Manual on

The Use of Thermocouples in Temperature Measurement

Fourth Edition

ASTM INTERNATIONAL

MANUAL ON THE USE OF THERMOCOUPLES IN TEMPERATURE MEASUREMENT

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Foreword

The Manual on the Use of Thermocouples in Temperature Measurement was sponsored by ASTM Committee E20 on Temperature Measurement and was compiled by E20.94, the Publications Subcommittee. The editorial work was co-ordinated by R. M. Park, Marlin Manufacturing Corp. Helen M. Hoersch was the ASTM editor.

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Acknowledgments

Editors for this Edition of the Handbook

Richard M. Park (Chairman), Marlin Mfg. Corp.
Radford M. Carroll (Secretary), Consultant
Philip Bliss, Consultant
George W. Burns, Natl. Inst. Stand. Technol.
Ronald R. Desmaris, RdF Corp.
Forrest B. Hall, Hoskins Mfg. Co.
Meyer B. Herzkovitz, Consultant
Douglas MacKenzie, ARi Industries, Inc.
Edward F. McGuire, Hoskins Mfg. Co.
Dr. Ray P. Reed, Sandia Natl. Labs.
Larry L. Sparks, Natl. Inst. Stand. Technol.
Dr. Teh Po Wang, Thermo Electric

Officers of Committee E20 on Temperature Measurement

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R. M. Park (1st Vice Chairman), Marlin Mfg. Corp.
D. MacKenzie (2nd Vice Chairman), ARi Industries, Inc.
T. P. Wang (Secretary), Thermo Electric Co., Inc.
R. L. Shepard (Membership Secretary), Martin-Marietta Corp.

Those Primarily Responsible for Individual Chapters of this Edition

Introduction—R. M. Park
Thermoelectric Principles—Dr. R. P. Reed
Thermocouple Materials—M. B. Herzkovitz
Sensor Design—Dr. T. P. Wang
Compacted Sheathed Assemblies—D. MacKenzie
Emf Measurements—R. R. Desmaris
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Calibration—G. W. Burns
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ASTM would like to express its gratitude to the authors of the 1993 Edition of this publication. The original publication made a significant contribution to the technology, and, therefore, ASTM, in its goal to publish books of technical significance, called upon current experts in the field to revise and update this important publication to reflect those changes and advancements that have taken place over the past 10 years.

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Chapter 1—Introduction

First Edition, 1970

This manual was prepared by Subcommittee IV of ASTM Committee E20 on Temperature Measurement. The responsibilities of ASTM Committee E20 include "Assembling a consolidated source book covering all aspects relating to accuracy, application, and usefulness of thermometric methods." This manual was addressed to the thermocouple portion of this responsibility.

The contents include principles, circuits, standard electromotive force (emf) tables, stability and compatibility data, installation techniques, and other information required to aid both the beginner and the experienced user of thermocouples. While the manual is intended to be comprehensive, the material, however, will not be adequate to solve all the individual problems associated with many applications. To further aid the user in such instances, there are numerous references and an extensive bibliography. In addition to presenting technical information, an attempt is made to properly *orient* a potential user of thermocouples. Thus, it is hoped that the reader of this manual will make fewer mistakes than the nonreader.

Regardless of how many facts are presented herein and regardless of the percentage retained, all will be for naught unless one simple important fact is kept firmly in mind. The thermocouple reports only what it "feels." This may or may not be the temperature of interest. The thermocouple is influenced by its entire environment, and it will tend to attain thermal equilibrium with this environment, not merely part of it. Thus, the environment of each thermocouple installation should be considered unique until proven otherwise. Unless this is done, the designer will likely overlook some unusual, unexpected, influence.

Of all the available temperature transducers, why use a thermocouple in a particular application? There are numerous advantages to consider. Physically, the thermocouple is inherently simple, being only two wires joined together at the measuring end. The thermocouple can be made large or small depending on the life expectancy, drift, and response-time requirements. It may be flexible, rugged, and generally is easy to handle and install. A thermocouple normally covers a wide range of temperatures, and its output is reasonably linear over portions of that range. Unlike many temperature transducers, the thermocouple is not subject to selfheating problems. In practice, thermocouples of the same type are interchangeable within specified limits of error. Also, thermocouple materials are readily available at reasonable cost, the expense in most cases being nominal.

The bulk of the manual is devoted to identifying material characteristics and discussing application techniques. Every section of the manual is essential to an understanding of thermocouple applications. Each section should be studied carefully. Information should not be used out of context. The general philosophy should be—let the user beware.

Second Edition, 1974

In preparing this edition of the manual, the committee endeavored to include four major changes which greatly affect temperature measurement by means of thermocouples. In 1968, at the same time the First Edition was being prepared, the International Practical Temperature Scale was changed. This new scale (IPTS-68) is now the law of the land, and Chapter 8 has been completely rewritten to so reflect this. In 1972–1973, new Thermocouple Reference Tables were issued by the National Bureau of Standards. Accordingly, Chapter 10 has been revised to include the latest tables of temperature versus electromotive force for the thermocouple types most commonly used in industry. Also, along these same lines, the National Bureau of Standards has issued new methods for generating the new Reference Table values for computer applications. These power series relationships, giving emf as a function of a temperature, are now included in Chapter 10.3. Finally, there have been several important changes in thermocouple material compositions, and such changes have been noted in the appropriate places throughout the text. The committee has further attempted to correct any gross errors in the First Edition and has provided a more complete bibliography in Chapter 12.

Third Edition, 1980

This edition of the manual has been prepared by ASTM E20.10, the publications subcommittee. The main impetus for this edition was the need for a reprinting. Taking advantage of this opportunity, the editors have carefully reviewed each chapter as to additions and corrections called for by developments in the field of temperature measurement by thermocouples since 1974. Chapters 3, 4, 5, 6, 7, and 8 have been completely revised and strengthened by the appropriate experts. An important addition is Chapter 12 on Measurement Uncertainty. This reflects the trend toward a more statistical approach to all measurements. A selected bibliography is still included at the end of each chapter. A final innovation of this edition is the index to help the users of this manual.

Fourth Edition, 1993

On 1 January 1990 a new international temperature scale, the ITS-90, went into effect. Differences between the new scale and the now superceded IPTS-68 are small, but this major event in thermometry has made it necessary to revise and update much of the material in this book. The work was undertaken by Publications Subcommittee E20.94 of Committee E20 on Temperature Measurement. All chapters have been thoroughly reviewed. Some have been completely rewritten. New and updated material has been added throughout.

Because of the major impact that an international temperature scale change has on calibration methods, the calibration chapter has been completely revised to reflect ITS-90 requirements. Reference tables and functions are presented here in a new handy condensed format. For each thermocouple type, °C and °F tables along with coefficients of the polynomials used to compute them will be found on facing pages. These data are in conventional form, giving emf for a known temperature. Included in this edition for the first time are the coefficients of inverse polynomials useful for computing temperature from a known emf. These inverse functions produce values that closely agree with the conventionally generated data.

Tables and functions for letter-designated thermocouple types in this edition are extracted from NIST (formerly NBS) Monograph 175. These tables incorporate results from recent research on the behavior of Type S thermocouple materials near 630°C and also include changes imposed by the ITS-90.

Additional tables for special thermocouple types suitable for work at low temperatures will be found in the chapter on cryogenics. These data are also based on the most current NIST published information.

As aids to the reader and user of this edition, a list of current ASTM standards pertaining to thermocouples and the complete text of the official description of the ITS-90 have been included as appendices.

Chapter 2—Principles of Thermoelectric Thermometry

2.0 Introduction

This manual is for those who use thermocouples for practical thermometry. It simplifies the essential principles of thermoelectric thermometry for the incidental user; yet, it provides a technically sound basis for general understanding. It focuses on thermocouples, circuits, and hardware of the kind ordinarily used in routine laboratory and industrial practice.

The thermocouple is said to be the most widely used electrical sensor in thermometry and perhaps in all of measurement. A thermocouple appears to be the simplest of all electrical transducers (merely two dissimilar wires coupled at a junction and requiring no electric power supply for measurement). Unfortunately, this apparent simplicity often masks complicated behavior in ordinary application with practical thermocouple circuits. The manner in which a thermocouple works is often misrepresented in ways that can lead the unwary user into unrecognized measurement error. These will be illustrated in Section 2.2.

The reader should spend the small amount of time necessary to study this chapter. That investment, to gain or to confirm an authentic understanding of the way in which thermoelectric circuits actually function, should be rewarded by an ability to recognize and avoid measurement pitfalls. Thermometry problems that can be easily avoided by proper understanding, if unrecognized, can significantly degrade accuracy or even invalidate measurements.

A few simple facts form a sufficient basis for reliable thermocouple practice. Therefore, we begin with the basic concepts that the user must well understand to make reliable measurements with thermocouple circuits under various conditions. Mathematical expressions are necessary to make the concepts definite and concise. But, for those readers who may feel that the mathematics obscures rather than clarifies, their meaning is also expressed in words.

The circuit model we use is not traditional. Nevertheless, it is physically consistent with the proven viewpoint of many modern authors who address applied thermoelectric thermometry [*1–6*]. The model is also fully consistent with modern thermoelectric theory and experiment [*7–18*]. The circuit model used here is general, and it accurately describes the actual behavior of the most complex practical thermoelectric circuits. It is important that the user understand at least the model presented in Sections 2.1 and 2.2 before using thermocouples for thermometry. That model of thermoelectric circuits can be understood with no advanced technical background; yet, it is sufficient for the reliable practice of thermoelectric thermometry in all real-life situations.

2.1 Practical Thermoelectric Circuits

2.1.1 The Thermoelectric Voltage Source

A thermocouple directly produces a voltage that can be used as a measure of temperature. That terminal voltage used in thermometry results only from the Seebeck effect. The interesting practical relationships between the Seebeck effect, the Thomson effect, and the Peltier effect (the only three thermoelectric effects) will be discussed later in Section 2.4 as the latter do not directly affect thermocouple application.

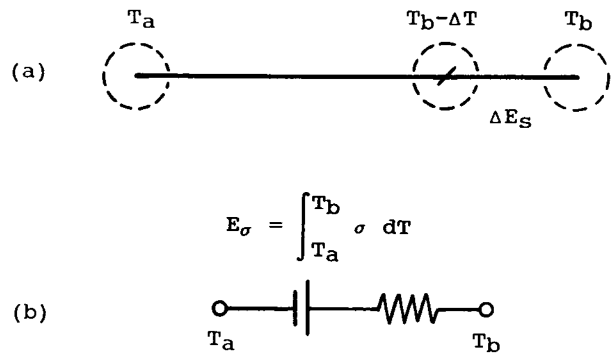
The *Seebeck electromotive force* (*emf*) is the internal electrical potential difference or electromotive force that is viewed externally as a voltage between the terminals of a thermocouple. This Seebeck source emf actually occurs in any electrically conducting material that is not at uniform temperature even if it is not connected in a circuit.[1] The Seebeck emf occurs within the legs of a thermocouple. It does not occur at the junctions of the thermocouple as is often asserted nor does the Seebeck emf occur as a result of joining dissimilar materials as is often implied. Nevertheless, for practical reasons (Section 2.1.3) it is always the net voltage between paired dissimilar materials that is used in thermocouple thermometry.

2.1.2 Absolute Seebeck Characteristics

Thermoelectric characteristics of an individual material, independent of any other material, by tradition are called *absolute.* These actual characteristics are measured routinely though not in a thermocouple configuration. If any individual electrically conducting material, such as a wire (Fig. 2.1), is placed with one end at any temperature, T_a, and the other at a different temperature, T_b, a net Seebeck emf, E_σ, actually occurs between the ends of the single material. If T_a is fixed at any arbitrary temperature, such as 0 K, any change in T_b produces a corresponding change in the Seebeck emf. This emf in a single material, independent of any other material, is called the *absolute Seebeck emf.*

With the temperature of endpoint *a* fixed, from any starting temperature

[1]For the justification of this assertion and terminology see Section 2.4.4.1. A few authors have formerly elected to call this identical quantity the Thomson emf, a usage that this book discourages. Others assign a different erroneous meaning to Thomson emf.



(*a*) An isolated electric conductor.
(*b*) Seebeck cell equivalent circuit element.

FIG. 2.1—*The Seebeck thermoelectric emf cell.*

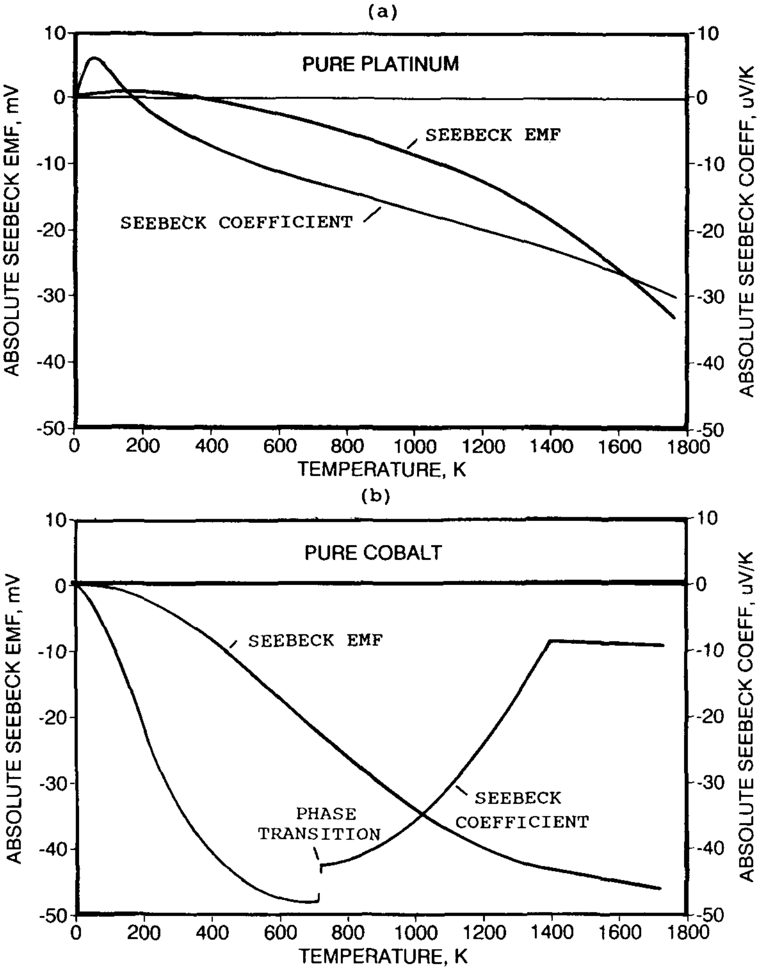
of endpoint *b*, a small change, ΔT, of its temperature, T_b, results in a corresponding increment, ΔE_σ, in the absolute Seebeck emf. The ratio of the net change of Seebeck emf that results from a very small change of temperature to that temperature increment is called the *Seebeck coefficient.*[2] This is the measure of thermoelectric sensitivity of the material. Where the sensitivity is for an individual material, separate from any other material, it is called the *absolute Seebeck coefficient.* Typical measured relations between absolute Seebeck emf and coefficient and the absolute temperature for pure platinum alone and also for pure cobalt alone are shown in Fig. 2.2.[3] We designate the thermoelectric sensitivity, or Seebeck coefficient, by, σ.[4] As this coefficient is not generally a constant, but depends on temperature, we note the dependence on temperature by $\sigma(T)$. Mathematically, this coefficient is defined by the simple relation

$$\sigma(T) = \lim_{\Delta T \to 0} \frac{\Delta E_\sigma(T)}{\Delta T} \tag{2.1}$$

[2]Unfortunately, for historic reasons, even now the *Seebeck coefficient* is called most commonly by the outdated technical misnomers: *thermoelectric power* or *thermopower* (with physical units, [V/Θ]). Although these three terms are strictly synonymous, the latter terms logically conflict with the appropriate present day use of *thermoelectric power* (with different physical units, [J]) to denote motive electrical power generated by thermoelectric means.

[3]Recommended normal characteristics for the absolute Seebeck coefficients of individual reference materials, such as lead, copper, platinum, and others, are available [*19–22*]. They are not intended for direct use in accurate routine thermometry in place of the standardized relative Seebeck coefficients. However, they do have many practical thermometry applications as in the development of thermoelectric materials, temperature measurement error estimation, and thermoelectric theory.

[4]This manual uses and recommends the mnemonic Greek symbols π (pi) for Peltier, τ (tau) for Thomson, and σ (sigma) for Seebeck coefficients. Many authors have used σ for the Thomson coefficient and α (alpha) for Seebeck coefficient. Do not confuse these different notations.



(*a*) Pure platinum.
(*b*) Pure cobalt.

FIG. 2.2—*Absolute Seebeck thermoelectric characteristics of pure materials.*

or

$$\sigma(T) = \frac{dE_\sigma}{dT} \tag{2.2}$$

where ΔT is the temperature difference between ends of a segment, *not* the change of average temperature of the segment. On a graph of E_σ versus T, $\sigma(T)$ corresponds to the local slope of the curve at any particular temperature, T (see Fig. 2.2).

In the situation described, one end of the thermoelement was at 0 K; the other was at $T \pm \Delta T$. In that situation, the temperature of some point along the thermoelement was necessarily at temperature T and another at $T \pm \Delta T$. Effectively, the segment of the material bounded by adjacent temperatures T and $T \pm \Delta T$ contributed the increment of emf, ΔE_σ. Therefore, significantly, the basic relation applies locally to any isolated homogeneous segment of a conductor as well as to that conductor as a whole. The relation is true for any *homogeneous* segment regardless of its length. As an experimental fact, the relation is also true regardless of any detail of the complex physical mechanism that causes the change of Seebeck emf.

A thermoelectrically homogeneous material is one for which the Seebeck characteristic is the same for every portion of it. For a homogeneous material, the net Seebeck emf is independent of temperature distribution along the conductor. For any particular homogeneous material, the endpoint temperatures alone determine the net Seebeck voltage. Note, however, that this relates only to a homogeneous material. Also note that temperatures of all *incidental junctions* around a practical circuit must be appropriately controlled (see Section 2.2.3).

The relation between absolute Seebeck emf and temperature is an inherent transport property of any electrically conducting material. Above some minimum size (of submicron order) the Seebeck coefficient does not depend on the dimension nor does it depend on proportion, cross-sectional area, or geometry of the material. Determined experimentally, the relation between the Seebeck emf and the temperature difference can be expressed alternately by an equation or by a table as well as by a graph.

2.1.2.1 The Fundamental Law of Thermoelectric Thermometry—The basic relation (Eq 2.2) can be expressed in a form that states the same fact in an alternate way

$$dE_\sigma = \sigma(T)\, dT \tag{2.3}$$

Equation 2.3 has been called *The Fundamental Law of Thermoelectric Thermometry* in direct analogy to such familiar physical laws as Ohm's Law of Resistance and Fourier's Law of Heat Conduction [6]. It is very important to recognize that it is merely this simple relation that must be true if the Seebeck effect is to be used in practical thermometry. For thermometry, nothing more mysterious is required than that Seebeck emf and the temperatures of segment ends be uniquely related. That the relation is actually true for practical materials is confirmed by both experiment and theory.

Equation 2.3 can be expressed in yet another useful form that expresses the absolute Seebeck emf of an individual material

$$E_\sigma(T) = \int \sigma(T)\, dT + C \tag{2.4}$$

This indefinite integral defines the absolute Seebeck emf only to within the arbitrary constant of integration, C. It definitely expresses the relative change of voltage that corresponds to a change of temperature condition, but it does not define the absolute value of that emf. To remove this uncertainty, it is necessary to establish one definite temperature condition.

The absolute Seebeck coefficient is attributed to the entropy of conduction electrons [*15,16,18*]. It is a principle of thermodynamics that entropy vanishes at the zero of the thermodynamic temperature scale [*15,16*]. Therefore, at 0 K the Seebeck coefficient and emf must vanish for all materials. This provides, for evaluating the definite integral, the necessary condition of a known voltage at a known temperature. In principle (the third law of thermodynamics) 0 K can not be realized although it has been approached within less than 10^{-7} K. Also, the phenomenon of *superconductivity* provides real reference materials for which the observed values of both Seebeck emf and Seebeck coefficient are zero over a significant temperature span from 0 K up to the vicinity of some superconductive threshold critical temperature, T_c. Presently, recognized values of T_c for different materials range from much less than 1 K to as much as 120 K [*18*]. Above its T_c transition region a superconductor exhibits normal thermoelectric behavior.

The absolute Seebeck emf can be conveniently referenced to 0 K. Therefore, the net absolute Seebeck emf between the two endpoints of any homogeneous segment with its endpoints at different temperatures is

$$E_\sigma = \int_0^{T_2} \sigma(T)\, dT - \int_0^{T_1} \sigma(T)\, dT \tag{2.5}$$

or

$$E_\sigma = \int_{T_1}^{T_2} \sigma(T)\, dT \tag{2.6}$$

Distinct from Eq 2.4, this definite integral unambiguously represents the net absolute Seebeck emf across any homogeneous nonisothermal segment. It simply adds all the contributions from infinitesimal temperature increments that lie between two arbitrary temperatures. Equation 2.6 also establishes the thermoelectric sign convention. The absolute Seebeck coefficient is positive if voltage measured across the ends of the segment would be positive with the positive probe on the segment end with the higher temperature. The result of integration is merely the difference of absolute Seebeck emfs for the two endpoint temperatures

$$E_\sigma = E_\sigma(T_2) - E_\sigma(T_1) \tag{2.7}$$

as directly obtained from a table, a graph, or from Eq 2.6. The net Seebeck emf is found in this simple way regardless of the intermediate values along the element between those two temperatures and also regardless of the common reference temperature chosen. Fortunately, while it may be convenient to refer the Seebeck emf to 0 K, the reference temperature can be any value. For example, it may be chosen to be 0°C, 273.15 K, 32°F, or any other arbitrary value within the range for which the Seebeck characteristic is known.

Also, in Eq 2.3, the Seebeck emf need not be a linear function of temperature (see Fig. 2.2). Indeed, the absolute Seebeck coefficient of any real material, such as pure platinum, is rarely constant over any extended temperature range. For some materials, such as cobalt, iron, and manganese, the Seebeck coefficient is also discontinuous at phase transition temperatures [*19–21*]. Nevertheless, but only over any temperature range where the Seebeck emf is adequately linear, the relation can be simplified to the product of an approximately constant absolute Seebeck coefficient and the temperature difference between endpoints

$$E_\sigma \simeq \sigma (T_2 - T_1) \tag{2.8}$$

This simplified linear relation is sometimes adequate for individual real materials over some narrow temperature span. However, in accurate practice the nonlinear nature of the Seebeck emf usually must be considered.

2.1.2.2 Corollaries from the Fundamental Law of Thermoelectric Thermometry—Despite its simplicity, the one simple law expressed by Eq 2.3 implies all the facts expressed by the traditional "laws" of thermoelectric thermometry (Section 2.4.1) that are merely corollaries of that equation [*6*]. For example, any segment or collection of dissimilar segments, regardless of inhomogeneity, contributes no emf so long as each is isothermal. From Eq 2.6 or 2.8, any homogeneous segment with its endpoints at the same temperatures contributes no net Seebeck emf regardless of temperature distribution apart from the endpoints. Any segment for which the Seebeck coefficient is negligible over the temperature span, such as a superconducting material below the critical temperature, contributes no emf. At least two dissimilar materials are required for a useful thermoelectric circuit.

2.1.2.3 The Seebeck EMF Cell—Because of Eq 2.6, any *homogeneous* segment of a conducting material (Fig. 2.1*a*), can be represented, as in Fig. 2.1*b*, as a single thermoelectric *Seebeck cell.* The Seebeck emf cell is a nonideal thermoelectric voltage source (an electromotive source with an internal resistance like that of the segment and an emf given by Eq 2.6). Also, as for any electromotive cell, the external voltage across the segment will be less than the open-circuit Seebeck emf if current is allowed to flow because current produces a voltage drop across the internal resistance of the cell. Fortunately, the segment resistance has no effect for open-circuit measurement where current is suppressed as in most modern thermometry. From Eq 2.6, it is apparent that the electric polarity of a Seebeck cell depends on the sign of the Seebeck coefficient, but it also depends on the relative temperatures of its ends. Note that an interchange of endpoint temperatures reverses the electric polarity.

2.1.3 Inhomogeneous Thermoelements

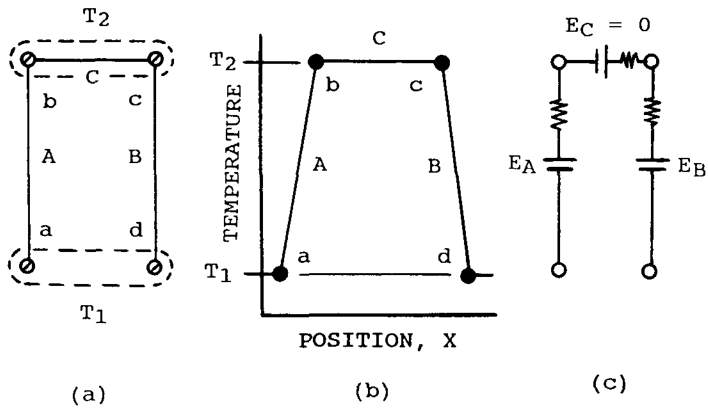
Any slender *inhomogeneous* conductor can be treated as a series-connected set of Seebeck cells, each segment of arbitrary length, each segment essentially homogeneous, each segment with its own $\sigma(T)$ relation. Effectively, an inhomogeneous conductor is a Seebeck battery (or pile) composed of series-connected Seebeck cells with different characteristics that must be considered individually. If the distribution of Seebeck coefficient and temperature along any conductor were known the net Seebeck emf across it could be calculated easily from Eq 2.6. Ordinarily, this distribution information is not known. Unfortunately, for any unknown temperature distribution around a circuit, if only the net emf from an inhomogeneous conductor is known, neither the temperature distribution, the distribution of Seebeck coefficient, nor the endpoint temperatures can be deduced. It is for this reason that an inhomogeneous thermocouple cannot be used for accurate thermometry. Recognize that *thermoelectric homogeneity is the most critical assumption made in thermocouple thermometry.*

In real materials, σ might also depend significantly on environmental variables other than temperature. Some dependences are reversible such as dependence on magnetic field, elastic strain, or pressure. Other environmental variables can produce irreversible changes to σ such as dependence on plastic strain, metallurgical phase change, transmutation, or chemical reaction. For accurate thermometry the thermocouple must be immune to or isolated from all significant variables other than temperature.

2.1.4 Relative Seebeck Characteristics

In Section 2.1.2 the basic Seebeck voltage phenomenon was described as occurring in individual materials. In this section we explain why practical thermometry uses only relative properties of paired dissimilar thermoelectric materials, we describe the nature of practical thermocouple circuits, and we distinguish the functions of the thermoelements and junctions. In Section 2.2 we will illustrate why, despite the fact that it is the relative properties that are used almost always in normal thermometry, recognition of the absolute properties is also important in practical thermometry.

Consider a pair of materials, A and B, Fig. 2.3*a*, each having one end at temperature T_2 and joined at that end to a third material, C, of any electrically conducting material and of any length. The three materials are each homogeneous. The free ends are both at T_1. Figure 2.3*b* presents the distribution of the junction temperatures, $T(X)$, from end to end along the circuit. The *position* effectively represents the important sequence in which thermoelements are connected in a circuit. We refer to such a plot as a junction-temperature/circuit-position plot (T/X plot) [*6,17,18*]. This nontraditional form of graphic presentation best reveals the momentary locations and the very important, but obscure, temperature pairings of emf sources.



(*a*) Temperature zones of the circuit.
(*b*) Junction temperature/circuit position (T/X) plot.
(*c*) *The electrical equivalent circuit.*

FIG. 2.3—*Views of the elementary thermoelectric circuits.*

The plot is for visualization only so it is drawn as a simple sketch without graphic scale. The T/X plot will be seen to be a simple but very powerful tool for thermoelectric circuit analysis. It will be used in the analysis of examples in Section 2.2. Absolute Seebeck emf, E_σ, occurs locally in each leg but only where the temperature varies along it.

Note in Fig. 2.3 that the legs A and B are not joined directly to each other in the circuit. Nevertheless, they contribute (as a pair) *all* of the net Seebeck emf as C is isothermal. The open-circuit terminal voltage, summing the emfs from terminal to terminal, is, from Eq 2.6

$$E_\sigma = \int_{T_1}^{T_2} \sigma_A(T)\, dT + \int_{T_2}^{T_2} \sigma_C(T)\, dT + \int_{T_2}^{T_1} \sigma_B(T)\, dT \tag{2.9}$$

$$E_{AB} = (E_\sigma)_A \Big|_{T_1}^{T_2} + 0 - (E_\sigma)_B \Big|_{T_1}^{T_2} \tag{2.10}$$

So long as C is isothermal it contributes no emf. In this circumstance, the net circuit emf is only the difference between the absolute Seebeck emfs of the pair of materials, A and B, that happen (at the time) to span the same temperature interval even though they are not directly joined in the circuit. At some other time, different segments of the circuit might instead be paired in opposition across the same or different temperature spans to produce the net emf.

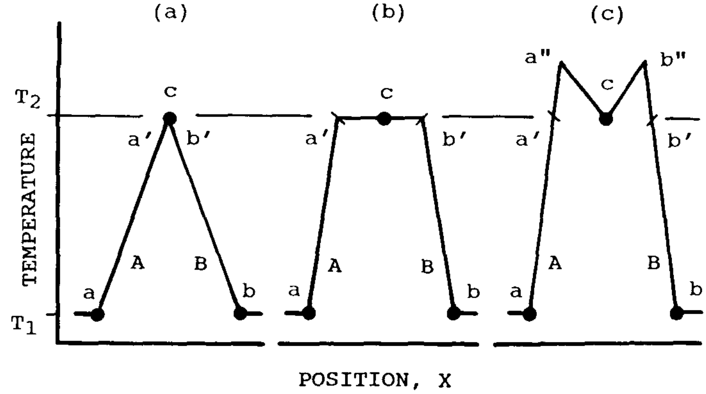
Such a net emf between a material *pair* while they share the same two endpoint temperatures is called the *relative Seebeck emf* of the pair. By convention, we denote the absolute Seebeck emf by E_σ and the relative Seebeck emf either by E alone or else, as in Eq 2.10, with subscripts that identify the particular temperature-paired materials such as A and B.

Consider the homogeneous legs as a pair of Seebeck cells (Fig. 2.3*c*). The cells are electrically in series, but this pair is necessarily in electrical opposition because of the temperature structure and their relative position in the circuit. In proceeding from one terminal of the thermocouple assembly to the other, the legs cross the temperature interval in opposite directions as the circuit is traversed proceeding from one terminal to the other. As they are in electrical opposition in the circuit, in summing, they may either augment or diminish the net voltage depending on the relative signs of their separate absolute Seebeck coefficients. If the materials are *identical,* the emf contributed by one leg is cancelled exactly by the equal emf of the opposing leg. This demonstrates why the materials of the opposing legs must be dissimilar for thermometry.

Endpoints of thermoelements define the boundaries of temperature zones spanned by each material. A practical thermocouple may consist of several different materials that define several temperature zones. More generally, it will be noted that regardless of the complexity of the circuit and whatever the temperature structure, each zone of temperature will be occupied by an even number of material segments. Where there is more than one pair of thermoelements that span the same temperature zone, the same material can cross the zone in either a complementary or in an opposing direction. Therefore, paired segments of the same material may either augment or cancel each other.

The simple T/X form of graphic presentation emphasizes that the voltage contribution of pairs of thermoelements depends only on the fact that they currently happen to span the same temperature interval, *not* that they are coupled directly to each other. It is this subtle fact that allows the preparation of tables for pairs of thermoelement materials and the ready understanding of errors that result when unintended pairings of thermoelements occurs because junction temperatures are not correctly controlled. This example illustrates the role of thermoelements in measurement; the thermoelements contribute the emf and determine the sensitivity. Then, what function do the junctions serve?

By eliminating the isothermal bridging conductor, C, with both its ends at T_2, the endpoints of A and B could be coupled at a common junction assuring that they share in common the temperature, T_2. This does not change the net emf. It is just such an assembly of only two dissimilar conducting legs electrically coupled at a common material interface, Fig. 2.4, that is properly called a *thermocouple* and each leg, that can contribute emf, is called a *thermoelement.* Practical circuits are more complex and are composed of such thermocouples. Any physical interface between dissimilar materials is called a *thermocouple junction,* a *thermojunction* or—in a solely thermoelectric context—simply a *junction.* A junction that is intended to



(*a*) Measuring junction at the highest temperature.
(*b*) Measuring junction in an isothermal region.
(*c*) Measuring junction at an intermediate temperature.

FIG. 2.4—*The basic thermocouple with different temperature distributions.*

sense a temperature that is to be determined, is called a *measuring junction.* Junctions where known temperatures are imposed as reference values are called *reference junctions.* All other junctions of a circuit that serve neither as measuring or as reference junctions are *incidental junctions.* Any physical interface between materials with different properties is a *real junction,* even though it might occur by accidental contact or as a material phase boundary introduced in service between normal and degraded portions of a thermoelement. Such incidental junctions also occur, for example, at connections between materials that have the same name but are actually slightly dissimilar.

The *interface* between materials that constitutes a *junction* should not be confused with the material *bead* that is an intermediate alloyed third dissimilar material formed incidentally in producing a junction. Actually, such a bead usually has two junctions that separate it from the pair of the adjacent thermoelements that it joins. Beads must be kept isothermal so that they can not contribute emf from the uncalibrated intermediate material of the bead. In a proper temperature measurement, the bead is intended to contribute no emf.

The actual measurement role of the *junctions* in thermometry will be now described. The emf is generated and the thermoelectric sensitivity is determined by nonisothermal segments of the legs, but it is the temperatures of thermoelement *endpoints* that determine the value of the net Seebeck emf. Junctions coincide with endpoints of thermoelements. Junction temperatures are endpoint temperatures. Junction temperatures physically define the endpoints of segments that contribute emf. Therefore, the junctions *sense* the temperature and determine which segments are thermally paired but the legs *produce* the emf.

Peculiarly, in proper measurement the endpoints of emf contributing segments nearest the junctions are usually some distance from those junctions. This is best shown by illustration on a T/X sketch. Figure 2.4 shows a simple thermocouple with three different temperature distributions.

In Fig. 2.4*a* the measuring junction temperature is *greater* than any other temperature of the thermoelements. In Fig. 2.4*b*, the junction is centered in an isothermal region, *remote* from the nonisothermal portions of the thermoelements. In Fig. 2.4*c* the junction temperature lies *below* the maximum temperature along the thermoelements. However, in applying the relation in Eq 2.6, it is clear that the net Seebeck emf is the same for each case. It is determined by the temperatures of only all the real junctions. In all these instances, it is the segments from a to a' and from b to b' that contribute all the *net* emf. Note that the positions along the circuit of endpoints of every net emf contributing segment, points such as a' and b' of Fig. 2.4*b* and *c*, are all defined by the temperatures of real junctions. These temporarily functional endpoints within a thermoelement, indicated on T/X plots by diagonal ticks across the thermoelement, can be treated as *virtual junctions* when convenient for analysis. Absolute Seebeck emf may actually occur in segments such as between a' and b'; yet, they contribute no *net* emf in this instance as their paired emfs are opposed and cancel each other. These simple illustrations of the effect of temperature structure factually depict the way that the net emf is actually produced in a practical thermoelectric circuit of any complexity.

We emphasize that the net Seebeck emf contributed by any pair of thermoelements in a series circuit, whether directly coupled to each other in the circuit or not, depends only on the fact that their two endpoints are at corresponding temperatures (that is, they simultaneously span the same temperature range). The net emf they contribute does not require that they be joined directly at a real junction in the circuit. Thermally paired segments may be remote from each other in the circuit and may even be separated by other materials that might also contribute to the net circuit Seebeck emf. Implicitly, thermocouple tables for paired elements merely presume such a temperature structure. They do not imply that thermoelements must be joined directly for the table to apply.

In a series thermoelectric circuit, such as Fig. 2.4, the net Seebeck emf from any pair of thermoelement segments of materials A and R that span the same temperature interval from T_1 to T_2, regardless of their proximity in the circuit, is

$$E = \int_{T_1}^{T_2} \sigma_A \, dt - \int_{T_1}^{T_2} \sigma_R \, dT \tag{2.11}$$

$$E = \int_{T_1}^{T_2} (\sigma_A - \sigma_R) \, dT \tag{2.12}$$

or

$$E_{AR} = \int_{T_1}^{T_2} \sigma_{AR}(T)\, dT \tag{2.13}$$

Under this specific temperature condition, where the two thermoelements share the same endpoint temperatures, we have in Eq 2.13 defined an effective Seebeck coefficient for the pair A and R as

$$\sigma_{AR} = (\sigma_A - \sigma_R) \tag{2.14}$$

This equation defines the *relative Seebeck coefficient* of material A referenced to material R so that the two characteristics can be considered jointly by a single lumped effective Seebeck coefficient for convenience. Therefore, E_{AR} is called the *relative Seebeck emf* for the temperature-paired materials. It is the relative Seebeck emf that is most commonly tabulated for practical thermometry [*22–24*]. By choice of materials that have appropriate complementary characteristics to pair for thermometry, the relative Seebeck coefficient of a pair can be designed to be larger and more nearly constant with temperature over some temperature span than that of either of the materials separately. The absolute and relative Seebeck emfs of representative individual materials are shown in Fig. 2.5. This illustrates the difference between absolute and relative properties and the possible improvement of linearity and sensitivity.

A *naming convention* is applied for the pairings of materials standardized for thermometry. The first-named material is considered to be the "positive" thermoelement of the pair with regard to the sign of their relative See-

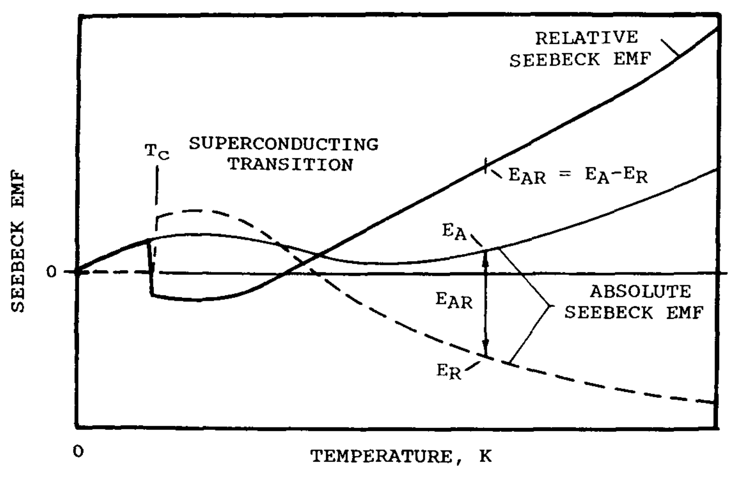


FIG. 2.5—*Comparison of absolute and relative Seebeck emfs of representative thermoelements.*

beck coefficient, as implied by Eq 2.14, over their normal temperature range of application. This arbitrary convention for a pair does not imply that the *absolute* Seebeck coefficient of either individual leg is necessarily positive as shown in Fig. 2.5.

Note again that if thermoelements A and R are thermoelectrically alike then their relative Seebeck coefficient necessarily is zero for all temperature spans. It is for this reason that the absolute Seebeck coefficient of a single material, although quite real, can not be measured using a thermocouple configuration. The usual means for experimentally determining absolute Seebeck coefficients will be described in Section 2.4.4.1.

From Eq 2.14 the absolute Seebeck coefficient of material A can be calculated from a measurement of the relative coefficient σ_{AR} and the separately known absolute Seebeck coefficient of a corresponding reference material, R, using

$$\sigma_A = \sigma_{AR} + \sigma_R \tag{2.15}$$

Note also that if the relative Seebeck coefficients of materials A and B are each known relative to the same reference material, R, that the relative coefficient of A relative to B can be calculated from

$$\sigma_{AB} = (\sigma_A - \sigma_R) - (\sigma_B - \sigma_R)$$

or

$$\sigma_{AB} = (\sigma_{AR} - \sigma_{BR}) \tag{2.16}$$

Corresponding relations exist between the absolute and relative emfs as between the absolute and relative coefficients.

Section 2.1 has presented the basic facts necessary to fully understand or to explain the functioning of any thermoelectric circuit, whether normal or abnormal, no matter how complex. These principles are general and apply equally to series circuits as used in thermometry, to parallel circuits, and to three-dimensional configurations that are sometimes encountered in general thermoelectric thermometry. Notably, these facts all follow from the single *Fundamental Law of Thermoelectric Thermometry* (Eq 2.3).

The facts presented previously concerning thermoelectric circuits and thermometry are simple and they are well proven. Once understood, they are very easy to apply either in routine or special circumstances. The general topic of thermoelectricity, on the other hand, is extremely complex. Fortunately, additional theory relates principally to why the thermoelectric effects occur, to essential relations between them, and to prediction of characteristics. No matter how sophisticated the theory or how complex the mathematics or notation, advanced thermoelectric theory and analysis contribute nothing beyond the model in Section 2.1 that is essential to the analysis and application of thermoelectric circuits to thermometry using experimentally characterized materials.

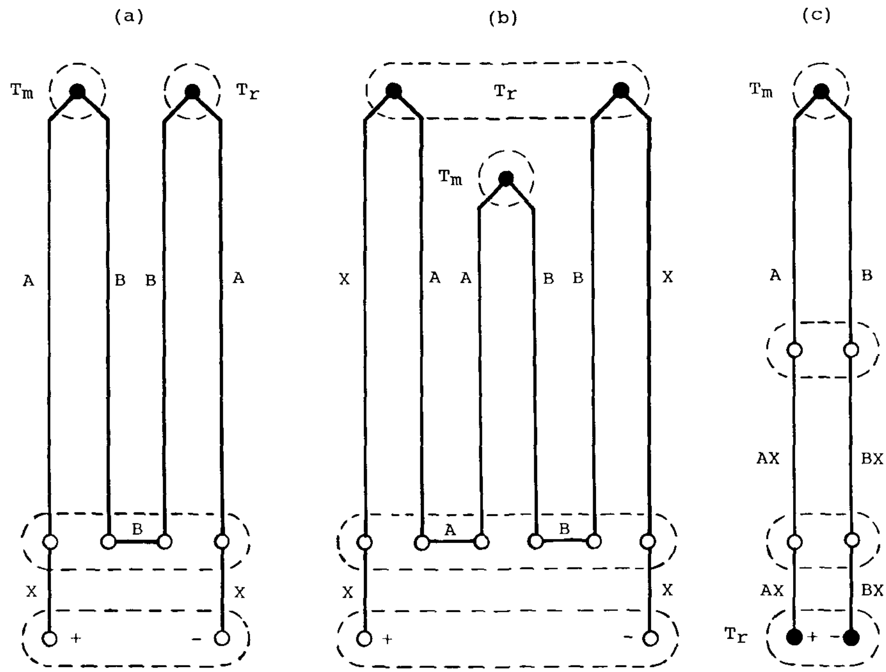
Principal facts of Section 2.1 are:

1. All thermoelectric voltage is produced by the Seebeck effect alone.
2. The Seebeck emf occurs only in the thermoelements, not in the junctions of a circuit.
3. The Seebeck emf occurs in any nonisothermal electrical conductor, whether intended or not.
4. Junctions "sense" temperature but thermoelements determine sensitivity.
5. Individual materials are characterized by absolute Seebeck properties; paired materials can be characterized by relative Seebeck characteristics.
6. Thermoelements must be homogeneous for accurate temperature measurement.
7. Thermometry is best conducted by open-circuit measurement of the Seebeck emf to avoid error or the need for correction due to resistive voltage drops that occur when current is allowed to flow in a circuit.

2.2 Analysis of Some Practical Thermoelectric Circuits

The basic thermocouple (see Fig. 2.4) consists of only two dissimilar conductors coupled at a single sensing junction. However, this elementary thermocouple is almost never used alone in practice. One of the three circuits shown in Fig. 2.6 is ordinarily used in practical thermometry. For thermometry, the terminal voltage observed must be a function of only two junction temperatures, T_m and T_r. Only one of them may be unknown. Therefore, the temperature of the measuring junction must be measured relative to the independently known *actual* temperature of one or more reference junctions. A practical thermocouple assembly adds to the basic thermocouple several other essential components. These may include reference thermocouples, short flexible "pigtail" thermoelements, lengthy extension leads, feed-throughs, terminals, and connectors. All of these, as unpowered electrical conducting elements, play an active thermoelectric role that must be considered in practical analysis. The detailed analysis, using the model of Section 2.1.3, is simple and is the same for all such elements.

Furthermore, beyond the terminals or reference junctions of the thermocouple assembly there are always other thermoelectrically active circuit components such as isothermal zone plates, reference junction compensators, relays, selector switches, filters, amplifiers, and monitoring or recording instruments. Many of these functional components may be hidden from the user within commercial instruments. Nevertheless, they are necessarily part of the thermoelectric circuit and can contribute Seebeck emf. These external components are rarely at uniform temperature. The temperature distribution across some of these varies during powered operation. They are composed of many dissimilar materials and so must be recognized as potential contributors of irrelevant Seebeck emf. Each follows exactly the same ther-



(*a*) Single reference junction thermocouple.
(*b*) Dual reference junction thermocouple circuit.
(*c*) Thermocouple with external reference junctions.

FIG. 2.6—*Thermocouple circuits for thermometry.*

moelectric law as the thermocouple. In proper systems, these spurious sources are controlled so that they do not affect measurement.

In Fig. 2.6*a* the thermocouple with its measuring junction at temperature, T_m, is complemented by an auxiliary reference thermocouple that provides a single reference junction at T_r. The reference thermocouple often is in the form of a separate metal-sheathed thermocouple probe. It is of the same nominal material type as the measuring thermocouple but usually is of a slightly different and often unconfirmed calibration.

Ordinary extension leads that are not intended as thermoelectric source elements may be used only *beyond* the reference junctions (that is, not between the measuring and reference junctions). Both of the legs, X, of any extension lead that are placed external to the thermocouple circuit and all paired elements of external connecting hardware used should be of the same nominal material type. While they often are of ordinary copper electrical wire, to minimize error they should be of at least thermocouple extension wire grade. It is desirable that they be of nominal material A or B. They should be maintained as nearly isothermal and as nearly at reference temperature as possible. This circuit is often used when the reference temperature is to be imposed by a physical fixed-point temperature reference such as an ice bath or water triple point cell or by Peltier refrigeration. The circuit may be also employed as a differential thermometer to measure approximate temperature difference, $T_m - T_r$. In this application there is no reference junction. The temperature measured is approximate to the degree that the Seebeck coefficient is nonlinear.

Figure 2.6*b* shows a common alternate thermocouple assembly form that employs two reference junctions. These reference junctions also can be in the form of separate metal-sheathed thermocouple probes. This circuit often is used with reference baths that literally impose a temperature on the reference junctions. The simpler form of Fig. 2.6*a* avoids those errors that are introduced if the two reference temperatures of Fig. 2.6*b* are not identical.

A functionally equivalent form, shown in Fig. 2.6*c*, is the most commonly used thermocouple assembly in modern practice. This circuit also has a single measuring junction and two reference junctions. In such devices, the reference junctions must both be at the same temperature. That temperature is usually different from the standard reference value of the conversion table. Ordinarily, the reference junctions are a part of a separate electronic reference junction compensator that is a part of the monitoring instrument (see Chapter 7). Corrections for the reference offset are made electrically or numerically. That reference temperature may be maintained at an accurately fixed value within the monitoring instrument, or else it may vary and be separately monitored. It should be noticed, as in these practical examples, that the *terminals* of the measuring thermocouple often are not the reference junctions of the thermoelectric circuit.

Using traditional circuit models and analysis tools, it is difficult to recognize sources of problems in such practical compound circuits that are composed of several elements (many of which may be of different and indefinite calibration). For measurement quality assurance, it is essential to be able to recognize problem areas, to evaluate the possible measurement uncertainty, and to effect controls that reduce or eliminate the error sources.

Contrary to common belief, many of these uncertainties cannot be avoided by the manufacturer nor by the most accurate calibration. The illustrations to follow clearly show some of the reasons why traceability to a primary standards laboratory of the temperature calibration of only a portion of a thermocouple assembly does not assure quality traceability nor accuracy of a temperature measurement made using it. The model presented in Section 2.1.3 allows the user to identify easily those portions of the overall circuit that otherwise might be ignored in application with a consequence of significant error.

Any portion of the external circuit that is isothermal contributes no net emf. Any portion of the external circuit that has a fixed temperature distribution during the period of measurement contributes, at most, a fixed emf that biases the voltage measurement and can be offset to avoid error. All other circuit segments must be considered as possible sources of error.

Instruments that are properly designed and operated for thermoelectric measurement compensate for many such thermal effects after a suitable warm-up period. General purpose electrical instruments, even if otherwise accurate, should not be used for thermoelectric measurement without assuring that they contribute no inappropriate thermoelectric emf under the actual conditions of measurement.

2.2.1 Example: An Ideal Thermocouple Assembly

The following practical examples are all based on the commonplace circuit as simplified in Fig. 2.6*c*. The circuit, that shows components that would often be used in practice, is shown in Fig. 2.7. The extension leads must be of either matching or compensating kind. In the three examples that follow the circuit is the same. Only the materials and temperature distribution are varied. For the purpose of illustration, it is assumed, realistically, that any signal conditioning external to the thermocouple assembly contributes no unintended net emf during measurement.

The conversion from thermocouple voltage to measuring junction temperature or *vice versa* is very simple in practice. Nevertheless, it first must be assured that the installation justifies the simple treatment. Once it is assured that every component of the circuit of Fig. 2.7 is adequately homogeneous, all components are properly arranged in the circuit, all like materials are identical in Seebeck characteristics, the temperatures of all incidental junctions are properly controlled, the actual characteristics are the same as the standardized values, and the physical reference temperature is the same as the standardized value used in analysis, the simple approach is justified.

Under this ideal condition, the determination of temperature from voltage or the prediction of voltage from temperature requires merely referring to the standard table, reading a plot, or calculating with a standardized equation (see Chapter 8) [*22–24*]. For a Type K thermocouple in the circuit, as

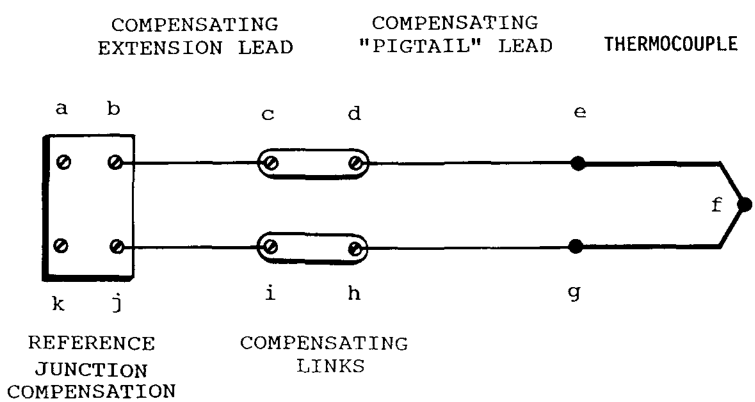


FIG. 2.7—*Typical practical thermocouple assembly.*

shown in Fig. 2.7, with measuring junction known to be at 200°C, the total emf expected is simply read from the table as 8.138 mV. This is the voltage that would occur between the terminals if they were at 0°C. But, as the terminals are actually at 20°C where connected to the monitoring instrument, the voltage at the thermocouple terminals actually would be only 7.340 mV. The voltage equivalent to 20°C (0.798 mV) would have to be added to an observed voltage to compensate for the temperature offset of the terminals relative to the table reference value of 0°C.

