. D., Review of high-temperature, immersion thermal sensing devices for in-flight control, Rev. Sci. Instr. **29,** 917 (Nov.).

Warshawsky, I., Measurements of rocket exhaust-gas temperatures, ISA Journal **5,** 91 (Nov.).

Werner, T. D., Total temperature measurement, Abstract, Mech. Eng. **80,** 110 (June).

1959

Culpin, M. F., and D. M. Jones, Measurement of the temperature of a running thread line, J. Sci. Instr. **36,** 22 (Jan.).

Kennedy, R. H., Tunnel kiln temperature measurement, Am. Ceram. Soc. Bull. **38,** 45 (Feb.).

Kitchen, B. G., Precise measurement of process temperature differences, ISA Journal **6,** 39 (Feb.).

Krause, L. N., et al., Cooled-gas pyrometer for use in high-temperature gas streams, Control Eng. **6,** 185 (Mar.).

Pattison, J. R., Ingot surface-temperature measurement in forging furnaces, J. Iron Steel Inst. (London) **191,** 163 (Feb.).

Pattison, J. R., Ingot surface-temperature measurement in induction hardening, Metallurgia **59,** 86 (Feb.).

Sandlin, B. J., and J. C. Thompson, Precision thermometer system for the liquid helium region, Rev. Sci. Instr. **30,** 659 (Aug.).

Sebulkin, M., Total-temperature probe for high-temperature boundary-layer measurements, J. Aero/Space Sci. **26,** 458 (July).

9. Nuclear Applications of Temperature Measurement

1945

Barbaras, G., et al., Design and construction of boron coated thermopiles for use in neutron fields, U.S. Atomic Energy Comm. AECD–2975, Univ. of Chicago (Feb.).

1947

LaGraff, J. Modifications in compound 10 couple copper-constantan thermocouple used for determination of hydrogen fluoride in uranium hexafluoride, U.S. Atomic Energy Comm. K–106 (OTS) (Dec.).

1949

Barbaras, G., J. Farr, and J. Kuranz, Design and construction of boron coated thermopiles for use in neutron fields, U.S. Atomic Energy Comm. AECD–2985 (OTS) (Feb.).

1950

Wilkinson, P. E., and G. O. Whitman, High temperature ion source and Thermohn development for stable isotope production, U.S. Atomic Energy Comm. Y–705 (OTS) (Dec.).

1954

Thermocouple developed for nuclear reactor, Elec. World **142,** 130 (July) 12.

Thermocouple for atomic reactors, Materials and Methods **40,** 226 (July).

Thermocouple measures temperatures in nuclear reactor, Iron Age **173,** 170 (May 6).

1956

Replogle, F. S., Jr., Stacked-disk neutron thermopile, PB 120026 (LC) (June).

Yockez, Y. P., Use of thermocouples in a radiation field, Phys. Rev. **101,** 1426 (Feb. 15).

Annual progress report under contract N5 ORI–07876, NR 025–164 M.I.T. (Neutron Sensitive Thermopile and Assoc. Equip.), PB 119650 (LC) (June).

1957

Cohen, P., Reliability of PWR fuel element thermocouples at high pH with LiOH, Westinghouse At. Power Division Rept. WAPD–CDA–126 (Dec.).

F. R. Sias, Resistance thermometer for nuclear-reactor service, Nucleonics **15,** No. 8, 75.

1958

Palladino, N. J., PWR seed metal thermocouples, Westinghouse At. Power Division Rept. WAPD–PWR–RD 603 (May).

1959

De Lorenzo, J. T., Thermocouple design and test program for reactor projects, Oak Ridge National Laboratory Rept. ORNL–2686 (May).

10. Associated Equipment and Testing Procedure

1953

Bailey, C. M., Jr., and A. I. Dahl, Vibration tests of thermocouples, U.S. Air Force Wright Air Development Center Tech. Rept. 53–340, PB 134797 (LC).

Dahl, A. I., and E. F. Fiock, Circuitry errors of ladder-type thermocouple-harness assemblies, U.S. Air Force Wright Air Development Center Tech. Rept. 53–4, PB 135243 (LC).

1954

Higgins, S. P., and J. R. Kein, Thermal sine wave apparatus for testing industrial thermometers, Am. Soc. Mech. Engrs. M.P. 54–SA–20.

Looney, R., Thermal sine wave generator for speed of response studies, Am. Soc. Mech. Engrs. M.P. 54–SA–28.

Lytle, E. A. L., A portable potentiometer for measuring the emfs of thermocouples, ASTIA AD–50 058 (Oct.).

Sherman, A., Thermocouple circuit restorer, Instr. and Automation **27,** No. 1, 124 (Jan.).

Welch, J. H., Simple microscope attachment for observing high-temperature phenomena, J. Sci. Instr. **31,** No. 12, 458 (Dec.).

1955

Jones, D. H., Device improves thermocouple pyrometer operation, Iron Age **176,** 108 (Dec. 15).

Kauffman, A. B., Telemetered temperatures, Instr. and Automation **28,** No. 8, 1320 (Aug.).

Walter, L., Pyrometry—some suggestions for maintenance, Steel Processing **41,** 435 (July).

Thermophil thermometer; portable electronic instrument, Automobile Eng. **45,** 459 (Nov.).

1956

Malmberg, P. R., and C. G. Matland, Thermistor temperature control, Rev. Sci. Instr. **27,** 136.

Morris, P. R., Inductance-type thermocouple tester, Instr. and Automation **29,** 2217 (Nov.).

Premak, W., Gouy modulator for thermocouples, Rev. Sci. Instr. **27,** 877 (Oct.).

Robertson, G. R., Design and operation of a thermometer comparator, J. Chem. Educ. **33,** 40 (Jan.).

Zeffert, D. M., and R. E. Witherspoon, Thermistor temperature recorder, Anal. Chem. **28,** 1701.

1957

Proctor, C. M., Principles of laboratory temperature control, PB 121120 (OTS) (May).

Stainless steel collector ring for exhaust gas thermocouples, Machinery (N.Y.) **63,** 159 (Aug.); J. Franklin Inst. **264,** 300.

1958

Durgin, G. E., Tester checks thermocouples without flame, ISA Journal **5,** 57 (Mar.).

Gordov, A. N., et al., New equipment for checking heat-power instruments, Measurement Techniques No. 6, 674.

Hermach, F. L., Definition and measurement of the time constant and response time of thermal converters, Commun. and Electronics, 277 (July).

Morphew, K. L., The performance of thermally inert metal blocks as cold junction enclosures for thermocouples, Elec. Energy **2,** 172 (May).

Robinson, W. M., and F. H. Allen, Flange-inserted thermowell easy to install, Chem. Eng. **65,** 125 (Dec.).

Roeser, W. F., and S. T. Lonberger, Methods of testing thermocouples and thermocouple materials, Nat. Bur. Standards (U.S.) Cir. No. 590 (Feb.).

Trigger, K. J., R. K. Campbell, and B. T. Chao, A tool-work-thermocouple compensating circuit, Trans. Am. Soc. Mech. Engrs. **80,** 302.

Ziegler, J., Thermocouple compensating using a thermistor, Australian J. Instr. Technol. **14,** 146.

1959

Burwen, R. S., Amplifiers for strain gages and thermocouples, Electronics **32,** 43 (July 24).

Dickinson, T. A., Soldering Chromel and Alumel wire, Wire and Wire Products **34,** 469 (Apr.).

Lovejoy, D. R., H. J. Kostkowski, H. Kunz, and H. Wagenbreth, Standardization of W-filament lamps, Procès-verbaux séances, Comité intern. poids et mesures, Ser. 2, **26A,** T133.

Specht, H., Apparatus for the welding of thin thermocouples, Z. Metallk. **50,** 36 (Jan.).

Tramposch, H., et al., Rapid scanning system for recording thermocouple outputs, ASTM Bull., 41 (May).

Improved thermal, electrical layout ups radiation pyrometer accuracy, stability, Machine Design **31,** 134 (Oct. 1).

Sleeve guards thermocouple against thermal shock, Steel **144,** 89 (June 22).

1960

Bochkov, F. V., Study of the properties of protective shields for thermocouples, Ogneupory **25,** 39.

11. General

1950

Baker, H. D., Manual on thermometry; with emphasis on thermocouple techniques, United Aircraft Corp., East Hartford.

Weber, R. L., Heat and temperature measurement, Prentice Hall, New York, N.Y.

1951

Campbell, C. H., Modern pyrometry, Chemical Publ. Co., New York.

Freeze, Paul D., Bibliography on the measurement of gas temperature, Nat. Bur. Standards (U.S.) Cir. 513 (Aug. 20).

1953

Baker, H. D., E. A. Ryder, and N. H. Baker, Temperature measurement in engineering, Vol. I, John Wiley & Sons, Inc., New York, N.Y.

Burton, E. J., and D. J. Weeks, Temperature measurement, J. Inst. Fuel **26,** No. 154, 260 (Nov.).

1954

Belcher, W. E., Jr., Donald Robertson, and W. F. Hicks, Temperature measurements, Am. Soc. Metals (Oct.).

Keonjian, E., and J. S. Schaffner, Shaping characteristics of temperature-sensitive elements, Trans. Am. Inst. Elec. Engrs. **73,** Part 1, No. 14, 396 (Sept.).

1955

Barry, H., Temperature measuring instruments, Metal Ind. (N.Y.) **86,** No. 25, 537 (June 24).

Clement, J. R., J. K. Logan, and J. Faggney, An examination of the 1948 liquid helium vapor pressure-temperature scale, ASTIA AD-62 277 (May).

Leon, K. S., and W. L. Harries, Temperature transducers PB 121296 (OTS) (June).

Temperature, its measurement and control in science and industry, American Inst. of Physics, Reinhold Publ. Corp., New York, N.Y., Vol 1—1941; Vol 2—1955.

1956

Ambler, E., and R. P. Hudson, Examination of the helium vapor-pressure scale of temperature using a magnetic thermometer, J. Research Nat. Bur. Standards **56,** 99 (Feb.).

Finkelstein, V. E., E. S. Shpiegelman, and V. V. Kandyba, Pirometry EOP-51M i OP-48M dlia izmereniia temperatury do 6000° C, Zemer. Tekh. **1,** 52 (Sept.).

Godridge, A. M., R. Jackson, and G. G. Thurlow, Industrial measurements of gas temperature, Trans. Soc. Instr. Tech. **8,** 103 (Sept.).

Herzfeld, C. M., A study of basic limitations to the concept and measurement of temperature; incomplete equilibrium, ASTIA AD-85 386 (Jan.).

Kandyba, V. V., Instruments for accurate measurement of high temperature, Izmer. Tekh. **1,** 36.

Land, T., Recent developments in temperature measurement and control, Met. Rev. **1,** Part 2, 271.

Lindorf, H., Technical temperature measurements, Verlag W. Girardet, Essen, Germany.

Panel discussion on pyrometric practices, Am. Soc. Testing Materials—Special Tech. Pub. No. 178.

British pyrometer progress, Brit. Steelmaker **22,** No. 12, 358 (Dec.).

1957

Beede, H. M., High-temperature measurements of gas streams in turbo-machinery, Instr. and Automation **30,** 1896.

Moreau, H., J. A. Hall, and V. M. Leaver, Mercury in quartz thermometers for very high accuracy, J. Sci. Instr. **34,** 147.

Oughton, H. G., Primary elements for temperature measurement, Instr. Engr. **2,** 76 (Oct.).

Warshawsky, I., Pyrometry of high velocity gases, Sixth Symposium (International) on Combustion, New Haven, Connecticut, Reinhold Pub. Corp., New York, N.Y. (1957), p. 739.

1958

Farber, E. A., Methods and systems used for temperature measurement, Air Conditioning, Heating and Ventilating **55,** 76 (July).

Hall, J. A., Accurate measurement of temperature, Research **11,** 147 (Apr.).

Herzfeld, C. M., New high-temperature measuring techniques at National Bureau of Standards, Control Eng. **5,** 30 (Nov.).

1959

Bingham, C. R., Temperature detectors, Electronics **32,** 55 (July).

Foskett, A. C., Thermocouples for high temperature measurement (a bibliography), United Kingdom Atomic Energy Authority, AERE—Bib. 125.

Humphreys, J. D., Radiation shielded thermometer design, Electronic Inds. **18,** 102 (Mar.).

UNITED STATES DEPARTMENT OF COMMERCE • Alexander B. Trowbridge, *Acting Secretary*
NATIONAL BUREAU OF STANDARDS • A. V. Astin, *Director*

Bibliography of Temperature Measurement

July 1960 to December 1965

Lief O. Olsen and Carl Halpern

Institute for Applied Technology
National Bureau of Standards
Washington, D.C. 20234

National Bureau of Standards Monograph 27

Supplement 2

Issued April 28, 1967
Supersedes Supplement 1 to Monograph 27, Sept. 13, 1963

This second supplement to National Bureau of Standards Monograph 27 has been combined with the references given in Supplement 1 (May 13, 1963) and issued as a single publication to assist the users of this material.

Library of Congress Catalog Card Number: 61–61148

July 1960 to December 1962

Contents

January 1963 to December 1965

Contents

Bibliography of Temperature Measurement

July 1960 to December 1962

Carl Halpern

(May 9, 1963)

There are presented in this supplement to NBS Monograph 27, "Bibliography of Temperature Measurement, January 1953 to June 1960" issued April 6, 1961, about 700 additional references to the field of temperature measurement. The period covered is from July 1960 to December 1962 with some earlier references which came to our attention. The arrangement of material is the same as in Monograph 27, and the journal abbreviations used are those employed in Chemical Abstracts.

Introduction

The material contained herein was collected from two general sources: scientific and technical journals and reports of investigations sponsored or conducted by various governmental agencies. English, German, and French journals and translations in English of Russian journals were covered as well as the more commonly used abstract journals. Some references to material in other languages, obtained from the abstract journals, are also included. To obtain references to governmental reports the following were consulted: Technical Abstract Bulletin, Armed Services Technical Information Agency (ASTIA); U.S. Government Research Reports, Office of Technical Information, U.S. Department of Commerce; and Scientific and Technical Aerospace Reports, National Aeronautics and Space Administration (NASA). While reasonably complete coverage was intended, it is inevitable that oversights and other unintentional omissions have occurred.

1. Thermoelectric Theory and Calibration

1950

Barber, C. R., The emf-temperature calibration of Pt, 10% Rh Pt and Pt, 13% Rh Pt thermocouples over the temperature range 0–1760°C, Proc. Phys. Soc. (London) **63B**, 492.

1958

Aikhenbaum, B. L., Changes in the testing system in the field of temperature measurement, Measurement Techniques No. 5, 547 (Sept.–Oct.).

Kurti, N., The absolute temperature scale at low temperatures, Z. Physik. Chem. (Frankfurt) **16**, 281.

1959

Astrov, D. N., A. S. Borovik-Romanov, M. P. Orlova, and P. G. Strelkov, Evolving a practical temperature scale in the region of 10–90°K, Measurement Techniques No. 11, 876 (Nov.).

Astrov, D. N., M. P. Orlova, P. G. Strelkov, and D. I. Sharevskaya, Comparison of low-temperature scales of platinum resistance thermometers, Measurement Techniques No. 8, 613 (Aug.).

Barber, C. R., New gas thermometer measurements over the range from 10° to 90°K and the extension of the International Temperature Scale below 90°K, Proc. Intern. Congr. Refrig., 10th, Copenhagen, 1959, **1**, 174.

Bragin, B. K., A thermoelectric method of evaluating the purity of platinum for standard thermocouples, Measurement Techniques No. 10, 776 (Oct.).

Dzyuba, A. S., and P. B. Kantor, A semiconductor thermocryostat for calibration of standard thermometers, Measurement Techniques No. 11, 880 (Nov.).

Gertsriken, S. D., M. M. Novikov, and V. S. Kopan, Nature of the thermal electromotive force that arises from metal deformation, Ukrain. Fiz. Zh. **4**, 293.

Kropschot, R. H., and F. J. Blatt, Thermoelectric power of cold-rolled pure copper, Phys. Rev. **116**, 617.

Orlova, M. P., Reproducibility of the boiling temperature of oxygen, Measurement Techniques No. 5, 330 (May).

Pilipchuk, B. I., Units for the measurement of thermal quantities, Measurement Techniques No. 1, 26 (Jan.).

Swindells, J. F., Calibration of liquid-in-glass thermometers, Natl. Bur. Std. (U.S.) Circ. 600.

Usoltsev, V. A., Stability of the distillation temperature of carbon dioxide, Measurement Techniques No. 2, 118 (Feb.).

Yayshev, N. A., Approximation theory of the heat inertia of technical thermocouples and resistance thermometers, Nauch. Trudy Leningrad. Inst. Tochnoi Mekh. i Optiki 1959, No. 37, 64–90.

1960

Berry, R. J., The reproducibility of the sulfur point, Can. J. Phys. 38, 1027 (Aug.).

Blatt, F. J., M. Garber, R. H. Kropschot, and B. Scott, Thermoelectric power of dilute copper and silver alloys, Australian J. Phys. 13, 223.

Blatt, F. J., and R. H. Kropschot, Thermoelectric power of dilute copper alloys, Phys. Rev. 118, 480.

Boerdijk, A. H., Diagrams representing states of operation of a general thermocouple, J. Appl. Phys. 31, 1141 (July).

Borovik-Romanov, A. S., M. P. Orlova, and P. G. Strelkov, Designing a practical temperature scale for the 10–90°K interval, Measurement Techniques No. 1, 42 (Jan.).

Bragin, B. K., Calibration of rare-metal thermocouples against the melting point of palladium, Measurement Techniques No. 12, 1019 (Dec.).

Brickwedde, F. G., H. van Dijk, M. Durieux, J. R. Clement, and J. K. Logan, The "1958 He^4 scale of temperatures," J. Res. Natl. Bur. Std. (U.S.) **64A**, 1; Natl. Bur. Std. (U.S.) Monograph 10 (June 17).

Corruccini, R. J., Interpolation of platinum resistance thermometers, Rev. Sci. Instr. **31**, 673 (June).

Costa, P., Determination of the thermoelectric power of uranium and plutonium, J. Nucl. Mater. **2**, 75.

Danishevskii, S. K., Selection and calibration of tungsten and molybdenum wire for thermocouples, Measurement Techniques No. 5, 333 (June).

Donahoe, F. G., Theoretical bound on the thermoelectric figure of merit, Elec. Eng. **79**, 488 (June).

Donde, Yu. Ya., and M. A. Pisarevskaya, The use of alternating currents for calibration commercial optical pyrometers, Measurement Techniques No. 9, 766 (Sept.)

Fink, E. W., An infrared radiation method for calibrating transient thermocouples, Westinghouse Electric Corp., Bettis At. Power Lab., Pittsburgh, WAPD–R(TH)–575 (Apr.).

Harrison, W. N., et al., Standardization of thermal emittance measurements, WADC Tech. Rept. 59–510, Pt I and II (Aug. 1959 and Nov. 1960).

Heusinkveld, W. A., Comparison of the temperature scales of various laboratories in the 600–3500°C range, Electrotechniek **38**, 536 (Oct.).

Hughes, W. F., and E. W. Gaylord, Theoretical analysis of a dynamic thermocouple. II. The continuous area interface, J. Appl. Mech. **27**, 259.

Kaufman, A. B., Temperature-probe response time, Instr. Control Systems **33**, 804 (May).

Kirenkov, I. I., New thermodynamic temperature measurements of solidifying gold and zinc, Measurement Techniques No. 6, 493 (June).

Kirenkov, I. I., V. A. Kovalevskii, and G. A. Krakhmalnikova, Reproduction of the color-temperature scale by photometric methods, Measurement Techniques No. 2, 112 (Feb.).

Lewis, H. W., and J. R. Reitz, Efficiency of the plasma thermocouple, J. Appl. Phys. **31**, 723.

Lougher, E. H., Measurement of the parameters in the thermoelectric figure of merit, Elec. Eng. **79**, 358 (May).

McLaren, E. H., and E. G. Murdock, The freezing points of high purity metals as precision temperature standards, Can. J. Phys. **35**, 1086 (1957); **36**, 585, 1131 (1958); **38**, 100, 577 (1960).

McNish, A. G., Temperature standards, Instr. Control Systems **33**, 775 (May).

Meyer, G., and J. F. Oosterom, Calibration of millivoltmeters and thermoelements and the combination of the two, Rec. Trav. Chim. **79**, 622.

Müller, R. H., New precise temperature standard, Anal. Chem. **32**, 123A (Sept.).

Myers, W. C., and R. T. Bate, Measure of figure of merit of thermoelectric materials, Rev. Sci. Instr. **31**, 464 (Apr.).

Pearson, W. B., The thermoelectric power of annealed and cold-worked silver and gold at low temperature, Can. J. Phys. **38**, 1048.

Pearson, W. B., Interpretation of relative thermoelectric phenomena at low temperature with special consideration of the effects of cold work on copper, Phys. Rev. **119**, 549.

Plyukhin, B. I., Laws of the temperature radiation of a flame, Dokl. Akad. Nauk SSSR **131**, 68.

Quandt, Jr., E. R., and E. W. Fink, Experimental and theoretical analysis of the transient response of surface-bonded thermocouples, U.S. At. Energy Comm. WAPD–BT–19.

Roeser, W. F., Calibrating thermocouples, Instr. Control Systems **33**, 796 (May).

Schindler, A. I., and R. J. Smith, Low temperature dependence of the electrical resistivity and thermoelectric power of palladium and palladium nickel alloys containing absorbed hydrogen, PB 146217 (LC) (Oct.).

Sharevskaya, D. I., and P. G. Strelkov, Thermometric platinum resistivity in the region of liquid helium temperatures, Measurement Techniques No. **12**, **1023** (Dec.).

Sharevskaya, D., et al., Differences in the relation between resistance and temperature of several grades of platinum in the range of 10.8 to 273.16°K, Measurement Techniques No. 7, 598 (July).

van Dijk, H., The 1958 scale of temperatures for the liquid helium-4 region, Progr. Cryog. **2**, 121.

Williams, S. B., Triple-point-of-water temperature reference, Instr. Control Systems **33**, 1918.

Wilson, R. E., Temperature standards, Instr. Control Systems **33**, 770 (May).

Temperature calibration survey, Instr. Control Systems **33**, 778 (May).

1961

Bauerle, L. E., Analysis of "immersed" thermocouple error, Rev. Sci. Instr. **32**, 313 (Mar.).

Boerdijk, A. H., Zero-, first-, and second-order theories of a general thermocouple, J. Appl. Phys. **32**, 1584 (Aug.).

Bowley, A. E., et al., Measurement of the figure of merit of a thermoelectric material, J. Sci. Instr. **38**, 433 (Nov.).

Bragin, B. K., A normal platinum thermal electrode, Measurement Techniques No. 7, 596 (Feb.).

Bragin, B. K., Certain errors in checking commercial resistance thermometers, Measurement Techniques No. 3, 194 (Mar.).

Bragin, B. K., Errors in the calibration of technical resistance thermometers, Izmeriteln. Tekhn. No. 3, 17.

Crawford, G. J. B., Note on the measurement of the figure of merit of thermoelectric materials and of refrigerating junctions, Rev. Sci. Instr. **32**, 353.

Gordov, A. N., and B. I. Kovshev, Nature of dynamic errors in measuring pulsating temperatures of a gas flow with a pulsating speed, Measurement Techniques No. 5, 363 (May).

Haas, A., Calibration of contact surface thermometers, Acta Imeko, 91.

Haase, R., K. Hoch, and H. Schouert, Thermocouples. VI. Evaluation of the measurements, Z. Physik. Chem. (Frankfurt) **27**, 421.

Jones, T. P., On the accuracy of realization of the international temperature scale above 1063°C, Australian J. Appl. Sci. **12**, 141 (June).

Kennedy, G. C., and R. C. Newton, Effect of pressure on the electromotive force of a platinum-bismuth thermocouple, J. Geophys. Res. **66**, 1491.

Krikorian, O. H., Optical pyrometer calibration with a standard carbon arc, Proc. Instr. Soc. Am. **16**, Paper No. 151–LA–61.

Madison, J. H., Calibration of Chromel-Constantan thermocouples for nuclear heat rate sensors, General Electric Co., Aircraft Nucl. Propulsion Dept., Cincinnati, TID–11927 (Jan. 23).

Maulard, J., The theoretical determination of the response time of a thermometric probe, Rech. Aeron. No. **83**, 41 (July).

Moser, H., Thermodynamic temperature scale, its realization between 90° and 1500°K, Pure Appl. Chem. **2**, 167.

Oleinik, B. L., New regulations on the international practical temperature scale, Measurement Techniques No. 7, 538 (July).

Orshanskii, D. L., On very high temperatures, the physical basis of their concept and their measurement, Acta Imeko, 136.

Prinz, W., Indication delay and indication error functions of thermometers. The significance of the half value time and nine tenths value time of thermometers, Allgem. Waermetech. **10**, 85.

Reich, A. D., and J. R. Madigan, Transient response of a thermocouple circuit under steady currents, J. Appl. Phys. **32**, 294 (Feb.).

Roy, J., and G. Gohard, "Fixed point" apparatus for thermocouple calibration, Mesur. Control Ind. **26**, 269 (Mar.).

Sharevskaya, D. I., and P. G. Strelkov, Methods for calibrating against the practical temperature scale in the region of 10–90°K, Measurement Techniques No. 2, 110 (Feb.).

Shpiegelman, E. S., Utilization of aluminum for calibrating first-grade thermometers, Measurement Techniques No. 5, 405 (Jan.).

Stimson, H. F., International practical temperature scale of 1948. Text revision of 1960, Natl. Bur. Std. (U.S.) Monograph 37 (Sept. 8).

Stimson, H. F., International practical temperature scale of 1948, J. Res. Natl. Bur. Std. (U.S.) 65A, 139.

Suzuki, M., Temperature standard below an oxygen point, Res. Electrotech. Lab., Tokyo, No. 615 (Sept.).

Tingwaldt, C., Thermodynamic temperature scale, its realization in solid bodies for temperatures above 1500°-K, Pure Appl. Chem. 2, 173.

Toenshoff, D. A., Automatic calibration of thermocouples, Engelhard Inds. Tech. Bull. 2, 88 (Dec.).

van Dijk, H., The thermodynamic temperature scale and its realization below 90°K, Pure Appl. Chem. 2, 157.

Wagner, N. K., Theoretical time constant and radiation error of a rocketsonde thermistor, J. Meteorol. 18, 606 (Oct.).

Calibration of optical pyrometers, Glass Ind. 42, 638 (Nov.).

Calibration of optical pyrometers, Natl. Bur. Std. (U.S.) Tech. News Bull. 45, 184 (Nov.).

Calibration of optical pyrometers, Instr. Pract. 15, 1558 (Dec.).

Calibration of platinum resistance thermometers, Engineer 211, 1048.

Calibration of platinum resistance thermometers, Instr. Pract. 15, 863.

Calibration of platinum resistance thermometers, Natl. Bur. Std. (U.S.) Tech. News Bull. 45, 62 (Apr.).

How to calibrate thermocouples to high accuracies, Space/Aeronautics 35, 89 (May).

Ice point standardization mercury-in-glass thermometers, Bu Weps-Bu Ships Calibration Program, Secondary standards laboratory measurement system operation procedure, NT–01, PB 171725.

The international practical temperature scale, Natl. Bur. Std. (U.S.) Tech. News Bull. 45, 65 (Apr.).

Thermocouple calibration, Natl. Bur. Std. (U.S.) Tech. News Bull. 45, 44 (Mar.).

Thermocouple calibration, Electron. Ind. 20, 231 (Mar.).

Thermocouple calibration, Instr. Pract. 15, 428 (Apr.).

Thermocouple calibration, Instr. Control Systems 34, 1663 (Sept.).

Triple point of water standardization, Bu Weps-Bu Ships Calibration Program, Secondary standards laboratory measurement system operation procedure NT–04, PB 171726.

1962

Barber, C. R., The establishment of a practical scale of temperature for the range 10–90/K, Brit. J. Appl. Phys. 13, 235 (May).

Berry, R. J., A precision oxygen point calibration bath, Can. J. Phys. 40, 859 (July).

Blackburn, G. F., and F. R. Caldwell, Reference tables for 40 percent iridium-60 percent rhodium versus iridium thermocouples, J. Res. Natl. Bur. Std. (U.S.) 66C, 1 (Jan.–Mar.).

Bussard, R. W., Some considerations of dynamic behavior in the plasma thermocouple, J. Appl. Phys. 33, 606 (Feb.).

Davis, J., and G. Lanza, Conventional and plasma thermo-Couples, U.S. Air Force, Office of Aerospace, Res, AFCRL 62–630 (June 5).

Freeze, P. D., F. R. Caldwell, and E. R. Davis, Reference tables for the palladium vs platinum-15 percent iridium thermocouple, ASD–TDR–62–525 (Dec.); ASTIA AD–295 607.

Kelly, G. D., How to calibrate optical pyrometers, Ceram. Ind. 79, 64 (Oct.).

Krikorian, O. K., Optical pyrometer calibration with a standard carbon arc, ISA Trans. 1, 273 (July).

Lovejoy, D. R., Temperature scales above 1000°C, Pure Appl. Chem. 5, 565.

Myers, H. S., Convenient laboratory temperature standard, Chem. Eng. 69, 192 (Mar.).

Obrowski, W., and W. Prinz, Determination of basic values for the thermocouples Pt 30% Rh-Pt 6% Rh, Arch. Eisenhuettenw. 33, 1.

Thorn, R. J., and G. H. Winslow, Contribution to the realization of the visual optical pyrometer temperature scale, Rev. Sci. Instr. 33, 961 (Sept.).

Zholkov, Yu. A., Thermal inertia of thermocouples, Measurement Techniques No. 12, 938 (June).

Calibration of optical pyrometers, Instr. Control Systems 35, 84 (May).

Reference tables for iron v constantan thermocouples, Brit. Std. Inst., B. S. 1829.

The thermodynamic and practical temperature scales, R & D No. 15, 40 (Nov.).

2. Thermoelectric Devices

1949

Steven, G., and W. C. Troy, The mechanical protection of the W/Ir thermocouple, PB 138320 (LC), (June).

1950

Steven, G., and W. C. Troy, The development of thermocouples for temperatures in the region of 1600° to 2000°C, PB137512 (LC), (Sept.).

1956

Haase, G., and G. Schneider, Thermoelements from the rhenium-iridium system, U.S. At. Energy Comm. AEC–tr–3835.

1957

Matton, G., and C. Fouré, Thermoelectric probes for measuring high temperatures in gas streams: their application to the study of flames stabilized by obstacles, 6th Symposium (International) on Combustion, New Haven, Conn., 757, Reinhold Pub. Corp.

1958

Danishevskii, S. K., The immersion of thermocouples, Ind. Lab. 24, 1608.

Ergardt, N. N., Stability of platinum-rhodium/platinum thermocouples, Trudy Vsesoyuz, Nauch.-Issledovatel. Inst. Metrol. 1958, No. 35, 87.

Gordov, A. N., and N. N. Ergardt, Some causes of errors in the measurement of temperatures by means of thermocouples, Ind. Lab. 24, 1605.

Kislyi, P. S., and G. V. Samsonov, High temperature semiconductor thermocouples, Izv. Akad. Nauk, SSSR, Otd. tekh. Nauk, Metall. Topl'e. 6, 135 (Nov.–Dec.).

Meyers, M. N., Irradiation study of platinum and platinum-rhodium thermocouple wire, U.S. At. Energy Comm. DC–58–5–730.

Sitnitskii, Yu. I., Dynamic characteristics of rapidly acting thermocouples, Avtomatika, Akad. Nauk Ukr. R.S.R. 1958, No. 1, 85.

1959

Altshuler, Y. A., Z. I. Bakushchik, and B. G. Klikshtein, Temperature measurement of rotating surfaces, Priborostroenie 1959, No. 5, 24.

Hartley, J. J., Thermal electromotive force of copper-constantan thermocouples as a function of junction fabrication, U.S. At. Energy Comm. SCTN–373–59 (16).

Obrowski, W., Temperature measurement with thermoelements, Dechema Monograph 35, No. 528–55, 203.

Ogorodnikov, N. N., and V. Ya. Levin, Use of instruments with thermal inertia compensation for measurement of rapidly changing temperature in gases, Trudy Kubyshev. Avisto. Inst. 1959, No. 8, 65.

Potts, J. F., and D. L. McElroy, Some results of base-metal thermocouple research at Oak Ridge National Laboratory, U.S. At. Energy Comm. TID–7856, Pt. 1.

Rudnitskii, A. A., Noble metal thermocouples for measuring high temperatures, Issledovaniya po Zhaproch. Splavam. Akad. Nauk, SSSR, Inst. Met. im. A. A. Baikova 4, 380.

Rudnitskii, A. A., Thermocouple measurement of high temperatures during steel manufacture, Fiz.-Khim. Osnovy Proizv. Stali, Akad. Nauk, SSSR, Inst. Met., Tr. 5–oi Konf. 1959, 311.

Serota, A. M., and B. K. Maltsev, A gold-platinum thermocouple, Measurement Techniques No. 8, 611 (Aug.).

Sukhov, S. A., S. Ya. Kadletz, and G. D. Pavlyuk, Investigation of electrolytic thermocouples, Measurement Techniques No. 2, 121 (Feb.).

Shiba, K., Thermoelectric thermometer of noncontacting type, Oyo Butsuri 28, 422.

Tomizaroa, K., and T. Ushijama, Measurement of surface temperature by Cu-Co (Constantan) thermocouple, Denkisik iho 23, 586.

1960

Accinno, D. J., and J. F. Schneider, Platinel- a noble metal thermocouple to replace Chromel-Alumel, Engelhard Ind., Tech. Bull. 1, 53 (Sept.).

Anderson, A. R., and D. J. Mackenzie, Materials for high (2500–4000 deg. F) gas engine temperature measurements, Aircraft Eng. 32, 201 (July).

Barrows, H., and D. J. Ryley, Temperature recovery factors in steam, Engineer 209, 903.

Bennet, H. E., The Pallador thermocouple, Platinum Metals Rev. 4, 66 (Apr.).

Berezin, G. F., A simple and highly sensitive thermocouple battery for the measurement of body surface temperature, Ind. Lab. 25, 502 (Apr.).

Blue, M. D., Thermoelectric effects in copper-gold alloys, Phys. Rev. 117, 137.

Boudreaux, R. A., Induced thermal error for thermocouples attached to thin plates, General Electric Co. Aircraft Nucl. Propulsion Dept., Cincinnati, DC–60–5–45 (May 9).

Chandler, R. L., and E. J. Dent, Temperature compensated strain gauges, Electron. Eng. 32, 414 (July).

Christy, R. W., Electric conductivity and thermoelectric power in ionic crystals, Am. J. Phys. 28, 457 (May).

Davisson, J. W., et al., Thermoelectricity, NRL Mem. Rept. 1089 (Aug.); PB 161977 (Dec.).

Edwin, B., Recent developments in nickel/nickel-chromium thermocouples, Elektrowärme 18, 222 (July).

Edwin, B. E., New developments in Ni/Ni-Cr thrmocouples, Eng. Dig. 21, 88 (Nov.).

Eller, H. C., and J. B. Stewart, Connect thermocouples firmly to burner tip, Elec. World 154, 45 (Sept. 5).

Haig, L. B., Thermocouple probe design method, Abstract: S.A.E. J. 68, 81 (Aug.).

Heath, J. H., High temperature thermocouples, Part I, United Kingdom At. Energy Admin. Rept. AEEW–R–141 (Dec.).

Jordan, H. C., Welded thermocouple junctions, Instr. Control Systems 33, 988 (June).

Krivka, H. A., Make your own thermocouples, Machine Design 32, 184 (June 9).

Kröckel, O., New thermocouple for high-temperature measurements, Silikat Tech. 11, 108.

Krol, L. Ya., et al., Thermocouples from intermetallic compounds, Zn Sb and Cd Sb, Instr. Construct. No. 8, 33 (Aug.).

Kuether, F. W., and J. C. Lachman, How reliable are the two new high-temperature thermocouples in vacuum, ISA J. 7, 67 (Apr.).

Lachman, J. C., Refractory metal thermocouples, Abstract: Metal Progr. 78, 161 (Aug.).

Lacroix, R., Platinum-rhodium/platinum thermocouples, Bull. Soc. Franc. Ceram. No. 48, 19.

Levin, E. D., A thermocouple for measuring the top layer temperature of a coke mass, Ind. Lab. 25, 503 (Apr.).