With a modern digital monitoring system the determination is even simpler. No more is required than to observe directly an explicit displayed number that has been reference junction compensated for the temperature reference offset, linearized, and scaled to or from temperature in any chosen units. This simple approach makes thermocouples extremely easy to apply in modern measurement. It is the usual and appropriate method of use of thermocouples that are known to be normal.

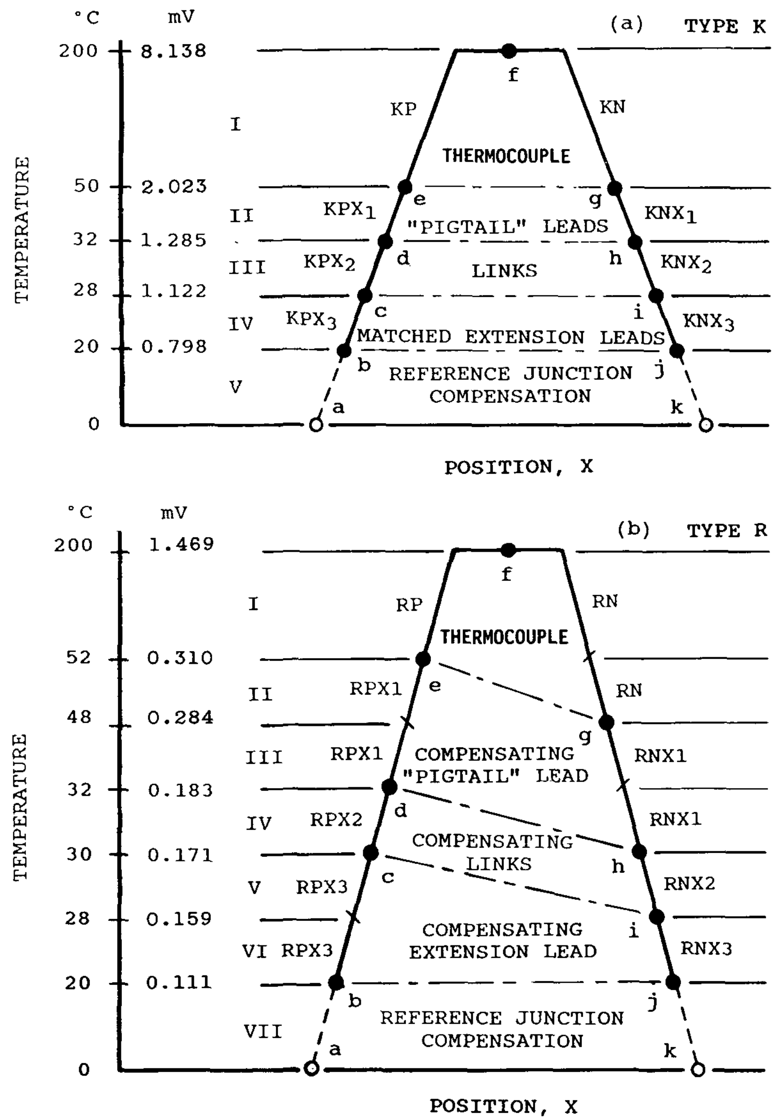
The next two examples illustrate the use of the *T/X* plot visualization to aid in the validation process [*6,17,18*]. It helps to recognize conditions that could produce error, to estimate their possible magnitude, and to allow their effect to be reduced or eliminated. The simple approach must be justified for each real thermocouple circuit as it is actually applied. Real thermocouples are imperfect. Adequate thermocouples can be misused. Initially acceptable thermocouples may degrade in application [*25*]. It is for this reason that careful experimenters will assure that the assumptions are essentially and continually fulfilled.

2.2.2 Example: A Nominal Base-Metal Thermocouple Assembly

This second example illustrates the consequence of unrecognized contributions from uncalibrated or lesser-accuracy components of the circuit. Otherwise, the circuit is normal in every way. The thermocouple assembly is of ANSI Type K thermoelement material. The thermocouple, e-f-g, is of *premium grade* calibrated Type K material. The remainder of the circuit is of standard grade ANSI Type KX extension material with the flexible "pigtail," thermocouple alloy terminal lugs, and extension cable each having slightly different Seebeck coefficients (but all presumed to be within commercial tolerance) [*24*].

A *T/X* plot sketch of a realistic temperature distribution around the circuit is shown in Fig. 2.8*a*. The measuring junction, *f*, is at 200°C. The terminals at 20°C are input to a thermocouple indicator that internally provides electrical icepoint reference compensation, linear scaling from voltage to temperature, and presentation of a digital indicated-temperature value.

Temperatures (arbitrarily assigned to the incidental junctions between circuit elements, for illustration) are noted at the left of the figures. The corresponding emfs, as read from a standard icepoint-referenced table, are



(*a*) Consequence of normal temperature distribution on elements of a nominal base-metal thermocouple circuit.
(*b*) Consequence of an improper temperature distribution on a nominal precious-metal thermocouple assembly.

FIG. 2.8—*Junction-temperature/circuit-position* (T/X) *plot used in error assessment of practical circuits.*

given beside them [*22*]. This particular distribution of junction temperatures defines five temperature zones, I through V. Each zone is bounded by temperatures of real and virtual junctions. These zones reveal a temperature-dictated actual pairing of one or more pairs of thermoelement materials. The net tabulated Seebeck emf corresponding to the 200°C temperature of the measuring junction is 8.138 mV. For this temperature distribution, as before, the net Seebeck emf between thermocouple assembly endpoint terminals b and j is $E = 8.138 - 0.798 = 7.340$ mV. This is created in Zones I through IV. The 0.798 mV emf deficiency must be provided in Zone V by the cold junction compensation of the monitoring instrument for proper direct temperature indication.

The emf increments that are generated in the five temperature zones reveal that in this normal circuit, only 75.14% of the net emf is contributed by the special grade (and accurately calibrated) thermocouple, Zone I. For this temperature distribution, uncalibrated portions of the circuit in Zones II through V actually contribute 24.86% of the total emf. The possibly lower grade (usually uncalibrated) KX material contributes 15.05% of the total (9.07% from the pigtail, 2.00% from the terminal lugs, 3.98% from the extension leads). The remaining 9.81% of the emf is added by the (usually uncalibrated) reference junction compensation of the monitoring instrument.

In this example of a normal thermocouple, note that a significant portion of the emf is from segments of indefinite uncertainty. That uncertainty is usually greater than that of the premium thermocouple. The errors can be limited by the producer-controllable tolerance of characteristics of auxiliary thermoelement components, but, as this illustrates, they can be eliminated only by the user with appropriate control of intermediate junction temperatures. The user can minimize uncertainty by properly controlling the temperatures of incidental junctions c-e and g-j all to about the same 20°C ambient temperature of the input terminals. In this circumstance, most of the emf would be accurately supplied by either the specially calibrated premium grade Type K material or else by the reference junction compensator.

Uncertainty of the measurement is affected by the uncertainty of each individual component that contributes emf. A system that includes emf contributing thermoelements of different characteristics can not be generally calibrated overall to eliminate error as the portion of the total emf contributed by each depends on the circuit temperature distribution as shown by this example.

Zone V represents the emf contribution added by the reference junction compensation. At best, this compensation can only represent the standard characteristic for nominal Type K material; it can not reproduce exactly the specific characteristic of the particular calibrated thermocouple. Applied as a hardware correction, the emf generally only approximates the standard Seebeck characteristic within a specified tolerance over a limited temperature range (usually only around room temperature).

It is customary to "calibrate" a thermocouple indicator by applying to the input terminals a voltage corresponding to the voltage that would exist at the terminals of a thermocouple of the desired type with its measuring junction at the desired calibration temperature and its output terminals at the *presumed* temperature of the indicator input terminals. Note that this does *not* actually calibrate the cold junction compensation as that calibration depends on the actual unknown temperature of the input terminals and on the temperature dependent characteristics of the internal sensor that controls the compensation.

2.2.3 Example: A Normal Precious-Metal Thermocouple Assembly with Improper Temperature Distribution

This third example illustrates a quite different source of thermocouple error from a thermocouple that also is undamaged and used within its initial tolerance. This error occurs when the user fails to properly control the *relative* temperatures of connections around the circuit. The incidental junctions (connections between nominally alike or similar but not identical materials) actually are real junctions even if not intended or recognized as such. They are associated with several compensating thermoelement segments that are individually somewhat different in their Seebeck characteristics. This can be an insidious and particularly significant source of error. This error source is particularly common in the use of precious metal, refractory, or nonstandardized thermocouple materials that often have auxiliary components such as compensating "pigtail" or extension leads.

For illustration, consider the identical circuit (Fig. 2.7), but with materials of a different kind (Type R) and only slightly modified temperature distribution as shown in Fig. 2.8*b*. The different temperature distribution introduces additional temperature zones as defined by the temperatures of the real incidental junctions. This new temperature distribution involves seven temperature zones, I through VII, each defined by the temperatures of real junctions. Here, the thermocouple element in Zones I and II is of special grade individually calibrated ANSI Type R material (Pt/Pt13Rh). The expense of special material and calibration would have been incurred only because a slight increase in accuracy was considered an important consideration.

For mechanical strength, flexibility, and economy, the extension elements might be of ANSI Type RX material. Such auxiliary thermoelements, called compensating extension leads (Chapter 3), are intended to have, *as a specially matched RX pair,* approximately the same relative Seebeck coefficient as the primary Type R thermocouple pair with which they are to be used. However, the individual positive and negative extension thermoelements usually have absolute or individual Seebeck characteristics that are very different from the corresponding thermoelement to which each is to be joined. An RX extension often consists of a copper positive extension thermoelement, RPX, paired with a negative leg, RNX, of a proprietary material (see

Chapter 3). Different forms of extension elements, such as wire, ribbon, links, feed-throughs, and connectors are unlikely to have identical Seebeck characteristics.

For illustration, suppose that the temperatures of points *e* and *g* are respectively 2°C higher and lower than in the previous example (Fig. 2.8*a*). Observe that this introduces a temperature band, Zone II, over which a segment of the RPX (equivalent to copper, TP) "pigtail" compensating thermoelement is wrongly paired with the RN (platinum) primary thermoelement. Fortunately, the emf from this unintended pairing of TP and RN thermoelements, mismatched by improper temperature distribution of incidental real junctions, can be determined directly from some existing thermocouple tables for the relative Seebeck emf of individual thermoelements against platinum [*22–24*]. Such nonstandard pairings can be also treated conveniently using the absolute Seebeck emfs of each paired element though the necessary information is not as readily available [*19–21*]. In this example, the temperature interval spanned by the improper pair in Zone II is 4°C (from 48 to 52°C.) The emf contribution over this interval is 0.031 mV (0.357 to 0.326 mV) for the improper TP/RN pairing compared to 0.026 mV (0.310 to 0.284 mV) for the intended RP/RN pairing. Fortunately, the 0.005 mV increase in emf raises the indicated temperature by only 0.57°C in this particular example. For this direction of temperature offset and for this pair of materials, the error in indicated temperature happens to be smaller by a factor of 7 than the 4°C junction discrepancy. However, the offset could be also magnified if the temperatures of the two incidental junctions were reversed or if the thermoelement materials were different.

Another common error can occur if a pair of simple copper terminal links are used instead of paired compensating thermoelement material as in Zones IV and V. In this example, it would substitute, in Zone V, a null emf for the normal 0.012 mV contribution from this zone (28 to 30°C) reducing the temperature indication to 199.2°C. This produces a total error, in addition to tolerance uncertainty, of 0.8°C from a circuit for which the special initial tolerance on the primary thermocouple is 0.6°C. The unnoticed misuse of links of incorrect material would have cancelled the benefit of premium material.

Zones IV and VI pair thermoelements that are of the proper nominal kind but for which the thermoelements probably are not matched as a pair. As thermoelectric compensating leads, if from different sources, they might actually have very different Seebeck characteristics. In all instances, the stated tolerances would not apply for such arbitrary pairings of materials not intended for use together. The tolerances would be indefinite. Only Zones I, III, and VI correctly pair materials as they were intended for use. And, as in the previous example, Zones II and IV pair materials of broader tolerance than for the primary thermocouple. These examples illustrate why, for the most accurate measurement, it is recommended that the primary thermocouple material extend continuously from measuring to reference junctions.

Frequently this is not possible so error must be avoided by maintaining incidental junctions all at nearly the same temperature.

Commonplace errors such as these usually go undetected and in many casual applications they are insignificant. However, in accurate applications they may be very significant. Also, for inappropriate pairing of arbitrary materials the errors are often very much larger than those shown here. Even significant errors may not be obvious in temperature records. Recognize that they cannot be avoided by calibration. They can be reduced only by careful application by the user. In fact, calibration may indirectly cause them to be overlooked because the user may inappropriately rely on certification alone as an assurance of accuracy. But, such errors are easily avoided if the circuit is properly viewed using a model as presented here and if temperatures are properly controlled. A simple T/X plot sketch is used as a visualization tool and temperatures of incidental junctions are controlled as necessary.

These examples in Section 2.2 are for realistic situations often encountered even with normal undamaged and carefully calibrated thermocouples. Many situations are more extreme. The benefit of expensive special grade material and calibration can be completely nullified by portions of the circuit that appear to function merely as ordinary electrical leadwires yet actually are normal, but unintended, sources of Seebeck emf.

The examples are realistic, yet actual thermoelectric circuits often are much more complex. The analysis for circuits of any complexity is just as direct. The analysis approach applied here is even more valuable as a means of detecting or estimating plausible error from circuits that are subject to damage or degradation in fabrication or use. The measurement consequences of plausible degradation of one or more thermoelements can be easily evaluated in experiment planning, in monitoring during measurement, or in later interpretation of suspect data [25]. Once understood, this approach to circuit analysis is intuitive and is performed informally as a tool of measurement verification. Only in unusual instances of complex or suspect circuits is it necessary to apply the technique formally and quantitatively.

Section 2.2 has illustrated the practical application of the circuit model and its T/X plot in the error analysis of a thermoelectric measurement circuit that is most often used in industry. The examples of sources of errors revealed has suggested the kind and magnitude of typical errors. They have pointed up areas to consider in order to reduce or eliminate thermoelectric error in measurement. Errors usually involve improper control of the temperature of reference and incidental real junctions or failure to recognize uncalibrated materials that contribute a significant fraction of the observed emf. To visualize and analyze such problems, it is most convenient to use the T/X plot as a simple sketch and, where necessary, the absolute rather than relative Seebeck material properties. As evident from a T/X plot that showed only small deviations from expected temperatures, failure to recognize and control the temperatures of incidental real junctions often causes an unrecognized, unintended, and nonstandard pairing of thermoelement materials. Of course, the temperatures of incidental junctions will not usually be accurately known, but the significance of plausible temperature offsets can be easily estimated by assigning credible temperature deviations to all real junctions.

The preceding sections, 2.1 and 2.2, provide an authentic conceptual model that should help the careful user, simply by recognition of problem areas, easily to avoid much of the thermoelectric error in practical thermometry. With that model in mind, the reader is better equipped to measure temperature with thermocouples and also to better appreciate the significance of the specific facts presented in the chapters to follow.

For those readers who continue to study the background material in the remainder of the present chapter, the model may be also helpful. With the model of Section 2.1.3 in mind, the interested reader may better appreciate the conceptual problems faced by those pioneers who first recognized the thermoelectric effects and may better visualize the special conditions to which the more complex thermoelectric theory relates.

2.3 Historic Background

At the discovery of thermoelectricity its nature was misunderstood. This is not surprising (it is more surprising that the true functional nature of thermocouples is so widely misunderstood even today). Even the now familiar elementary concepts of voltage, current, and resistance were not yet clearly formulated in 1821 when thermoelectricity was discovered [*26*]. In fact, the Seebeck effect provided the electric current source that later helped to clarify some of these basic electric concepts during their development. However, the substance of rules to be presented in Section 2.4.1 was first understood and expressed informally by authors no later than 1850.

The three thermoelectric effects were recognized over a span of about thirty-five years. The novel discovery that eventually led to the recognition of thermoelectricity was first disclosed in 1786 and published in book form in 1791. Luigi Galvani noticed that the nerve and muscle of a dissected frog contracted abruptly when placed between dissimilar metal probes. Alessandro Volta, in 1793, concluded that the electricity which caused Galvani's frog to twitch was due to the interaction of the tissue with metals that were dissimilar. This observation, though not of the Seebeck effect, eventually did lead indirectly to the principle of the thermocouple that also uses dissimilar conductors (but in a quite different way) to create an emf as a measure of temperature.

Pioneers of thermoelectricity built on Volta's observation. The discoveries by Thomas Johann Seebeck (1821), Jean Charles Althanese Peltier

(1834), and William Thomson (1848, 1854) are indirect descendents of Galvani's discovery decades before. During this same brief technologic epoch many familiar basic concepts of physics were first formulated: Jean Baptiste Joseph Fourier published his basic heat conduction equation (1821), Georg Simon Ohm discovered his equation for electrical conduction (1826), James Prescott Joule found the principle of the first law of thermodynamics and the important Joule (I^2R) heating effect (1840–1848), and Rudolph Emanuel Clausius announced the principle of the second law of thermodynamics and introduced the concept of entropy (1850). This productive period provided the conceptual insights that allow us now easily to understand the simple thermoelectric principles today.

2.3.1 The Seebeck Effect

The Seebeck effect concerns the conversion of thermal energy into electrical energy. The Seebeck emf is any electric potential difference that results from nonuniform temperature distribution in conducting materials not subject to a magnetic field. Seebeck discovered the electrical aspect of thermoelectricity while attempting to extend the work of Volta and to develop a dry electromotive cell using combinations of metals [*27*].

In his experiments, in 1821 Seebeck noticed that when connections between dry dissimilar metals forming a closed circuit were exposed to different temperatures a magnetized needle suspended near the circuit was deflected. His friend, Hans Christian Oersted, immediately recognized (from his own recent discovery in 1820) that the needle was moved by a magnetic field that resulted from an electric current generated in the wires of the closed circuit by the previously unrecognized thermal effect. Seebeck always rejected that correct explanation. Nevertheless, his discovery of the electrical aspect of thermoelectricity eventually led to the use of the thermocouple for thermometry.

Superficially, as observed by Seebeck and as now often incorrectly described, the essential nature of the Seebeck effect wrongly appears to be the occurrence of thermoelectric *current* in *closed* circuits and it appears to occur only when dissimilar materials are *joined*. Now, however, with the understanding of modern physics, it is recognized that the Seebeck effect, most fundamentally, is a voltaic, rather than a current, phenomenon and that it occurs in individual materials apart from circuits. The Seebeck emf universally occurs, though it is not readily observable, in individual open-circuited conducting materials even in the absence of current. It is *not* a junction phenomenon [*18*]. It is *not* a contact potential [*18*]. The external effect observed in either open or closed circuits of two or more dissimilar materials is simply the net value of absolute Seebeck emfs from segments of dissimilar legs of the circuit as described in Section 2.1.3. The strength of the effect is expressed by the Seebeck coefficient, σ, that relates emf to temperature difference. The Seebeck effect is the only thermoelectric effect that produces a voltage. The two other thermoelectric effects describe heat transport by electrical current driven by the Seebeck emf or else by external applied emf. The Seebeck effect is the only heat-to-electricity effect and the only thermoelectric effect that occurs without electrical current.

2.3.2 The Peltier Effect

J. C. A. Peltier, in 1834, discovered novel cooling and heating effects when he introduced large external electric currents in a bismuth-antimony thermocouple [*28*]. When he passed, from an external source, an electric current in one direction through an interface between two dissimilar metals, the immediate vicinity of that interface was cooled and absorbed heat from its surroundings. When the direction of the current was reversed through that interface, the same junction was heated and released heat to its cooler surroundings. Remarkably, the sense of the heat exchange depended on the direction of the electric current through the interface relative to the dissimilar materials.

The Peltier effect, the second discovered of the three thermoelectric effects, concerns the reversible evolution or absorption of heat that takes place when an electric current crosses an abrupt interface between two dissimilar metals or an isothermal gradient of Seebeck property. This Peltier effect takes place whether the current is introduced by an external source or is weakly induced by the Seebeck emf of the thermocouple itself. The rate of Peltier heat transport was found to be proportional to the current (no electric current, no Peltier heat exchange), so that

$$dQ_\pi = \pi I\, dt \tag{2.17}$$

where π is a coefficient of proportionality known as the *Peltier coefficient.* As with the Seebeck coefficient, the Peltier coefficient is an inherent transport property of an individual material, not an intrinsic property of an interface. Unlike the Seebeck effect, the Peltier heat transfer *is* localized to an interface between dissimilar materials where the different thermoelectric heat transport properties of materials on either side of the interface locally change the rate at which heat can be transported along the conductor requiring heat to be absorbed from or dissipated to its environment.

Although the physical dimensions of the Peltier coefficient can be expressed in physical units equivalent to volts, the Peltier effect concerns only heat exchange and does *not* have the nature of an emf [*8*]. The direction and the magnitude of the Peltier heat exchange at an interface between dissimilar materials depends on the direction of electric current across the interface and on the difference between the Peltier coefficients of the materials joined at the junction, quite independent of the temperature of other junctions.

The Peltier effect is relevant to thermocouple thermometry only in the sense that for thermocouple circuits in which current is allowed to flow, a (usually insignificant) Peltier heating or cooling at the junction may slightly perturb the temperature being measured. The Peltier effect, with significant externally supplied current, is used also in thermoelectric refrigerators that can be used to apply controlled temperatures to thermocouple reference junctions.

2.3.3 The Thomson Effect

The Thomson effect concerns the reversible evolution, or absorption, of heat that occurs wherever an electric current traverses a temperature gradient along a single homogeneous conductor regardless of whether the current is supplied externally or is induced by the thermocouple itself. Like the Seebeck effect, the Thomson effect occurs along the legs of the thermoelectric circuit and is associated with temperature gradients. Unlike the Seebeck effect, the Thomson effect concerns only heat exchange, not voltage.

William Thomson (Lord Kelvin) predicted, and eventually demonstrated, the third thermoelectric effect and showed that the Seebeck coefficient and the Peltier coefficient are related by an absolute temperature on Kelvin's linear thermodynamic temperature scale that he introduced in 1848 [*29*]. Thomson also concluded that an electric current produces different thermal effects, depending upon the direction of its passage through a temperature gradient, from hot to cold or from cold to hot, in a homogeneous electrically conducting material [*30,31*]. The strength of this effect is described by the *Thomson coefficient,* τ.

Concerned with demonstrating thermodynamic relationships, not with thermometry, Thomson considered the most elementary thermoelectric closed circuit consisting of only two dissimilar materials joined at both ends. The two junctions were placed at different temperatures. This created temperature gradients along the two legs. He considered the energy relations in the closed circuit where the only electric current was created by the Seebeck emf arising from the temperature difference alone.

Thomson applied the (then) new principles of thermodynamics to this thermoelectric circuit. He deliberately disregarded the irreversible Joule (I^2R) and the conduction-heat processes. He reasoned that if the thermoelectrically induced current produced only reversible Peltier heating effects at the junctions then the net energy of the Peltier heat effect should be linearly proportional to the temperature difference between junctions of the thermocouple. This reasoning implied that the thermoelectric emf should be linearly proportional to the temperature difference. However, by all observations, the relation was known to be nonlinear (Becquerel had by 1823 already discovered a thermoelectric neutral point, that is, $\Delta E_{\sigma}/\Delta T = 0$, for an iron-copper couple at about 280°C [*31*]. Thomson started his thermodynamic reasoning from Becquerel's observation). Thomson concluded that the net Peltier heat is not the only heat exchange in a closed thermocouple circuit where the Seebeck emf is the only source of current. Rather that a single conductor itself, wherever it is exposed to a longitudinal temperature gradient, must be also the site of heat exchange.

The rate at which Thomson heat is absorbed, or generated, in a unit volume of a homogeneous conductor is proportional to the temperature difference across it and, like the Peltier effect, is proportional to the electric current, that is

$$dQ_\tau = \left(\int \tau \, dT\right) I \, dt \tag{2.18}$$

Thomson referred to τ (his σ) as the specific heat of electricity because of an analogy between τ and the specific heat, c, of thermodynamics. Note that τ represents the rate at which heat is absorbed, or evolved, per unit temperature difference per unit current, whereas c represents the heat transfer per unit temperature per unit mass. The units of the Thomson coefficient can be represented as volts per unit difference in temperature. But, as with the Peltier effect, the Thomson effect has the physical nature of heat transport rather than voltage. Also, as with the Peltier effect, no current, no Thomson effect.

Long after making his prediction, Thomson succeeded in indirectly demonstrating the existence of his predicted heat exchange. He sent an external electric current through a closed circuit formed of a single homogeneous conductor that he subjected to a temperature gradient and found the I^2R heat local to the gradient region be augmented slightly or else diminished by the reversible Thomson heat in proceeding from cold to hot or from hot to cold, depending upon the direction of the current, the sign of the temperature gradient, and the material under test.

The Thomson effect is of practical interest in thermoelectric thermometry primarily because it now allows, through the Kelvin relations (Section 2.4.4.1), the indirect experimental determination of the absolute Seebeck and Peltier coefficients of individual materials. The Thomson effect produces no emf.

2.4 Elementary Theory of the Thermoelectric Effects

Two aspects of theory affect thermoelectric thermometry. Theory can be used simply to assure that experimental observations are consistent with basic physical law. Theory also can be used to explain why the effects occur, to describe the mechanisms, predict magnitudes, and to lead to improved thermometric materials.

Particularly over the past half century it has been customary to base the practice of thermocouple thermometry on empirical "laws" that were tested for validity against thermodynamic theory. More recently, physical theory has advanced to provide qualitative explanations of the reasons that the effects occur and, in many instances, accurate quantitative predictions of the magnitude of thermoelectric properties [*17,18*].

2.4.1 Traditional "Laws" of Thermoelectric Circuits

Empirical rules concerning the electrical behavior of thermoelectric circuits were first proposed by Seebeck, Magnus, and Becquerel over a period of decades [*27,32,33*]. These individual rules were first widely treated as independent operational principles. Experimentally recognized before 1852, each was justified eventually on the basis of thermodynamic theory, and all of them were confirmed by extensive experimental evidence. The thermodynamic justification of all of them was suggested by Kelvin. They were treated in detail by Bridgman [*34*].

The traditional principles have been expressed in several equivalent ways. However, they were apparently first codified as a formal set that were identified as necessary and sufficient "laws" by Roesser [*35*]. His statement of the laws (italics added for emphasis) was:

2.4.1.1 The "Law" of Homogeneous Metals—

"A thermoelectric *current* cannot be sustained in a circuit of a *single* homogeneous material, however varying in cross-section, by the application of heat alone."

2.4.1.2 The "Law" of Intermediate Metals—

"The algebraic *sum* of the thermoelectromotive forces in a circuit composed of any number of dissimilar materials is *zero* if all of the circuit is at a *uniform temperature.*"

2.4.1.3 The "Law" of Successive or Intermediate Temperatures—

"If *two* dissimilar homogeneous metals produce a thermal emf of E_1, when the junctions are at temperatures T_1 and T_2, and a thermal emf of E_2, when the junctions are at T_2 and T_3, the emf generated when the junctions are at T_1 and T_3, will be $E_1 + E_2$."

These principles, presented as laws, were immediately accepted by the thermometry community and, since Roesser's paper, have been applied universally as independent thermodynamically based laws that provide a necessary and sufficient technical basis for thermoelectric thermometry. In fact, these laws are simply corollaries of the single simple *Fundamental Law of*

Thermoelectric Thermometry expressed in Section 2.1 by Eq 2.3. It is often proclaimed correctly that these laws have never been challenged successfully by theory nor contradicted by valid experiment.

While the basis for the laws is thermodynamically sound they express no more than is evident from Eq 2.16. In the form they are expressed, the traditional laws conceal more than they reveal about the behavior of practical thermoelectric circuits. They are expressed obliquely in terms that misdirect the attention from essentials relevant to thermometry. They are overly restrictive. The electric current variable that is not directly relevant to practical thermometry is emphasized. The existence of absolute Seebeck emf is concealed. Circuits of more than two emf contributing thermoelements effectively are not addressed. The very important hidden significance of the laws is exposed more often by supplementary comment than by their direct wording (Section 2.1.2.2) [*36*].

2.4.2 The Mechanisms of Thermoelectricity

Why the simple facts required for thermoelectric practice are true is explained in more detail in the following sections for those who appreciate such background. While not absolutely essential to reliable thermocouple thermometry, an understanding of why the simple facts happen to be true is valued by many users who are not satisfied with mere assertions of facts.

Thermoelectricity is generally well understood although, even now, not all experimentally observed characteristics of some materials are well explained by theory, almost two centuries after the discovery of thermoelectric phenomena. The general topic of thermoelectricity has served as a proof subject for a variety of scientific fields. Accurate representation and prediction of thermoelectric characteristics has confirmed theories in many related scientific areas. Thermoelectricity is explained from very different perspectives and with varying degrees of success by thermodynamics, transport theory, solid state physics, physical chemistry, and others. Much of this theory is not directly related to thermometry. However, some elementary aspects of theory are directly useful in temperature measurement. In this section we present only the more relevant features of elementary theory that have a direct bearing on applied thermometry as practiced above the deep cryogenic region in the most common temperature range of measurement.

The traditional laws describe what happens in a thermocouple circuit and they provide practical rules of functional behavior. The Fundamental Law of Thermoelectric Thermometry expresses the same essentials more concisely. Yet these approaches merely assert facts; they do not describe why or how the effects occur. A simple description is given here. Details of the process are complex and are described elsewhere [*7–18*].

Consider, first, the Seebeck effect. In grossly simplified terms, a conducting material is represented as containing a collection of free conduction electrons distributed over the volume of the body and each is associated with its electrical charge. In a statistical sense, the electrons, and so the charges, are distributed uniformly throughout the volume if the body is homogeneous, isothermal, and not subjected to a significant magnetic field or significant mechanical load.

However, the distribution of the relative density of charge throughout a particular conductor depends on the temperature distribution. If the body temperature is nonuniform, charge is concentrated in some regions and rarefied in others. The uneven charge distribution produces a corresponding nonuniform equilibrium distribution of electrical potential throughout the body. For example, if the body is in the form of a homogeneous slender wire a nonuniform longitudinal temperature distribution results in a variation of electrical potential along the wire. If the two ends of the wire are at different temperatures there necessarily will exist a net potential difference between the endpoints. Any emf produced only by nonuniform temperature distribution in such a homogeneous electrically conducting body is the Seebeck emf.

If the free ends of that wire are then joined electrically to form a circuit the temperatures of those joined ends are forced to be the same and, following a very brief transition interval, the charge distribution will equilibrate to a new static distribution. Only during the very brief interval while equilibrium is being established is there statistically a net motion of the charge that constitutes a transient Seebeck current. In the closed nonisothermal homogeneous material circuit at equilibrium there is a nonuniform distribution of charge but no net charge motion and, therefore, no steady-state Seebeck current. The transient temperature state is not well addressed by equilibrium thermodynamics, and the equilibrium thermoelectric state in a single homogeneous circuit is of only incidental thermodynamic interest and is of no benefit in thermometry.

If two slender homogeneous dissimilar conducting materials are joined only at one of their ends and the junction and terminals are maintained at different temperatures then there persists a continual potential difference between the ends of each of the legs (*but not current* so neither Thomson nor Peltier effects occur) and generally there will be a difference between the net potentials between the separate ends of the two legs. It is this net equilibrium open-circuit Seebeck potential difference that is best used in thermometry.

If the free ends of the two dissimilar materials are then joined and the temperatures of the material endpoints are maintained at different temperatures by a continuous supply of heat, a Seebeck current will persist in the closed electrical circuit. That electrical current, a net drift of charge, is sustained by the heat energy supplied from an external source to maintain the two temperatures. It is this heat exchange and Seebeck current that was first noticed and that most interests the thermodynamicist. However, the closed circuit condition where significant current is allowed should be avoided in thermometry as it usually introduces error.

2.4.3 The Thermodynamics of Thermoelectricity

2.4.3.1 The Kelvin Relations—Willam Thomson analyzed a closed circuit of only two dissimilar materials. By neglecting the Joule and heat conduction effects, external current sources and magnetic fields, Thomson arrived at the net rate of absorption of heat required by a simple thermoelectric circuit of two dissimilar materials to maintain equilibrium in the presence of its own Seebeck current

$$q = \frac{Q_{\text{net}}}{\Delta T} = \left(\pi_2 - \pi_1 + \int_{T_1}^{T_2} (\tau_A - \tau_B)\, dT\right) I = E_\sigma I \qquad (2.19)$$

This is in accord with the first law of thermodynamics, according to which heat and work are mutually convertible. Thus, the net heat absorbed must equal the work accomplished or an energy balance requires that

$$dE_\sigma = d\pi + (\tau_A - \tau_B)\, dT \qquad (2.20)$$

Regrettably, this valid energy relation between coefficients expressed by Thomson and conditioned on his assumptions has sometimes been misinterpreted to incorrectly assert that the Seebeck emf is the result of and consists of the sum of four discrete sources of emf, two "Peltier emf" sources localized at the junctions and two "Thomson emf" sources distributed along the legs in regions of thermal gradients.

The latter "emfs" do not physically exist [*8,18*]. Considering them as virtual emfs, by convention, is merely confusing. It serves no purpose in thermometry. While the equilibrium thermodynamic relation expressed between coefficients correctly reflects the necessary conservation of energy, the physical interpretation extended to imply emf source locations is not. The source emf is due solely to the Seebeck effect described in Section 2.4.2, and its location is described by that section and by the model in Section 2.1.3.

Assuming thermodynamic reversibility, the second law of thermodynamics may be applied also to the closed thermoelectric circuit, the entropy change again being considered, as

$$\Delta S_{\text{rev}} = \sum \frac{\Delta Q}{T} = 0 \qquad (2.21)$$

where ΔQ implies the various components of the net heat absorbed (that is, the components of E_σ), and T is the absolute temperature (temperature measured on the linear Kelvin Thermodynamic Temperature Scale) at which the heat is transferred across the system boundaries. Equation 2.21 can be expressed in the differential form

$$dS_{\text{rev}} = d\left(\frac{\pi}{T}\right) + \frac{(\tau_A - \tau_B)}{T}\,dT = 0 \tag{2.22}$$

Combining the differential expressions for the first and second laws of thermodynamics, we obtain the very important Kelvin relations, in terms of the absolute temperature

$$\pi_{AB} = T\left(\frac{dE_{AB}}{dT}\right) \tag{2.23}$$

or

$$\pi_{AB} = T\sigma_{AB} \tag{2.24}$$

and

$$(\tau_A - \tau_B) = -T\left(\frac{d^2E_{AB}}{dT^2}\right)_{AB} \tag{2.25}$$

or

$$(\tau_A - \tau_B) = -T\left(\frac{d\sigma_{AB}}{dT}\right)_{AB} \tag{2.26}$$

from which we can determine σ, π, and $\Delta\tau$, when E_{AB} is known as a function of T.

Lord Kelvin, for thermodynamic demonstration, expressed his relations in terms of relative properties between pairs of materials. However, they apply correspondingly to absolute intrinsic transport properties of an individual conducting material, A, so that also

$$\pi_A = T\sigma_A \tag{2.27}$$

and

$$\tau_A = -T\left(\frac{d\sigma_A}{dT}\right) \tag{2.28}$$

The three thermoelectric coefficients are interrelated. If any one of the coefficients is known, the other two can be calculated. Thus, the Seebeck coefficient can be expressed in terms of either the Peltier or the Thomson coefficient

$$\sigma_A = \frac{\pi_A}{T} = -\int_0^T \frac{\tau_A}{T_{\text{abs}}}\,dT \tag{2.29}$$

The Thomson coefficient must be known from 0 K to allow the evaluation. Thomson first recognized the relationships, but it was Borelius who first performed a detailed measurement of $\tau(T)$ and used that measurement to determine $\sigma(T)$ for lead (Pb) [*37*].

Even now, the experimental determination of $\tau(T)$ is not easy. It requires specialized equipment and very careful technique. William Thomson labored for years in his eventually successful attempt merely to confirm his theory. Modern technology has made the task much easier so that the measurement of the Thomson coefficient for a variety of reference materials has been performed by many workers in especially equipped laboratories to deduce the absolute Seebeck properties [*19–21*].

Equation 2.29 can be integrated relative to T to determine the absolute thermoelectric emf[5] that occurs in the individual material, so that

$$E_\sigma = \int_0^T \sigma_A\, dT = \int_0^T \frac{\pi_A}{T}\, dT = -\int_0^T \int_0^T \frac{\tau_A}{T}\, dT \qquad (2.30)$$

In this manual, the absolute thermoelectric emf described by these three alternate equations has been termed the absolute Seebeck emf (see Section 2.1.2). The Thomson coefficient measurement is often motivated by a need to know the absolute Seebeck coefficient or the absolute Peltier coefficient that are of more general applied interest. Reliable values for the absolute Seebeck coefficient experimentally obtained through the Thomson coefficient and Eq 2.29 are now available for many reference materials [*19–22*]. Because the temperature, 0 K, can be merely approached, the measurement can be subject to very slight uncertainty near that crucial limiting temperature except for superconducting materials that are thermoelectrically inactive below some critical temperature that is well above 0 K.

However, once reliable measurements of the Thomson coefficient (and the absolute Seebeck and Peltier coefficients deduced from it) are available for any suitable reference material up to a temperature of interest, then routine and simple measurements of the three absolute coefficients can be made for any other material by simple relative thermocouple measurement and application of Eq 2.15.

2.4.3.2 The Onsager Relations—It has been noted previously that Thomson's analysis deliberately ignored the possible effect of irreversible I^2R Joule heat and Fourier heat conduction. The Kelvin relations could not

[5] As the Kelvin relationships and Eq 2.30 show, the absolute thermoelectric Seebeck emf can be expressed alternately in terms of either the Seebeck, Thomson, or Peltier coefficients. Because it is the Thomson coefficient that can be *measured* most readily, at least one author has rationally chosen to refer to the absolute thermoelectric emf of Eq 2.30 as the Thomson emf. Regrettably, some other authors have assigned a very different and invalid physical meaning to the term Thomson emf. Many authors who have addressed the absolute thermoelectric emf in the physical literature have used the term absolute Seebeck emf. Most seem to agree that Peltier and Thomson effects are only heat effects. The usage of Seebeck to identify both thermoelectric emf and coefficient is consistent with parallel terminology of the Peltier and Thomson heat effects. Therefore, this manual encourages the use of "Seebeck emf" and discourages the term "Thomson emf" even where it has been used synonymously.

follow from the reversible thermodynamic theory available to Thomson without these assumptions. He required the assumptions in order to arrive at the useful and experimentally confirmed Kelvin relations. Present day irreversible thermodynamics, through reciprocity relations later developed by the American chemist Lars Onsager in 1931, eventually justified Thomson's assumptions [*7,8*]. With their modern assurance that the Kelvin relations are thermodynamically sound, the Onsager relations have fulfilled the practical needs of thermoelectric thermometry. The very important Onsager relations and their application to thermoelectricity have been described extensively elsewhere [*7–18*]. However, as they have no further direct application in applied thermoelectric thermometry, the interested reader is directed to those references for further detail.

2.5 Summary of Chapter 2

The elementary theory of thermoelectricity presented here is intended only to provide some technical assurance to the user that the circuit model of Section 2.1, though simple, is physically based and is authentic. The scientific literature contains many physically and mathematically rigorous and detailed treatments of thermoelectricity presented from the distinctive and advanced viewpoints of a number of disciplines. Unfortunately, to nonspecialists in those fields they may be cryptic and perhaps even intimidating. Occasional misconceptions, misleading statements, and contrary terminology, as well as inconsistencies with alternate treatments, often appear in even the most advanced works. The approach presented here may help the reader to read critically both theoretical and applied publications.

Chapter 2 has presented the basic principles and explanations needed to perform thermoelectric thermometry with justified assurance. Thermocouple measurements reported in both the research and applications literature are sometimes invalid because they are based on a misunderstanding of the manner in which thermocouples actually function. Unfortunately, the experimental detail needed to recognize such error is not often reported. Subtle errors sometimes pass unrecognized. The model presented in Chapter 2 is as helpful in recognizing possible published errors and in evaluating the plausibility of results published in the literature as it is in performing reliable measurements.

Because the presentation in Chapter 2 is not traditional, some unfamiliar concepts may at first seem complicated. To some experienced thermocouple users who have not recognized error sources, the general treatment may seem unnecessarily detailed. It is not. The T/X plot is applied most often as a very simple tool for visualization of potential problems or for error analysis instead of for conversion of temperature to emf. The approach used here can be as simple as is justified by the particular thermometry application.

To other readers, the approach may even be contrary to their prior understanding. Indeed, it is contrary to a significant fraction of explanations in the current casual technical literature. Nevertheless, the principles are simple, they are practical, they are factual, and they are very easy to apply to the most complex circuits, once understood.

2.6 References

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2.7 Nomenclature

Roman

$a,b,c \ldots k$	Circuit locations
A,B,C,R	Thermoelement materials
E	Electric potential
I	Electric current
Q	Heat
S	Entropy
t	Time
T	Temperature
X	Position around circuit

Subscripts

A,B,C,R	Thermocouple materials
a,b,c,d	General subscripts
R	Reference

rev Reversible
1,2 States
π Peltier
σ Seebeck
τ Thomson

Greek

Δ,δ Finite difference
π Peltier coefficient
σ Seebeck coefficient
τ Thomson coefficient

Chapter 3—Thermocouple Materials

3.1 Common Thermocouple Types

The commonly used thermocouple types are identified by letter designations originally assigned by the Instrument Society of America (ISA) and adopted as an American Standard in ANSI MC 96.1. This chapter covers general application data on the atmospheres in which each thermocouple type can be used, recommended temperature ranges, limitations, etc. Physical and thermoelectric properties of the thermoelement materials used in each of these thermocouple types are also presented in this section.

The following thermocouple types are included (these are defined as having the emf-temperature relationship given in the corresponding letter-designated Table in Chapter 10 within the limits of error specified in Table 10.1 of that chapter):

Type T–Copper (+) versus nickel-45% copper (−).
Type J–Iron (+) versus nickel-45% copper (−).
Type E–Nickel-10% chromium (+) nickel-45% copper (−).
Type K–Nickel-10% chromium (+) versus nickel-5% aluminum and silicon (−).
Type N–Nickel-14% chromium-1½% silicon (+) versus nickel-4½% silicon-⅒% magnesium (−).
Type R–Platinum-13% rhodium (+) versus platinum (−).
Type S–Platinum-10% rhodium (+) versus platinum (−).
Type B–Platinum-30% rhodium (+) versus platinum-6% rhodium (−).

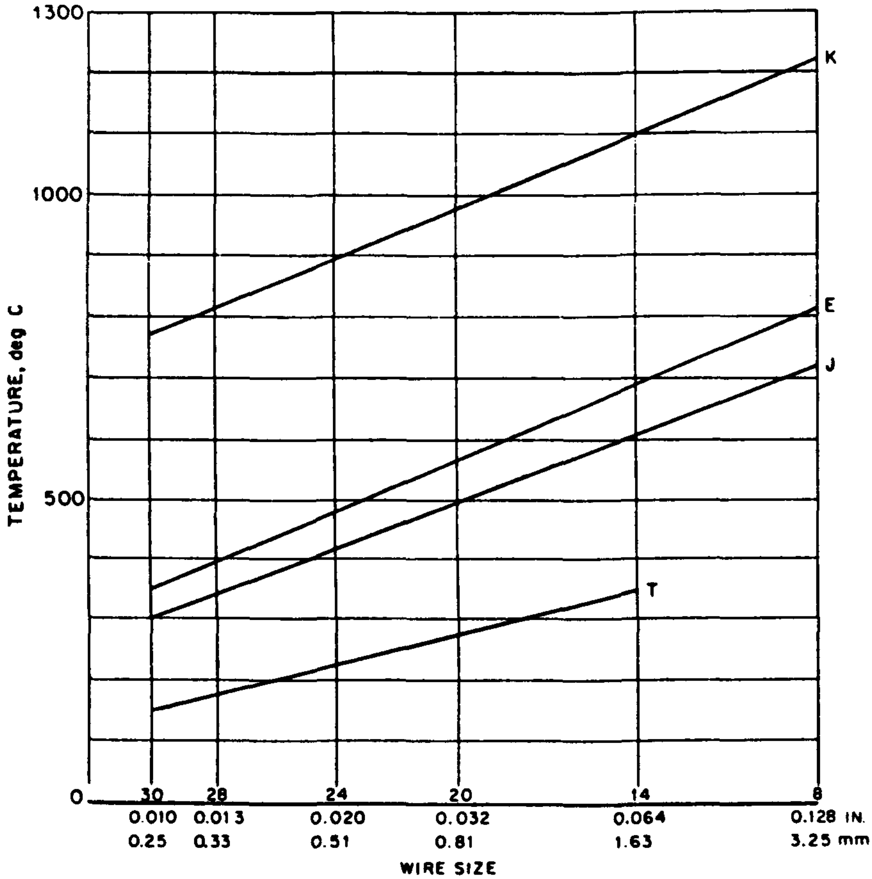
Temperature limits stated in the text are maximum values. Table 3.1 gives recommended maximum temperature limits for various gage sizes of wire. Figure 3.1 is a graphical presentation of maximum temperature limits from Table 3.1 and permits interpolation based on wire size. Table 3.2 gives nominal Seebeck coefficients for the various types. Temperature-emf equivalents and commercial limits of error for these common thermocouple types are given in Chapter 10.

A conservative approach should be used in selecting material and thermocouple types. The time at temperature, thermal cycling rate, and the chemical, electrical, mechanical, or nuclear environment may impact on the proper choice. A person experienced in thermometry, or a reliable supplier, should be consulted before a choice is made.

TABLE 3.1—*Recommended upper temperature limits for protected thermocouples.*

Thermocouple Type	Upper Temperature Limit for Various Wire Sizes (awg), °C (°F)					
	No. 8 Gage, 3.25 mm (0.128 in.)	No. 14 Gage, 1.63 mm (0.064 in.)	No. 20 Gage, 0.81 mm (0.032 in.)	No. 24 Gage, 0.51 mm (0.020 in.)	No. 28 Gage, 0.033 mm (0.013 in.)	No. 30 Gage, 0.25 mm (0.010 in.)
T	...	370 (700)	260 (500)	200 (400)	200 (400)	150 (300)
J	760 (1400)	590 (1100)	480 (900)	370 (700)	370 (700)	320 (600)
E	870 (1600)	650 (1200)	540 (1000)	430 (800)	430 (800)	370 (700)
K and N	1260 (2300)	1090 (2000)	980 (1800)	870 (1600)	870 (1600)	760 (1400)
R and S	...	...	...	1480 (2700)	...	...
B	...	...	...	1700 (3100)	...	...

NOTE—This table gives the recommended upper temperature limits for the various thermocouples and wire sizes. These limits apply to protected thermocouples, that is, thermocouples in conventional closed-end protecting tubes. They do not apply to sheathed thermocouples having compacted mineral oxide insulation. Properly designed and applied sheathed thermocouples may be used at temperatures above those shown in the tables. Other literature sources should be consulted.



NOTE—This graph gives the recommended upper temperature limits for the various thermocouples and wire sizes. These limits apply to thermocouples used under the atmospheric limitations outlined in the text. They do not apply to sheathed thermocouples having compacted mineral oxide insulation. In any general recommendation of thermocouple temperature limits, it is not practicable to take into account special cases. In actual operation, there may be instances where the temperature limits recommended can be exceeded. Likewise, there may be applications where satisfactory life will not be obtained at the recommended temperature limits. However, in general, the temperature limits listed are such as to provide satisfactory thermocouple life when the wires are operated continuously at these temperatures.

FIG. 3.1—*Recommended upper temperature limits for Types K, E, J, T thermocouples.*

3.1.1 General Application Data

Type T—These thermocouples are resistant to corrosion in moist atmospheres and are suitable for subzero temperature measurements (see Table 10.1 for limits of error in the subzero region.) Their use in air or in oxidizing environments is restricted to 370°C (700°F) due to oxidation of the copper

TABLE 3.2—*Nominal Seebeck coefficients.*

	Thermocouple Type							
Temperature	E	J	K	N	R	S	T	B
°C	Seebeck Coefficient-Microvolts/°C							
−190	27.3	24.2	17.1	11.2	...	...	17.1	...
−100	44.8	41.4	30.6	20.9	...	...	28.4	...
0	58.5	50.2	39.4	26.1	...	...	38.0	...
200	74.5	55.8	40.0	32.9	8.8	8.5	53.0	2.0
400	80.0	55.3	42.3	37.1	10.5	9.5	...	4.0
600	81.0	58.5	42.6	38.9	11.5	10.3	...	6.0
800	78.5	64.3	41.0	39.2	12.3	11.0	...	7.7
1000	...	...	39.0	38.5	13.0	11.5	...	9.2
1200	...	...	36.5	33.1	13.8	12.0	...	10.3
1400	...	...	...	...	13.8	12.0	...	11.3
1600	...	...	...	...	...	11.8	...	11.6
°F	Seebeck Coefficient-Microvolts/°F							
−300	15.5	14.4	...	6.6	...	...	9.7	...
−200	22.0	20.6	...	10.2	...	...	13.7	...
−100	27.0	24.6	...	12.7	...	...	17.3	...
32	32.5	28.0	21.7	14.4	3.0	3.0	21.0	...
200	37.5	30.1	23.2	16.3	4.1	4.0	25.7	0.5
400	41.5	30.9	22.3	18.3	4.9	4.8	29.8	1.1
600	43.5	30.7	23.1	19.8	5.5	5.1	32.7	1.8
800	45.0	30.6	23.5	20.8	5.9	5.3	...	2.4
1000	45.0	31.7	23.7	21.4	6.2	5.5	...	3.0
1500	44.0	35.7	22.8	21.7	6.9	6.1	...	4.4
2000	...	...	21.1	21.1	7.6	6.6	...	5.4
2500	...	...	...	...	7.6	6.6	...	6.2
3000	...	...	...	...	7.6	6.5	...	6.5

thermoelement. They may be used to higher temperatures in some other atmospheres.

They can be used in a vacuum and in oxidizing, reducing or inert atmospheres over the temperature range of −200 to 370°C (−330 to 700°F). The upper temperature limit is due primarily to oxidation of the copper element.

This is one of the few thermocouple types for which limits of error are established in the subzero temperature range (see rates under Table 10.1, Chapter 10).

Type J—These thermocouples are suitable for use in vacuum and in oxidizing, reducing, or inert atmospheres, over the temperature range of 0 to 760°C (32 to 1400°F). The rate of oxidation of the iron thermoelement is rapid above 540°C (1000°F), and the use of heavy-gage wires is recommended when long life is required at the higher temperatures. Type J may be used to higher temperatures in some atmospheres. However, they should not be used in sulfurous atmospheres above 540°C (1000°F).

This thermocouple is not recommended for use below the ice point because rusting and embrittlement of the iron thermoelement make its use less desirable than Type T. Limits of error have not been established for Type J thermocouples at subzero temperatures.

Type E—Type E thermocouples are recommended for use over the temperature range of −200 to 900°C (−330 to 1600°F) in oxidizing or inert atmospheres. In reducing atmospheres, alternately oxidizing and reducing atmospheres, marginally oxidizing atmospheres, and in vacuum, they are subject to the same limitations as Type K thermocouples.

These thermocouples are suitable for subzero temperature measurements since they are not subject to corrosion in atmospheres with high moisture content. Limits of error are shown in Table 10.1, Chapter 10.

Type E thermocouples develop the highest Seebeck coefficients of all the commonly used types and are often used primarily because of this feature.

Type K—Type K thermocouples are recommended for use in an oxidizing or completely inert atmosphere over the temperature range of −200 to 1260°C (−330 to 2300°F). Because their oxidation resistance characteristics are better than those of Types E, J, and T thermocouples, they find widest use at temperatures above 540°C (1000°F).

Type K thermocouples are suitable for temperature measurements as low as −250°C (−420°F), although limits of error have been established only for the temperature range given previously.

Type K thermocouples should not be used in:

1. Atmospheres that are reducing or alternately oxidizing and reducing.
2. Sulfurous atmospheres, since sulfur will attack both thermoelements and will cause rapid embrittlement and breakage of the negative thermoelement wire through integranular corrosion.
3. Vacuum, except for short time periods, since preferential vaporization of chromium from the positive element may alter calibration.
4. Atmospheres that promote "green-rot" corrosion of the positive thermoelement. Such corrosion results from preferential oxidation of chromium when the oxygen content of the atmosphere surrounding the thermocouple is low. Green-rot corrosion can cause large negative errors in calibration and is most serious at temperatue levels of 815 to 1040°C (1500 to 1900°F).

Green-rot corrosion frequently occurs when thermocouples are used in long unventilated protecting tubes of small diameter. It can be minimized by increasing the oxygen supply through the use of large diameter protecting tubes or ventilated protecting tubes. Another approach is to decrease the oxygen content below that which will promote preferential oxidation by inserting a "getter" to absorb the oxygen in a sealed protecting tube.

Type N—The Type N thermocouple is the latest ISA letter designated thermocouple and was developed by Noel A. Burley of the Australian defence command. The Type N thermocouple differs from Type K by the addition of silicon in both the NP and NN wires, and an increase of chromium in the NP wire. The NN wire also contains about 0.15% magnesium. This thermocouple provides lower drift rates about 1000°C, does not exhibit the short range ordering of the Type K materials (see Ref *1*), and is less susceptible to preferential oxidation effects (green-rot) compared to Type K thermocouples. Type N thermocouples should not be used in vacuum or reducing atmospheres in an unsheathed configuration.

Types R and S—Types R and S thermocouples are recommended for continuous use in oxidizing or inert atmospheres over the temperature range of 0 to 1480°C (32 to 2700°F).

They should not be used in reducing atmospheres, nor those containing metallic or nonmetallic vapors. They never should be inserted directly into a metallic primary protecting tube.

Continued use of Types R and S thermocouples at high temperatures causes excessive grain growth which can result in mechanical failure of the platinum element. It also renders the platinum susceptible to contamination which causes a reduction in the emf output of the thermocouple.

Calibration changes may be caused by diffusion of rhodium from the alloy wire into the platinum, or by volatilization of rhodium from the alloy. All of these effects tend to produce inhomogeneity.

Type B—Type B thermocouples are recommended for continuous use in oxidizing or inert atmospheres over the temperature range of 870 to 1700°C (1000 to 3100°F). They are also suitable for short-term use in vacuum. They should not be used in reducing atmospheres, nor those containing metallic or nonmetallic vapors. They should never be inserted directly into a metallic primary protecting tube or well.

Under corresponding conditions of temperature and environment, Type B thermocouples will show less grain growth and less drift in calibration than Types R and S thermocouples.

3.1.2 Properties of Thermoelement Materials

This section indicates in Tables 3.3 to 3.9 and in Fig. 3.2 the physical and electrical properties of thermoelement materials as used for the common letter-designated thermocouple types (Types T, J, E, K, N, R, S, and B). These are typical data and are listed for information only. Additional information on the physical properties of thermoelectric material should be requested from the manufacturer. They are not intended for use as specifications for ordering thermocouple materials.

Thermoelement materials are designated in the tables by the established American Standard letter symbols JP, JN, etc. The first letter of the symbol designates the type of thermocouple. The second letter, P or N, denotes the positive or negative thermoelement. Typical materials to which these letter designations apply are:

TABLE 3.3—*Nominal chemical composition of thermoelements.*

Element	JP	JN, TN, EN[a]	TP	KP, EP	KN	NP	NN	RP	SP	RN, SN	BP	BN
	Nominal Chemical Composition, %											
Iron	99.5	...	...	...	...	...	...	...	...	...	...	...
Carbon	[b]	...	...	...	...	...	...	...	...	...	...	...
Manganese	[b]	...	...	...	2	...	...	...	...	...	...	...
Sulfur	[b]	...	...	...	...	...	...	...	...	...	...	...
Phosphorus	[b]	...	...	...	...	...	...	...	...	...	...	...
Silicon	[b]	...	...	...	1	1.4	4.4	...	...	...	...	...
Nickel	[b]	45	...	90	95	84.4	95.5	...	...	...	...	...
Copper	[b]	55	100	...	...	...	...	...	...	...	...	...
Chromium	[b]	...	...	10	...	14.2	...	...	...	...	...	...
Aluminum	...	...	...	...	2	...	...	...	...	...	...	...
Platinum	...	...	...	...	...	...	...	87	90	100	70.4	93.9
Rhodium	...	...	...	...	...	...	...	13	10	...	29.6	6.1
Magnesium	...	...	...	...	...	...	0.15	...	...	...	...	...

[a]Types JN, TN, and EN thermoelements usually contain small amounts of various elements for control of thermal emf, with corresponding reductions in the nickel or copper content, or both.
[b]Thermoelectric iron (JP) contains small but varying amounts of these elements.

TP	Copper
JP	Iron, ThermoKanthal JP[1], HAI-JP[5]
TN, JN, and EN	Constantan, Cupron[2], Advance[3], ThermoKanthal JN[1], HAI-TN[5], HAI-JN[5], HAI-EN[5]
KP or EP	Nickel-chrome, Chromel[4], Tophel[2], T-1[3], Thermo-Kanthal, KP[1], HAI-KP[5], HAI-EP[5]
KN	Nickel-silicon, Alumel[4], Nial[2], T-2[3], ThermoKanthal KN[1], HAI-KN[5]
NP	Nickel-chromium-silicon, Nicrosil, HAI-NP[5]
NN	Nickel-silicon, Nisil, HAI-NN[5]
RP	Platinum-13% rhodium
SP	Platinum-10% rhodium
RN and SN	Platinum
BP	Platinum-30% rhodium
BN	Platinum-6% rhodium

Note that TN, JN, and EN thermoelements, as just listed, are composed of the same basic types of material. The typical data contained in the following pages are applicable to any of these thermoelements. The thermal emf

[1]Trademark of the Kanthal Corporation.
[2]Trademark of Carpenter Technology Corporation.
[3]Trademark of Driver Harris Company.
[4]Trademark of the Hoskins Manufacturing Company.
[5]Trademark of Harrison Alloys, Incorporated.

TABLE 3.4—*Environmental limitations of thermoelements.*

Thermoelement	Environmental Recommendations and Limitations (see notes)
JP	For use in oxidizing, reducing, or inert atmospheres or in vacuum. Oxidizes rapidly above 540°C (1000°F). Will rust in moist atmospheres as in subzero applications. Stable to neutron radiation transmutation. Change in composition is only 0.5% (increase in manganese) in 20-year period.
JN, TN, EN	Suitable for use in oxidizing, reducing, and inert atmospheres or in vacuum. Should not be used unprotected in sulfurous atmospheres above 540°C (1000°F). Composition changes under neutron radiation since copper content is converted to nickel and zinc. Nickel content increases 5% in 20-year period.
TP	Can be used in vacuum or in oxidizing, reducing or inert atmospheres. Oxidizes rapidly above 370°C (700°F). Preferred to Type JP element for subzero use because of its superior corrosion resistance in moist atmospheres. Radiation transmutation causes significant changes in composition. Nickel and zinc grow into the material in amounts of 10% each in a 20-year period.
KP, EP	For use in oxidizing or inert atmospheres. Can be used in hydrogen or cracked ammonia atmospheres if dew point is below −40°C (−40°F). Do not use unprotected in sulfurous atmospheres above 540°C (1000°F). Not recommended for service in vacuum at high temperatures except for short time periods because preferential vaporization of chromium will alter calibration. Large negative calibration shifts will occur if exposed to marginally oxidizing atmospheres in temperature range 815 to 1040°C (1500 to 1900°F). Quite stable to radiation transmutation. Composition change is less than 1% in 20-year period.
NP	Same general use as type KP, except less affected by sulfurous atmospheres because of the silicon addition. Best used in oxidizing or neutral atmospheres.
KN	Can be used in oxidizing or inert atmospheres. Do not use unprotected in sulfurous atmospheres as intergranular corrosion will cause severe embrittlement. Relatively stable to radiation transmutation. In 20-year period, iron content will increase approximately 2%. The manganese and cobalt contents will decrease slightly.
NN	Can be used in oxidizing or inert atmospheres. Do not use unprotected in sulfurous atmospheres as intergranular corrosion will cause severe embrittlement. Relatively stable to radiation transmutation. In 20-year period, iron content will increase approximately 2%. The manganese and cobalt contents will decrease slightly.
RP, SP, SN, RN, BP, BN	For use in oxidizing or inert atmospheres. Do not use unprotected in reducing atmospheres in the presence of easily reduced oxides, atmospheres containing metallic vapors such as lead or zinc, or those containing nonmetallic vapors such as arsenic, phosphorus, or sulfur. Do not insert directly into metallic protecting tubes. Not recommended for service in vacuum at high temperatures except for short time periods.

TABLE 3.4—*(Continued)*

Thermoelement	Environmental Recommendations and Limitations (see notes)
	Types RN and SN elements are relatively stable to radiation transmutation. Types BP, BN, RP, and SP elements are unstable because of the rapid depletion of rhodium. Essentially, all the rhodium will be converted to palladium in a 10-year period.

NOTE 1—Refer to Table 3.5 for recommended upper temperature limits.
NOTE 2—Stability under neutron radiation refers to chemical composition of thermoelement, not to stability of thermal emf.
NOTE 3—Radiation transmutation rates[a] are based on exposure to a thermal neutron flux of 1×10^{14} neutrons/cm^{2}s.

[a]Browning, W. E., Jr., and Miller, C. E., Jr., "Calculated Radiation Induced Changes in Thermocouple Composition," *Temperature, Its Measurement and Control in Science and Industry,* Part 2, Rheinhold, New York, Vol. C, 1962, p. 271.

of these thermoelements when referenced to platinum may differ significantly.

It also should be noted that positive and negative thermoelements for a given type of thermocouple, as supplied by any one manufacturer as a thermocouple, will conform to the calibration curve for that thermocouple within specified limits of error. However, because materials used for a given thermoelement by various manufacturers may differ slightly in thermal emf, larger errors may occur if positive and negative thermoelements from different sources are combined.

3.2 Extension Wires

3.2.1 General Information

Extension wires are inserted between the measuring junction and the reference junction and have approximately the same thermoelectric properties as the thermocouple wires with which they are used. Table 3.10 gives comparative data on extension wires available for thermocouples in common use. Extension wires are normally available as single or duplex, solid or stranded, insulated wires in sizes ranging from 14 to 20 B&S gage. A variety of insulations and protective coverings is available in several combinations to suit the many types of environments encountered in industrial service (see Chapter 4).

Some advantages of using extension wires are:

1. Improvement in mechanical or physical properties of the thermoelectric circuit. For example, the use of stranded construction or smaller diameter solid wire may increase the flexibility of a portion of the circuit. Extension wires also may be selected to adjust the electrical resistance of the circuit.

TABLE 3.5—*Recommended upper temperature limits for protected thermoelements.*

	Upper Temperature Limits for Various Wire Sizes (awg), °C (°F)					
Thermoelement	No. 8 Gage, 3.25 mm (0.128 in.)	No. 14 Gage, 1.63 mm (0.064 in.)	No. 20 Gage, 0.81 mm (0.032 in.)	No. 24 Gage, 0.51 mm (0.020 in.)	No. 28 Gage, 0.33 mm (0.013 in.)	No. 30 Gage, 0.25 mm (0.010 in.)
JP	760°C (1400°F)	593°C (1100°F)	482°C (900°F)	371°C (700°F)	371°C (700°F)	320°C (600°F)
JN, TN, EN	871°C (1600°F)	649°C (1200°F)	538°C (1000°F)	427°C (800°F)	427°C (800°F)	427°C (800°F)
TP	... ...	371°C (700°F)	260°C (500°F)	204°C (400°F)	204°C (400°F)	150°C (300°F)
KP, EP, KN, NP, NN	1260°C (2300°F)	1093°C (2000°F)	982°C (1800°F)	871°C (1600°F)	871°C (1600°F)	760°C (1400°F)
RP, SP, RN, SN	... ...	... ...	... ...	1482°C (2700°F)	... ...	... ...
BP, BN	... ...	... ...	... ...	1705°C (3100°F)	... ...	... ...

NOTE—This table gives the recommended upper temperature limits for the various thermoelements and wire sizes. These limits apply to protected thermoelements, that is, thermoelements in conventional closed-end protecting tubes. They do not apply to sheathed thermoelements having compacted mineral oxide insulation. In any general recommendation of thermoelement temperature limits, it is not practicable to take into account special cases. In actual operation, there may be instances where the temperature limits recommended can be exceeded. Likewise, there may be applications where satisfactory life will not be obtained at the recommended temperature limits. However, in general, the temperature limits listed are such as to provide satisfactory thermoelement life when the wires are operated continuously at these temperatures.

TABLE 3.6—*Seebeck coefficient (thermoelectric power) of thermoelements with respect to Platinum 67 (typical values).*

Thermoelement	JP	JN, TN, EN	TP	KP, EP	KN	NP	NN	RP	SP	BP	BN
Temperature, °C	Seebeck Coefficient, μV/°C										
−190	3.5	20.9	−4.0	...	...	...	...	...	...	...	...
−100	14.2	26.9	1.2	...	...	...	...	...	...	...	...
0	17.9	32.5	5.9	25.8	13.6	15.4	10.7	5.3	5.4	...	...
200	14.6	40.9	11.9	32.8	7.2	23.0	10.0	8.8	8.5	9.2	7.2
400	9.7	45.4	16.3	32.5	7.7	26.3	10.8	10.4	9.6	11.7	7.6
600	11.7	46.8	...	33.7	8.8	28.0	11.0	11.3	10.2	13.8	7.9
800	17.8	46.4	...	32.2	8.8	29.2	10.0	12.3	10.9	15.8	8.1
1000	...	...	...	30.8	8.2	30.2	8.4	13.2	11.5	17.6	8.5
1200	...	...	...	29.2	7.3	30.7	6.5	13.9	12.0	19.1	8.7
1400	...	...	...	...	...	...	...	14.1	12.1	20.0	8.7
1600	...	...	...	...	...	...	...	13.9	11.8	20.0	8.3
Temperature, °F	Seebeck Coefficient, μV/°F										
−300	2.5	11.9	−2.1	...	...	...	...	...	...	...	...
−200	6.5	13.9	−0.3	...	...	...	...	...	...	...	...
−100	8.8	15.8	1.5	...	...	...	...	...	...	...	...
32	9.9	18.0	3.3	14.4	7.6	8.6	6.0	2.9	3.0	...	...
200	9.6	20.5	5.1	16.6	6.4	10.9	5.4	4.1	4.0	4.0	3.6
400	8.0	22.8	6.7	18.2	4.0	12.8	5.6	4.9	4.7	5.1	4.0
600	6.3	24.4	8.1	19.0	4.1	14.0	5.8	5.5	5.1	6.0	4.2
800	5.3	25.4	...	19.2	4.3	14.8	6.0	5.8	5.4	6.7	4.3
1000	5.6	25.9	...	19.0	4.7	15.3	6.1	6.1	5.6	7.3	4.3
1500	9.9	25.8	...	17.8	4.9	16.3	5.5	6.9	6.1	8.8	4.5
2000	...	...	...	16.7	4.3	16.9	4.2	7.6	6.6	10.2	4.8
2500	...	...	...	14.7	4.2	...	...	7.8	6.7	11.1	4.9
3000	...	...	...	...	...	...	...	7.6	6.5	11.0	4.5

TABLE 3.7—*Typical physical properties of thermoelement materials.*

	Thermoelement Material				
Property	JP	JN, EN, TN	TP	KP, EP	KN
Melting point (solidus temperatures)	1 490	1 220	1 083	1 427	1 399
°C	2 715	2 228	1 981	2 600	2 550
°F	...	...	...	...	...
Resistivity					
$\mu\Omega\cdot$cm	8.57	48.9	1.56	70	28.1
at 0°C	9.67	48.9	1.724	70.6	29.4
at 20°C	51.5	294.2	9.38	421	169
Ω cmil/ft	58.2	294	10.37	425	177
at 0°C	...	...	...	...	...
at 20°C	...	...	...	...	...
Temperature coefficient of resistance, $\Omega/\Omega\cdot$°C (0 to 100°C)	65×10^{-4}	-0.1×10^{-4}	4.3×10^{-4}	4.1×10^{-4}	23.9×10^{-4}
Coefficient of thermal expansion in./in. °C (20 to 100°C)	11.7×10^{-6}	14.9×10^{-6}	16.6×10^{-6}	13.1×10^{-6}	12.0×10^{-6}
Thermal conductivity at 100°C	...	...	...	...	...
Cal$\cdot$cm/s$\cdot$cm$^2\cdot$°C	0.162	0.0506	0.901	0.046	0.071
Btu$\cdot$ft/h$\cdot$ft$^2\cdot$°F	39.2	12.2	218	11.1	17.2
Specific heat at 20°C, cal/g$\cdot$°C	0.107	0.094	0.092	0.107	0.125
Density				8.73	
g/cm^3	7.86	8.92	8.92	0.315	8.60
lb/in.^{3}	0.284	0.322	0.322	...	0.311
Tensile strength (annealed)					
MPa	345	552	241	655	586
psi	50 000	80 000	35 000	95 000	85 000
Magnetic attraction	strong	none	none	none	moderate

2. Cost improvement in thermoelectric circuitry. For example, certain base metal extension wires may be substituted for noble metal wires when the reference junction is situated at a distance from a noble metal thermocouple.

Extension wires may be separated into two categories having the following characteristics:

Category 1—Alloys substantially the same as used in the thermocouple. This type of extension wire normally is used with base metal thermocouples.

Category 2—Alloys differing from those used in the thermocouple. This type of extension wire normally is used with noble metal thermocouples and with several of the nonstandardized thermocouples (see Section 3.3).

3.2.2 Sources of Error

Several possible sources of error in temperature measurement accompany the use of extension wires in thermocouple circuits. Most of the errors can be avoided, however, by exercising proper precautions.

One type of error arises from the disparity in thermal emf between ther-

Thermoelement Material						
NP	NN	RP	SP	RN, SN	BP	BN
1 420	1 330	1 860	1 850	1 769	1 927	1 826
2 590	2 425	3 380	3 362	3 216	3 501	3 319
97.4	32.5	19.0	18.4	9.83	...	...
97.8	34.6	19.6	18.9	10.4	19.0	17.5
...	...	114.3	110.7	59.1	...	...
...	...	117.7	114.0	62.4	114.5	106
13.3×10^{-4}	12.1×10^{-4}	15.6×10^{-4}	16.6×10^{-4}	39.2×10^{-4}	13.3×10^{-4}	20.6×10^{-4}
...	...	9.0×10^{-6}	9.0×10^{-6}	9.0×10^{-6}	...	...
0.0358	0.0664	0.088	0.090	0.171	...	...
8.67	16.07	21.3	21.8	41.4	...	...
0.11	0.12	...	...	0.032	...	...
8.52	8.70	...	...	...	...	...
...	0.3143	19.61	19.97	21.45	17.60	20.55
0.3078	...	0.708	0.721	0.775	0.636	0.743
690	621	317	310	138	483	276
100 000	90 000	46 000	45 000	20 000	70 000	40 000
none	none	none	none	none	none	none

mocouples and nominally identical extension wire components of Category 1.

The disparity results from the variations occurring among thermoelements lying within the standard limits of error for each type of thermocouple and extension wire. Thus, for example, it is possible that an error as great as ± 4.4°C (± 8°F) could occur in the Type K/KX and J/JX thermocouple extension wire combinations, where the standard limits of error are ± 2.2°C (± 4°F) for the thermocouple and the extension wires treated as separate combinations. Such errors can be eliminated substantially by selecting extension wires whose emf closely matches that of the specific thermocouple, up to the maximum temperature of the thermocouple-extension wire junction.

A second source of error can arise if a temperature difference exists between the two thermoelement-extension wire junctions. Errors of this type are potentially greater in circuits employing extension wires of Category 2, where each extension element may differ significantly in emf from the corresponding thermoelement. Such errors may occur even though the extension pair emf exactly matches the thermocouple emf at each temper-

TABLE 3.8—*Thermoelements—resistance to change with increasing temperature.*

Thermoelements	Ratio of Resistance at Temperature Indicated to Resistance at 0°C (32°F)									
	0°C (32°F)	20°C (68°F)	200°C (392°F)	400°C (752°F)	600°C (1112°F)	800°C (1472°F)	1000°C (1832°F)	1200°C (2192°F)	1400°C (2552°F)	1500°C (2732°F)
JP	1.00	1.13	2.46	4.72	7.84	12.0	13.07	. . .	. . .	. . .
JN, TN, EN	1.00	0.999	0.996	0.994	1.02	1.056	1.092	. . .	. . .	. . .
TP	1.00	1.11	1.86	2.75	3.70	4.75	5.96	. . .	. . .	. . .
KP, EP	1.00	1.01	1.09	1.19	1.25	1.30	1.37	1.43	. . .	. . .
KN	1.00	1.05	1.43	1.64	1.82	1.98	2.15	2.32	. . .	. . .
NP	1.00	1.01	1.02	1.07	1.08	1.08	1.10	. . .	. . .	. . .
NN	1.00	1.07	1.13	1.27	1.39	1.55	1.68	. . .	. . .	. . .
RP	1.00	1.03	1.31	1.60	1.89	2.16	2.41	2.66	2.90	3.01
SP	1.00	1.03	1.33	1.65	1.95	2.23	2.50	2.76	3.01	3.13
RN, SN	1.00	1.06	1.77	2.50	3.18	3.81	4.40	4.94	5.42	5.66
BP	1.00	1.03	1.26	1.51	1.76	1.98	2.20	2.41	2.62	2.73
BN	1.00	1.03	1.40	1.78	2.14	2.47	2.78	3.08	3.37	3.51

TABLE 3.9—*Nominal resistance of thermoelements.*

Awg. No.	Diameter, in.[b]	KN	KP, EP	TN, JN, EN	TP	JP	Awg. No.	Diameter No.[b]	NP	NN	RN, SN	RP	SP	BP	BN
		Nominal Resistance, ohms per foot at 20°C (68°F)													
6	0.1620	0.0067	0.0162	0.0112	0.000395	0.0027	6	0.1620	.02210	.008383	0.00243	0.00448	0.00438	0.00440	0.00407
9[a]	0.148	...	...	...	...	0.0033	9	0.1480	.04463	.01693	...	0.00537	...	...	...
8	0.1285	0.0107	0.0257	0.0179	0.000628	0.0043	8	0.1285	.03540	.01343	0.00386	0.00713	0.00697	0.00700	0.00648
10	0.1019	0.0170	0.041	0.0283	0.000999	0.0069	10	0.1019	.05575	.02115	0.00614	0.00113	0.01108	0.01113	0.01030
12	0.0808	0.0270	0.065	0.0448	0.00159	0.0109	12	0.0808	.08840	.03353	0.00976	0.01803	0.01761	0.01769	0.01637
14	0.0641	0.0432	0.104	0.0718	0.00253	0.0174	14	0.0641	.1416	.05371	0.0155	0.0286	0.0280	0.0281	0.0260
16	0.0508	0.0683	0.164	0.113	0.00402	0.0276	16	0.0508	.2230	.08458	0.0247	0.0456	0.0445	0.0447	0.0414
17	0.0453	0.0874	0.209	0.145	0.00506	0.0349	17	0.0453	.2864	.1086	0.0311	0.0574	0.0562	0.0564	0.0523
18	0.0403	0.111	0.266	0.184	0.00648	0.0446	18	0.0403	.3625	.1375	0.0399	0.0725	0.0719	0.0722	0.0669
20	0.0320	0.173	0.415	0.287	0.0102	0.0699	20	0.0320	.5664	.2148	0.0624	0.1149	0.1125	0.1130	0.1046
22	0.0253	0.276	0.663	0.456	0.0161	0.1111	22	0.0253	.9061	.3437	0.0993	0.1839	0.1790	0.1798	0.1664
23	0.0226	0.347	0.833	0.576	0.0204	0.1401	23	0.0226	1.136	.4307	0.1251	0.2913	0.2257	0.2267	0.2099
24	0.0201	0.438	1.05	0.728	0.0257	0.1767	24	0.0201	1.436	.5445	0.1578	0.4656	0.2847	0.2859	0.2647
25	0.0179	0.553	1.33	0.918	0.0324	0.2228	25	0.0179	1.810	.6866	0.1990	0.7414	0.3589	0.3605	0.3337
26	0.0159	0.700	1.68	1.16	0.0408	0.281	26	0.0159	2.294	.8702	0.2509	1.177	0.4526	0.4546	0.4208
28	0.0126	1.11	2.48	1.85	0.0649	0.447	28	0.0126	3.653	1.386	0.3989	1.839	0.7197	0.7229	0.6692
30	0.0100	1.77	4.25	2.94	0.1032	0.710	30	0.0100	5.800	2.20	0.6344	2.965	1.144	1.149	1.064
32	0.0080	2.76	6.65	4.59	0.1641	1.13	32	0.0080	9.063	3.438	1.009	4.708	1.819	1.827	1.691
34	0.0063	4.45	10.7	7.41	0.2609	1.80	34	0.0063	14.61	5.543	1.604	7.356	2.893	2.906	2.690
36	0.0050	7.08	17.0	11.8	0.4148	2.86	36	0.0050	23.20	8.800	2.550	12.25	4.600	4.620	4.277
38	0.0040	11.1	26.6	18.4	0.6597	4.54	38	0.0040	36.25	13.75	4.056	...	7.316	7.348	6.803
40	0.0031	18.4	44.2	30.6	1.049	7.22	40	0.0031	60.35	22.89	6.448	...	11.63	11.68	10.81

[a] #9 Birmingham wire gage.
[b] 1 in. = 25.4 mm.

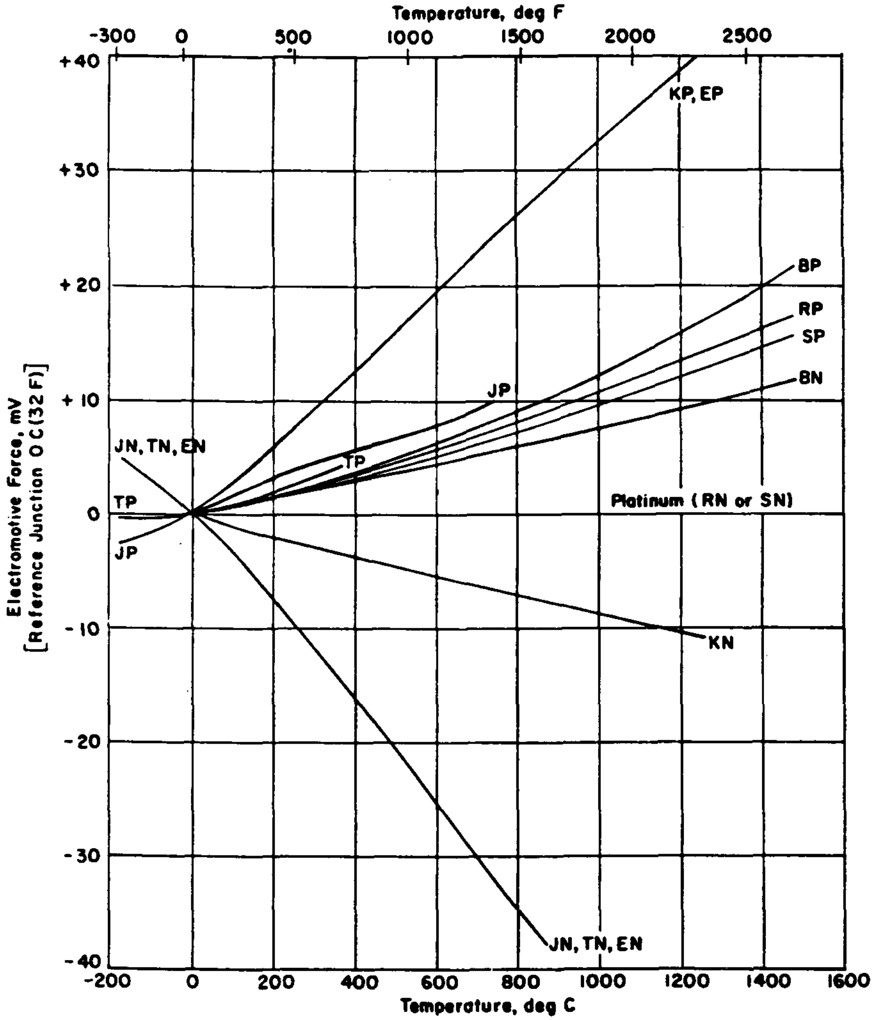


FIG. 3.2—*Thermal emf of thermoelements relative to platinum.*

ature. Referring to Fig. 3.3, schematically representing emf versus temperature curves for positive and negative thermoelements P and N, and corresponding extension wire elements PX and NX, the following relationships apply at any temperature T within the operating range of the extension wires:

Thermocouple output = extension pair output

That is

$$E_P - E_N = E_{PX} - E_{NX} \tag{1}$$

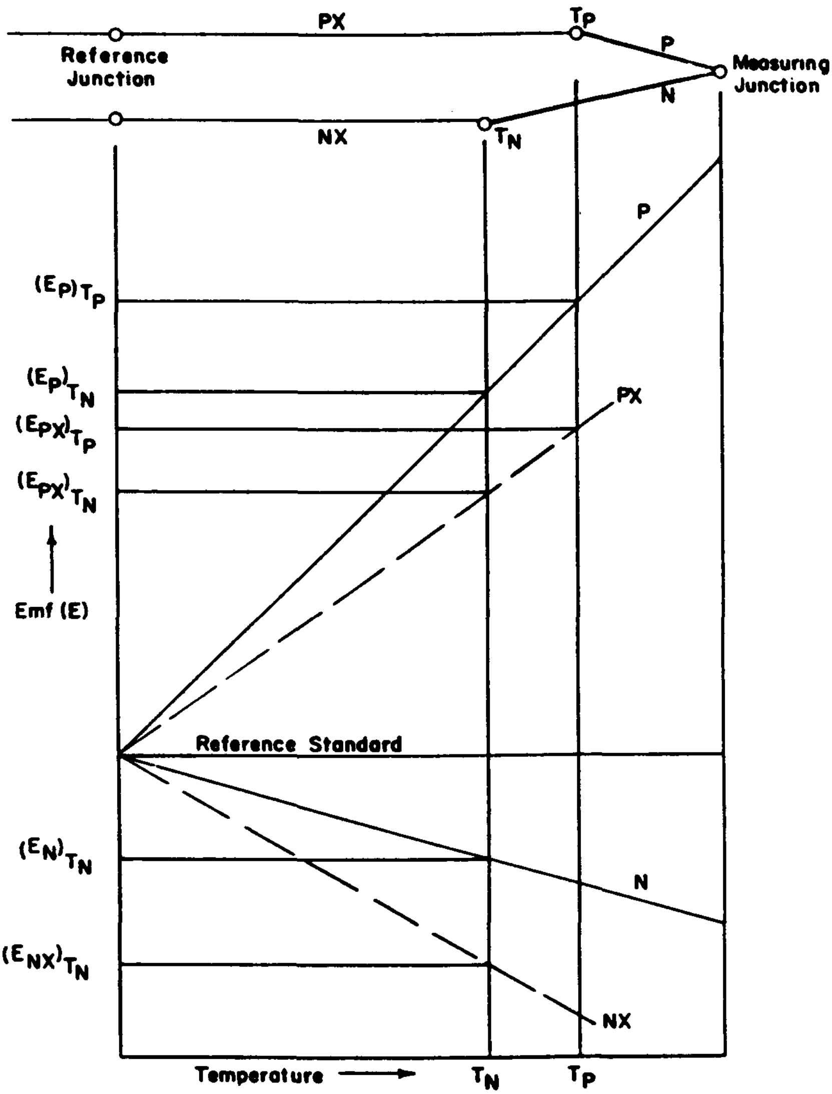


FIG. 3.3—*Error due to* ΔT *between the thermocouple-extension wire junctions.*

Rearranging to

$$E_P - E_{PX} = E_N - E_{NX} \tag{2}$$

If a temperature difference exists between the two junctions such that P joins PX at T_P, and N joins NX at T_N, an unwanted emf will exist across the two junctions, of magnitude

$$\Delta E = (E_P - E_{PX})_{TP} - (E_N - E_{NX})_{TN} \tag{3}$$

TABLE 3.10—*Extension wires for thermocouples mentioned in Chapter 3.*

Thermocouple Type	Extension Wire Type	Alloy Type	
		Positive	Negative
Base metal	Category 1		
E	EX	Ni-Cr	Cu-Ni
J	JX	iron	Cu-Ni
K[c]	KX	Ni-Cr	Ni-Al
N	NX	Ni-Cr-Si	Ni-Si-Mg
T	TX	copper	Cu-Ni
Noble metal	Category 2		
B	BX	copper	copper
	proprietary	Cu-Mn[f]	copper
R	SX	copper	Cu-Ni[d,f]
S	SX	copper	Cu-Ni[d,f]
	proprietary	Ni-Cr[e]	Fe-Cr[e]
Refractory metal	Category 2		
W/W-26Re	proprietary	Ni-Cr[e]	Ni-Cr[e]
W-5Re/W-26Re	proprietary	Ni-Al[e]	Ni-Cu[e]
W-3Re/W-25Re	proprietary	Ni-Cr[e]	Ni-Cr[e]
Base metal			
Ni-18Mo/Ni-0.8Co[g]	Category 1	Ni-Mo	Ni-Co[f]
Noble metal			
Pt-20Rh/Pt-5Rh	Category 2	copper	copper
Pt-40Rh/Pt-20	Category 2	copper	copper
Pt-13Rh/Pt-1Rh	Category 2	copper	copper
Pt-15Ir/Pd	Category 2	base metal	base metal
Pt-5Mo/Pt-0.1Mo	Category 2	copper	Cu-Ni
Ir-40,50,60Rh/Ir	Category 2	copper	AISi 347 SS or aluminum
83Pd-14Pt-3Au-66Au-35Pd	Category 2	KP	KN
55Pd-31Pt-14Au/65Au-35Pd	Category 2	KP	KN
	Category 2	base metal	base metal

[a]See also ANSI MC96.1. Reference junction 0°C (32°F).
[b]M denotes strong magnetic response. O denotes little or no magnetic response at room temperature.
[c]Includes special Type K alloys discussed in 3.3.4.1.
[d]Harrison Alloys, Inc.
[e]Hoskins Manufacturing Company.
[f]Carpenter Technology Corporation.
[g]Type KX wire may be used from −20 to +120°C.

Temperature Range		Limits of Error[a]				Magnetic Response[b]	
		Normal		Special			
°C	°F	±°C	±°F	±°C	±°F	P	N
Standard Thermocouples							
0 to 200	32 to 400	1.7	3.0			O	O
0 to 200	32 to 400	2.2	4.0	1.1	2.0	M	O
0 to 200	32 to 400	2.2	4.0	1.1	2.0	O	M
0 to 200	32 to 400	2.2	4.0	1.1	2.0	O	O
−60 to 100	−75 to 200	1.0	1.8	0.5	0.9	O	O
0 to 100	32 to 200	+0.0	+0.0	measured junction		O	O
0 to 320	32 to 600	−3.7	−6.7	>1000°C (1830°F)		O	O
0 to 200	32 to 400	5.0	9.0	measured junction		O	O
0 to 200	32 to 400	5.0	9.0	>870°C (1600°F)		O	O
0 to 540	32 to 1000	2.8	5.0	or ± 1%		O	O
				(whichever is greater)		O	M
Other Thermocouples							
				Equivalent to less than			
0 to 260	32 to 500	±0.14 MV		±0.5% of measured		O	M
0 to 870	32 to 1600	±0.11 MV		temperature in range		M	M
0 to 260	32 to 500	±0.11 MV		1370 to 2200°C		O	M
				(2500 to 4000°F)			
0 to 200	32 to 400	2.2	4.0			O	M
0 to 175	32 to 350	not established				O	O
0 to 175	32 to 350	not established				O	O
0 to 175	32 to 350	not established				O	O
0 to 700	32 to 1300	not established					
0 to 70	32 to 160	not established				O	O
not established	not established	not established				O	O
at about 800	at about 1470	not established				O	M
at about 800	at about 1470	not established				O	M
0 to 160	32 to 320						

Rearranging Eq 3 according to Eq 2

$$\Delta E = (E_P - E_{PX})_{TP} - (E_P - E_{PX})_{TN}$$

The sign of ΔE will depend on the relationship of temperature T_P to T_N and the emf relationship of PX and NX to P and N.

This ΔE will be interpreted as an error in the output of the measuring thermocouple. Such errors do not exceed about one degree at the measuring junction, per degree of ΔT between the thermocouple-extension wire junctions. These errors can be eliminated by equalizing the temperatures of the two junctions.

A third source of error lies in the presence of reversed polarity at the thermocouple-extension wire junctions, or at the extension wire-instrument junctions. Although a single reversal of polarity in the assembly would be noticeable, an inadvertent double reversal likewise may produce measurement errors, but could escape immediate detection.

A fourth source of error concerns the use of connectors in the thermocouple assembly. If the connector material has thermal emf characteristics which differ appreciably from those of the thermocouple extension wires, then it is important that a negligible temperature difference be maintained across the connector. This follows directly from the Law of Intermediate Metals (see Section 2.2.2). Thus, in situations where a connector made of a third metal spans a substantial temperature gradient, unwanted emfs are generated between the thermoelectric materials and the extremities of the connector, and they appear as errors in the output of the thermocouple. The magnitude of errors of this type can vary over a wide range depending on the materials involved and the temperature difference spanned by the connector.

If the emf errors arising from the use of extension wires or from other sources are to be expressed as temperature errors, the Seebeck coefficient of the thermocouple at the measuring junction temperature must be used.

A useful graphical method of evaluating error sources in thermoelectric circuits is detailed in a paper by Moffat (see Ref *2*).

3.3 Nonstandardized Thermocouple Types

Newer thermocouple materials are being evaluated constantly to find combinations which perform special functions more reliably than the common thermocouples. The special applications for which these newer combinations are required frequently involve very high temperatures, but also may include unusual environments such as special atmospheres or areas susceptible to vibration.

Each of the combinations described in this section has been designed to measure temperatures under specific conditions and to perform with a degree of reliability superior to other combinations under these same conditions. The properties of each combination are detailed to allow a quick selection of a combination which is most likely to be suitable for a special condition. Thermocouple compositions are given in weight percent with the positive thermoelement of the thermocouple named first.

The information on newer thermocouple materials is presented using comments, tables, and curves. The comments made for the various thermocouple systems are intended to convey information not easily shown by tables or curves. The information contained in the tables is intended to help the reader to quickly decide if a certain thermocouple system, or a specific thermocouple, is suited to his particular needs. The information given is general and nominal, and cannot be used too literally. For example, the useful maximum temperature of a thermocouple depends in part on wire size, insulation used, method of installation, atmosphere conditions, vibration present, etc. The evaluation of certain properties as good, fair, or poor is subject to wide ranges of interpretation in terms of a particular application; hence, no attempt is made to define these terms. Approximate millivolt-versus-termperature relations for the various thermocouples are shown by curves. The curves are presented to show general temperature ranges for the various thermocouples but are not intended for use in converting emf to temperature. The reader should contact the wire manufacturer for temperature-emf tables.

The thermocouples described here are in use, and sufficient data and experience are available to warrant their inclusion. No attempt is made to include the many other thermocouple materials described in the literature which may have limited uses, or for which there are limited data, or for which there are serious problems of stability, emf reversibility, structural strength etc.

The best source of information for a specific thermocouple in the "newer material" classification is considered to be the manufacturer of the particular thermocouple under consideration (see Ref *3*).

3.3.1 Platinum Types

3.3.1.1 Platinum-Rhodium Versus Platinum-Rhodium Thermocouples—The standard Types R and S thermocouples can be used for temperature measurement to the melting point of platinum, 1769°C (3216°F) on a short-term basis, but, for improved service life at temperatures over 1200°C (2192°F), special platinum-rhodium thermocouples are recommended.

The platinum-40% rhodium versus platinum-20% rhodium thermocouple, called the "Land-Jewell" thermocouple, is useful especially for continuous use to 1800°C (3272°F) or occasional use to 1850°C (3362°F). However, it is seldom used where the Type B thermocouple will suffice because of lower output and greater cost. Other thermocouples suggested for high-temperature measurement have been a platinum-13% rhodium versus platinum-1% rhodium combination and a platinum-20% rhodium versus platinum-5% rhodium combination. The former shows slightly less tendency toward mechanical failure or contamination at high temperatures than the standard Types R and S thermocouples, while the latter has properties very similar to those of the Type B thermocouple.

Figure 3.4 and Table 3.11 show the characteristics of these alloys.

All special platinum-rhodium versus platinum-rhodium thermocouples, like the standard Types R, S, and B thermocouples, show improved life at

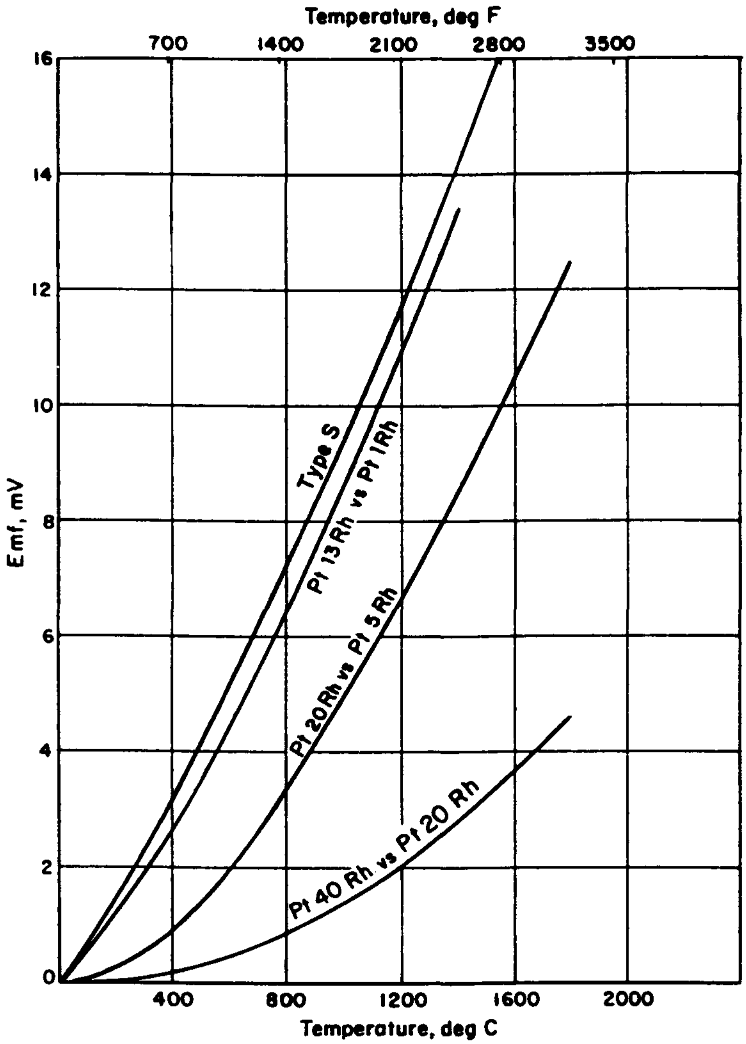


FIG. 3.4—*Thermal emf of platinum-rhodium versus platinum-rhodium thermocouples.*

TABLE 3.11—*Platinum-rhodium versus platinum-rhodium thermocouples.*

	Pt-20Rh Versus Pt-5Rh	Pt-40Rh Versus Pt-20Rh	Pt-13Rh Versus Pt-1Rh
Nominal operating temperature range, in.			
Reducing atmosphere (nonhydrogen)	NR[a]	NR	NR
Wet hydrogen	NR	NR	NR
Dry hydrogen	NR	NR	NR
Inert atmosphere	1700°C (3092°F)	1800°C (3272°F)	1600°C (2912°F)
Oxidizing atmosphere	1700°C (3092°F)	1800°C (3272°F)	1600°C (2912°F)
Vacuum (short-time use)	1700°C (3092°F)	1800°C (3272°F)	1600°C (2912°F)
Maximum short-time temperature	1770°C (3218°F)	1850°C (3362°F)	1770°C (3218°F)
Approximate microvolts per degree			
Mean, over nominal operating range	6.8/°C (12.2/°F)	2.5/°C (4.5/°F)	9.9/°C (17.8/°F)
At top temperature of normal range	9.9/°C (17.8/°F)	4.7/°C (8.45/°F)	12.2/°C (22.0/°F)
Melting temperature, nominal			
Positive thermoelement	1900°C (3452°F)	1930°C (3520°F)	1865°C (3389°F)
Negative thermoelement	1820°C (3308°F)	1900°C (3452°F)	1771°C (3220°F)
Stability with thermal cycling	good	good	good
High-temperature tensile properties	good	good	good
Stability under mechanical working	good	fair	good
Ductility (of most brittle thermoelement) after use	good	fair	good
Resistance to handling contamination	fair	fair	fair
Recommended extension wire, 175°C (347°F) max			
Positive conductor	Cu	Cu	Cu
Negative conductor	Cu	Cu	Cu

[a]NR = not recommended.

high temperatures when protected by double-bore, full-length insulators of high-purity alumina.

3.3.1.2 Platinum-15% Iridium Versus Palladium Thermocouples—The platinum-15% iridium versus palladium combination was developed as a high-output noble-metal thermocouple. It combines the desirable attributes of noble metals with a high emf output at a lower cost than other noble-metal thermocouples.

The output becomes more linear and the Seebeck coefficient (thermoelectric power) increases with increasing temperature. In the absence of vibration, the useful range can probably be extended closer to the melting point of palladium, 1550°C (2826°F).

Figure 3.5 and Table 3.12 show the characteristics of these alloys.

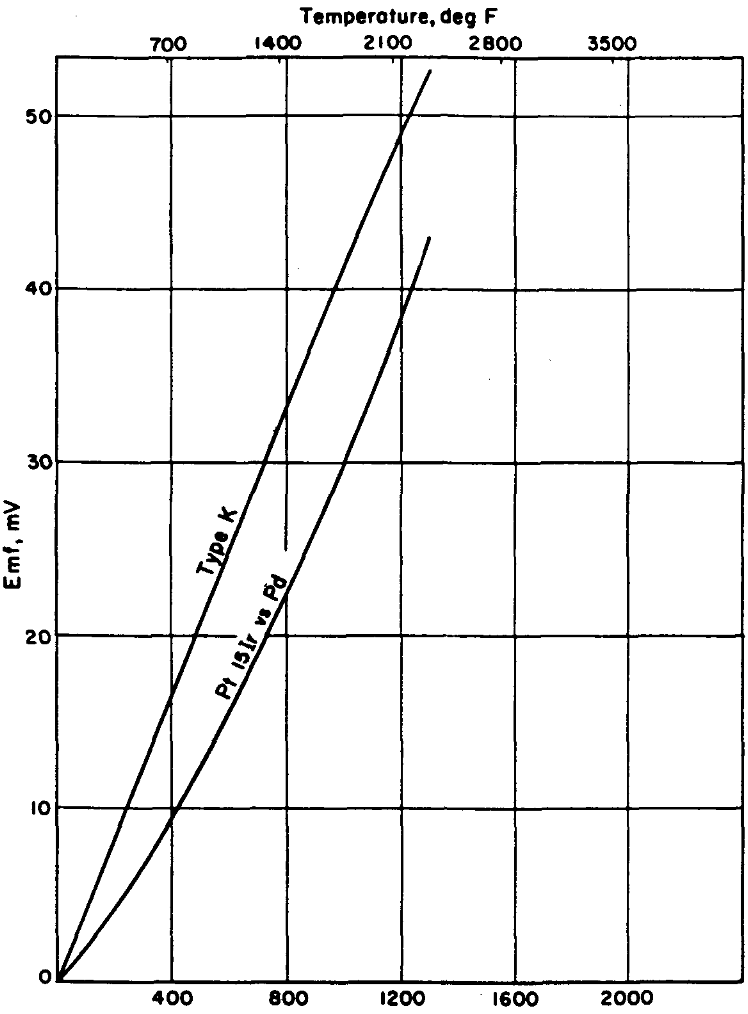


FIG. 3.5—*Thermal emf of platinum-iridium versus palladium thermocouples.*

Extension wires of base metals have been developed to provide a reasonable match with the thermocouple to about 700°C (1292°F).

Resistance to corrosion of the platinum-15% iridium alloy is better than that of the platinum-rhodium alloys in current use. Palladium is slightly less resistant to corrosion than the platinum alloy group. It will oxidize superficially at 700°C (1292°F). The oxide decomposes at about 875°C (1607°F) leaving a bright metal. When subjected to alternating oxidizing and reducing atmospheres, surface blistering may result. As with all noble metals, the cat-

TABLE 3.12—*Platinum-iridium versus palladium thermocouples.*

	Pt-15Ir Versus Pd
Nominal operating temperature range, in.	
Reducing atmosphere (nonhydrogen)	NR[a]
Wet hydrogen	NR
Dry hydrogen	NR
Inert atmosphere	1370°C (2500°F)
Oxidizing atmosphere	1370°C (2500°F)
Vacuum	NR
Maximum short-time temperature	1550°C (2826°F)
Approximate microvolts per degree	
Mean, over nominal operating range	39.6/°C (22/°F)
At top temperature of normal range	44.3/°C (24.6/°F)
Melting temperature, nominal	
Positive thermoelement	1785°C (3245°F)
Negative thermoelement	1550°C (2826°F)
Stability with thermal cycling	good
High-temperature tensile properties	fair
Stability under mechanical working	good
Ductility (or most brittle thermoelement) after use	good
Resistance to handling contamination	fair
Recommended extension wire	
Positive conductor	base metal alloys[b]
Negative conductor	base metal alloys[b]

[a]NR = not recommended.
[b]General Electric Company.

alytic effect of the wires must be considered in combustible atmospheres. Its use may be preferred to base metals, however, for many applications. Both wires are ductile and may be reduced to very small sizes and still be handled with relative ease.

3.3.1.3 Platinum-5% Molybdenum Versus Platinum-0.8% Cobalt Thermocouple—Platinum alloys containing rhodium are not suitable for use under neutron irradiation since the rhodium changes slowly to palladium. This causes a drift in the calibration of thermocouples containing rhodium. However, a thermocouple of platinum-5% molybdenum versus platinum-0.1% molybdenum is suitable for use in the helium atmosphere of a gas-cooled atomic reactor. Good stability at temperatures up to 1400°C (2552°F) has been reported. The output of the thermocouple is high and increases in a fairly uniform manner with increasing temperature.

Figure 3.6 and Table 3.13 show the characteristics of these alloys.

The thermocouple usually is used in an insulated metallic sheath of platinum-5% molybdenum alloy. The sheath may be joined to a Type 321 stainless steel sheath beyond the area of the helium atmosphere. Both the platinum-molybdenum alloy and the Type 321 stainless steel behave well under neutron irradiation and are compatible with graphite which normally is used in the reactor.