Mekheev, V. S., Some sources of error in measuring temperatures with thermocouples, Ind. Lab. 26, 691.

Ongkiehong, L., and J. van Duijn, Construction of a thermocouple for measuring surface temperatures, J. Sci. Instr. 37, 221 (June).

Parrott, J. E., The interpretation of the stationary and transient behavior of refrigerating thermocouples, Solid State Electron, 1, 135 (May).

Raezar, S. D., and H. L. Olsen, The intermittent thermometer: a new technique for the measurement of extreme temperature, Johns Hopkins Univ., Silver Spring, Md., Appl. Phys. Lab. NP–11314 (Dec.).

Rudnitskii, A. A., and I. I. Tyurin, A search for alloys suitable for high temperature thermocouples, Zh. Neorgan. Khim. 5, 401 (Feb.).

Short, W. W., and B. H. Sage, Temperature measurements in a spherical field; transfer coefficients and corrections for thermocouples in boundary flow, A.I.Ch.E. J. 6, 163 (Mar.).

Shoults, D. R., Aircraft nuclear propulsion program brings useful byproducts, S.A.E. J. 68, 35 (Apr.).

Stevenson, J. A., The metal-clad thermocouple, Platinum Metals Rev. 4, 127 (Oct.).

Stover, C. M., Method of butt welding small thermocouples 0.001 to 0.010 inch in diameter, Rev. Sci. Instr. 31, 605 (June).

Walker, J. E. C., and R. E. Wells, Thermometry of respired air, J. Appl. Physiol. 15, 541.

West, E. D., Techniques in calorimetry: noble-metal thermocouples for differential use, Rev. Sci. Instr. 31, 896.

Yazliev, S., An investigation of the thermoelectric properties of nickel-palladium alloys, Zh. Neorgan. Khim. 5, 2446.

Expendable immersion thermocouple, Mech. Eng. 82, 77 (Sept.).

Hi-temp thermocouples bend to fit test parts, Prod. Eng. 31, 9 (Dec. 5).

Kanthal base metal thermocouple wire, Ind. Heating 27, 637.

Soviet thermocouple is sensitive, Chem. Eng. News 38, 44 (Aug. 1).

Thermocouple measures temperatures of molten metal, J. Franklin Inst. 269, 428.

Thermocouples for low temperature application, Electronics 33, 85 (Nov. 4).

Tungsten vs tungsten 74 rhenium 26 thermocouple, Englehard Ind. Tech. Bull. 1, 56 (Sept.).

Where to get the new high-temperature thermocouple materials, ISA J. 7, 66 (Apr.).

1961

Arai, T. T., and J. R. Madigan, Response of a thermocouple circuit to non-steady currents, J. Appl. Phys. 32, 609 (Apr.).

Bard, J. A., Thermocouples for high temperatures, Instr. Control Systems 34, 1874 (Oct.).

Bennett, H. E., The contamination of platinum metal thermocouples, Platinum Metals Rev. 5, 132 (Oct.).

Boggs, B. C., Common parallel thermocouples for average temperature measurement, WADD TR–60–650; ASTIA AD–255 753.

Bostwick, W. E., Thermocouple loading—an exercise in impedance matching, Instr. Control Systems 34, 863 (May).

Bradley, D., and A. G. Entwistle, Determination of the emissivity, for total radiation, of small diameter platinum-10% rhodium wires in the temperature range 600–1450°C, Brit. J. Appl. Phys. 12, 708 (Dec.).

Brands, F. W., Two hot junctions up thermocouple output, Electronics 34, 118 (Apr. 28).

Bundy, F. P., Effect of pressure on emf of thermocouples, J. Appl. Phys. 32, 483 (Mar.).

Burnett, D. R., Transient temperature measurement errors in heated slabs for thermocouples located at the insulated surface, J. Heat Transfer 83, 505.

Cutler, M., Thermoelectric measurements at small-area contacts, J. Appl. Phys. **32,** 1075.

Darling, A. S., Thermoelectric properties of rhodium-platinum alloys, Instr. Control Systems **34,** 861 (May).

de Percin, F., Some observations of the effect of direct and snow-reflected solar radiation on exposed and shielded thermocouples, Quartermaster Research and Engineering Center, Natick, Mass., Study Rept. RER–19 (Apr.); PB 152070 (Jan.).

Emelhanenko, O. V., and F. P. Kesamanly, Concerning a rapid method of precise measurements of thermal emf of semiconductors, Soviet Phys.: Solid State **2,** 1356 (Jan.).

Franks, E., High-temperature thermocouples using non-metallic members, Abstract: Electro-Technol. (New York) **68,** 12 (July).

Glawe, G. E., R. C. Johnson, and L. N. Krause, A cooled-tube pyrometer with experimental results obtained in a high-temperature gas stream, NASA Tech. Note D–870.

Hill, J. S., The use of Fibro platinum in thermocouple elements, Engelhard Inds. Tech. Bull. **2,** 85 (Dec.).

Hsu, S. T., and F. W. Smidt, Measured variations in local surface temperatures in pool boiling of water, Trans. ASME **C83,** 254 (Aug.).

Johnson, W., Temperature measurement in high-temperature X-ray powder cameras, J. Sci. Instr. **38,** 373.

Kelley, M. J., et al., Effect of nuclear radiation on thermocouples, Abstract: Electro-Technol. (New York) **68,** 11 (July).

Kislyi, P. S., and G. V. Samsonov, High-temperature thermoelements from semiconductors, Planseeber. Pulvmet **8,** 200.

Kislyi, P. S., el al., Thermoelectric characteristics of high-temperature thermocouples with electrodes made of high melting point alloys, Measurement Techniques No. 5, 366 (May).

Lachman, J. C., New developments in tungsten/tungsten-rhenium thermocouples, Proc. Instr. Soc. Am. **16,** Paper No. 150–LA–61.

Lachman, J. C., Thermocouples for ultrahigh temperatures, Metal Progr. **80,** 73 (July).

Lachman, J. C., and J. A. McCurty, Use of refractory metals for high temperature thermocouples, Abstract: Electro-Technol. (New York) **68,** 11 (July).

Lowell, H. H., H. W. Allen, and J. E. Jenkins, Electrical characteristics of four ternary platinum-rhodium-base alloys containing chromium, cobalt, or ruthenium, NASA Tech. Note D–867.

Lutz, O., and F. von Burger-Scheidlin, Point-by-point determination of very high temperatures, Deutch. Forsch. Anst. Luft. Ber., 147.

McCarhty, D. E., Response characteristics of a radiation thermocouple at various pressures, J. Opt. Soc. Am. **51,** 801.

Moffat, R. J., Gradient approach to thermocouple circuitry, Abstract: Electro-Technol. (New York) **68,** 12 (July).

Nadler, M. R., and C. P. Kempter, Thermocouples for use in carbon atmospheres, Rev. Sci. Instr. **32,** 43 (Jan.).

Obrowski, W., Thermoelements, Arch. Tech. Messen, 183 (Aug.).

Potts, J. F., and D. L. McElroy, Basic studies on base-metal thermocouples, Abstract: Metal Progr. **80,** 162 (Apr.).

Powell, R. L., M. D. Bunch, and L. P. Caywood, Low-temperature thermocouple thermometry, Advan. Cryog. Eng. **6,** 537.

Powell, R. L., M. D. Bunch, and R. J. Corruccini, Low temperature thermocouples—I. Gold-cobalt or constantan versus copper or "normal" silver, Cryogenics **1,** 139 (Mar.).

Powell, R. L., and L. P. Caywood, Low temperature characteristics of some commercial thermocouples, Advan. Cryog. Eng. **7,** 517.

Sagoschen, J., Temperature measurements with thermocouples of platinum group metals, Metall. **15,** 34.

Salva, S. J., Calculate change in resistance of thermocouple wire, Power **105,** 96 (Feb.).

Samsonov, G. V., P. S. Kislyi, and A. D. Panasyuk, Thermoelectric properties of thermocouples with high-melting solid electrodes, Measurement Techniques No. 10, 810 (Oct.).

Scadron, L., Ceramic-insulated thermocouples, Instr. Control Systems **34,** 856 (May).

Sirs, J. A., Measurement of rapid temperature changes by thermocouples, J. Sci. Instr. **38,** 489 (Dec.).

Smith, E. C., Swaged MgO thermocouples, Instr. Control Systems **34,** 858 (May).

Sochor, B., Instruments and methods for measuring thermal quantities, Acta Imeko, 161.

Stover, C. M., Method of making small pointed thermocouples, Rev. Sci. Instr. **32,** 366 (Mar.).

Tau, K., and M. Boudart, Recombination of atoms at the surface of thermocouple probes, Can. J. Chem. **39,** 1239.

Temme, M. I., and W. H. Giedt, Dual probe for high-temperature-gas measurements, U.S. At. Energy Comm. Rept. ARL 174 (Dec. 1961); ASTIA AD–274 352.

Weiss, H., An apparatus for the measurement of temperatures, using thermocouples, in high speed rotating machines, Elektrotech. Z. **13B,** 353 (June 26).

Wong, P., and P. S. Schaffer, Development of a tungsten/molybdenum immersion thermocouple for measuring molten metal temperatures in vacuum, ASTIA AD–253 949 (Apr.).

A thermocouple for the surface of high-speed cylinders, Eng. Mater. and Design **4,** 599 (Sept.).

New thermocouple up to 4200F, Metalworking Prod. **105,** 83 (Sept. 20).

Recent advances in thermocouple technology, Electro-Technol. (New York) **68,** 11 (July).

Thermocouple alloy for 5000F, Mater. in Design Eng. **54,** 13 (Sept.).

Thermocouples for high temperature, Nucl. Power **6,** 70 (June).

Thermocouples, base metal (except copper-constantan) ambient to 1100°C, Bu Weps-Bu Ships Calibration Program. Standards lab. Measurement system operation NT–05 (Oct. 25); PB 181147.

1962

Baas, P. B. R., Effect of oxide finish on nickel alloy thermocouple wires, S.A.E. Paper 524H; Abstract S.A.E. J. **70,** 102 (Sept.).

Bansal, T. D., Copper—Advance thermocouples in the temperature range 0–100°C, J. Sci. Ind. Res. (India) **21D,** 23 (Jan.).

Beck, J. V., Thermocouple temperature disturbances in low conductivity materials, Trans. ASME **84C,** 124 (May).

Benson, J. M., and R. Horne, Surface temperature of thin sheets and filaments, Instr. Control Systems **35,** 115 (Oct.).

Bostwick, W. E., A note on platinum/platinum-rhodium thermocouple uncertainty, Trans. Inst. Radio Engrs. NS–9, 253 (Jan.).

Caldwell, F. R., Thermocouple materials, Natl. Bur. Std. (U.S.) Monograph 40 (Mar. 1).

Chin, J. H., Effect of uncertainties in thermocouple location on computing surface heat fluxes, ARS J. **32,** 273.

Clark, R. B., Time-temperature effect on jet engine thermocouple accuracy and reliability, S.A.E. Paper 524K; Abstract: S.A.E. J. **70,** 102 (Sept.).

Davenport, M. E., et al., Thermocouple attachment to a direct-current heater, Trans. ASME **84C,** 124 (May).

Denison, J. W., Technique to construct fine wire thermocouples, Rev. Sci. Instr. **33,** 870 (Aug.).

Dreisner, A. R., et al., High temperature W/W–25 Re thermocouples, Instr. Control Systems **35,** 105 (May).

Faul, J. C., Thermocouple performance in gas streams, Instr. Control Systems **35,** 104 (Dec.).

Freeze, P. D., and L. O. Olsen, Thermoelectric and mechanical stability of Platinel II thermocouples in oxidizing atmospheres, ASD–TDR–62–835 (Nov.).

Hadfield, D., Immersion pyrometry and open hearth furnace productivity, Platinum Metals Rev. **6**, 1 (Jan.).

Hahn, P. M., Evaluation of spring-loaded thermocouple probes under transient temperatures, Mater. Res. Std. **2**, 403 (May).

Hawley, S. A., J. E. Breyer, and F. Dunn, Fabrication of miniature thermocouples for uhf acoustic detectors, Rev. Sci. Instr. **33**, 1118 (Oct.).

Heyne, W., Precision measurements in examining the relation between thermal e.m.f. and temperature of Pt-Rh/Pt thermocouples by comparison with a normal thermocouple, Feingerätetech. 11, 400 (Sept.).

Jackson, P. L., Use of a large thermocouple junction to locate temperature disturbances, Rev. Sci. Instr. **33**, 334 (Mar.).

Kislyi, P. S., Prospects of utilizing refractory compounds for high temperature thermocouples, Poroshkovaya Met., Akad. Nauk SSSR **2**, No. 4, 50.

Lachman, J. C., Coaxial thermocouple viewed as improvement, Abstract: S.A.E. J. **70**, 128 (July).

Lachman, J. C., High temperatures thermocouples using tungsten-rhenium alloy tubing, S.A.E. Paper 524D, Abstract: S.A.E. J. **70**, 102 (Sept.).

Lachman, J. C., New developments in W/W–RE (tungsten/tungsten rhenium) thermocouples, ISA Trans. **1**, 340.

Ling, F. F., and T. E. Simkins, Measurement of point-wise junction condition of temperature at the interface of two-bodies in sliding contact, ASTIA AD–283 932.

MacKenzie, D. J., and M. D. Scadron, Selection of thermocouples for high gas temperature measurement, S.A.E. Paper 524E, Abstract: S.A.E. J. **70**, 102 (Sept.).

Olsen, L. O., Catalytic effects of thermocouple materials, ASD–TDR–62–304; ASTIA AD–284 880; S.A.E. Paper 524G, Abstract: S.A.E. J. **70**, 94 (May).

Patzke, H., A new vacuum-thermocouple made by VEB Carl Zeiss Jena, Jena Rev. No. 1, 32.

Stewart, P. J., Study of temperature distribution with rhodium-platinum thermocouple probes, Platinum Metals Rev. **6**, 126 (Oct.).

Walker, B. E., C. T. Ewing, and R. R. Miller, Thermoelectric instability of some noble metal thermocouples at high temperatures, Rev. Sci. Instr. **33**, 1029 (Oct.).

Walker, B. E., C. T. Ewing, and R. R. Miller, Thermoelectric instability of some noble metal thermocouples at high temperatures, U.S. Naval Res. Lab., Washington, D.C., Rept. 5792 (June 29); ASTIA AD–282 154.

White, F. J., Accuracy of thermocouples in radiant-heat testing, Exp. Mech. **2**, 204 (July).

Wolfe, R., and J. H. Wernick, Thermoelectric devices and materials, Bell Lab., Record **40**, 190 (June).

Wormser, A. F., and R. A. Pfuntner, Thermocouple tells temperature above its melting point, S.A.E. J. **70**, 56 (May).

Zenin, A. A., Errors in the readings of thermocouples passed through flames, Inzh. Fiz. Zh. **5**, 68 (May).

A rhodium-platinum thermocouple for high temperature, Platinum Metals Rev. **6**, 96 (July).

Gage eliminates surface heat loss, Missiles and Rockets 11, 36 (Dec. 3).

How and when precious metal thermocouples should be used, R & D, **45** (Jan.).

3. Resistance Devices

1955

Hotta, H., Substitute for platinum/platinum-rhodium thermocouples, Kinzoku **25**, 459.

1957

Ciborowski, F., Influence of epitemperature of thermistors on temperature measuring, Pomiary, Automat., Kontrola 3, No. 3, 105.

1959

Estrin, B. S., and P. B. Kantor, Temperature measurement in the range of 300–500°C, Measurement Techniques No. 10, 774.

Grashdankina, N. P., L. I. Domanskaya, and A. K. Kikrin, Measurements of temperature in high-pressure chambers by means of thermistors, Measurement Techniques No. 10, 771.

Manassi, V., The measurement of temperature with electric resistance thermometers, Elletrotecnica **46**, 503 (Aug. 10).

1960

Ambler, E., and H. Plumb, Use of carbon resistors as low temperature thermometers in the presence of stray r.f. (radio frequency) fields, Rev. Sci. Instr. **31**, 656.

Barber, C. R., Resistance thermometers for low temperatures, Progr. Cryog. **2**, 147.

Belinskii, L. I., and A. I. Pilorskii, Semiconductor thermometer, Instr. Construct. No. 10, 25 (Oct.).

Christiansen, W. H., The use of fine unheated wires in shock tubes, Phys. Fluids **3**, 1027.

Gniewek, J. J., and R. J. Corruccini, Carbon resistance thermometry with mixed dc and rf currents, Rev. Sci. Instr. 31, 899.

Herr, A. C., H. G. Terbeck, and M. W. Tiefermann, Suitability of carbon resistors for field measurements of temperatures in the range of 35° to 100°R, NASA Tech. Note D–264 (Feb.).

Kostryukov, V. N., Platinum thermometer for calorimetric work, Instr. Exp. Tech. No. 6, 978 (Sept.).

Leslie, W. H. P., J. J. Hunter, and D. Robb, Precision temperature measurement outside the laboratory, Research **13**, 250 (July).

Lockett, C. J., A clinical thermometer, Lançet **1**, 1391.

Lowenthal, G. C., and A. F. A. Harper, Resistance-temperature relationship of platinum at low temperatures and its influence on precision thermometry, Brit. J. Appl. Phys. 205 (May).

Norton, H. N., Resistance elements for missile temperatures, Instr. Control Systems **33**, 922 (June).

Obrowski, W., Platinum resistance thermometer for high temperatures, Platinum Metals Rev. **4**, 102.

Pavlova, I. A., The use of semiconductor thermometers for measuring low temperatures, Proc. Intern. Congr. Refrig., 10th, Copenhagen 1959, **1**, 410.

Perelshina, A. P., The results of an experimental investigation of thermoelectromotive force in thermistors, Inzh. Fiz. Zh. **3**, 119 (Apr.).

Rogers, G. B., and F. A. Raal, Semiconducting diamonds as thermistors, Rev. Sci. Instr. **31**, 663.

Rose, V. W., Resistance temperature detector, Instr. Control Systems **33**, 790 (May).

Sharven, Yu. V., Anthracite coal thermometers for various temperature ranges, Instr. Exp. Tech. No. 1, 153 (Jan.).

Smith, R. W., An evaluation of thermistors: thermally sensitvie semiconductors, General Motors Eng. J. **7**, 14 (Oct.).

Sterling, P. H., and H. Ho, Modern trends in resistance thermometry, Ind. Eng. Chem. **52**, 59A (July).

Blue diamonds make rugged thermistors, Electronics **33**, 78 (Aug.).

Platinum resistance thermometers, ISA J. **7**, 60 (Aug.).

Resistance thermometer claimed accurate to 1560°F, Prod. Eng. 31, 9 (Aug. 29).

What do you know about platinum resistance thermometers, ISA J. **7**, 60 (Aug.).

1961

Anderson, A. R., and T. M. Stickney, Ceramic resistance thermometers as temperature sensors above 2200°R, Instr. Control Systems **34**, 1864 (Oct.).

Ballard, H. N., Response time of and effects of radiation on the VECO bead thermistor, Proc. Instr. Soc. Am. **16**, Paper No. 159–LA–61.

Barber, C. R., and W. W. Blanke, A platinum resistance thermometer for use at high temperatures, J. Sci. Instr. 38, 17 (Jan.).

Bird, F. F., and W. E. Jackson, Accuracy in resistance thermometer measurements, Proc. Instr. Soc. Am. 16, Paper No. 157–LA–61.

Edlow, M. H., and H. H. Plumb, Reproducibilities of carbon and germanium thermometers at 4.2°K, Advan. Cryog. Eng. 6, 542.

Flanagan, C. D., Continuous recording temperature measurement by resistance, Electro-Technol. (New York) 67, 158 (Apr.).

Gogin, Yu. N., A resistance thermometer made from a sparking plug, Measurement Techniques No. 5, 411 (Jan.).

Hornung, E. W., and D. N. Lyon, Characteristics of several carbon thermometer-heaters at low temperature and in magnetic fields to 100 kilogauss, Rev. Sci. Instr. 32, 684 (June).

Kachurin, L. G., Checking the sensitivity of differential resistance thermometers in unbalanced bridge circuits, Measurement Techniques No. 7, 603 (Feb.).

Kaganov, M. A., and Yu. L. Rozenshtok, Utilization of thermistors for correcting differential temperature-difference measuring circuits, Measurement Techniques No. 9, 712 (Sept.).

Kozhukh, V. Ya., Automatic measurement of small temperature differences, Measurement Techniques No. 11, 887 (Nov.).

Lindenfeld, P., Tests and comparison of carbon and germanium thermometers, Rev. Sci. Instr. 32, 9 (Jan.).

Low, F. J., Gallium-doped germanium resistance thermometers, Advan. Cryog. Eng 7, 514.

Low, F. J., Low temperature germanium bolometer, J. Opt. Soc. Am. 51, 1300.

Martin, P. E., and H. Richards, Thermistors as cryogenic temperature sensors, Advan. Cryog. Eng. 7, 522.

Mikhailov, N. N., and A. Ya. Kaganovskii, Carbon resistance thermometers for low temperatures, Inst. Exp. Tech. No. 3, 606 (May–June) ; Cryogenics 2, 98 (Dec.).

Nagao, F., S. Ohigashi, and I. Higashino, A radio-frequency resistance thermometer, Jap. Soc. Mech. Engrs. Bull. 4, 340 (May).

Nussbaum, A., Semiconductor thermometers, Control Eng. 8, 145 (Sept.).

Orlov, V. Yu., Linearization of the scales of semiconductor thermistor thermometers, Instr. Exp. Tech. No. 1, 198 (Jan.).

Pallett, J. E., The transistor as a temperature-sensing device in temperature control systems, Electron. Eng. 33, 360 (June).

Ramanadham, R., A. V. S. Murty, and M. P. M. Reddy, A thermometer for the study of microthermal structure of the turbulent layer of the ocean, J. Sci. Ind. Res. (India) 20D, 233 (June).

Ryner, H., Temperature measurement in a crystal-oven design, Electron. Design 9, 34 (May 10).

Schweb, O., and G. C. Temes, Thermistor-resistor temperature sensing networks, Electro-Technol. (New York) 68, 71 (Nov.).

Shaw, D., The transistor as a temperature-sensing device, Electron. Eng. 33, 528 (Aug.).

Ipatov, V. V., and I. Ya. Magin, Miniature resistance thermometers for checking the operation of bearings, Measurement Techniques No. 3, 196 (Mar.).

Tserikh, F. A., Experience gained in using semiconductor resistance thermometers for remote measurements of temperature, Measurement Techniques No. 3, 197 (Mar.).

Yates, B., and C. H. Panter, Indium resistance thermometer, J. Sci. Instr. 38, 196 (May).

Zavaritskii, N. V., and A. I. Shal'nikov, Preparation of miniature carbon resistance thermometers for low temperatures, Instr. Exp. Tech. No. 1, 195 (Jan.).

1962

Altenburger, S., New method for the determination of temperature from the resistance of a standard platinum-resistance thermometer, Feingeräte Tech. 11, 116.

Barber, C. R., and J. A. Hall, Progress in platinum resistance thermometry, Brit. J. Appl. Phys. 13, 147 (Apr.).

Barton, L. E., Measuring temperature with diodes and transistors, Electronics 35, 38 (May 4).

Blakemore, J. S., Design of germanium for thermometric applications, Rev. Sci. Instr. 33, 106 (Jan.).

Blakemore, J. S. Germanium for low-temperature resistance thermometry, Instr. Control Systems 35, 94 (May).

Blakemore, J. S., J. W. Schultz, and J. G. Meyers, Measurements on gallium-doped germanium thermometers, Rev. Sci. Instr. 33, 545.

Brown, R. E., W. M. Hubbard, and J. F. Haben, Low temperature thermometers from silicon carbide heating elements, Rev. Sci. Instr. 33, 1282 (Nov.).

Campanella, A. J., A telemetering thermometer, Marine Sci. Instr. 1, 39.

Chambers, J. T., Feasibility investigation and development of 2000°C resistance temperature sensor, ASTIA AD–282 358.

Gadzhiev, S. N., M. Ya. Agarunov, and K. A. Sharifov, Measurement of small temperature differences with thermistors, Zh. Fiz. Khim. 36, 897.

Glick, H. S., Thin film bolometer, Rev. Sci. Instr. 33, 1268 (Nov.).

Godin, M. C., A method of equalizing thermistors, J. Sci. Instr. 39, 241 (May).

Hehenkamp, T., Sensitive pyrometer with high relative reproductivity, Rev. Sci. Instr. 33, 229 (Mar.).

Hunter, J. J., Precision temperature measuring equipment, J. Brit. Inst. Radio Engrs. 24, 251 (Sept.).

McNamara, A. G., Semiconductor diodes and transistors as electrical thermometers, Rev. Sci. Instr. 33, 330 (Mar.).

Mikhailov, B. I., Thermistor thermometer with a temperature compensating shunt, Instr. Construct. No. 1, 22 (Jan.).

Michaylov, V. A., L. M. Zmusko, and A. G. Lazarev, A device for measuring the temperature and sampling molten metal, ASTIA AD–265 686.

Nordon, P., and N. W. Bainbridge, The use of unmatched thermistor for the measurement of temperature difference under varying ambiant conditions, J. Sci. Instr. 39, 399 (July).

Polyakov, Yu. A., and E. A. Mit-kina, A thin-film resistance thermometer, Instr. Exp. Tech. No. 4, 764 (July–Aug.).

Sandborn, V. A., Application of the hot-wire, resistance-temperature transducer to the measurement of transient flows, NASA N62–12358.

Sandri, R., R. J. Brisebois, and J. K. S. Wong, On the measurement of the average temperature of a fluid stream in a tube by means of a special type of resistance thermometer, Can., Natl. Res. Council, Div. Mech. Eng., Fuel and Lubricants Lab., Mech. Eng. Rept. MI–826 (Apr.) ; ASTIA AD–283 307.

Schiemer, E. W., A portable temperature indicator, ASTIA AD–284 328.

Vanik, M. C., and W. T. Barrett, et al., Reproducible thermistor refinement program, W. R. Grace and Co., ASTIA AD–276 659.

Diode makes accurate cryogenic thermometer, Electronics 35, 28 (Nov. 9).

Gallium arsenide diode proves good low temperature thermometer, Machine Design 34, 26 (Nov. 22).

Silicon temperature sensors, Radio Electron. Components 3, 312 (Apr.).

4. Radiation Devices

1957

Popov, V. A., Photopyrometric determination of the temperature of a burning moving particle, 6th Symposium (International) on Combustion, New Haven, Conn., 751, Reinhold Pub. Corp., N.Y.

Tyroler, J., A self-calibrating high speed photographic pyrometer, 6th Symposium (International) on Combustion, New Haven, Conn., 763, Reinhold Pub. Corp., N.Y.

1958

Gordov, A. N., A. M. Brodskii, M. S. Kaiander, and A. L. Skragan, New equipment for checking heat-power instruments, Measurement Techniques No. 6, 679 (Nov–Dec.).

Gordov, A. N., and E. A. Lapina, A technique of calculating permissible errors in industrial optical pyrometers, Measurement Techniques No. 5, 545 (Sept.–Oct.).

Kandyba, V. V., et al., Apparatus for the determination of flame temperature from the intensity of spectral lines, Trudy Komissii po Pirometrii, Vsesoyuz. Nauch. Issledovatel. Inst. Metrol., Sbornik **1958**, No. 1, 69.

Merson, Y. I., Methods and apparatus for measuring flame temperatures from their radiation in the infrared region, Trudy Komissii po Pirometrii, Vsesoyuz. Nauch. Issledovatel. Inst. Metrol., Sbornik 1958, No. 1, 22.

1959

Boyarskii, L. A., et al., Photoelectric method for precise optical pyrometric determination, Proces-Verbaux Séances Comite Inter-Nat. Poids Mesures Ser. 2, **26A**, T151.

Burlakov, V. D., Measurement of surface temperature by the brightness-balancing method, Nekotorye Vopr. Eksperim. Fiz. **1959**, No. 1, 13.

Greenshields, D. H., Spectrographic temperature measurements in a carbon-arc powered air jet, NASA Tech. Note D–169.

Katys, G. P., Dynamic properties of devices for measuring unstable temperatures, Measurement Techniques No. 3, 230 (Mar.).

Kirenkov, I. I., and E. A. Lapina, A new method for the determination of the effective wavelength of optical and photoelectric brightness pyrometers, Measurement Techniques No. 4, 288 (Apr.).

Rossler, F., Distribution of temperature of sooty flames, Ann. Phys. **4**, 396.

Vollmer, J., G. C. Rein, and J. A. Duke, Light guide radiation pyrometry, J. Opt. Soc. Am. **49**, 75.

1960

Ackerman, S., and J. S. Lord, Automatic brightness pyrometer uses a photomultiplier eye, ISA J. **7**, 48 (Dec.).

Agnew, W. G., Two-wavelength infrared radiation method measures end-gas temperatures near their peak, Abstract: S.A.E. J. **68**, 62 (Oct.).

Bell, E. E., P. B. Burnside, and F. P. Dickey, Spectral radiance of some flames and their temperature determination, J. Opt. Soc. Am. **50**, 1286 (Dec.).

Boyarskii, L. A., and V. A. Kovalevskii, A laboratory objective spectropyrometer, Measurement Techniques No. 1, 38.

Burrows, M. C., et al., Infrared pyrometer reads engine gas temperature to ±20°R, S.A.E. J. **68**, 76 (June).

Butivchenko, I. G., Pyrometer with an automatic signaling of the registration instant, Measurement Techniques No. 11, 957 (Nov.).

Finkelshtein, V. E., and N. G. Starunov, A spectropyrometer for temperature measurements with respect to monochromatic infrared radiation, Instr. Exp. Tech. No. 3, 480 (Dec.).

Finkelshtein, V. E., N. G. Starunov, A standard infrared spectropyrometer, Measurement Techniques No. 1, 35.

Hanel, R. A., The dielectric bolometer, a new type of thermal radiation detector, NASA Tech. Note D–500.

Kirenkov, I. I., Metrological features of color pyrometry, Measurement Techniques No. 1, 33 (Mar.).

Larenz, R. W., Concerning a method for the measurement of very high temperatures in nearly transparent arc columns, NASA Tech. Transl. F–54.

Lieneweg, F., and A. Schaller, New technical radiation pyrometer, with special consideration of its optical construction, Appl. Sci. Res. Section B, 241.

Lieneweg, F., and A. Schaller, Recent industrial radiation pyrometers, with special reference to their optical construction, Arch. Tech. Messen, 241 (Nov.); 267 (Dec.).

Lovejoy, D. R., Absorbing filters and high-temperature optical pyrometry, J. Opt. Soc. Am. **50**, 698.

Ludwig, H. C., The measurement of temperature in welding arcs. Trans. Am. Inst. Elec. Engrs. **79**, 191 (July); Elec. Eng. **79**, 565.

McDonald, R. K., Gas temperature by infrared, Instr. Control Systems **33**, 1926.

McDonald, R. K., Infrared radiometry, Instr. Control Systems **33**, 1527 (Sept.).

Overbye, V. D., et al., Surface temperature variations measured in an operating engine, S.A.E. J. **68**, 132 (Oct.).

Parkinson, W. H., and R. W. Nicholls, Spectroscopic temperature measurements in a shock tube using CN as a thermometric molecule, Can. J. Phys. **38**, 715.

Pepperhoff, W., Optical pyrometry in polarized light, Z. Angew. Phys. **12**, 168.

Rossler, F., Temperature measurement of a luminous flame, Opt. Acta **7**, 20 (Jan.).

Spath, H., and H. Krempl, Temperature measurements in spark discharges made with time resolved spectroscopy, Z. Angew. Phys. **12**, 8.

Russell, D. C., and F. H. Schofield, A theory of the filament temperature distribution of the tungsten vacuum-lamp, with special reference to optical pyrometry, Phil. Trans. Roy. Soc. (London) **A252**, 463 (May).

Svet, D. Ya., An automatic photoelectric color pyrometer TsEP–3, Measurement Techniques No. 6, 494 (June).

Svet, D. Ya., New methods for determining the emissivity and reflectivity coefficients and the actual temperature of a self-radiating surface, Soviet Phys.-Doklady **4**, 1375 (May-June).

Svet, D. Ya., Radiation pyrometry of metals in the near infrared, Dokl. Akad. Nauk SSSR **130**, 61.

Svet, D. Ya., and A. A. Poskachei, some infra-red spectrum pyrometry systems, Instr. Construct. No. 7, 30 (July).

Viasov, M. P., Errors in measuring the temperature of turbulent flames by optical methods, Measurement Techniques No. 11, 50 (Nov.).

Design, construction, and test of an absorption-emission pyrometer, PB 152013 (Dec.).

Measuring temperature: radiation pyrometer, Engineer **210**, 810.

Two color pyrometer tells correct temperature, Steel **146**, 144 (Apr. 4).

1961

Agnew, W. G., End gas temperature measurement by a two-wavelength infrared radiation method, S.A.E. Trans. **69**, 495.

Bekefi, G., and S. C. Brown, Microwave measurements of the radiation temperature of plasmas, J. Appl. Phys. **32**, 25 (Jan.).

Berman, H. L., The infrared radiometric method and its application to remote temperature measurement, Trans. Inst. Radio Engrs. **IE–8**, 18 (Aug.).

Burrows, M. C., S. Shimigu, P. S. Myers, and O. A. Uyehara, The measurement of unburned gas temperatures in an engine by an infrared radiation pyrometer, S. A. E. Trans. **69**, 514.

Chao, B. T., et al., Experimental investigation of temperature distribution at tool-flank surface; using infrared radiation detector, Trans. Am. Soc. Mech. Engrs. **B83**, 496 (Nov.).

Clouston, J. G., A. G. Gaydon, I. I. Glass, and I. R. Hurle, Temperature measurements of shock waves by spectrum-line reversal method, Proc. Roy. Soc. (London) **A248**, 429 (1958); **A252**, 143 (1959); **A262**, 38 1961).

Edwards, D. K., and K. E. Nelson, Maximum error in total emissivity measurements due to non-grayness of samples, ARS J. **31**, 1021, (July).

Elder, S. A. Designing phototransistor pyrometers with and without feedback, Electronics **34**, 56 (Dec.).

Euler, J., Precision in optical pyrometry, Chem.-Ing.-Tech. **33**, 448.

Felder, S. A., Designing phototransistor pyrometers, electronics **34**, 56 (Dec. 8).

Freeman, L. H., A precision photon counting pyrometer, Los Alamos Sci. Lab., New Mexico, TID–12631.

Gicquel, M., and L. Nadaud, Optical measurement of gas temperatures up to 10,000°K, Rech. Aeron. No. 84, 31 (Sept.–Oct.).

King, A. R., Compensating radiometer, Brit. J. Appl. Phys. **12**, 633.

Kolb, A. C., Measurement of plasma temperatures in the 10,000,000°K range, Office of Naval Research, Washington, D.C., ONR–9, 323.

Kostina, E. N., Temperature compensation in a radiation pyrometer for measuring "low" temperatures, Instr. Construct. No. 6, 3 (June).

Lalos, G. T., and M. Wolk, Feasibility study of the spectroscopic determination and temperature of an adiabatically compressed gas, NAVORD Rept. 6727; ASTIA AD–232696; PB 154720.

Middlehurst, J., and T. P. Jones, Photoelectric optical pyrometer, J. Sci. Instr. **38**, 202.

Millikan, R. C., Measurement of particle and gas temperatures in a slightly luminous pre-mixed flame, J. Opt. Soc. Am. **51**, 535.

Müller, H., Temperature measurement by measuring radiation, Arch. Tech. Messen, 99 (May).

Nagler, R. G., Application of spectroscopic temperature measuring method to definition of a plasma arc flame, Jet Propulsion Lab. Calif. Inst. Tech. Rept. No. 32–66; ASTIA AD–251 105.

Neuroth, N., Rapid indicating radiation pyrometer for temperature measurement between 300 and 900°C, Glastech. Ber. **34**, 197 (Mar.).

Penner, S. S., Spectroscopic methods of temperature measurements, Calif. Inst. Tech., Pasadena, Guggenheim Jet Propulsion Center, Tech. Rept. AFOSR–286 (Mar.).

Poland, D. E., J. W. Green, and J. L. Margrave, Corrected optical pyrometer readings, Natl. Bur. Std. (U.S.) Monograph 30 (Apr.).

Reynolds, P. M., Emissivity errors of infra-red pyrometers in relation to spectral response, Brit. J. Appl. Phys. **12**, 401 (Aug.).

Shiba, K., and K. Doi, Polarization optical pyrometer, Oyo Butsuri **30**, 17.

Stall, A. M., The measurement of bioclimatological heat exchange, ASTIA AD–259 074.

Sterling, P. H., and H. Ho, Radiative pyrometry, Ind. Eng. Chem. **53**, 53A (Aug.).

Takenaka, Y., Study on radiation pyrometer, J. Japan Soc. Aero. and Space Sci. **9**, 1 (Mar.).

Tingwaldt, C., and U. Schley, An optical method for the direct determination of the true temperature of glowing metal, Z. Instrumentenk. **69**, 205 (July).

Tsuchiya, S., Temperature measurement by modified Na D line reversal method, Aeron. Res. Inst. Tokyo Univ. Rept. 366 (June).

Van Laethem, R., et al., Temperature measurement of glass by radiation analysis, Am. Ceram. Soc. J. **44**, 321.

Walesch, W., and F. Becker, Continuous temperature control with an optically-regulated control thermometer, Z. Physik. Chem. (Frankfurt) **29**, 371.

Wilson, J. H., Temperature measurement with disappearing-filament pyrometer, R & D No. 3, 58 (Nov.).

Wurster, W., Spectroscopic measurement of the temperature of shock-heated oxygen, Planetary & Space Sci. **3**, 158 (Feb.).

High-speed three-color pyrometer, Natl. Bur. Std. (U.S.) Tech. News Bull. **45**, 148 (Sept.); Instr. Control Systems **34**, 1873 (Oct.).

Photoelectric pyrometer developed, Natl. Bur. Std. (U.S.) Tech. News Bull. **45**, 165 (Oct.).

Solar cells improve pyrometer precision, Engineering **182**, 362.

Symposium on optical spectrometric measurement of high temperatures, Univ. of Chicago, 1960. Optical spectrometric measurements of high temperatures, Univ. of Chicago Press, Chicago.

1962

Allen, R. D., Total emissivity and spectral emissivity at 0.65 μ of porous tungsten and tungsten bearing alloys above 1600°K, ARS J. **32**, 965.

Cooper, J., A fast total response total-radiation detector, Nature (London) **194**, 269 (Apr. 21).

Cooper, J., Minimum detectable power of a pyroelectric thermal receiver, Rev. Sci. Instr. **33**, 92 (Jan.).

Crabol, J., Solutions to some problems of wall temperature determination, O.N.E.R.A. TR 108 (Nov.).

Donahue, R. J., and R. F. Majkowski, Spectroscopic measurements of temperatures and densities in a cesium plasma, J. Appl. Phys. **33**, 3 (Jan.).

Fuhs, A. E., Spectral radiance and emissivity of plasma and temperature determination, ASTIA AD–273 590.

Funk, J. P., Ribbon thermopile, J. Sci. Instr. **39**, 32 (Jan.).

Grandin, M., G. Maillot, and P. Rodicq, Two-color pyrometer, Mesur. Control Ind. **27**, 633 (May).

Hecht, G. J., A near infrared two wavelength pyrometer, Autom. Control **16**, 51 (Mar.).

Hottel, H. C., G. C. Williams, P. H. Dundas, and W. P. Jensen, Optical methods of measuring plasma jet temperatures, WADD TR 60–676 (June 1961 and Feb. 1962); ASTIA AD–266 723.

Hukuo, N., et al., Measurement of brightness temperature by a photomultiplier, Rept. Gov. Ind. Res. Inst., Nagoya **11**, 70 (Feb.).

Kadyshevich, A. E., The present state and lines of development of optical flame pyrometry, Soviet Phys.-Uspekhi **5**, 346 (Oct.).

Knopp, C. F., C. F. Gottschlich, and A. B. Cambel, A spectroscopic technique for the measurement of temperature in transparent plasmas, AFOSR–1100; ASTIA AD–277 352.

Kostkowski, H. J., and R. D. Lee, Theory and methods of optical pyrometry, Natl. Bur. Std. (U.S.) Monograph 41 (Mar. 1).

Lader, S., Spectrographic investigation of temperatures in a plasma jet arc tunnel, Picatinny Arsenal Tech. Mem. 1001 (Apr.).

Lapworth, K. C., J. E. G. Townsend, and K. Bridgeman, Reservoir temperature measurements in a hypersonic shock tunnel by sodium line reversal. Part I. Single beam method, Aeron. Res. Council (Gt. Brit.) Rept. No. 23341 (Dec. 1961); ASTIA AD–274 711 (July).

Lee, R. D., A new photoelectric pyrometer, Mesur. Control Ind. **27**, 647 (May).

Moffit, G., Study of a temperature measuring system for the 1000°C to 2500°C range, U.S.A.F., Systems Command, Aero Systems Div., Flight Control Lab. ASD TR–61–487 (Feb.); ASTIA AD–274 794.

Penzias, G. J., S. A. Dolin, and R. H. Tourin, Infrared rays find rocket gas temperature, Abstract: S.A.E. J. **70**, 99 (July).

Peperone, S. J., X-band measurement of shock-tube plasma temperature, J. Appl. Phys. **33**, 767 (Feb.).

Schumacher, B. W., W. Wojcik, and R. C. Zavitz, Monitoring system for an oxygen steel furnace using a beta-ray gauge in the flame, Intern. J. Appl. Radiation Isotopes **13**, 123 (Mar.).

Spinrad, H., Spectroscopic temperature and pressure measurements in the Venus atmosphere, Jet Propulsion Lab., Calif. Inst. Tech. JPL–TR–32–251 (June).

Svet, D. Ya., Radiation pyrometry in the blue-violet and ultraviolet regions of the spectrum. Soviet Phys.-Doklady **6**, 907 (Apr.).

Themelis, N. J., and W. H. Gauvin, Two-wavelength pyrometer for temperature measurements in gas-solid systems, Can. J. Chem. Eng. 40, 157 (Aug.).

Tourin, R. H., Infrared techniques for temperature measurement in plasmajets, Trans. Am. Soc. Mech. Engrs. 84C, 164 (May).

Tourin, R. H., P. M. Henry, E. T. Liang, M. L. Hecht, and S. Dolin, Measurement of temperatures in ionized gases by means of infrared radiation, Wright-Patterson AFB, Aeron. Res. Lab., ARL 62–314 (Mar.); ASTIA AD–278 045.

Vali, W., and R. S. De Voto, A two-color pyrometer for the measurement of temperature and contamination level in a spark-heated hypervelocity wind tunnel, Arnold Eng. Develop. Center TDR–62–174 (Aug.).

Watson, R., Spectroscopic temperature measurements on the $OH^2\ \Sigma \rightarrow 2\pi$ band system for a transparent gas in a shock tube, Guggenheim Jet Propulsion Center, Calif. Inst. Tech., Pasadena, Tech. Rept. No. 29 (June).

Photoelectric pyrometer, Instr. Control Systems 35, 178 (July).

Photoelectric pyrometer, Instr. Pract. 16, 77 (Jan.).

5. Expansion Devices

1959

Yaryshev, N. A., Inertia response curves for liquid-in-glass thermometers, Nauch. Trudy Leningrad, Inst. Tochnoi Mekh. i Optiki 1959, No. 37, 91–8.

1960

Durieux, M., and H. van Dijk, The use of vapor-pressure thermometer in the liquid He^4 region, Proc. Intern. Congr. Refrig., 10th, Copenhagen, 1959, 1, 197.

1961

Hall, J. A., and V. M. Leaver, Stabilization of thermometers of borosilicate glass for use at high temperatures, J. Sci. Instr. 38, 178 (May).

Kebbon, E. R., Bimetal thermometers, Instr. Control Systems 34, 841 (May).

Nelson, R. C., Temperature measurement by filled system, Instr. Control Systems 34, 849 (May).

Oishi, J., High temperature determination by a new gas thermometer with constant bulb temperature. I. Measuring methods, J. Phys. Soc. Japan 16, 2056.

Swindells, J. F., Liquid-in-glass thermometers, Instr. Control Systems 34, 846 (May).

Sychev, I. A., Temperature error of liquid manometric thermometers and methods for compensation, Measurement Techniques No. 10, 803 (Oct.).

Filled-system thermometers, Instr. Control Systems 34, 1250 (July).

1962

Bendt, P. J., Liquid level He thermometer, Rev. Sci. Instr. 33, 759.

Gruzsniczki, F., Very precise calibration of glass thermometers, Metrol. Apl. (Bucharest) 9, No. 2, 49.

Schnabel, O., and H. Löber, Physical procedure in the construction of clinical thermometers, Glastech. Ber. 35, 131 (Mar.).

6. Aspirated Devices

1960

Goltsov, I. P., Pneumatic thermometer, Priborostroenie 1960, No. 5, 13.

Hochreiter, H. M., Status report on the pneumatic temperature measuring system studies for the EGCR, Oak Ridge Natl. Lab., Tenn., CF–60–12–114 (Dec. 30).

1962

Edmonson, R. B., W. R. Thompson, and A. L. Hines, Theory of a pneumatic dilution calorimetric probe, ARS J. 32, 257.

Welshimer, D. E., The experimental application of sonic-pneumatic probe systems to temperature measurement in a hypersonic air stream, U.S. Air Force, Aeron. Res. Lab. ARL–62–364.

Zalmonzon, L. A., High-response measurement of the temperature of gasses and liquids by means of the simplest pneumatic and hydraulic sensing devices, Intern. Chem. Eng. 2, 169 (Apr.).

7. Other Methods, Descriptive Articles

1958

Chukaev, K. A., A thermodynamic method of determining mean temperature of flowing gas, Measurement Techniques No. 5, 541 (Sept.–Oct.).

1960

Dean, C., Using nuclear resonance to sense temperature, Electronics 33, 52 (July).

Fasoli, U., F. S. Gaeta, F. Scaramuzzi, and J. O. Thomson, Possibility of an ionic thermometer in the He II temperature range, Proc. Intern. Congr. Refrig., 10th, Copenhagen, 1959, 1, 192.

John, R. S., Field tests of a sonic anemometer-thermometer, Bull. Am. Meteorol. Soc. 41, 618.

Leask, M. J. M., and W. P. Wolf, Magnetic method of temperature measurement between 4° and 14°K, Proc. Intern. Congr. Refrig., 10th, Copenhagen, 1959, 1, 179.

McFee, J. H., P. M. Marcus, and I. Estermann, Possible application of molecular beam techniques to the measurement of surface temperature, Rev. Sci. Instr. 31, 1013.

Meyer, R. F., A heat flux meter for use with thin film surface thermometers, Natl. Res. Council (Can.), Natl. Aeron. Estab., NRC LR–279 (Apr.).

Pokhil, P. F., V. M. Maltsev, and L. N. Galperin, Apparatus for the determination of temperature from the flame height of burning gun powder, Zh. Fiz. Khim. 34, 1131.

Scott, D. S., Flowmeters for the measurement of gas temperatures, Chem. Eng. Sci. 12, 127.

Siviter, Jr., J. H., and H. K. Strass, An investigation of a photographic technique of measuring high surface temperatures, NASA Tech. Note D–617.

High temperatures inferred from properties of heated gas-stream, Control 4, 120 (Feb.).

1961

Baskin, Y., and D. C. Schell, Rocket nozzles as temperature indicators, ARS J. 31, 1275.

Brodskii, A. D., Electroacoustic gas thermometer for the low temperature range, Measurement Techniques No. 6, 453 (Dec.).

Byler, W. H., and F. R. Hayes, Fluorescence thermography, Non-destructive Testing 19, 177 (May).

Clark, F. L., and C. B. Johnson, Determination of real-gas stagnation temperature based on mass-flow consideration J. Aerospace Sci. 28, 742 (Sept.).

Hoge, H. J., Temperature measurement based on the viscous flow of gas in a Wheatstone-bridge network, Rev. Sci. Instr. 32, 1 (Jan.).

Louisnard, N., The measurement of surface temperatures by infrared cinemaphotography, Rech. Aeron. No. 80, 29 (Jan.-Feb.).

Miller, J., Temperature-indicating paints and melts, Eng. Mater. and Design 4, 728 (Nov.).

Schultz-Grunow, F., and G. Wortberg, Interferometric measurements in a flat flame, Intern. J. Heat Mass Transfer 2, 56.

Taylor, R. D., A low temperature thermometer utilizing the Mossbauer effect, Los Alamos Sci. Labs., New Mexico, TID 12627.

1962

Apfel, J. H., Acoustic thermometry; measuring temperatures by means of the velocity of sound in a gas, Rev. Sci. Instr. **33,** 428 (Apr.).

Best, G. T., and T. N. L. Patterson, Temperature determination from a cloud of alkali vapour in the upper atmosphere, Queen's Univ. Belfast (Gt. Britain), AFCRL–62–1049.

Cataland, G., and H. H. Plumb, Acoustical interferometer employed as an instrument for measuring low absolute temperature, J. Acoust. Soc. Am. **34,** 1145 (Aug.).

Danberg, J. E., The equilibrium temperature probe, a device for measuring temperatures in hypersonic boundary layers, Naval Ordnance Lab., White Oak, Md., Aeroballistic Research Rept. 146, NOL TR–61–2 (Feb.).

Fletcher, K. A., Precise temperature measurement and control using a.c. bridge techniques, SIMA Rev. **2,** 93 (July).

Fournet, M., Kinetic measurement of temperatures, J. Phys. Radium **23,** Suppl. No. 3, 25A.

Gorini, I., and S. Sartori, Quartz thermometer, Rev. Sci. Instr. **33,** 883 (Aug.).

Grey, J., and P. F. Jacobs, A calorimetric probe for the measurement of high gas temperature, Guggenheim Labs. for the Aerospace Propulsion Sciences, Princeton, N.J., Aeron. Eng. Lab. Rept. 602 (Apr.); AD–275 359.

Grey, J., P. F. Jacobs, and M. P. Sherman, Calorimetric probe for the measurement of extremely high temperatures, Rev. Sci. Instr. **33,** 738 (July).

Higgins, L. L., Measurement of temperature, salinity and velocity of water through electrolytic conductivity measurements, ASTIA AD–276 746.

Hisam, E., and W. Bez, Development of a diagnostic device for the determination of mean effective temperatures in plasmas using shock wave measurements, PB 153626 (LC); ASTIA AD–235 859.

Long, V. D., Estimation of the mean radiating temperature of a cylinder of combustion gas, J. Inst. Fuel **35,** 431 (Oct.).

Schumacher, B. W., W. Wojik, and R. C. Zavitz, Monitoring system of an oxygen steel furnace using a β-ray gage in the flame, Intern. J. Appl. Radiation Isotopes **13,** 123.

Wade, W. H., and L. J. Slutsky, Quartz crystal thermometer, Rev. Sci. Instr. **33,** 212 (Feb.).

Walsh, D., The measurement of temperature in an argon shock tube by microwave noise radiation, Aeron. Res. Council (Gt. Brit.) ARC 22930 (June 13).

Low temperature ultrasonic thermometer, Engineering **194,** 730 (Nov. 30).

Temperature measurement by change in hardness in metals, Motortech. Z. **23,** 49.

8. Special Applications, Method Not Specified in Title

1957

Moutet, A., Instantaneous flame-temperature measurements, France, O.N.E.R.A. Tech. Rept. No. 88.

1960

Affleck, J. H., Measuring cathode temperatures, Electronics **33,** 80 (Apr. 15).

Becker, F. S., and F. M. Kepler, How to measure tube-wall temperature, Oil Gas J. **58,** 101 (July 18).

Culpin, M. F., and K. A. Martin, Instruments for measuring the temperature of a running thread-line and of a jet of viscous liquids, J. Sci. Instr. **37,** 250 (July).

Daunt, J. G., Thermometers for the temperature range 0.1°K to 20°K, Ohio State Univ. Res. Found. Rept. 712 (Dec.); PB 149504.

Dyakonov, I. I., Certain problems in measuring the temperature of rotating objects, Measurement Techniques No. 1, 44 (Nov.).

Eckert, E. R. G., R. Eichhorn, and T. L. Eddy, Measurement of temperature profiles in laminar and turbulent axisymmetric boundary layers on a cylinder with non-uniform wall temperature, USAF, Aeron. Res. Lab., Wright-Patterson AFB, ARL TN 60–61 (Dec.).

Hame, T. G., W. H. Peake, et al., Preliminary analysis of methods for temperature determination at altitudes above 120,000, Ohio State Univ. Res. Found. Rept. 973–2 (May); PB 152669 (LC); ASTIA AD–242 206.

Joseph A. J. V., Fuel nozzle temperature measurement, Engineering **190,** 762.

Joseph, A. J. V., Temperature measurement of fuel injection nozzles, Hawker Siddeley Tech. J. **2,** 2 (Aug.).

Losev, S. A., and N. A. Generalov, Measuring the temperature of a gas downstream from a shock wave, Instr. Exp. Tech. No. 3, 454 (Apr.).

Ryley, D. J., An indirect method of measuring static temperature in supersaturated expanding steam, Engineer **210,** 343.

Stewart, L. E., New Ways to measure temperature; 1000F and above, Power **104,** 218 (May).

Sturgeon, G. M., New wire temperature meter, Wire and Wire Prod. **35,** 721 (June).

Sturgeon, G. M., Wire temperature measurement, Wire Inds. **27,** 261 (Mar.).

Svinoruk, V. I., and L. F. Lependin, Temperature measurement at a point on the surface of an electrically conductive sample, Ind. Lab. **26,** 785.

Thun, R. E., Rugged film resistor thermometer for the measurement of surface temperature, Rev. Sci. Instr. **31,** 446 (Apr.).

Wood, R. D., Heated hypersonic stagnation-temperature probe, J. Aerospace Sci. **27,** 556 (July).

Flame temperature determination, Instr. Control Systems **33,** 821 (May).

Precision thermometry at low temperature, Electronics **33,** 98 (June).

Thermometer for 600 deg. C plus. Space/Aeronautics **33,** 242 (May).

Thermometry for low temperature, Instr. Control Systems **33,** 1917.

Wire temperature meter, Metallurgia **62,** 64 (Aug.).

1961

Beattie, J. R., The measurement of the temperature of transparent materials, Acta Imeko, 210.

Blackshear, P. L., Probe senses fast temperature changes, Chem. Eng. News **39,** 39 (Aug. 28).

Blackshear, P. L., and L. M. Fingerson, Some new measuring techniques in high temperature measurements, James Forrestal Res. Center, Princeton Univ., N.J., Tech. Rept. MIN–3–P (Dec.); ASTIA AD–270 364.

Brodskii, A. D., and A. V. Savataev, A new method of absolute temperature measurement, Measurement Techniques No. 5, 397 (Jan.).

Brown, E. A., et al., Steady-state heat flux gauge, Rev. Sci. Instr. **32,** 984 (Aug.).

Daunt, J. G., and D. O. Edwards, Measurement of temperature below 1 degree K, ASTIA AD–255 582.

De Leo, R. V., F. D. Werner, and F. W. Hagen, Measurement of mean temperature in a duct, Instr. Control Systems **34,** 1659 (Sept.).

Elliott, R. D., Dynamic behavior of missile skin temperature transducers, Proc. Instr. Soc. Am. **16,** Paper No. 160–LA–61.

Gordov, A. N., et al., Complex of metrological work on establishing methods and apparatus for precise measurements of high temperature, Measurement Techniques No. 1, 31 (Jan.).

Kazachkov, R. V., Measurements of the piston temperature of high-speed internal combustion engines, Measurement Techniques No. 5, 402 (Jan.).

Lemke, B., Determination of final temperature in a gun tunnel, J. Aerospace Sci. **28,** 827 (Oct.).

Moore, F. D., and R. B. Mesler, Measurement of rapid surface temperature fluctuations during nucleate boiling of water, A.I.Ch.E. J. **7,** 620 (Dec.).

Netter, P., G. Seyffarth, and H. John, Design and function of a submerged temperature measuring device in an open hearth steelworks, Neue Hütte 6, 475 (Aug.).

Ney, E. P., R. W. Maas, and W. F. Huch, The measurement of atmospheric temperature, J. Meteorol. 18, 60 (Feb.).

Overbeck, C. J., Apparatus review; demonstration thermometer, Am. J. Phys. 29, 368 (June).

Rae, D., A measurement of the temperature of some frictional sparks, Combust. Flame 5, 341.

Reimer, L., and R. Christenhuss, a reversible temperature indicator in the form of an evaporated layer for estimating the temperature of an object in the electron microscope, Naturwissenschaften 48, 619.

Schoolman, S. A., and D. A. McBlain, The measurement of temperature changes in an adiabatic expansion, Proc. Iowa Acad. Sci. 68, 439.

Stewart, L. E., Measure gas temperature by multipoint traversing, Power 105, 180 (Feb.).

Walker, R. E., and S. E. Grenleski, Instrument for measuring total incident radiant heat transfer to a jet engine surface, ARS J. 31, 77 (Jan.).

Werner, F. D., R. V. De Leo, and B. Rogal, Total temperature probes, Flight 80, 737.

Measurement of engine temperature, Engineer 211, 386.

Pyrometer for moving surfaces, Control 4, 120 (Feb.).

Temperature measurement of moving engine components Shell Aviation News No. 281, 8.

1962

Baldwin, A. L., Dynamic temperature coefficient measurements, Instr. Control Systems 35, 97 (May).

Cooper, J., A fast-response pyroelectric thermal detector, J. Sci. Instr. 39, 467 (Sept.).

Ebel, H., A method of measuring rapidly changing temperatures, Naturwissenschaften 49, 80.

Eschenbach, R. C., Water temperature measurement, Am. J. Phys. 30, 604 (Aug.).

Fletcher, K. A., Industrial temperature measurement, Ind. Electron. 1, 66 (Nov.).

Hadfield, D., Periodic pyrometer checks accelerate steel process, Steel 150, 92 (Feb.).

Land, T., Advances in glass temperature measurement, Glass Ind. 43, 244 (May).

Magnus, A. B., Calculating temperatures in hydraulic systems, Hydraulics and Pneumatics 15, 69 (Nov.).

Manson, D. J., Temperature measurements in oxy-hydrogen flames using scattered neutrons and conventional methods, ASTIA AD-277 747.

Muntz, E. P., Static temperature measurements in a flowing gas, Phys. Fluids 5, 80.

Rosenberg, N. W., W. H. Hamilton, and D. J. Lovell, Rocket exhaust radiation measurements in the upper atmosphere, Appl. Optics 1, 115 (Mar.).

Swain, R. R., Pyrometer monitors molten metal temperatures, Steel 150, 78 (June 4).

Vidal, R. J., Transient surface temperature measurements, Cornell Aeron. Lab. Rept. 114 (Mar.); ASTIA AD-275 818.

Woodley, J. G., and J. F. W. Crane, A boundary layer probe for the direct measurement of aerodynamic heating, Royal Aircraft Establ. (Gt. Brit.), Tech. Note No. Aero 2808 (Jan.); ASTIA AD-274 842 (July).

Maximum temperature indicators, R & D, 48 (Jan.).

Measuring traction motor commutator temperature, Engineer 214, 30 (July 6).

Miniature thermometer for moving parts, Engineering 194, 800.

Probe for measurements in high-temperature fluids, Control 5, 96 (July).

Surface pyrometer for high-speed cylinders, Engineer 214, 960 (Nov. 30).

Temperature measurement of metallic surfaces, Eng. Mater. and Design 5, 116 (Feb.).

9. Nuclear Applications of Temperature Measurement

1960

Clark, R. G., Clamp-on resistance temperature detectors for reactor use, Metal Progr. 78, 156 (Aug.).

Gilbert, R. L. G., Analogue-digital converter with long life, equipment designed for temperature measurement in nuclear power stations, J. Brit. Inst. Radio Engrs. 20, 529 (July).

Guskov, Yu. K., and A. V. Zvonarev, Thermocouple system for measurement of large neutron fluxes, Instr. Exp. Tech. No. 5, 821 (June).

Harmon, T. P., An electroplated neutron thermopile for the 3-Mw GTR, NARF-59-20T; MR-N-226; PB 150016 (LC).

Kosut, B. S., Specifications for thermocouples, stainless steel sheathed, corrosion resistant for nuclear service, General Electric Co., Hanford At. Prod. Operation, Richland, Wash., HW-64744 (Apr.).

Lovett, D. B., Use of isolated junction sheathed thermocouples for moderator temperature measurements, General Electric Co., Hanford At. Prod. Operation, Richland, Wash., HW-65738 (June 16).

1961

Clough, D. J., Temperature control and measurement in sodium-filled irradiation capsules, AERE R-3689 (Apr.).

Ross, C. W., Effect of thermal neutron irradiation on thermocouples and resistance thermometers, Trans. Inst. Radio Engrs. NS-8, 110 (Oct.).

Shenault, L. H., and T. F. McGrath, Reactor core temperature measurement, ARS J. 31, 799 (June).

Development of high temperature sensors, U.S. At. Energy Comm. PWAC-339 (June 30).

Driesner, A. R., L. P. Kempter, C. P. Landahl, C. A. Linder, and T. E. Springer, High temperature thermocouples in the Rover Program, Trans. Inst. Radio Engrs. NS-9, 247 (Jan.).

McCann, J. A., Temperature measurement theory, At. Energy Comm. Rept. KAPL 2067-2 (Apr. 1).

Ross, C. W., Effect of thermal neutron irradiation on thermocouples and resistance thermometers, Commun. Electron., 192 (July).

10. Associated Equipment and Testing Procedure

1951

Tarr, P. R., Methods for connection to revolving thermocouples, NACA Res. Mem. E50J23a (Jan. 18).

1958

Lalos, G. T., R. J. Corruccini, and H. P. Broida, Design and construction of a black body and its use in the calibration of a grating spectroradiometer, Rev. Sci. Instr. 29, 505.

Levin, G. M., and V. I. Volmir, Characteristic thermal inertia curves of conventional thermocouples and resistance thermometers, Measurement Techniques No. 6, 686 (Nov-Dec.).

Nikiforov, V. D., Testing thermocouples and pyrometric instruments, Measurement Techniques No. 5, 548 (Sept.-Oct.).

1959

Arefev, A. A., Three-channel amplifier equipment for thermocouples, Measurement Techniques No. 2, 120 (Feb.).

1960

Almond, R. J., Errors in thermocouple circuits, Instr. Control Systems 33, 80 (Jan.).

Ashekhmin, V. I., and E. V. Kovalskii, A slide rule for thermocouples, Measurement Techniques No. 2, 115 (Nov.).

Briscoe, W. L., Improved bridge for low temperature measurements, Rev. Sci. Instr. 31, 999 (Sept.).

Dauphinee, I. T. M., and H. Preston-Thomas, Direct reading resistance thermometer bridge, Rev. Sci. Instr. 31, 253.

Eisner, R. L., Apparatus for accurate measurement of thermoelectric power, Rev. Sci. Instr. 31, 462 (Apr.).

Foltz, H. L., and W. R. Brown, Self-sealing thermocouple gland, Machine Design 32, 176 (May 12).

Harman, G. G., Hard gallium alloys for use as low contact resistance electrodes and for bonding thermocouples into samples, Rev. Sci. Instr. 31, 717 (July).

Holden, T. S., Multipoint digital temperature recorder with punched tape output, J. Sci. Instr. 37, 269 (Aug.).

Kane, M. V., Thermocouple current indicators, Instr. Control Systems 33, 608 (Apr.).

Kurtzrock, R. C., Quick connector for multipoint thermocouple assemblies, Rev. Sci. Instr. 31, 457 (Apr.).

Levin, G. M., and V. I. Volmir, Methods for testing thermal inertia in thermocouples and resistance thermometers, Measurement Techniques No. 4, 309.

Moeller, C. E., Do shields improve thermocouple response? ISA J. 7, 56 (Aug.).

Premak, W., and E. Edwards, Large recording potentiometer errors caused by furnace leakage currents, Rev. Sci. Instr. 31, 1242 (Nov.).

Ross, G. S., and H. D. Dixon, Automatic precise recording of temperature, J. Res. Natl. Bur. Std. (U.S.) 64C, 271.

Sirota, A. M., et al., Methods of testing thermocouples and thermocouple wires, Ind. Lab. 26, 126 (Jan.).

Multipoint temperature scanner, Engineer 209, 693.

USN develops new thermowell for high-velocity steam, ISA J. 7, 34 (Nov.).

1961

Accinno, D. J., A vacuum furnace for high temperature thermocouple calibration, Engelhard Ind., Tech. Bull. 2, 16 (June).

Andreev, S. V., B. K. Martens, and A. N. Trushinskii, Transistorized instrument for remote measurement and control of temperature, Measurement Techniques No. 11, 882 (Nov.).

Antier, G., A thermostatic enclosure for thermocouples, Mesur. Control Ind. No. 294, 1335 (Nov.).

Avdeev, A. I., D. A. Ilmenskii, and M. D. Notarius, Application of asymmetrical bridge in electromagnetic measuring instruments for resistance thermometers, Instr. Construct. No. 6, 1 (June).

Beerman, H. P., High temperature black body radiation source, Bull. Am. Ceram. Soc. 40, 308 (May).

Bratkowski, W., Fast-response temperature controls, Prod. Eng. 32, 40 (May 29).

Freeman, R. J., Thermoelectric stability tests, General Electric Co., Nuclear Mater. and Propulsion Operation, Cincinnati, U.S. At. Energy Comm. APEX–746 (Aug.).

Godin, M. C., Simple bridge for the direct measurement of temperature differences, J. Sci. Instr. 38, 330 (Aug.).

Green, B. A., Simple ac resistance bridge using a dc breaker amplifier, Rev. Sci. Instr. 32, 364.

Kayander, M. S., Differential instrument for comparing radiation pyrometers, Measurement Techniques No. 2, 119 (Feb.).

Middlehurst, J., Mercury switch for establishing the true electrical zero in precise thermocouple measurements, J. Sci. Instr. 38, 165 (Apr.).

Moodie, W. C., Thermal switches and transducers for discreet and continuous temperature control, Space Aeronautics 36, 127 (July).

Nalle, D. H., Accurate recordings of fast-changing temperatures, ISA J. 8, 58 (June).

Pak, V., Computation of the basic parameters for a telescope of a radiation pyrometer with a thermistor, Measurement Techniques No. 12, 879 (Dec.).

Seshadri, T. N., and S. P. Jain, A constant ice point junction for thermocouples in continuous use for long periods, J. Sci. Ind. Res. (India) 20D, 161 (Apr.).

Simmons, F. S., A. G. De Bell, and Q. S. Anderson, A 2000°C slit-aperture blackbody source, Rev. Sci. Instr. 32, 1265 (Nov.).

Sutcliffe, J., Direct-reading resistance-thermometer bridge, Instr. Control Systems 34, 293 (Feb.).

Testardi, L. R., and G. K. McConnel, Measurement of the Seebeck coefficient with small temperature differences, Rev. Sci. Instr. 32, 1067 (Sept.).

1962

Ballard, G. G., Transistor thermocouple trip amplifier, J. Brit. Inst. Radio Engrs. 23, 35 (Jan.).

Bansal, T. D., Calibration equipment for surface pyrometers and pipe thermometers, J. Sci. Instr. 39, 232 (May).

Belling, P. R., High-pressure thermocouple feed-through, Instr. Control Systems 35, 119 (Nov.).

Benedict, B. V., Vibration test of thermocouple type 300RD P/N 8968365, ASTIA AD–275 686.

Bose, B. N., Thermocouple well design, ISA J. 9, 89 (Sept.).

Boudreaux, P. J., Providing thermocouple compensation at low cost, Electronics 35, 72 (Nov.).

Bridle, J. A., and J. L. Morgan, High-speed temperature recording, J. Iron Steel Inst. (London) 200, 318 (Apr.).

Brownwood, J. B., Thermocouple compensating circuit design, Electronics 35, 98 (Jan. 5).

Cameron, G., and R. L. Blanchard, Design and operation of a pressure-type cryostat for thermometer calibration in the liquid-hydrogen region, ISA Trans. 1, 255 (July).

Greenwood, T. L., Indicator warns of excessive rise rates, Electronics 35, 54 (Feb.).

Katadeladze, K. S., E. N. Zedginidze, and T. V. Nozadze, Thermocouple immersion tips for measuring the temperature of molten metals, Ogneupory 27, 223.

Katateladze, K. S., E. N. Zedginidze, and P. A. Pirumova, Thermocouple protection tubes made of carborundum with a nitride binder, Stal 22, 237.

Kocho, V. S., A. D. Panasyuk, G. V. Samsonov, A. G. Strelchenko, and I. G. Khavrunyak, Zirconium boride cermet protection tubes for thermocouples, Stal 22, 317.

Lash, J. B., Inexpensive testing for precision sensors, Instrumentation 15, 4.

MacDonald, W. R., Simple amplifier for use with metal-film thermometers in timing applications, J. Sci. Instr. 39, 35.

Mandt, R. D., Fusing thermocouple leads, ISA J. 9, 82 (Nov.).

McAllan, J. V., Selector switch to avoid transient self-heating in resistance thermometers, J. Sci. Instr. 39, 447.

Manigan, J., and E. J. Nichols, Thermocouple sensing tip, Mater. in Design Eng. 55, 147 (Apr.).

Pitts, E., and P. T. Priestly, Constant sensitivity bridge for thermistor thermometers, J. Sci. Instr. 39, 75 (Feb.).

Priem, M., Method for sealing thermocouple wire through fused silica for use at high temperature, J. Sci. Instr. 39, 130 (Mar.).

Ramage, R. V., Ultra-high pressure seals for instrumentation leads, Design Eng. 55, 156 (May).

Rautio, W. S., Metal-sheathed ceramic-insulated thermocouples; swage or draw?, Instr. Control Systems 35, 101 (May).

Samsonov, G. V., P. S. Kislyi, and A. D. Panasyuk, Zirconium boride tips for immersion thermocouples, ASTIA AD–283 891.

Sondericker, J., Zener diodes replace thermacouple ice-junction, Electron. Design 10, 42 (Feb. 1).

Thomas, D. B., A furnace for thermocouple calibrations to 2200°C, J. Res. Natl. Bur. Std. (U.S.) 66C, 255.

Turco, J. F., J. Hickey, and I. Bar-Gadda, Sample holder for use in the measurement of thermoelectric power of thermoelectric materials, Rev. Sci. Instr. 33, 384 (Mar.).

Whiteway, S. G., Sintering long thermocouple sheaths without warping, Am. Ceram. Soc. Bull. 41, 95 (Feb. 15).

Wright, H. C., A thermocouple slide-rule, J. Sci. Instr. **39,** 238 (May).

An improved resistance thermometer bridge, Instr. Pract. 16, 191 (Feb.).

Improved resistance-thermometer bridge, Electro-Technol. (New York) **70,** 146 (Oct.).

Sealing thermocouples in pressure vessels, Engineering **193,** 4.

Time temperature integration device, General Electric Co., ASTIA AD–271 416.

11. General

1958

Frost, F. E., High temperature production and measurement—a bibliography, Lawrence Radiation Lab., Univ. Calif., Livermore, Calif., UCRL–5409.

1959

Allegre, R., et al., Etudes de Pyrometrie pratique, Editions Eyrolles, Paris.

Bayley, H. G., Recent developments in the precise measurement of temperature, J. Inst. Engrs. Australia **31,** 227 (Sept.).

Hurwitz, H., Review of methods for measuring temperatures up to 20,000°K, Naval Ordnance Lab., White Oak, Md., NAVORD–6680 (July 6); ASTIA AD–232 698; PB 154722 (LC).

Lier, R. H., High temperature measuring techniques 1948 to present (bibliography), U.S. Sci. Lab. Los Alamos, LAMS–2325.

McCoy, E., Bibliography on gas temperature measurement, United Kingdom At. Energy Authority, I. G. information series 68 (RD/CA).

Strelkov, P. G., and D. I. Sharevskaya, Results of comparing temperatures calculated by the M SH T and the comparison method, Measurement Techniques No. 2, 124 (Feb.).

Theoretical and experimental research in thermoelectricity (Dec.), PB 161468.

1960

Angello, S. J., Recent progress in thermoelectricity, Elec. Eng. **79,** 353 (May).

Beltran, A. A., A preliminary literature survey. High temperature strain and temperature sensing devices, Lockheed Aircraft Corp., Missiles and Space Division, Special bibliography SB–60–3.

Combes, J. J., Temperature measuring devices, Automation **7,** 87 (May).

Coxon, W. F., Temperature measurement and control, Macmillan, N.Y.; Heywood and Co., London.