Extension wires for this thermocouple can be copper for the positive con-

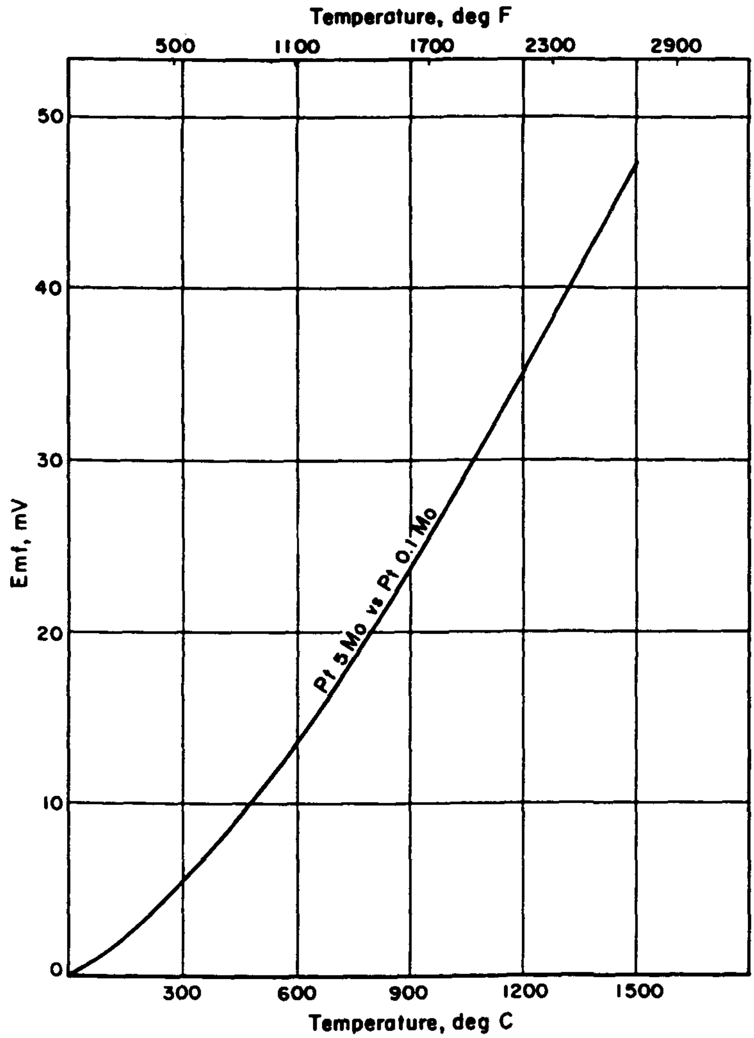


FIG. 3.6—*Thermal emf of platinum-molybdenum versus platinum-molybdenum thermocouples.*

ductor and copper-1.6% nickel for the negative conductor. Using these materials the junctions between the thermocouple and the extension wires should be maintained below 70°C (158°F).

3.3.2 Iridium-Rhodium Types

3.3.2.1 Iridium-Rhodium Versus Iridium Thermocouples—Iridium-rhodium versus iridium thermocouples are suitable for measuring temper-

TABLE 3.13—*Platinum-molybdenum versus platinum-molybdenum thermocouples.*

	Pt-5Mo Versus Pt-0.1Mo
Nominal operating temperature range, in.	
Reducing atmosphere (nonhydrogen)	NR[a]
Wet hydrogen	NR
Dry hydrogen	NR
Inert atmosphere (helium)	1400°C (2552°F)
Oxidizing atmosphere	NR
Vacuum	NR
Maximum short-time temperature	1550°C (2822°F)
Approximate microvolts per degree	
Mean, over nominal operating range	32/°C (17.8/°F)
At top temperature of normal range	36/°C (20/°F)
Melting temperature, nominal	
Positive thermoelement	1788°C (3250°F)
Negative thermoelement	1770°C (3218°F)
Stability with thermal cycling	good
High-temperature tensile properties	fair
Stability under mechanical working	good
Ductility (of most brittle thermoelement) after use	good
Resistance to handling contamination	fair
Recommended extension wire 70°C (158°F) max	
Positive conductor	Cu
Negative conductor	Cu-1.6Ni

[a]NR = not recommended.

ature to approximately 2000°C (3632°F), and generally are used above the range served by platinum-rhodium versus platinum thermocouples. They can be used in inert atmospheres and in vacuum, but not in reducing atmospheres, and they may be used in oxidizing atmospheres with shortened life.

The alloys of principal interest are those containing 40, 50, and 60% rhodium. They may be used for short times at maximum temperatures 2180, 2140, and 2090°C (3956, 3884, and 3794°F), these temperatures being 60°C (110°F) or more below the respective melting points.

Figure 3.7 and Table 3.14 show the characteristics of these alloys. The wires must be handled carefully. They are flexible in the fibrous (as drawn) state, but when annealed are broken easily by repeated bending.

Metals said to be suitable for extension wires are 85% copper-15% nickel alloy for the positive conductor and 81% copper-19% nickel alloy for the negative conductor.[6]

3.3.2.2 Iridium-Rhodium Versus Platinum-Rhodium Thermocouples—Platinum-40% rhodium alloy[7] has been chosen by Lewis Research Center (NASA) as a substitute for an iridium thermoelement in combustor

[6]Johnson Matthey Incorporated.
[7]National Aeronautics and Space Administration Technical Brief, Nov. 1975.

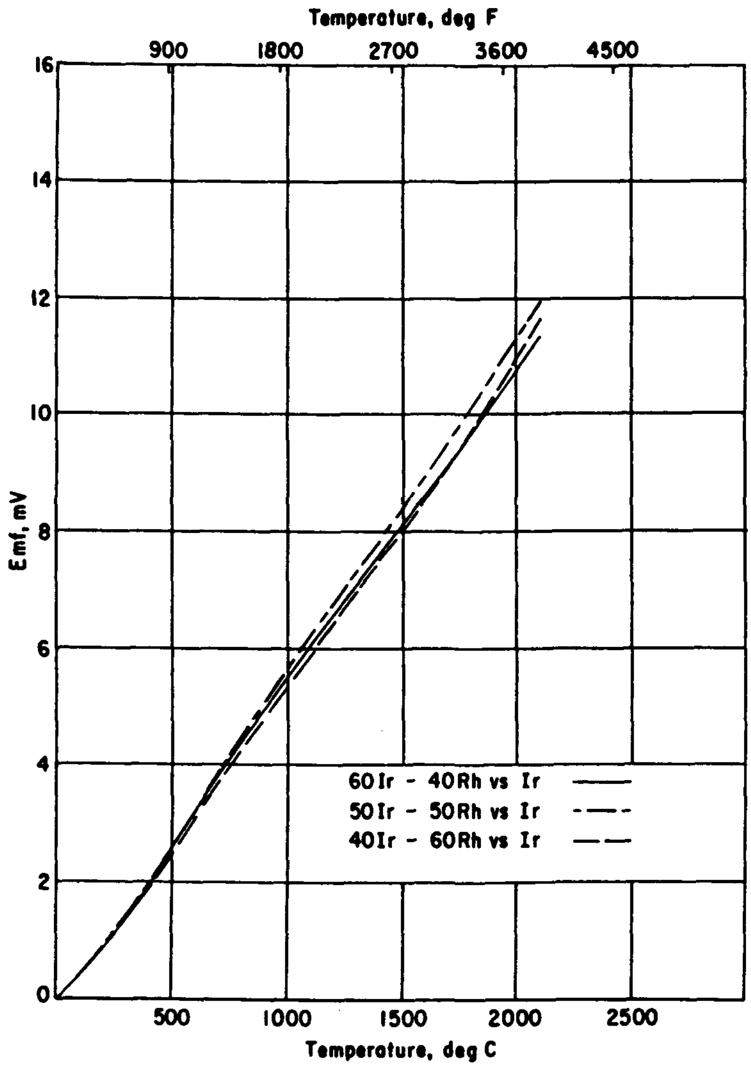


FIG. 3.7—*Thermal emf of iridium-rhodium versus iridium thermocouples.*

gas streams at pressures above 20 atmospheres and temperatures approaching 1600°C (2912°F). The thermocouple, consisting of a positive element of iridium-40% rhodium and a negative element of platinum-40% rhodium, showed reasonable oxidation resistance under these conditions.

Calibration to 1400°C (2552°F) showed the thermocouple output to be nearly linear and the absolute emf to be close to that of the iridium-40% rhodium versus iridium thermocouple.

TABLE 3.14—*Iridium-rhodium versus iridium thermocouples.*

	60Ir-40Rh Versus Ir	50Ir-50Rh Versus Ir	40Ir-60Rh Versus Ir
Nominal operating temperature range, in.	...	...	...
Reducing atmosphere (nonhydrogen)			
Wet hydrogen	NR[a]	NR	NR
Dry hydrogen	NR	NR	NR
Inert atmosphere	2100°C (3812°F)	2050°C (3722°F)	2000°C (3632°F)
Oxidizing atmosphere	NR	NR	NR
Vacuum	2100°C (3812°F)	2050°C (3722°F)	2000°C (3632°F)
Maximum short-time temperature	2190°C (3974°F)	2140°C (3884°F)	2090°C (3794°F)
Approximate microvolts per degree			
Mean, over nominal operating range	5.3/°C (2.9/°F)	5.7/°C (3.2/°F)	5.2/°C (2.9/°F)
At top temperature of normal range	5.6/°C (3.1/°F)	6.2/°C (3.5/°F)	5.0/°C (2.8/°F)
Melting temperature, nominal:			
Positive thermoelement	2250°C (4082°F)	2202°C (3996°F)	2153°C (3907°F)
Negative thermoelement	2443°C (4429°F)	2443°C (4429°F)	2443°C (4429°F)
Stability with thermal cycling	fair	fair	fair
High-temperature tensile properties	...	...	...
Stability under mechanical working	...	...	...
Ductility (or most brittle thermoelement) after use	poor	poor	poor
Recommended extension wire			
Recommended extension wire	...	...	...
Positive conductor	...	...	...
Negative conductor	...	...	...

[a]NR = not recommended.

3.3.3 Platinel Types

3.3.3.1 Platinel Thermocouples—Platinel,[8] a noble-metal thermocouple combination, was designed metallurgically for high-temperature indication and control in turbo-prop engines. This combination approximates within reasonable tolerances the Type K thermocouple curve.

Actually, two combinations have been produced and are called Platinel I

[8]Trademark of the Engelhard Industries Incorporated.

and Platinel II. The negative thermoelement in both thermocouples is a 65% gold-35% palladium alloy (Platinel 1503), but the positive one in Platinel I is composed of 83% palladium, 14% platinum, and 3% gold (Platinel 1786), while that used in Platinel II contains 55% palladium, 31% platinum, and 14% gold (Platinel 1813). Platinel II is the preferred type and has superior mechanical fatigue properties. The thermal emfs of these combinations differ little, as shown in Fig. 3.8. Other properties are given in Table 3.15.

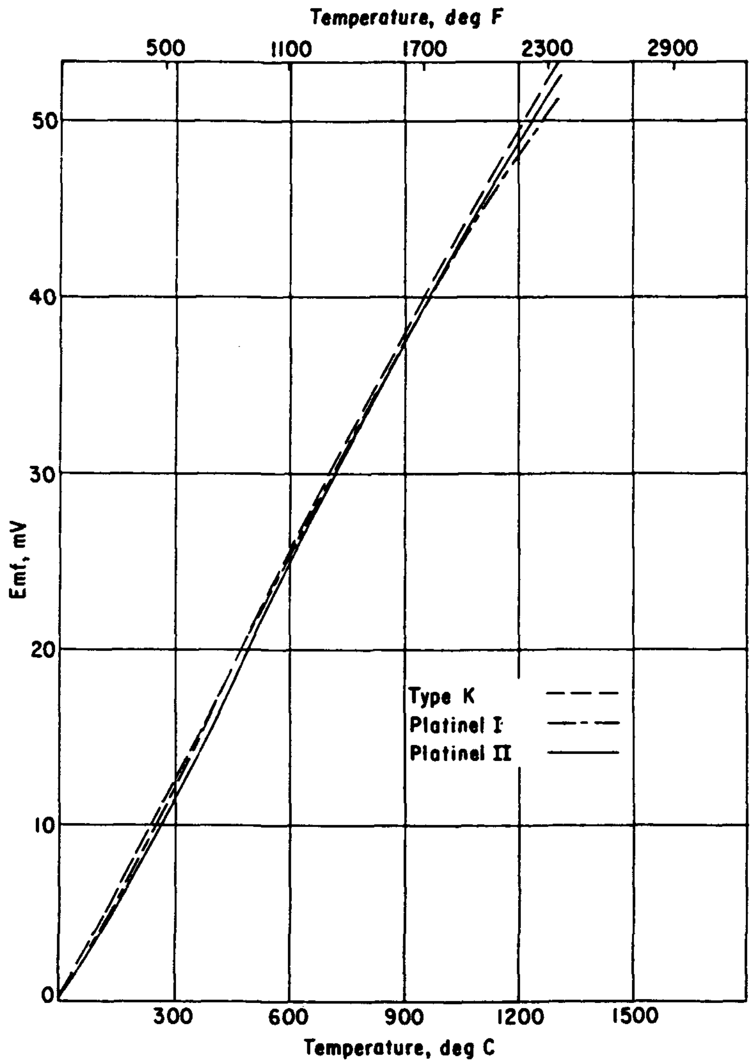


FIG. 3.8—*Thermal emf of platinel thermocouples.*

TABLE 3.15—*Platinel thermocouples.*

	Platinel II	Platinel I
Nominal operating temperature range, in.		
Reducing atmosphere (nonhydrogen)	NR[b]	NR
Wet hydrogen	NR	NR
Dry hydrogen[a]	1010°C (1850°F)	1010°C (1850°F)
Inert atmosphere	1260°C (2300°F)	1260°C (2300°F)
Oxidizing atmosphere	1260°C (2300°F)	1260°C (2300°F)
Vacuum	NR	NR
Maximum short-time temperature (<1 h)	1360°C (2480°F)	1360°C (2480°F)
Approximate microvolts per degree		
Mean, over nominal operating range (100 to 1000°C)	42.5/°C (23.5/°F)	41.9/°C (23.3/°F)
At top temperature of normal range (1000 to 1300°C)	35.5/°C (19.6/°F)	33.1/°C (18.4/°F)
Melting temperature, nominal		
Positive thermoelement—solidus	1500°C (2732°F)	1580°C (2876°F)
Negative thermoelement—solidus	1426°C (2599°F)	1426°C (2599°F)
Stability with thermal cycling	good	good
High-temperature tensile properties	fair	fair
Stability under mechanical working	?	?
Ductility (of most brittle thermoelement) after use	good	good
Resistance to handling contamination	?	?
Recommended extension wire at approximately 800°C (1472°F)		
Positive conductor	Type KP	Type KP
Negative conductor	Type KN	Type KN

[a]High-purity alumina insulators are recommended.
[b]NR = not recommended.

From Fig. 3.8 it is apparent that the emf match with the Type K thermocouple is excellent at high temperatures, but some departure occurs at low temperatures. Generally, the user of Platinel makes the connection between the thermocouple and the extension wire (Type K thermocouple wire) at an elevated temperature (800°C) where the match is good. However, if this is done, care should be taken to ensure that the junctions of both conductors are at the same temperature. If the junction is made at a temperature where the extension wire/thermocouple emf match is not too close, the corrections should be made. Other base-metal extension wires capable of matching the emf of the Platinels very closely at low temperatures to 160°C (320°F)J are also available.

It is recommended that precautions usually followed with the use of platinum-rhodium versus platinum thermocouples be observed when the Platinels are employed. Tests have shown that phosphorus, sulfur, and silicon have a deleterious effect on the life of the thermocouples.

3.3.3.2 Pallador I—Material, known as Pallador I (10% iridium 90% platinum) versus 40% palladium gold thermocouple was developed for use

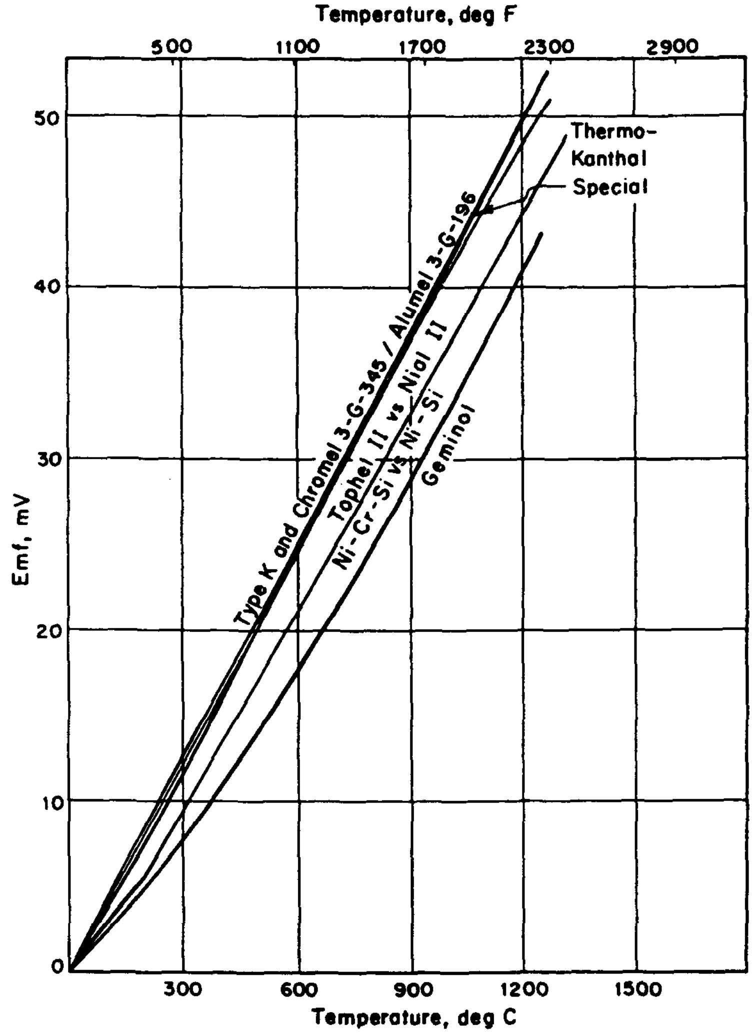


FIG. 3.9—*Thermal emf of nickel-chromium alloy thermocouples.*

in those regions where Type J material is used, but is not used in reducing atmospheres. This thermocouple may be used to 1000 C.

3.3.3.3. Pallador II—Pallador II provides a noble element thermocouple in the range of Type K, and may be used to 1250°C. The composition is 12.5% platinum-palladium versus 46% palladium-gold.

3.3.4 Nickel-Chromium Types

3.3.4.1 Nickel Chromium Alloy Thermocouples—Special nickel-chromium alloys are supplied by various manufacturers as detailed in the following paragraphs. Figure 3.9 and Table 3.16 give characteristics of these alloys.

3.3.4.1.1 Geminol—The Geminol[3] thermocouple, although not in production, is noted because some thermocouple materials may exist from earlier manufacturing and fabrication.

The composition of the positive thermoelement has been adjusted specifically to combat in reducing atmospheres the destructive corrosion known as "green rot."

The substitution of an 80% nickel-20% chromium type alloy for conventional (Type KP) 90% nickel-10% chromium alloy positive thermoelement, and a 3% silicon in nickel alloy for the conventional (Type KN) manganese-aluminum-silicon in nickel alloy negative thermoelement, results in a more oxidation-resisting thermocouple.

The temperature-emf curve is practically parallel to that of the conventional Type K thermocouple above 760°C (1400°F).

3.3.4.1.2 Thermo-Kanthal Special—The Thermo-Kanthal special thermocouple was developed to give improved stability at temperatures between 982°C (1800°F) and 1260°C (2300°F) over that obtained with conventional base-metal thermocouple materials.

3.3.4.1.3 Tophel II-Nial II—The Tophel-Nial thermocouple, although not in production, is noted because some thermocouples may exist from earlier manufacturing and fabrication.

1. The Tophel II-Nial II thermocouple was developed for improved oxidation resistance and emf stability over the conventional Type K thermocouple alloys in both oxidizing and reducing atmospheres at elevated temperatures.
2. Tophel II, which is the positive thermoelement, is a nickel-10% chromium base alloy with additions to resist "green rot" attack in reducing atmospheres at elevated temperatures. The emf of Tophel II is within the standard tolerance of the conventional Type K positive thermoelement over the entire temperature range of 0 to 1260°C (32 to 2300°F). Tophel II can be matched with any acceptable Type K negative thermoelement to form a thermocouple which is within the standard tolerance for the Type K thermocouple.
3. Nial II, which is the negative thermoelement, is a nickel-2.5% silicon base alloy with additions to improve the oxidation resistance and emf stability in an oxidizing atmosphere at elevated temperatures.
4. The Tophel II-Nial II thermocouple meets the emf tolerances designated in ASTM Specification E 230 for the Type K thermocouple from 149 to 1093°C (300 to 2000°F). From 0 to 149°C (32 to 300°F), the Tophel II-

TABLE 3.16—*Nickel-chromium alloy thermocouples.*

	Geminol	Thermo-Kanthal Special	Tophel II-Nial II	Chromel 3-G-345, Alumel 3-G-196
Nominal operating temperature range, in.				
Reducing atmosphere (nonhydrogen)	1205°C (2200°F)	...	1205°C (2200°F)	1205°C (2200°F)
Wet hydrogen	1205°C (2200°F)	1205°C (2200°F)	1205°C (2200°F)	1205°C (2200°F)
Dry hydrogen	1205°C (2200°F)	1205°C (2200°F)	1205°C (2200°F)	1205°C (2200°F)
Inert atmosphere	1205°C (2200°F)	1205°C (2200°F)	1205°C (2200°F)	1205°C (2200°F)
Oxidizing atmosphere	1205°C (2200°F)	1205°C (2200°F)	1205°C (2200°F)	1205°C (2200°F)
Vacuum	1040°C (1904°F)	...	1040°C (2000°F)	1040°C (2000°F)
Maximum short-time temperature	1260°C (2300°F)	1260°C (2300°F)	1260°C (2300°F)	1260°C (2300°F)
Approximate microvolts per degree				
Mean, over nominal operating range	18.7/°C (10.4/°F)	22.6/°C (12.6/°F)	40 μV/°C (22.5 μV/°F)	40.7 μV/°C (22.6 μV/°F)
At top temperature of normal range	22.2/°C (12.3/°F)	20.0/°C (11.1/°F)	36 μV/°C (20 μV/°F)	36 μV/°C (20 μV/°F)
Melting temperature, nominal				
Positive thermoelement	1400°C (2550°F)	1432°C (2610°F)	1430°C (2600°F)	1430°C (2600°F)
Negative thermoelement	1430°C (2600°F)	1410°C (2570°F)	1400°C (2550°F)	1400°C (2550°F)
Stability with thermal cycling	good	good	good	good
High-temperature tensile properties	good	good	good	good
Stability under mechanical work	intermediate	intermediate	fair	fair
Ductility (of most brittle thermoelement) after use	good	good	good	good
Resistance to handling contamination	good	good	good	good
Recommended extension wire				
Positive conductor	Geminol P	Thermo-Kanthal P	Tophel II or any Type K(+)	Chromel 3-G-345 or any Type K(+)
Negative conductor	Geminol N	Thermo-Kanthal N	Nial II	Alumel 3-G-196 and Type K(−)

Nial II thermocouple generates 0.1 mV (or 5 deg equivalent) less than the standard Type K thermocouple at the same temperature.

5. Tophel II-Nial II thermocouples can be used on existing instruments designed for the Type K thermocouples for temperatures sensing and control within the range of 149 to 1260°C (300 to 2300°F). If extension wire is needed, the negative extension wire should be Nial II, while the positive extension wire could either be Tophel II or any acceptable Type K (+) extension wire.

6. Through the improvements in both oxidation resistance and emf stability, Tophel II-Nial II thermocouples offer longer useful and total service life than conventional Type K thermocouples of the same size. As a corollary benefit, finer size Tophel II-Nial II thermocouples can be used to achieve equivalent or better stability than conventional Type K couples of larger sizes.

3.3.4.1.4 Chromel 3-G-345-Alumel 3-G-196—The Chromel 3-G-345-Alumel 3-G-196 thermocouple is designed to provide improved performance under extreme environmental conditions where the conventional Type K thermocouple is subject to accelerated loss of stability.

More specifically, Chromel 3-G-345 is a Type K positive thermoelement in which the basic 10% chromium-nickel alloy is modified to give improved resistance to preferential chromium oxidation ("green rot"). At temperatures from 871 to 1038°C (1600 to 1900°F), conventional Type K positive thermoelements operating in marginally oxidizing environments are subject to embrittlement and loss of output as a result of such attack.

Under those conditions, Type K thermocouples employing Chromel 3-G-345 positive thermoelements offer greater stability than conventional Type K thermocouples. The usual precautions regarding protection of Type K thermocouples in corrosive environments apply to the special thermocouple as well.

The modified Chromel thermoelement meets the accepted curve of emf versus platinum for Type K positive thermoelements, within standard tolerances. It can be combined with either Alumel 3-G-196 or conventional Alumel to form Type K thermocouples meeting standard emf tolerances.

Alumel 3-G-196 is a Type K negative thermoelement of greatly improved oxidation resistance. It is suited to use in both reducing and oxidizing atmospheres, where its stability of output is especially advantageous in fine wire applications at high temperatures. It is nominally 2.5% silicon-nickel.

Alumel 3-G-196 meets the accepted curve of emf versus platinum for Type K negative thermoelements at all temperatures from 0 to 1260°C (32 to 2300°F). It can be combined with either Chromel 3-G-345 or regular Chromel to form thermocouples meeting standard Type K thermocouple tolerances over the entire range from 0 to 1260°C (32 to 2300°F).

Type K thermocouples employing either or both special thermoelements can be used with conventional extension wires at no sacrifice in guaranteed accuracy of the thermocouple-extension wire combination.

3.3.5 Nickel-Molybdenum Types

3.3.5.1 20 Alloy and 19 Alloy[9] *(Nickel Molybdenum-Nickel Alloys)—*

1. The 20 Alloy/19 Alloy thermocouple was developed for temperature sensing and control applications at elevated temperatures in hydrogen or other reducing atmospheres. The emf table of the 20 Alloy versus the 19 Alloy does not conform to the Type K or any existing base metal thermocouples designated by ASTM Specification E 230.
2. The 19 Alloy, which is the negative thermoelement, is nickel-0.8% cobalt alloy. Its emf versus platinum values are somewhat more negative than those of the Type K negative thermoelement within the range of 0 to 1260°C (32 to 2300°F).
3. The 20 Alloy, which is the positive thermoelement, is essentially a nickel-18% molybdenum alloy. Its emf versus platinum values are less positive within the range of 0 to 260°C (32 to 500°F) than the Type K positive thermoelement, but more positive within the range of 260 to 1260°C (500 to 2300°F). Figure 3.10 and Table 3.17 show the characteristics of these alloys.
4. The 20 Alloy/19 Alloy thermocouple, when properly sealed in a protection tube, offers excellent emf stability at elevated temperatures in hydrogen or other reducing atmospheres.
5. The oxidation resistance of the 20 Alloy/19 Alloy thermocouple is not good. Metal sheathed 20 Alloy/19 Alloy has been used in oxidizing atmospheres, (see Ref *4*) but the unsheathed use of this alloy is not recommended for use in an oxidizing atmosphere above 649°C (1200°F).
6. 20 Alloy/19 Alloy extension wire may be used in connection with the 20 Alloy/19 Alloy thermocouple. Type KX extension wire may also be used from -20 to $+120$°C.

3.3.6 Tungsten-Rhenium Types

There are three tungsten-rhenium thermocouple systems available: (*a*) tungsten versus tungsten-26% rhenium, (*b*) doped tungsten-3% rhenium

[9] The 20 Alloy versus 19 Alloy thermocouple was developed by the General Electric Company. Since 1962 the Carpenter Technology Corporation has been the sole manufacturer of the 20 Alloy and the 19 Alloy.

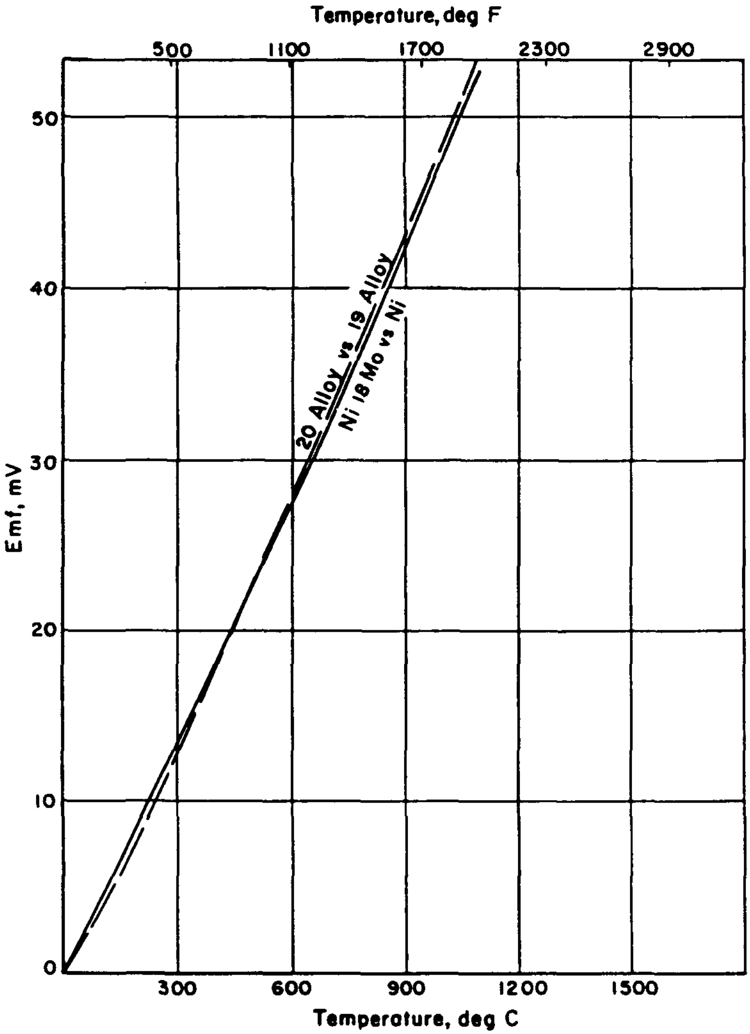


FIG. 3.10—*Thermal emf of nickel-molybdenum versus nickel thermocouples.*

versus tungsten-25% rhenium, and (*c*) doped tungsten-5% rhenium versus tungsten-26% rhenium. Refer to ASTM 988 for properties of tungsten-3 rhenium/tungsten-25 rhenium and tungsten-5 rhenium versus tungsten-26 rhenium has the lowest cost. All have been employed to 2760°C (5000°F), but general use is below 2316°C (4200°F). Applications for these couples have been found in space vehicles, nuclear reactors, and many high-temperature electronic, thermoelectric, industrial heating, and structural proj-

TABLE 3.17—*Physical data and recommended applications of the 20 Alloy/19 Alloy thermocouples.*

	20 Alloy/19 Alloy
Nominal operating temperature range, in.	
Reducing atmosphere (nonhydrogen)	1205°C (2200°F)
Wet hydrogen	1205°C (2200°F)
Dry hydrogen	1205°C (2200°F)
Inert atmosphere	1205°C (2200°F)
Oxidizing atmosphere	NR[a]
Vacuum	1205°C (2200°F)
Maximum short time temperature	1260°C (2300°F)
Approximate microvolts per degree	
Mean, over nominal operating range	55 μV/°C (31.0 μV/°F)
At top temperature of normal range	between the range of 1000 to 2300°F, 59 μV/°C (32.9 μV/°F)
Melting temperature, nominal	
Positive thermoelement	1430°C (2600°F)
Negative thermoelement	1450°C (2640°F)
General stability with thermal cycling (good, fair, poor)	good
High temperature tensile properties (good, fair, poor)	good
Unaffected by mechanical working (good, fair, poor)	fair
Ductility (of most brittle thermal element) after use (good, fair, poor)	fair
Resistance to handling contamination (good, fair, poor)	good
Recommended extension wire	
Positive conductor	20 Alloy
Negative conductor	19 Alloy

[a]NR = not recommended.

ects. However, when employed in a nuclear environment, the effect of transmutation of the thermal emf of the couples should be considered.

The use of tungsten in certain applications as the positive element may pose a problem, since heating tungsten to or above its recrystallization temperature (approximately 1200°C) causes embrittlement resulting in loss of room-temperature ductility; an effect that is not experienced with the alloy leg containing high rhenium. With proper handling and usage this combination can be employed satisfactorily for long periods. One approach to the brittleness problem is to add rhenium to the tungsten thermoelement. Early research showed that the addition of 10% rhenium to the tungsten element did much to retain ductility after recrystallization. This much rhenium, however, greatly reduced the emf response for the thermocouple. Other techniques to retain room-temperature ductility are used by manufacturers; these include special processing and doping with the addition of 5% or less rhenium to the tungsten thermoelement.

Doping usually consists of using additives during the process of preparing the tungsten powder and results in a unique microstructure in the finished wire. The additives essentially are eliminated during the subsequent sintering of the tungsten-rhenium powder compact. In fact, presently known analytical techniques do not disclose the presence of the additives above the background level of such substances normally present as impurities in non-doped tungsten or tungsten-rhenium alloys.

The emf response of tungsten-3% rhenium and tungsten-5% rhenium thermoelements used with thermoelements containing high percentages of rhenium is satisfactory. The thermoelectric power of the tungsten versus tungsten-26% rhenium, tungsten-3% rhenium versus tungsten-25% rhenium, and tungsten-5% rhenium versus tungsten-26% rhenium is comparable at lower temperatures, but drops off slightly for the latter two as the temperature is increased.

The tungsten thermoelement is not supplied to the user in a stabilized (recrystallized) condition; therefore, a small change in emf is encountered at the operating temperature. In the case of the doped tungsten-3% rhenium, doped tungsten-5% rhenium, tungsten-25% rhenium, and tungsten-26% rhenium thermoelements, these are supplied in a stabilized (recrystallized) condition.

All three thermocouple combinations are supplied as matched pairs guaranteed to meet the emf output of producer developed tables within ± 1%. In addition, compensating extension wires are available for each of the three combinations with maximum service temperatures as high as 871°C (1600°F) for tungsten-5% rhenium versus tungsten-26% rhenium.

Important factors controlling the performance at high temperatures are: (*a*) the diameter of the thermoelements (larger diameters are suitable for higher temperatures), (*b*) the atmosphere (vacuum, high-purity hydrogen, or high purity inert atmospheres required), (*c*) the insulation, and (*d*) sheath material. Some evidence is at hand, however, which indicates the possibility of selective vaporization of rhenium at temperatures of the order of 1900°C and higher when bare (unsheathed) tungsten-rhenium thermocouples are used in vacuum. For this reason, the vapor pressure of rhenium should be considered when a bare couple is used in a high vacuum at high temperatures. This, of course, is not a problem when these couples are protected with a suitable refractory metal sheath.

Figure 3.11 and Table 3.18 show the characteristics of these alloys.

3.3.7 Gold Types

3.3.7.1 Thermocouples Manufactured from Gold Materials—These are used primarily for research and development, and are not used in industrial

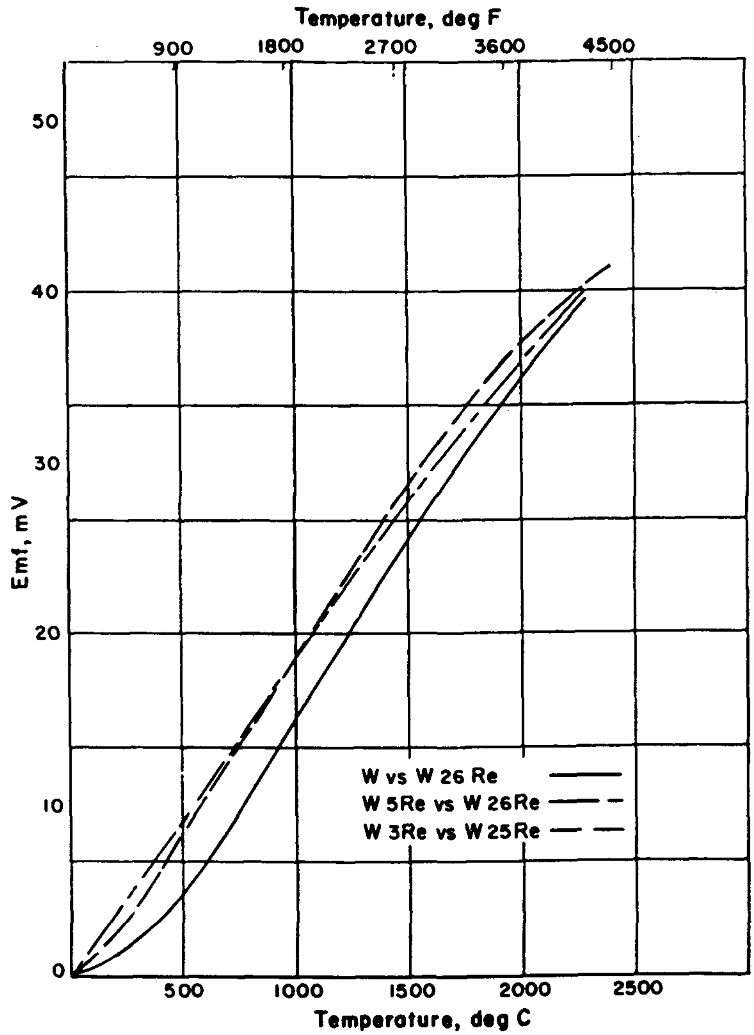


FIG. 3.11—*Thermal emf of tungsten-rhenium versus tungsten-rhenium thermocouples.*

application because of cost and accountability factors. Useful sensors have been used from as low as 1.341 K up to 1000°C.

3.3.7.2 KP or EP Versus Gold-0.07 Atomic Percent Iron Thermocouples—This thermocouple is for use in the cryogenic temperature measurement range from 1.341 K to approximately 300 K. The characteristics of this thermocouple material are described in Chapter 11—Cryogenics.

TABLE 3.18—*Tungsten-rhenium thermocouples.*

	W Versus W-26Re	W-3Re Versus W-25Re	W-5Re Versus W-26Re
Nominal operating temperature range, in.			
Reducing atmosphere (nonhydrogen)	NR[a]	NR	NR
Wet hydrogen	NR	NR	NR
Dry hydrogen	2760°C (5000°F)	2760°C (5000°F)	2760°C (5000°F)
Inert atmosphere	2760°C (5000°F)	2760°C (5000°F)	2760°C (5000°F)
Oxidizing atmosphere	NR	NR	NR
Vacuum[b]	2760°C (5000°F)	2760°C (5000°F)	2760°C (5000°F)
Maximum short-time temperature	3000°C (5430°F)	3000°C (5430°F)	3000°C (5430°F)
Approximate microvolts per degree			
Mean, over nominal operating range 0°C to 2316°C (32°F to 4200°F)	16.7/°C (9.3/°F)	17.1/°C (9.5/°F)	16.0/°C (8.9/°F)
At top temperature of normal range 2316°C (4200°F)	12.1/°C (6.7/°F)	9.9/°C (5.5/°F)	8.8/°C (4.9/°F)
Melting temperature, nominal			
Positive thermoelement	3410°C (6170°F)	3360°C (6080°F)	3350°C (6062°F)
Negative thermoelement	3120°C (5648°F)	3120°C (5648°F)	3120°C (5648°F)
Stability with thermal cycling	good	good	good
High-temperature tensile properties	good	good	good
Stability under mechanical work	fair	fair	fair
Ductility (of most brittle thermoelement after use)	poor	poor to good depending on atmosphere or degree of vacuum	poor to good depending on atmosphere or degree of vacuum
Resistance to handling contamination	good	good	good
Extension wire	available	available	available

[a]NR = not recommended.

[b]Preferential vaporization of rhenium may occur when bare (unsheathed) couple is used at high temperatures and high vacuum. Check vapor pressure of rhenium at operating temperature and vacuum before using bare couple.

3.3.7.3 Gold Versus Platinum Thermocouples—This thermocouple[10] is used primarily for research, and is characterized by excellent stability characteristics. It is useful to 1000°C, the range of a Type R or S thermocouple.

[10]Sigmund Cohn Corporation.

3.4 Compatibility Problems at High Temperatures

In order for thermocouples to have a long life at high temperatures, it is necessary to limit reactions between the metals, the atmosphere, and the ceramic insulation. Such reactions may change the strength or corrosion-resistant properties of the alloys, the electrical output of the thermocouple, or the electrical insulation properties of the ceramic insulant.

At extremely high temperatures, reactions can be expected between almost any two materials. Table 3.19 has been included to show the temperatures at which such reactions occur between pairs of metallic elements. At lower temperatures, certain reactions do not occur and such as do occur, proceed at a slower rate. Because of potential reactions, it is important to identify the impurities and trace elements as well as the major constituents of the thermocouple components. The "free energy of formation" (Gibbs free energy) for the oxides of each element at the temperatures of interest, can be determined to predict possible oxide reactions. Other reactions may occur and attention should be given to the possible formation of the carbides, nitrides, etc. of the various elements.

Helpful data may be obtained from published reports, but, because of the importance of trace elements and impurities, the sources should be treated with caution. In some cases, the amount and types of impurities in the materials used were unknown.

Certain reactions may be somewhat self-limiting in that the reaction product provides a protective film against further reaction. However, spalling or chipping off of the reaction product may occur because of thermal or physical stress. Thus, the reaction rate and the use of the corrosion product as protection can be ascertained only if tested under the desired operating conditions and times.

The use of oxygen-gettering material should be considered in instances where oxygen is present in limited amounts (see Ref *7*). This method has been employed with enclosed Type K thermocouples to limit the preferential oxidation of the positive thermoelement. A thin tube (or sliver) of titanium at the hottest location of the thermocouple has been used.

3.5 References

[*1*] Kollie, T. G. et al., "Temperature Measurement Errors with Type K (Chromel vs Alumel) due to Short Ranged Ordering in Chromel," *Review of Scientific Instruments,* Vol. 46, No. 11, November 1975.

[*2*] Moffat, R. J., "Understanding Thermocouple Behavior: The Key to Precision," Paper 60-628, Instrument Society of America, Vol. 5, Oct. 1968.

[*3*] Caldwell, F. R., "Thermocouple Materials," *NBS Monograph 40,* National Bureau of Standards, 1 March 1962.

TABLE 3.19—*Minimum melting temperatures of binary systems.*[a]

Element	W	Re	Os	Ta	Mo	Ir	Cb	Ru	Hf	Rh	V	Cr	Zr	Pt	Ti	Fe	Co	Ni	Si
Melting Point, °F	6170	5724	5432	5423	4730	4428	4425	4082	4030	3560	3452	3407	3353	3224	3034	2802	2723	2651	2588
Element																			
Si	2550	~2057	...	2525	~2570	2588	2372	...	...	...	~2550	~2408	~2480	1526	2426	2192	2183	1770	...
Ni	~2651	2651	...	2480	~2398	...	2145	2651	2102	...	2198	2444	~1764	~2651	1727	2588	~2646	...	...
Co	~2696	~2723	~2723	2331	2444	~2460	2255	~2550	2214	~2550	2264	2552	1789	~2590	1860	~2696	...	...	...
Fe	2775	~2802	...	~2462	2624	...	2480	2802	2372	~2750	2675	2743	1705	~2730	1985	...	...	...	...
Ti	~3034	~3034	...	~3034	~3034	2687	~3034	...	2985	...	~2777	2525	~2876	2390	...	...	...	...	...
Pt	~3224	~3224	...	...	3224	~3224	~3092	...	...	~3224	...	2552	2165	...	...	...	...	...	...
Zr	~3020	2912	...	3308	2740	...	3164	...	3353	...	2246	~2372	...	...	...	...	...	...	...
Cr	3038	3407	...	3092	3380	...	3020	2453	...	...	3182	...	...	...	...	...	...	...	...
V	2974	3452	...	3308	3452	...	3290	...	...	...	...	...	...	...	...	...	...	...	...
Rh	...	...	...	...	3524	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Hf	3488	~3416	...	...	3506	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Ru	4001	...	...	3578	3533	...	3056	...	...	...	...	...	...	...	...	...	...	...	...
Cb	~4425	4415	...	~4425	~4250	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Ir	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Mo	~4730	4424	~4406	~4730	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Ta	~5423	4874	~4388	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Os	4937	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Re	~5070	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
W	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...

[a] Adapted from: *Constitution of Binary Alloys* by Rodney P. Elliot, McGraw-Hill, New York, 1965.

[4] Wang, T. P., "Thermocouples for High Temperature Applications," Paper 87-1273, Instrument Society of America, Advances in Instrumentation, Vol. 42, 1987.
[5] *NBS Monograph 161,* National Bureau of Standards.
[6] McLaren, E. H. and Murdock, E. G., "The PT/AU Thermocouple," National Research Council of Canada, Oct. 1987.
[7] Neswald, R. G., "Titanium for Realists," *Space/Aeronautics,* Vol. 48, No. 5, Oct. 1967, pp. 90–99.

Chapter 4—Typical Thermocouple Designs

A complete thermocouple temperature sensing assembly, in accordance with the present state of the art, consists of one or more of the following:

A. Sensing Element Assembly—In its most basic form this assembly includes two dissimilar wires, supported or separated or both by electrical insulation, and joined at one end to form a measuring junction. Such assemblies usually fall into one of three categories; (1) those formed from wires having nonceramic insulation, (2) those with hard-fired ceramic insulators, and (3) those made from sheathed, compacted ceramic-insulated wires. This chapter will deal only with the first two. See Chapter 5 for complete details on the latter.

B. Protecting Tube—Ceramic and metal protecting tubes serve the purpose of protecting the sensing element assembly from the deleterious effects of hostile atmospheres and environments. In some cases, two concentrically arranged protecting tubes may be used. The one closest to the sensing element assembly is designated the primary protecting tube, while the outer tube is termed the secondary protecting tube. Combinations such as an aluminum oxide primary tube and a silicon carbide secondary tube often are used to obtain the beneficial characteristics of the combination, such as resistance to cutting flame action and ability to resist thermal and mechanical shock.

C. Thermowell—More critical or demanding applications may require the use of specially machined and drilled solid bar stock called thermowells for not only protection of the thermocouple, but also to withstand high pressure or stresses or erosion or both caused by material flows within containment vessels. These drilled wells, as they are sometimes called, are machined to close tolerances, and highly polished to inhibit corrosion.

D. Terminations—Sensing element assembly wire terminations are made to:

(*a*) Terminals (usually screw type)
(*b*) Connection head
  1. General purpose type
  2. Screw cover type
  3. Open type

(*c*) Plug and jack quick-disconnect
(*d*) Military standard (MS) type of connector
(*e*) Miscellaneous connection devices such as crimp-on sleeves, transition fittings filled with epoxy or other potting materials, and so on.

E. Miscellaneous Hardware—These include:

(*a*) Pipe nipple or adapter—to join the protecting tube to the head
(*b*) Thermocouple gland—used primarily with sheathed, compacted ceramic-insulated thermocouple assemblies to serve the dual function of mounting and sealing-off pressure in the mounting hole (see Chapter 5). Such glands may also be used with small protecting tubes.
(*c*) Threaded bushing—welded or brazed to the protecting tube and screwed into the mounting hole.

4.1 Sensing Element Assemblies

Typical thermocouple element assemblies, shown in Fig. 4.1, A and B, illustrate common methods of forming the measuring junction, A—by twisting and welding (twisting provides added strength), and B—by butt-welding. C shows an assembly using nonceramic insulation such as asbestos or fiber glass. New ceramic fibers are available which extend the upper temperature limits of this form of insulation. D, E, and F show the use of various forms of hard fired ceramic insulators, double bore (D) fish-spine or ball and socket (E) and four-hole (F). Fish-spine provides flexibility, and four-hole provides for two independent sensing elements.

4.2 Nonceramic Insulation

The normal function of thermocouple insulation is to provide electrical separation for the thermoelements. If this function is not provided or is compromised in any way, the indicated temperature may be in error. Insulation is affected adversely by moisture, abrasion, flexing, temperature extremes, chemical attack, and nuclear radiation. Each type of insulation has its own limitations. A knowledge of these limitations is essential, if accurate and reliable measurements are to be made.

Some insulations have a natural moisture resistance. Teflon, polyvinyl chloride (PVC), and some forms of polyimides are examples of this group. With the fiber type insulations, moisture protection results from impregnating with substances such as wax, resins, or silicone compounds. Protection from abrasion and flexing is also generally provided by impregnating materials. However, one cycle over their rated temperatures will result in a deterioration of this protection. Once the impregnating materials have been

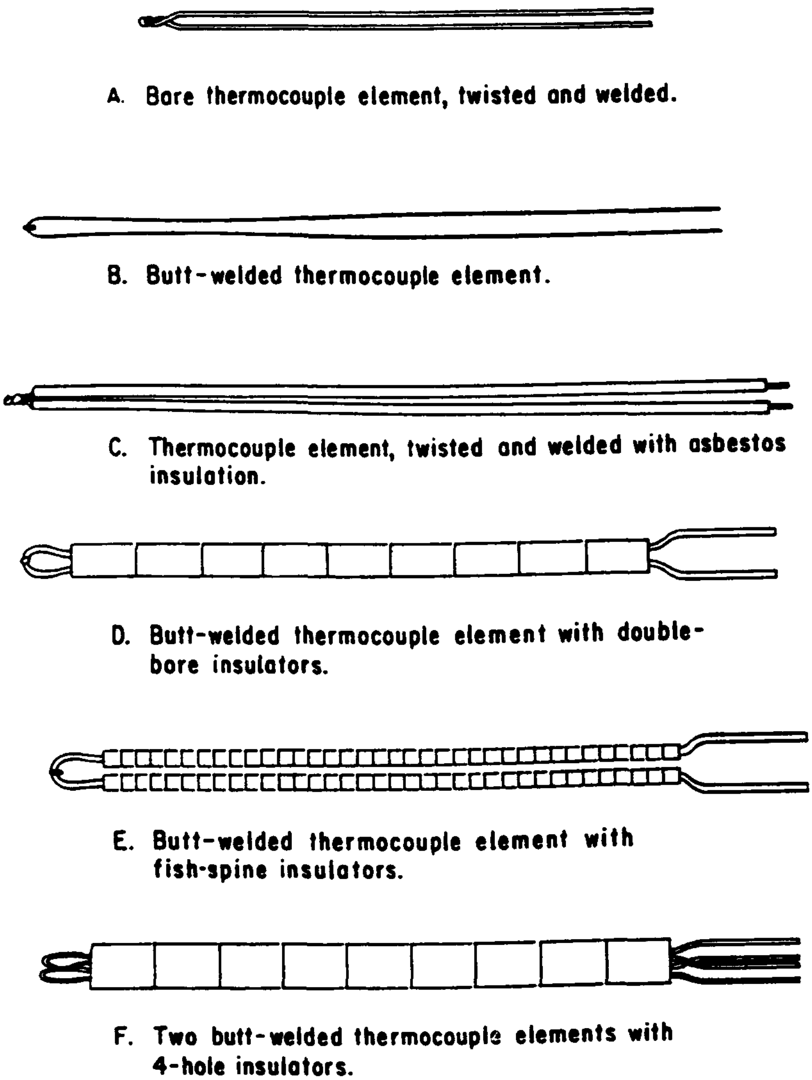


FIG. 4.1—*Typical thermocouple element assemblies.*

exposed to temperatures at which they vaporize there is no longer moisture or mechanical protection.

The moisture penetration problem is not confined to the sensing end of the thermocouple assembly. For example, if the thermocouple passes through hot or cold zones or through an area which becomes alternately hot and cold, condensation may produce errors in the indicated temperature, unless adequate moisture resistance is provided.

After exposure to temperatures exceeding the limitations of the insulation, whole sections of the insulation can fall away resulting in bare wire and a possible "short." Thermocouples in this condition should not be used if any flexing or abrasion is expected. It is recommended that they be discarded or that the exposed portion of the thermocouple assembly be cut off and the measuring junction reformed.

Insulations are rated for a maximum temperature both for continuous usage and for a single exposure. It is imperative to observe the limits when selecting an insulating material. At elevated temperatures even those insulations which remain physically intact may become conductive. Under these conditions, the output of the thermocouple may be a function of the highest temperature to which the insulation is exposed, rather than the temperature of the measuring junction. The change in insulation resistance may be permanent if caused by deterioration of organic insulants or binders which leave a carbon residue. In considering the temperature to which the insulation is exposed, it should not be assumed that this is the temperature of the measuring junction. A thermocouple may be attached to a massive specimen which is exposed to a high-temperature source to achieve a rapid heating rate. Parts of the thermocouple wires, not in thermal contact with the specimen, can be overheated severely while the junction remains within safe temperature limits. With this in mind, high quality insulation should be used when rapid heating rates are expected. Very little factual information is available on actual deterioration rates and magnitudes, but the condition is real, so a conservative approach is a requisite of good engineering practice.

The basic types of flexible insulations for elevated temperature usage are fiber glass, fibrous silica, and asbestos.[1] Of the three materials, fibrous silica has the best high-temperature electrical properties, but, because this insulation normally is not impregnated, its handling and abrasion characteristics leave something to be desired. The next best high-temperature insulation is asbestos. Because this material has very poor mechanical properties a carrier fiber or an impregnating material is added. In some instances, this carrier is cotton or another organic compound which leaves a carbon residue after exposure to a temperature at which it burns. This results in a breakdown of electrical insulation. Asbestos loses its mechanical strength after exposure to elevated temperatures and may break away from the wire with little or even no handling. A more commonly used insulation is fiber glass. It can be impregnated to provide improved moisture and mechanical characteristics within the temperature limitations of the impregnating compound. The most frequently used type of fiber glass has an upper temperature limit of approximately 500°C (900°F) for continuous use. If one is willing to sacrifice the handling characteristics, nonimpregnated fiber glass insulations are available which withstand higher temperatures.

[1]Asbestos can be hazardous to health. Proper precaution should be exercised in its use.

Modern technology has led to the development of ceramic fibers which markedly increase the upper use temperature of flexible insulations. These insulations, if properly applied and handled, will allow base metal thermocouples to be used to their upper use temperatures within their limits of exposure to the environment in which they are placed. For example, Type K thermocouples can be exposed to their stated upper temperature limit, and be adequately insulated provided the environmental factors do not otherwise affect the serviceability of the insulation. The same precautions must be observed with these thermocouples as with any other thermocouple installation. The user must be knowledgeable about his application and the materials which he intends to use. These extremely high-temperature insulations should be employed without impregnants for maximum termperature service.

Chemical deterioration of insulation materials can produce a number of problems. If the environment reacts with the insulation, both the insulation and environment can be affected adversely. The insulation can be removed easily or become electrically conductive, and the process system can become contaminated. For example, some insulation materials are known to cause cracking in austenitic stainless steels.

In summary, an insulation should be selected only after considering possible exposure temperatures and heating rates, the number of temperature cycles, mechanical movement, moisture, routing of the thermocouple wire, and chemical deterioration (Table 4.1).

Industry has established insulation color codes for standardized letter-designated thermocouple and extension wire types. U.S. color codes are shown in Table 4.2.

In Table 4.3, the color code of the United States is listed in comparison with those from United Kingdom, Germany, Japan, France, China, U.S.S.R., and IEC (International Electro-Chemical Commission) codes. In the United States code, the color of all negative conductors is red. For the United Kingdom code, the color of all negative conductors is blue. For the German code, the color of all positive conductors is red. For the French code, the color for all positive conductors is yellow. In the Japanese code, the color for all positive conductors is red and the color for all negative conductors is white. The color of overall insulation is different for different types of thermocouples. For the IEC code, the color of all negative conductors is white. The color of all positive conductors is the same as the overall insulation. For the Chinese code, the color of all positive conductors is red. The color code for all overall insulation is black for standard grade material, gray for premium grade general purpose, and yellow for premium grade for high-temperature applications. For the U.S.S.R. code, one or both of the conductors may have two colors which are similar in shades.

Letter Code V is used to designate alternate extension wire for Type K thermocouple. It is not a standard designation in the United States. Coun-

TABLE 4.1—*Insulation characteristics.*

Insulation	Lower Temperature Limit, °C (°F)	Continuous Use Temperature Limit, °C (°F)	Single Exposure Temperature Limit, °C (°F)	Moisture Resistance	Abrasion Resistance
Cotton	...	95 (200)	95 (200)	poor	fair
Enamel and cotton	...	95 (200)	95 (200)	fair	fair
Polyvinyl chloride	−40 (−40)	105 (220)	105 (220)	excellent	good
Type R[a]	−55 (−67)	125 (257)	125 (257)	excellent	good
Nylon[b]	−55 (−67)	125 (260)	125 (260)	poor	good
Teflon[b]	−55 (−67)	205 (400)	315 (600)	excellent	good
Kapton[b]	−260 (−436)	260 (500)	260 (500)	excellent	excellent
B fiber[a]	...	260 (500)	260 (500)	fair	excellent
Teflon and fiberglass[c]	...	315 (600)	370 to 540 (700 to 1000)	excellent to 600°F	good
Fiberglass-varnish or silicone impregnation E[d]	...	480 (900)	540 (1000)	fair to 400°F, poor above 400°F	fair to 400°F, poor above 400°F
Fiberglass nonimpregnated S[e]	...	540 (1000)	650 (1200)	poor	fair
Asbestos[f] and fiberglass with silicone[g]	...	480 (900)	650 (1200)	fair to 400°F	fair to 400°F, poor above 400°F
Felted asbestos	...	540 (1000)	650 (1200)	poor	poor
Asbestos over asbestos	...	540 (1000)	650 (1200)	poor	poor
Refrasil[h]	...	870 (1600)	1100 (2000)	very poor	very poor
Ceramic fibers (for example, Nextel[i] and Cefir[j]	...	1000 (1830)	1370 (2500)	very poor	poor

[a]Type R and B-fiber trademark of Thermo Electric's Thermoplastic Elastomer and Polyimide fiber, respectively.
[b]Nylon, Teflon and Kapton, Trademarks of the E. I. duPont.
[c]The Teflon vaporizes at 315°C (600°F) with possible toxic effects.
[d]E = Electrical grade fiberglass
[e]S = Structural grade fiberglass
[f]Asbestos is hazardous to our health and environment. The users are encouraged to use alternate material.
[g]Individual wires are asbestos and overbraid is fiberglass.
[h]Trademark of the H. I. Thompson Company.
[i]Trademark of the 3M Corporation, Nextel 312 and Nextel 440 can be used up to 1200°C (2200°F) and 1370°C (2500°F), respectively.
[j]Trademark of Thermo Electric Company.

TABLE 4.2—*U.S. color code of thermocouple and extension wire insulations.*

Thermocouple Wire			Thermocouple Extension Wire		
	Insulation Color Code			Insulation Color Code	
Symbol	Single	Duplex	Symbol	Single[b]	Duplex
E		brown	EX		purple
EP	purple		EPX	purple	
EN	red		ENX	red, or red with purple trace	
J		brown	JX		black
JP	white		JPX	white	
JN	red		JNX	red, or red with white trace	
K		brown	KX		yellow
KP	yellow		KPX	yellow	
KN	red		KNX	red, or red with yellow trace	
N		brown	NX		orange
NP	orange		NPX	orange	
NN	red		NNX	red, or red with orange trace	
T		brown	TX		blue
TP	blue		TPX	blue	
TN	red		TNX	red, or red with blue trace	
B	...[a]		BX		gray
BP	...[a]		BPX	gray	
BN	...[a]		BNX	red, or red with gray trace	
R	...[a]		RX		green
RP	...[a]		RPX	black	
RN	...[a]		RNX	red, or red with black trace	
S	...[a]		SX		green
SP	...[a]		SPX	black	
SN	...[a]		SNX	red, or red with black trace	

NOTE—For a more complete explanation of color codes see ANSI MC96.1.

[a]Normally noble metal thermocouples are not insulated with colored insulations. However, if they were, the color codes of the extension wire singles but with brown duplex would apply.

[b]The trace colors are recommended when duplex coverings are not present, but optional when duplex coverings are applied.

tries having both the Type K and Type V grades are United Kingdom, Japan, France, and China. United States, Germany, and IEC have only Type K thermocouple and extension wire. Based on composition of the conductors supplied by our source, U.S.S.R. has only the equivalent of V grade extension wire.

4.3 Hard-Fired Ceramic Insulators

Hard-fired ceramic insulators most commonly used with bare thermocouple elements are mullite, aluminum oxide, and steatite, the latter being the most common material where fish-spine insulators are concerned. Single, double, and multibore insulators are available in a wide variety of sizes

TABLE 4.3—*Comparison of color codes for T/C extension wire cable.*

Letter code	Conductor	U.S.	U.K. BS1843	Germany DIN43714	Japan JIS1620	France NFC42-323	IEC 584-3 (1989)	China[b]	U.S.S.R.[c]
E	+	purple	brown	red	red	yellow	purple	red	purple or black
	−	red	blue	black	white	purple	white	brown	yellow or orange
	duplex	purple	brown	black	purple	purple	purple	[b]	. . .
J	+	white	yellow	red	red	yellow	black	red	white
	−	red	blue	blue	white	black	white	purple	yellow or orange
	duplex	black	black	blue	yellow	black	black	[b]	. . .
K	+	yellow	brown	red	red	yellow	green	red	. . .
	−	red	blue	green	white	purple	white	blue	. . .
	duplex	yellow	red	green	blue	yellow	green	[b]	. . .
V[a]	+	. . .	white	. . .	red	yellow	. . .	red	red or pink
	−	. . .	blue	. . .	white	purple	. . .	black	brown
	duplex	. . .	red	. . .	blue	red	. . .	[b]	. . .
N	+	orange	. . .	. . .	. . .	. . .	pink	. . .	. . .
	−	red	. . .	. . .	. . .	. . .	white	. . .	. . .
	duplex	orange	. . .	. . .	. . .	. . .	pink	. . .	. . .
T	+	blue	white	red	red	yellow	brown	red	red or pink
	−	red	blue	brown	white	blue	white	white	brown
	duplex	blue	blue	brown	brown	blue	brown	[b]	
B	+	gray	no standard	red	red	no standard	. . .	. . .	. . .
	−	red	use copper	gray	white	use copper	. . .	. . .	. . .
	duplex	gray	wire	gray	gray	wire	. . .	. . .	. . .
R	+	black	white	red	red	. . .	orange	red	. . .
	−	red	blue	white	white	. . .	white	green	. . .
	duplex	green	green	white	black	. . .	orange	[b]	. . .
S	+	black	white	red	red	yellow	orange	red	red or pink
	−	red	blue	white	white	green	white	green	green
	duplex	green	green	white	black	green	orange	[b]	. . .

[a]Compensating extension wire for Type K thermocouple, nonstandard in U.S.
[b]Info from (1/26/90) Prof. Ling of National Metrology Institute of China. Color code for overall insulation, black for standard grade material, gray for premium grade general purpose, yellow for high temperature premium.
[c]Information from A. Dmitriyev (12/4/90).

in both English and metric dimensions. Lengths commonly stocked by many suppliers are 1, 2, 3, 6, 12, 18, 24, and 36 in. Lengths to 72 in. are available on special order. The longer these insulators become, the more susceptible they are to breakage, so care must be exercised in handling.

It is advisable, especially in the case of precious metal thermocouple element assemblies, to keep the insulator in one piece to minimize contamination from the environment.

Hard-fired ceramic insulators are made in oval as well as circular cross-section examples of which are shown in Fig. 4.2. Properties of refractory oxides are tabulated in Table 4.4.

4.4 Protecting Tubes, Thermowells, and Ceramic Tubes

4.4.1 Factors Affecting Choice of Protection for Thermocouples

Thermocouples must be protected from atmospheres that are not compatible with the thermocouple alloys. Protecting tubes serve the double pur-

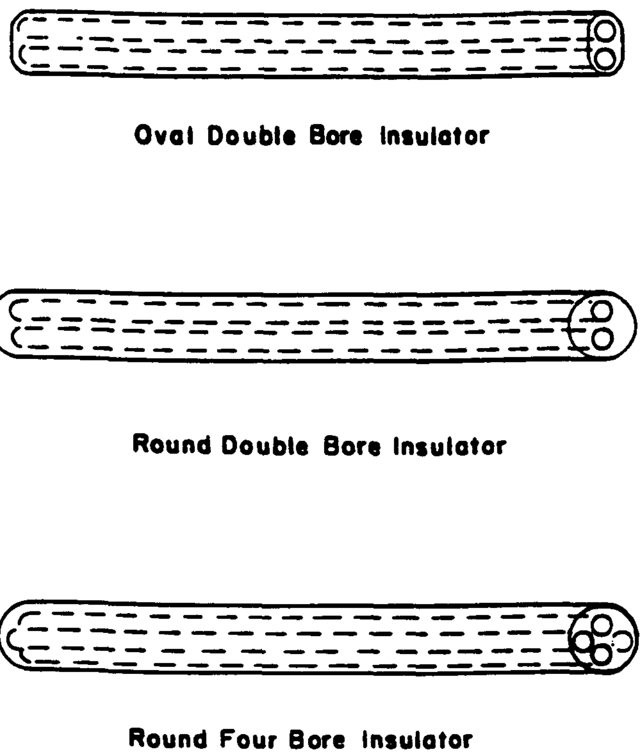


FIG. 4.2—*Cross-section examples of oval and circular hard-fired ceramic insulators.*

TABLE 4.4—*Properties of refractory oxides.*[a]

	Composition	Porosity, volume %	Fusion Temperature, °C	Maximum Normal Use Temperature, °C	Density Bulk (*b*), True (*t*), g/cm^3	Specific Heat Capacity (cal/g/°C) 20 to 1000°C	Linear Expansion (10^{-6} in./in./°C) 20 to 1000°C	Thermal Conductivity (cal s^{-1} C^{-1} cm^{-2} cm) At 100°C	Thermal Conductivity At 1000°C	Modulus of Rupture, psi At 20°C	Modulus of Rupture, psi At 1000°C	Modulus of Elasticity, 10^6 psi	Thermal Stress Resistance
Sapphire crystal	99.9 Al_2O_3	0	2030	1950	3.97(*t*)	0.26	8.6	0.072	0.019	40 000–150 000	30 000–100 000	55	very good
Sintered alumina	99.8 Al_2O_3	3 to 7	2030	1900	3.97(*t*)	0.26	8.6	0.069	0.014	30 000	22 000	53	good
Sintered beryllia	99.8 BeO[b]	3 to 7	2570	1900	3.03(*t*)	0.50	8.9	0.500	0.046	20 000	10 000	45	excellent
Sintered calcia	99.8 CaO	5 to 10	2600	2000	3.32(*t*)	0.23	13.0	0.033	0.017	...	...	...	fair-poor
Chrome-alumina cermet (Haynes Stellite LT-1)	77 Cr, 23 Al_2O_3	2	1850	1300	5.9(*b*)	0.16	8.9	0.08	0.05	45 000	20 000	37.5	excellent
Sintered magnesia	88.8 MgO	3 to 7	2800	1900	3.58(*t*)	0.25	13.5	0.082	0.016	14 000	12 000	30.5	fair-poor
Sintered mullite	72 Al_2O_3,28 SiO	3 to 10	1810	1750	3.03(*t*)	0.25	5.3	0.013	0.008	12 000	7 000	21	good
Sintered forsterite	99.5 Mg_2SiO_4	4 to 12	1885	1750	3.22(*t*)	0.23	10.6	0.010	0.005	10 000	...	...	fair-poor
Sintered spinel	99.8 $MgAl_2O_4$	3 to 10	2135	1850	3.58(*t*)	0.25	8.8	0.033	0.013	12 300	11 000	34.5	fair
Sintered titania	99.5 TiO_2	3 to 7	1840	1600	4.24(*t*)	0.20	8.7	0.015	0.008	8 000	6 000	...	fair-poor
Sintered thoria	99.8 ThO_2[b]	3 to 7	3050	2500	10.50(*t*)	0.06	9.0	0.022	0.007	12 000	7 000	21	fair-poor
Sintered yttria	99.8 Y_2O_3	2 to 5	2410	2000	4.50(*t*)	0.13	9.3	(0.02)	...	...	...	...	fair-poor
Sintered urania	99.8 UO_2	3 to 10	2800	2200	10.96(*t*)	0.06	10.0	0.020	0.007	12 000	18 000	25	fair-poor
Sintered stabilized zirconia	92 ZrO_2, 4 HfO_2, 4 CaO	3 to 10	2550	2200	5.6(*t*)	0.14	10.0	0.005	0.005	20 000	15 000	22	fair-good
Sintered zircon	99.5 $ZrSIO_1$	5 to 15	2420	1800	4.7(*t*)	0.16	4.2	0.015	0.008	12 000	6 000	30	good
Silica glass	99.8 SiO_2	0	1710	1100	2.20(*t*)	0.18	0.5	0.004	0.012	15 500	...	10.5	excellent
Mullite porcelain	70 Al_2O_3, 27 SiO_2, 3 Mo + M_2O	2 to 10	1750	1400	2.8(*b*)	0.25	5.5	0.007	0.006	10 000	6 000	10	good
High alumina porcelain	90–95 Al_2O_3, 4–7 SiO_2, 1 to 4 Mo + M_2O	2 to 5	1800	1500	3.75(*b*)	0.26	7.8	0.05	0.015	50 000	...	53	very good

[a]Kingery, W. D., "Oxides for High Temperature Applications," *Proceedings of the International Symposium on High Temperature Technology*, McGraw-Hill, New York, 1960.
[b]BeO and ThO_2 can be hazardous to health. Handle with caution.

pose of guarding the thermocouple against mechanical damage and interposing a shield between the thermocouple and its surroundings so as to maintain it as nearly as possible in its best working environment.

The conditions that must be excluded are: (*a*) metals (solid, liquid, or vapor) which, coming into contact with the thermocouple, would alter its chemical composition; (*b*) furnace gases and fumes which may attack the thermocouple materials (sulfur and its compounds are particularly deleterious); (*c*) materials such as silica and some of its metallic oxides, which, in contact with the thermocouple in a reducing atmosphere, are reduced, and combine with the thermocouple to attack it; and (*d*) electrolytes which would attack the thermocouple material.

The choice of the proper protecting tube is governed by the conditions of use and by the tolerable life of the thermocouple. On many occasions the strength of the protecting tube may be more important than the long-term thermoelectric stability of the thermocouple. On the other hand, gas tightness and resistance to thermal shock may be of paramount importance. In other cases, chemical compatibility of the protecting tube with the process may be the deciding factor. The problem of "green-rot" discussed in Section 3.1.1 also should be considered. In short, careful consideration must be given to each unique application.

As important as proper selection of the material is the cleanliness of the inside of the tube. Foreign matter, especially sulfur bearing compounds, can seriously affect the serviceability of the thermocouple as well as the tube itself.

4.4.2 Common Methods of Protecting Thermocouples

4.4.2.1 Protecting Tubes—By proper selection of material, metal protecting tubes can offer adequate mechanical protection for base metal thermocouples up to 1150°C (2100°F) in oxidizing atmospheres. It must be remembered that all metallic tubes are somewhat porous at temperatures exceeding 815°C (1500°F), so that, in some cases, it may be necessary to provide an inner tube of ceramic material; otherwise, damaging gaseous vapors may enter the tube and attack the thermocouple.

Typical use temperatures for protecting tubes are given next. These should be used only as a guide with careful selection of the proper material for each application.

(*a*) Carbon steels can be used to 540°C (1000°F) in oxidizing atmospheres, and considerably higher if protected.

(*b*) Austenitic stainless steels (AISI 300 series) can be used to 870°C (1600°F), in oxidizing atmospheres. Types 316, 317, and 318 can be used in some reducing atmospheres.

(*c*) Ferritic stainless steels (AISI 400 series) can, with proper selection, be used as high as 1093°C (2000°F) in both oxidizing and reducing atmospheres. Martensitic types (AISI 400 series), by contrast, are limited to lower temperatures for continuous use, with the top temperature being about 675°C (1250°F) for Type 410 stainless.

(*d*) High-nickel alloys, Nichrome,[2] Inconel,[3] etc., can be used to 1150°C (2100°F) in oxidizing atmospheres.

As with carbon steels, the stainless steels and other alloy steels used for protecting tubes can be exposed to higher temperatures if properly protected.

The majority of metal protecting tubes are made from pipe sized tubing, cut to the proper length, and threaded on one end for attachment of the terminal head. The other end is closed by welding using a filler metal which is the same as the parent metal.

4.4.2.2 Thermowells—Where the thermocouple assembly is subject to high-pressure or flow-induced stresses or both, a drilled thermowell often is recommended. Although less expensive metal tubes, fabricated by plugging the end, may satisfy application requirements, more stringent specifications usually dictate the choice of gun-drilled bar stock, polished and hydrostatically tested as a precaution against failure.

Examples of drilled thermowells are shown in Fig. 4.3.

4.4.2.3 Ceramic Tubes—Ceramic tubes are used usually at temperatures beyond the ranges of metal tubes although they are sometimes used at lower temperatures in atmospheres harmful to metal tubes.

The ceramic tube most widely used has a mullite base with certain additives to improve the mechanical and thermal shock properties. The upper temperature limit is 1650°C (3000°F).

Silicon carbide tubes are used as secondary protecting tubes. This material resists the cutting action of flames. It is not impermeable to gases and, where a dense tube is required, a nitride-bonded type material can be obtained with greatly reduced permeability.

Fused alumina tubes can be used as primary or secondary protecting tubes or both where temperatures to 1900°C (3450°F) are expected and a gas tight tube is essential. Fused alumina tubes and insulators should be used with-platinum-rhodium/platinum thermocouples above 1200°C (2200°F) in order to ensure long life and attain maximum accuracy. The mullite types contain impurities which can contaminate platinum above 1200°C (2200°F). The alumina tubes are more expensive than the mullite base tubes but can be obtained impervious to most gases to 1815°C (3300°F).

4.4.2.4 Metal-Ceramic Tubes—"Cermets" are combinations of metals and metallic oxides which, after proper treatment, form dense, high-strength, corrosion-resistant tubes and are available for use to about 1425°C (2600°F) in most atmospheres.

[2]Trademark of Harrison Alloys.
[3]Trademark of International Nickel Company.

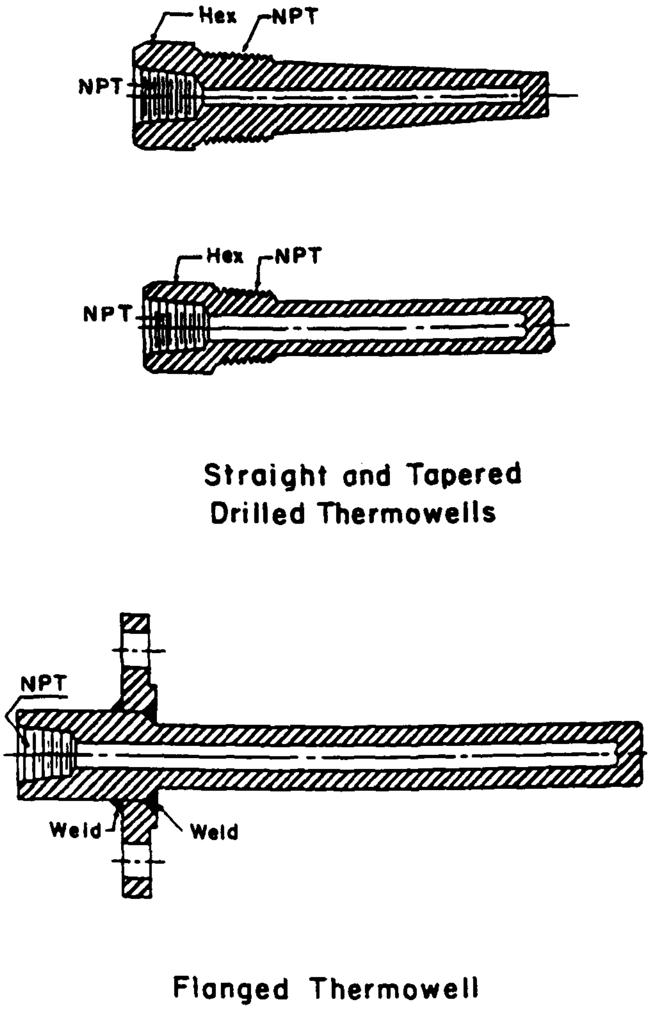


FIG. 4.3—*Examples of drilled thermowells.*

4.5 Circuit Connections

To reduce costs and provide suitable insulation in the low-temperature parts of the thermocouple circuit, extension wire (see Section 3.2) is often used to extend the circuit to the measuring instrument. The intermediate junction between the thermocouple and extension wires must be held below the upper temperature limit of the extension wires (see Table 4.2) or considerable errors may be introduced.

Sheathed, mineral-insulated thermocouples can incorporate a transition fitting within which the extension wires are welded or brazed to the thermocouple wires. Where hard-fired ceramic insulators are used, the thermocouple wires usually terminate in a "head" which is attached to the insulator or to the protecting tube in which the insulator is housed. The interconnections are made by clamps or binding posts to permit easy replacement of the thermocouple. One assumes in such a component that, if a third metal is introduced into the circuit between the thermocouple and extension wires, no temperature gradient exists along its length. If this is so, in accordance with the law of intermediate metals, no error will result.

Industrial thermocouples often use heads of cast iron, aluminum, or die cast construction with screw covers and a temperature resistant gasket seal. Terminal blocks are commonly provided consisting of a ceramic or phenolic block and brass terminals. These assemblies are particularly likely to introduce errors due to temperature gradients, so they should be used with caution. Where phenolic terminal blocks are used, an upper temperature of about 170°C (340°F) applies.

To reduce the likelihood of thermal gradient errors, connectors of the quick disconnect type intended for use in thermocouple circuits have contacts made of thermoelectric materials matching the thermocouple conductors. Even with these connectors some errors can result when extreme gradients across the connectors are encountered. Quick disconnect connectors are more commonly used with sheathed ceramic insulated assemblies. See Chapter 5 for more details on their application.

Since any material inhomogeneity in the circuit will introduce an error in the presence of a temperature gradient, best results will be obtained by avoiding extension wires, connectors, and terminal blocks. The thermocouple wires should be run directly to the reference junction after which copper wires are interconnected for extension to the measuring instrument.

4.6 Complete Assemblies

Figures 4.4 and 4.5 show complete assemblies of the components which have been described in the foregoing sections. Many other combinations are possible. Manufacturers' catalogs may be consulted for other varieties and details.

4.7 Selection Guide for Protecting Tubes

The following information in Table 4.5 has been extracted from various manufacturers' literature. It is offered as a guide to the selection of protecting tubes. Caution should be exercised in applying this information to specific situations.

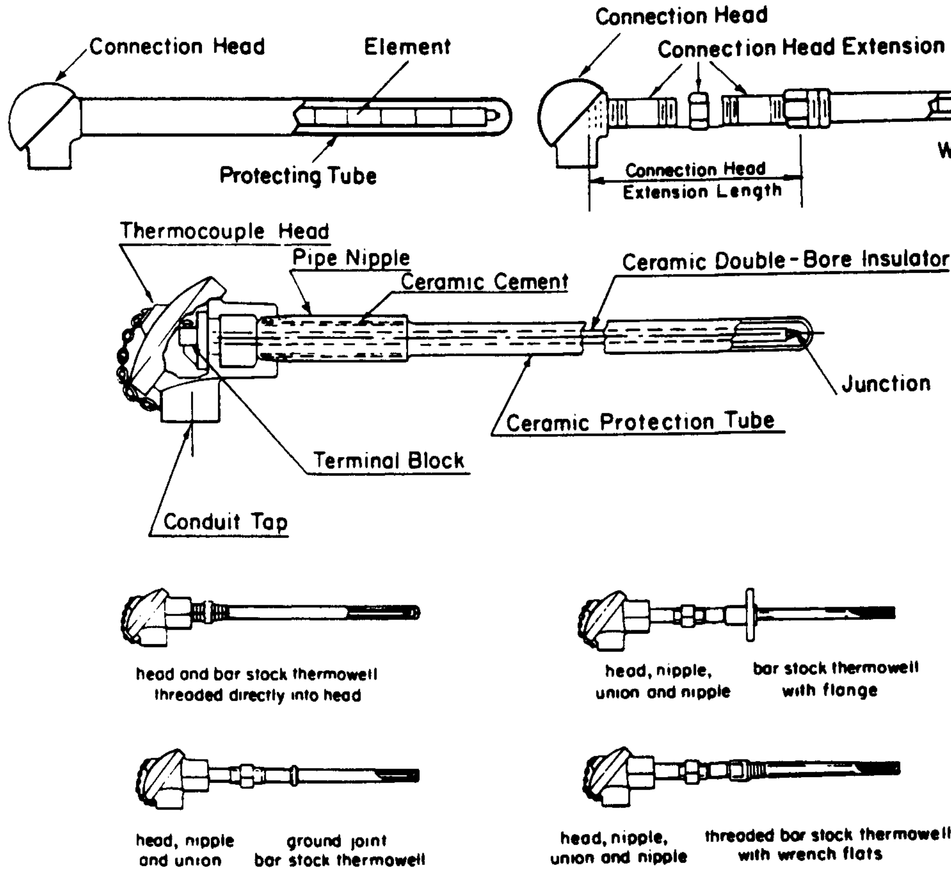


FIG. 4.4—*Typical examples of thermocouple assemblies with protecting tubes.*

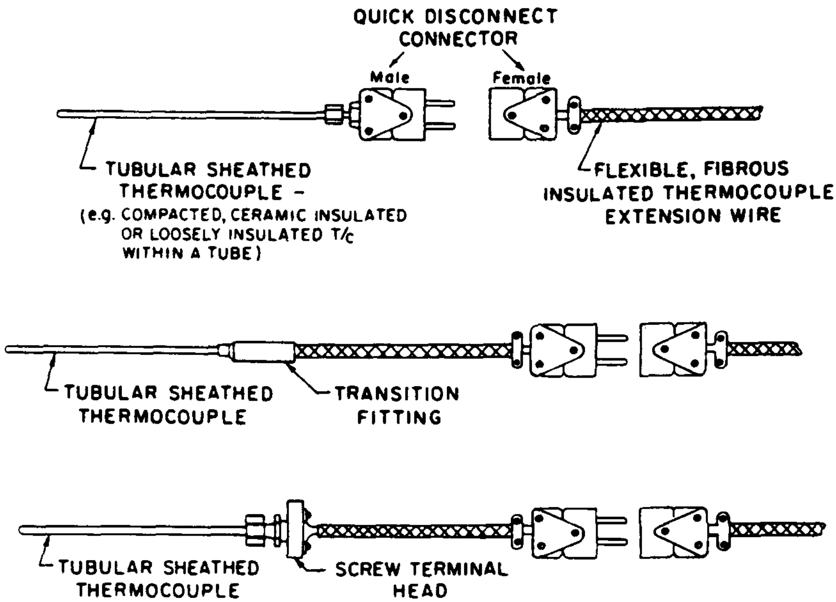


FIG. 4.5—*Typical examples of thermocouple assemblies using quick disconnect connectors.*

TABLE 4.5—*Selection guide for protecting tubes.*

Application	Protecting Tube Material
HEAT TREATING	
Annealing	
Up to 704°C (1300°F)	black steel
Over 704°C (1300°F)	Inconel 600,[a] Type 446 SS
Carburizing hardening	
Up to 816°C (1500°F)	black steel, Type 446 SS
1093°C (1500 to 2000°F)	Inconel 600, Type 446 SS
Over 1093°C (2000°F)	ceramic[b]
Nitriding salt baths	Type 446 SS
Cyanide	nickel (CP)
Neutral	Type 446 SS
High speed	ceramic[b]
IRON AND STEEL	
Basic oxygen furnace	quartz
Blast furnaces	
Downcomer	Inconel 600, Type 446 SS
Stove dome	silicon carbide
Hot blast main	Inconel 600
Stove trunk	Inconel 600
Stove outlet flue	black steel
Open hearth	
Flues and stack	Inconel 600, Type 446 SS
Checkers	Inconel 600, Cermets
Waste heat boiler	Inconel 600, Type 446 SS

TABLE 4.5—*(Continued)*

Application	Protecting Tube Material
Billet heating slab heating and butt welding	
Up to 1093°C (2000°F)	Inconel 600, Type 446 SS
Over 1093°C (2000°F)	silicon ceramic carbide[b]
Bright annealing batch	
Top work temperature	not required (use bare Type J thermocouple)
Bottom work temperature	Type 446 SS
Continuous furnace section	Inconel 600, ceramic[b]
Forging	silicon carbide, ceramic[b]
Soaking pits	
Up to 1093°C (2000°F)	Inconel 600
Over 1093°C (2000°F)	silicon ceramic carbide[b]
NONFERROUS METALS	
Aluminum	
Melting	cast iron (white-washed)
Heat treating	black steel
Brass or bronze	not required (use dip-type thermocouple)
Lead	Type 446 SS, black steel
Magnesium	black steel, cast iron
Tin	extra heavy carbon steel
Zinc	extra heavy carbon steel
Pickling tanks	chemical lead
CEMENT	
Exit flues	Inconel 600, Type 446 SS
Kilns, heating zone	Inconel 600
CERAMIC	
Kilns	ceramic[b] and silicon carbide[c]
Dryers	silicon carbide, black steel
Vitreous enamelling	Inconel 600, Type 446 SS
GLASS	
Fore hearths and feeders	platinum thimble
Lehrs	black steel
Tanks	
Roof and wall	ceramic[a]
Flues and checkers	Inconel 600, Type 446 SS
PAPER	
Digesters	Type 316 SS, Type 446 SS
PETROLEUM	
Dewaxing	Types 304, 310, 316, 321, 347 SS, carbon steel
Towers	Types 304, 310, 316, 321, 347 SS, carbon steel
Transfer lines	Types 304, 310, 316, 321, 347 SS, carbon steel
Factioning column	Types 304, 310, 316, 321, 347 SS, carbon steel
Bridgewall	Types 304, 310, 316, 321, 347 SS, carbon steel
POWER	
Coal-air mixtures	304 SS
Flue gases	black steel, Type 446 SS
Preheaters	black steel, Type 446 SS
Steel lines	Types 347 or 316 SS
Water lines	low carbon steels
Boiler tubes	Types 304, 309, or 310 SS

TABLE 4.5—*(Continued)*

Application	Protecting Tube Material
GAS PRODUCERS	
Producer gas	Type 446 SS
Water gas	
Carburetor	Inconel 600, Type 446 SS
Superheater	Inconel 600, Type 446 SS
Tar stills	low carbon steels
INCINERATORS	
Up to 1093°C (2000°F)	Inconel 600, Type 446 SS
Over 1093°C (2000°F)	ceramic (primary) silicon carbide (secondary)[a]
FOOD	
Baking ovens	black steel
Charretort, sugar	black steel
Vegetables and fruit	Type 304 SS
CHEMICAL	
Acetic acid	
10 to 50% 21°C (70°F)	Type 304, Hastelloy C,[d] Monel
50% to 100°C (212°F)	Type 316, Hastelloy C,[d] Monel
99% 21 to 100°C (70 to 212°F)	Type 430, Hastelloy C,[d] Monel
Alcohol, ethyl, methyl 21 to 100°C (70 to 212°F)	Type 304
Ammonia	
All concentration 21°C (70°F)	Types 304, 316 SS
Ammonium chloride	
All concentration 100°C (212°F)	Type 316 SS, Monel
Ammonium nitrate	
All concentration 21 to 100°C (70 to 212°F)	Type 316 SS
Ammonium sulphate, 10% to saturated, 100°C (212°F)	Type 316 SS
Barium chloride, all concentration, 21°C (70°F)	Monel, Hastelloy C
Barium hydroxide, all concentration, 21°C (70°F)	low carbon steels
Barium sulphite	Nichrome[e] Hastelloy C
Brines	Monel
Bromine	tantalum, Monel
Butadiene	Type 304 SS
Butane	Type 304 SS
Butylacetate	Monel
Butyl alcohol	copper, Type 304 SS
Calcium chlorate, dilute, 21 to 66°C (70 to 150°F)	
Calcium hydroxide	Type 304 SS
10 to 20% 100°C (212°F)	Type 304 SS, Hastelloy C
50% 100°C (212°F)	Type 316 SS, Hastelloy C
Carbolic acid, all, 100°C (212°F)	Type 316 SS
Carbon dioxide, wet or dry	2017-T4 aluminum, Monel, nickel
Chlorine gas	
Dry, 21°C (70°F)	Type 316 SS, Monel
Moist, −7 to 100°C (20 to 212°F)	Hastelloy C
Chromic acid, 10 to 50% 100°C (212°F)	Type 316 SS, Hastelloy C (all concentrations)

TABLE 4.5—*(Continued)*

Application	Protecting Tube Material
Citric acid	
15% 21°C (70°F)	Type 304 SS, Hastelloy C (all concentrations)
15% 100°C (212°F)	Type 316 SS, Hastelloy C (all concentrations)
Concentrated, 100°C (212°F)	Type 316 SS, Hastelloy C (all concentrations)
Copper nitrate	Types 304 SS, 316 SS
Copper sulphate	Types 304 SS, 316 SS
Cresols	Type 304 SS
Cyanogen gas	Type 304 SS
Dow therm[f]	low carbon steels
Ether	Type 304 SS
Ethyl acetate	Monel, Type 304 SS
Ethyl chloride, 21°C (70°F)	Type 304 SS, low carbon steel
Ethyl sulphate, 21°C (70°F)	Monel
Ferric chloride, 5% 21°C (70°F) to boiling	tantalum, Hastelloy C
Ferric sulphate, 5% 21°C (70°F)	Type 304 SS
Ferrous sulphate, dilute, 21°C (70°F)	Type 304 SS
Formaldehyde	Types 304 SS, 316 SS
Formic acid, 5% 21 to 66°C (70 to 150°F)	Type 316 SS
Freon	Monel
Gallic acid, 5% 21 to 66°C (70 to 150°F)	Monel
Gasoline, 21°C (70°F)	Type 304 SS, low carbon steel
Glucose, 21°C (70°F)	Type 304 SS
Glycerine, 21°C (70°F)	Type 304 SS
Glycerol	Type 304 SS
Hydrobromic acid, 98% to 100°C (212°F)	Hastelloy B
Hydrochloric acid	
1%, 5% 21°C (70°F)	Hastelloy C
1%, 5% 100°C (212°F)	Hastelloy B
25% 21 to 100°C (70 to 212°F)	Hastelloy B
Hydrofluoric acid, 60% 100°C (212°F)	Hastelloy C, Monel
Hydrogen peroxide, 21 to 100°C (70 to 212°F)	Types 316 SS,304 SS
Hydrogen sulphide, wet and dry	Type 316 SS
Iodine, 21°C (70°F)	tantalum
Lactic acid	
5% 21°C (70°F)	Type 304 SS, 316 SS
5% 66°C (150°F)	Type 316 SS
10% 100°C (212°F)	tantalum
Magnesium chloride	
5% 21°C (70°F)	Monel, nickel
5% 100°C (212°F)	nickel
Magnesium sulphate, hot and cold	Monel
Muriatic acid, 21°C (70°F)	tantalum
Naptha, 21°C (70°F)	Type 304 SS
Natural gas, 21°C (70°F)	Types 304 SS, 316 SS, 317 SS
Nickel chloride, 21°C (70°F)	Types 304 SS
Nickel sulphate, hot and cold	Type 304 SS
Nitric acid	
5% 21°C (70°F)	Types 304 SS, 316 SS

TABLE 4.5—*(Continued)*

Application	Protecting Tube Material
20% 21°C (70°F)	Types 304 SS, 316 SS
50% 100°C (70°F)	Types 304 SS, 316 SS
50% 100°C (212°F)	Types 304 SS, 316 SS
65% 100°C (212°F)	Type 316 SS
Concentrated, 21°C (70°F)	Types 304 SS, 316 SS
Concentrated, 100°C (212°F)	tantalum
Nitrobenzene, 21°C (70°F)	Type 304 SS
Oleic acid, 21°C (70°F)	Type 316 SS
Oleum, 21°C (70°F)	Type 316 SS
Oxalic acid	
5% hot and cold	Type 304 SS
10% 100°C (212°F)	Monel
Oxygen	
21°C (70°F)	steel
Liquid	SS
Elevated temperatures	SS
Palmitic acid	Type 316 SS
Pentane	Type 340 SS
Phenol	Types 304 SS, 316 SS
Phosphoric acid	
1%, 5% 21°C (70°F)	Type 304 SS
10% 21°C (70°F)	Type 316 SS
10% 100°C (212°F)	Hastelloy C
30% 21 to 100°C (70 to 212°F)	Hastelloy B
85% 21 to 100°C (70 to 212°F)	Hastelloy B
Picric acid, 21°C (70°F)	Type 304 SS
Potassium bromide, 21°C (70°F)	Type 316 SS
Potassium carbonate, 1% 21°C (70°F)	Types 304 SS, 316 SS
Potassium chlorate, 21°C (70°F)	Type 304 SS
Potassium hydroxide	
5% 21°C (70°F)	Type 304 SS
25% 100°C (212°F)	Type 304 SS
60% 100°C (212°F)	Type 316 SS
Potassium nitrate	
5% 21°C (70°F)	Type 304 SS
5% 100°C (212°F)	Type 304 SS
Potassium permanganate, 5% 21°C (70°F)	Type 304 SS
Potassium sulphate, 5% 21°C (70°F)	Types 304 SS, 316 SS
Potassium sulphide, 21°C (70°F)	Types 304 SS, 316 SS
Propane	Type 304 SS, low carbon steel
Pyrogallic acid	Type 304 SS
Quinine bisulphate, dry	Type 316 SS
Quinine sulphate, dry	Type 304 SS
Seawater	Monel or Hastelloy C
Salicylic acid	nickel
Sodium bicarbonate	
All concentration, 21°C (70°F)	Type 304 SS
5% 66°C (150°F)	Types 304 SS, 316 SS
Sodium carbonate, 5% 21 to 66°C (70 to 150°F)	Types 304 SS, 316 SS
Sodium chloride	
5% 21 to 66°C (70 to 150°F)	Type 316 SS
Saturated 21 to 100°C (70 to 212°F)	Type 316 SS, Monel
Sodium fluoride, 5% 21°C (70°F)	Monel

TABLE 4.5—*(Continued)*

Application	Protecting Tube Material
Sodium hydroxide	Types 304 SS, 316 SS, Hastelloy C
Sodium hypochlorite, 5% still	Type 316 SS, Hastelloy C
Sodium nitrate, fused	Type 316 SS
Sodium peroxide	Type 304 SS
Sodium sulphate, 21°C (70°F)	Types 304 SS, 316 SS
Sodium sulphide, 21°C (70°F)	Type 316 SS
Sodium sulphite, 30% 66°C (150°F)	Type 304 SS
Sulphur dioxide	
Moist gas, 21°C (70°F)	Type 316 SS
Gas, 302°C (575°F)	Types 304 SS, 316 SS
Sulphur	
Dry molten	Type 304 SS
Wet	Type 316 SS
Sulphuric acid	
5% 21 to 100°C (70 to 212°F)	Hastelloy B, 316 SS
10% 21 to 100°C (70 to 212°F)	Hastelloy B
50% 21 to 100°C (70 to 212°F)	Hastelloy B
90% 21°C (70°F)	Hastelloy B
90% 100°C (212°F)	Hastelloy D
Tannic acid, 21°C (70°F)	Type 304 SS, Hastelloy B
Tartaric acid	
21°C (70°F)	Type 304 SS
66°C (150°F)	Type 316 SS
Toluene	2017-T4 aluminum, low carbon steel
Turpentine	Types 304 SS, 316 SS
Whiskey and wine	Type 304 SS, nickel
Xylene	copper
Zinc chloride	Monel
Zinc sulphate	
5% 21°C (70°F)	Types 304 SS, 316 SS
Saturated, 21°C (70°F)	Types 304 SS, 316 SS
25% 100°C (212°F)	Types 304 SS, 316 SS

[a]Trademark of International Nickel Company.
[b]Due to susceptibility to cracking, sudden thermal shocks should be avoided.
[c]Due to susceptibility to cracking, sudden thermal shocks should be avoided.
[d]Trademark of the Cabot Corporation.
[e]Trademark of the Driver-Harris Company.
[f]Trademark of the Dow Chemical Corporation.

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Chapter 5—Sheathed, Compacted, Ceramic-Insulated Thermocouples

5.1 General Considerations

Compacted ceramic insulated thermocouple material consists of three parts as shown in Fig. 5.1. This type of thermocouple is in common use because it isolates the thermocouple wires from environments that may cause rapid deterioration and provides excellent high-temperature insulation for thermocouple wires. The sheath can be made of a metal compatible with the process in which it is being used and provides mechanical protection. The material is easy to use because it forms easily, retains the bent configuration, and is readily fabricated into finished thermocouple assemblies.

5.2 Construction

All compacted types of thermocouples are made by similar processes. They begin with matched thermocouple wires surrounded by noncompacted ceramic insulating material held within a metal tube. By drawing, swaging, or other mechanical reduction processes the tube is reduced in diameter, and the insulation is compacted around the wires. Several options are available depending upon the material combinations selected for the temperature measurement application.

A ductile sheath and brittle refractory metal wire combination requires a design wherein the starting tubing diameter is only slightly larger than the finished size and only large enough on the inside diameter to accommodate a crushable preformed ceramic insulator with the wire strung through the insulators. This combination then would be reduced to the final diameter by one of the compaction methods usually in a single reduction pass. The process is such that the wire is neither elongated nor reduced in diameter in recognition of its brittle nature at room temperature.

A brittle sheath/brittle wire combination does not lend itself to a compacted insulation design and, therefore, is assembled as a tube-insulator-wire combination without the subsequent sheath reduction. Ductile wire/ductile sheath combinations cover the widest range of commonly used materials and offer the producer the widest choice of design approaches.

Nominal physical dimensions of sheathed ceramic insulated thermocou-

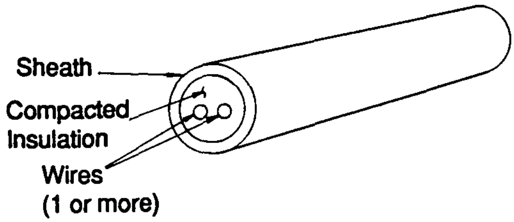

FIG. 5.1—*Compacted ceramic insulated thermocouple showing its three parts.*

ples are listed in a standard specification for sheathed base-metal thermocouple materials (ASTM E 585), illustrated in Fig. 5.2. The ratios of sheath outside diameter to wire size and to sheath wall thickness offer a balance between maximum wall thickness (for protection of the sheath compacted insulant) and suitable insulation spacing for effective insulation resistance

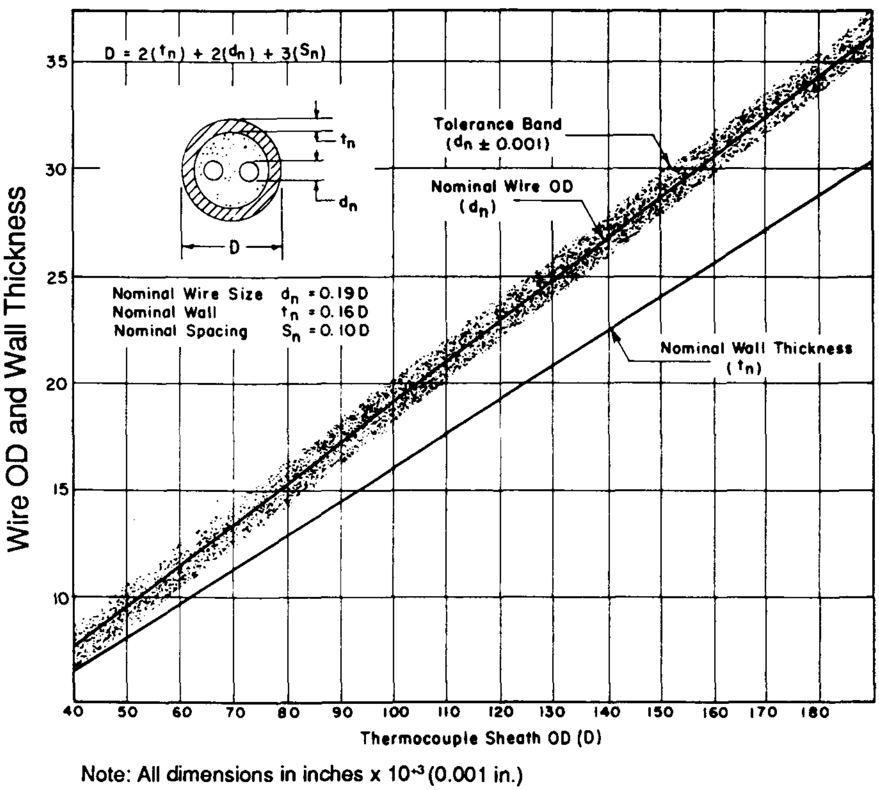

FIG. 5.2—*Nominal thermocouple sheath outside diameter versus internal dimensions.*

at elevated temperature. It is estimated that 90% of all sheathed thermocouples produced to date have used magnesium oxide (MgO) as the insulation material. Magnesium oxide is popular as a thermocouple insulator because of its overall compatability with standard thermoelements and sheathing materials, its relative low cost, and its availability.

Aluminum oxide, thorium oxide, and the potentially toxic beryllium oxide insulations are also available from suppliers for use with certain wire and sheath combinations. The latter two materials are usually combined with refractory metal sheaths and thermoelements.

Because many applications of ceramic insulated thermocouples are at temperatures above 200°C (400°F), much attention must be given to cleanliness and chemical and metallurgical purity of the components. Great pains and expense having been taken to control the purity of the insulation during fabrication, the user would be foolish to abuse the sheathed material during assembly or application of the finished thermocouple. Any insulation contaminant can degrade thermocouple performance, useful life, or both. This contamination includes moisture pickup from ambient air during fabrication or after any breech of the metal sheath.

5.3 Insulation

For most practical purposes the sheathed thermocouple material should have a minimum insulation resistance of 100 megohms. This is readily obtained using dry, uncontaminated compacted ceramic. The capture of oil, oil vapors, moisture, perspiration, and lint during manufacture can cause low insulation resistance. The hygroscopic nature of the insulants, especially MgO, and capillary attraction cause rapid absorption of moisture through exposed ends of the sheath. Also, the insulation resistance of all ceramics, compacted and uncompacted, reduces with an increase in temperature, especially if contaminated.

When purity has been maintained so that the insulation resistance is greater than 1000 megohms, special techniques are required to maintain these values. Such material exposed to 21°C (70°F) air and a relative humidity above 50% will experience a degradation of insulation resistance to less than 0.1 megohm in 15 min. Higher humidity will cause a more rapid degradation. The following precautions should be exercised when handling compacted ceramic insulated thermocouples:

1. Do not leave an end exposed for periods longer than one minute. Immediately seal the end, preferably immediately after heating to expel any moisture.
2. Expose ends only in a region of low relative humidity.
3. Store sealed assembly in a warm (above 38°C (100°F)) and dry (relative humidity less than 25%) area.