Grimes, W. R., and D. R. Cuneo, eds., High temperature thermometry seminar, held Oct. 1–2, 1959 at Oak Ridge Natl. Lab., U.S. At. Energy Comm. TID–7586 (pt. 1) (Aug.).

Hedge, J. C., et al., Temperature measuring techniques, Wright Air Develop. Div., Wright-Patterson AFB, WADD–TR–60–487 (June); ASTIA AD–253 483.

Jackson, E. W., Temperature measurement and control, Chem. Process Eng. **41,** 139 (Apr.).

Kebbons, E. R., Miscellaneous temperature-measuring methods, Instr. Control Systems **33,** 1921 (Nov.).

Kostkowski, H. J., The accuracy and precision of measuring temperatures above 1000°K, International Symposium on high temperature technology, Asilomar conference grounds, Calif., Oct. 5–9, 1959, McGraw-Hill Book Co., N.Y., 1960, p. 33.

Meyer-Wittig, O., Calculation for determining the response lag of temperature probes under periodic changes of temperature, Electrotech. **38,** 501 (Sept. 29).

Plumb, H. H., Secondary thermometry grows more precise, Chem. Eng. News **38,** 40 (Oct. 31).

Stewart, L., How to handle the problem of measuring low temperature, Power **104,** 208 (Nov.).

Werner, F. D., Total-temperature measurements, Instr. Control Systems **33,** 800 (May).

Thermoelectricity abstracts (Mar.), PB 161301 (OTS).

Thermoelectricity abstracts, PB 161174 (Dec.).

Thermoelectricity, OTS selective bibliography SB–432 (Sept.).

Thermopiles and thermocouples, OTS selective bibliography SB–430 (Aug.).

1961

Awano, M., Precisionization of gas thermometry, J. Phys. Soc. Japan **16,** 2560.

Baker, H. D., E. A., Ryder, and N. H. Baker, Temperature measurement in engineering, Vol. II, John Wiley & Sons, Inc., N.Y.

Brinich, P. F., Recovery temperature, transition and heat-transfer measurements at Mach 5, NASA Tech. Note D–1047.

Danlouz-Dumensnils, M., From the Florentine thermometer to that of Lyons, Mesur. Control Ind. **26,** 1023 (Sept.).

Kallen, H. P., Handbook of instrumentation and controls, McGraw-Hill Book Co., N.Y.

Kennedy, J. H., et al., High temperature measurement and production—a bibliography, Lawrence Radiation Lab., Univ. Calif., Livermore, Calif., UCRL–6424.

Pivovonsky, M., and M. Nagel, Tables of blackbody radiation functions, Macmillan Co., N.Y.

Snyder, P. E., Chemistry of thermoelectric materials, Chem. Eng. News **39,** 102 (Mar. 13).

Sterrett, S. J., Improved manufacturing techniques for blood-flow probes, J. Sci. Instr. **38,** 59 (Feb.).

Upton, Jr., E. F., Measuring industry's hot spots, Plant Eng. **15,** 117 (Oct.); 109 (Nov.).

Yaryshev, N. A., Inertial parameters of resistance thermometers and thermocouples, Measurement Techniques No. 9, 716 (Sept.).

Yeaple, F., a new look at temperature-measuring transducers, Prod. Eng. **32,** 49 (May 22).

The platinum metals in temperature measurement, Platinum Metals Rev. **5,** 89 (July).

1962

Ball, I. D. L., Temperature-measurement techniques discussed, R&D No. 13, 30 (Sept.).

Coombe, R. A., Measuring temperature and Mach number in a high temperature gas flow, R&D No. 15, 38 (Nov.).

Hertzfeld, C., ed. in chief, Temperatures, its measurement and control in science and industry. Volume 3, part 1, Basic concepts, standards and methods, F. G. Brickwedde, ed.; Volume 3, part 2, Applied methods and instruments, A. E. Dahl, ed., Rheinhold Pub. Corp., N.Y.

Holland, M. G., L. G. Rubin, and J. Welts, Temperature measurement from 2°K to 400°K, Instr. Control Systems **35,** 89 (May).

Holzbock, W. G., Instruments for measurement and control, 2nd ed., Reinhold Pub. Corp., N.Y.

Hunter, J. J., Precision temperature measuring equipment, J. Brit. Inst. Radio Engrs. **24,** 251 (Sept.).

Huovila, S., Contributions to the measurement and interpretation of small-scale temperature fluctuations, Academic Bookstore, Helsenki, Finland.

Katz, A. J., Thermal testing, Space-Aeronautics **38,** 30 (Oct.).

Lathrop, P., Technique for temperature measurement, Ind. Phot. **11,** 12 (Mar.).

Liddiard, F. E., and J. H. Heath, Temperature measurement, Control, part 1, **5,** 95 (Sept.); part 2, **5,** 109 (Oct.); part 3, **5,** 110 (Nov.).

Lieneweg, F., Temperature measurement, Arch. Tech. Messen No. 313, 47 (Feb.).

White, F. J., Accuracy of thermocouples in radiant-heat testing, Exp. Mech. **2,** 204 (July).

Yarishev, N. A., and A. S. Makhnovetskiy, Errors in the measurement of transient surface temperatures, ASTIA AD–265 800.

Bibliography of Temperature Measurement

January 1963 to December 1965

Lief O. Olsen and Carl Halpern

There are presented in this supplement to NBS Monograph 27, "Bibliography of Temperature Measurement, January 1953 to June 1960" issued April 6, 1961 and Supplement 1, July 1960 to December 1962 issued September 13, 1963, about 1200 additional references to the field of temperature measurement. The period covered is from January 1963 to December 1965 with some earlier references which came to our attention. With the exception of Part 1 which has been changed to include theory; calibration and temperature scales, the arrangement of material is the same as in Monograph 27. The journal abbreviations used are those employed in Chemical Abstracts.

Key words: Temperature, thermometry, thermocouples, thermistors, resistance thermometer, and radiation pyrometry

INTRODUCTION

The material contained herein was collected from two general sources: scientific and technical journals and reports of investigations sponsored or conducted by various governmental agencies. English, German, and French journals and translations in English of Russian journals were covered as well as the more commonly used abstract journals. Some references to material in other languages, obtained from the abstract journals, are also included. To obtain references to governmental reports the following were consulted: Technical abstract Bulletin, Armed Services Technical Information Agency; Scientific and Technical Aerospace Reports, National Aeronautics and Space Administration (NASA); Nuclear Science Abstracts, United States Atomic Energy Commission; and U.S. Government Research Reports, Office of Technical Information, U.S. Department of Commerce. While reasonably complete coverage was intended, it is inevitable that oversights and other unintentional omissions have occurred.

The topical subdivisions are shown in the table of contents. Each subdivision is arranged chronologically and within the chronological sections, alphabetically by author. "Anonymous" articles appear at the end of each section.

The period covered is from January 1963 to December 1965 with some earlier entries which had been overlooked in the original bibliography NBS Monograph 27 and its first supplement.

The journal abbreviations used are those employed in Chemical Abstracts. Volume numbers are underlined and date of issue is given where page numbers do not run consecutively throughout a given volume. Since the year of issue apears at the head of each chronological section, this is not repeated in the individual references.

Numbers prefixed by the letters AD refer to report numbers in the Technical Abstract Bulletin; those by N63, N64, and N65 are identifying numbers in the Scientific and Technical Aerospace Reports; and those by NSA refer to the report numbers in Nuclear Science Abstracts.

1. Theory, Calibration and Temperature Scales

1958

Lowenthal, G.C., W.R.G. Kemp and A.F.A. Harper, Temperature scale down to 20°K using platinum resistance thermometers, Low Temp. Phys. Thermodyn., Proc. Meeting Comm. I Intern. Inst. Refrig., Delft, Neth., 107.

1960

Aryhanov, A. S., A. N. Gordov, and U. V. Diikov, A new determination of the melting point of gold, Tr. Vses. Nauchn.-Issled. Inst. Metrol., 49, 5.

1961

Hudson, R. P., Low temperature thermometry, Exptl. Cryophys. 1961, 213.

Sherman, R. H., T. R. Roberts, and S. E. Sydoriak, Helium-3 vapour pressures: a standard for improved thermometry below 1°K, Bull. Inst. Intern. Froid, Annexe 5, 1961, 125.

1962

Barber, C.R., Boiling points of hydrogen, Comite Consultatif Thermometrie, Comite Intern. Poids Mesures, 6e, Sevres, France, 1962, 97.

Bragin, B.K., Solidification point of copper, Measurement Techniques No. 3, 214 (Sept.).

Brodsky, A. D., V. P. Kemlevsky, and A.V. Savateev, New methods of realizing the thermodynamic scale in the low temperature region, Comite Consultatif Thermometrie, Comite Intern. Poids, Mesures, 6e, Sevres, France, 1962, 171.

Jaumot, F.E., Thermoelectricity, Advanced Electron. and Electron Phys. 17, 207.

Kirenkov, I.I., et al, New measurements of the thermodynamic temperatures of the reference points of tin, cadmium zinc and gold, Izmeriteln. Tekhn. No. 9, 31.

Kirenkov, I. I., Investigation of thermodynamic temperature reference points, Measurement Techniques No. 4, 286 (Sept.).

Pak, V., Calibration of thermocouples in a dynamic condition, Measurement Techniques No. 6, 475 (Dec.).

Sherman, R. H., T_{62} Helium-3 temperature scale IV. Tables, U.S. At. Energy Comm. LAMS - 2701.

1963

Benedict, R.P., The generation of thermocouple reference tables, Electro-Technology (N.Y.) 72, 80 (Nov.).

Benedict, R. P., and H. F. Ashby, Emperical determination of thermocouple characteristics, Trans. ASME (J.Eng. Power) 85A, 9.

Benedict, R.P., and J.W. Murdock, Steady-state thermal analysis of a thermometer well, Trans. ASME (J. Eng. Power) 85A, 235.

Bonanno, A. M., Commercial laboratory temperature calibrating services with reference traceable to the National Bureau of Standards, Proc. Instr. Soc. Am. 18 Paper No. 57-2-63.

Bragin, B.K., Calibration of standard thermocouples at the freezing point of copper, Tr. Inst. Kom. Standartov, Mer i Izmerit. Priborov pri Sov. Min. SSSR 1963, 97.

Brickwedde, F. G., International practical temperature scale, Phys. Today 16, 24 (May).

Brindley, J. H., Calibration of surface-attached thermocouples on a flat-plate fuel element by electrical analogue and analytical techniques, Trans. Am. Nucl. Soc. 6, 333 (Nov.).

Brodskiĭ, A. D., V. P. Kremlevskii, and A. V. Savateev, New methods of producing the thermodynamic scale at low temperatures, Measurement Techniques, No. 9, 757 (Apr.).

Gramburg, G., and H. G. Flust, Developments in the field of thermoelectricity, Naval Engrs. J. 75, 925.

Hall, J. A., Role of the platinum-resistance thermometer in the International Practical Scale of Temperature, Proc. Inst. Elect. Engrs. 110, 1502 (Aug.).

Kamochkina, E. M., and N. N. Ergardt, Constant solidification point of palladium, Tr. Inst. Kom. Standartov, Mer i Izmerit. Priborov pri Sov. Min. SSSR No. 71, 237.

Kirenkov, I.I., New evaluation of the thermodynamic temperatures of the tin, cadmium, zinc and gold reference points, Measurement Techniques No. 9, 752 (April).

Kirenkov, I. I., The thermodynamic and the international practical temperature scales, Z. Instrumentenk. 71, 43 (Feb.).

Kocherzhinskii, Yu. A., et al, Calibration of the VR - 5/20 thermocouple by critical points up to 3000°, Sb Nauchn. Tr. Inst. Metallfiz., Akad. Nauk Ukr. SSR No. 17, 200.

Lovejoy, D. R., Some boiling and triple points below 0°C, Nature 197, 353 (Jan. 26).

Lucke, W. H., A brief survey of elementary thermoelectric theory, NRL Rept. 5880 (May), AD-405854; N 64-20326.

McLaren, E. H., and E. G. Murdock, The Freezing points of high purity metals as precision temperature standards. VII Thermal analysis on seven samples of bismuth with purities greater than 99.999%, Can. J. Phys. 41, 95 (Jan.).

Null, M. R., and W. W. Lozier, Carbon-arc radiation standard, Instr. Control Systems 36, 93 (May).

Rebiene, J., R. Beranger, and P. Perroud, Calibration of thermocouples for low temperatures, Comm. Energie At. (France) Note No. 418.

Rechter, M., Use of high purity materials in thermometry, Reinststoffe Wiss. Tech., Intern. Symp., 1, Dresden 1961, 345.

Swindells, J. F., Calibration of temperature measuring instruments at the Natl. Bur. of Std., Misc. Publ. U. S. Bur. Stand. 240 (Aug. 16).

Sydoriak, S. G., T. R. Roberts, and R. H. Sherman, The T_{62} Helium-3 temperature scale, Proc. Intern. Conf. Low temp. Phys., 8th. London 1962, 437; Low Temperature Physics, Butterworth's Washington, D. C. (1963), 437.

Van Dijk, H., Units of temperature and temperature scale, Z. Angew. Phys. 15, 561 (June).

Calibration of temperature measuring instruments at the Natl. Bur. of Std., Engineer 215, 501.

Temperature calibrations, Instr. Pract. 17, 190 (Feb.).

The International Committee on Weights and Measures, Nature 197, 1055 (Mar. 16).

1964

Astrov, D.N., M.P. Orlova, and D. I. Sharevskaya, Extension of the practical international scale of temperature below -182.97° (90.18°K), Comite Consultatif Thermometrie, Comite Intern. Poids Mesures, 6e, Sevres, France 1962, 102.

Bedford, R.E., Reference tables for platinum 20% rhodium/platinum 5% rhodium thermocouples, Rev. Sci. Instr. 35, 1177 (Sept.).

Blackburn, G.F., and F.R. Caldwell, Reference tables for thermocouples of iridium- rhodium alloys versus iridium, J. Res. Natl. Bur. Std. (U.S.) 68C, 41 (Jan.-Mar.).

Bonilla, C.F., et al, Thermoelectric potentials of molten and refractory metals, N 64-20479.

Davisson, E.G., and R.K. Adams, Smoothed thermocouple tables, U.S. At. Energy Comm. Rept. ORNL-P-227; Proc. Instr. Soc. Am. 19, Paper No. 11, 1-3-64.

Eisenstein, J.C., R.P. Hudson, and B. W. Mangum, A magnetic fixed point for thermometry below 1°K, Appl. Phys. Letters 5, 231 (Dec. 1).

Georgian, J.C., The temperature scale, Nature 201, 695 (Feb. 15).

Hall, J.A., The pyrometric scale of temperaturebetween 20 and 1063°, Comite Consultatif Thermometrie, Comite Intern. Poids Mesures, 6e, Sevres, France 1962, 72.

Hall, J.A., and C.R. Barber, Calibration of temperature measuring instruments, Nat'l. Phys. Lab. (Gt. Brit.) Notes Appl. Sci. No. 12 (3rd. ed.).

Hauback, W.J., and W.L. Taylor, Measuring precisely near absolute zero; helium-3 and low temperature thermometry, Research/Development 15, 19 (Sept.).

Hensinkveld, W.A., and K. Scheerer, Comparison of the pyrometric scale of temperature of the University of Utrecht to those of N.P.L. and of P.T.B., Comite Consultatif Thermometrie, Comite Intern. Poids Mesures, 6e, Sevres, France, 1962, 67.

Heyne, W., Precision measurement for testing thermoelectric voltages and temperature relationships of Pt-10% Rh/Pt thermoelements by means of the solidification points of copper, aluminum and zinc, Feingeratetech. 13, 311 (July).

Heyne, W., Investigation of the determination of the relation of thermal emf and temperature of Pt 10% Rh vs Pt thermocouples by means of the freezing points of metals, Exptl. Tech. Physik 13, 90.

Heyne, W., Determination of the freezing point of copper, Exptl. Tech. Physik 12, 87.

Lapp, G.B., and D.J. Popova, Calibration of tungsten-rhenium thermocouples, Measurement Techniques No. 10, 847 (Mar.).

Le Fevre, E.J., The temperature scale, Nature 203, 1158 (Sept. 12).

Lovejoy, D.R., Theory of two bands for high purity platinum and the reproducibility of the temperature scale, Comite Consultatif Thermometrie, Comite Intern. Poids Mesures, 6e, Sevres, France, 1962, 138.

Magdeburg, H., A new method for realizing pyrometric fixed points, Z. Instrumentenk 72, 205(July).

Minard, D., Effective temperature scale and its modification, Naval Medical Research Inst. Bethesda, Md., Rept. 6, (Mar.); AD-603186; N64-30629.

Moser, H., and W. Thomas, Comparison of the practical international temperature scale with the thermodynamic scale between the zinc and gold points according to the most recent gas thermometer measurements, Comite Consultatif Thermometrie, Comite Intern. Poids Mesures, 6e, Sevres, France 1962, 34.

Olsen, L.O., and P.D. Freeze, Reference tables for the Platinel II Thermocouple, J. Res. Natl. Bur. Std. (U.S.) 68C, 263 (Oct.).

Roberts, T.R., et al, The 1962 Helium-3 scale of temperatures, U. S. At. Energy Comm. Rept. LADC-5757.

Sherman, R. H., et al, 1962 Helium-3 scale in 4 parts, NBS Journal 68A, pp 547, 559, 567, & 579.

Spengler, W.E., and D.K. Graham, Equations and tables for thermocouples, 32°F reference junction, AD-432828; N64-17456.

Sydoriak, S.G., et al, The 1962 Helium-3 scale of temperature, J. Res. Natl. Bur. Std. (U.S.) 68A, 547.

1965

Adams, R.K., and E.G. Davisson, Smoothed Thermocouple tables of extended significance (°C): platinum vs platinum-10% rhodium thermocouples, Oak Ridge Natl. Lab., Tenn. Instrumentation and Controls Div., ORNL - 3649, Vol. 2, Sect. 2.1 (Mar.); AD 19-20263; N65-20680.

Adams, R.K., and E.G. Davisson, Smoothed thermocouple tables of extended significance (°C): platinum vs platinum-13% rhodium thermocouples, ORNL-3649, Vol. 2, Sect. 2.2; AD-20264; N65-20681.

Adams, R.K., and E.G. Davisson, Smoothed thermocouple tables of extended significance (°C): Chromel-Alumel thermocouples, ORNL-3649, Vol. 2, Sect. 2.3; AD-20265; N65-20682.

Adams, R.K., and E.G. Davisson, Smoothed thermocouple tables of extended significance (°C): iron-constantan thermocouples, ORNL-3649, Vol. 2, Sect. 2.4; AD-20266; N65-20683.

Adams, R.K., and E.G. Davisson, Smoothed thermocouple tables of extended significance (°C): copper-constantan thermocouples, ORNL-3649, Vol. 2, Sect. 2.5; AD-20267; N65-20684.

Adams, R.K., and E.G. Davisson, Smoothed thermocouple tables of extended significance (°C): Chromel-constantan thermocouples, ORNL-3649, Vol. 2, Sect. 2.6: AD-20267: N65-20684.

Adams, R.K., and E.G. Davisson, Smoothed thermocouple tables of extended significance (°C): tungsten vs tungsten-26% rhenium thermocouples, ORNL-3649, Vol. 2, Sect. 2.7; AD-20269; N65-20152.

Adams, R.K., and E.G. Davisson, Smoothed thermocouple tables of extended significance (°C): tungsten-5% rhenium vs tungsten-26% rhenium tehrmocouples, ORNL-3649, Vol. 2, Sect. 2.8; AD-20270; N65-20153.

Adams, R.K., and E.G. Davisson, Smoothed thermocouple tables of extended significance (°C): tungsten-3% rhenium vs tungsten-25% rhenium thermocouples, ORNL-3649, Vol. 2, Sect. 2.9; AD-20271; N65-20154.

Adams, R.K., and E.G. Davisson, Smoothed thermocouple tables of extended significance (°C): gold-2.1% cobalt vs copper cryogenic thermocouples, ORNL-3649, Vol. 2, Sect. 2.10; AD-20272; N65-20155.

Adams, R.K., and E.G. Davisson, Smoothed thermocouple tables of extended significance (°C): constantan-copper cryogenic thermocouples, ORNL-3649, Vol. 2, Sect. 2.11; AD-20273; N65-20156.

Adams, R.K., and E.G. Davisson, Smoothed thermocouple tables of extended significance (°C): Alumel-Chromel cryogenic thermocouples, ORNL-3649, Vol. 2, Sect. 2.12; AD-20274; N65-20157.

Adams, R.K., and E.G. Davisson, Smoothed thermocouple tables of extended significance (°C): constantan (JN)-iron (JP) cryogenic thermocouples, ORNL-3649, Vol. 2, Sect. 2.13; AD-20275; N65-20158.

Adams, R.K., and E.G. Davisson, Smoothed thermocouple tables of extended significance (°C): constantan (YN)- iron(YP) cryogenic thermocouples, ORNL-3649, Vol. 2, Sect. 2.14; AD-20276: N65-20159.

Barber, C.R., and A. Horsford, Differences between the thermodynamic scale and the International Practical Scale of Temperature from 0°C to -183°C, Metrologia 1, 75 (July).

Beattie, J.A., et al, Experimental study of the absolute temperature scale, J. Chem. Phys. 42, 2274 (April).

Bedford, R.E., Reference tables for platinum 40% rhodium vs platimum 20% rhodium thermocouples, Rev. Sci. Instr. 36, 1571 (Nov.).

DeBoer, J., Temperature as a basic physical quantity, Metrologia, 1, 158 (Oct.).

Dingle, H., et al, Linear temperature scale, Nature 206, 1347 (June 26).

Furukawa, G.T., and M.L. Reilly, Application of precise heat capacity data to the analysis of the temperature intervals of the NBS (1955) and the international practical temperature scales in the region of 90°K, J. Res. Nat'l. Bur. Std. (U.S.) 69A, 5 (Jan.).

Grenis, A.F., and M.J. Matkovich, Blackbody reference for temperatures above 1200°K: Study for design requirements, Army Material Research Agency, Watertown, Mass., Tech. Rept. AMRA-TR-65-02; AD-614638.

Groves, W.D., and L. Lielmezs, The linear temperature scale, Nature 205, 489 (Jan. 30).

Hall, J.A., The radiation scale of temperature between 175°C and 1063°C, Metrologia 1, 140 (Oct.).

Marshall, T.W., A classical treatment of blackbody radiation, Nuovo Cimento(Italy) 38, 206 (July 1).

Rath, R., and R. Dubbe, Pyrometers and their calibration for production control, Feinwk.-Tech. 69, 97 (March).

2. Thermoelectric Devices

1960

Adakhovskii, A.P., et al, New types of thermocouples for measuring temperatures up to 1800°, Tr. Vses. Nauchn.- Issled. Inst. Metrol. 1960, No. 42, 29.

Ciborowski, F., The effect of non-homogeneous thermocouple elements on the accuracy of NiCr-Ni thermocouples, Prom. Avtomat. Kontrol 1960, No. 2, 64.

Kuether, F.W., The thermal emf scatter of rhenium, Rhenium Papers Symp., Chicago, 1960, 149.

Lachman, J.C., and J.A. McGurty, Thermocouples for 5000°F, using rhenium alloys, Rhenium Papers Symp., Chicago 1960, 153.

L'vov, S.M., and V.F. Nemchenko, Tungsten-molybdenum thermocouple, Ezhegodnik Nauchn. Rabot, Khersonsk. Gos. Ped. Inst., Estestvoznanie, Kherson 1960, 3.

Moeller, G.K., R.B. Branfin, and P. Whitmarsh, Error determination in high temperature thermocouple measurements, U.S. At. Energy Comm. Rept. K-T-552, (Nov. 30); NSA 18-12418.

1961

Green, S.J., and T.W. Hunt, Accuracy and response of thermocouples for surface and fluid temperature measurement, U.S. At. Energy Comm. Rept. WAPD- T-1270.

1962

Begot, R., and R. Faivre, Experimental

study of the very rapid cooling obtained by direct quenching in water of solders on thermocouples, Compte Rend. 255, 3128 (Dec. 5).

Bouisson, H., and H. Cordier, Measurement of surface temperatures with thermocouples. Effect of radiation received by the thermocouple and the method of attachment, Compt Rend. Acad. Sci. 255, 1296 (Aug. 27).

Challe, J., Study of the dynamic behavior of thermowells, U.S. At. Energy Comm. Rept. NP-13288 (Sept.).

Cherpakov, P.V., The thermal inertia of thermocouples, Inzh. Fiz. Zh. 5, 94 (Sept.).

Ciborowski, F., Factors affecting constancy and stability of the thermoelectric characteristics of industrial thermocouples, Pomiary, Automat., Kontrola 8, 509 (Nov.).

Doyle, J., High voltage electron beam welding of W- Re thermocouples, U.S. At. Energy Comm. Rept. CNLM-4351 (Dec. 13).

Fitzpatrick, V.F., Fretting corrosion of 1/8-inch Zr - 2(Zy -2) clad thermocouples, U.S. At. Energy Comm. Rept. HW-75626 (Nov.).

Golubev, A.V., Influence of the electrochemical effect in thermocouples on the precision of temperature measurements, Materialy k Ucheniyu o Merzlykh Zonakh Zemnoi Kory., Akad. Nauk SSSR, Akad. Stroit. i Arklritekr., Inst. Merzotored. 8, 113.

Karasina, E.S., L.I. Kropp, and M.S. Mints Aplication of suction thermocouples for measuring high gas temperatures, Ind. Lab. 23, 665 (Dec.).

Kortum, H., G. Luck, and E. Stutter, Resistance measurement on thermocouples and thermopiles, Feingeratetech. 11, 534 (Dec.).

Kroeckel, O., High-temperature thermoelements, Abhandl. Deut. Akad. Wiss. Berlin, Kl. Math., Physik. Tech. 1962, No. 1, 437.

Kutateladze, K.S., et al, Sheaths for immersion thermocouples for measuring the temperature of molten metals, Ogneupory 27, 223.

Margulis, O.M., et al, Tips for immersion type thermocouples made from zirconium dioxide of increased resistance to heat, Ogneupory 12, 552; AD-411058.

McGurty, J.A., and W.C. Kuhlman, Tungsten vs tungsten-rhenium thermocouple research and development, U.S. At. Energy Comm. Rept. TID-20944.

Morita, Y., Average temperature measurements using thermocouples, Bull. Tokyo Inst. Technol. No. 50, 27.

Olszewski, J., Effect of thermocouple sheathing on reading temperatures of blast-furnace blast, Hutnik 29, 366.

Owczarski, W.A., Tungsten-rhenium thermocouples for difficult measurements of Zircalloy-2 weldments, U.S. At. Energy Comm. Rept. TID-17734.

Plyukhin, V.S., and V.N. Kologrivov, Emf of thermocouples compressed by a shock wave, Zh. Prikl. Mekhan. i Tekn. Fiz. No. 5, 175 (1962); Air Force Systems Command, Wright Patterson AFB, Ohio, Foreign Technology Division FTD-TT-63-1057/1 and 2; AD-426901; N64-23314.

Shaidurov, G.F., Measurement of the temperature of a wall, Inzh. Fiz. Zh. 5, 86 (Dec).

Stottman, P., Measuring high temperature gas flames with thermoelectric elements, Wiss. Ges. Luft - u Raumfahrt, Cologne (W. Germany) Proc. of the joint meeting of the Comm. on air-breathing engines, and the Subcomm. on areodynamic measuring techniques (July 6, 1962); N64-20181.

Vasanova, L.K., et al, The measurement of temperature in poly-dispersion media during induction heating, Inzh. Fiz. Zh. 5, 82 (April).

W-Re takes Zircalloy-2's temperature, Am. Machinist 106, 122 (Nov.).

1963

Adorni, N., and A. Parmaggiani, Device for high accuracy measurement of wall temperature using thermocouples, Energia Nucl. 10, 34.

Berman, R., and D.J. Huntley, Dilute gold-iron alloys as thermocouple material for low-temperature heat conductivity measurements, Cryogenics 3, 70.

Bertodo, R.J., A thermocouple for the measurement of gas temperatures up to 2000°C, Proc. Inst. Mech. Engrs. (London) 177, 603.

Bertodo, R.J., Thermocouples for use in oxidizing atmospheres at high temperatures, R and D No. 20, 62 (April).

Bostwick, W.E., Some experiences with noble-metal, metal-sheathed thermocouples, U.S. At. Energy Comm. Rept. UCRL-7361 (May 10, 1963).

Bragin, B.K., G.B. Lapp, and I.R. Lepin, Effect of annealing on the thermal electromotive force of platinum-rhodium thermocouples, Tr. Inst. Kom. Standartov, Mer. i Izmerit. Priborov pri Sov. Min. SSSR 1963 (71), 220.

Bullis, L.H., Vacuum-deposited thin film thermocouples for accurate measurement of substrate surface temperature, J. Sci. Instr. 40, 592 (Dec.).

Chambers, J.T., D.L. Rall, and W.H. Geidt, Experimental evaluation of a dual-element transducer for high temperature gas measurements, Aeron. Res. Labs. Office of Aerospace Res., U.S. Air Force Rept. ARL 63-58; AD-409816.

Cox, J.E., High vacuum thermocouple, Rev. Sci. Instr. 34, 931 (Aug.).

Danishevskii, S.K., et al, Tungsten-rhenium alloy thermocouples for the measurement of temperatures up to 2500°, Zavosk. Lab. 29, 1139.

Deniidenko, I.I., N.J. Mitina, and V.G. Padalka, Investigation of plasmoids by means of a thermocouple, Ukrain. Fiz. Zh. 7, 61 (Jan.).

de Sigoyer, B.B., F. Jaques, and P. Thome, Zircalloy sheathed fuel element rods fitted with thermocouples, U.S. At. Energy

Comm. Rept. CEA-2290.

Dougherty, L.W., Thermocouple hot-junction mounting techniques, Tech. Memo. SL-M-15; AD-290914.

Efremova, R.I., et al, Temperature measurements by means of copper-constantan thermocouples, Measurement Techniques No. 3, 214 (Sept.).

Gross, J., and C.B. Griffith, A thermocouple for molten steel, Metal Progr. 83, 106 (June).

Hahnemann, H.W., Thermoelements for measuring gas temperatures up to 2000°C, Forsh. Geb. Ingen-Wes. 29, 203.

Ham, A.C., and R.E. Jones, Some measurements on thermocouples subjected to radiation, Royal Aircraft Establishment, Farnborough, England, RAE-TN-STRUCT-343 (Oct. 1963); AD-433036; N65-25351.

Hick, E.W., The requirements for a direct reading 5000°F Thermocouple, Proc. Instr. Soc. Am. 18, Paper No. 29.2.63.

Hughes, P.C., and N.A. Burley, Metallurgical factors affecting stability of nickel-base thermocouples, J. Inst. Metals 91, 373.

Janeschitz-Kriegel, H., et al, A temperature probe for flowing polymer melts, J. Sci. Instr. 40, 415 (Aug.).

Koslapov, V., and Yu . M. Skvortsov, Thermocouple needle, Ind. Lab. 28, 1474 (July).

Krysiak, K.F., et al, A thermocouple suitable for use from 2500 to 4500°F on aerospace vehicles, ASD-TDR-63-592; AD-414562.

Kuhlman, W.C., Research and evaluation of materials for thermocouple application suitable for temperature measurements up to 4500°F on the surface of guide reentry vehicles, Wright Patterson AFB, Ohio, ASD-TDR-63-233; AD-404577.

Lakh, V.I., B.I. Stadnyk, and Yu.B. Kuzma, Thermoelectric stability of thermocouples made of tungsten-rhenium alloys at high temperature, High Temperature 1, 267 (Sept.-Oct.).

Ling, F.F., and T.E. Simkins, Measurement of pointwise juncture condition of temperature at the interface of two bodies in sliding contact, Trans. ASME (J. Basic Eng.) 85D, 481.

Loskutov, V. I., New method of measuring the temperature of molten steel, Instr. Construct. No. 11, 9 (Nov.).

Lyusternik, V.E., Reproducibility of the calibration of platinum vs platinum rhodium thermocouples over a wide temperature range, High Temperature 1, 120 (July-Aug.).

Moeller, C.E., Special surface thermocouples, Instr. Control Systems 36, 97 (May).

Moen, W.K., Use thermocouples right and melt away weight, Abstract: S.A.E. J. 71, 58 (Nov.).

Morrison, R.D., and R.R. Lachenmayer, Thin film thermocouples for substrate temperature measurement, Rev. Sci. Instr. 34, 106 (Jan.).

Nanigan, J., Thermal properties of thermocouples, Instr. Control Systems 36, 87 (Oct.).

Nanigan, J., Matching TC well material to wall improves accuracy, ISA J. 10, 75 (Feb).

Oetken, E.R., Evaluation of surface attached thermocouples during forced convection heat transfer, U.S. At. Energy Comm. Rept. IDO-16889.

Panasyuk, A.D., and G.V. Samsonov, Thermocouples with electrodes of refractory carbides for use up to 3000°C, High Temperature 1, 116 (July-Aug.).

Pokhodnya, I.K., and I.I. Fruman, The temperature of a weld pool, AD-400930.

Rainy, W.T. Jr., and R.L. Bennett, Stability of base metal thermocouples in helium atmospheres, ISA Trans. 2, 34 (Jan.).

Reichardt, F.A., Measurement of high temperatures under irradiation conditions, Platinum Metals Rev. 7, 122 (Oct.).

Sabadell, A.J., and J. Wenograd, The measurement of the temperature profiles of burning solid propellant by microthermocouples, Princeton U., Guggenheim Labs. Aeronaut. Eng. Rept. 664; AD-422387.

Schmidt, A.J., A hall generator arrangement for the measurement of small temperature differences in metals, Z. Naturforsch 18a, 37 (Jan.).

Schweyher, K., Temperature measurement and heat distribution during heat treatment in an electrically heated experimental furnace, Stahl u Eisen 83, 1162 (Sept. 12).

Sharp, J.D., Rapid immersion pyrometry with expendable couples, Iron and Steel 36, 320 (June).

Sharp, J.D., Expendable-Tip thermocouples, Metal Ind. 102, 556.

Sharp, J.D., Continuous temperature measurement of molten steel, Platinum Metals Rev. 7, 90 (July); J. Metals 15, 902 (Dec.).

Skoglund, V.J., and D.M. Yano, The development of a temperature probe and temperature survey of the interaction of an oblique shock wave and a turbulent boundary layer, U.S. At. Energy Comm. Rept. SC-DC-3565 (Oct.).

Stamper, J.A., Differential Sensing controlled thermocouple, Rev. Sci. Instr. 34, 444 (April).

Stevenson, J.A., Temperature measurement with the expendable immersion thermocouple, Platinum Metals Rev. 7, 2 (Jan.).

Thomas, D.B., Studies on the tungsten-rhenium thermocouple to 2000°C, J. Res. Nat'l. Bur. Std. (U.S.) 67C, 337 (Oct.).

Vanvor, H., Special problems in the use of thermocouples for the measurement of temperatures above 1500°C, Ber. Dtsch. Keram. Ges. 40, 615.

Vlasov, V.V., Results of testing batteries of differential thermocouples, Instr. Construct. No. 4, 28 (April).

Wechter, G.H., The accuracy of thermocouples in measuring surface temperatures of stainless steel specimens subjected to radiant heat, Aeronaut. Structures Lab., Naval Air and Engineering Center, Phila., Pa., Rept. NAES ASL13R360FR101 (July 10); AD-412317.

Weissenberger, E.G., Metal sheathed thermocouples, Instr. Control Systems 36, 109 (May).

Wormser, A.F., and R.A. Pfuntner, Pulse thermocouple measures at 5700°F, Space/Aeronautics 40, 116 (July).

Zysk, E.D., D.A. Toenshoff, and J. Penton, Tungsten 3% rhenium vs tungsten 25% rhenium, a new high temperature thermocouple, Engelhard Inds. Tech. Bull. 3, 130 (Mar.).

Gold thermocouples in cryogenic investigations, Design Electron. 1, 9 (Oct.).

Improved thermocouple techniques for safe operation of modern boilers, Power 107, 54 (Jan.).

More on welding thermocouples, ISA J. 10, 76 (April).

Pyrometer for moving surfaces, Mech. Eng. 85, 76 (May).

Surface temperature measurements with thermoelectric materials, AD-286098.

Unusual thermocouples and accessories,
Instr. Control Systems 36, 91 (May)
" " " 36, 110 (June)
" " " 36, 99 (July)
" " " 36, 130 (Aug.).