TABLE 5.1—*Characteristics of insulating materials used in ceramic-packed thermocouple stock.*

Insulator	Minimum Purity, %	Melting Point, °C (°F)	Approximate Usable Temperature, °C (°F)
Magnesia (MgO)	99.4	2800 (5072)	1650 (3000)
Alumina (Al_2O_3)	99.5	2030 (3686)	1650 (3002)
Zirconia (ZrO_2)	99.4	2420 (4388)	650 (1202)
Beryllia (BeO)	99.8	2570 (4658)	2315 (4200)
Thoria (ThO_2)	99.5	3050 (5222)	2500 (4532)
Hafnia (HfO_2)	99.8	2900 (5252)	2000 (3632)
Yttria (Y_2O_3)	99.8	2410 (4370)	2000 (3632)

Once a surface of the compacted oxide insulator is exposed to normal ambient humidity, moisture enters and diffuses inward through the insulator. The rate of diffusion depends on the humidity, the insulation temperature, and the material and degree of compaction of the oxide. As indicated, it is usually rapid. In fact, the ultimate purity can be only maintained if all operations are performed in an inert-gas dry box [*1*]. After having been absorbed and diffused, the moisture is very difficult to remove. Heat added to drive out the moisture will only increase its rate of reaction (oxidation) with the sheath wall and the thermoelements. Even though the insulation resistance may be restored, the damage has been done. Failure to recognize the effect and nature of this phenomenon is responsible for the poor performance reported by many users of sheathed thermocouples.

In the special case of a brief exposure of high-density material, limited success has been achieved by moving a moderate heat source 200 to 300°C (400 to 600°F) toward the exposed end and immediate sealing with epoxy.

Some of the characteristics of the more common compacted ceramics are shown in Tables 5.1 and 5.2.

TABLE 5.2—*Thermal expansion coefficient of refractory insulating materials and three common metals.*

Material	Average Coefficient of Expansion $\times 10^{-6}$ (25 to 700°C), °C^{-1}
Copper	16.5
Stainless steels	19 to 24
Aluminum	23.5
Magnesia	11 to 15
Beryllia	8 to 9
Alumina	6 to 9
Zirconia	4 to 5
Thoria	7.5
Hafnia	5.8
Yttria	9.3

5.4 Thermocouple Wires

The characteristics of the wires are no different from those of other thermocouples described in this manual. Since they are contained in a protective sheath and firmly held, small diameter wires can be exposed to high temperatures for long periods of time with less deterioration than that experienced by bare wire of the same size, provided they are properly fabricated and sealed.

5.5 Sheath

The sheath material performs several functions in the ceramic-insulated thermocouple system:

1. It holds the ceramic in compaction.
2. It shields the ceramic and thermoelements from the environment.
3. It furnishes mechanical strength to the assembly.

Since there is no sheath material suitable for all environments, a wide variety of different materials are offered. Table 5.3 shows a group of materials that can be used as sheaths and some of their characteristics. For maximum life a sheath diameter should be selected that offers the heaviest wall.

5.6 Combinations of Sheath, Insulation, and Wire

Precautions to be observed in selecting combinations are:

1. Be sure the sheath material will survive the environment. Remember that a thin sheath will deteriorate more rapidly than a thick one.
2. Be sure the assembly of sheath and wire is suitably annealed for optimum sheath life and stability of wire calibration.
3. Select a sheath and wire material of similar coefficients of linear expansion. For example: Platinum-rhodium and platinum have about one half the expansion of stainless or Inconel; a grounded hot junction may pull apart. The usual solution is to use hard-fired insulators in place of crushable and perhaps isolate the junction. Another solution is to use a platinum-rhodium sheath.
4. Select a sheath and wire material of similar annealing characteristics.
5. Do not use Types K, N, J, or E with an aluminum or copper sheath.

Table 5.4 indicates the compatibility of wire and sheath materials.

Table 5.5 give dimensions of typical ceramic-packed stock.

5.7 Characteristics of the Basic Material

1. The sheath can usually be bent around a mandrel twice the sheath diameter without damage.

2. The life of material having a diameter of 0.81 mm (0.032 in.) or less may be limited by grain growth in the sheath wall.
3. Four wires in 1.57 mm (0.062 in.) sheath diameter and smaller are not practical to handle.
4. Two wires in 0.81 mm (0.032 in.) sheath diameter and smaller are difficult to handle but are used in laboratory environments.

Stock material and completed thermocouples are supplied usually to the end user in the fully annealed state with proper metallurgical grain size and no surface corrosion. Improper handling can easily destroy this condition. When wire is delivered coiled, it should not be uncoiled until needed for fabrication. Repeated or excessive bending will affect the annealed state. Sometimes the wire has been further heat treated after solution annealling, to control or stabilize calibration. If this is the case, further heat treatment to remove cold work will destroy these characteristics.

5.8 Testing

Many tests have been devised to evaluate sheathed ceramic insulated thermocouples. These tests cover the physical and metallurgical properties of the sheath and thermoelements, the electrical properties of the insulation, and the thermoelectric properties of the thermoelements.

ASTM has issued a standard specification (E 235) [*2*] for sheathed, Type K thermocouples for nuclear and other high reliability applications which covered Type K thermoelements in various sheath materials, with alumina or magnesia insulations and alternative thermoelements. In Aerospace Information Report 46 [*3*] the Society of Automotive Engineers has covered the preparation and use of Type K thermocouples for turbojet engines, while the military has issued Mil T23234 (Ships) for nuclear application of the sheathed thermocouples. In addition many government and commercial laboratories, thermocouple fabricators, and thermocouple users have issued specifications covering specific tests and test procedures for evaluating sheathed thermocouples.

Scadron [*4*] outlined some of the tests and tolerances that are applied for the verification of physical, electrical, and thermoelectric integrity of the sheathed thermocouple.

Most manufacturers' catalogs cover some aspects of the tests, guarantees, and procedures used to verify product integrity. Fenton et al. [*5*] were concerned with inhomogeneity in bare and sheathed thermoelements and developed procedures and apparatus for testing for drift and inhomogeneity. NIST Special Publication 250-35 (Library of Congress 89-600732) covers thermocouple testing. While this publication applies to the bare thermoelements it is applicable to the electrical characteristics of the metal sheathed ceramic insulated material.

TABLE 5.3—*Sheath materials of ceramic-packed thermocouple stock and some of their properties.*

Material	Melting Point	Recommended Maximum in Air	Recommended: Operating Atmosphere	Recommended: Continuous Maximum Temperature	Tensile Strength,[a] psi: At 93°C (200°F)	Tensile Strength,[a] psi: At 871°C (1600°F)
Stainless steel	°C (°F)	°C (°F)	...	°C (°F)	...	...
304	1404 (2560)	1049 (1920)	ORNV	899 (1650)	68 000	...
309	...	...	ORNV	1093 (2000)	...	...
310	1404 (2560)	1093 (2000)	ORNV	1147 (2100)	87 000	23 000
316	1371 (2500)	899 (1650)	ORNV	927 (1700)	75 000	23 000
321	1399 (2550)	899 (1650)	ORNV	871 (1600)	70 000	17 000
347	1427 (2600)	915 (1680)	ORNV	871 (1600)	75 000	...
430	1482 (2700)	843 (1550)	ORNV	649 (1200)	...	...
446	1482 (2700)	1093 (2000)	ORNV	1093 (2000)	...	...
Inconel	1399 (2550)	1093 (2000)	ONV[b]	1149 (2100)	93 000	5 000
Inconel X	1438 (2620)	1371 (2500)	ONV[b]	1204 (2200)	150 000	11 000
Incoloy	1371 (2500)	893 (1640)	...	...	77 000	3 000
Hastelloy X	1288 (2350)	1260 (2300)	...	...	106 000	7 000
Hastelloy C	1265 (2310)	993 (1820)	...	...	136 000	64 000
Haynes 25	1329 (2425)	993 (1820)	...	...	147 000	13 000

Hastelloy B	1302 (2375)	760 (1400)	...	...	125 000	51 000
Monel	1349 (2460)	893 (1640)	...	...	...	...
Chromel	1427 (2600)	1149 (2100)	ONV	...	90 000	21 000
Copper	1081 (1980)	315 (600)	ORNV	315 (600)	...	...
Brass	1010 (1850)	371 (700)	...	...	...	...
Aluminum	660 (1220)	426 (800)	ORNV	371 (700)	...	...
Nichrome	1399 (2550)	1204 (2200)	...	1093 (2000)	...	...
Alumel	1399 (2550)	1149 (2100)	ONV	...	82 000	19 000
Nickel	1453 (2647)	593 (1100)	...	...	...	...
Iron	1537 (2798)	315 (600)	...	...	...	...
Zircaloy	1841 (3350)	760 (1400)	...	...	...	...
Platinum	1768 (3217)	1649 (3000)	ON[b]	1699 (3000)	...	...
Pt-Rh 10%	1848 (3362)	1704 (3100)	ON	1703 (3100)	...	...
Niobium	2468 (4474)	871 (1600)	VN	2091 (3800)	110 000	...
Molybdenum	2610 (4730)	204 (400)	VNR	...	137 000	30 000
Molybdenum disilicized	...	1703 (3100)	ON	1649 (3000)	...	...
Molybdenum chromalized	...	1703 (3100)	ON	1649 (3000)	...	...
Tantalum	2996 (5425)	399 (750)	V	2778 (5000)	96 000	22 000
Titanium	1668 (3035)	315 (600)	VN	1093 (2000)	...	...

NOTE—Symbols describing atmospheres are: O = oxidizing; R = reducing; N = neutral; V = vacuum. 32°F = 0°C.

[a]Nonreactive atmosphere required.

[b]Very sensitive to sulfur corrosion.

TABLE 5.4—*Compatibility of wire and sheath material* [6].

Wire	Sheath													
	304	310	316	321	347	440	Platinum Alloys	Hastelloy X	Copper	Aluminum	Inconel 600	Inconel 702	Tantalum	Niobium Alloys
Type K, N	1	1	1	1	1	1	1	3	4	4	1	1	3	3
Type J	1	1	1	1	1	1	2	4	4	4	3	3	4	4
Type T	1	1	1	1	1	1	2	4	1	4	2	3	3	3
Type E	1	1	1	1	1	1	1	1	4	4	1	1	3	3
Types B, R, and S	1	1	1	1	1	1	1	1	4	4	1	1	4	4
Tungsten rhenium alloys	3	3	3	3	3	3	3	3	4	4	3	3	3	3
Iridium rhodium alloys	3	3	3	3	3	3	3	3	4	4	3	3	3	3
Copper	3	4	3	3	3	4	4	4	1	2	3	4	2	2
Nickel	1	1	1	1	1	1	1	1	4	4	1	1	3	3
Aluminum	4	4	4	4	4	4	4	4	4	1	4	4	4	4
Nichrome[a]	1	1	1	1	1	1	1	1	4	4	1	1	3	3

NOTE—1. Easy manufacturing and good operation compatibility.
2. Easy manufacturing but poor operational compatibility.
3. Difficult manufacturing but good operational compatibility.
4. Difficult manufacturing and poor operational compatibility.

[a]Trademark of Harrison Alloys.

TABLE 5.5—*Dimensions and wire sizes of typical ceramic-packed material, Reference ASTM E 585.*

(*a*)

Sheath Outside Diameter, in.	Outside Diameter Tolerance, ± in.	Minimum Wall Thickness, in.	Maximum Wire, in.	Nominal Production Length, ft
0.020	0.001	0.002	0.003	250
0.032	0.001	0.003	0.004	250
0.040	0.001	0.004	0.006	250
0.062	0.002	0.005	0.010	150
0.090	0.002	0.009	0.014	125
0.125	0.002	0.012	0.020	100
0.188	0.003	0.017	0.028	60
0.250	0.003	0.025	0.037	40
0.313	0.003	0.031	0.047	40
0.375	0.003	0.037	0.056	30
0.430	0.003	0.043	0.064	30
0.500	0.003	0.050	0.075	30

(*b*)

Sheath Diameter, in.	Nominal Conductor Diameters, in.			
	1-Wire	2-Wire	3-Wire	4-Wire
0.313	0.064	0.051	0.040	0.040
0.250	0.051	0.040	0.032	0.032
0.188	0.040	0.032	0.022	0.022
0.125	0.032	0.022	0.011	0.011
0.062	0.022	0.011	0.006	0.006
0.040	0.011	0.006	...	...
0.025	0.006	0.004	...	...

NOTE—1 in. = 25.4 mm; 1 ft = 0.3048 m.

Table 5.6 shows various characteristics, tests, and the source of testing procedures which are applicable to sheathed ceramic-insulated thermocouples. This table includes tests from E 235 and Standard Methods of Testing Sheathed Thermocouples and Sheathed Thermocouple Materials (ASTM E 839).

5.9 Measuring Junction

Numerous variations in junction construction are possible with this type of material. The application dictates the most desirable method.

1. *Exposed or Bare Wire Junction (Fig. 5.3)*—In this type of junction the sheath and insulating material are removed to expose the thermocouple wires. These wires are joined to form a measuring junction. The junction may be of the twist-and-weld or butt-weld type. While the thermocouple will

TABLE 5.6—*Various characteristics tests and the source of testing procedure applicable to sheathed ceramic-insulated thermocouples.*

Characteristics	Tests	Procedure	Comments
		PHYSICAL AND METALLURGICAL	
1. OD of sheath	ring gage, micrometer, or met mounts for high precision	good mechanical practice or transverse section per ASTM E 3[a]	tolerances per Table 5.5 sample preparation: requires care to prevent smear
2. Roundness of sheath	rotate for total indicated reading	Vee block and dial indicator	important for tube fitting use
3. Sheath surface finish	profilometer or roughness gage	ANSI Standard B46.1	also check clean finish for welding and brazing
4. Sheath wall thickness	thread gage micrometer or metallurgical mount	transverse section per ASTM E 3	concerns machining, bending, welding, life: can be checked only at ends
5. Insulation spacing	comparator or metallurgical mount	transverse section per ASTM E 3	see electrical tests
6. Insulation compactness	(A) tap test, (B) helium pressure, (C) dye absorption, (D) compaction density	(A) supplier catalog, (B) MIL-T-23234, (C) and (D) ASTM D 2771[b]	relative values must be related to application
7. Wire diameter	micrometer or metallurgical mount	visual or transverse section per ASTM E 3	±1 wire gage size
8. Wire surface and roundness	micrometer and visual	3-point diameter check	10% out of round max showing slight embedment of insulating material into wire
9. Ductility and formability	bend and visual or metallurgical mount	ASTM E 235	bend 90 deg only for ease of making metallurgical mount
10. Sheath integrity	(A) water immersion, (B) hydrostatic, (C) helium leak, (D) dye penetrant	ASTM E 839	(A) may use hydrostatic pressure or steam for some applications: seal weld to protect insulation
11. Junction integrity	radiographs	ASTM E 235	application for junction and 4 in. of sheath
12. Material compatibility	thermal cycling	ASTM E 235	thermal expansion for grounded junction integrity check

13. Metallurgial integrity	metallurgical mount	ASTM E 235	checks grain size
14. Response time	thermal response test	gas: SAE 46, liquid [24]	assesses thermal mass and welding technique
15. Uniformity of properties	Tests 1, 2, 3, 10, 11, and 13 full length	as noted	use sampling procedure for large runs
16. Stability under service conditions	application experience or life tests	as required	check with other users in same field
		CONSTANT TEMPERATURE ELECTRICAL	
17. Insulation resistance	megohm meter between wires and sheath and wires	ASTM E 235	50 V for OD less than 0.061, 500 V for greater than 0.062
18. Electrical resistance (loop)	Wheatstone bridge	Chapter 3	tolerances ± 1 gage size based on wire type, length and dia; also checks continuity
19. High temperature insulation resistance	megohm meter or Wheatstone bridge	immerse full length except for end in temperature chamber: test with ungrounded junction or before junction is made	relative to operational requirement, effective means of testing insulation quality at expected operating temperature of thermocouple
20. Dielectric strength	high potential generator	ac voltage (current limited) applied at room temperature for 1 min 80 V per mil of insulation [32]	seldom used check for contamination and voids in insulation: voltage usually 500 V for 0.062 OD and larger
		ISOTHERMAL ELECTRICAL	
21. Capacitance	capacitance bridge	. . .	test is usually not applied to thermocouples
22. Uniformity along length	Test 17, 18, 19, 20, 21 for full length	check samples or full lengths coiled if necessary	all tests are seldom necessary for single application
23. Stability under service conditions	application experience or life tests	as required	check for experience by other users

TABLE 5.6—(*Continued*).

Thermoelectric Properties			
24. Emf versus temperature	potentiometer and heat or cold source	Chapter 6	test at one or more points up to maximum use temperature
25. Homogeneity	heat source and galvanometer	NBC Circular 590 and Ref 6	max of $\pm 100\ \mu V$ for J, K, N, T; $\pm 25\ \mu V$ for B, R, S thermoelements
26. Uniformity full length	Test 24 and 25 for full length	applying sampling procedure for large quantities	random sampling is most economical approach

[a]ASTM E 3 Methods of Preparation of Metallographic Samples.
[b]ASTM D 2771 Test Methods for Compaction Density of Electrical Grade Magnesium Oxide.

FIG. 5.3—*Exposed or bare wire junction.*

FIG. 5.4—*Grounded junction.*

have a fast response, the exposed ceramic is not pressure tight and will pick up moisture, and the wires are subject to mechanical damage and are exposed to the environment.

2. *Grounded Junction (Fig. 5.4)*—A closure is made by welding in an inert atmosphere so that the two thermocouple wires become an integral part of the sheath weld closure. Thus, the wires are "grounded" to the sheath. This will give a slower response than exposed wire but the insulation is pressure tight, and the wires are protected from mechanical damage and from the environment. Grounded junctions should not be used when ground loops or other electrical interference is likely.

3. *Ungrounded or Isolated Junction (Fig. 5.5)*—This type is similar to the grounded junction except that the thermocouple wires are first made into a junction which is then insulated from the sheath and the sheath closure. The closure is formed by welding without touching the thermocouple wires. Thus, the thermocouple is "ungrounded" to the sheath material. This junction has slower response than the grounded junction but is still pressure tight and protected from mechanical damage and from the environment. The strain due to differential expansion between wires and sheath may be reduced.

4. *Reduced Diameter Junction (Fig. 5.6)*—This may be either grounded or insulated and is used where fast response is required, and a heavier sheath

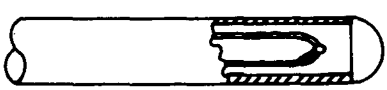

FIG. 5.5—*Ungrounded or isolated junction.*

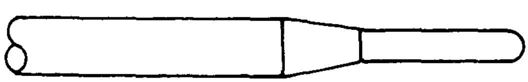

FIG. 5.6—*Reduced diameter junction.*

or wires are desired for strength, life, or lower circuit resistance over the balance of the unit.

5.10 Terminations

There are numerous ways in which thermocouples of this type can be treated at the reference end. The most common treatments are as follows:

1. *Wires Exposed and Sealed*—The sheath and the insulation are removed leaving the bare thermocouple wires exposed for a specific length. The insulating material is then sealed with epoxy to inhibit moisture absorption.
2. *Transition Fitting (Fig. 5.7)*—The terminal end is provided with a fitting wherein the thermocouple wires are joined to more suitable wires. In this fitting the necessary sealant for the mineral insulant is also provided. The fitting can be either metal or plastic, suitable for the anticipated exposure environment.
3. *Terminals or Connectors*—Various types of fittings are available to facilitate external electrical connections. These include screw terminal heads, open or enclosed, and plug or jack connections (Fig. 5.8).

5.11 Installation of the Finished Thermocouple

Many types of installation are possible with sheathed thermocouples. Typical installations are shown in Figs. 5.9, 5.10, and 5.11. Other special flanges and adaptors are available from many thermocouple manufacturers.

5.12 Sheathed Thermocouple Applications

Application information for sheathed thermocouples has been well covered in the literature. Many suggested applications are made in the various suppliers' catalogs. The Sannes article [7] on the application of the smaller

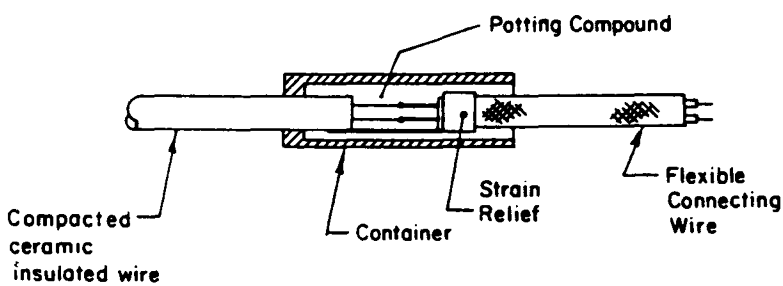

FIG. 5.7—*Termination with flexible connecting wires.*

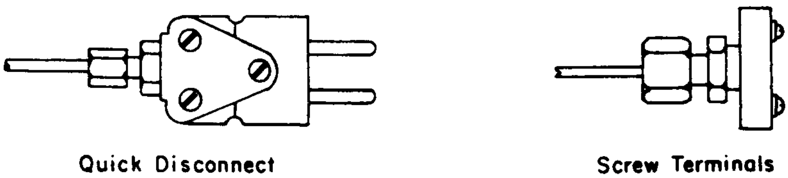

FIG. 5.8—*Quick disconnect and screw terminals.*

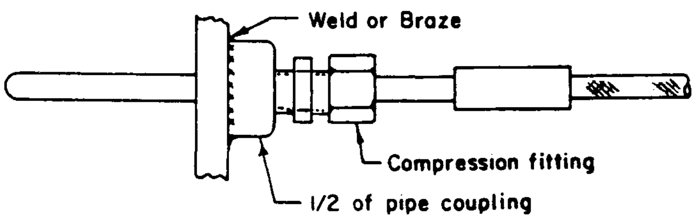

FIG. 5.9—*Fittings to adapt into process line* [*up to 3.48* $\times$ *10*^{4} *kPa (5000 psi)*].

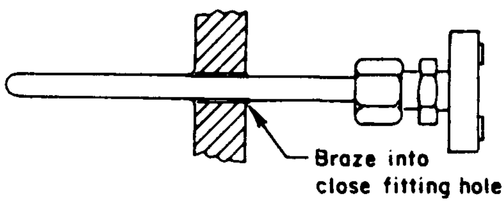

FIG. 5.10—*Braze for high pressure operation* [*up to 6.89* $\times$ *10*^{5} *kPa (100 000 psi)*].

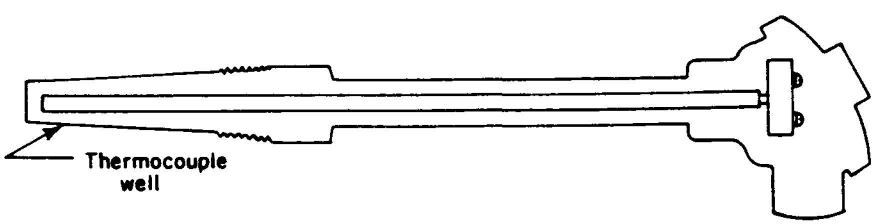

FIG. 5.11—*Thermocouple in thermowell.*

sheath diameters is useful. Chapter 9.2 of this manual is an excellent reference on surface temperature measurement. Gas stream performance is well documented [*8–10*] because of the applications to jet engines and rockets.

Nuclear reactor applications have used sheathed thermocouples extensively for monitoring and control. Johannessen [*12*] discussed the reliability assurance of such applications.

5.13 References

[*1*] Bliss, P., "Fabrication of High-Reliability Sheathed Thermocouples," *Temperature. Its Measurement and Control in Science and Industry,* Vol. 4, Part 3, Section VIII-C, June 1971.

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[*3*] Committee AE-2, Society of Automotive Engineers, "The Preparation and Use of Chromel-Alumel Thermocouples for Turbojet Engines," Aerospace Information Report No. 46, 15 March 1956.

[*4*] Scadron, L., "Ceramic Insulated Thermocouples," *Instruments and Control Systems,* May 1961.

[*5*] Fenton, A. W., Dacey, R., and Evans, E. J., "Thermocouples: Instabilities of Seebeck Coefficient," TRG Report 1447 (R), United Kingdom Atomic Energy Authority, 1967.

[*6*] *NIST Calibration Services User Guide,* NIST, National Institute of Standards and Technology (Formerly NBS) Special Publication SP250-35. Library of Congress 89-600732.

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[*8*] Faul, J. C., "Thermocouple Performance in Gas Streams," *Instruments and Control Systems,* Vol. 35, Dec. 1962.

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Chapter 6—Thermocouple Output Measurements

6.1 General Considerations

The basic principle of thermoelectric thermometry is that a thermocouple develops an emf which is a function of the difference in temperature of its measuring and reference junctions. If the temperature of the reference junction is known, or compensated for by the use of a reference junction as described in Chapter 7, the temperature of the measuring junction can be determined by measuring the emf generated in the circuit. The use of a thermocouple in temperature measurements, therefore, requires the use of an instrument capable of measuring the output voltage of the Thermocouple circuit.

There are many instruments used today to measure this output voltage or temperature. These instruments include the deflection meters (millivoltmeters), digital voltmeters, and potentiometers historically used for this purpose, as well as data loggers and computer based data acquisition systems which have increased in popularity. Thermocouple transmitters also have become a standard item in industrial thermocouple measurements where long lengths of thermocouple extension wire or remote measurements are needed.

Since manufacturers are constantly improving on the instruments used in measuring thermocouple circuits, it seems best to refer specific questions about the instruments to the manufacturers. In most cases up to date information is available immediately upon request. Referring the user to the manufacturer insures that the user will be provided with the most current information available.

In the following sections, short discussions are included on the various instruments used in measuring thermocouple circuits. Although not meant to be comprehensive, it is included to provide a background familiarity of the type of instruments available and their typical use.

6.2 Deflection Millivoltmeters

The deflection meter consists of a galvanometer with a rigid pointer which moves over a scale graduated in millivolts or degrees. The galvanometer indicates by its deflection, the magnitude of the current passing through it.

If the circuit in which it is placed includes a thermocouple, the galvanometer indicates the current I generated by the thermocouple in the circuit. If the circuit has a resistance R and the emf is E, by Ohm's law, $E = RI$. If R is kept constant, then I is proportional to E and the scale can be calibrated in terms of millivolts rather than in milli- or microamperes. This calibration holds as long as R remains constant. Any change in R introduces an error in the indicated value of E. Changes in resistance may result from changes in the temperature of the thermocouple, its extension wires or of the copper galvanometer coil. Corrosion of the thermocouple wires, changes in the depth of immersion of the thermocouple, or changes in contact resistance at switches or binding posts will also change the resistance of the thermocouple circuit.

In general, the reference junctions of the thermocouple measuring circuit are located near the meter movement. The effect of temperature changes on these junctions is compensated for by a bimetallic spiral attached to one of the control springs of the pointer. This system maintains accurate meter calibration during changes in ambient temperature.

In spite of its limitations, the deflection meter serves a very useful purpose in a great variety of industrial measurements of temperature where the precision and accuracy required are not of a high order. Its insensitivity to small a-c signals may prove an advantage.

6.3 Digital Voltmeters

Two kinds of digital meters are generally available: (1) the integrating type and (2) the successive approximation type. The integrating type compares the value of the emf being measured to an internal reference voltage standard by timed charging and discharging of a reference capacitor. Measurements are relatively slow, on the order of a second, but are relatively unaffected by the presence of some types of electrical noise.

The successive approximation type digital meter operates by first estimating a voltage and comparing it with that being measured. The error is noted by the circuit, and a second approximation is made and compared, etc., until the estimated voltage equals the unknown. Solid-state circuitry enables this type of meter to display a reading within milliseconds. It is, however, susceptible to errors from electrical noise interference.

Both types of meters may display voltage, or a linearizing circuit can be included to provide readings directly in temperature.

6.4 Potentiometers

6.4.1 Potentiometer Theory

Accurate measurement is usually a matter of comparing an unknown quantity against a known quantity or standard—the more direct the comparison, the better. Accurate weighing, for example, often is accomplished by direct comparison against standard weights using a mechanical balance. If the measured weights are too heavy for direct comparison, lever arms may be used to multiply the forces.

The potentiometer, as the term is used here, serves a similar function in the measurement of voltage, and, in fact, may be called a "voltage balance," the standard voltage being furnished by a standard cell, the "lever" being resistance ratios, and the galvanometer serving as the balance indicator. Since no current is drawn from the standard cell or the measured source at balance, the measurement is independent of external circuit resistance, except to the extent that this affects galvanometer or balancing mechanism sensitivity.

6.4.2 Potentiometer Circuits

Figure 6.1 shows a simple potentiometer circuit which includes a resistor R, a standard cell S, a battery B, a galvanometer G, and a rheostat r. R may be a calibrated slide wire with a known resistance, and R' a fixed resistor such that R plus R' is some simple multiple of the emf of S. If the end of S is taken as 1.019 V, the sum of R plus R' may be chosen as 101.9 ohms. If the switch K is turned to the standard cell position, the galvanometer, in general, will deflect. The setting of rheostat r, is adjusted until the galvanometer remains at rest when K is closed. The drop of potential of the battery current through R and R' is exactly equal to the emf of S, so that if the current in R and R' (I = 1.019 V per 101.9 ohms) is 10 mA, there is then a drop of potential of 0.010 V through each ohm of R. If R is 20 ohms the total drop through the slide wire is 0.2 V.

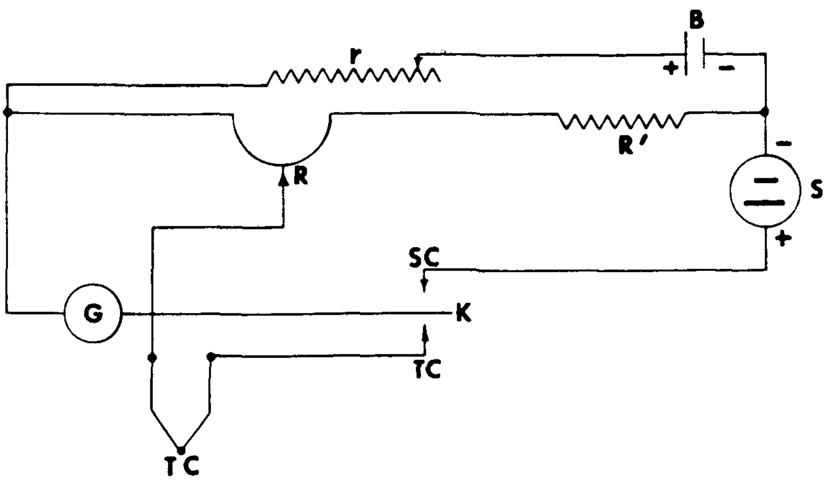

FIG. 6.1—*A simple potentiometer circuit.*

Now if K is turned to the "thermocouple" position, a setting may be found for the sliding contact on R at which there will be no deflection of the galvanometer. At this position, the drop of potential through R of the contact is equal to the emf of the thermocouple. If balance occurs at the 5 ohm point, the emf of the thermocouple is 0.01 V per ohm times 5 ohms = 0.05 V = 50 mV.

In this measurement the galvanometer has been used only as a means of detecting the presence of a current, and readings are made only when no perceptible current is passing through it. Therefore, it is not calibrated, and it is only called upon to indicate on balance with sufficient sensitivity to give the desired precision of setting of the sliding contact. An increase in the resistance of the thermocouple circuit can increase only the limits of positions of the contact between which there is no perceptible deflection, but does not affect the position of balance, nor the measured value of the emf. Since the galvanometer is used only to indicate the existence and direction of current, it is not necessary to design it to give a linear relationship between current and deflection. Zero stability is not extremely important since it is only necessary to look for departure from any equilibrium position which should be made. The galvanometer may be of the suspension type or an electronic null balance detector.

The calibration of an instrument of this type is stable since resistors and slide wires can be made with a high degree of stability. The emf of an unsaturated standard cell, as used for potentiometric work, does not change more than about 0.01% per year and has a negligible temperature coefficient.

The usefulness of an elementary potentiometer of this sort, having its entire range across the slide wire, is limited by the resolution possible in setting and reading the position of the contact on R.

6.4.3 Types of Potentiometer Instruments

6.4.3.1 Laboratory High Precision Type—The six dial potentiometer meets the most exacting requirements for standardizing, research, and testing laboratories. It is particularly useful for precise temperature measurements in studies of specific heats, melting, and boiling points, and for calibrating less precise potentiometers. It also is used for precise measurements such as required in calorimetry cryogenics. It measures emfs in the range of 0 to 1.6 V. It is essentially free of thermal emfs and transients.

6.4.3.2 Laboratory Precision Type—The three dial, manually operated potentiometer, also is used for precise measurements of voltage. As applied to the measurement of thermal emfs, its characteristics are such as to make it the most generally used of all the potentiometers in this field when accuracy and convenience of measurement are demanded. It is not portable in the sense in which the term is applied to self-contained potentiometers, since to attain the results of which it is capable, some parts of the circuit such as the null detector and the reference voltage source must be mounted separately.

6.4.3.3 Portable Precision Type—This potentiometer is a self-contained, three-dial, manually balancing instrument. It is used for precision checking of thermocouple pyrometers in laboratory and plant locations, and for general temperature measurements. The measuring range typically extends from -10.0 to 100.1 mV readable to 1 μV.

The reference junction compensation (*b*) is provided by an additional slide wire. This slide wire is used to set the reference junction voltage to the value which corresponds to the temperature of the reference junction.

The portable precision potentiometer is designed to measure thermocouple emfs with a precision adequate for all but the more refined laboratory applications. It includes a built-in lamp and scale galvanometer.

6.4.3.4 Semiprecision Type—Potentiometers are available which are similar to those used for precision potentiometry except for limits of error. They are essentially of the two-dial type with self-contained galvanometer, standard cell, and battery. They are used primarily for general temperature measurements by means of thermocouples, checking thermocouple pyrometers in laboratory and plant, and as a calibrated source of voltage.

6.4.3.5 Recording Type—Recording potentiometers are used widely for industrial process temperature measurement and control. These instruments balance automatically. When reliability and convenience are the prime concern, such instruments are satisfactory. However, because of potential inaccuracies in charts caused by printing limitations, humidity effects, and practical limits on chart widths and scale lengths resulting in inadequate readability, they are not generally used where precision is the criterion.

6.5 Voltage References

Both digital meters and potentiometers require a standard voltage reference for comparison.

Digital voltmeters and moderate precision potentiometers generally use the Zener diode, although many potentiometers still use Weston-type standard cells. High-precision potentiometers use standard cells. Two types of cells are available: saturated and unsaturated.

The saturated cell containing undissolved cadmium sulfate crystals is used in standardizing laboratories such as the National Institute of Standards and Technology (NIST) to represent the value of the volt. A typical cell has a potential of 1.0184 V at 20°C (68°F) reproducible to a few microvolts. This voltage is constant for a long period of time. (As long as 60 years or more is possible with proper care of the cell.) These cells have a substantial but predictable negative temperature coefficient ranging from about -40 μV/°C at 20°C to -70 μV/°C at 37°C. It is, therefore, necessary to control their temperature environment very precisely, confining their usefulness to the laboratory.

Unsaturated cells have a very low temperature coefficient but a less stable voltage output. Normal voltage drift rates can be expected to be -20 to -40 μV/year. The temperature coefficient is only a few microvolts/°C between 15 and 45°C and may be either positive or negative, depending upon the chemical composition of the particular cell. Useful life of these cells may be ten years or more. As the cells age, the emf decreases. When it drops to about 1.0130 V, the potential becomes erratic, the temperature coefficient increases, and excessive temperature emf hysteresis occurs.

A standard cell must be never short circuited, nor should its emf be measured with a voltmeter. In precise measurements, the balances should be made with a resistance of at least 10 000 ohms in series with the cell until the balance is well within the range of the detector scale.

6.6 Reference Junction Compensation

Temperature measurement with thermocouples always requires the knowledge of the reference junction temperature. It can be either held at a constant known temperature or allowed to follow ambient temperature with the necessary compensation applied. For a discussion on reference junctions, see Chapter 7.

6.7 Temperature Transmitters

In a simple thermocouple measuring circuit, a sensor is connected to a reference junction or measuring instrument by means of thermocouple extension wires. If the distance between the sensor and the measuring equipment is significant, then procurement and installation of the thermocouple extension cable can be significant. Additionally, errors can be realized in the circuit due to electrical noise, thermal effects, and improper installation. One way which has proven popular in industry for reducing the cost and eliminating these problems has been the use of transmitters.

Transmitters are electronic devices which provide reference junction compensation to a thermocouple, and then condition the output signal. The conditioned output signal typically takes the form of an amplified voltage or a current. This change in the signal allows the transmitter to be connected to the measuring instrument by means of standard instrumentation cable. The signal in the amplified voltage or current states is also less susceptible to problems such as noise and electromagnetic interference.

Transmitters are available in a number of configurations such as two wire, four wire, and "smart" or programmable transmitters. Each type of transmitter has benefits or drawbacks for different applications. Since the operational characteristics and types of transmitters available change frequently, the user is encouraged to review the information available at the time of interest.

6.8 Data Acquisition Systems

6.8.1 Computer Based Systems

This type of data acquisition system combines computers with digital voltmeters or other electronic equipment or both to obtain temperature measurements. These systems allow multiple measurements to be obtained over a specified time frame, with the information processable as required by the user. Analyses can be performed, and reports prepared without additional time or effort.

One particular area where computer based data acquisition systems are becoming more common is in the calibration or standards laboratory. In this setting, a number of temperature readings can be taken and the information statistically analyzed. This provides the user with information on both stability and drift which can be used in determining sensor accuracy and calibration uncertainty.

6.8.2 Data Loggers

Data loggers differ from computer based systems in the fact that they are dedicated normally to data acquisition. In computer based systems, the computer may be used for a variety of other uses. Data loggers are normally self contained units with circuit cards or modules included for reference junction compensation and temperature conversion from output voltage.

Capabilities of data loggers can be just as extensive as computer based systems for some applications. Temperature information can be collected, analyzed, and provided in report form in some programmable models, while other models are used as simple measure and print systems.

Chapter 7—Reference Junctions

7.1 General Considerations

A thermocouple circuit is, as shown in Fig. 7.1, by its nature a differential measuring device, producing an emf which is a function of the temperatures of its two junctions. One of these junctions is at the temperature which is to be measured and is referred to as the measuring junction. The other junctions are at a known temperature and are referred to as the reference junction. (In a practical thermocouple circuit (see Section 2.3) copper wires are often connected to the thermocouple alloy conductors at the reference junction. The term reference junctions will be used to refer to this situation.) If these junctions are both at the same temperature, the presence of the copper "intermediate metal" introduces no change in the thermocouple's emf [*1*]. Refer to Sections 2.4 for a discussion of this theory.

The uncertainty in the temperature of the reference junction will reflect a similar uncertainty in the deduced temperature of the measuring junction. However this situation does not exist for all thermocouple pairs. Notable exceptions occur in the case of the high rhodium-in-platinum alloy thermocouples [*2,3*]. In particular, if the reference junction of a platinum-30% rhodium versus platinum-6% rhodium (Type B) thermocouple lies within the range 0 to 50°C (32 to 122°F), a 0°C (32°F) reference junction may be assumed, and the error will not exceed 3 μV. This represents about 0.3°C (0.5°F) error in high-temperature measurements [*4*].

7.2 Reference Junction Techniques

Three basic methods are used to take account of the reference junctions of the thermocouple circuit: (1) the junction is maintained at a known fixed temperature, (2) the temperature of the reference junction is allowed to vary, and a compensating emf is introduced into the circuit or accounted for by calculation, (3) the temperature of the reference junction is allowed to vary, and compensation is made by a manual adjustment of the readout instrument.

Some variations of these techniques will be described in the following sections. Sources of error which are common to several techniques will be discussed in Section 7.3.

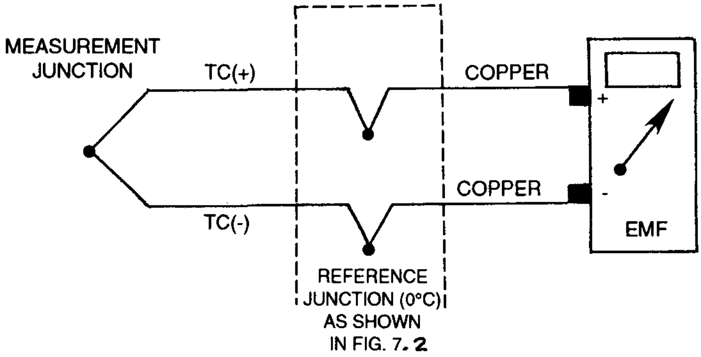

FIG. 7.1—*Basic thermocouple circuit.*

7.2.1 *Fixed Reference Temperature*

7.2.1.1 Triple Point of Water—A cell can be constructed in which there is an equilibrium between ice, water, and water vapor [*5*]. The temperature of this triple point is 0.01°C on the International Temperature Scale of 1990, and it is reproducible to about 0.0001°C. Williams [*6*] describes a commercially available cell which is not affected by factors such as air saturation and pressure which can cause several millikelvins fluctuation in the temperature of an ice bath. To utilize such precision, extreme attention to immersion error and galvanic error is required, and the measurement system must be of the highest quality.

7.2.1.2 Ice Point—An ice bath, consisting of a mixture of melting, shaved ice and water, forms an easy way of bringing the reference junctions of a thermocouple to 0°C (32°F). If a proper technique is used, the uncertainty in the reference junction temperature can be made negligibly small. With extreme care the ice point can be reproduced to 0.0001°C [*7*].

A recommended form of ice bath is described in Ref *8* and is shown in Fig. 7.2. Using the illustrated construction, with 14 gage B&S iron or nickel-base alloy wires and 20 gage B&S copper and noble metal wires, immersed at least 110 mm (4.5 in.) in the water-ice mixture, Caldwell [*9*] found the immersion error (see Section 7.3.1) to be less than 0.05°C. Smaller diameter wires would reduce the error. If large conductors must be used, Finch [*10*] describes a technique which minimizes the error.

To avoid the use of mercury[1] in the glass tubes, the tubes may be filled with moisture-free oil. Transformer oil and silicone oil are suitable [*11*–

[1]Mercury is considered a hazardous material. This publication does not purport to address all of the safety problems associated with its use. It is the responsibility of whoever uses mercury to consult and establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

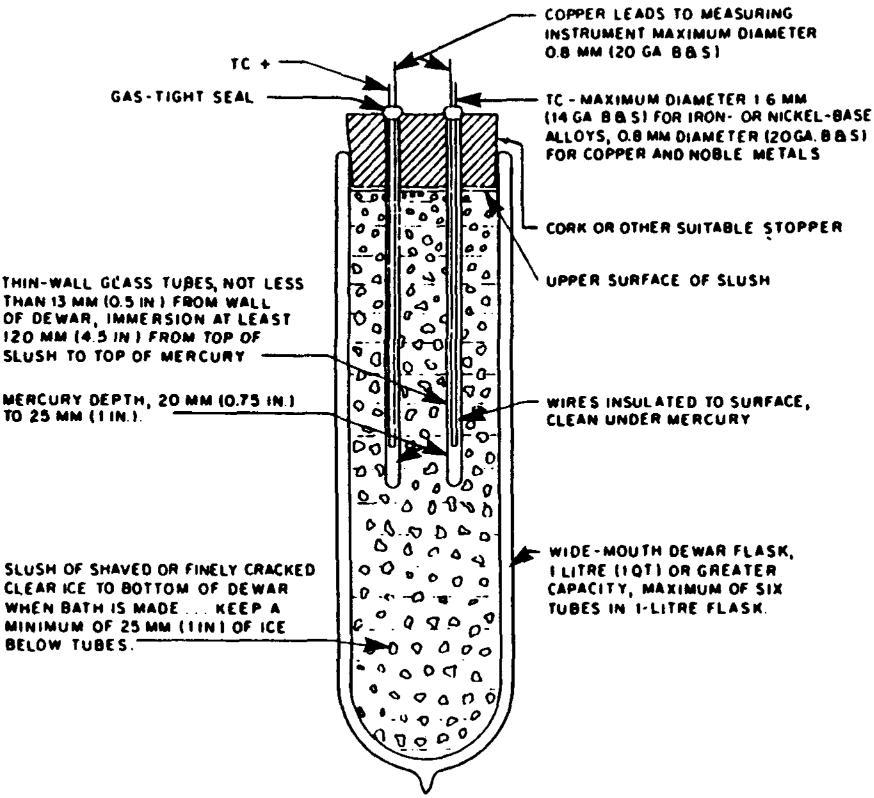

FIG. 7.2—*Recommended ice bath for reference junction.*

13].[2] Moisture-proof insulation should extend beneath the surface of the oil to the ends of the wires where they may be connected by any means which ensures a low resistance contact (for example, welding, soldering, crimping, etc.). If the glass tubes are immersed 200 mm (8 in.) in the ice-water mixture and the oil extends to within a few millimeters of the ice-water surface, the immersion error will be negligible. Sutton [*11*] plots the error as a function of the wire material, diameter, and immersion depth.

If the ice bath is used improperly, serious errors can result. The largest error which is likely to occur arises due to melting of the ice at the bottom of a bath until the reference junctions are below the ice level and surrounded by water alone. This water may be as much as 4°C above the ice point. While an ice bath is being used excess water should be removed periodically and

[2]Care should be taken to prevent oil contamination of that part of the thermocouples which will be exposed to high temperatures.

more ice added, so that the ice level is maintained safely below the reference junctions [*8,12*].

If the ice used to prepare the bath has been stored in a freezer at a temperature below 0°C, it may freeze the surrounding water and remain at a temperature below 0°C for some time. To avoid the condition, the ice should be shaved rather than crushed and thoroughly wetted with water before placing it in the vacuum bottle [*11–13*].

If appreciable concentrations of salts are present in the water used to make the ice bath, the melting point can be affected. McElroy [*14*] investigated various combinations of tap and distilled water to determine the error introduced. He observed bath temperatures of +0.013°C using distilled water with tap ice and −0.006°C using tap water and tap ice. It is probable that the proper use of tap water will not introduce significant errors unless accuracies better than 0.01°C are required [*9*].

Another possible source of error is galvanic action which is discussed in Section 7.3.2.

Although the ice bath is an easy way of achieving a convenient fixed point for the reference junctions in the laboratory, the need for constant attention makes it unsuitable for industrial application where some form of automatic reference junction is desirable.

7.2.1.3 Automatic Ice Point—The development of the thermoelectric refrigerator (Peltier cooler) has enabled the production of practical devices in which an equilibrium between ice and water is constantly maintained [*15,16*].

This device can provide a reference medium which is maintained at a precise temperature, but careful design is necessary if this precision is to be utilized fully. The system is subject to immersion error (Section 7.3.1) and galvanic error (7.3.2) due to condensation.

Some commercially available devices provide wells into which the user may insert reference junctions formed from calibrated wire. Others are provided with many reference junction pairs brought out to terminals which the user may connect into his system. The latter type are subject to the wire matching error (Section 7.3.3).

If the potential errors have been successfully overcome, the error introduced into a system by these devices can be less than 0.1°C.

Automatic ice points can be used to further advantage in conjunction with a "zone box" (see 7.2.2.1).

7.2.1.4 Constant Temperature Ovens—A thermostatically controlled oven provides a way of holding a reference junction at an approximately constant temperature. The major advantage of this method is that one oven can be used with a large number of circuits while maintaining isolation between the circuits without the need for providing separate power supplies for each circuit.

The oven must be maintained at a temperature above the highest anticipated ambient temperature. The need for temperature uniformity within the oven and a precise temperature control system are inherent complications, in addition to the immersion error (Section 7.3.1) and the wire matching error (Section 7.3.3).

Ovens are available with rated accuracies ranging from 0.1 to 0.05°C. A common commercially used junction temperature is 66°C (150°F), although other values may be specified.

Elevated temperature reference junctions can be used with instruments or tables based on 0°C reference junctions, provided an appropriate correction is applied.

A device using two ovens is available which makes this correction automatically. To generate the necessary emf (for example, 2.662 mV for a Type K system with a 66°C (150°F) reference junction temperature) an additional internal thermocouple is connected in series with the external thermocouple circuit. This internal thermocouple has its reference junction in the first oven and its measuring junction in the second oven. The second oven is maintained at a suitable temperature above that of the first so that the required emf is generated. The external thermocouple circuit then behaves as if its reference junction were at 0°C. The manufacturers' stated accuracies of these devices are similar to those of single oven units.

7.2.2 Electrical Compensation

If the temperature of the reference junction of a thermocouple is allowed to change, the output emf will vary in accordance with the Seebeck coefficient of the couple at the reference temperature. A compensating circuit containing a source of voltage, a combination of fixed resistors, and a temperature sensitive resistor (TSR) can be designed which will have a similar variation of emf as the temperature of the TSR is varied. If the reference junction of the thermocouple is coupled thermally to the TSR and the compensating circuit is connected in series with the thermocouple so that its temperature-variable emf opposes that caused by the reference junction, the thermocouple behaves as if the reference junction temperature were held constant. In addition, by suitable choice of the fixed resistors, any fixed reference junction temperature may be simulated. Since the TSR is at the temperature of the reference junction, no warmup or stabilization time is involved. Muth [*17*] has given a more extended description of these circuits.

The disadvantages of this arrangement include the need for a stable power source for each thermocouple circuit, the difficulty of adequately matching the Seebeck coefficient over an extended temperature range, and the addition of series resistance in the thermocouple circuit, which is insignificant if an open circuit measurement is made.

This principle is used in almost all self-balancing recording thermocouple potentiometers. Here the power source already is present as part of the potentiometer circuit. The Seebeck coefficient is matched adequately to allow the accuracy of the entire instrument to be typically 0.25% of full scale over a reasonable range of ambient temperatures.

Electric reference junction compensators are also available as small circuit modules with self-contained battery power sources or for connection to a-c power. A typical specification for a battery powered unit is compensation to ±0.3°C over an ambient of 13 to 35°C (55 to 95°F). Improved specifications are quoted for more elaborate devices.

Some portable manually balanced potentiometers are provided with a thermometer to read the reference junction temperature and an adjustable circuit calibrated in millivolts or temperature. The control must be set manually to add the required emf to simulate an ice-point reference junction temperature.

7.2.2.1 Zone Box—In systems employing large numbers of thermocouples, an alternative method of dealing with the reference junctions is particularly useful. All of the thermocouples are routed to a device called a zone box where each thermocouple conductor is joined to a copper wire which is routed to the emf measuring instrument [*18,19*].

Within the zone box all of the reference junctions between the thermocouples and the copper wires are insulated electrically but kept in good thermal contact with each other and with a transducer which measures the temperature within the zone box. This transducer can be a thermocouple of the same type as the measuring thermocouples with its reference junction in an automatic ice point or any of the other devices described in Section 7.2.1. The output of this thermocouple can be added to that of the measuring thermocouples, either electrically or in a data-collection computer. Several thermocouples are sometimes used in the zone box to monitor its temperature uniformity.

Alternatively, the zone box temperature can be measured by other transducers such as thermistors or resistance thermometers which need no reference temperature. In this case the measuring instrument determines the necessary correction to the thermal emfs, based on the temperature of the measuring-thermocouple reference junctions in the zone box. Several variations of this technique are described in Ref *19*.

The advantage of the zone box is its simplicity. It generally requires no heaters, controls or power supplies. Since it is approximately at the ambient temperature, the immersion error (Section 7.3.1) can be made negligible with a moderate amount of thermal insulation if care is taken to avoid locations having extreme thermal gradients. The wire matching error (Section 7.3.3) should receive attention because the reference junctions are at ambient temperature and the calibration error at this temperature must be accounted for.