1964

Adsitt, C.L., Minimization of carbon deposit grounding effects on thermocouple measurements, AD-448821.

Allen, J.G., and C.D. Pears, Evaluation of the performance of tungsten-tungsten 26 rhenium thermocouples to about 5000° F, NASA Rept. CR-55626; N64-16269.

Alvermann, W., and P. Stottmann, Temperature measurements in combustion gases by means of thermocouples, N65-16643.

Beck, J.V., Correction of transient thermocouple temperature measurements in heat-conducting solids, AD-445633.

Bennett, R.L. et al, Stability of thermoelectric materials in a helium-graphite environment, U.S. At. Energy Comm. Rept. ORNL-TM-746.

Berman, R., J.C.F. Brock, and D.J. Huntley, Properties of gold + 0.03 percent (At.) iron thermoelements between 1 and 300°K and behaviour in a magnetic field, Cryogenics 4, 233 (Aug.).

Bradfield, W.S., A.R. Hanson, and J. J. Sheppard Jr., Design, calibration, and application of a miniature total temperature probe, Trans. ASME (J. Heat Transfer) 86, 462 (Aug.).

Bragin, B.K., and R.N. Tetyueva, Thermoelectric uniformity of Chromel, Copel, Alumel and copper wire at low temperatures, Measurement Techniques No.6, 498 (Dec.).

Byrne, M.F., Thermocouple introduced into vessel under pressure, Chem. Eng. 71, 154 (Nov. 23).

Carlson, A.V., Radiation compensating thermocouple temperature sensors, Intern. Convention on Military Electronics, 8th., Wash., D.C., Sept. 14-16, 1964 Conference Proc, p. 171.

Chevallier, J.P., Transitory response of thermal receptors utilizing thermocouples, France, O.N.E.R.A. TP-157.

Clark, R.B., Calibration and stability of W/W Re thermocouples to 2760°C(5000°F), Proc. Instr. Soc. Am. 19, Paper No. 16, (Nov.4).

Collins, C.G., Organic, structural and control materials, U.S. At. Energy Comm. Rept. APEX-917.

Cookson, R.A., P.G. Dunham, and J.K. Kilham, Non-catalytic coatings for thermocouples, Combust. Flame 8, 168 (June).

Crisp, R.S., and W.G. Henry, The design of a low temperature thermocouple material, Cryogenics 4, 361 (Dec.); AD-614881.

Czohara, E.A., Resistance welding of strain gages and surface thermocouples, AD-448518.

Dalle Donne, M., Tests and data concerning Platinel, a new high temperature thermocouple, Engelhard Inds. Tech. Bull. 5, 5 (June).

Danburg, J.E., The equilibrium temperature probe. A device for measuring temperatures in hypersonic boundary layers, Naval Ordnance Lab., White Oak, Md. TR612; AD-439624.

Danishevskii, S.K., et al, Thermocouples made of tungsten alloys with rhenium for measuring temperatures up to 2500°C, Ind. Lab. 29, 1242 (Mar.).

Dinian, J., Thermocouples, CEA-Bib-34; NSA N-18132.

Dow, M.B., Comparison of measurements of interval temperatures in ablation materials by various thermocouple configurations, NASA Tech. Note D-2165 (Nov.).

Dunbar, W.G., High temperature effects on ceramic insulated thermocouple wires, Trans. Inst. Elect. Electron. Engrs. AS-2, 452 (April).

Fricke, H.W., Miniature encased thermocouple for the highest mechanical efficiency, Rigelungstech. Praxis 6, 173.

Furey, M.J., Surface temperatures in sliding contact, Trans. Am. Soc. Lubrication Engrs. 7, 133 (April).

Gaevskii, M.M., Errors in dynamic calibration of thermoelectric transducers with differences between their thermal inertias, Measurement Techniques No. 8, 666(Feb.).

Gelb, G.H., B.D. Marcus, and D. Dropkin, Manufacture of fine wire thermocouple probes, Rev. Sci. Instr. 35, 80 (Jan.).

Gross, P.M., et al, A re-entry thermocouple for use up to 4500°F, ISA Trans. 3, 305.

Heitzman, W.P., Dual- thermocouple temperature controls, Instr. Control Systems 37, 109 (May).

Hensel, R., and M. Gohler, Tests with a tungsten/molybdenum immersion thermocouple for measuring the temperature of steel melts, Neue Hutte 9, 237 (April).

Hicks, E.W, Investigation of tungsten vs tungsten-26 percet rhenium thermocouples above 3500°F in oxidizing environments, Proc. Instr. Soc. Am. 19, Paper No. 16 (Oct. 3).

Hurst, N.J., Effect of thermocouple size and installation on temperature readings, Army Missile Command, Huntsville, Ala.

RS-TM-64-1; AD-612493; N65-20521.

Irvine, F.H., J. Picken, and G.H. Greenwood, Measurements of the response of various thermocouple arrangements, Royal Aircraft Establishment, Farnborough, England, RAE-TN-AERO-2959 (April); N65-20514.

Jensen, J.T., J. Klebanoff, and G.A. Haas, Thermocouple errors using Pt-Pt(Rh) thermocouples on Ni surfaces, Rev. Sci. Instr. 35, 1717 (Dec.).

Klein, C.A., and M.P. Lepie, Operational performance characteristics of pyrolytic graphite thermocouples, Solid State Electronics 7, 241 (April).

Klein, C.A. et al, Development of an ultra high temperature pyrolytic graphite thermocouple, ASD-TDR-63-844; AD-431203; N64-16594.

Kornilov, V.V., and B.I. Makarov, Measurement of rapidly changing temperatures of conducting solid bodies by means of thermocouples, Measurement Techniques No. 10, 849 (Mar.).

Kovacs, A., and R.B. Mesler, Making and testing small surface thermocouples for fast response, Rev. Sci. Instr. 35, 485 (April).

Lagedrost, J.F., Laboratory studies toward improvement of high-temperature thermocouples, U.S. At. Energy Comm. Rept. TID 7697.

Lapp, G.B., and D.L. Popova, Certain thermometric properties of tungsten-rhenium thermoelectrodes, Measurement Techniques No. 11, 917 (April).

Leto, F., Source approval for thermocouple specification, NA5-2722, NA5-27230, NA5-27256, NA5-27290, NA5-27334, NA5-27340, and NA5-27344, Rocketdyne, Canoga Park, Calif. Rept. No. E-438-40; AD-470412.

Lorch, H.R., Mineral insulated thermocouples, Euronuclear 1, 42 (Sept.).

McCausey, R.J., and E.R. Funk, A high accuracy primary-element-system for temperature measurements in turbine performance tests, Proc. Instr. Soc. Am. 19, Paper No. 15 (Jan. 1).

Markovskii, E.A., and M.M. Krasnoshchekov, Measurement of the temperature of friction surfaces of parts by means of a junctionless thermocouple, Ind. Lab. 29, 1203 (Mar.).

Middlehurst, J. et al, Electrochemical effects in thermocouples, J. Sci. Instr. 41, 676 (Nov.).

Moen, W.K., Spacecraft thermocouple installation design, Proc. Instr. Soc. Am. 19, Paper No. 16 (Oct. 2).

Moran, J., Molten metal temperature measurement by expendable thermocouples, Instr. Pract. 18, 1033 (Oct.).

Mulcahy, E.L., Attachment techniques for the "C" section tests in the space environment simulator, AD-439157.

Nanigan, J., Temperature measurements in the 3000°F to 5000°F range using ribbon thermocouples, ISA Annual Conference, 19th New York, N.Y., (Oct. 19).

Palmer, E.P., and G.H. Turner, Response of a thermocouple junction to shock waves in copper, J. Appl. Phys. 35, 3055 (Oct.).

Pletenetskii, G.E., Thermocouple for measuring high temperatures in vacuum and helium, Ind. Lab. 30, 786 (Dec.).

Pletenetskii, G.E., and A.T. Mandrich, Testing of thermoelectrode metals in helium at 1500°, Zavosk. Lab. 30, 1243.

Raag, V., Silicon-germanium thermocouple development, N64-17386.

Ramachandran, S., and T.R. Acre, Measuring molten steel temperatures, ISA J. 11, 54 (Mar.).

Robinson, J.E., Thermoelectric junctioning project, AD-430243.

Rosenbaum, R.L., R.R. Oder, and R.B. Goldner, Low temperature thermoelectric power of gold-iron vs copper thermocouples, Cryogenics 4, 333 (Oct.).

Sabadell, A.J., J. Wenograd, and M. Summerfield, The measurement of temperature profiles through solid propellant flames using fine theemoocooouples, N64-14547.

Sarychev, G.S., I.M. Veselnitskii, and G.N. Rokhlin, New technique for fixing surface thermocouples, Measurement Techniques No. 9, 753 (Feb.).

Semkina, N.V., N.M. Permikina, and T.N. Kodryartseva, Corundum heat-resistant shields for immersion thermocouples, Tr. Vost. Inst. Ogneuporov 5, 49.

Stadnyk, B.I., and G.V. Samsonov, Thermocouples for measuring high temperatures, High Temperature 2, 573 (July-Aug.).

Thomson, A., The thermal response time of sheathed mineral-insulated thermocouples, U.S. At. Energy Comm. Rept. 658 (R).

Truchasson, C., Making very fine heat probes for the measurement of temperatures in water, J. Phys. (France) 25 Supplement No. 3, 17A (Mar.).

Turner, R.C., and G.D. Gordon, Thermocouples for vacuum tests minimizes errors, Space/Aeronautics 41, 256 (Jan.).

Vickers, P.T., Proper probes keep thermocouples reading true, S.A.E. J. 72, 54 (Dec.).

Vidadi, Yu.A., Thermocouple with a compensating heater, Pribory Tekh. Eksper.(USSR) No. 6, 152 (Nov.-Dec.): Instr. Exp. Tech. No. 6, 1301 (May 1965).

Wormser, A.F., and R.A. Pfuntner, Pulse technique extends range of Chromel-Alumel to 7000°F, Instr. Control Systems 37, 101 (May).

Continuous immersion thermocouple aids blast furnace control, Iron & Steel Eng. 41, 179 (July).

1965

Alvermann, W., and P. Stottmann, Temperature measurements with thermocouples in combustion gases, NASA-TT-F-9537; N65-33954.

Bailey, H.T., Procedure is simple for making thermocouples, Foundry 93, 226 (May).

Brooks, E.J., and E.W. O'Neal, Keep your thermocouple leads dry, ISA J. 12, 94(Mar.).

Cheesewright, R., A technique for stripping small diameter metal sheathed thermocouple wire, J. Sci. Instr. 42, 815 (Nov.).

Chichinadze, A.V., E.D. Braun, and A.G. Abukumkin, Thermocouples for the investigation of materials in friction, Ind. Lab. 31; 928 (June).

Cooper, M.G., and A.J.P. Lloyd, Miniature thin film thermometers with rapid response, J. Sci. Instr. 42, 791 (Nov.).

Daniells, G.E., Measurement of gas temperature and the radiation compensating thermocouple, Inst. of Environmental Sci. Annual Tech. Meeting, 11th, Chicago, Ill., April 21-23, 1965 Proc. A65-29982 19-11.

Devita, V.A., Predicting cryogenic thermocouple time constant, Control Eng. 12, 63 (July).

Fanciullo, S., Drift and endurance testing of Chromel/Alumel, W-5 Re/W-26 Re and Mo/W-26 Re thermocouples at 1950-2000°F for 10,000 hours, U.S. At. Energy Comm. Rept. PWAC-454; N65-17407.

Finnemore, D.K., J.E. Ostenson, and T.F. Stromberg, Secondary thermometer for the 4 to 20°K range, Rev. Sci. Instr. 36, 1369 (Sept.)

Finnemore, D.K., et al, AuFe vs Cu Thermocouples, N65-13852.

Genet, F., and B. Milloit, Mesure du temps de remataux de thermocouples dans les dircuits de metaux liquides, European Atomic Energy Community, Ispara, Italy EUR-2281. F; NSA 19-22659.

Gordov, A.N., et al, An experimental investigation of the inertia of microthermocouples, High Temperature 3, 268 (Mar.-April).

Farrow, R.L., and A.P. Levitt, Tungsten/tungsten-rhenium thermocouples in a carbon atmosphere, Army Materials, Research Agency, Watertown, Mass., Materials Eng. Div. Rept. AMRA-TR-64-12, July 1964; AD-606565; N65-10886.

Hall, B.F. Jr., and N.F. Spooner, Study of high temperature thermocouples (Final Rept.) AFCRL-65-251; AD-619038; N65-36842.

Hanneman, R.E., and H.M. Strong, Pressure dependence on the emf of thermocouples to 1300°C and 50 K bar, J. Appl. Phys. 36, 523 (Feb.); ASME Preprint No. 64-WA/PT-21 (Dec. 1964).

Hendricks, J.W., and D.L. McElroy, High temperature high vacuum thermocouple drift, Oak Ridge Natl. Lab., Tenn. ORNL-P-1069; NSA 19-20278.

Kamenetskii, A.B., and N.V. Gul'ko, Interaction of thermal electrodes in tungsten-rhenium thermocouples with pure oxides insulation, Measurement Techniques No.6, 506 (June).

Kisliy, P.S., and M.A. Kuzenkova, Gas impervious protective coatings for thermocouples made of zirconium boride Poroshkovaya Met., Akad. Nauk Ukr. SSR No. 1, 32; Rev. Metal Lit. 22, No. 5 (May 1965).

Klapper, J.A., et al, High temperature corrosion of constantan thermocouple conductors, Mater. Protect 4, 72.

Kocho, V.S., et al, Operation of thermocouple tips made from zirconium boride in the Bessemer convertor, Poroshkovaya Met., No. 3, 88.

Makarov, B.I., Errors in temperature measurement on the surface of a solid body using a thermocouple when heating and cooling follow an arbitary law, NASA-TT-F-9496; N65-29736.

Matthew, H.L., Thermocouple calibration in subsonic air flow, Wyoming Univ., Laramie Masters Thesis AD-617305; N65-31753.

McCoy, H.E. Jr., Influence of $CO-CO_2$ environments on the calibration of Chromel P-Alumel thermocouples, Oak Ridge Natl. Lab., Tenn. ORNL-P-1070; NSA 19-22664.

Novak, P.E., and R.R. Asamoto, Evaluation of thermocouples for use to 2600°C in mixed-oxide fuel, Trans. Am. Nucl. Soc. 8, 388 (Nov.).

Pak, V., and Yu.P. Krinskii, Thermoelectric method for measuring the mean temperature of metallic specimens, Ind. Lab. 30, 1033 (Feb.).

Phillips, L.S., The Measurement of thermoelectric properties at high temperatures, J. Sci. Instr. 42, 209 (April).

Pinchevskii, A.D., Transfer functions for commercial thermoelements, Measurement Techniques No. 5, 416 (May).

Rollinger, C.N., Convectively cooled thermoelements with variable cross sectional area, J. Heat Transfer 87, 259.

Sabadell, A.J., et al, Measurement of temperature profiles through solid propellant flames using fine thermocouples, AIAA J. 3, 1580 (Sept.).

Salzano, F.J., Stability of a rhenium-graphite thermocouple, U.S. At. Energy Comm. Rept. BNL-8812.

Samsonov, G.V., and P.S. Kislyi, Protective sheaths of thermocouples for the continuous control of the temperature of molten metals, Ogneupory No. 4, 28.

Smith, R.R. Jr., High temperature thermocouple research and development program, NASA-CR-67348; N65-35412.

Appendix 1: Drawings and design notes NASA-CR-67196, T-1097; N65-35416.

Appendix 2: Calibrations NASA-CR-67197, T-1097; N65-35415.

Appendix 3: Miscellaneous technical data NASA-CR-67347, T-1097; N65-35358.

Appendix 4: New technology NASA-CR-67195, T-1097; N65-34904.

Sparks, L.L., and R.L. Powell, Available low temperature thermocouple information and services, Natl. Bur. Std., Boulder, Colo., NASA-CR-63149; NBS-8750; N65-25244.

Studennikov, Yu. A., and G.E. Erkovich, Compensation wires for VR5/20 thermocouples (exchange of experience) Ind. Lab. 31, 469 (Mar.).

Svede-Shvets, N.I., et al, Thermoelectric characteristics of metallic sintered alloys on a tungsten and molybdenum base, FTD-TT-65-642; AD-619334; NSA 19-47019.

Tallman, C.R., Analytical model for study of thermocouple error attributed to electrical conduction in insulation, Los Alamos Scientific Lab., Univ. of Calif., (N. Mex.). Contract W-7405-eng-36.

Thomson, A., The thermal response time of

sheathed mineral-insulated thermocouples, Trans. Soc. Instr. Technol. 17, 49 (June).

Tschang, P.S., Temperature determination in moderately dense, high-temperature gases by transient thermocouple probes, Columbia Univ., New York ARL-65-95; AD-617702; N65-30297.

Ubbelohde, A.R., The anisotropy of graphite, Endeavour 24, 63 (May).

Van Drasek, J.J., and B.A. Short, Conversion formulas for copper-constantan thermocouples, Instr. Control Systems 38, 106 (Feb.).

Walker, B.E., C.T. Ewing, and R.R. Miller, Instability of refractory metal thermocouples, Rev. Sci. Instr. 36, 816; NRL-6231; AD-621484.

Walker, B.E., et al, Study of the instability of noble metals in vacuum, Rev. Sci. Instr. 36, 601 (May); NRL-6236; AD-620322; N65-36740.

Yakimov, A.V., V.A. Sipailov, and Yu. A. Kazimirchik, Thermocouple calibration for temperature measurements in the grinding zone, Ind. Lab. 31, 1018 (July)

Zabawsky, Z., and F.M. Gavan, Thermocouples and their usage in ASTM standards, Mater. Res. Std. 5, 80 (Feb.).

Zenin, A.A., On heat exchange of microthermocouples under conditions of combustion of condensed substances, N65-30419.

Zuikov, N.V., et al, A thermocouple for measuring temperature up to 2500°K, Teplofizika Vysokikh Temperatur 3, 815 (Sept.) Russian.

A rhodium-platinum thermocouple for high temperatures, Platinum Metals Rev. 9, 9 (Jan.)

Evaluation of the pperformance of seven refractory metal thermocouples (Final Rept.) Southern Research Inst., Birmingham, Ala. NASA-CR-63809; N65-28366.

3. RESISTANCE DEVICES

1958

de Vroomen, A.R., Practical interpolation procedure for carbon thermometry between 1.5 and 30°K, Probl. Low Temp. Phys. Thermodyn., Proc. Meeting Comm. I, Intern. Inst. Refrig., Delft, Neth., p. 137.

Sachse, H.B., Thermistors as sensing elements for low temperatures, Probl. Low Temp. Phys. Thermodyn., Proc. Meeting Comm. I, Intern. Inst. Refrig., Delft, Neth., p. 154.

van Dijk, H., Platinum resistance thermometers between 90 and 4°K, Probl. Low Temp. Phys. Thermodyn., Proc. Meeting Comm. I, Intern. Inst. Refrig., Delft, Neth., p. 155.

1960

Yaryshev, N.A., and A.S. Makhnovetskii, On the errors occurring in the measurement of non stationary surface temperatures, Priborostroenie 3, No. 6, 100.

1961

Somers, L.M., The variation of $(K_p c_p)^{\frac{1}{2}}$ with temperature in 'Pyrex', Cornell Aeronaut. Lab., Buffalo, N.Y. Rept. CAL-106; AD-279897; N65-10672.

1962

Alieva, T.Z., and V.P. Chekulaev, Design characteristics of resistance thermometers, Tr. Inst. Kom. Standartov, Mer i Izmerit., Priborov Pri Sov. Min. SSSR 1962 No. 63, 218.

Cherepin, V.T., Measurement of temperatures at high rates of heating and cooling, Ind. Lab. 28, 211 (Aug.).

Corruccini, R.J., Cryogenic temperature measurement with platinum resistance thermometers- is fixed-point calibration adequate, Proc. Instr. Soc. Am. 8, 139.

Golovashkin, A.I., and G.P. Motulevich, A sensitive low-inertia thermal resistor for helium temperatures, Instr. Exp. Tech. No. 2, 404 (Nov.).

Gunbin, B.L., Instrument for remote measurement of temperature of moving media, Measurement Techniques No. 4, 288 (Sept.).

La Fond, E.C., The Usnel thermistor chain, Navy Electronics Lab., San Diego, Calif. Rept. No. NEL-1114; AD-471158.

McAllan, J.V., Comparison of resistance thermometers used to measure freezing points of metals, Comite Consultatif Thermometrie, Comite Intern. Poids Mesures, 6e, Sevres, France 1962 p.52.

Mikhailov, N.N., and A. Ya. Govor, Lead brass resistance thermometers for low temperature measurement, Pribory i Tekh. Eksper. 1962, 180 (Mar. - April).

Raymond J.R., A well water tempetature lagging system, U.S. At. Energy Comm. Rept. HW-73994.

Riddle, J.L., Constant of the interpolation formula for platinum resistance thermometers, Comite Consultatif Thermometrie, Comite Intern. Poids Mesures, 6e, Sevres, France 1962, 198.

Sokolov, Yu.E., Miniature copper resistance thermometer with an unbalanced bridge, Measurement Techniques No. 2, 126 (July).

1963

Abichandani, C.T., P.T. Bhatt, and E.N. Blagoveschenskii, Wire resistance thermometers for determining soil temperatures, Res. Ind. (New Delhi) 8, 257.

Adirovich, E.I., S.P. Lunezhev, and E.I. Chernomorskaya, Application of thermistors to cryoscopic measurements, Dokl. Akad. Nauk Uz. SSR 20, No. 9, 18.

Andirch, E., and T. Van der Sterre, Structure and properties of thermistors, Elektron. Rundschau 17, 63 (Feb.).

Alieva, F.Z., Calibration of platinum resistance thermometers at two points, Measurement Techniques No. 11, 931 (June).

Alieva, F.Z., Measuring temperature in

the -182.97 to + 630° range with a platinum resistance thermometer calibrated at two points, Tr. Inst. Kom. Standartov, Mer i Izmerit. Priborov pri Sov. Min. SSSR 1963 No. 71, 134.

Barber, C.R., Low temperature platinum resistance thermometry, Platinum Metals Rev. 7, 15 (Jan.).

Beck, A.E., Lightweight borehole temperature measuring equipment for resistance thermometers, J. Sci. Instr. 40, 452 (Sept.).

Berry, R.J., Relationship between the real and ideal resistivity of platinum, Can. J. Phys. 40, 946.

Brodskii, A.D., Measuring low temperatures with a platinum resistance thermometer without calibration at the oxygen boiling point, Tr. Inst. Kom. Standartov Mer i Izmerit. Priborov pri Sov. Min. SSSR 1963 No. 71, 149.

Clark, J.N., J.A. Spahr, and R.A. Hendle, The effect of freezing-thawing cycles on thermistor calibration, PB 162793.

Cook, J.C., and K.E. Kenyon, Fast-response thermistor probes for temperature microstructure studies at sea, Rev. Sci. Instr. 34, 496 (May).

Dunn, W.F., A temperature measuring system using RDF Stilson resistance elements, Allegany Ballistics Lab., Rept. ABLE 87; AD-408503.

Godin, M.C., A modified thermistor thermometer, J. Sci. Instr. 40, 500 (Oct.).

Golovashkin, A.N., and G.P. Motulevich, a sensitive low inertia thermal resistor for helium temperatures, Cryogenics 3, 167 (Sept.).

Hinkelmann, H., and H.M. Ihme, An electrical dep-sea thermometer with short adjustment time, Z. Angew. Phys. 15, 429.

Hoover, H.M., A rapid response high accuracy thermal probe, Marine Sci. Instr. 2, 43.

James, B.W., and B. Yates, Indium resistance thermometery, J. Sci. Instr. 40, 193 (April).

Kalinkina, I.N., Resistance of carbon thermometers as a function of temperature, Instr. Exp. Tech. No. 3, 580(Nov.)

Kaufman, A.B., Bonded-wire temperature sensors, Instr. Control Systems 36, 103 (May).

Knobler, C.M., W.I. Honeywell, and C.J. Pings, Thermal and hydrostatic behaviour of miniature platinum resistance elements, Rev. Sci. Instr. 34, 1437 (Dec.).

Kozhukh, V. Ya, Selecting the value of a thermistor for remote measurements of temprature, Measurement Techniques No. 6, 477 (Nov.).

McKnight, G.P., Resistors for precise temperature measurements, Electron. Ind. 22, 97 (July).

Mikhailov, N.N., and A. Ya. Govor, Leaded brass resistance thermometers for measuring low temperatures, Cryogenics 3 205 (Dec.); Instr. Exp. Tech. No. 2, 402 (Nov.).

Misek, K., and J. Polak, Measurement of temperature of thin metallic wires, Cesk. Casopis Fys. 13, 87.

Nalle, D.H., Recording small temperature changes, Measurement and Control 2, 363 (Sept.).

Orlova, M.P., D.N. Astrov, and L.A. Medvedeva, Indium resistance Thermometers for temperatures in the 3.4-300°K range, Instr. Exp. Tech. No. 2, 342 (Nov.).

Priestley, P.T., A thermistor thermometer with digital display, J. Sci. Instr. 40, 505 (Oct.).

Riddle, J.F., Temperature measurements below 1000°K, NASA Measurement of Thermal Radiation Properties of Solids 1963 p. 11; N64-10939.

Saburi, O., and R. Wakino, Processing techniques and applications of positive temperature coefficient thermistors, IEEE Trans. CP-10, 53 (June).

Sachse, H.B., Measurement of low temperatures with semiconductor resistance thermometers, Z. Angew. Phys. 15, 4 (Jan.).

Sapoff, M., and R.N. Oppenheim, Theory and application of self-heated thermistors, Proc. IEEE 51, 1292 (Oct.).

Scagnetti, M.S., and J. Crabol, Fast-response platinum film temperature probes, Rech. Aerospatiale No. 97, 23 (Nov.-Dec.).

Scheppner, E., Resistance bulb time constants, AD-409337.

Srivastava, K.C., and J. Singh, Apparatus for measuring temperature in a settling concrete block and controlling it adiabatically, Indian J. Technol. 1, 6 (Jan.).

Terris, D., Platinum resistance Thermometer circuit with 5 volts output, U.S. At. Energy Comm. Rept. NAA-SR-Memo-8073 (Jan. 15); NSA N-20283.

Vakalov, I.A., Influence of ultra-sound on electrical conductivity of thermoresistors, AD-412211.

Vanik, M.C. et al, Reproducible thermistor refinement program, AD-407792.

Voronel, A.V., and V.V. Shchekochikhina, Miniature platinum resistance thermometer, Instr. Exp. Tech. No. 2, 364 (Nov.).

Wienke, H.J., P.S. Myers, and O.A. Uyehara, A resistance thermometer for engine compression temperatures, S.A.E. J. 71, 104 (July).

Corrections for use in low temperature platinum resistance thermometry, Natl. Bur. Std. (U.S.) Tech. News Bull. 47, 101 (June).

Wafer thermistors provide the route to high precision in resistor manufacture, R & D No. 19, 51(Mar.).

1964

Alieva, F.Z., A method of measurng temperature with a platinum resistance thermometer, Air Force Systems Command, Wright Patterson AFB, Ohio, Foreign Technology Division FTD-TT-64-83/1&4; AD-601561; N64-25461.

Alieva, F.Z., New platinum resistance thermometer for precision measurements of high temperatures, Measurement Techniques No. 6, 487 (Dec.).

Ambrok, G.S., Method of calibrating thermal flow detectors, Measurement Techniques No. 11, 918 (April).

Barber, C.R., International Comparison of platinum resistance thermometers S167, R13 and N 109 in ten laboratories (Measurement of the interval 0-100° of the practical international scale of temperature), Comite Consultatif Thermometrie Comite Intern. Poids Mesures, 6e, Sevres, France 1962, 64 (Publ. 1964).

Bardila, P.I. et al, New platinum resistance thermometer, Measurement Techniques No. 5, 389 (Nov.).

Batha, H.D., and P.E. Carroll, Unicrystalline silicon carbide thermistor, IEEE Trans. CP-11, 129 (June).

Berry, R.J., Choice of resistance thermometer for the region 10-90°K, Comite Consultatif Thermometrie, Comite Intern. Poids Mesures, 6e, Sevres, France 1962, 125 (Publ. 1964).

Black, W.C. Jr., et al, Speer Carbon resistors as thermometers for use below 1°K, Rev. Sci. Instr. 35, 587 (May).

Boel, M., and B. Erickson, A correlation study of a thermistor thermometer, Polytechnic Inst. of Brooklyn PIBAL-696 (May); AD-601656; N64-30589.

Bogdan, L., High temperature thin film resistance thermometers for heat transfer measurement, NASA Contract Rept. CR-26 (1964); AD-414970; N64-17988.

Bogdan, L., Measurement of radiative heat transfer with thin film resistance thermometers NASA Contract Rept. CR-27(1964).

Bulychev, V.S., Thermistor for temperature meter with stabilized supply, Measurement Techniques No. 8, 673 (Feb.).

Chao, J.L., and V.A. Sandborn, A resistance thermometer for transient temperature measurements, AD-600346.

Chappell, R.W., and A. Moilliet, A sensitive resistance thermometer with fast response for use in the sea, Pacific Naval Lab., Esquimalt, British Columbia PNL TM64-3 (May 1964); AD-443817.

Davis, W.T., Engine temperature indicator, Electronics World 71, 36 (April).

Dupre, A., et al, The use of graphite thermometers in heat conducting experiments below 1°K, Cryogenics 4, 354 (Dec.).

El Agib, A.A.R., The pair ratio method of measuring small temperature difference, J. Sci. Instr. 41, 592 (Oct.).

Evans, J.P., and G.W. Burns, Stability of a platinum resistance thermometer at high temperatures, Comite Consultatif Thermometrie, Comite Intern. Poids Mesures, 6e, Sevres, France 1962, (Publ. 1964).

Fluke, G.L., Winsco platinum resistance temperature transducer-Model 2610-2, AD-439778.

Goldwater, F.J., Linearization of resistance thermometer output, J. Sci. Instr. 41, 46 (Jan.).

Hartunian, R.A., and R.L. Varwig, A correction to thin-film heat transfer measurements, AD-606036.

Jessop, A.M., A lead compensated thermistor probe, J. Sci. Instr. 41, 503 (Aug.).

Kaganov, M.A., Precision of differential thermistor measuring circuits, Measurement Techniques No. 3, 231 (Oct.).

Kaganov, M.G., and I.S. Lisker, Inertia of electric resistance thermometers, Inzh. Fiz. Zh. 7, 28 (April).

Kalinkina, I.N., Temperature dependence of the resistance of carbon thermometers, Cryogenics 4, 327 (Oct.).

Karbe, Yu.V., Semiconductor surface thermometer, Instr. Construct No. 7, 27 (July).

Kirsa, V.I., Method of selecting identical semiconductor thermistors from a batch, Instr. Construct. No. 5, 26 (May).

Kozhukh, V. Ya., The accuracy of temperature measurement with semiconductor resistors, Instr. Construct. No. 3, 10 (Mar.).

LaForce, R.C., S.F. Ravitz, and W.B. Kendall, Device for the precise measurement of small temperature changes, Rev. Sci. Instr. 35, 729 (June).

Langlands, R.C., A stable copper resistance thermometer for field use, J. Sci. Instr. 41, 478 (July).

London, G.E., An apparatus for measuring rapidly changing temperatures, Wright-Patterson AFB, Ohio, FTD-TT-64-82/1,2&4; AD-601508.

Manche, E.P., and B. Carroll, Temperature measurement in thermogravimetry, Rev. Sci. Instr. 35, 1486 (Nov.).

Meservey, R.H., Fuel plateresistance thermometer, U.S. At. Energy Comm. Rept. IDO-16965 (March).

Mishchenko, K.P., and V.P. Tungutsov, New method for the calibration of semiconductor resistance thermometers in the determination of the heat capacity of pure liquids and solutions, Zh. Prikl. Khim. 37, 1243.

Nakaya, S., and H. Uchiyama, Thermometry of high temperatures with the aid of a platinum resistance thermometer, Comite Consultatif Thermometrie, Comite Intern. Poids Mesures, 6e, Sevres, France 1962, 57 (Publ. 1964).

Novopavlovskii, V.S., Errors in the measurement of surface temperature with the resistance thermometer, Inzh. -Fiz. Zhur. 7, 52 (May).

Oreshkin, P.T. et al, Thermistors for measuring the surface temperatures of bodies, Ind. Lab. 30, 296 (Sept.).

Orlova, M.P. et al, Germanium resistance thermometer for low temperatures, Inst. Exp. Tech. No. 1, 253 (Sept.).

Orlova, M.P., D.N. Astrov, and L.A. Medvedeva, Indium resistance thermometer for the temperature range 3.4 to 300°K, Cryotenics 4, 95 (April).

Pearson, P.H., An investigation into the response and corrections to a thermistor and a platinum wire resistance thermometer for temperature measurement in the upper atmosphere, N64-22493.

Quarmby, A., Transient response of wire resistancethermometers, J. Roy. Aeronaut. Soc. 68, 696 (Oct.).

Ruskin, J.M., Thermistors as temperature transducers, Data Systems Eng. 19, 24 (Feb.).

Seuf, G., Temperature measurement with semiconductor diodes, Exptl. Tech. Physik. 12, 70.

Stanishevskiy, V.N., Use of thermistors for measurement of temperature, N65-15513.

Tebo, A.R., Precise measurement of atmospheric temperatures, Army Signal Res. and Development Agency, Fort Monmouth, N.J., USAELDR-TR-2405; AD-430573; N64-20854.

Tsien, H.C., Piston zone temperature measurement, Instr. Control Systems 37, 103 (May).

van Dijk, H., Results obtained from measurements on platinum resistance thermometers at the thermometry section of the Kamerlingh Onnes Laboratorium, Leiden, Physica 30, 1498 (Aug.).

Vautier, C., and A. Colambani, Thin film platinum resistance thermometers, Compte Rend. 258, 4706.

Zaitsev, A.M., Miniature low-inertia platinum resistance thermometer, Instr. Exp. Tech. No. 1, 250 (Sept.).

Zsombor-Murray, P.J., A heat transfer probe for use in a high temperature gas, AD-435096.

Platinum films as temperature probes, Platinum Metals Rev. 8, 146 (Oct.).

1965

Boel, M., and B. Erickson, Correlation study of a thermistor thermometer, Rev. Sci. Instr. 36, 904 (July).

Chevako, R.J., Thermistor bibliography, Proc. IEEE 53, 175 (Feb.).

Clark, G.Q., and J.G. McCoy, Upper Atmospheric temperature sensing using the head thermistor, N65-33645.

Coor, T., and L. Szmauz, Digital thermometer, Instr. Control Systems 38, 125 (May).

Cunsolo, S. et al, Interpolation and extrapolation of carbon resistance thermometer calibration data in the liquid helium II region, Cryogenics 5, 168.

George, J.T., and F.D. DeMarco, ML-419 thermistor P.E.M. final engineering report, Jan. 1, 1963-Aug. 31, 1964, Bendix Corp., Baltimore, Md., Friez Instr. Div., AD-608963; N65-26306.

Gerber, R., F. Vilim, and K. Zaveta, Measurement of low temperature with a carbon thermometer, Cesk. Casopis Fys. 15, 340 (Czech).

Hales, J.L., and E.F.G. Herington, A new method for the computation of temperature in platinum resistance thermometry, J. Sci. Instr. 42, 203 (April).

Hardy, D., Temperature sensing resistor environment test, Texas Instr. Inc. Rept. No. 5849-E; AD-460242.

Janicke, J.M., Direct-reading platinum thermometer, Instr. Control Systems 38, 129 (May).

Jones, E.W., Calibration techniques for thermistors, Instr. Control Systems 38, 123 (May).

Lakh, V.I., and V.A. Kochan, Overheating of platinum resistance thermometers by a measuring current, Teplofizika Vysokikh Temperatur 3, 661 (July).

Nechaev, G.K., Semiconductor thermistors in automation Wright-Patterson AFB, Ohio, Foreign Tech. Div. Rept. No. FTD-MT-64-210; AD-618048; N65-31893.

Orlova, M.P. et al, Germanium resistance thermometer for low temperatures, Cryogenics 5, 165.

Pharo, L.C., Some characteristics of the VECO 32A8 thermistor operating in a self heated condition, Rev. Sci. Instr. 36, 211 (Feb.).