7.2.2.2 Extended Uniform Temperature Zone—To reduce the length of thermocouple wires required to reach a zone box, Sutton [*11*] extended the zone by the use of a piped water system. The system operates at ambient temperature. By circulating water with a low power pump, uniformity within 0.1°C is achievable. The isothermal zone length may extend to many tens of meters.

7.2.3 Mechanical Reference Compensation

To complete this account of methods used to compensate for the temperature of thermocouple reference junctions, a device used on millivolt pyrometers must be included. The millivolt pyrometer measures the thermal emf of a thermocouple circuit by measuring the current produced in a circuit of fixed and known resistance. The current operates a galvanometer with a rigid pointer which moves over a scale graduated in degrees [*10*]. The reference junction is at the temperature of the instrument, and hence the available thermal emf is a function of the temperature of the instrument. Compensation often is accomplished by attaching one of the hairsprings of the D'Arsonval galvanometer movement to a bimetallic thermometer element so that the electrical zero of the instrument is adjusted to correspond to the temperature of the instrument. This system is subject to the wire matching error (Section 7.3.3), but the precision of the pyrometer seldom justifies making corrections.

7.3 Sources of Error

Several sources of error that may disturb the control or measurement of the reference junction temperature are discussed in this section.

7.3.1 Immersion Error

Whenever reference junctions are being maintained at a temperature that differs from the ambient, heat is transferred between the reference temperature medium (oven, ice bath, etc.) and the ambient via the electrical insulation which separates the junctions from the medium and via the wires which emerge from the reference junctions. Thus the temperature of the junctions always differs from that of the reference medium to a greater or lesser degree. Caldwell [*9*] gives data which allow the error to be estimated for the standard type of ice bath. For other situations the error may be calculated by methods outlined in Refs *20* and *21*, if the coefficients governing heat flow between the medium, the wires, and the ambient can be evaluated.

With careful design the immersion error usually can be made negligible.

7.3.2 Galvanic Error

If water is allowed to contact the thermocouple alloy and copper wires of the reference junction, a galvanic cell may be set up, causing voltage drops which disturb the thermal emfs. If the reference junction is at a temperature below the dew point, the water may appear due to condensation. Insulation on both wires and precautions to avoid the accumulation of water in contact with the wires normally will prevent this error [*9,14*].

7.3.3 Contaminated Mercury Error

Calibration laboratories which routinely calibrate thermocouple wire on a production basis using mercury-contact reference junctions should be aware that contaminated mercury can cause false readings. These false readings could be due to poor contact of the wires with the contaminated mercury. Contaminated mercury can be cleaned and reused.

7.3.4 Wire Matching Error

Thermocouple wire normally is calibrated with its reference junction at 0°C, and corrections are determined to enable accurate measurements at elevated temperatures. The calibration deviation at ambient temperature is seldom of interest and usually is not determined.

Many reference junction devices are equipped with thermocouple alloy wires, and provision is made for interconnection with the user's thermocouples at ambient temperatures. If the calibration of the wire supplied with the device differs from that of the thermocouples at the ambient temperature, a significant error can result due to the interconnection of the wires. This source of error often is overlooked, since it is assumed that if the interconnection of both wires of a thermocouple pair occurs at the same temperature no error is introduced. The existence of this error is visualized easily if the circuit is analyzed using Moffat's [*1*] or Reed's [*22*] methods.

A simple correction for the wire matching error can be made if the ambient temperature deviation of the wire supplied with the reference junction device is known and the user's thermocouples are calibrated at ambient temperature.

The wire matching error is avoided in those reference junction devices in which the user's wire is used to form the reference junctions.

7.4 References

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Chapter 8—Calibration of Thermocouples

The calibration of a thermocouple consists of the determination of its electromotive force (emf) at a sufficient number of known temperatures so that, with some accepted means of interpolation, its emf will be known over the entire temperature range in which it is to be used. The process requires a reference thermometer to indicate temperatures on a standard scale, a means for measuring the emf of the thermocouple, and a controlled environment in which the thermocouple and the reference thermometer can be brought to the same temperature. Some of the more commonly used techniques for accomplishing such calibrations will be discussed in this chapter.

Much of this material is based upon the National Institute of Standards and Technology (NIST) Special Publication 250-35, *The Calibration of Thermocouples and Thermocouple Materials* and the calibration methods appearing in the following ASTM Standards:

E 207 Method of Thermal EMF Test of Single Thermoelement Materials by Comparison with a Secondary Standard of Similar EMF-Temperature Properties,
E 220 Method for Calibration of Thermocouples by Comparison Techniques,
E 452 Method for Calibration of Refractory Metal Thermocouples Using an Optical Pyrometer, and
E 563 Practice for Preparation and Use of Freezing Point Reference Baths.

8.1 General Considerations

8.1.1 Temperature Scale

The International Temperature Scale of 1990 (ITS-90) is realized and maintained by the National Institute of Standards and Technology to provide a standard scale of temperature for use by science and industry in the United States. This scale [*1,2*] was adopted by the International Committee of Weights and Measures at its meeting in September 1989, and it became the official international temperature scale on 1 January 1990 (see Appendix

II of this Manual). The ITS-90 supersedes the International Practical Temperature Scale of 1968, Amended Edition of 1975 (IPTS-68(75)) [*3*] and the 1976 Provisional 0.5 to 30 K Temperature Scale (EPT-76) [*4*].

Temperatures on the ITS-90 can be expressed in terms of International Kelvin Temperatures, with the symbol T_{90}, or in terms of International Celsius Temperatures, with the symbol t_{90}. The units of T_{90} and t_{90} are the kelvin, symbol K, and the degree Celsius, symbol °C, respectively. The relation between T_{90} (in K) and t_{90} (in °C) is

$$t_{90} = T_{90} - 273.15$$

Values of Fahrenheit temperature (t_f), symbol °F, are obtained from the conversion formula

$$t_f = (9/5)t_{90} + 32$$

The ITS-90 was designed in such a way that temperature values on it very closely approximate Kelvin thermodynamic temperature values. Temperatures on the ITS-90 are defined in terms of equilibrium states of pure substances (defining fixed points), interpolating instruments, and equations that relate the measured property to T_{90}. The defining equilibrium states and the values of temperature assigned to them are listed in Table 8.1.

The ITS-90 extends upward from 0.65 K to the highest temperature measurable in terms of the Planck radiation law using monochromatic radiation. The scale has alternative definitions of T_{90} in certain temperature ranges. These and other details of the ITS-90, as well as the differences between it and the previous scales (IPTS-68 and EPT-76), are covered in the publication presented in Appendix II of this Manual. In addition, guidelines for realizing the ITS-90 are discussed in NIST Technical Note 1265 [*5*].

In addition to the defining fixed points of the ITS-90, given in Table 8.1, the equilibrium states of certain other pure substances may be useful as secondary fixed points for calibration purposes. Some of these and their reported temperatures are given in Table 8.2. Except for the triple point of benzoic acid, each temperature is for a system in equilibrium under a pressure of 1 standard atm.

8.1.2 Reference Thermometers

Any one of several types of thermometers, calibrated in terms of the ITS-90, may be used as a reference thermometer for the calibration of thermocouples. The choice will depend upon the temperature range covered, whether a laboratory furnace or a stirred liquid bath is used, the accuracy expected of the calibration, or in cases where more than one type will suffice, the convenience or preference of the calibrating laboratory.

8.1.2.1 Resistance Thermometers—Standard platinum resistance thermometers are the most accurate reference for use from approximately

TABLE 8.1—*Defining fixed points of the ITS-90.*

Material[a]	Equilibrium State[b]	Temperature[d]	
		T_{90}, K	t_{90}, °C
He	VP	3 to 5	−270.15 to −268.15
e-H_2	TP	13.8033	−259.3467
e-H_2 (or He)	VP (or CVGT)	≈ 17	≈ −256.15
e-H_2 (or He)	VP (or CVGT)	≈ 20.3	≈ −252.85
Ne[c]	TP	24.5561	−248.5939
O_2	TP	54.3584	−218.7916
Ar	TP	83.8058	−189.3442
Hg[c]	TP	234.315	−38.8344
H_2O	TP	273.16	0.01
Ga[c]	MP	302.9146	29.7646
In[c]	FP	429.7485	156.5985
Sn	FP	505.078	231.928
Zn	FP	692.677	419.527
Al[c]	FP	933.473	660.323
Ag	FP	1234.93	961.78
Au	FP	1337.33	1064.18
Cu[c]	FP	1357.77	1084.62

[a]e-H_2 indicates equilibrium hydrogen, that is, hydrogen with the equilibrium distribution of its ortho and para states. Normal hydrogen at room temperature contains 25% para- and 75% orthohydrogen.

[b]VP indicates vapor pressure point; CVGT indicates constant volume gas thermometer point; TP indicates triple point (equilibrium temperature at which the solid, liquid, and vapor phases coexist); FP indicates freezing point and MP indicates melting point (the equilibrium temperatures at which the solid and liquid phases coexist under a pressure of 101 325 Pa, one standard atmosphere). The isotopic composition is that naturally occurring.

[c]Previously, these were secondary fixed points.

[d]The effect of pressure on the temperature of the defining fixed points is given in Ref *1* (see Appendix II of this Manual). The reference pressure for melting and freezing points is 101 325 Pa, one standard atmosphere. For triple points the pressure effect is a consequence only of the hydrostatic head of liquid in the cell.

TABLE 8.2—*Some secondary fixed points. The pressure is 1 standard atm, except for the triple point of benzoic acid.*

Equilibrium State	t_{90}, °C
Boiling point of normal hydrogen	−252.762
Boiling point of nitrogen	−195.798
Sublimation point of carbon dioxide	−78.465
Freezing point of water	0.00
Triple point of benzoic acid	122.340
Freezing point of cadmium	321.069
Freezing point of lead	327.46
Freezing point of antimony	630.63
Freezing point of nickel	1455
Freezing point of palladium	1554.8
Freezing point of platinum	1768.1

−260°C (−436°F) to 962°C (1764°F). In cases where an uncertainty approaching 0.1°C is necessary at temperatures below −36°C (−33°F) or above about 200°C (392°F) there are few alternatives to the use of resistance thermometers as a reference.

8.1.2.2 Liquid-in-Glass Thermometers—This type of thermometer may be used from approximately −200°C (−328°F) to 400°C (752°F), or even higher with special types. Generally, the accuracy of these thermometers is less below −36°C (−33°F) where organic thermometric fluids are used, and above 300°C (572°F) where instability of the bulb glass may require frequent calibration. Specifications for ASTM liquid-in-glass thermometers are given in ASTM E1.

8.1.2.3 Types E and T Thermocouples—Either of these types of thermocouples may be used down to a temperature of −183°C (−297°F) or lower, but the attainable accuracy may be limited by the accuracy of the emf measurements and the inhomogeneity of the wire at low temperatures. Recommended upper temperature limits for these thermocouple types are 250°C (482°F) for Type E and 200°C (392°F) for Type T. The stability of the larger sizes of wire is greater than that of smaller wires under the same conditions. Twenty-four gage wire is a useful compromise between the lesser stability of smaller wire and the greater thermal conduction (greater required depth of immersion) of larger wire.

8.1.2.4 Types R and S Thermocouples—Type S and Type R thermocouples are suitable reference thermometers for use in the range from 200°C (392°F) up to about 1200°C (2192°F). Their use may be extended down to room temperature if it is desired to use the same reference over a wide range, but their sensitivity falls off appreciably as temperatures below 200°C (392°F) are reached. Twenty-four gage wire most commonly is used for these types of thermocouples.

8.1.2.5 High Temperature Standards—The ITS-90 above 961.78°C (1763.20°F) is defined by the Planck law of radiation, and the scale is realized usually by means of an optical pyrometer. The optical pyrometer [*6*], sighted on a blackbody cavity built into the calibration furnace, therefore, can serve as a reference thermometer for all temperatures above 961.78°C. On the other hand, thermocouples, calibrated on the optical pyrometer scale, can be used themselves as references. The Type B thermocouple is useful up to about 1700°C (3092°F). Tungsten-rhenium alloys can be used to higher temperatures, but the optical pyrometer more commonly is used.

8.1.3 Annealing

Practically all base-metal thermocouple wire is annealed or given a "stabilizing heat treatment" by the manufacturer. Such treatment generally is considered sufficient, and seldom is it found advisable to further anneal the wire before testing.

Although new platinum and platinum-rhodium thermocouple wire as sold by some manufacturers already is annealed, it has become regular practice in many laboratories to anneal all Types R, S, and B thermocouples, whether new or previously used, before attempting an accurate calibration. This is accomplished usually by heating the thermocouple electrically in air. The entire thermocouple 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 determined most conveniently with an optical pyrometer.[1]

There are some questions as to the optimum temperature and length of time at which such thermocouples should be annealed to produce the most constant characteristics in later use [7] and 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 heatings at 1400 to 1500°C (2552 to 2732°F), but it has been claimed that the changes in the thermal emf of a couple 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 grain growth. It has been found that annealing at temperatures much above 1500°C (2732°F) produces changes in the emf and leaves the wire very weak mechanically. In addition, rapid cooling [7] of the wires following annealing at elevated temperatures should be avoided since it can alter substantially the emf. Except for work of the highest precision, cooling at a rate not exceeding about 400°C/min is satisfactory. The National Institute of Standards and Technology has adopted the procedure of annealing Types R, S, and B thermocouples for 45 min at 1450°C (2642°F), followed by 30 min at 750°C (1382°F) and then slow cooling to room temperature [*8*].

It has not been demonstrated conclusively that Types R, S, and B thermocouples after contamination can be improved materially 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.

8.1.4 Measurement of Emf

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

[1]The ordinary portable type of visual optical pyrometer is very satisfactory for this purpose. As commonly used, the magnification is too low for sighting on an object as small as the wires of noble-metal thermocouples, but this is remedied easily by lengthening the telescope tube or using an objective lens of shorter focal length.

measurements. For work of the highest accuracy it is advisable to use a potentiometer of the type designed by Diesselhorst [*9*], White [*10*], or Wenner [*11*], in which there are no slidewires and in which all the settings are made by means of dial switches. However, for most work on which an accuracy of 5 μV will suffice, slidewire potentiometers of the laboratory type are sufficiently accurate.

Electronic digital voltmeters and analog-to-digital converters that are of potentiometric or other high-impedence design and that possess sufficient accuracy may be also used. Such instruments permit fast readings of a large number of thermocouples. For a more detailed consideration of emf measurements see Chapter 6.

8.1.5 Homogeneity

The emf developed by a thermocouple made from homogeneous wires will be a function of the temperature difference between the measuring and the reference junction. If, however, the wires are not homogeneous, and the inhomogeneity is present in a region where a temperature gradient exists, extraneous emfs will be developed, and the output of the thermocouple will depend upon factors in addition to the temperature difference between the two junctions (see Chapter 2). The homogeneity of the thermocouple wire, therefore, is an important factor in accurate measurements.

Thermocouple wire now being produced is usually 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.

While 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. Abrupt changes in the Seebeck coefficient may be detected by connecting the two ends of the wire to a sensitive galvanometer and slowly moving a source of heat, such as a bunsen burner or small electric furnace, along the wire. This method is not satisfactory for detecting gradual changes in the Seebeck coefficient 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 250 mm (10 in.) in a furnace with a sharp temperature gradient so that two points on the wire 500 mm (20 in.) 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.

Another simple experimental method for detecting thermoelectric inhomogeneity in thermocouple wire consists of observing the variation of emf as a loop of the wire is immersed into a cryogenic fluid, such as liquid nitrogen or helium. Typical emf variations found for commonly used types of base-metal thermocouple wire by this method are reported by Hust et al. [*12*]. More elaborate test methods and apparatus for examining thermocouples for inhomogeneities are described by Fenton [*13*], by Bentley and Jones [*14*], by McLaren and Murdock [*15*], and by Mossman et al. [*16*].

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 [*8*].

The experimental methods described in the literature cited previously allow thermocouple users to select materials for their purposes that are most homogeneous. They also provide emf data necessary for making realistic assessments of measurement uncertainties due to thermoelectric inhomogeneities. However, since the emf developed along inhomogeneous thermocouple wires depends upon the temperature distribution, it is evident that corrections for inhomogeneity are impracticable if not impossible to make during calibration.

8.1.6 General Calibration Methods

The temperature-emf relation of a homogeneous [*17*] 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 numerous 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. However, the emf of a thermocouple with its measuring junction at a specified temperature depends upon the temperature difference between its measuring and reference junctions. Therefore, whatever method of calibration is used, the reference junction must be maintained constant at some known temperature (see Chapter 7), and this temperature must be stated as a necessary part of the calibration results.

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 ITS-90 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 usually will suffice. The most accurate calibrations in the range −260°C (−436°F) to 962°C (1764°F) are made by comparing the couples directly with a standard platinum-resistance thermometer in a stirred liquid bath or a metal-block comparator. Thermocouples are also calibrated very accurately at the freezing points of the pure metals given in Tables 8.1 and 8.2. Above 962°C (1754°F), the most basic calibrations are made by observing the emf when one junction of the thermocouple is heated in a blackbody furnace, the temperature of which is measured with an optical pyrometer. However, the difficulties encountered in bringing a blackbody furnace to a uniform temperature make the direct comparison of these two types of instruments by no means a simple matter.

Type S and Type R thermocouples calibrated by comparison with a PRT and at fixed points are used extensively both above and below 962°C (1764°F) as reference thermometers in the calibration of other thermocouples. For most industrial purposes a calibration accurate to 2 or 3°C in the range from room temperature to 1200°C (2192°F) is sufficient. Other thermocouples can be calibrated by comparison with such reference thermocouples almost as accurately as the calibration of the reference thermocouple is known. At the lower temperatures (below 200°C, or 392°F) certain types of base-metal thermocouples are better adapted for precise measurements than those noble-metal types.

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 calibrated reference thermometers, such as thermocouples, resistance thermometers and liquid-in-glass thermometers.

In order to obtain the high accuracies referred to previously 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 paragraphs, but for an accuracy of about 5°C the more elaborate apparatus to be described need not be employed.

8.1.7 Calibration Uncertainties

The several factors which contribute to the uncertainties in the emf versus temperature relationship for a particular thermocouple as determined by calibration may be grouped into two kinds; those influencing the observations at calibration points, and those arising from any added uncertainty as a result of interpolation between the calibration points. Errors from either of these sources of uncertainty can be reduced materially, within limits, through use of well designed equipment and careful techniques; hence, the required accuracy should be clearly understood when choosing calibration facilities.

Estimates of the uncertainties in calibrating homogeneous thermocouples by different techniques are given in Tables 8.3, 8.4, 8.5, 8.6, and 8.7. The

TABLE 8.3—*Calibration uncertainties using fixed point techniques.*

Type	Temperature Range, °C	Calibration Points[a]	Calibration Uncertainty At Observed Points, °C	Calibration Uncertainty Of Interpolated Values, °C
S	0 to 1064	Sn, Zn, Al, Ag, Au	0.2	0.4
R	0 to 1064	Sn, Zn, Al, Ag, Au	0.2	0.4
B	600 to 1064	Al, Ag, Au	0.2	0.4
E	0 to 870	Sn, Zn, Al	0.2	0.5
J	0 to 760	Sn, Zn, Al	0.2	1.0
K	0 to 1100	Sn, Zn, Al, Ag, Au	0.2	1.0

[a]Metal freezing points.

estimates assume that reasonable care is exercised in the work. More or less accurate results are possible using the same methods, depending upon soundness of the techniques used. While excessive care is a waste when relatively crude measurements are sufficient, it should be emphasized that inadequate attention to possible sources of error is more often found to be the practice than the converse. In the following some of the important considerations associated with the various calibration methods are emphasized briefly.

8.1.7.1 Uncertainties Using Fixed Points—The equilibrium temperatures listed in Table 8.2 are sufficiently exact, and the materials are readily available in high enough purity, that accurate work can be done using these fixed points with no significant error being introduced by accepting the temperatures listed. Using freezing points, however, good designs of freezing point cells and furnaces are important for controlling the freezes and for providing sufficient immersion for the thermocouple, if the full potential of the method is to be realized.

Although uncertainties of the order of ±1°C in the temperatures are assigned to the freezing points (and hence by implication to the melting

TABLE 8.4—*Calibration uncertainties using comparison techniques in laboratory furnaces (Types R or S standards).*

Type	Temperature Range, °C	Calibration Points	Calibration Uncertainty At Observed Points, °C	Calibration Uncertainty Of Interpolated Values, °C
R or S	0 to 1100	about every 100°C	0.6	0.7
B	600 to 1100	about every 100°C	0.6	0.7
E	0 to 870	about every 100°C	1.0	1.2
J	0 to 760	about every 100°C	1.0	1.2
K	0 to 1100	about every 100°C	1.0	1.2

TABLE 8.5—*Calibration uncertainties using comparison techniques in stirred liquid baths.*

				Calibration Uncertainty	
Type	Temperature Range, °C	Calibration Points	Type of Standard[a]	At Observed Points, °C	Of Interpolated Values, °C
E	−196 to 425	about every 100°C	PRT	0.1	0.2
	−196 to 435	about every 50°C	PRT	0.1	0.1
	−196 to 435	about every 50°C	E or T	0.2	0.2
	−56 to 200	about every 50°C	LIG	0.1	0.1
T	−196 to 250	about every 100°C	PRT	0.1	0.2
	−196 to 250	about every 50°C	PRT	0.1	0.1
	−196 to 250	about every 50°C	E or T	0.2	0.2
	−56 to 200	about every 50°C	LIG	0.1	0.1

[a]PRT = standard platinum resistance thermometer; E or T = Type E or T thermocouple; and LIG = liquid-in-glass thermometer.

points) of palladium and platinum, these contribute in only a minor way to overall uncertainties of calibrations using freezing point techniques.

8.1.7.2 Uncertainties Using Comparison Methods—The accuracy attained at each calibration point using the comparison method will depend upon the degree to which the reference thermometer and the test thermocouple are maintained at the same temperature and the accuracy of the reference thermometer used. Comparison measurements made in stirred liquid baths usually present no special problems provided that sufficient immersion is used. Because of the high-thermal conductivity of copper, special attention should be given to the problem of immersion when calibrating Type T thermocouples.

As higher and higher temperatures are used, the difficulties of maintaining the test and reference thermocouples at the same measured temperature are magnified whether a tube furnace, an oven with moderating block, or whatever means is used for maintaining the desired temperature. In addition, at temperatures of about 1500°C (2732°F), and higher, the choice of insulating materials becomes very important (see Chapter 4). Special attention must

TABLE 8.6—*Calibration uncertainties: tungsten-rhenium type thermocouples.*

Calibration Uncertainty		
At Observed Points		Of Interpolated Values[a]
Gold (1064.18°C)	±0.5°C	1000 to 1455°C, ±2.7°C
Nickel (1455°C)	±3.5°C	1455 to 1554°C, ±4.0°C
Palladium (1555°C)	±3.0°C	1554 to 1768°C, ±4.0°C
Platinum (1768°C)	±3.0°C	1768 to 2000°C, ±7.0°C
Rhodium (1963°C)	±5.0°C	...

[a]These values apply only when all five observed points are taken.

TABLE 8.7—*Calibration uncertainties using comparison techniques in special furnaces (visual optical pyrometer standard).*

Type	Temperature Range, °C	Calibration Uncertainty At Observed Points, °C	Calibration Uncertainty Of Interpolated Values,[a] °C
IrRh versus Ir[b]	1000 to 1300	2	3
IrRh versus Ir[b]	1300 to 1600	3	4
IrRh versus Ir[b]	1600 to 2000	5	8
W versus WRe[c]	1000 to 1300	2	3
W versus WRe[c]	1300 to 1600	3	4
W versus WRe[c]	1600 to 2000	5	8
R, S, or B	1100 to 1450	2	3
B	1450 to 1750	3	5

[a]Using difference curve from reference table with calibration points spaced every 200°C.
[b]40Ir60Rh versus Ir, 50Ir50Rh versus Ir, or 60Ir10Rh versus Ir.
[c]W versus 74W26Re, 97W3Re versus 75W25Re, or 95W5Re versus 74W26Re.

be paid to possible errors arising from contamination from the insulators or protection tube and from electrical leakage.

When an optical pyrometer is used as the reference thermometer, a good blackbody must be used, and the design must be such that the test thermocouple is at the same temperature as the blackbody.

8.2 Calibration Using Fixed Points

If a Type S or a Type R thermocouple is calibrated at the freezing points of tin, zinc, aluminum, silver, and gold (or copper), a reference thermometer will result which is accurate to about 0.4°C in the range 0 to 1100°C (32 to 2012°F). The fixed-point calibration method is also useful in the calibration of other types of thermocouples. Fixed points can be used with various degrees of accuracy, ranging from 0.1 to 5°C, for the calibration of various types of thermocouples in the range −260°C (−436°F) to the melting point of platinum at 1768°C (3214°F). The ITS-90 defining fixed points and some secondary fixed points for which values have been determined accurately are listed in Section 8.1.1, Tables 8.1 and 8.2, respectively. Because of experimental difficulties, fixed points at temperatures higher than the freezing point of copper usually are realized as melting points rather than freezing points, as described later.

8.2.1 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 measuring 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.

Techniques for achieving these conditions are well developed [*5,8,18–20*]. Nearly all of the metals listed in Tables 8.1 and 8.2 of Section 8.1.1 are available commercially in high purity (99.9999 percent) and can be used assuming the freezing point temperatures given in the tables. It is essential, however, that protecting tubes and crucibles be chosen of such material (see Chapter 4) that the pure metals will not be contaminated. Copper and silver must be protected from oxygen contamination and it is also advisable to protect aluminum and antimony; this is done usually by using covered crucibles made of graphite and covering the freezing point metals with powdered graphite or by sealing the crucible in a glass tube that contains a nonoxidizing gas such as argon or helium. The choice of a suitable furnace is also important. The furnace must provide uniform heating in the region of the freezing point sample, and have adequate controls to bring the sample slowly into its freeze. Complete units consisting of freezing point sample, crucible, and furnace are available commercially. Freezing point standard samples of tin, cadmium, zinc, aluminum, and copper may be purchased from the NIST Office of Standard Reference Materials. Their application as fixed points is described in Ref *20*.

8.2.2 Melting Points

The emf of a thermocouple at the melting point of a metal may be determined with the same apparatus as that described previously for freezing points, but the use of the freeze is usually more satisfactory. Melting points are used to advantage, however, when only a limited amount of material is available or at high temperatures where experimental techniques with freezing points are difficult. To apply this method [*21–23*], a short length of metal whose melting point is known is joined between the end of the two wires of the thermocouple and placed in an electrically heated furnace the temperature of which is raised slowly. When the melting point of the metal is reached, the emf of the thermocouple remains steady for several minutes and then drops to zero as the fused metal drops away from the junction. With good technique[2] the method can result in accuracies comparable to those with which the ITS-90 is realized above 962°C (1764°F) by optical pyrometry.

[2]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.

8.3 Calibration Using Comparison Methods

The calibration of a thermocouple by comparison with a reference thermometer (see ASTM Standard E 220) 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 measuring junction of the thermocouple to the same temperature as the actuating element of the reference thermometer, such as the measuring junction of a Type S thermocouple, the bulb of a liquid-in-glass thermometer, or the resistor of a resistance thermometer. The accuracy obtained is further limited by the accuracy of the reference thermometer. Of course, the reference junction temperature must be known, but this can be controlled, as described in Chapter 7. The method of bringing the measuring junction of the thermocouple to the same temperature as that of the actuating element of the reference thermometer depends upon the type of thermocouple, type of reference thermometer, and the method of heating.

8.3.1 Laboratory Furnaces

The calibration procedure consists of measuring the emf of the thermocouple being calibrated at selected calibration points, the temperature of each point being measured with a reference thermometer. The number and choice of calibration points will depend on the type of thermocouple, the temperature range covered, and the accuracy required (see Sections 8.1.6 and 8.4).

8.3.1.1 Noble-Metal Thermocouples—Such thermocouples usually may be calibrated at temperatures from ambient up to 1200°C by comparison with either a Type S or Type R reference thermocouple in electrically heated furnaces. Above 1200°C (2192°F) the Type B thermocouple is a preferred reference thermometer because of its greater stability at high temperatures. This thermocouple may be used to 1700°C (3092°F) or higher.

An automated method [*8*] of making comparison calibrations of such thermocouples is based upon the simultaneous reading of the emf, the reference thermocouple, and that of the test thermocouple without waiting for the furnace to stabilize completely at any given temperature. The values of emf are measured and recorded with an automatic digital data acquisition system that includes a microcomputer, a switch scanner, and two digital voltmeters. The test thermocouples are connected to one digital voltmeter by means of the switch scanner, and the reference thermocouple is connected to the other digital voltmeter so that measurements of the test and reference thermocouples may be made simultaneously. The measuring junctions of the test and reference thermocouples are maintained always at close to the same temperature by welding them into a common bead or by wrapping them together with platinum wire or ribbon. This method is particularly adapted to the calibration of thermocouples at any number of selected points over the operating temperature range of the furnace used. The number of test thermocouples that may be calibrated together in the same calibration run will depend principally on the size of the furnace used. To reduce the time required to calibrate by this method, the furnace should be so constructed that it may be heated or cooled rapidly. One such furnace which employs a nickel-chromium tube as the heating element is described in ASTM E 220 and in Ref *8*.

A similar furnace using a silicon carbide tube as the heating element can be used to extend the calibration range upward [*8*]. At temperatures above 962°C (1764°F) the ITS-90 is defined in terms of the Planck radiation law using monochromatic radiation which is measured usually with an infrared pyrometer or with a visual optical pyrometer. If the test thermocouple is inserted into the back of a blackbody cavity built into a furnace, a pyrometer may be used directly as the reference thermometer. Alternatively, a Type B thermocouple can be used as the reference thermometer after it has been calibrated against a pyrometer.

The thermocouples are insulated and protected by suitable ceramic tubes (Chapter 4). It is essential that good insulation be maintained between the two measuring instruments and between the thermocouple circuits except at the point where the measuring junctions are welded together. The reference junctions must be maintained at a known temperature (Chapter 7) when the emf measurements are made.

If two measuring instruments are not available for taking simultaneous readings, the furnace may be brought to essentially a constant temperature, and then with appropriate switching, automatically or manually operated, the emf of each thermocouple read alternately with one measuring instrument as described in ASTM E 220. Various types of wire-wound electric tube furnaces suitable for calibrations by this method are available commercially. Some considerations in selecting an appropriate furnace are given in Appendix X1.1 of ASTM E 220.

When the thermocouples are calibrated by welding or wrapping the junctions together, both would be expected to be close to the same temperature even when the temperature of the furnace is changing. If it is necessary or advisable to calibrate the thermocouples without removing them from the protecting tubes, then the junctions of the thermocouple being tested and that of the reference thermocouple 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.

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 salt, 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. Ceramic tubes are sufficient protection, but to avoid breakge 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.

8.3.1.2 Base-Metal Thermocouples—The methods of testing base-metal thermocouples above room temperature are generally the same as those just described for testing noble-metal thermocouples with the exception, in some cases, of the methods of bringing the junctions of the reference and the thermocouple being tested to the same temperature and the methods of protecting platinum-rhodium reference thermocouples from contamination. One arrangement of bringing the junction of a platinum-rhodium reference thermocouple to the same temperature as that of a large base-metal thermocouple for accurate calibration is to insert the junction of the reference thermocouple into a small hole (about 1.5 mm (0.06 in.) in diameter) drilled in the measuring junction of the base-metal thermocouple. The platinum-rhodium reference thermocouple is protected by ceramic tubes to within several tenths of an inch of the measuring junction, and the end of the ceramic tube is sealed to the thermocouple by pyrex glass or by a small amount of kaolin and water-glass cement. This protective measure minimizes contamination of the reference thermocouple, with the exception of the small length of about 2 or 3 mm which is necessarily in contact with the base-metal thermocouple. If the furnace is heated uniformly in this region (and it is of little value to make such a test unless it is) contamination of the unprotected portion of the reference thermocouple will not cause any error. If the wire of the reference thermocouple becomes brittle at the junction, this part of the wire may be cut off and enough wire drawn through the softened 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 measuring instruments 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. When wires, insulators, and protection tubes are large, tests should be made to ensure that the depth of immersion is sufficient.

8.3.2 Stirred Liquid Baths

At temperatures below 620°C (1148°F) stirred liquid baths provide an efficient medium for bringing a thermocouple and a reference thermometer to the same temperature.

Water, petroleum oils, or other organic liquids, depending upon temperature range, are commonly used bath media. Molten salts or liquid tin are used at temperatures higher than are suitable for oil. Baths suitable for this work are described in ASTM E 77 and in Ref *8*.

Base-metal thermocouples, either bare wire or insulated, may be calibrated accurately in such baths. Usually no special preparation of the thermocouple will be required other than to insert it to the bottom of a protection tube for immersion in the liquid bath. Borosilicate glass tubing, such as Pyrex glass, is convenient for use up to 500°C (932°F). Vitreous silica or ceramic tubing may be used to 620°C (1148°F). The tube should be closed at the immersed end and of an internal diameter such as to permit easy insertion of the thermocouple or thermocouples to be calibrated but no larger than necessary. Unfavorable heat transfer conditions in an unnecessarily large diameter tube will require a greater depth of immersion in the bath than would a close fitting tube. If a bare wire thermocouple is being calibrated, the wires must be provided with electrical insulation over the length inserted in the protection tube. Sheathed thermocouples may be immersed directly in the bath liquid in cases where the sheath material will not be attacked by the liquid. Salt baths for use at high temperature must be provided with suitable wells into which the thermocouple protection tubes and reference thermometers may be inserted for protection from the molten salt.

The reference thermometer may be a calibrated thermocouple inserted in the protection tube with the thermocouple being calibrated, or it may be a liquid-in-glass thermometer or a resistance thermometer immersed in the bath close to the thermocouple protection tube. The choice of a reference thermometer will be governed principally by the degree of uncertainty which can be tolerated.

8.3.3 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 heterogeneous after such use [*24*] and in such a condition that the emf developed by the thermocouples depends upon the temperature distribution along the wires. If possible, such a thermocouple should be tested under the same conditions and in the same installation in which it is used. Although it is not usually possible to obtain as high a precision by testing the thermocouple in place as is obtained in laboratory tests, the result is far more useful in the sense of being representative of the behavior of the thermocouple [*23*]. The calibration is accomplished by comparing the thermocouple with a reference thermocouple.

In this case, as in the calibration of any thermocouple by comparison methods, the main objective is to bring the measuring junction to the same temperature as that of the thermocouple being tested. One method is to drill a hole in the furnace, flue, etc., at the side of each thermocouple permanently installed, large enough to permit insertion of the reference thermocouples. The hole is kept plugged, except when tests are being made. The reference thermocouple is inserted through this hole to the same depth as the thermocouple being tested with the measuring junction ends of the protecting tubes as close together as possible. Preferably a potentiometer or digital voltmeter should be used to measure the emf of the reference thermocouple.

In many installations the base-metal thermocouple and its protecting tube are mounted inside another protecting tube of iron, fire clay, carborundum, or some other refractory which is permanently cemented or fastened into the furnace wall. Frequently there is room to insert a reference thermocouple in this outer tube alongside of the fixed thermocouple. A third method, much less satisfactory, is to wait until the furnace, flue, etc., have reached a constant temperature and make observations with the thermocouple being tested, then remove this thermocouple and insert the reference 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 (16°F at 599°F) had changed only the equivalent of 6°C at 1100°C (11°F at 2012°F).

It may be thought that the method of calibrating thermocouples under working conditions is unsatisfactory because, in most furnaces used in industrial processes, large temperature gradients exist, and there is no certainty that the reference 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 reference thermocouple represents the temperature of the fixed thermocouple as closely as the temperature of the latter represents that of the furnace.

Another advantage of calibrating thermocouples in the same installation in which they are used is that the thermocouple, extension wires, and indicator are tested as a unit and under the conditions of use.

8.4 Interpolation Methods

An experimental thermocouple calibration consists of a series of voltage measurements determined at a finite number of known temperatures. If a test thermocouple were compared with a standard temperature instrument at 100 temperatures within a 5°C (10°F) range, there would be little need for interpolation between the calibration points. However, if from 4 to 10 calibration points are all that can be afforded in a given range of interest, then what is needed to characterize an individual thermocouple is a continuous relation, by means of which temperatures can be approximated with a minimum uncertainty from voltage measurements at intermediate levels. Efforts to obtain such a continuous relation appear thwarted from the start because of the small number of discrete calibration points available. However, interpolation between the calibration points is possible since the emf changes only slowly and smoothly with temperature.

One can present raw calibration data directly in terms of temperature (T) and voltage (E_{couple}), on a scale so chosen that the information appears well represented by a single curve (Fig. 8.1). However, in general, this practice of directly representing thermocouple characteristics does not yield results within the required limits of uncertainty.

A better method[3] is based on the use of differences between observed values and values obtained from standard reference tables. Such reference tables and the mathematical means for generating them are presented in Chapter 10 of this Manual. The data of Fig. 8.1 are replotted in Fig. 8.2 in terms of differences from the proper reference table. The maximum spread between points taken at the same level (replication), but obtained in random order with respect to time, and level (randomization) is taken as the uncertainty envelope. This information, taken from Fig. 8.2 is plotted in Fig. 8.3, and constitutes a vital bit of information about the particular thermocouple and the calibration system. In lieu of an experimental determination of the uncertainty, one must rely on judgment or on the current literature for this information.

Usually, only a single set of calibration points is available. Typical points would be those taken from one run shown in Figs. 8.1 or 8.2, and these are shown in Fig. 8.4 together with four of the many possible methods for representing the thermocouple difference characteristic. Although at first it

[3]Much of the material in this section is based on Refs *25* to *27*.

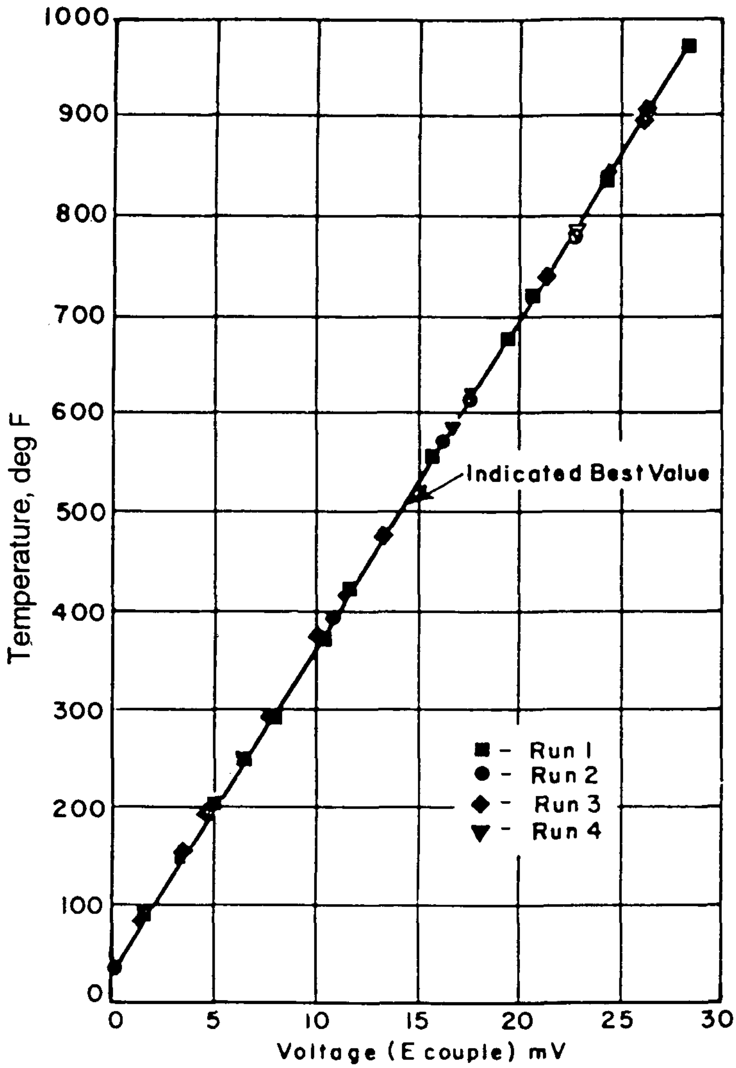

FIG. 8.1—*Temperature emf plot of raw calibration data for an iron/constantan thermocouple* [$°C = 5/9(°F - 32)$].

appears that the most probable relation characterizing a given thermocouple is sensibly indeterminate from a single set of calibration points, it is an important fact that all experimental points must be continued within the uncertainty interval when the uncertainty interval is centered on the most probable interpolation equation.

Making use of this principle, together with the fact that overall experimental uncertainties are minimized by use of the least squares technique,

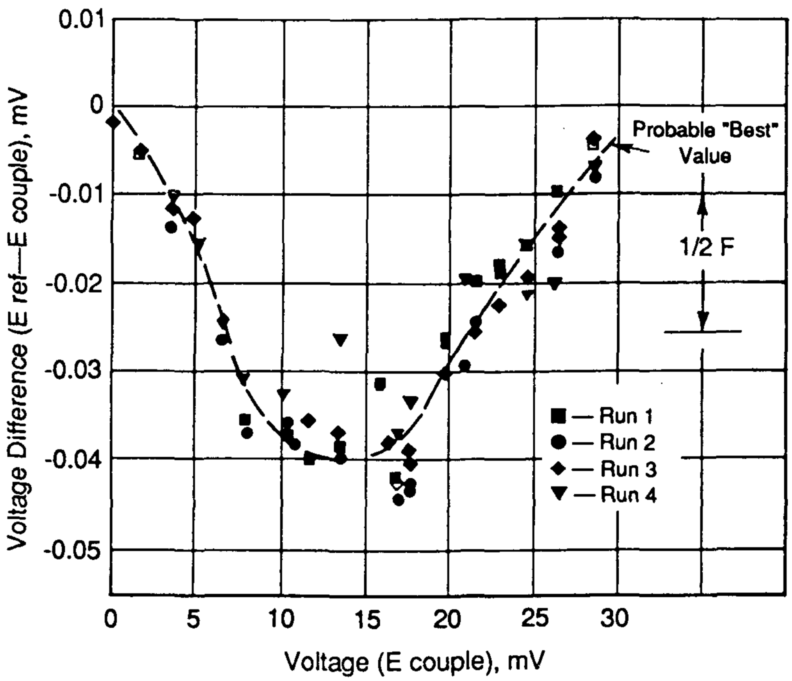

FIG. 8.2—*Difference plot of raw calibration data for an iron/constantan thermocouple.*

one starts the search for the most probable interpolation equation by passing a least squares equation of the first degree through the experimental data. A check is then made to ascertain whether all experimental points are contained within the uncertainty envelope which is centered on the linear interpolation equation (Fig. 8.5). One proceeds, according to the results of the foregoing check, to the next highest degree equation, stopping at the lowest degree least squares equation which satisfies the uncertainty requirements. For the example given here, a third degree interpolation equation is required (Fig. 8.6). By obtaining voltage differences from the least squares fit of any set of calibration points, the uncertainty in the thermocouple difference characteristic will be within one half the uncertainty interval. Generally, the form of the uncertainty envelope and the degree of the most probable least squares interpolation equation are dependent strongly on the amount of calibration data available and on the temperature range under consideration. It is recommended that the number of distinct calibration points available should be at least 2 multiplied by (degree + 1). The factor two is arrived at from numerical analysis reasoning. A distinct calibration point is defined arbitrarily as one which is separated, temperaturewise, from all other points in the set by as much as one tenth the difference in temperature between the maximum and minimum temperatures of the particular run. The choice of

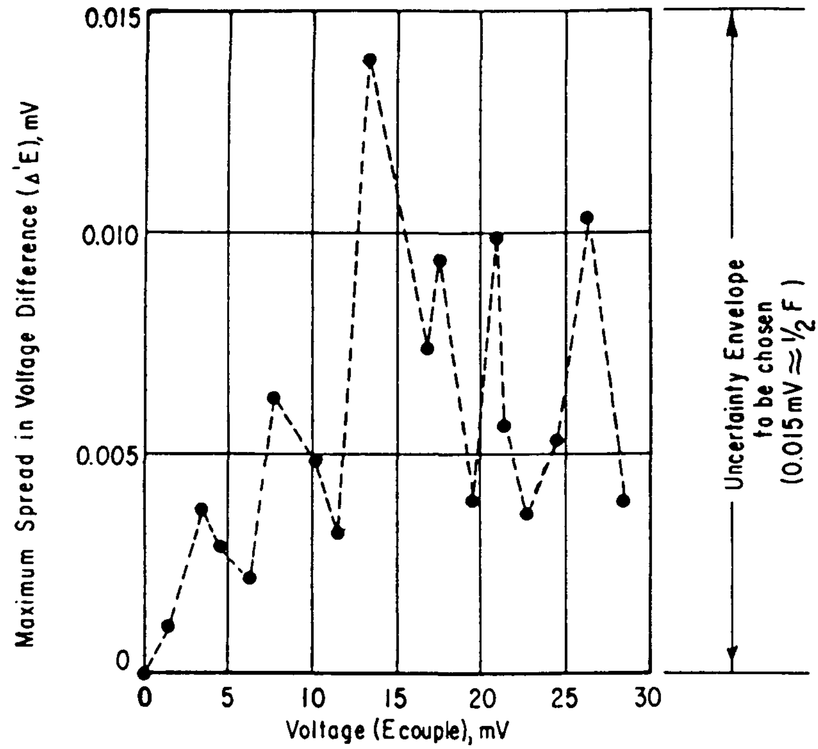

FIG. 8.3—*Typical determination of uncertainty envelope (from data of Fig. 8.2).*

one tenth presupposes a maximum practical degree of four for the least squares interpolation equation, in keeping with the low degree requirement of numerical analysis. Indeed, if the data cannot be represented by a fourth degree interpolation equation, one should increase the uncertainty interval and start the fitting procedure again.

Thus, in general, by using the proper reference table in conjunction with a difference curve, greater precision in temperature determination by means of thermocouples can be obtained from a given number of calibration points than from the use of the calibration data alone.

8.5 Single Thermoelement Materials

The standard method provided by ASTM for evaluating the emf characteristics of single thermoelement materials used in thermocouples for temperature measurement is ASTM E 207. The method covers the determination of the emf of single thermoelement materials (thermoelements) against standard platinum (NIST Pt-67), the reference junction being at the ice point, by comparison to the emf of a reference thermoelement of similar

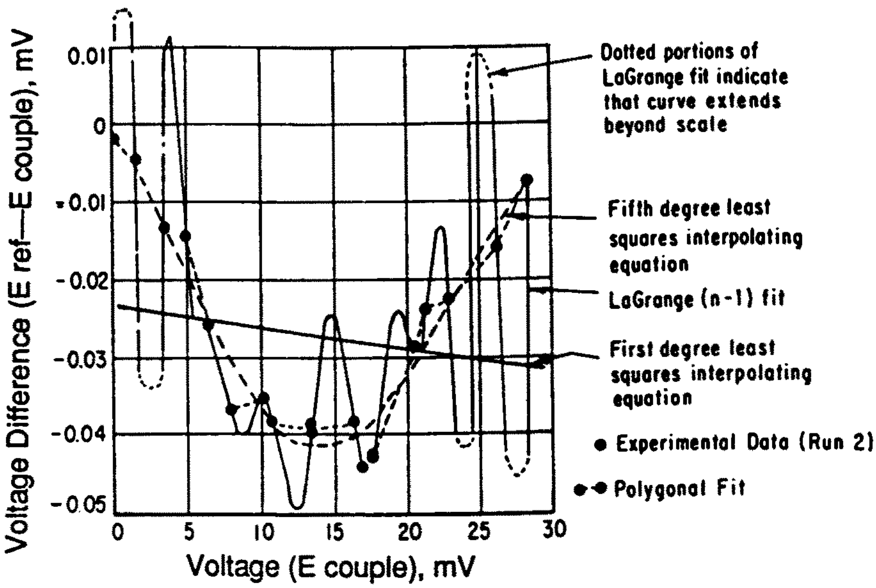

FIG. 8.4—*Various possible empirical representations of the thermocouple characteristic (based on a single calibration run).*

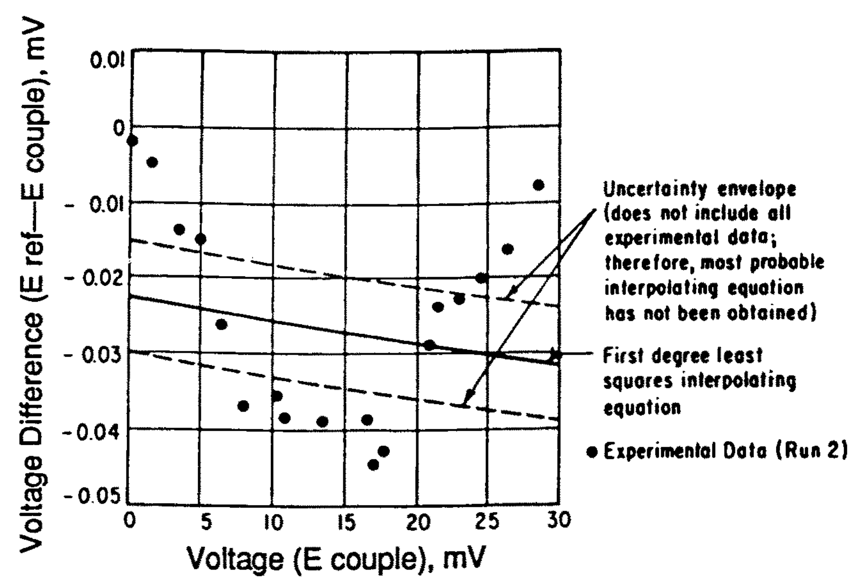

FIG. 8.5—*Uncertainty envelope method for determining degree of least squares interpolating equation for a single calibration run (linear).*

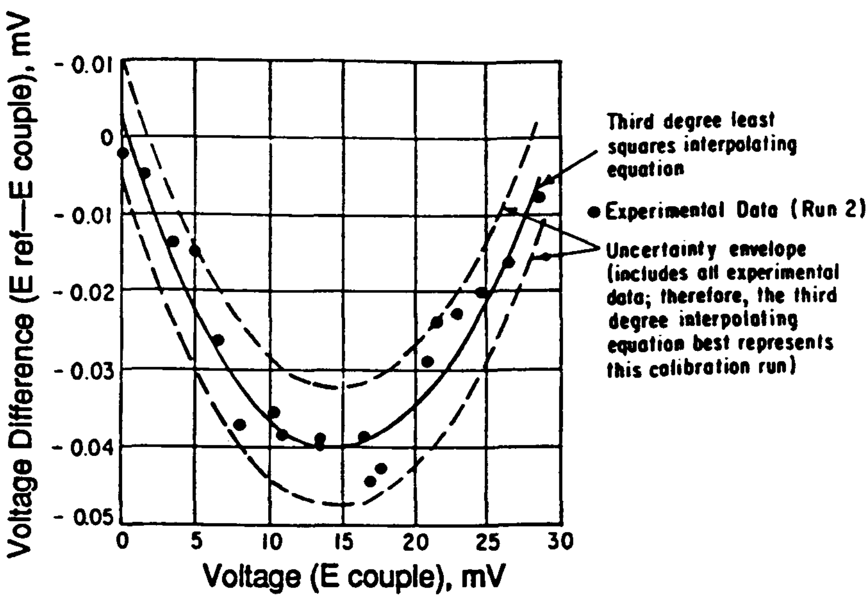

FIG. 8.6—*Uncertainty envelope method for determining degree of least squares interpolating equation for a single calibration run (cubic).*

emf-temperature properties independently standardized with respect to the same standard platinum.