Priestly, P.T., Multiple thermistor indicator for thermometric analysis, J. Sci. Instr. 42, 35 (Jan.).

Sapoff, M., and R.M. Oppenheim, A blanket approach to a linear thermistor network Part 1. The method, Electron. Design 13, 20 (Mar.).

Sapoff, M., and R.M. Oppenheim, A blanket approach to a linear thermistor network. Part 2. Examples, Electron. Design 13, 32 (April).

Schneider, D.B., The thermistor thermometer, Instr. Control Systems 38, 119 (May).

Seginer, A., A. Cohen, and J. Rom, Calibration of thin film resistance thermometers for heat flux measurements in a shock tube, Israel J. Tech. 3, 25 (Feb.).

Sychev, V.V., and N.I. Gorbunova, Accuracy of temperature measurement by means of the standard platinum resistance thermometer, Teplofizika Vysokikh Temperatur 3, 632(July).

Toenshoff, D.A., Bird-cage resistance thermometer, Engelhard Inds. Tech. Bull. 5, 127.

Resistor, Thermal (Thermistor) Kearfott Div. General Precision Inc., Little Falls, N.J., Rept. No. 603-006; AD-463 509.

Thin film thermistor temperature sensor. Final report, Metrophysics Inc., Santa Barbara, Calif., AD-472737.

4. Radiation Devices

1960

Babushkin, V.V., Apparatus for measuring a high-temperature gas stream at high pressure, Tr. Inst. Kom. Standartov Mer i Izmerit. Priborov pri Sov. Min. SSR 42, 26.

1961

Beattie, J.R., Measurement of the temperature of transparent materials, Acta Imeko 4, 210.

1962

Beer, J.M., and I.J. Claus, The "traversing" method of radiation measurement in luminous flames, J. Inst. Fuel 35, 437.

Burns, E.A., and R.J.P. Lyon, Errors in the measurement of the temperature of the moon, Nature 196, 463 (Nov.).

Casselton, R.E.W. et al, Black-body radiation from partially enclosed cavities,

J. Inst. Metals 91, 408.

Faizullov, F.S., Pyrometric investigation of the state of air, nitrogen and argon behind a shock wave, Tr. Fiz. Inst., Akad. Nauk SSSR 18, 105.

Grien, H.R., Plasma spectroscopy, Ionization Phenomena in Gases, Vol. II, North Holland Publishing Co., Amsterdam (1962) p. 1857.

Kean, L., A contribution to the theory of schlieren sensitivity and quantitative evaluation, Aeron. Systems Div., Wright-Patterson AFB, Ohio, ASD-TDR-62-924 (Dec.).

Kocho, V.S., V.I.Grankovskii, and V.G. Antosyak, Measurement of gas temperature with a radiation pyrometer, Ind. Lab. 28, 219 (Aug.).

Kroepelin, H., Temperature determination in arcs in hydrocarbon atmospheres, Ionization Phenomena in Gases, Vol. II, North-Holland Publishing Co., Amsterdam (1962) p. 1830.

Kudroyavtsev, E.M. et al, Pyrometric investigation of the state of a gas behind a reflected shock wave, Tr. Fiz. Inst., Akad, Nauk SSSR 18, 159.

Lovejoy, D.R., Detection limits in radiation and optical pyrometer, J. Opt. Soc. Am. 52, 1387 (Dec.).

Maleev, E.M., and D.S. Ermakov, Single beam two-frequency pyrometer for measuring flame temperatures, Optics and Spectroscopy 13, 339 (Oct.).

Reeves, E.M., and W.H. Parkinson, Spectral energy distribution and brightness temperatures in continuous flash sources, Ionization Phenomena in Gases, Vol. I, North-Holland Publishing Co., Amsterdam (1962) p. 1017.

Shaw, V.G., Two color pyrometry in the metals industry, Proc. Instr. Soc. Am. 17, Paper No. 58.3.62.

Smith, W.M., and J.L. Frank, Low temperature infrared thermometer, Proc. Instr. Soc. Am. 17, Paper No. 21.4.62.

Sobelev, N.N. et al, A spectroscopic investigation of the state of gases behind a shock wave, Ionization Phenomena in Gases, Vol. II, North-Holland Publishing Co., Amsterdam (1962) p. 2122.

Volk-Levanovits, M.V., Measurement of temperature of a mercury arc by the method of Bartels, Inzh. Fiz. Zh. 5, 87 (Aug.).

1963

Adhav, R.S., and J.G. Kemp, Infrared radiometer, J. Sci. Instr. 40, 26 (Jan.).

Bates, R.L., and W.L. Eisenman, Improved black radiation detector, Naval Ordnance Lab., Corona, Calif., NOLC Rept. 594, Photodetector Series 60 (Dec. 15, 1963); AD-426778.

Bruckner, R., Spectrometeric measurements of temperatures above 3500°C and determination of temperature distribution in a plasma burner at atmospheric pressure, Ber. Dtsch. Keram. Ges. 40, 603.

Casselton, R.E.W., G. Erez, and T.J. Quinn, Black-body radiation from partially enclosed cavities, J. Inst. Metals (G.B.) 91 pt 12, 408 (Aug.).

Clark, R.G., Monitoring surface temperatures of irradiated fuel elements, U.S. At. Energy Comm. Rept. HW-SA-3036 (May 6).

Drawin, H.W., Spectroscopic temperature and density measurement of plasmas in the absence of thermodynamic equilibrium, Z. Phys. 172, 429.

Dreyfus, M.G., Spectral variation of black-body radiation, Appl. Optics 2, 1113(Nov.).

Euser, P., Compensation pyrometer for the measurement of surface temperatures of moving parts independent of the surface emissivity, Instr. Pract. 17, 487 (May).

Fairbairn, A.R., Temperature measurements of C_2 and CN radicals generated in a shock tube, II Detonation, Proc. Roy. Soc. (London) A276, 513.

Fateeva, N.S. et al, An optical method of determining the melting temperature of graphite as a function of pressure up to 40,000 atm, Soviet Physics-Doklady 8, 904 (Mar.).

Frock, H.N., and W.T. Shreve, A new automatic balancing optical pyrometer, Proc. Instr. Soc. Am. Paper No. 29.5.63.

Gaydon, A.G., I.R. Hurle, and G.H. Kimbell, Temperature measurements of shock waves and detonations by spectrum-line reversal, IV Development of detonation, Proc. Roy. Soc. (London) A273, 241 (May 21).

Gilardini, A., Microwave determination of after glow temperatures and electron collision parameters in nitrogen and oxygen, AD-418360.

Golub, L.M., and E.S. Shpigelman, Rationalizing the calibration method of reference telescopic radiation pryometers, Measurement Techniques No. 4, 317 (Oct.).

Gordov, A.N., Noncontact methods of measuring the true temperature of heated bodies, High Temperature 1, 128 (July-Aug.).

Gordov, A.N., Simplification of the method for calibrating and testing color pyrometers, Measurement Techniques No. 1, 41 (Aug.).

Goryachev, B.A., Photoelectric pyrometer, Ind. Lab. 28, 1202 (Mar.).

Greenshields, D.H., Spectrometric measurements of gas temperatures in arc-heated jets and tunnels, NASA Tech. Note D-1960 (Oct.).

Ioselson, G.L., Methods for automatic compensation of the emission coefficient in measuring the plasma temperature with respect to radio-frequency thermal radiation, High Temperature 1, 391(Nov.-Dec.).

Kandyba, V.V., Measurement of temperature in flames, gas flows, and plasmas from spectral line intensities, High Temperature 1, 386 (Nov.-Dec.).

Kelsall, D., An automatic emissivity compensated radiation pyrometer, J. Sci. Instr. 40, 1 (Jan.).

Kirenkov, I.I., Effective wave length of a photoelectric spectral pyrometer, Measurement Techniques No. 6, 474 (Nov.).

Kogan, A.V., A method of reducing the error of a disappearing filament pyrometer, High Temperature, 1, 273 (Sept.-Oct.).

Kozyrev, B.P., Basic problems of radiation pyrometry of slightly heated or cooled objects, Inzh.-Fiz. Zh. 6, 9.

Kusch, H.J., Development of methods for quantitative spectroscopic temperature determination of plasmas, Keel U. Inst. Exp. Phys. N-21786.

Land, T., and R. Barber, Some recent developments in radiation pyrometry, Trans Soc. Instr. Technol. 15, 1 (Mar.).

Lapina, E.A., An infrared pyrometer for the determination of spectral coefficients of black body radiation of some types of oxide cathodes, Tr. Inst. Gos. Kom. Standartov, Mer i Izmeritel'n. Priborov SSSR No. 71, 153.

Lapp, M., and L.P. Harris, Influence of alkali-vapor atmospheres on pyrometrically determined temperatures; cesium and potassium, J. Appl. Phys. 34, 3622 (Dec.).

Laughin, R.D., Needle temperature measurement by infrared pyrometry, Textile Res. J. 33, 35 (Jan.).

Lehman, W.J. Jr., Black body radiance-temperature conversion table, Aberdeen Prooving Ground Rept. DPS 1059 (Aug.); AD-417811.

Magdeburg, H., The measurement of temperature distribution on the surface of temperature radiatiors, Z. Instrumentenk. 71, 22 (Jan.).

Mak, W.H., Sodium line reversal temperature measurements in shock-tube flows, Toronto U. Inst. Aerophysics (Canada) UTIA-TN-66 (May); AD-419307; N63-19188.

McGregor, W.K., Spectroscopic measurements in plasma, Northwestern U. and Am. Inst. Aeronautics and Astronautics, Biennial Gas Dynamics Symposium, 5th, Physics-Chemical Diagnostics of Plasmas, Evanston, Ill., (Aug. 14-16); Northwestern University Press (1964), p. 143.

Meyer, J.H., and J.P. Puckett, A rotary kiln shell temperature scanner, Elec. Eng. 82, 618 (Oct.).

Miller, J.T., Revised course in industrial instrument technology. Chapter 10. Radiation pattern thermometers on pyrometers, Instr. Pract. 18, 153 (Feb.).

Moffitt, G., Study of a temperature measuring system for the 1000°C to 2500°C range, Wright-Patterson AFB, Ohio, Flight Control Lab. ASD-TR-61-487; AD-274794; N63-16853.

Nadaud, L., and M. Gicquel, Optical measurement of high temperatures, NASA Sci. and Tech. Aerospace Rept. N-15329.

Ohm, E.A., and W.W. Snell, A radiometer for a space communications receiver, Bell System Tech. J. 42, 2047 (Sept.).

Pekker, I.I., E.I. Fandeev, and V.E. Shuksheenov, Radiation temperature transducer for moving surfaces, Izv. vyss. ucheb. Zaved. Priborostr. 6, 145.

Peloquin, R., and M. Weiss, Airborne instrument for precision measurement of sea surface temperature using infrared radiation emitted by the sea, Marine Sci. Instr. 2, 61.

Penzias, G.J., and R.H. Tourin, Measurement of temperature ingaseous detonations by monochromatic radiation pyrometry, ARL 6385 (May); AD-418763; N63-15058.

Percy, J.W., Basic oxygen steelmaking-continuous bath temperature measurement, Proc. Instr. Soc. Am. 18, Paper 21.2.63.

Peuteman, A., New pyrometer using a lead sulfide cell. Surface measurement of temperatures over 100°, Rev. Gen. Thermique 2, 417.

Poskachei, A.A., Radiation measurement of temperatures below 800°, Tsvetn. Metal. 36, No. 9, 76.

Porter, R.A., Significance of radiative sky temperature in the determination of the apparent temperatures of materials, Rand Corp. The application of precise microwave technology to satellite meteorology, A Symposium (Aug. 1963), p. 157.

Powling, J., and W.A.W. Smith, The surface temperature of burning ammonium perchlorate, Combust. Flame 7, 269.

Ramsey, P.W. et al, Infrared temperature sensing systems for automatic fusion welding, Welding J., Res. Suppl. 42, 3375 (Aug.).

Rowen, T.R., Black body radiation tables, Army Missile Command, Huntsville, Ala. TN-AMSMI-RNR-1-63; AD-418979; N64-13856.

Ryan, L.R., H.J. Babrov, and R.H. Tourin, Infrared spectra and temperatures of plasma jets: spectrometric and spectroradiometric measurement of plasma jet temperature distributions, Wright-Patterson AFB, Ohio, Aeronautical Research Labs., ARL-63-35 (Feb.); AD-404867; N63-16512.

Schwarz, F., Infrared detectors, Electro-Technol. (N.Y.) 72, 116 (Nov.).

Semikin, I.D., A radiation thermometer, Foreign Tech. Div., Air Systems Command, Wright-Patterson AFB, Ohio, FTD-TT-63-64; AD-409749; N64-21943.

Simmons, F.S., Spectroscopic pyrometry of gases, flames and plasmas, ISA Trans. 2, 168 (April).

Sorgenicht, W., Radiometer based on the Gerlach principle and radiometer probes in industrial use, Elektrowarme 21, 45 (Jan.).

Taft, W.C., K.C. Stotz, and E.H. Holt, A gated radiometer for plasma after-glow study, IEEE Trans. on Instrumentation and Measurement IM-12, 90 (Sept.).

Takata, S., On the procedures and the accuracy of brightness matching in optical pyrometry, Natl. Res. Lab. of Metrology (Japan) Bull. No. 7, 7 (Nov.).

Tourin, R.H., Recent developments in gas pyrometry by spectroscopy, AFOSR J 1483; AD-427539.

Tourin, R.H., L.R. Ryan, and H.J. Babrov, Some spectrometric and spectroradiometric measurements of temperature in plasma jets, N63-23486.

Tsuchiya, S., Instantaneous temperature measurement by a modified sodium-D line reversal method, Nippon Kagaku Zasshi 84, 300.

Walker, M., J. Roschen, and E. Schlegel, An infrared scanning technique for determination of temperature profiles in microcircuits, Trans. Inst. Elect. Electron.

Engrs. ED-10, 263 (July).

Wildey, R.L., Bolometric-correction and effective temperature scale, Nature 199, 988.

Woolvet, G.A., and J.M. Alexander, Radiation pyrometer for temperature measurement in the hot extrusion of aluminum, J. Inst. Metals 92, 430.

Adaptable radiation pyrometer, Engineer 216, 781 (Nov.).

A pyrometer with characteristics independent of emissivity, Control 7, 135 (Sept.).

NBS photoelectric pyrometer increases accuracy in temperature measurement, Ind. Heating 30, 660 (April).

Plasma temperature in fusion research, J. Franklin Inst. 276, 270 (Sept.).

Radiometer measures temperatures to 2500° C, Electron. Design 11, 78 (May).

Test equipment for high temperature studies; Optical pyrometer, Engineering 196, 93.

1964

Allen, R.A., Nonequilibrium shock front rotational, vibrational and electronic temperature measurement, NASA Contract Rept. 58673; N64-28885.

Alvares, N.J., Measurement of the temperature of the thermally irradiated surface of alpha-cellulose, AD-600768; N64-22966.

Anufrier, A.A., and L.V. Leskov, Optical pyrometry of nonuniform light sources, Optika i Spektroskopiya 16, 325.

Beattie, J.R., The application of radiation pyrometry to glass temperature measurement and control, Proc. Instr. Soc. Am. 19, Paper No. 4 (Feb. 1).

Bernard, B., Determining emissivity, Inst. Control Systems 37, 87 (May).

Boberskii, G.A., Instrument for measuring spectral black-body radiation factors, Measurement Techniques No. 8, 675(Feb.).

Bowen, T.R., Blackbody radiation tables, AD-418979.

Breqev, L.E., Spectroscopy of a supersonic plasma. II Exitation temperature, Arnold Eng. Develop. Center AEDC-TDR-64-196 (Sept.); AD-447735; N64-31069.

Brodi, G., A.E. Abbott, and D. McCright, Evaluation of infrared radiation pyrometer for measuring remelt pour temperatures, U.S. At. Energy Comm. Rept. NLCO-890.

Broussaud, G., and P. Fombonne, The application of Hertzian radiometry for measuring the temperature of the atmosphere, J. Inst. of Navigation 17, 418 (Oct.).

Buchele, D.R., Nonlinear-averaging errors in radiation pyrometry, NASA Tech. Note D-2406 (Aug.).

Buchele, D.R., Radiometer-pyrometer for analysis of gaseous combustion products, NASA Tech. Note D-2405; N64-27092.

Burns, J., Research on effects of arc fluctuations on spectroscopically determined temperatures in arc plasmas, N64-14777.

Burton, J.T.A., and J.A. Hicks, Detonation emissivities and temperatures in some liquid explosives, Nature 202, 758 (May 23).

Cammerer, J.S., F.C. Cammerer, and G. Fischer, Measurement of surface temperatures and of thermal radiation of large industrial equipment of uneven temperature, Brennstoff-Warme-Kraft 16, 120 (Mar.).

Caulton, G.K., Ratio pyrometer ignores surface variations, Control Eng. 11, 111 (Nov.).

Christenson, R.W.S., Environmental errors in use of the airborne infrared radiation thermometer to measure sea-surface temperature, AD-601473; N64-27622.

Combs, H.C., Meteorological applications of infrared radiometry, AD-425911; N64-19406.

Doering, H., and P. Shahinian, Brightness and two-color pyrometry applied to the electron beam furnace, Naval Research Lab., Wash., D.C., NRL-6062 AD-602292; N64-26914.

Duchon, C.E., Estimates of the infrared radiation temperature correction for cylindrical temperature sensors, J. Appl. Met. 3, 327 (June).

Esser, F., Radiation pyrometer with a germanium diode as receiver, Neue Hutte 9, 612 (Oct.).

Filippov, L.P., N.A. Tuqareva, and L.I. Markina, Methods for determining small pulsations of high temperature and their application to determining metal heat capacities, Inzh. Fiz. Zh. 7, 3 (June).

Finkelshtein, V.E., Precise determination of effective wavelengths of spectro-pyrometers, Measurement Techniques No. 1, 43 (July).

Fussell, W.B., and J.B. Schutt, Temperature of a gray body most closely fitting the solar extra terrestrial spectrum, NASA Tech. Note D-1845.

Gallagher, G., and A. Lemay, Temperature measurements of the near wake generated by hypervelocity bodies, N64-29423.

Hooker, W.J., Preliminary hypervelocity wake brightness temperature measurements, AD-434999; N64-20139.

Houston, J.M., and P.K. Dederick, Pyrometer correction due to Dimer absorption, AD-430855; N64-16625.

Izakov, M.N., Measuring the temperature of the atmosphere with the aid of satellite-borne instruments, NASA-TT-F-8569.

Kamada, O., Method of measuring target temperature in a solar furnace, Appl. Optics 3, 1397 (Dec.).

Kandyba, V.V., The method and instrument for measuring temperatures of flames, gas flows and plasmas, Acta Imeko 2, 359; NSA 19-46734.

Kanzler, R.J., An instrument for air temperature measurement using infrared emission of CO_2, Bull. Am. Meteorol. Soc. 45, 48.

Kennedy, R.H., Infrared temperature measurement and its application to textile finishing operations, Am. Dyestuff Reporter 53, 56 (Jan. 20).

Kirenkov, I.I., Particular features in the development of radiation pyrometry, Measurement Techniques, No. 4, 330 (Nov.).

Kohler, W., and R. Fischer, Temperature measurement by dispersion filters, Optik 21, 624 (Nov.).

Laramore, G.E., and D.M. Johnson, A method for determining the effective emitting temperature of a radiating body, Naval Ammunition Depot, Crane, Ind., Research and Development Dept. Rept. RDTR-40 (Aug. 3); AD-604015; N65-10466.

Lieneweg, F., and K. Menge, A two-color automatic pyrometer, Mesures 29, 67 (Mar.).

Magison, E.C., The "whys" of radiation pyrometry, Instrumentation, 17, 19.

Meredith, R. et al, Superheterodyne radiometers for short millimeter wavelengths, Electronics Record 1964, 241 (Feb.).

Mikelson, W., Comparing pyrometer methods for hot strip applications, ISA J. 11, 61 (Sept.).

Montgomery, P.W., The detection of turbine wheel temperatures by infrared radiation instrumentation, AD-426917.

Muller, G.O., Contactless temperature measurement with the aid of semiconductor filters, Acta Imeko 1964, 383 Paper No. 23-DDR-233.

Muntz, E.P., and S.J. Abel, The direct measurement of static temperature in shock tunnel flows, AD-436700; N64-24586.

Murray, B.C., and R.L. Wildey, Surface temperature variations during the lunar night time, N64-20608.

Nadaud, L., and M. Gicquel, Optical high temperature measurement, AGARD ograph No. 68, 281 (1962), Publ. 1964 (France).

Napier, D.H. et al, Temperature measurement in a chemical shock tube by sodium line reversal and C_2 reversal methods, AIAA J. 2, 1136.

Okayama, S., Photoelectric optical pyrometer, Tokyo Kogyo Daigaku Gakuko No. 28, 1.

Overington, I., and D.J. Williams, Colour densitometry applied to temperature measurement, R & D No. 30, 38 (Feb.).

Parkinson, W.H., and E.M. Reeves, Design and construction of a new shock tube and experimental measurement of temperatures and oscillator strengths, AD-433547; N64-22226.

Paul, F.W., Temperature measurements with an optical pyrometer under adverse conditions, Appl. Optics 3, 297 (Feb.).

Paul, M.C., and P.E. Oberg, Modified pyrometer temperature measurement technique, Rev. Sci. Instr. 35, 1078 (Aug.).

Penzias, G.J., R.H. Tourin, and S.A. Dolin, Infrared techniques for air temperature measurements in a hypersonic wind tunnel, AD-608983.

Platunov, E.S., and V.B. Fedorov, Use of photographic pyrometry in thermo-physical studies, Teplofiz. Vysokikh Temperatur, Akad. Nauk SSSR 2, 628.

Reeves, E.M., and W.H. Parkinson, Temperature measurement for shock heated powdered solids, AD-433550.

Reynolds, P.M., A review of multicolor pyrometry for temperature below 1500°C, Brit. J. Appl. Phys. 15, 579 (May).

Richard, B. et al, Measurement of temperature by Hertzian radiometry, Mesures 29, 85 (Sept.).

Roberts, A.S., and W.H. Bennett, Plasma temperature measurement for the hollow cathode discharge, J. Appl. Phys. 35, 3434 (Dec.).

Robinson, D., Heavy particle temperature measurements in a nitrogen plasma by a spectroscopic method, J. Quantitative Spectroscopy 4, 335; AD-440101.

Roth, J., Measured temperatures of strong shock waves in argon, J. Appl. Phys. 35, 1429 (May).

Schofield, D., Effect of laminar boundary layer development on spectrum-line reversal temperature measurement: dispersion line profile, N64-14237.

Shcherbina, D.M., Temperature measurement in solar furnaces, High Temperature 2, 84 (Jan.-Feb.).

Soltyk, V.Ya., and V.G. Tishchenko, Pyrometer for remote reading of temperatures (exchange of experience), Ind. Lab. 30, 1593 (Oct.).

Surh, M.T., and M.G. Whybra, Theoretical studies of a radiation balance, NASA Tech. Note D-2246.

Svet, D.Ya., and T.N. Zavarza, Selection and rational utilization of the spectral sensitivity of photocells in bichromatic pyrometry, Measurement Techniques No. 2, 107 (Aug.).

Tingwaldt, C., and J. Schley, Two new optical methods for the laboratory determination of surface temperatures of solids, Acta Imeko 1964, 353 Paper No. 23-DBR-152.

Weiss, M., High temperature ultraviolet radiometer, Instr. Control Systems 37, 95 (May).

Wells, A., and R.H. Kennett, Temperature measurements on a plasma jet, Aeronautical Research Council (G.B.) ARC-CP-756; N65-10563.

Wilson, J., Discrepencies between theoretical and experimental values of temperature behind a shock wave, Aeronautical Research Council (G.B.) ARC-CP-712; AD-407106; N64-18156.

Wormser, E.M., Radiation thermometer with in-line blackbody reference, Instr. Control Systems 37, 101 (Dec.).

Emissivity-compensated radiation pyrometer, Instr. Pract. 18, 291 (Mar.).

Radiation pyrometer, Prod. Eng. 35, 94(Apr. 27).

1965

Bakhir, L.P., Optical pyrometry of nonuniform sources of radiation, Zh. Prikl. Spektroskopii, Akad. Nauk Belorussk. SSR 2, 279.

Barber, R., and J.D. Cresswell, An evaluation of the accuracy of radiation pyrometers in a rolling mill, Proc. 15th

Natl. Conf. Instr. Iron Steel Ind. 15, paper No. 12.

Berty, M., Spectrographic measurement of the temperature of a hydrogen plasma jet by the Stark effect, J. Phys. 26, 469 (Aug.).

Bivans, E.W., Scanning radiation pyrometer, Instr. Control Systems 38, 115 (July).

Burley, B.W., Radiation pyrometers to measure the temperature of small objects, Instr. Eng. (G.B.) 4, 33 (April).

Eppig, H.J., E.C. Magison, and D.F. Wood, High speed radiation pyrometer for glass temperature measurement, Glass Ind. 46, 457 (Aug.).

Exton, R.J., A variable exposure photographic pyrometer, ISA Trans. 4, 365 (Oct.).

Ferriso, C.C., and C.B. Ludwig, An infrared band ratio technique for temperature determinations of hot gases, Appl. Optics 4, 47 (Jan.).

Galley, J., M. Rouannet, and G. Urbain, New photoelectric pyrometer for industrial applications, Engr. Dig. (London) 26, 91 (May).

Greig, J.R., The sodium D-line reversal method of temperature measurement in ionized flame gases, Brit. J. Appl. Phys. 16, 957.

Il'in, V.M., Infrared semiconductor optical pyrometer, Measurement Techniques No. 3, 250 (Aug.).

Kogan, A.V., Optical systems of pyrometers for measuring the temperature of small bodies, Teplofizika Vysokikh Temperatur 3, 747 (Sept.).

Kottenstette, J.P., Fast response optical pyrometer, ISA Trans. 4, 270 (July).

Krakow, B., Determination of hot-gas temperature profiles from infrared emission and absorption spectra, AIAA J. 3, 1359 (July).

Lauver, M.R., J.L. Hall, and F.E. Belles, Shock tube gas temperature measurements by infrared monochromatic radiation pyrometry, NASA Tech. Note D-2955 (Aug.); N65-30899.

Lieneweg, F., Temperature measurement-radiation pyrometer, Arch. Tech. Messen. No. 359, 285 (Dec.).

Lord, J.S., Brightness pyrometry, Instr. Control Systems 38, 109 (Feb.).

Molchanov, V.M., Use of an optical method for measuring temperature differences, Instr. Exp. Tech. No. 1, 165 (Aug.).

Montgomery, P.W., and R.L. Lowery, Turbojet temperature by IR pyrometry, ISA J. 12, 61 (April).

Morgan, J.P., Radiant energy measurement, Instr. Control Systems 38, 127 (July).

Nodwell, R.A., and J.C. Irwin, A method of determining the reversal temperatures in an excited gas, Can. J. Phys. 43, 1182 (July).

Reed, T.B., and J.T. Roddy, Optical pyrometer measurement of r.f. power, Rev. Sci. Instr. 36, 620 (May).

Reingold, L., Theoretical study of the colour temperature and the real temperature of a body radiating in the visible spectrum, C.R. Acad. Sci. (France) 260, 1111 (Jan. 25).

Reingold, L., Experimental determination of relative emissive monochromatic powers and true temperatures of radiating bodies in the visible and near infrared range, Compte Rend. 261, 71.

Sadykov, B.S., Temperature dependence of the radiating power of metals, High Temperature 3, 352 (May-June).

Suckewer, S., Spectral measurements of temperature in the plasmatron, High Temperature 3, 178 (Mar.-April).

Svet, D.Ya., Comparison of classical methods of pyrometry for real bodies with a continuous emission spectrum, High Temperature 3, 407 (May-June).

Tourin, R.H., and B. Krakow, Applicability of infrared emission and absorption spectra to determination of hot gas temperature profiles, Appl. Optics 4, 237 (Feb.).

Verch, J., Analysis of optical-pyrometrical temperature measurements, Optik 19, 640 (May); NASA-TT-F-9359; N65-23794.

Wright, M.A., Some spectroscopic methods of gas temperature measurement in the range 3000° to 10,000°K, Brit. Coal Util. Res. Assoc. Monthly Bull. 29, 137.

Yamamoto, N. et al, Effective utilization of radiation and two-color pyrometers, J. Metals 17, 718 (July).

Young, F.L., Use of infrared instrumentation for detection of jet engine turbine wheel temperature, N65-18398.

Young, L.A., Infrared temperature measurement of the laminar wake of a hypersonic sphere, AIAA J. 3, 610 (April).

5. Expansion Devices

1958

Roshwarf, F., and J. Steinberg, Variable sensitivity gas thermometer for use at low temperatures, Probl. Low Temp. Phys. Thermodyn., Proc. Meeting Comm. I, Intern. Inst. Refrig., Delft, Neth. 1958, 117.

1959

Glagolev, Yu. A., Distillation of alcohol in a minimum temperature thermometer, Tr. Nauchn.-Issled. Inst. Gidrometioval, Priborostronie 1959, No. 7, 105.

1962

Folsom, T.R., R.A. Schwartz, and F.D. Jennings, Scale errors on oceanographic mercurial thermometers, Deep-Sea Research 9, 219.

Hale, C.E., Gas-filled thermometer for thermocouple calibration, U.K. At. Energy Authority TRG, Rept. 261 R (1962).

Jucheim, P., Attainable control precision of adjustable contact glass thermometers, Glass Instr. Tech. 6, 322.

Tulin, V.A., A field precision thermostat using mercury contact thermometers, Bull. Acad. Sci. USSR, Geophys. Ser. (8), 677

(Nov.).

1963

Foster, R.B., Complete Immersion testing of liquid-in-glass thermometers, Proc. Instr. Soc. Am. 18, Paper No. 57-1-63.

Miller, J.T., The revised course in industrial technology. Non-electrical thermometers, Instr. Pract 17, 1323 (Dec.).

Moser, H., J. Otto, and W. Thomas, Gas thermometric measurements at high temperatures. III Determination of the thermodynamic temperatures of fixed Points between 419 1065°, Z. Phys. 175, 327.

1964

Holten, D.C., Static and dynamic behaviour of helium-gas thermometers below 77°K, Advances in Cryogenic Engineering 9, 406; Proc. of the Cryogenic Engineering Conf., University of Colorado and the National Bureau of Standards, Boulder, Colo., Aug. 19-21, 1963, Ed. by K.D. Timmerhaus, New York, Plenum Press, 1964 U.S. At. Energy Comm. Rept. UCRL-7327, April 16, 1963.

Orlova, M.P., and D.N. Astrov, Vapor pressure of a helium thermometer for realizing the T_{58} scale, Comite Consultatif Thermometrie, Comite Intern. Poids Mesures, 6e, Sevres, France 1962, 176 (Publ. 1964).

Pamely-Evans, O.G., Capsule and bulb fluid expansion instruments, Mech. World 144, 415 (Oct.).

Pemberton, L.H., Further consideration of emergent column correction in mercury thermometry, J. Sci. Instr. 41, 234 (April).

1965

Anderson, R.L., and L.A. Guildner, National Bureau of Standards gas thermometer; Constant volume valve, Rev. Sci. Instr. 36, 615 (May).

Hagen, E.W., Dynamic gas thermometry, Oak Ridge National Lab., Tenn. ORNL-P-1068; NSA 19-20277.

Hanak, B., Pressure thermometers with nitrogen filling, Jemna Mechanika a Optika 10, 54 (Feb.).

Hanak, B., Pressure thermometers with nitrogen filling, Jemna Mechanika a Optika 10, 82 (Mar.).

Hanak, B., Characteristics, artificial aging, and quality of nitrogen thermometers, Jemna Mechanika a Optika 10, 209 (July).

Lieneweg, F., Temperature measurement. Expansion thermometers, Arch. Tech. Messen No. 357, 237 (Oct.).

Moser, H., Gas thermometry at higher temperatures, Metrologia 1, 68 (April).

Swindells, J.F., Calibration and use of liquid-in-glass thermometers, Natl. Bur. Std. (U.S.), Monograph 90 (Feb. 12).

Sychev, I.A., Certain properties of liquid manometric thermometers, Measurement Techniques No. 7, 627 (July).

6. Aspirated Devices

1962

Temme, G., A three-vent probe for measuring flow field pressure and temperature, Wiss. Ges. Luft-u. Raumfahrt, Cologne (W. Germany), Proc. of the joint meeting of the Comm. on Air-Breathing Engines and the Subcomm. on Aerodynamic Measuring Techniques, July 16, 1962, Aachen p. 26; N63-20183.

1963

Kahnwald, H., Development of a new suction pyrometer for the measurement of higher gas temperatures, Arch. Eisenhutten. 34, 673 (Sept.).

1965

Forster, S., A pneumatic apparatus for measurement of high and rapidly changing gas temperatures, Arch. Tech. Messen No. 349, R13 (Feb.).

7. Other Methods, Descriptive Articles

1958

van Itterbeek, A. et al, Temperature measurements with an acoustic thermometer, Probl. Low Temp. Phys. Thermodyn., Proc. Meeting Comm. I Intern. Inst. Refrig., Delft, Neth. 1958, 137.

1960

Taylor, J.W., Residual temperatures of shocked copper, U.S. At. Energy Comm. Rept. LADC-573.

1961

Ato, Y., R. Huzimura, and M. Oishi, A study on radioactive self luminous compounds. II On the application of radioactive self-luminous compounds, Proc. Japan Conf. Radio-Isotopes, 4th, 607 (1961); NSA 17-29965.

Hock, R., Modern electrical temperature measuring device, Chem. Rundschau 14, 528.

1962

Becker, F., and W. Walisch, Precision thermostat with optical control thermometer and controlled Peltier cooling, Z. Physik. Chem. (Frankfurt) 34, 369.

Cataland, G., and H.H. Plumb, Absolute temperatures determined from measurements of the velocity of sound in helium gas, Proc. Advisory Comm. on Thermometry to the Intern. Bur. of Weights and Measures, 6th Session p. 175 (Sept. 26-27, 1962); Proc. Intern. Conf. Low Temp. Phys. 8th, London

1962, 439 (Publ. 1963); Low Temperature Physics, Butterworth's, Wash., D.C. (1963).

Cohen, B.G., Gallium arsenide diode used as low-temperature thermometer, Bell Lab. Record 40, 421 (Dec.).

Forster, S., A pneumatic pyrometer technique-description and applications, Wiss. Ges. Luft-u. Raumfahrt, Cologne (W. Germany), Proc. of the joing meeting of the Comm. on Air-Breathing Engines and the Subcomm. on Aerodynamic Measuring Techniques (July 6, 1962). Aachen p. 11.

Leroux, J.P., and M. Poncin, Determination of the temperature of surfaces from 0° to 400° by means of photoluminescent emmissions of thin layers, Publ. Sci. Tech Min. Air (France) Notes Tech. No. 119.

Plotkin, E.R., and E.J. Molchanov, Use of temperature indicating paints for measuring the temperatures of machine parts Ind. Lab. 28, 214 (Aug.).

Savateev, A.V., Compensated thermal noise thermometer, Measurement Techniques No. 2, 114 (July).

Shekhovtsov, A.F., Pneumatic contact device for measuring the temperature of pistons in working engines, Measurement Techniques No. 5, 381 (Nov.).

Solovev, V.I., and A.D. Brodskii, Apparatus for measuring a temperature by means of nuclear quadrupole resonance, Instr. Exp. Tech. No. 2, 332 (Nov.).

Thorne, E.A., The measurement of high temperatures by the determination of the velocity of sound waves in materials, Acoustics Congress, Copenhagen, 1962, Paper P23.

Thureau, P., Measurement of surface temperatures by photoluminescence, Journees Intern. Transmission Chaleur, Paris, 1961, 2, 865 (1962).

Vernotte, P.V., Device for measurement of a quantity of heat at ordinary temperatures, Compte Rend. 255, 2914.

Electroacoustic thermometer having a frequency output, Instr. Exp. Tech. No. 2, 408 (Nov.).

Mechanical thermometers, Measurement and Control 1, 530 (Dec.).

1963

Bouchard, F., and P. Thureau, On a new development in measuring temperatures by photoluminescence, Compte Rend. 256, 87 (Jan.).

Brodskii, A.D., An electro-acoustic gas thermometer for use in low temperatures, Feinwerk Tech. 67, 299 (Aug.).

Brodskii, A.D., and V.I. Solovev, Reproduction of the temperature scale reference points by quadrupole nuclear resonance, Measurement Techniques No. 9, 763 (April).

Chabbal, R., M. Clement, and R. Geller, Measurement of the temperature in a P I G reflex pulse discharge using a Faboy-Perot interferometer, Nucl. Instr. and Methods, 23, 325 (June).

Cohen, B.G., W.B. Snow, and A.R. Tretola, G FaAs p-n junction diodes for wide range thermometry, Rev. Sci. Instr. 34, 1091 (Oct.).

Dimick, R.C., and G.J. Trezek, Photodiode as a sensitive temperature probe, Rev. Sci. Instr. 34, 981 (Sept.).

Flynn, T.M., H. Hinnak, and D.E. Newell, An improved cyrogenic thermometer, Advan. Cyrog. Eng. 8, 334.

Fragnaud, F., Application in convection of temperature measurement by luminescence methods, Ministeve de l'air (France) Sci. et Tech. No. 400 (Nov.).

Haas, F.C., An evaporative film colorimetric enthalpy probe, AD-404619.

Howard, D.R., A photographic technique for the measurement of transient high temperatures, Engineer 215, 475 (Mar. 15).

Kundra, K.D., and R. Potshad, Microwave crystals as thermometers in low temperature range, Current Sci. 32, 302 (July).

Levine, D., Unresolved fine structure of the nitric oxide gamma 0-0 band for the determination of temperature, N63-14492.

Libby, H.L., The measurement of metal temperature by an electromagnetic induction method, U.S. At. Energy Comm. Rept. HW-79621 (Aug. 12, 1963); N64-15834.

Montgomery, H., and G.P. Pells, Errors in helium vapour thermometry, Brit. J. Appl. Phys. 14, 525 (Aug.).

Morozov, V.A., and L.S. Tyufyakin, measuring the equivalent temperature of pulse-type noise radiation, Measurement Techniques No. 4, 320 (Oct.).

Pallett, J.E., Electric thermometer, Electron. Eng. 35, 313 (May).

Pearson, P.H.O., Measurement of atmospheric density, temperature and pressure at Woomera on 29th March, 1962 by the falling shere method, Res. Weapons Establishment (Australia) Tech. Note SAD-121 (May 1963); N63-19997.

Quneshi, M.H., and F.A. Farqui, Low-temperature pyrometer cones, Pakistan J. Sci. Res. 15, 100.

Richardson, P.D., A swinging thermometer, Am. J. Phys. 31, 395 (May).

Rothert, I.L., and N.P. Udalov, Semiconductor diode as a temperature pick up, Automatika i Telemekhanika 24, 696 (May).

Shepard, G.G., The use of the junction diode as a low temperature thermometer, Ohio State Univ. Research Foundation, Antenna Lab. Columbus, Rept. 1083-22 (Jan. 1963); AD-402415; N63-18324.

Smith, P.L. Jr., Limitations on the accuracy of sonic thermometers, Midwest Research Inst., Kansas City, Mo., Rept. AFCRL 63687 (June 1, 1963); AD-412479.

Smith, W.L., and W.J. Spencer, Quartz crystal thermometer for measuring temperature deviations in the 10^{-3} to 10^{-6} °C range Rev. Sci. Instr. 34, 268 (March).

Solovev, V.I., and A.D. Brodskii, An apparatus for measuring temperature by nuclear Quadrupole resonance, Cryogenics 3, 201 (Dec.).

Willkie, D., and S.A. Fisher, Measurement of temperature by Mach-Zender interferometry, Chartered Mech. Engr. 10, 612.

Gallium-arsenide diode used as low temperature thermometer, Instr. Pract. 17, 37 (Jan.).

Ocean thermometer uses ultrasonics, Electron. Design 11, 18 (May).

Ultrasonics takes the ocean's temperature, Elect. Eng. 82, 422 (June).

Ultrasonic thermometer for low temperature determinations, J. Franklin Inst. 275, 56 (Jan.).

Ultrasonic thermometer measures to 0.05 °F, Electronics 36, 77 (April).

1964

Abel, W.R., A.C. Anderson, and J.C. Wheatly, Temperature measurements using small quantities of cerium magnesium nitrate, Rev. Sci. Instr. 35, 444 (April); U.S. At. Energy Comm. Rept. TID 19533.

Betts, D.S. et al, A susceptibility thermometer for use at very low temperatures J. Sci. Instr. 41, 515 (Aug.).

Chognot, M., Method of measuring surface temperatures using the temperature sensitivity of luminescence, Int. J. Heat Mass Transfer, 7, 577 (May).

Court, G.R., and J. Sayers, An experimental study of the use of a Langmuir probe to measure electron temperatures and densities in after glows, J. Sci. Instr. 41, 462 (July).

Crorini, L., and S. Sartori, Thermal noise and absolute temperature, Recerca Scientifica 4, 155 (March).

Doherty, D.D., Temperature measurements in hot gases by thermal neutron scattering, NSA - 26157.

Fogelson, I.B., Tmperature measurement by means of germanium triodes, Instr. Exp. Tech. No. 1, 248 (Sept.).

Giedt, W.H., and J.T. Chambers, A dual element transducer for measuring high gas temperatures, ASME Winter Annual Meeting, New York, N.Y., Nov. 29-Dec. 4, 1964, Paper 64- WA/HT-45.

Govelik, L.S., and I.B. Fogelson, Tests for measuring temperature by the application of triode thermal detecting units, Instr. Construct. No. 4, 31(Apr.)

Hammond, D.L., C.A. Adams, and P. Schmidt, A linear quartz cystal temperature sensing element, Proc. Instr. Soc. Am. 19, Paper No. 11 (Feb. 3).

Khan, S.A., and P.S. Kohatkar, Instrument for measuring small temperature variations using thermocaps, Res. Ind. (New Delhi) 9, 296 (Oct.).

Larson, G.S., R.N. Lawson, and L.C. Lynnworth, Upper atmospheric sonic thermometry, Proc. Instr. Soc. Am. 19, Paper No. 19 (Jan. 5).

Lee, R.D., Some results and problems of the standardization of the photoelectric pyrometer of the National Bureau of Standards in 1961, Comite Consultatif Thermometrie, Comite Intern. Poids Mesures, 6e, Sevres, France 1962, 79 (Published 1964).

Lezberg, E.A., and D.R. Buchele, Some optical techniques for temperature and concentration measurements of combustion in supersonic streams, NASA Tech. Note-D-2441.

Libby, H.L., The measurement of metal temperature by an electromagnetic induction method, U.S. At. Energy Comm. Rept. HW-SA-3035 (May 3); NSA N-20282.

Olsen, W.D., and H.J. Leinbach, Applicability of dual-path sound propagation measurements to temperature determination over a six-mile path, Army Electronics Research and Development Activity, White Sands, Missile Range, N. Mex., ERDA-112: AD-432009: N64-17438.

Pertsovskiy, G.A., Determination of the bath temperature in the electroslag process by the calorimetric method, N64-11920.

Peterson, J.W., and K.D. McWatters, The measurement of upper-air density and temperature by two radar-tracked falling spheres, N64-17831.

Shaffstall, E.L., A measurement of the noise temperature of a shock- induced plasma at 420 MCPS and 690 MPCS, AD-427067.

Terao, K., Flame temperature measurement using the double probe method, Japan J. Appl. Phys. 3, 169 (March).

Terao, K., Electron temperature in a flame front, Japan J. Appl. Phys. 3, 486.

Uo, K.A., Measurement of the perpendicular temperature of the C-stellarator plasma by the diamagnetic coil, N64-21735.

Weder, E., An ultrasonic thermometer for low temperatures, Kaltekchnik 16, 398 (Dec.).

Willkie, D., and S.A. Fisher, Measurement of temperature by Mach-Zender interferometry, Proc. Inst. Mech. Engrs. (London) 178, 461.

Acoustical thermometer establishes provisional low-temperature scale, Nat. Bur. Std. (U.S.) Tech. News Bull. 48, 189 (Nov.).

Colour strip thermometer, Engineer 217, 447 (March 6).

1965

Bernert, R.E., Cryogenic temperature gage, Chem. Eng. 72, 140 (July).

Bos, L., Probe for the measurement of gas compositions and temperature in the fusion zone of a cupola furnace, Metalen 20, 79.

Calvet, E., and C. Guillard, Microcalorimeter equipped with semiconductor thermoelements, Compte Rend. 260 (Groupe 7), 525.

Carnevale, E.H., L.C. Lynnworth, and G.S. Larson, High temperature measuring device. Final report, Parameters Inc., Waltham, Mass., NASA-CR-54339 (Feb. 1); N65-24568.

Cheng, D.Yu., and P.L. Blackshear Jr., Factors influencing the performance of a fast response, transpiration cooled, high temperature probe, Am. Inst. of Aeronautics, Preprint No. 65-359; NSA 19-44204.

Fogel'son, I.B., Measuring temperature with germanium transisor thermoelements, Measurement Techniques No. 12, 1053 (May).

Fogel'son, I.B., Measuring temperature with silicon transistors, Instr. Exp. Tech. No. 4, 915 (Feb.)

Fogel'son, I.B., Operation of the transistor as a thermosensitive element, N65-10150.

Giedt, W.H., A dual element transducer for measuring high gas-stream temperatures, Trans. ASME, Ser C (J. Heat Transfer) 87, 397 (Aug.).

Hammond, D.L. et al, A linear, quartz crystal, temperature sensing element, ISA Trans. 4, 349 (Oct.).

Hammond, D.L., and A. Benjaminson, Linear quartz thermometer, Instr. Control Systems 38, 115 (Oct.).

Joyce, D.E., Capacitance temperature sensor, General Electric Co., Cincinnati, Ohio, GEMP-89 (June 25); N65-26336; NSA 19-36748.

Kerman, M., Investigation of microstate electronics, gallium arsenide as cyrogenic temperature sensors, Final report, Simmonds Precision Products Inc., Tarrytown, N.Y., Rept. No. 11029 (July): AD-469914L.

Lang, S.B., and F. Steckel, Study of the ultrasensitive pyroelectric thermometer, Rev. Sci. Instr. 36, 1817 (Dec.).

Lovborg, L., A linear temperature to frequency convertor, J. Sci. Instr. 42, 611 (Aug.).

Malozemov, V.V., and I.A. Turchin, Determination of temperature fields with the interferometer, Inzh. Fiz. Zh. (USSR) 8, 182 (Feb.).

Oleson, S., An improved sonic anemometer-thermometer, AD-619996; N65-34567.

Planer, G.V., and P.J. Evison, Temperature sensing capacitors, Electron. Components 6, 217 (March).

Plumb, H.H., and G. Cataland, Absolute temperature scale from 4°K to 20°K determined from measurements with an acoustical thermometer, J. Res. Natl. Bur. Std. (U.S.) 69A, 375 (July).

Reeves, D., M.E. Inglis and L. Airey, The fluid oscillator as a temperature sensor, Fluid Logic and Amplification Conference, Paper No. D1, (Sept. 1965); N65-36403.

Reisman, E., and P.M. Sutton, Measurement of air temperature distributions with the schlieren interferometer, Appl. Opt. 4, 144 (Jan.).

Robins, P.J., Temperature measurements by ultrasonics, Ind. Electron. 3, 482(Oct.).

Sargeant, D.H., Note on the use of junction diodes as temperature sensors, J. Appl. Meteorology 4, 644 (Oct.).

Sato, M., Electrochemical geothermometer; a possible new method of geothermometry with electroconductive minerals, Econ. Geol. 60, 812 (June).

Wheeler, E.E., Sensitive suppressed zero thermometer, J. Sci. Instr. 42, 42 (Jan.).

8. Special Applications, Method Not Specified in Title

1961

Roessler, F., Temperature measurement of a flame combined with a high-frequency torch, Proc. Intern. Conf. Ionization Phenomena Gases, 5th, Munich, 1961, 1, 842 (Publ. 1962).

1962

Bereznikov, V.V., and G.A. Lavrenter, Thermocouple installation in parts made of polymer material, Ind. Lab. 28, 526(Oct.).

Danberg, J.E., The equilibrium temperature probe, a device for measuring temperatures in hypersonic boundary layers, Advances in Hypervelocity Techniques, Plenum Press, N.Y. 1962, p. 693.

Froebel, A.T., On the measurement of temperatures in shock waves, N65-36373.

Hukuo, N., Measurement of temperature in a solar furnace, Nagoya Kogyo Gijutsu Shikensho Hokoku 11, 303.

Michalski, L., Measurement of surface temperature of rotating cylinders, Pomiary, Automat., Kontrola 8, 407 (Sept.).

Pavia, R.V., and D.H. Edwards, A Precision jet pipe temperature indicator for flight use, Aeronaut. Res. Lab., Melbourne, Australia ARL/F-33 (Sept.); N63-19903.

Rozenblit, G.B., Measurement of small temperature variations on the surface of solid bodies, Measurement Techniques No. 2, 120 (July).

Strauss, W., The measurement of high gas temperatures, Australian J. Instr. Technol. 18, 141 (Nov.).

1963

Arai, T., Studies on the air temperature measurement, Army Missile Command, Huntsville, Ala., Redstone Scientific Information Center, RSIC-31 (July 23); N63-19755.

Bahgat, F., Furnace gas temperature evaluation for marine boilers, Naval Eng. J. 75, 647.

Beck, G., and R. Bigot, On the recording of temperature differences between the center and surface of a cylinder of nickel cooled by tempering, Compte Rend. Acad. Sci. 256, 619 (Jan. 14).

Benedict, R.P., High response aerosol probe for sensing gaseous temperature in a two-phase two component flow, Trans ASME (J. Eng. Power) 85A, 245.

Benson, J., Gauging fiber temperatures, Rubber Age 93, 410 (June).

Branger, M., Veil cooling of radial-flow turbines, The Garrett Corp., Air Research Manufacturing Div. Rept. K-500 (Oct. 11).

Coombe, R.A., Measuring temperatures in the range 1000°C to 5000°C. Part I, R & D No. 28, 18 (Dec.).

Crabtree, R.I., and G. A. Wheeler, Radiation effects investigation of selected transducers and materials for Nerva program. Volume I, U.S. At. Energy Comm. Rept. FZK-159-1 (April 26).

Critides, L., Instrument measures thread surface temperature, Ind. Eng. Chem. 55, 10 (Sept.).

Crook, R.F., Determining the operating temperature of an AC coil, Electro- Technol.

(N.Y.) 71, 160 (May).

Dudnik, L.A., and E.B. Perchik, Measurement of the grid temperature of an electron tube by change of resistance, Inzh. Fiz. Zh. 5, 110 (Mar.).

Gee, K.H., Metal temperature and slag analysis improve blast-furnace control, J. Metals 15, 512 (July).

Geil, F.G., and J.H. Thompson, An in situ temperature sensor, Marine Sci. Instr. 2, 35.

Graves, F.L., and H.S. Loveless, Convenient measurement of deflection temperature under load and Vicat softening point, Mater. Res. Std. 3, 33 (Jan.).

Grey, J., Sensitivity analysis for the calorimetric probe, Rev. Sci. Instr. 34, 857 (Aug.).

Gutzwiller, W.R., Tool measures piston temperature of Diesels, Abstract SAE J. 71, 83 (May).

Headly, J.A., and J. McGeagh, Specimen heating with temperature measurement from -150°C to 2200°C inside the EN6 electron microscope, J. Sci. Instr. 40, 484 (Oct.).

Hudimac, A.A., J.R. Olson, and D.F. Brumley, A mobile instrument of ocean temperature in the thermocline region, Marine Sci. Instr. 2, 49.

Karp, T., Electronic dark room thermometer, Radio Electronics 34, 60 (Oct.).

Kourim, G., Electrical temperature measuring device for installation where danger of explosions exist, Arch. Tech. Messen. No. 334, 257 (Nov.).

Kudlacik, H.W., and D.M. Willyoung, Local rotor winding temperature measurements for large turbine generator fields, Power Apparatus and Systems No. 64, 687 (Feb.).

Kurzrock, J.W., Selection of surface thermometers for measuring heat flux, Cornell Aeronaut. Lab., AD-404770; N63-18751.

La Fond, E.C., Towed sea temperature structure profiler, Marine Sci. Instr. 2, 53.

Lee, P. W. et al, Method for predicting temperatures in continuous hot strip mills, J. Inst. Iron Steel (London) 201, 270.

Leontev, A.K., A simple method for determining the temperature of a heat transfer surface, Inzh. Fiz. Zh. 5, 78(July).

Lubbs, E.K., Device for measuring temperature in a closed rotating flask, J. Chem. Educ. 40, 200.

MacHattie, L.E., Temperature measurement of textile fabrics under intense irradiation, Brit. J. Appl. Phys. 14, 267 (May).

Malin, W., J. Davison, and C. Krollman, Development of a deiced fast response dual element total temperature sensor, AD-622247.

Markussen, B.H., How to estimate piston temperature, Abstract: SAE J. 71, 97 (May).

Marshall, G.S., and R.H. Henderson, Recording temperatures in deep bore holes, Engineering 196, 540 (Oct. 25).

Masalovich, G.I., Local temperature measurements in forging and stamping, Measurement Techniques No. 11, 935 (June).

McLaren, T.I., J.N. Fox and R.M. Hobson, Double probe measurements of electron temperatures in a shock tube, Nature 198, 1264 (June 29).

Miers, B.T., and N.J. Beyers, Rocket-sonde wind and temperature measurements between 30 and 70 KM for selected stations, Army Electronics Research and Development Activity, White sands Missile Range, N. Mex., Rept. ERDA-70 (Sept.); N63-22783.

Moeller, F., and H. Meyer, Surface temperature measurement, Arch. Tech. Messen. No. 323, 269 (Dec. 1962) No. 324, 1 (Jan. 1963).

Nanigan, J., Temperature measurements and heat transfer calculations in rodset nozzle throats and exit cones, Proc. Instr. Soc. Am. 18 Paper No. 29. 3. 63.

Orlova, M.P., and D.N. Astrov, Measurement of remperatures below 10°K, Measurement Techniques No. 8, 669 (Feb.).

Perls, T.A., and J.J. Hartog, Pyroelectric transducers for heat-transfer measurements, ISA Trans. 2, 21 (Jan.).

Petit, Y., and M. Dembno, Measurement of surface temperatures of rotating machine elements Mesures Controle Ind. 28, 699 (May).

Redstreake, W.N., Sensors promise to close loop on control of molten metal, Iron Age 191, 73 (June).

Reid, A.F., Filament temperatures from geometry-independent electron emission junctions, J. Electrochem. Soc. 110, 135 (Feb.).

Smith, R.A., Atmospheric radiative temperature measurements, Rand Corp., The Application of Passive Microwave Technology to Satellite Meteorology, A Symposium (Aug. 1963) p. 37; N63-16497.

Tassicker, O.J., Effect of inductance on the measurement of winding temperature in electrical plant, Proc. Inst. Elec. Engrs. (London) 110, 419 (Feb.).

Teweles, S., Time section and hodograph analysis of Churchill rocket and radiosonde winds and temperatures, Intern. Geophys. Year World Data Center A. Wash., D.C., A Third Compilation of U.S. IGY-IGC Rocket Program Results, (April 1963) p. 72; N63-19679.

Wald, D., Measuring temperature in strong fields, Instr. Control Systems 36, 100 (May).

Zinman, W.G., Temperature measurements in hydrogen-oxygen detonations, J. Chem. Phys. 39, 3534. A low-temperature pyrometer Control 6, 102 (Feb.).

Evaluation of soil temperature thermometers, Army Electronic Prooving Ground,j Fort Huachuca, Ariz., AD-408192.

Generator temperatures monitored by failsafe system, Elec. World 159, 116 (Feb. 25).

Mapping the temperature of the ocean surface, New Scientist 18, 723 (July).

Measuring surface temperature of subliming solids, R & D No. 21, 42 (May).

160 (Oct.).

Pyrometer reads molten iron temperature continuously, Foundry 91, 86 (Nov.).

Surface pyrometer for high speed cylinders, Power and Works Eng. 58, 47 (March).

Temperature measuring screws, Eng. Mater. and Design 6, 239 (April).

Temperature probe for moving sheets, belts and drums, R & D No. 18, 52 (Feb.).

1964

Benson, R.S., Measurement of transient exhaust temperatures in internal combustion engines, Engineer 217, 377(Feb.)

Boynton, F.P., Chemical kinetic analysis of rocket-exhaust temperature measurements, AIAA J. 2, 577.

Cato, G., Measurement of free air properties from on board a large launch vehicle, N64-24906.

Chappel, R.M., Bonding of electrical leads to germanium for ultrahigh-vacuum and high temperature measurements, J. Appl. Phys. 35, 2783 (Sept.).

Chen, F.F., Double-probe method for unstable plasmas, Rev. Sci. Instr. 35, 1208 (Sept.).

Chizhov, A.F., Temperature measurements of the free atmosphere taking into account the recombination of atoms, N64-24591.

Clark, G.Q., and J.G. McCoy, Rocketsonde measurement of stratospheric temperature, Army Electronics Research and Debelopment Activity, White Sands Missile Range, N. Mex., ERDA-24Z: AD-453993; N65-17924.

Clayton, W.H., B.J. Eckelkamp and J.H. Machetta, A wet and dry bulb temperature measuring system for microemteorological application, Texas A & M Univ. College Station AFCRL-64-938: AD-610107; N65-18982.

Cowne, R.W., Atmospheric temperature measurement from aircraft, Proc. Inst. Soc. Am. 19, Paper No. 19 (Jan. 4).

Fendly, J.R. Jr. and K.G. Hernqvast, Ionization mechanism and electron temperature in cesium arecs, Proc. IEEE 52, 964 (Aug.).

Fischer, W.A., and H.J. Fleischer, Continuous temperature measurement for basic oxygen steelmaking, J. Metals 16, 483 (June).

Grabowsky, W.R., L.Y. Lam, and D.A. Durran, Double shock tube method for simultaneous determination of high pressure and temperature of an enclosed gas, N64-16129.

Haas, A., Ambient temperature compensated non-contacting surface thermometer, Acta Imeko 1964, 339 Paper No. 23-HU-105.

Hamilton, R.L., and C.H. Miller, Yarn temperatures attained during cyclic straining and heat transfer properties of yarns, Textile Res. J. 34, 20 (Jan.).

Hvetz, J., J.P. Leroux, and G. Palazy, Contribution to the measurement of surface temperatures, Compte Rend. 259, 2801 (Oct.).

Kirchhoff, R.H., Calorimetric heating rate probe for maximum response time interval, AIAA J. 2, 966 (May).

Kirk, W.B., Flue gas temperature measurement procedures, ASHRAE J. 6, 40 (June).

Kordig, J.W., Backside temperatures of an interval insulator in a solid-propellant motor, AIAA J. 2, 1475 (Aug.).

Lapworth, K.C., Temperature measurements in a hypersonic shock tunnel, AGARDograph 1964, 267; AGARD, The high temperature aspects of hypersonic flows (1964) 255.

Lenschaw, D.H., and J.A. Dutton, Surface temperature variations measured from an airplane over several surface types, J. Appl. Meteorol. 3, 65 (Feb.)

Logan, C.A., and R.P. Johnson, Automatic temperature measurement as applied to a cement kiln, Proc. Instr. Soc. Am. 19, Paper No. 4 (Jan. 1).

Lorenz, D., Measurement of the earth's surface temperature from aircraft, N64-24953.

Meieran, S., Temperature sensor for strain gage transducer, Electronics 37, 77 (May 4).

Merryman, R.G., A study of temperature measurement. Precision in Debye - Scherrer specimens during high temperature x-ray diffraction measurement of thermal expansion, N64-21873.

Minzner, R.A., G. Sauermann, and L.R. Peterson, A new method for atmospheric temperature determination, AD-427618.

Newcomb, T.P., Clutch temperatures, Automobile Eng. 54, 154 (April).

Penskii, F.I., Temperature measurements of internal combustion engine pistons, Measurement Techniques No. 7, 610 (July).

Powell, W.B., and T.W. Price, A method for the determination of local heat flux from transient temperature measurements, ISA Trans. 3, 246 (July).

Sterbutzel, G.A. et al, A probe for the instantaneous measurement of surface temperature, RTD TDR63-4015; AD-431314; N64-21489.

Subbotin, V.I., M. Kh. Ibragimov, and E.V. Nomofelov, Statistical study of turbulent temperature pulsations in a liquid stream, High Temperature 2, 59 (Jan.-Feb.).

Tskhai, N.S., A method of determining the kinetic temperature of a gas Teplofizika Vysokikh Temperatur 2, 294 (March-April).

Whittaker, A.G., and D.C. Barham, Surface-temperature measurements on burning solids, J. Phys. Chem. 86, 196.

1965

Auskern, A.B., and W.E. Thompson, Temperature indication during hot pressing, Am. Ceram. Soc. Bull. 44, 459.

Ballard, H.N., Rocketsonde techniques for the measurement of temperature and wind in the stratosphere, ERDA-269; AD-458308; N65-22478.

Barrett, R.E., and H.R. Hazard, Problems in flue - gas temperature measurements, ASHRAE J. 7, 88 (Jan.).

Bates, J.J., Measurement of commutator temperature by a sliding -contact thermometer, Proc. Inst. Elec. Eng. 112, 835 (April).

Bernard, B., Flame temperature measurements, Instr. Control Systems 38, 113 (May).

Brunschwig, F.S., G.E. Kock, and J.K. Wilhelm, Thermal sensor design for glide reentry vehicles, NASA Washington Symp. on Thermal Radiation of Solids, N65-26911.

Cox, G.B., Effects of reduced pressures on passive temperature indicators (Temp-Plates), McDonnell Aircraft Corp., St. Louis, Mo., Rept. No. 051-065.73; AD-460040

cutt, R.A., Proportional control steadies cryosurgical probe temperature, Control Eng. 12, 103 (Mar.).

Fateyev, A.V., A device for measuring the temperature of rotating bodies, Priborstronie 8, 26; N65-24155.

Fomin, Yu.Ya., and B.K. Gundorin, Measurement of rapidly changing temperatures of fuel at high pressures, Measurement Techniques 2, 152 (July).

Forgacs, R.L., B.A. Parafin, and E. Eichen, High voltage cathode temperature measurement, Rev. Sci. Instr. 36, 1198 (Aug.).

Gallagher, H.P., and B.D. Mallet, Liquid oxygen temperature instrumentation model DM-18, AD-454062.

Goldberger, R., Thermal probe speeds environmental testing, Electron. Ind. (Phila.) 24, 114 (May).

Gordov, A.N., Peculiarities of the measurements of temperature under conditions of alternating heat emissions, Foreign Tech. Div., Air Force Systems Command, Wright-Patterson AFB, Ohio, FTD-TT-64-1076; AD-615431.

Gurevich, Ya.B., and A.P. Bashchenko, Measurement of the metal surface temperature in rolling, Measurement Techniques No. 11, 989 (April).

Hall, B.F. Jr., and N.F. Spooner, Temperature measurement in a graphite environment from 1600° to 2500°C, ISA Trans. 4, 355 (Oct.).

Keglin, B.G., and B.I. Khrapov, Measurement of temperature in a point of the surface during unsteady friction, Ind. Lab. 30, 1197 (Mar.).

Kiselev, V.M., Thermal probes for measuring the density of heat flows, FTD-TT-64-1115; AD-614949.

Land, T., Probe pyrometer for glass, Ind. Process Heat 5, 4 (Aug.).

Lieneweg, F., Temperature measurement; contact thermometers Part 1, Arch. Tech. Messen. No. 357, 237 (Oct.).

Lutsker, I. Sh., Device for the remote measurement of the temperature of rotating parts in a closed chamber, Ind. Lab. 31, 465 (Mar.).

Marlatt, W.E., The measurement of the surface temperature of the earth, NASA-CR-62117; N65-21425.

Mehrishi, J.N., and J.W. Lorimer, Temperature measurement in rotating-cylinder viscometers, J. Sci. Instr. 42, 173 (Mar.).

Merryman, R.G., and C.P. Kempter, Precise temperature measurement in Debye-Scherrer specimens at elevated temperatures, J. Am. Ceram. Soc. 48, 202.

Mikhailov, M.D., Measuring the temperature of flows with a pulsating velocity, Measurement Techniques, No. 5, 419 (May).

Parafin, B.A., and E. Eichen, High voltage cathode temperature measurement , Rev. Sci. Instr. 36, 1198 (Aug.).

Terrey, D.R., A contact pyrometer for the measurement of specimen temperatures on a thermobalance, J. Sci. Instr. 42, 507 (July).

Watson, G.G., Surface temperature measurement, Design Components Engineering No. 20, 32 (Nov.).

Weinstein, I., and R.R. Howell, Technique for measuring high-temperature isotherm patterns on aerodynamically heated models with experimental results, NASA-TN-D-2769; N65-23162.

9. Nuclear Applications of Temperature Measurement

1960

Lampe, D.A., Reactor cone thermal instrumentation, U.S. At. Energy Comm. Rept. TID 18103.

1962

Brindley, J.H., Experimental calibration of surface attached thermocouples on a flat plte fuel element, Trans. Am. Nucl. Soc. 5, 478 (Nov.).

Brook, E.J., W.C. Kramer, and R.D. McGowan, High temperature sensors for BORAX-V boiling fuel rods, U.S. At. Energy Comm. Rept. ANL6636 (Oct.).

Walstedt, R.E., Pulsed nuclear magnetic resonance thermometer, Problems of Low Temperature Physics and Thermodynamics Vol. 3. MacMillan Co., N.Y., 1962, p. 109.

1963

Browning, W.E. Jr., Methods of measuring temperature in nuclear reactors, Progr. Nucl. Energy. Ser. IV, 5, 1.

Budak, H., Cl^{35} isotope in $NaClO_3$ as nuclear Q.R. thermometer, Istanbul Univ. Fen. Fak. Mecmuasi, Seri C, 28, 142 (July-Oct.).

Conkling, D.R., and T.L. Rasmussen, Thermocouple attachment for the initial EOCR cone, U.S. At. Energy Comm. Rept. IDO-16836 (Feb.).

DuBridge, R.A., In-core instrumentation development program. Detectors for in-core power monitoring, U.S. At. Energy Comm. Rept. GEAP-4222; NSA 30852.

Greenberg, H. J., Clamp on process tube temperature detector for monitoring nuclear reactor operation, Engelhard Inds. Tech. Bull. 4, 101 (Dec.).

Rainey, W.T. Jr., R.L. Bennett, and H.L. Hemphill, Measurement of temperature in reactor environments, U.S. At. Energy Comm. Rept. ONRL-3417.

Terry, F.D., Effects of transient nuclear radiation on transducers and electrical cables, U.S. At. Energy Comm. Rept. IDO-16914 (Nov. 30).

Nerva components irradiation program. Vol. 4, GTR test 7A, General Dynamics Corps., Fort Worth, Texas, FZK-170-4; NSA 19-14868.

1964

Babbe, E.L., Increasing thermocouple reliability for in-pile experiments, Trans. Am. Nucl. Soc. 7, 55 (June).

Babbe, E.L., Development program to increase thermocouple reliability for in-pile experiments, U.S. At. Energy Comm. Rept. TID 7697.

Bianchi, G., and S. Moretti, Behaviour of thermocouples under irradiations, Energie Nucleare 11, 426 (Aug.).

Bianchi, G., and L. Matteuzzi, Description of an apparatus for testing of n - gamma irradiated thermocouples, U.S. At. Energy Comm. Rept. RT/ING(64-1).

Bianchi, G., and L. Matteuzzi, Description of experiment for thermocouple irradiation tests, U.S. At. Energy Comm. Rept. RT/ING(64-2).

Breen, B.P., and G. Burnet, Peak heat flux in nucleate boiling heat transfer, U.S. At. Energy Comm. Rept. IS-810; N64-17740.

Briggs, N.H., E.L. Long, and F.R. McQuilkin, Summary of experience with high temperature thermocouples used in the ORNL-GCR program fuel experiments, ORNL-P-1065; NSA 19-20401.

Chapin, W.E., and E.N. Wyler, Transducers in nuclear environments, ISA J. 11, 45 (Dec.).

Chappell, E.E. et al, Nerva components irradiation program. Vol. 3, GTR test 13, General Dynamics Corp., Fort Worth, Texas, FZK-184-3; NSA 19-13812.

Dallman, A.C., Mechanical reliability and thermoelectrical stability of noble metal thermocouples at 2600°F temperature and dose rates up to 10^{20} Nvt.

Davoine, F., R. Schley, and M. Villamayor, Les couples thermoelectriques D'alliages tungstene - rhenium, Commissariat a l'Energie Atomique. Centre d'Etudes Nucleaires, Saclay, CEA-R-2481; NSA 19-9438.

Elliot, M.N., and J.R. Grover, The measurement and control of gas temperature in the Fingal process, AERE-R-4512 (Dec.); N65-21943.

Fanciullo, S., Thermocouple development for the lithium cooled reactor experiment, U.S. At. Energy Comm. Rept. PWAC-422 (Mar. 5).

Hawkins, R.C., Neutron flux monitors and thermocouples for in-core reactor measurements, At. Energy of Canada Ltd., Chalk River, Ontario, AECL-2033.

Hluchan, S.A., Pressure and temperature transducers for high temperature and nuclear radiation environments, U.S. At. Energy Comm. Rept. Conf-658-1.

Krohova, M., and I. Saxl, Radiation stability of thermocouples, U.S. At. Energy Comm. Rept. UJV-987.

McCarty, W.K., Thermocouple evaluation program, U.S. At. Energy Comm. Rept. NAA-SR-Memo-9635.

Tallman, C.R., Cryogenic temperature measurement in a nuclear radiation environment, U.S. At. Energy Comm. Rept. LA-DC-6549.

Walters, C.T., and E.O. Fromm, Automatic reduction of long term irradiation capsule thermocouple data, U.S. At. Energy Comm. Rept. 7697.

Applications of ultra sonic energy: ultrasonic instrumentation for nuclear applications, Bimonthly progress Rept. No. 19, (Oct. 1- Nov. 30), Aerojets, Inc., West Chester, Pa. NYO-2910-7 (Dec.); NSA 19-11478.

Periodic calibration of temperature sensing elements - reactor plant portion, U.S. At. Energy Comm. Rept. WAPD-PWR-TE-159.

Reactor instrumentation and control progress Rept. No. 85, General Electric Co., Cincinnati, Ohio GEMP-85 (Nov. 30); NSA-19-10467.

1965

Asphaug, B., Gamma thermometer development at HBWR, U.S. At. Energy Comm. Rept. HPR (Vol. 1) (Sec. 7).

Broks, E.J., Some in-vessel instrumentation programs representative of the United States, Argonne Natl. Lab., Idaho Falls, Idaho. CONF-640607(Vol. 1) (Paper A-14); NSA 19-24013.

Carroll, R.M., and P.E. Reagan, In-pile performance of high temperature thermocouples, Oak Ridge Natl. Labs., Tenn. ORNL-P-1066; NSA 19-18344.

Eubank, H.P., Electron temperature measurements with atomic beams, Princeton Univ., N.J., Plasma Physics Lab., Rept. MATT-276 (June); N65-10598.

Falk, J., Instrumentation of the Swedish R2 - loop No. 2, Aktiebolaget Atomenergi, Stockholm, Sweden CONF-640607 (Vol. 1) (Paper B-3); NSA 19-24168.

Hawkings, R.C., In-core instrumentation at C.R.N.L., At. Energy of Canada Ltd., Chalk River, Ontario CONF-640607 (Vol. 1) (Paper A-3); NSA 19-2407.

Kjaerheim, G.K., Central oxide temperature measurements, U.S. At. Energy Comm. Rept. (HPR-35 (Vol. 11) (Sec. 13)).

Kjaerheim, G.K., Measuring fuel rod center temperatures, Euro Nuclear 2, 72 (Feb.).

Kuhlman, W.C., Evaluation of thermal neutron induced errors in the W/W-25 Re thermocouple, AIAA Propulsion Joint Specialist Conference, Colorado Springs, Colo., June 14-18, 1965, Paper 65-563.

Lupoli, P., G. Bianchi, and S. Morretti, Behaviour of irradiated thermocouples, experimental investigations, Comitato Nazionale per l'Energia Nucleare, Ispra (Italy) CONF-640607 (Vol. II) (Paper D-4); NSA 19-24014.

Morretti, S., Behaviour of irradiated ther-

mocouples. Theoretical investigations, Comitato Nazionale per l' Energia Nucleare, Ispra (Italy) CONF-640607 (Vol. 2) (Paper D-5); NSA 19-22657.

Morrison, R.G., Application of miniature intrinsic thermocouples for reactor transient diagnostics, Los Alamos Scientific Lab., N. Mex., LA-3313-MS; N65-27629; NSA 19-38236.

Prince, W.R., and W.L. Sibbitt, High temperature reactor core thermocouple experiments, Los Alamos Scientific Lab., N. Mex., LA-3336; N65-29244; NSA 19-38237.

McQuilkin, F.R., N.H. Briggs, and E.L. Long Jr., Summary of experience with high temperature thermocouples in the ORNL-GCR program, fuel-irradiation experiments, Trans. Am. Nucl. Soc. 8, 69 (May).

Rolstad, E., Thermocouples, cables and tubes for in core instruments at HBWR, U.S. At. Energy Comm. Rept., HPR-35 (Vol. 2) (Sec. 10).

Stentz, R.H., and R.L. Treinen, Development of nuclear sensors, Final report, General Electric Co., Cincinnati, Ohio, GEMP-90; NSA 19-38091.

Subbotin, V.I. et al, Small scale thermocouples for measuring temperature in the reactor of the first atomic power station, Teploenergetika No. 5, 91 (May).

Walstedt, R.E. et al, Nuclear spin thermometry below 1°K, Proc. Roy. Soc. (London) 284A, 499.

Component development, Oak Ridge Natl. Lab., Tenn., ORNL - 3812; NSA 19-35772.

High temperature materials and reactor component development programs. Fourth Annual Rept. Vol. 1, Materials, General Electric Co., Cincinnati, Ohio, GEMP-334A: NSA 19-24916.

High temperature materials and reactor component development programs. Vol. 3, Instrumentation and controls, Gen. Elec. Co., Cincinnatti, Ohio, GEMP-334C; NSA 19-25639.

High temperature materials program Progress Rept. No. 43, Part A, Oct. 15-Dec. 15, 1964, General Electric Co., Cincinnati, Ohio, GEMP-43A; N65-30592.

High temperature materials program, Progress Rept. No. 49, Part A, Gen. Elec. Co., Cincinnati, Ohio, GEMP-49A; N65-30592.

Process instrumentation development, Oak Ridge Natl. Lab., Tenn., ORNL-3782; NSA-19-42690.

Reactor instrumentation and control. Progress Rept. No. 87, Gen. Elec. Co., Cincinnati, Ohio, GEMP-87; NSA 19-24016.

Reactor instrumentation and control, Progress Rept. No. 88, Gen. Elec. Co., Cincinnati, Ohio, GEMP-88; NSA 19-38090.

10. Associated Equipment and Testing Procedure

1961

Houke, H.F., Study of high-current resistance testing of grounded shielded Chromel-Alumel thermocouples, AD-459284.

Nordberg, W., and W.G. Stroud, Results of IGY rocket-grenade experiments to measure temperatures and winds above the island of Guam, J. Geophys. Res. 60, (Feb.); Intern. Geophys. Year World Data Center A. Washington, D.C. A third compilation of U.S. IGY-IGC Rocket Program Results, April 1963, p.23; N63-19678.

Schlegel, E.S., Apparatus for determining temperature profiles in microstructures, Rev. Sci. Instr. 34, 360 (April).

1962

Bulychev, V.S., Automatic indication of broken thermocouples in potentiometer EPP-09, Measurement Techniques No. 2, 125 (July).

Gehrmann, E., and I. Schusta, Method for the determination of the time constant of thermocouples, Wiss Z. Hochsch. Elektrotech. Ilmenau. 8, 419.

Lehmann, K., and K. Schmeiser, New temperature measuring equipment for rotatable furnaces, Elektrotech. Z. 14B, 462 (Aug. 20).

Pak, V., and Yu. P. Krinskii, Automatic equipment for calibrating platinum platinorhodium thermocouples, Measurement Techniques No. 1, 38 (June).

Rahlfs, P., Testing contact thermometers, Arch. Tech. Messen. No. 323, 279 (Dec.).

1963

Brown, D.L. et al, Instrumentation and recording equipment used in conjunction with the ARL twenty-inch hypersonic wind tunnel, Wright Patterson AFB, Ohio, Aeron Res. Lab., Rept. ARL 63-162 (Sept.).

Cameron, G., and R. L. Blanchard, Performance and use of metal freezing-point cells which generate precise temperature, ISA Trans. 2, 224 (July).

Cox, C.D., and W.D. Edwards, Ice point maintained thermoelectrically and regulated by change of state, Rev. Sci. Instr. 34, 704 (June).

Dengler, C.O., A new mercury freezing point cell, ISA Trans. 2, 298 (Oct.); Instr. Control Systems 36, 119 (Dec.).

Dengler, C.O., A freezing apparatus for the triple point of water cell, Proc. Instr. Soc. Am. 18, Paper No. 57.4.63.

Foord, T. R., R. C. Langlands, and A. J. Binnie, Transformer-ratio bridge network with precise lead compensation and its aplication to the measurement of temperature and temperature difference, Proc. Inst. Elec. Engrs. 110, 1693(Sept.).

Foster, R.B. Jr., An air-bath comparator for liquid-in-glass thermometers, U.S. At. Energy Comm. Rept. SCTM-21-63 (24) (Feb.).

Hill, J.J., and A.P. Miller, An AC double bridge with inductively coupled ratio arms for precision platinum-resistance thermometry, Proc. Inst. Elec. Engrs. 110, 419 (Feb.).

Isakov, M.N., Measurement of atmospheric temperature by means of satellite-borne equipment, Kosmicheskie issledovaniia, 1, 159 (July - Aug.).

John, R.E., Temperature distribution and thermal efficiency of low power arc-heated plasma jets, Brit. J. Appl. Phys. 14, 585 (Sept.).

Jones, T.P., The suitability of tungsten strip lamps as secondary standard sources in photoelectric pyrometry, J. Sci. Instr. 40, 101 (March).

Kayander, M.S., Radiator with large sighting coefficient for calibrating radiation pyrometers, Measurement Techniques No. 10, 850 (June).

Margulis, O.M. et al, Refractory insulation for thermal electrodes used for measuring high temperatures, Measurement Techniques No. 6, 480 (Nov.).

McDonough, R., and H.A. Hawthorne, An inexpensive resistance welder for thermocouple fabrication, U.S. At. Energy Comm. Rept. TID 19268.

Meiran, S., Tester checks out thermocouple circuits, Electronics 36, 102 (Mar. 15).

Metzler, A.J., and J.R. Branstetter, Fast response blackbody furnace for temperatures up to 3000°R, Rev. Sci. Instr. 34, 1216 (Nov.).

Murdock, J.W., C.J. Foltz, and C. Gregory, A practical method of determining response time of thermometers in liquid baths, Trans. ASME (J. Eng. for Power) 85A, 27.

Pak, V., Yu. P. Krinskii, and I.S. Belyaeva, Simplified equipment for calibrating precious metal thermocouples in a dynamic condition, Measurement Techniques No. 11, 923 (June).

Rotbert, I.L., and N.P. Udalov, Temperature transmitters incorporating semiconductor diodes and transistors, Instr. Construct. No. 10, 1 (Oct.).

Russell, A., An inexpensive thermocouple-scanner using gold-plated relays, Control 7, 132 (Sept.).

Sata, T., and R. Kiyoura, Studies on the tungsten furnace and its temperature measurement by W-WRe thermocouple up to 2700°C, Tokyo Inst. Technol. Bull. No. 53.

Savage, B., A multipoint thermocouple reference junction, J. Sci. Instr. 40, 45 (Jan.).

Silverman, L., Reference junctions, Instr. Control Systems 36, 107 (June).

Tao, Li-ten, Automatic potentiometer circuits with temperature compensations for thermocouples, Instr. Construct. No. 8, 9 (Aug.).

Vanvor, H., Testing and standardization of apparatus to measure temperatures. Resistance thermometers and thermocouples, Intern. Elektrowaerme - Kongr., 5., Wiesbaden, Ger. 1963, 625.

Voitenko, A.E., F.O. Kuznetsov, and I.S. Model, The use of an IFK-50 lamp as a high-intensity, pulsed standard source, Instr. Exp. Tech. No. 6, 1184 (July).

Weiner, S., and F. Schwartz, Thermopile IR detectors, Space/Aeronautics 40, 95 (Aug.).

A useful temperature duration recorder R&D No. 18, 42 (Feb.).

Automatic thermocouple comparator, Natl. Bur. Std. (U.S.) Tech. News Bull. 47, 82 (May).

1964

Astheimer, R.W., and S. Weiner, Solid-backed evaporated thermopile radiation detectors, Appl. Optics 3, 493 (April).

Barber, C.R. et al, A full-radiator lamp designed to replace the tungsten strip lamp as a pyrometric standard, Nature 202, 686 (May 16).

Brouwer, G.P., A highly sensitive recording electronic pyrometer, Philips Res. Rept. 19, 471 (Oct.).

Buynyachenko, G.P., Multi-range potenitometer bridge, N64-13581.

Ebinger, A., and G. Siegfried, Potentiometer for thermoelectric voltages with electronic stabilized auxiliary current source, Z. Instrumentenk. 72, 103 (April).

El Agib, A.A.R., A hydraulic bridge for measuring small temperature difference, J. Sci. Instr. 41, 596 (Oct.).

Gelfond, L., Evaluation of the model PRAIC thermocouple reference junction, Rocketdyne, Canoga Park, Calif., Rept..No. TR-64-7; AD-470 583.

Goldberg, J.L., and H.M. King, Automatic switching of sensitive thermocouples, Electron. Eng. 36, 591 (Sept.).

Grote, H.H., Improvement of sensor response by an analog technique, Army Signal Research and Development Agency and Lab., Fort Monmouth, N.J. USAELRDL-2445; N64-26507; AD-600 141.

King, J., The design of a temperature-compensated thermocouple reference circuit, AD-600 675.

Knowlson, P.M., and P.M. Bartle, Sealing a stainless-steel-sheated thermocouple into a Magnox end cap, J. Inst. Metals 93, 52 (Oct.).

Kozhukh, V. Ya., Computation of thermistor bridge circuits for automatic measurements of temperature difference, Measurement Techniques No. 7, 601 (July).

Lancia, F.M., and J.D. McGervey, Apparatus for measurements of Peltier coefficients, Rev. Sci. Instr. 35, 1302 (Oct.).

Levi, L.I., E.A. Chernin, and A.I. Degaltsev, Device for determining the dynamic properties of immersion thermocouples, Ind. Lab. 29, 1674 (June).

Meyer, H., and E. Wilde, Thermoelement leads for high vacuum devices and which can be thoroughly heated, Exp. Tech. Physik 12, 447.

Pak, V., and Yu. P. Krinskii, Automatic testing of commercial thermocouples made of non-precious metals, Measurement Techniques No. 5, 391 (Nov.).

Ruff, A.W. Jr., Open-probe thermocouple control of radio-frequency heating, Rev. Sci. Instr. 35, 760 (June).

Schechowzow, A.F., Pneumatic contact device for measuring piston temperature in a running motor, Feinwerk Technik 63, 18 (Jan.).

Schmitz, L.S., Nonlinear analog network to convert surface temperature to heat flux, N64-18176.

Shcherbina, D.M., Application of a Kerr cell for comparing luminous fluxes, Measurement Techniques No. 1, 41 (July).

Shcherbina, D.M., Supplies for standard temperatature lamps from rectifiers, Measurement Techniques No. 8, 620 (Feb.).

Shimanskiy, Yu. N. et al, A device for high-speed recording of small temperature drops, N64-29149.

Skuratov, S.M., and M.N. Goroshko, Simple bridge circuit for measuring the resistance of a platinum resistance thermometer, Measurement Techniques No. 2, 104 (Aug.).

Thomson, J.H., Development of an improved time-temperature integrator, AD-434147.

Zhinkin, B.N., Electrical oven for testing thermocouples, Measurement Techniques No. 1, 45 (July).

A new temperature measuring apparatus for laboratory purposes, Arch. Tech. Messen. No. 344, 209 (Sept.).

Automatic thermocouple comparator, Instr. Control Systems 37, 91 (May).

Digital thermometer covers wide range, Electronics 37, 113 (May 4).

1965

Boom, G., and F. van der Woude, Very stable and simple compensator for thermocouples, Rev. Sci. Instr. 36, 857 (June).

Caldwell, F.R., Temperatures of thermocouple reference junctions in an ice bath, J. Res. Natl. Bur. Std. (U.S.) 69C, 95 (April).

Claggett, T.J., External thermocouple compensation, Instrumentation 18, 24.

Dengler, C.O., Frezing apparatus for the triple-point-of-water cell, Instr. Control Systems 38, 117 (May).

Feldman, C.L., Automatic ice-point thermocouple reference junction, Instr. Control Systems 38, 101 (Jan.).

Greenwood, T.L., Thermocouple-continuity monitor, ISA J. 12, 88 (Feb.).

Hobson, D.L., and B. Cohen, Temperature measuring test set, Ind. Electron. 3, 117 (March).

Ichiye, T., and N.B. Plutchak, Calibration and field test of IRT, Lamont Geological Observatory, Palisades, N.Y. Rept. No. CU-12-65 Nonr-26648; AD-470 136.

Kochan, V.A. et al, Automatic recording instrument for measuring low temperatures, Measurement Techniques No. 1, 52 (June).

Kol'tsov, A.A., and G. Kh. Valeyeva, Analysis of one measuring circuit for automatic electronic potentiometers measuring temperature, N65-24157.

Miksch, E.S., Equilibrium of the ice-water temperature standard, Rev. Sci. Instr. 36, 797 (June).

Pak, V., Bridge method for comparing precious metal thermocouples, Measurement Techniques No. 2, 149 (Feb.).

Perrey, H.E., Amplifier for temperature sensors, ISA J. 12, 67 (Jan.).

Schrenker, H., Automatic, electronic compensators in submerged pyrometric installations, Arch. Tech. Messen. No. 358, R142 (Nov.).

Schwarzer, H., Electrical temperature measurement and equipment, Arch. Tech. Messen. No. 356, 197 (Sept.).

Sereznov, A.N., Method for reducing the noise level at the input of an instrument used in measuring temperature with thermocouples, Measurement Techniques No. 6, 503 (June).

Sharpe, J., An application of photomultiplier tubes in temperature measurement, Ind. Electron. 3, 471 (Oct).

Stansbury, E.E. et al, Modified dauphinee thermocouple comparator circituit for adiabatic calorimetry, Rev. Sci. Instr. 36, 480 (April).

11. General

1962

Kirk, F.W., and N.R. Rimboi, Instrumentation, Am. Tech. Soc., Chicago, Ill.

Ohring, G., W. Tang, and Y. DeSanto, Theoretical estimates of the average surface temperature on Mars, J. Atmospheric Sci. 19, 444 (Nov.).

Slaughter, J.I., and J.L. Margrave, Temperature measurement, Aerospace Corp., Los Angeles, Calif. Rept. No. TDR-169 (3240-20) TN-1 (Oct.); AD-298142.

Temperature of Venus, Instr. Pract. 16, 1494 (Dec.).

1963

Agabohov, S.G., and A. Komarek, Blackness of platinum and platinum-rhodium wires, Inzh. Fiz. Zh. 6, 79.

Ambrok, G.S., A.N. Gordov, and A.G. Ivanova, Method of determining the thermal inertia of some types of temperature measuring devices, High Temperature 1, 413 (Nov.-Dec.).

Benedict, R.P., Temperature and its measurement, Electro-Technol. (New York) 72, 71 (July).

Benedict, R.P., Temperature measurement in moving fluids, Electro-Technol. (New York) 72, 56 (Oct.).

Billing, B.F., Thermocouples, a critical survey, Royal Aircraft Establishment, Farnborough, England, RAE-TN-CPM-18(May); N65-20747.

Bodea, E., Rationalizing the kinetic definition of temperature, Acta Phys. Austriaca 16, 80.

Cook, N.H., and E. Rabinowicz, Physical measurement and analysis, Addison-Wesley Publishing Co., Reading, Mass.

Corruccini, R.J., Temperature measurements in cryogenic engineering, Advan. Cryog. Eng. 8, 315.

Fruchtman, I., Temperature measurements of hot gas streams AIAA J. 1 1909 (Aug.).

George, A.L. et al, Conversion formula for thermocouples, Instr. Control Systems 36, 133 (July).

Gershenzon, S.S., and K.N. Manuylov, On the rate of detecting temperature gradient changes by measuring instruments, Foreign Tech. Div., Air Force Systems Command, FTD-TT 63 540; AD 415 007.

Graziano, E.E., Experimental measurements of velocity and temperature profiles and skin-friction in supersonic turbulent compressible flow: an annotated bibliography, N63-23615.

Hertzfeld, C.M., ed. in chief, Temperature, its measurement and control in science and industry. Volume 3, part 3, Biology and medicine, J.D. Hardy, ed., Rheinhold Pub. Corp., N.Y.

Kostkowski, H.J., and G.W. Burns, Thermocouple and radiation thermometry above 900°K, NASA Measurement of thermal radiation properties of solids, p. 13.

Kurti, N., Temperatures below 1°K, Advan. Cryog. Eng. 8, 1.

Malone, E.W., Surface temperature measurement errors, Trans. Inst. Elect. Electron. Engrs. AS-1 15 (Feb.).

Marcus, H., Present and future requirements for high temperature measurements, NASA Measurement of thermal radiation properties of solids, p. 434.

Sokeland, W.P. et al, A typical problem in heat transfer: determine the steady-state axial temperature distribution in a conical thermocouple support, Eng. J. (Montreal) 10, No. 2, 42.

Sokeland, W.P. and J.A. Payne, Solution to the previous problem: determine the steady-state axial temperature distribution in a conical thermocouple support, Eng. J. (Montreal) 10, No. 4, 50.

Stimson, H.F., J.F. Swindells, and R. E. Wilson, Temperature scales, thermocouples and resistance thermometers, Am. Inst. Phys. Handb. Second ed. Sec. 4a, pp. 2-21.

Stotzek, H., Thermal measurement systems and their construction from individual measuring instruments, Arch. Tech. Messen No. 331, 181 (Aug.).

Timmerhaus, K.D., Measurement of low temperatures, Cryogenic Engineering, John Wiley & Sons, N.Y. p. 196.

Some developments in techniques for temperature measurement, Proc. of a Symposium (April 26, 1962) Inst. Mech. Engrs. (London) 1963.

1964

Barber, C.R., Temperature scale measurement techniques for the range 10 to 90°K, Acta Imeko p. 415, Paper No. 23-UK-246.

Barber, C.R., Tempperature scale of the National Physical Laboratory in the range 10-90°K, Comite Consultatif Thermometrie, Comite Intern. Poids Mesures, 6e, Sevres, France 1962, 19 (Pub. 1964).

Barber, C.R., Conference on the measurement of high temperatures, London May 1964, Brit. J. Appl. Phys. 15, 1003 (Sept.).

Bauer, W., and R. Buschner, Report on measurement of the air temperature with various types of radiation shielding, N64-16484.

Bollinger, L.E., Transducers for measurement. Part 3 Temperature from one extreme to the other, ISA J. 11, 73 (Oct.).

Conison, J., Process temperature measurement, Instr. Control Systems 37, 141 (June).

Coombe, R.A., Measuring temperatures in the range 1000°C to 5000°C, Part 2, R&D No. 29, 14 (Jan.).

Diamond, J.J. ed., Bibliography on the high temperature chemistry and physics of materials in the condensed state, International Union of Pure and Applied Chemistry 1964, No. 4 (Oct. - Dec.).

Grey, J., Thermodynamic methods of high temperature measurement, ISA Trans. 4, 102 (Apr. - June).

Hall, W.M., The application of temperature rate measurements to the determination of thermal emittance, N64-20604.

Hammond, C.M., and D.L. Burk, A simplified thermal analysis technique for measuring transformation temperatures of steel, Mater. Res. Std. 4, 275 (June).

Hoffman, E.E., Potadssssium corrosion test loop development Quarterly Progress Rept. No. 5 (July 15, 1964-Oct. 15, 1964) General Electric Co., Cincinnati, Ohio, NASA-CR-54269; NSA 19-20473.

Holbeche, T.A., and D.A. Spence, A theoretical and experimental investigation of temperature variation behind attenuating shock waves, Proc. Roy. Soc. (London) A-279, 111 (May 12).

Hunt, L.B., The early history of the thermocouple, Platinum Metals Rev. 8, 23 (Jan.).

Ito, T., and T. Morikawa, The methods of the measurement of temperature and electron density of arc plasma, Mitsubishi Denki Giho 38, 8 (Dec.).

Kirenkov, I.I., Basic metrological problems in temperature measurements, Measurement Techniques No. 12, 1009 (June).

Koch, H., Application of temperature measuring methods in flow technology, Arch. Tech. Messen No. 340, 97 (May).

Landensperger, W., and D. Stark, The total optical emissivity of rhenium, rhodium, palladium, and titanium, Z. Physik 180, 178.

Lapworth, K.C., Investigation of the Physical properties of gases at high temperatures, J. Roy. Aeronaut. Soc. 68, 189 (Mar.).

Lehmberg, A.E., Calculation of temperature sensor error introduced by frictional heating, AD-48 866.

Lieneweg, F., Indication delay of thermometers, Arch. Tech. Messen No. 340, R46 (May).

Louis, J.R., and W.E. Hartman, The determination and compensation of temperature sensor transfer functions, ASME Winter Annual Meting, New York, Nov. 29-Dec. 4, Paper 64-WA/AUT-13.

Miller, J.T., Revised course in industrial instrument technology. Chapter 9, Electrical thermometers, Instr. Pract. 18, 41 (Jan.).

Rozenshtok, Yu. L., Statistical characteristics of the temperature measurement procedure for a uniform steady-state turbulent flow, Inzh. Fiz. Zh. 7, 87 (Feb.).

Shashkov, A.G., Block diagrams for measuring flow parameters by means of thermistors, Inzh. Fiz. Zh. 9, 87 (Sept.).

Shu, H. H. H., E. W. Gaylord, and W. F. Hughes, Relation between the rubbing interface temperature distribution and dynamic thermocouple temperatures, Trans. ASME D86, 417 (Sept.).

Sklarew, S., The problem of accurately measuring changing temperatures of nonmetallic surfaces, Am. Soc. Metals 2, 235.

Slaughter, J.I., and J.L. Margrave, Temperature measurement, AD-448 346.

Smetanina, L.I., The dynamic method of measuring high temperature, High Temperature 2, 80 (Jan.).

Soviani, R., A new way of determining the thermal inertia of temperature transducers, Acta Imeko 1964, 369. Paper No. 23-RU-226.

Stepanov, G.P., and Yu. N. Kulikov, Investigation of dynamic characteristics of temperature sensors for a retarded air flow, N64-25590.

Strutter, E., and G. Luck, On the measurement of time constants of thermocouples, Jena Rev. No. 9, 210.

Tartakovskii, D.F., Computation of the thermal inertia of commercial thermal detectors Measurement Techniques No. 11, 922 (Apr.).

Tereshchenko, A.F., On the method of measuring surface temperature, Ind. Lab. 30, 422 (Oct.).

Vanvor, H., Temperature measurement in the laboratory, Glas-Instr. Tech. 8, 171.

Vrolyk, J.J., and P.A. Kinzie, Feasability investigation of heat-flowrote measuring techniques, Final Rept. (Jan.) RTD-TDR-63-4077; AD-431189; N65-22074.

Walker, R.F., High temperature measurements and standards 100° - 30°, High temperature technology; International union of pure and applied chemistry, Commission on high temperatures and refractories, International symposium, Pacific Grove, Calif., Sept. 8-11, 1963, Proceedings, Butterworth and Co. (Publishers), Ltd., London p. 7.

Zysk, E.D., Noble metals in thermometry-recent developments, Engelhard Inds. Tech. Bull. 5, 69 (Dec.).

Evaluation of temperature probes, AD-442 102.

Guide posts to keep thermocouple users out of hot water, S.A.E. J. 72, 82(Aug.)

High temperature materials program progress rept. No. 41, Part A, Nov. 30, General Electric Co., Cincinnati, Ohio, GEMP-41A; NSA 19-11669.

Mass flow by temperature measurement, Instr. Control Systems 37, 95 (Mar.).

1965

Angerhofer, A.W., Cryogenic instrumentation, 1Sensing temperature and level, Control Eng. 12, 67 (Oct.).

Atkins, R.M., Advances in thermal instrumentation, Ind. Research 7, 84 (June).

Barber, J.A., Measurements of high temperatures, U.S. At. Energy Comm., Sandia Corp., Albuquerque, N.M. CONF-650204-7; SC-DC-65-1237; NSA 19-30489.

Bliss, P., and S. Fanciullo, High temperature thermometry at Pratt and Whitney aircraft-canel, Pratt and Whitney Aircraft, Middletown, Conn. PWAC-462; N65-24965.

Field, R.T., Temperature sensors, N65-31353.

Harris, H., Comparing the three most popular temperature sensors, Electron. Design 13, 62 (Jan.).

Jasicki, Z., and A. Handke, Some problems concerning temperature measurement of a hot gas stream, Pomiary, Automat. Kontrola 11, 340 (Aug.).

Johansson, J., Cryogenic measurements, Instr. Control Systems 38, 107 (May).

Kennedy, R.H., Sensing and measuring temperature in manufacturing environments, Automation 12, 78 (Oct.).

Lieneweg, F., VDE/VDI 3511 Guide "Technical temperature measurement," Arch. Tech. Messen No. 350, 49 (Mar.).

McCoy, J.G., An improved method for the reduction of rocketsonde temperature data, Army Electronics Research and Development Activity, White Sands Missile Range, N.M. ERDA-279; AD-458 318; N65-19556.

Ogale, V.A., Temperature measurements at high temperatures and high speeds- a literature survey, N65-35056.

Oshima, K., Low temperature work in Japan, Cryogenics 5, 1 (Feb.).

Rozenshtok, Yu.L., Dynamic characteristics of a stationary linear system for measuring temperature, Measurement Techniques No. 3, 240 (Aug.).

Rozenshtok, Yu.L., Dispersion and accidental error of measurement of temperature of locally turbulent flow, N65-30420.

Schwarzer, H., The electrical measurement of temperature and measurement systems, Arch. Tech. Messen No. 356, 197 (Sept.).

Segletes, T., A bibliography of aerothermal sensing techniques, Martin Co., Baltimore, Md. Rept. No. ER-13687; AD-464 119.

Smith, C., Temperature sensing elements, Product Des. Eng. 3, 74 (Sept.).

Yaryshev, N.A., Heat-exchange formula for thermometers which takes into account heat removal and radiation, Measurement Techniques No. 5, 411 (May).

Methods of high-temperature measurement of gases: compilation of abstracts, Aerospace Technology Div., Library of Congress Rept. ATD-P-65-53; AD-618 532.

Subject Index

[Reference is to volume number, boldface, followed by page number of this volume.]

Author Index

NBS TECHNICAL PUBLICATIONS

PERIODICALS

JOURNAL OF RESEARCH reports National Bureau of Standards research and development in physics, mathematics, chemistry, and engineering. Comprehensive scientific papers give complete details of the work, including laboratory data, experimental procedures, and theoretical and mathematical analyses. Illustrated with photographs, drawings, and charts.

Published in three sections, available separately:

- **Physics and Chemistry**

Papers of interest primarily to scientists working in these fields. This section covers a broad range of physical and chemical research, with major emphasis on standards of physical measurement, fundamental constants, and properties of matter. Issued six times a year. Annual subscription: Domestic, $5.00; foreign, $6.00*.

- **Mathematical Sciences**

Studies and compilations designed mainly for the mathematician and theoretical physicist. Topics in mathematical statistics, theory of experiment design, numerical analysis, theoretical physics and chemistry, logical design and programming of computers and computer systems. Short numerical tables. Issued quarterly. Annual subscription: Domestic, $2.25; foreign, $2.75*.

- **Engineering and Instrumentation**

Reporting results of interest chiefly to the engineer and the applied scientist. This section includes many of the new developments in instrumentation resulting from the Bureau's work in physical measurement, data processing, and development of test methods. It will also cover some of the work in acoustics, applied mechanics, building research, and cryogenic engineering. Issued quarterly. Annual subscription: Domestic, $2.75; foreign, $3.50*.

TECHNICAL NEWS BULLETIN

The best single source of information concerning the Bureau's research, developmental, cooperative and publication activities, this monthly publication is designed for the industry-oriented individual whose daily work involves intimate contact with science and technology—*for engineers, chemists, physicists, research managers, product-development managers, and company executives.* Annual subscription: Domestic, $1.50; foreign, $2.25*.

---

*Difference in price is due to extra cost of foreign mailing.

NONPERIODICALS

Applied Mathematics Series. Mathematical tables, manuals, and studies.

Building Science Series. Research results, test methods, and performance criteria of building materials, components, systems, and structures.

Handbooks. Recommended codes of engineering and industrial practice (including safety codes) developed in cooperation with interested industries, professional organizations, and regulatory bodies.

Special Publications. Proceedings of NBS conferences, bibliographies, annual reports, wall charts, pamphlets, etc.

Monographs. Major contributions to the technical literature on various subjects related to the Bureau's scientific and technical activities.

National Standard Reference Data Series. NSRDS provides quantitative data on the physical and chemical properties of materials, compiled from the world's literature and critically evaluated.

Product Standards. Provide requirements for sizes, types, quality and methods for testing various industrial products. These standards are developed cooperatively with interested Government and industry groups and provide the basis for common understanding of product characteristics for both buyers and sellers. Their use is voluntary.

Technical Notes. This series consists of communications and reports (covering both other agency and NBS-sponsored work) of limited or transitory interest.

CLEARINGHOUSE

The Clearinghouse for Federal Scientific and Technical Information, operated by NBS, supplies unclassified information related to Government-generated science and technology in defense, space, atomic energy, and other national programs. For further information on Clearinghouse services, write:

Clearinghouse
U.S. Department of Commerce
Springfield, Virginia 22151

Order NBS publications from:
Superintendent of Documents
Government Printing Office
Washington, D.C. 20402

NATIONAL BUREAU OF STANDARDS

The National Bureau of Standards[1] was established by an act of Congress March 3, 1901. Today, in addition to serving as the Nation's central measurement laboratory, the Bureau is a principal focal point in the Federal Government for assuring maximum application of the physical and engineering sciences to the advancement of technology in industry and commerce. To this end the Bureau conducts research and provides central national services in three broad program areas and provides central national services in a fourth. These are: (1) basic measurements and standards, (2) materials measurements and standards, (3) technological measurements and standards, and (4) transfer of technology.

The Bureau comprises the Institute for Basic Standards, the Institute for Materials Research, the Institute for Applied Technology, and the Center for Radiation Research.

THE INSTITUTE FOR BASIC STANDARDS provides the central basis within the United States of a complete and consistent system of physical measurement, coordinates that system with the measurement systems of other nations, and furnishes essential services leading to accurate and uniform physical measurements throughout the Nation's scientific community, industry, and commerce. The Institute consists of an Office of Standard Reference Data and a group of divisions organized by the following areas of science and engineering:

Applied Mathematics—Electricity—Metrology—Mechanics—Heat—Atomic Physics—Cryogenics[2]—Radio Physics[2]—Radio Engineering[2]—Astrophysics[2]—Time and Frequency.[2]

THE INSTITUTE FOR MATERIALS RESEARCH conducts materials research leading to methods, standards of measurement, and data needed by industry, commerce, educational institutions, and government. The Institute also provides advisory and research services to other government agencies. The Institute consists of an Office of Standard Reference Materials and a group of divisions organized by the following areas of materials research:

Analytical Chemistry—Polymers—Metallurgy — Inorganic Materials — Physical Chemistry.

THE INSTITUTE FOR APPLIED TECHNOLOGY provides for the creation of appropriate opportunities for the use and application of technology within the Federal Government and within the civilian sector of American industry. The primary functions of the Institute may be broadly classified as programs relating to technological measurements and standards and techniques for the transfer of technology. The Institute consists of a Clearinghouse for Scientific and Technical Information,[3] a Center for Computer Sciences and Technology, and a group of technical divisions and offices organized by the following fields of technology:

Building Research—Electronic Instrumentation — Technical Analysis — Product Evaluation—Invention and Innovation— Weights and Measures — Engineering Standards—Vehicle Systems Research.

THE CENTER FOR RADIATION RESEARCH engages in research, measurement, and application of radiation to the solution of Bureau mission problems and the problems of other agencies and institutions. The Center for Radiation Research consists of the following divisions:

Reactor Radiation—Linac Radiation—Applied Radiation—Nuclear Radiation.

---

[1] Headquarters and Laboratories at Gaithersburg, Maryland, unless otherwise noted; mailing address Washington, D. C. 20234.

[2] Located at Boulder, Colorado 80302.

[3] Located at 5285 Port Royal Road, Springfield, Virginia 22151.

(cut here)

Announcement of New Volumes in the NBS Special Publication 300 Series Precision Measurement and Calibration

Superintendent of Documents
Government Printing Office
Washington, D.C. 20402

Dear Sir:

Please add my name to the announcement list of new volumes to be issued in the series: National Bureau of Standards Special Publication 300, Precision Measurement and Calibration.

Name____

Company______________________________________

Address______________________________________

City__________________State__________Zip Code______

(Notification key—N: 353)

☆ U.S. GOVERNMENT PRINTING OFFICE: 1968 O—295-704

Official SI Unit Names and Symbols

[For a complete statement of NBS practice, see
NBS Tech. News Bull. Vol. 52, No. 6, June 1968.]

Name	Symbol	Name	Symbol
meter	m	newton	N
kilogram	kg	joule	J
second	s	watt	W
ampere	A	coulomb	C
kelvin [1]	K	volt	V
candela	cd	ohm	Ω
radian	rad	farad	F
steradian	sr	weber	Wb
hertz	Hz	henry	H
lumen	lm	tesla	T
lux	lx		

Additional Names and Symbols approved for NBS use

curie [2]	Ci	mho	mho
degree Celsius [3]	°C	mole	mol
gram	g	siemens [4]	S

---

[1] The same name and symbol are used for thermodynamic temperature and temperature interval. (Adopted by the 13th General Conference on Weights & Measures, 1967.)

[2] Accepted by the General Conference on Weights & Measures for use with the SI.

[3] For expressing "Celsius temperature"; may also be used for a temperature interval.

[4] Adopted by IEC and ISO.

Table for Converting U.S. Customary Units to Those of the International System (SI)[5]

To relate various units customarily used in the United States to those of the International System, the National Bureau of Standards uses the conversion factors listed in the "ASTM Metric Practice Guide", NBS Handbook 102. These are based on international agreements effective July 1, 1959, between the national standards laboratories of Australia, Canada, New Zealand, South Africa, the United Kingdom, and the United States.

To convert from:

(1) inches to meters, multiply by 0.0254 exactly.
(2) feet to meters, multiply by 0.3048 exactly.
(3) feet (U.S. survey) to meters, multiply by 1200/3937 exactly.
(4) yards to meters, multiply by 0.9144 exactly.
(5) miles (U.S. statute) to meters, multiply by 1609.344 exactly.
(6) miles (international nautical) to meters, multiply by 1852 exactly.
(7) grains (1/7000 lbm avoirdupois) to grams, multiply by 0.064 798 91 exactly.
(8) troy or apothecary ounces mass to grams, multiply by 31.103 48 . . .
(9) pounds-force (lbf avoirdupois) to newtons, multiply by 4.448 222 . . .
(10) pounds-mass (lbm avoirdupois) to kilograms, multiply by 0.453 592 . . .
(11) fluid ounces (U.S.) to cubic centimeters, multiply by 29.57 . . .
(12) gallons (U.S. liquid) to cubic meters, multiply by 0.003 785 . . .
(13) torr (mm Hg at O °C) to newtons per square meter, multiply by 133.322 exactly.
(14) millibars to newtons per square meter, multiply by 100 exactly.
(15) psi to newtons per square meter, multiply by 6894.757 . . .
(16) poise to newton-seconds per square meter, multiply by 0.1 exactly.
(17) stokes to square meters per second, multiply by 0.0001 exactly.
(18) degrees Fahrenheit to kelvins, use the relation $t_K = (t_F + 459.67)$ 1.8.
(19) degrees Fahrenheit to degrees Celsius, use the relation $t_C = (t_F - 32)/1.8$.
(20) curies to disintegrations per second, multiply by 3.7×10^{10} exactly.
(21) roentgens to coulombs per kilogram, multiply by $2.579\,760 \times 10^{-4}$ exactly.

---

[5] Système International d'Unités (designated SI in all languages).