Summary of Method—The test thermoelements are welded to a reference thermoelement to form the test assembly. The method involves measuring the small emf developed between the test thermoelement and the reference thermoelement which has emf-temperature properties similar to the thermoelement being evaluated. The emf of the test thermoelement then is determined by algebraically adding this measured small emf to the known emf of the reference thermoelement versus standard platinum. The testing circuit is shown schematically in Fig. 8.7. Since the test and standard thermoelements are similar thermoelectrically, it is unnecessary to control or measure the junction temperatures accurately because the measured emf is insensitive to relatively large changes in temperature at the junctions. Actually, the need for the accurate control of the measuring and reference junction temperatures is not eliminated, but merely is shifted to the test method used for determining the emf of the reference thermoelement versus standard platinum.

8.5.1 Test Specimen

The test specimen is a length of wire, rod, ribbon, or strip of the coil or spool of the thermoelement material to be evaluated. The length is adequate

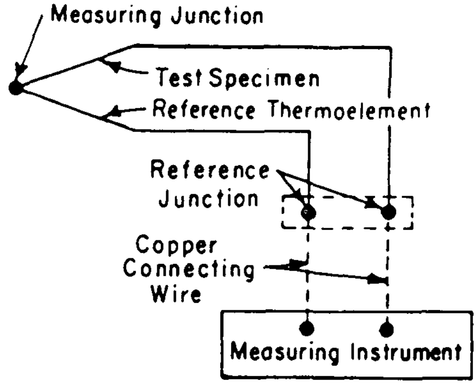

FIG. 8.7—*Circuit diagram for thermal emf test.*

to prevent the transfer of heat from the measuring junction to the reference junction during the period of test. A length of 0.6 to 1.2 m (2 to 4 ft), depending on the length of the testing medium and the transverse size of the thermoelement, is generally satisfactory. The transverse size of the specimen is limited only by the size of the test medium, the relative convenience of handling the specimens and reference thermoelement, and the maintenance of an isothermal test temperature junction.

8.5.2 *Reference Thermoelement*

A reference thermoelement is used which has emf-temperature properties similar to that of the test specimen and which previously has been standardized thermoelectrically with respect to NIST Platinum 67 (Pt-67). If a large amount of testing is anticipated, a coil or spool of reference thermoelement material is reserved. This material is selected on the basis of thermoelectric uniformity, and a minimum of three samples taken from the center and the ends of the coil is calibrated against the standard platinum. The reference thermoelement and the test specimen may differ in diameter, but it is convenient for their lengths to be about equal.

8.5.3 *Reference Junction*

The reference junction temperature of the test specimen and of the reference thermoelement is controlled at the ice point (0°C) during the period of test. An ice point bath is used because it is recognized as a convenient means for maintaining a constant reference temperature. The description and maintenance of ice point baths are given in Chapter 7. A reference temperature other than the ice point may be used. However, the reference thermoelement should be calibrated against standard platinum using the alternate reference temperature, or the calibration data adjusted to correspond to the alternate reference temperature.

8.5.4 Measuring Junction

The measuring junction consists of a welded union of the test specimen and reference thermoelement. The weldment may be prepared by any method providing a good electrical connection which can be immersed fully in the uniform temperature region of the testing medium. Any number of test specimens and reference thermoelements may be welded together provided the resulting test assembly does not introduce heat losses which prevent maintaining a uniform temperature region. If separation of the reference thermoelement and test specimen cannot be maintained during the test (except where they must make contact at the measuring junction), it is necessary that they be insulated from each other.

8.5.5 Test Temperature Medium

For temperatures up to 300°C (570°F), appropriate liquid baths may be used. For temperatures above 150°C (300°F), electrically heated tube or muffle type furnaces are recommended for comparison testing of base-metal or noble-metal thermoelement materials of similar emf-temperature properties. For convenience, a separate furnace may be controlled and available for each test temperature. This eliminates lost time in changing furnace temperatures when a large volume of testing is to be done. The length of each furnace is at least 381 mm (15 in.) so as to provide a minimum depth of immersion of 178 mm (7 in.) for the test assembly. A constant immersion depth is maintained, whether single or multiple furnaces are used. The inside diameter of the furnace tube is approximately 25 to 76 mm (1 to 3 in.), the specific diameter depending upon the size and the number of the specimens to be included in the test assembly. The furnace provides a uniform temperature zone extending at least 76 mm (3 in.) back from the measuring junction, or further if required to contain any inhomogeneity in the thermoelements. The temperature of each furnace is controlled manually or automatically to within $\pm$ 10°C ($\pm$ 18°F) of the desired value which is ample for comparison testing of thermoelements having compositions similar to that of the reference thermoelement.

8.5.6 Emf Indicator

The emf generated by the thermocouple consisting of the test specimen and the reference thermoelement is measured with instrumentation sensitive to $\pm$0.001 mV with an accuracy over a 2 mV range of $\pm$ 1% of the reading plus 0.003 mV. Any millivoltmeter, with circuitry errors taken into account, or potentiometer with a galvanometer or null indicator, providing measurements within these tolerances is acceptable. An indicator with a bidirectional scale (zero center) is convenient, but a unidirectional instrument may be used if a polarity switch is provided in the copper connecting circuit, or if the copper connecting wires to the instrument are exchanged whenever the polarity between the reference thermoelement and the test specimen is reversed.

8.5.7 Procedure

For a furnace medium the test assembly is inserted into the furnace so that the measuring junction extends at least 76 mm (3 in.) into the uniform temperature zone taking care there is no contact between the wires and the furnace wall. The free ends of the reference thermoelement and the test specimens are bent as required so they may be inserted into the glass tubes of the reference junction bath. Care is exercised to minimize distorting the wires prior to testing because of the effect of cold work on emf output. After bringing the test temperature to the specified value, sufficient time is provided for the test assembly to reach steady state conditions before recording the emf generated between the test specimen and the reference thermoelement.

In a similar manner the emf generated between all other test specimens in the assembly is measured with respect to the reference thermoelement. Then the test temperature is raised to the next higher specified value, or the test assembly is advanced to the next furnace or bath having the next higher specified temperature if multiple furnaces or baths are used. A second set of readings is taken at the new temperature, and the procedure is repeated with readings taken at all specified temperatures. In all cases the readings are taken in sequence from the lowest to the highest temperature to minimize test variations between producer and consumer if any of the alloys are affected by differences in short time heating cycles. A base-metal reference thermoelement is used for one series of temperature changes only. However, if a portion of it considerably exceeding the region previously exposed to the uniform heating zone is discarded, the remainder of the reference thermoelement may be used for another test assembly. For noble metals and their alloys, reuse depends on the known stability of the material involved.

The polarity of the test specimen with respect to the reference thermoelement is determined as follows:

1. If the test specimen is connected to the positive (+) terminal of a unidirectional potentiometer and balance can be achieved, the specimen is positive to the reference thermoelement.
2. If the connections must be reversed to achieve balance, that is, the reference thermoelement must be connected to the positive terminal, the test specimen is negative to the reference thermoelement.

3. If an indicating potentiometer with a bidirectional scale is used, the test specimen is connected to the positive (+) terminal and the reference thermoelement to the negative (−) terminal. The polarity of the test specimen with respect to the reference thermoelement then will be indicated by the direction of balance of the instrument scale.

The emf of the test specimen with respect to Pt-67 is then reported for each test temperature after algebraically adding the measured emf of the test specimen versus the reference thermoelement to the known emf of the reference thermoelement versus Pt-67.

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Chapter 9—Application Considerations

9.1 Temperature Measurement in Fluids

Fluids are divided readily into two types, compressible and incompressible, or more simply into gases and liquids. However, many concepts involved in the measurement of temperatures in fluids are common to both types, and these are discussed first.

9.1.1 Response

No instrument responds instantly to a change in its environment. Thus in a region where temperature is changing, a thermocouple will not be at the temperature of its environment and, hence, cannot indicate the true temperature. The simplified temperature changes considered here are the step change and the ramp change. In the step change, the temperature of the environment shifts instantaneously from T_1 to T_2. In the ramp change, the environment temperature shifts linearly with time from T_1 to T_2.

It is common practice to characterize the response of a temperature sensor by a first order thermal response time τ which is defined as

$$\tau = \frac{\rho V c}{hA} \tag{1}$$

where τ has the dimensions of time, ρ is density, V is volume, and c is specific heat, all of the sensor; while h is the heat transfer coefficient, and A is the area of the fluid film surrounding the sensor.

A solution of the first order, first degree, linear, differential equation [*1,2*] resulting from a heat balance between the fluid film surrounding the sensor and the sensor itself is

$$T = Ce^{-t/\tau} + \frac{1}{\tau} e^{-t/\tau} \int_0^t T_e e^{t/\tau}\, dt \tag{2}$$

where T is the sensor temperature, and T_e is the environment temperature, both at time t, and C is a constant of integration.

For a ramp change in temperature (as is found in a furnace being heated at a uniform rate) Eq 2 reduces to

$$(T_e - T) = R\tau \tag{3}$$

Equation 3 states that if an element is immersed for a long time in an environment whose temperature is rising at a constant rate $R = dT_e/dt$, then τ is the interval between the time when the environment reaches a given temperature and the time when the element indicates this temperature.

For a step change in temperature (as when a thermocouple is plunged into a constant temperature bath), Eq 2 reduces to

$$(T_e - T) = (T_e - T_1)e^{-t/\tau} \tag{4}$$

Equation 4 states that if an element is plunged into a constant-temperature environment, τ is the time required for the temperature difference between the environment and the element to be reduced to $1/e$ of the initial difference. Note that for practical purposes the sensor will reach the new temperature after approximately 5 time constants. See Fig. 9.1 for a graphical presentation of these equations.

The first 4 equations result from the common, but erroneous, practice of characterizing the response of a thermocouple as first-ordered. Conventionally, the time constant is described as that time required for the thermocouple to respond in a single-ordered mode by 63.2% $(1 - 1/e)$ of the imposed step change of external temperature. The term "time constant" implies that the temperature response is single ordered. However, the temperature response of a thermocouple is known to be multiordered. The time for the thermocouple to respond at 63.2% is still used to characterize the speed of response, but the time for 63.2% response is properly called the "response time."

The multiordered temperature response of a thermocouple can be described as

$$T(\mathrm{I}) = (T_i - T_f)[Ae(-t/\tau_1) - Be(-t/\tau_2) + Ce(-t/\tau_3) - \ldots] + T_i \tag{5}$$

where T_i is the initial temperature and T_f is the final temperature of the thermocouple. The values of $A,B,C,\ldots$, as well as $\tau_1,\tau_2,\tau_3,\ldots$, depend on the heat flow pattern within the thermocouple and the surrounding fluid [*3,4*].

Figure 9.1*c* shows the typical response of a thermocouple to a step increase of external temperature. When the time required to achieve 63.2% of the temperature span is measured and the time-temperature behavior is described with the single-ordered Eq 4, the predicted response curve will be as shown in Fig. 9.1*b* and *c*. The actual multiordered response will be as shown as in Fig. 9.1*c*. The predicted single-ordered response will correspond to the actual multiordered response only at the forced 63.2% and at the initial and final temperatures.

Below a Mach number of 0.4, the response time hardly is affected by the fluid velocity. The size of the temperature change affects τ because physical properties are not necessarily linear functions of temperature. References *5* and *6* consider these effects in greater detail. Scadron and Warshawsky [*7*] present convenient nomographs for determining the response time in the

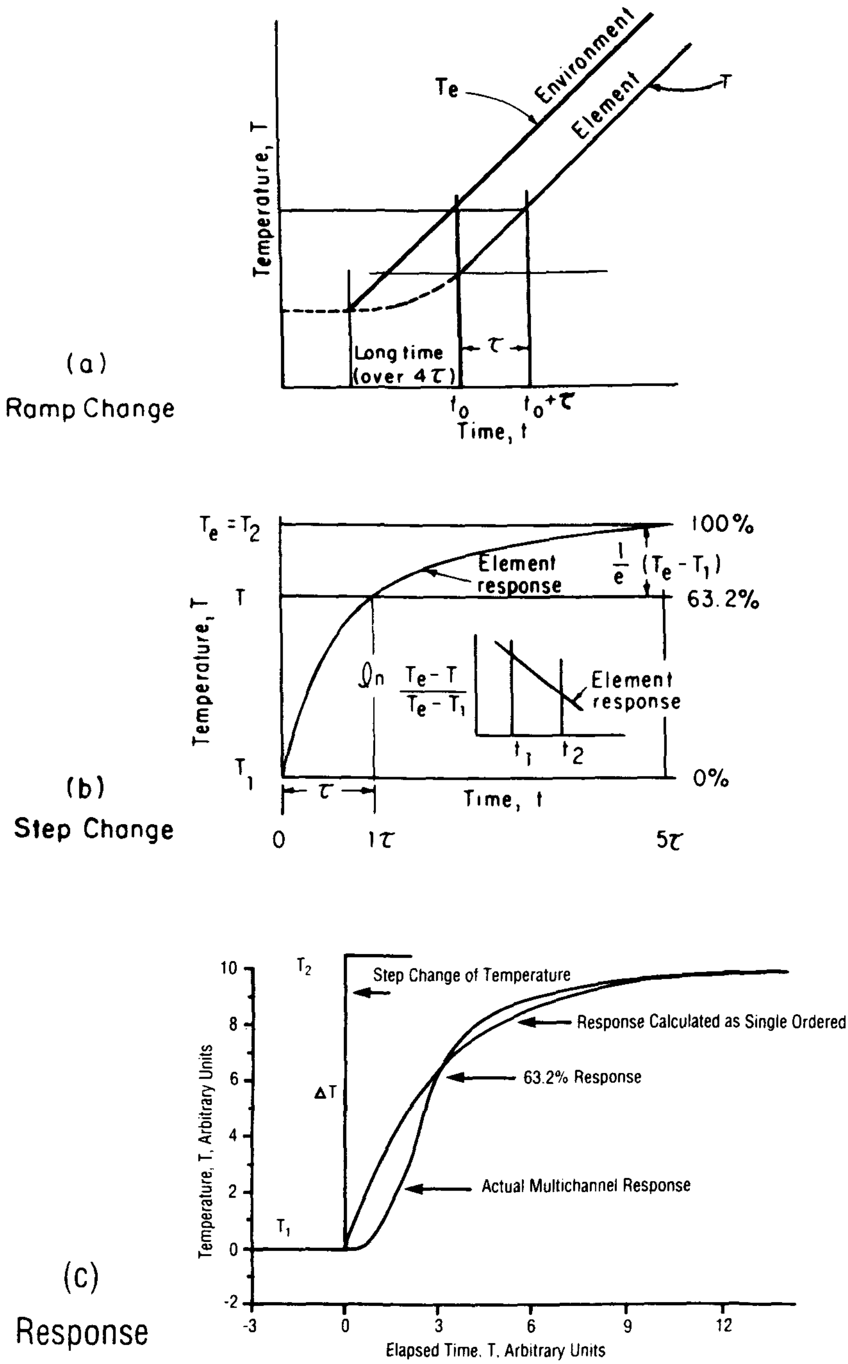

FIG. 9.1—*Graphical presentation of ramp and step changes.*

presence of heat transfer. Fluid turbulence tends to reduce the response time by increasing the film coefficient.

If the sensor is contained in a thermowell the response time is increased because of the extra mass and the additional heat transfer coefficient involved.

To achieve the best response time, the measuring junction should be in intimate contact with the well tip. Spring loading is sometimes used to accomplish this.

The response time usually is measured in liquids by plunging the thermocouple assembly into a bath at a known and constant fluid flow held at constant temperature. If the response time is of the same order as the immersion time, the velocity of immersion or depth of immersion or both become important parameters in the measurement. ASTM E 839-89 "Standard Methods of Testing Sheathed Thermocouples and Sheathed Thermocouple Material" describes a method for standardizing liquid baths used in this determination [*8*].

For the response time in gases, the literature should be consulted [*9,10*]. Manufacturers sometimes can supply this information for simple conditions.

Multijunctions [*11*] and electrical networks [*12*] have been used successfully to improve the response of a thermocouple.

9.1.2 Recovery

Whenever a gas moves with an appreciable velocity, in addition to the thermal energy in the form of random translational kinetic energy of the molecules, some of its thermal energy is in the form of directed kinetic energy of fluid flow. The static temperature is a measure of the random kinetic energy, while the dynamic temperature is a measure of the directed kinetic energy. The total temperature is a concept (not a measurement) which sums the static and the dynamic temperatures. Such a total temperature would be sensed by an adiabatic probe which completely stagnates an ideal gas. Thus

$$T_{\text{adi,ideal}} = T_t = T + \frac{V^2}{2Jg_c c_p} = T + T_V \tag{6}$$

where

T_t = total temperature,
T = static temperature,
T_V = dynamic temperature,
V = directed fluid velocity,
J = mechanical equivalent of heat,
g_c = standard acceleration of gravity, and
c_p = specific heat at constant pressure.

In real fluids, an adiabatic recovery factor (α) generally is defined such that

$$T_{\text{adi}} = T + \alpha T_V \tag{7}$$

where α may be more or less than one depending on the relative importance of thermal conductance and thermal capacitance in the boundary layers surrounding the sensor. Since the Prandtl number is the ratio of these two effects, it is common to express recoveries in terms of the Prandtl number. See Refs *13,14,15,* and *16* for more information on the recovery factor.

A real sensor immersed in a real fluid tends to radiate to its surroundings. Also there is a tendency for a conductive heat transfer along the probe stem. These two effects are balanced by a convective heat transfer between the probe and the fluid. In addition, real probes do not always stagnate a moving fluid effectively. To account for these realities in temperature measurement in moving fluids, a dynamic correction factor (K) is defined as

$$T_{\text{probe}} = T + KT_V \tag{8}$$

where K corrects for impact, viscosity, and conductivity effects in the fluid, and radiation and conduction effects in the probe. K may take on any value depending on the relative importance of these effects. Variations of K between ± 35 cannot be ruled out. Therefore, the factor KTV can far outweigh all other factors such as calibration deviations.

9.1.3 Thermowells

Protecting tubes or thermowells (see Chapter 4) or both often are used to separate the measuring junction of a thermocouple from the fluid whose temperature is of interest. Such devices are used to avoid contamination of the thermoelements, to provide safety in case of high pressure installations, to provide strength in the case of significant fluid bending forces in the thermocouple, etc. Thermocouples installed in wells can be withdrawn for inspection, calibration, and replacement. A thermocouple in a well responds more slowly to changes in fluid temperature. Typical wells and their strength requirements are defined in Ref *17.*

The depth of immersion in the fluid is an important consideration. One method of checking for adequacy of immersion is to increase the depth of immersion of the thermocouple well assembly in a constant temperature bath until the thermocouple output becomes constant. A minimum immersion depth of ten times the well outside diameter is a rule of thumb often used.

9.1.4 Thermal Analysis of an Installation

A thermocouple installation may give an indication which differs from the fluid temperature which is to be measured because:

1. The boundary walls are at a temperature different from that of the fluid.
2. There may be a temperature gradient along the well.
3. The fluid may be flowing with an appreciable velocity.
4. The thermocouple may be calibrated improperly.

Item 4 has been covered in Chapter 8 and will not be considered further here.

Basically, the thermocouple temperature is the result of a heat balance between the various modes of heat transfer.

$$q_c = q_r + q_k \tag{9}$$

where q indicates rate of heat transfer and the subscripts c, r, and k signify, respectively, convection, radiation, and conduction. An equation has been developed to describe this heat balance mathematically [*18*] as

$$\frac{d^2T}{dx^2} + a_1(x)\frac{dT_x}{dx} - a_2(x, y)T_x = -a_2a_3(x, y) \tag{10}$$

where $a_1(x) = dA_k/A_k dx$ which indicates the effect of a change in cross-sectional area of the well; $a_2(x, y) = dA_c(h_r + h_c)/kA_k dx$ which indicates the effect of radiation coefficient (h_r), convection coefficient (h_c), conductivity (k), surface area for convection (A_c) and cross-sectional area for conduction (A_k); $a_3(x, y) = (h_c T_{\text{adi}} + h_r T_w)/(h_c + h_r)$ which relates the heat transfer coefficients to the adiabatic fluid temperature (T_{adi}) and the surrounding wall temperature (T_w).

Various solutions are possible for Eq 10 depending on the assumptions one is willing to make. Three simplified solutions are:

1. *Overall Linearization*—When the radiation coefficient is based on an average well temperature, the result is

$$\frac{T_x - a_3}{T_w - a_3} = \frac{e^{mx}}{1 + e^{2ml}} + \frac{e^{-mx}}{1 + e^{-2ml}} \tag{11}$$

where

$$m = \left(\frac{4D(h_r + h_c)}{k(D^2 - d^2)}\right)^{1/2}$$

Typical values for h_r, h_c, and k are given in Ref *18*. This approach leads to quick, approximate answers whenever the fluid can be considered transparent to radiation.

2. *Tip Solution*—When conduction effects are neglected along the well or protecting tube, Eq 10 reduces to

$$T_{\text{tip}} = a_3 \tag{12}$$

which can be solved at once since h_r and h_c are available in the literature (see Ref *18*). This approximation normally would give tip temperatures which are too high since conduction tends to reduce T_{tip}.

3. *Stepwise Linearization*—This is the usual solution to Eq 10. Detailed equations are beyond the scope of this manual, but briefly one divides the well, lengthwise, into a number of elements. The temperature at the center of each element is taken to represent the temperature of that entire element. The heat balance equation is applied successively to one element after another until a match between the tip and base temperature is achieved. Each installation is different. Each must be evaluated carefully to determine if the installation is capable of yielding temperatures within the allowable uncertainties.

9.2 Surface Temperature Measurement

9.2.1 General Remarks

There is no easy method of attaching a thermocouple to a surface so that it can be guaranteed to indicate the true surface temperature. To do this, it would be necessary to mount the measuring junction so that it could attain, but not affect the surface temperature. In most cases, the presence of the thermocouple (or any alternative transducer) will cause a perturbation of the temperature distribution at the point of attachment, and thus it only will indicate the perturbed temperature.

9.2.1.1 Measurement Error—In many cases, a significant difference will exist between the indicated temperature and the "true" surface temperature, that is, the temperature that the surface would reach if no thermocouple were present. This difference is normally termed a "measurement error," but it should not be confused with calibration or extension wire errors which are common to all thermocouple measurements. The relationship between the indicated and true surface temperature is often defined by the equation

$$Z = \frac{T_s - T_i}{T_s - T_a} \tag{13}$$

where

Z = installation factor,
T_s = true surface temperature,
T_i = indicated surface temperature, and
T_a = temperature of the surroundings or coolant.

Equation 13 expressed the measurement error $T_s - T_i$ as a fraction of the difference between the surface and ambient temperatures.

The value of Z for a particular installation may be calculated or found by experiment; however, as several simplifying assumptions normally are made in any theoretical derivation, experimental verification is necessary if an accurate value of Z is required.

9.2.1.2 Installation Types—There are two basic types of surface thermocouple installation: the permanent, which is used to give a continuous history of the surface temperature, and the temporary, normally made with a sensing probe in mechanical contact with the surface to obtain spot readings. The basic principles for accurate measurement are similar for both types, but the probe type of sensors are more susceptible to measurement errors and generally have a lower accuracy.

9.2.2 Installation Methods

The method of attaching the thermocouple to the surface is governed by considerations of the metallurgical and thermal properties of the materials, their relative sizes, and the modes of heat transfer at the surface. Common methods are shown in Fig. 9.2.

9.2.2.1 Permanent Installations—For thin materials, the thermocouple junction is attached either directly to the surface (Fig. 9.2*a*) or is mounted in a heat collecting pad (Fig. 9.2*b*). It may be welded, brazed, cemented, or clamped to the surface. Thermal insulation may be required around the heat pad to minimize thermal conduction losses. Good mechanical support of the leads is necessary so that no stresses are applied to the junction.

For thicker materials, the thermocouple junction may be peened into the surface or installed in a groove (Fig. 9.2*c*). The groove may be filled so that the surface is restored to its original profile. A thermocouple in a groove normally will have its junction below the surface and will indicate the subsurface temperature. A similar technique used with tubes is shown in Fig. 9.2*d*.

The configuration shown in Fig. 9.2*e* may be used where rapid response is required, as the junction can be made very thin by electroplating or mechanical polishing techniques [*19–23*].

Several installation methods are illustrated in the literature cited, particularly in Refs *24* and *25*.

Metal sheathed thermocouples are suited particularly to surface measurements, especially for severe environments. They combine good strength and small size, and the measuring junction may be reduced in diameter or flattened to achieve good response with small errors.

9.2.2.2 Measuring Junctions—The measuring junction may be formed in several ways, each having its own advantages and disadvantages.

The bead junction commonly is used. The temperature indicated is a function of the temperatures where the wires leave the bead [*26,27*] so that the bead should be small, and the wires should leave the bead as close to the surface as possible. This may be accomplished by using a flattened bead. Good thermal contact between the bead and the surface is essential, especially if there are temperature gradients. If the surface is a material of poor

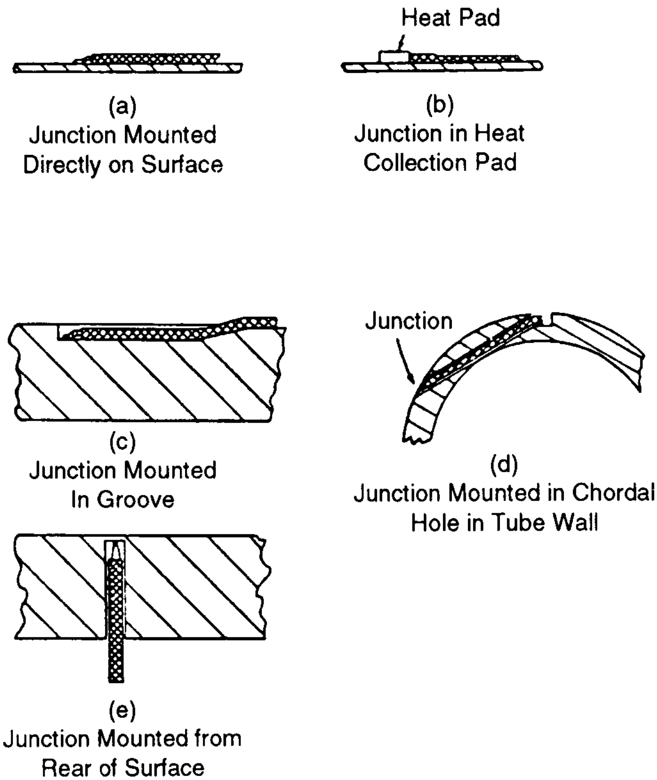

FIG. 9.2—*Common attachment methods.*

thermal conductivity, it may be advantageous to mount the measuring junction in a heat collecting pad, or button, which has a good conductivity [*28*].

A common variation is the separated junction shown in Fig. 9.3 in which each wire is joined separately to the surface (which must be an electrical conductor). This type, which is really two series junctions, has the advantage that the two junctions form a part of the surface. The output of such a thermocouple is a weighted mean of the two individual junction temperatures, of the form

$$e_0 = e_m + (b_1 - b_2)\frac{(T_1 - T_2)}{2} \tag{14}$$

where

T_1 and T_2 = junction temperatures,
e_0 = measured output,
e_m = output which would be measured if both junctions were at the mean temperature $(T_1 + T_2)/2$, and

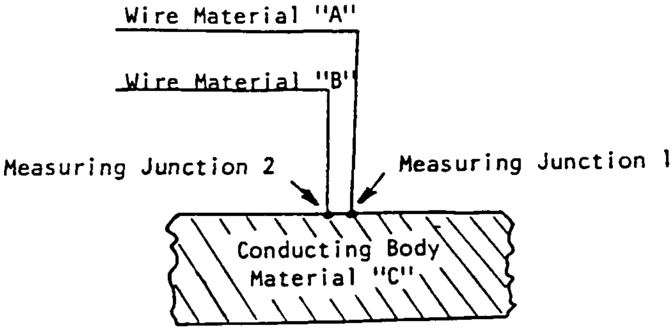

FIG. 9.3—*Separated junction.*

b_1 and b_2 = Seebeck coefficients of the two thermocouple wires versus the surface material.

Moffat [*29*] gives a graphical method of analysis.

Thus, the output will be greater or less than the mean depending upon which wire is at the higher temperature. The output generally cannot be calculated, as neither T_1, T_2, nor the relationship between each wire and the surface will be known. There will be, therefore, an uncertainty in the measured temperature if temperature gradients exist. This error is minimized if the wires are bonded to the surface as close together as possible, to reduce $(T_1 - T_2)$. This type of junction has been shown to be more accurate than a bead junction [*30,31*].

9.2.2.3 Probes—It is often desirable to know the temperature distribution over a surface or to make a spot check at one particular point. These measurements are made with a probe containing a thermocouple junction which is held in mechanical contact with the surface. The configuration of the junction is based on the intended application, and several types are commercially available. The probes are in most cases held normal to the surface, and for ease in use should be spring-loaded, which also reduces the error.

Probes are subject to the same errors as permanent installations, but the designer has no control over the conditions of use, and so the errors associated with this type of measurement may be significant. Since the probe provides a heat conducting path from the surface, thermal resistance due to oxide or dirt causes an additional error.

Correction factors [*32*] for several types of junctions range from 0.013 to 0.168, but in general must be determined for specific conditions.

The size of the junctions should be as small as possible. Several types of junction are illustrated in Fig. 9.4. The junction types in order of decreasing measurement error are: ungrounded, grounded, exposed, button, and separated.

In order to reduce measurement errors, probes with an auxiliary heater

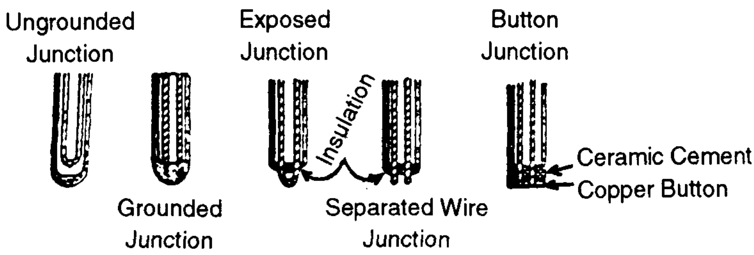

FIG. 9.4—*Types of junction using metal sheathed thermocouples.*

have been used [*33,34*]. The probe thermocouple is heated to the surface temperature so that no temperature gradients are set up when the probe is applied to the surface. One form of probe uses two thermocouples (Fig. 9.5). Equality of the auxiliary and surface junction temperatures indicates that no heat is being transferred along the probe and that the surface junction is at the surface temperature. With this type of probe, the two junctions must be very close, and the response to a change in heater power must be fast or an error can occur in transient measurements. A probe which is controlled automatically has been described [*35,36*]. It is claimed to have an accuracy of ⅜% and can be used to 760°C (1400°F) on a variety of materials, with a measurement time of less than one second. Sasaki and Kamanda [*37*] used a different approach and eliminated the auxiliary junction. The surface junction was arranged to contact the surface at two second intervals only. The heater input was modulated over a twenty second period and adjusted so that the maxima and minima were above and below the surface temperature. At contact the surface junction temperature changed due to heat

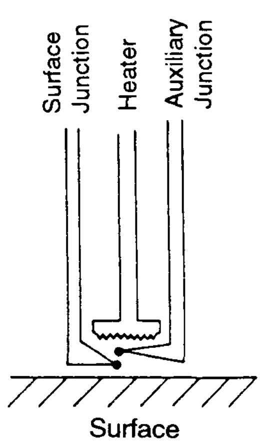

FIG. 9.5—*Thermocouple probe with auxiliary heater, diagramatic arrangement.*

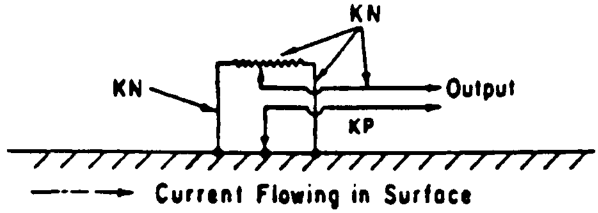

FIG. 9.6—*Three wire Type K thermocouple to compensate for voltage drop induced by surface current. (Other materials may be used.)*

exchange unless the two temperatures were equal. With this method the surface temperature of glass bulbs was determined with an accuracy of 0.3°C (0.5°F).

9.2.2.4 Moving Surfaces—Surface temperatures of moving bodies are measured by several methods. A junction mounted in a probe may be held against the body [*38*], but this method results in errors caused by friction. In metal cutting investigations, the metal body and the cutting tool are used as the thermocouple materials. The output of this type of junction has been investigated extensively and has been analyzed by Shu et al. [*39*]. Slip-rings to rotating members, intermittent and sliding contacts have been used also. A general review of such installations is given in Ref *25*.

9.2.2.5 Current Carrying Surfaces—A technique of eliminating errors caused by voltage drop in surfaces heated by the passage of d-c current has been described by Dutton and Lee [*40*]. A three-wire thermocouple forming two junctions is used (Fig. 9.6), and the emfs due to the voltage drop in the surface are balanced out during successive reversals of current. When the balance is correct, the thermocouple output is constant regardless of the direction of the heating current.

This technique is also useful for surfaces carrying large alternating currents. In other cases, filters will suffice to attenuate the a-c component. Self-balancing potentiometers usually are affected adversely if the a-c pickup level is high. Galvanometric instruments are normally insensitive to ac and present no problem unless the current is high enough to damage the coils. If the thermocouple junction is not isolated from the surface, voltages appearing between the surface and the instrument ground (common-mode voltages) cause an error with some instruments.

9.2.3 Sources of Error

When a thermocouple is attached to a surface, its presence alters the heat transfer characteristics of the surface and normally will change the temperature distribution. This causes an error which will be referred to as perturbation error.

9.2.3.1 Causes of Perturbation Error—The causes of perturbation error can be broken down into the following:

The heat transfer characteristics of the surface are changed by the installation, that is, the surface emissivity or effective thermal conductivity will be altered or the wires may act as fins providing additional heat transfer paths.

Thermal contact resistance between the junction and the surface will cause a temperature gradient which will prevent the measuring junction from attaining the correct temperature if heat is being exchanged between the surface and its surrounding.

If temperature gradients exist, there will be an error due to uncertainty in the exact position of the junction or junctions relative to the surface [*26,27*].

The response time of the thermocouple installation introduces errors during transient conditions [*41,42*] (see also Section 9.1.1). The response time will include that of the surface installation and not of the thermocouple alone.

Although not discussed in this chapter, the errors associated with any thermocouple measurement, such as deviations from standard emf and lead wire errors, must be taken also into consideration [*43,44*].

9.2.4 Error Determination

The perturbation error must be determined if the surface temperature must be known with a high degree of accuracy. The installation should be designed to minimize the error, but in many cases materials and size make compromises necessary, so that an ideal design cannot be achieved. The error, and hence the correction factor, can be determined by the following methods.

9.2.4.1 Steady-State Conditions—The direct calculation of the error involves solving the heat flow equation for the measuring junction and surface geometry. Normally simplifying assumptions are made, and the results must be interpreted in relation to them. The calculations show clearly the major sources of error and indicate means of reducing errors to a minimum [*45–49*].

Analog methods of solving the heat transfer equations using resistance or resistance-capacitance networks indicate the overall temperature distribution and show the perturbation effect of the thermocouple clearly. They are, however, difficult to make flexible, and so a number of analog models are required if a range of heat transfer conditions is to be studied [*48–51*].

Relaxation methods of solving the heat transfer equations have been used to calculate the temperature distribution; this method is attractive if a computer is available to perform the considerable amount of arithmetic required.

Direct experimental measurement on the installation is often the only satisfactory way to accurately determine the error. Care must be taken to simulate the service conditions exactly, as a change in a variable can significantly affect the error. The major problem is to determine the true surface temperature. This is discussed extensively in the literature [*20,51–56*].

9.2.4.2 Transient Conditions—If surface temperatures are changing, the response of the thermocouple attachment may cause a significant error. The response time of the thermocouple alone will have little significance for surface measurements if the heat transfer path between the surface and the measuring junction is poor or adds thermal mass.

The time required to change the measuring junction temperature causes the thermocouple output to lag the surface temperature in time and decreases its amplitude [*31,41,42*]. The response time may be determined experimentally from the response to step or ramp functions of surface temperature change.

A. Insulated Thermocouple Normal to an Electrically Heated Surface—For surfaces with changing temperatures a bead thermocouple attached normal to an electrically heated surface and insulated from the ambient has been analyzed by Quant and Fink [*55*] and Green and Hunt [*56*].

The analysis showed that in order to obtain a rapid response with a small, steady-state error, it is necessary to use a small junction bead with good surface contact, small diameter wires, and good insulation between the wires and the surroundings.

B. Surface Heated by Radiation—Thermcouples mounted on a surface subject to radiant heating at temperature-rise rates up to 17°C/s were investigated by White [*30*]. His results showed that a separated-junction thermocouple produced the least error.

The thermocouple errors increased with increasing plate thickness and with increasing rates of temperature rise. Furthermore, the amount of bare thermocouple wire between the junction and the insulation should be a minimum.

Kovacs and Mesler [*59*] investigated the response of very fast surface thermocouples subject to radiant heating as a function of size and type of junction. Junctions were formed by electroplating or mechanical abrasion. Very thin junctions were subject to an overshoot error for high rates of temperature rise, as heat could not be transmitted back through the thermocouple to subsurface layers fast enough. On the other hand, too thick a junction corresponded to a junction beneath the surface. The junction thickness should be of the same order of magnitude as the distance between the two thermocouple wires to avoid overshooting.

C. Surface Subject to Aerodynamic Heating—An analysis and design of a thermocouple installation which can be mounted in a thin-metal skin subjected to aerodynamic heating is given in Ref *60*. A finite difference calculation of the distorted temperature field indicated that errors due to insulation resistance at high temperatures were of the same order of magnitude as those due to the uncertainty of the exact junction location.

9.2.5 Procedures for Minimizing Error

The examples quoted in the preceding section have been treated separately. It is generally impossible to extrapolate from one set of conditions to another unless the installation is identical. The analyses show procedures that should be followed to reduce measurement errors. These are:

A. Use the smallest possible installation to avoid perturbation errors.

B. Bring the thermocouple wires away from the junction along an isotherm for at least 20 wire diameters to reduce conduction errors. The use of thermocouple materials with low thermal conductivity also will reduce this error.

C. Locate the measuring junction as close to the surface as possible rather than above or below it.

D. Design the installation so that it causes a minimum disturbance of any fluid flow or change in the emissivity of the surface, to avoid changes in convective or radiative heat transfer.

E. Design the installation so that the total response is fast enough to cause negligible lag for the transients expected in service.

F. Reduce the thermal resistance between the measuring junction and the surface to as low a value as possible. If the surface has a low thermal conductivity, a heat collecting pad may be used.

9.2.6 Commercial Surface Thermocouples

Many surface installations are custom engineered, but industry does offer several standard surface thermocouples intended for specific applications [*38,61*].

9.2.6.1 Surface Types—Figure 9.7 shows several types which are mounted on the surface. Type a is a gasket thermocouple which normally is mounted on a stud and Type b is a rivet head. The clamp attachment, Type c, is used on pipelines and will be reasonably accurate if the pipe is lagged thermally. The weldable pad attachment, Type d, is used on boiler or superheater tubes and uses a metal sheathed thermocouple with a grounded junction. The sheath and pad materials are chosen to be compatible with the boiler environment. An accuracy of $\pm 2\%$ is claimed for these thermocouples ($\pm 1\%$ if a correction factor supplied by the manufacturer is used).

For installations where it is possible to mount the thermocouples in the surface, stud- or rivet-mounted plugs similar to Type e are offered by several manufacturers. Variations of this type have been used extensively for heat

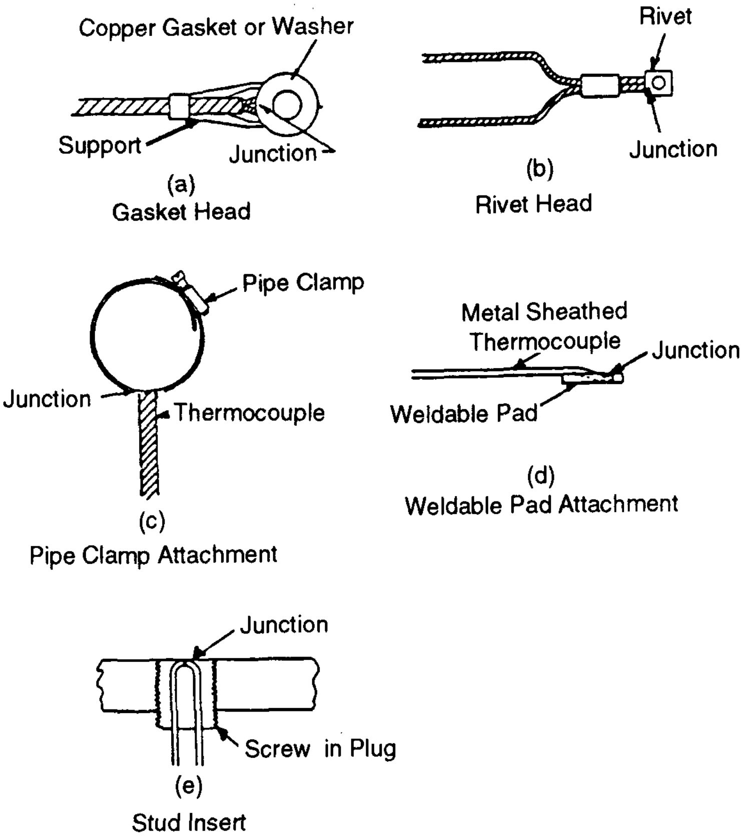

FIG. 9.7—*Commercially available types of surface thermocouples.*

transfer measurements [*45,62*] and for applications requiring very rapid response such as the measurement of surface temperatures in gun barrels and rocket exhaust chambers. The material of the plug must match the material of the surface, otherwise significant errors can be introduced [*63*], especially for materials with low thermal conductivity.

9.2.6.2 Probe Types—Probe type thermocouples for temporary or spot readings are offered usually as a complete package consisting of a thermocouple head which contains the measuring junction, a hand probe, and an indicating milliammeter calibrated in degrees. The measuring junctions are normally interchangeable so that one instrument can be used with a variety of heads. The type of head will depend on the surface characteristics. Common types are shown in Fig. 9.8.

The separated-junction probe is used on electrically conducting surfaces only. Dirt or oxide layers will introduce a thermal resistance error or even prevent the completion of the circuit. For greatest convenience, the two

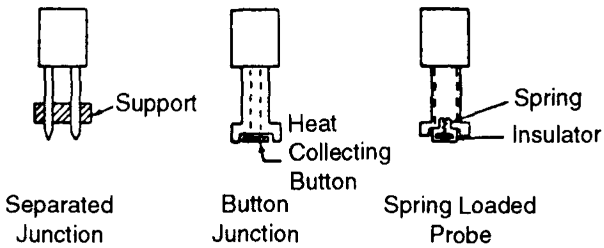

FIG. 9.8—*Commercial probe thermocouple junctions.*

wires should be separately spring-loaded against the surface. The button type of junction must be held carefully as any deviation from the normal will cause a change in the height of the junction above the surface, and the readings will be inconsistent. The spring-loaded type of junction is available in several forms and has been adapted for measurements on moving surfaces [*38*].

The accuracy obtainable with these probes is not high. However, the errors can be reduced to 2 or 3% for good conducting surfaces in still air cooled by natural convection. If the surface is a poor thermal conductor or the rate of heat transfer is high, the error will be considerably higher than this.

For rotating or moving surfaces, probe instruments utilizing a junction spring-loaded against the surface are used. Heat generated by friction causes an error which can be significant. (Bowden and Ridler [*64*] have shown that the temperatures may reach the melting point of one of the metals.)

A heated thermocouple probe instrument for measuring the temperature of wires or filaments is described by Bensen and Horne [*65*], and a wire temperature meter [*66*] has been marketed.

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Chapter 10—Reference Tables for Thermocouples

The practical use of thermocouples in industrial and laboratory applications requires that the thermocouple conform to an established temperature-electromotive force relationship within acceptable tolerances. Since the thermocouple in a thermoelectric thermometer system is usually expendable, conformance to established temperature-emf relationships is necessary in order to permit interchangeability.

Section 10.2 consists of reference tables that give temperature-emf relationships for the thermocouple types most commonly used in industry. These are identified as thermocouple Types B, E, J, K, N, R, S, and T, as defined in ASTM Standard E 230.

Data in these tables are based upon the SI volt [*1*] and the International Temperature Scale of 1990 (ITS-90) [*2*]. All temperature-emf data in Section 10.2 have been extracted from NIST Monograph 175 [*3*]. Values of emf are tabulated here at 10 degree intervals to show the general thermocouple temperature-emf characteristics and provide reference data against which the results of polynomial evaluations may be checked. The coefficients of polynomials for computing temperature-emf values for each of the above thermocouple types are given in Section 10.3

Reference tables giving temperature-emf relationships for single-leg thermoelements referenced to platinum (NIST Pt-67) are not included in this manual but are contained in NIST Monograph 175.

10.1 Thermocouple Types and Initial Calibration Tolerances

10.1.1 Thermocouple Types

The letter symbols identifying each reference table are those defined in ASTM Standard E 230. These symbols, which are used in common throughout industry, identify the following thermocouple calibrations:

Type B–Platinum-30% rhodium (+) versus platinum-6% rhodium (−).
Type E–Nickel-10% chromium (+) versus constantan (−).
Type J–Iron (+) versus constantan (−).

Type K–Nickel-10% chromium (+) versus nickel-5% aluminum and silicon (−).[1]

Type N–Nickel-14% chromium-1½% silicon (+) versus nickel-4½% silicon-1/10% magnesium (−).

Type R–Platinum-13% rhodium (+) versus platinum (−).

Type S–Platinum-10% rhodium (+) versus platinum (−).

Type T–Copper (+) versus constantan (−).

Detailed information covering the advantages and limitations of each of these thermocouple types, their recommended temperature ranges, and detailed physical properties of the thermoelements comprising them is contained in Section 3.1 of this manual.

10.1.2 Initial Calibration Tolerances

The tolerances on initial values of emf versus temperature for the eight letter-designated thermocouple types are given in Table 10.1. These tolerances are taken from ASTM Standard E 230. Most manufacturers supply thermocouples and matched thermocouple wire to these tolerances or better.

10.2 Thermocouple Reference Tables

The following list gives the page numbers and temperature ranges of the temperature-emf reference tables included in this section:

	Degrees Celsius Tables			Degrees Fahrenheit Tables		
T/C Type	Table No.	Page No.	Temperature Range, °C	Table No.	Page No.	Temperature Range, °F
B	10.2	192	0 to 1820	10.3	193	40 to 3300
E	10.4	194	−270 to 1000	10.5	195	−450 to 1830
J	10.6	196	−210 to 1200	10.7	197	−340 to 2190
K	10.8	198	−270 to 1370	10.9	199	−450 to 2500
N	10.10	200	−270 to 1300	10.11	201	−450 to 2370
R	10.12	202	−50 to 1760	10.13	203	−50 to 3210
S	10.14	204	−50 to 1760	10.15	205	−50 to 3210
T	10.16	206	−270 to 400	10.17	207	−450 to 750

Reference Tables 10.2 to 10.17 are based on reference junctions at 0°C (32°F) and give emf values to three decimal places (0.001 mV) for ten degree temperature intervals. Such tables are satisfactory for many industrial uses but may not be adequate for laboratory use and for computer and similar

[1]Silicon, or aluminum and silicon, may be present in combination with other elements.

TABLE 10.1—*Tolerances on initial values of emf versus temperature.*

NOTE 1—Tolerances in this table apply to new thermocouple wire, normally in the size range 0.25 to 3 mm in diameter (No. 30 to No. 8 Awg) and used at temperatures not exceeding the recommended limits of Table 3.1. If used at higher temperatures these tolerances may not apply.

NOTE 2—Where tolerances are given in percent, the percentage applies to the temperature being measured when expressed in degrees Celsius. To determine the tolerance in degrees Fahrenheit multiply the tolerance in degrees Celsius by 9/5.

NOTE 3—*Caution:* Users should be aware that certain characteristics of thermocouple materials, including the emf versus temperature relationship may change with time in use; consequently, test results and performance obtained at time of manufacture may not necessarily apply throughout an extended period of use. Tolerances given in this table apply only to new wire as delivered to the user *and do not allow for changes in characteristics with use.* The magnitude of such changes will depend on such factors as wire size, temperature, time of exposure, and environment. It should be further noted that due to possible changes in homogeneity, calibration of *used* thermocouples, unless performed in-situ by comparison, may yield irrelevant results.

Thermocouple Type	Temperature Range		Tolerances-Reference Junction 0°C (32°F)			
			Standard Tolerances		Special Tolerances	
	°C	°F	°C (whichever is greater)	°F	°C (whichever is greater)	°F
T	0 to 350	32 to 700	±1 or ±0.75 %	Note 2	±0.5 or 0.4 %	Note 2
J	0 to 750	32 to 1400	±2.2 ±0.75 %		±1.1 or 0.4 %	
E	0 to 900	32 to 1600	±1.7 or ±0.5 %		±1 or ±0.4 %	
K or N	0 to 1250	32 to 2300	±2.2 or ±0.75 %		±1.1 or ±0.4 %	
R or S	0 to 1450	32 to 2700	±1.5 or ±0.25 %		±0.6 or ±0.1 %	
B	870 to 1700	1600 to 3100	±0.5 %		±0.25 %	
T[A]	−200 to 0	−328 to 32	±1 or ±1.5 %		[B]	
E[A]	−200 to 0	−328 to 32	±1.7 or ±1 %		[B]	
K[A]	−200 to 0	−328 to 32	±2.2 or ±2 %		[B]	

[A] Thermocouples and thermocouple materials are normally supplied to meet the tolerances specified in the table for temperatures above 0°C. The same materials, however, may not fall within the sub-zero tolerances given in the second section of the table. If materials are required to meet the sub-zero tolerances, the purchase order must so state. Selection of materials usually will be required.

[B] Little information is available to justify establishing special tolerances for sub-zero temperatures. Limited experience suggests the following special tolerances for Types E and T thermocouples:

Type E −200 to 0°C ±1°C or ±0.5 % (whichever is greater)
Type T −200 to 0°C ±0.5°C or ±0.8 % (whichever is greater)

These tolerances are given only as a guide for discussion between purchaser and supplier.

Due to the characteristics of the materials, sub-zero tolerances for Type J thermocouples and special sub-zero tolerances for Type K thermocouples are not listed.

TABLE 10.2 -- *Type B thermocouples: emf-temperature (°C) reference table and equations.*

Thermocouple emf as a Function of Temperature in Degrees Celsius (ITS-90)

emf in Millivolts — Reference Junctions at 0 °C

°C	0	10	20	30	40	50	60	70	80	90	100
0	0.000	−0.002	−0.003	−0.002	−0.000	0.002	0.006	0.011	0.017	0.025	0.033
100	0.033	0.043	0.053	0.065	0.078	0.092	0.107	0.123	0.141	0.159	0.178
200	0.178	0.199	0.220	0.243	0.267	0.291	0.317	0.344	0.372	0.401	0.431
300	0.431	0.462	0.494	0.527	0.561	0.596	0.632	0.669	0.707	0.746	0.787
400	0.787	0.828	0.870	0.913	0.957	1.002	1.048	1.095	1.143	1.192	1.242
500	1.242	1.293	1.344	1.397	1.451	1.505	1.561	1.617	1.675	1.733	1.792
600	1.792	1.852	1.913	1.975	2.037	2.101	2.165	2.230	2.296	2.363	2.431
700	2.431	2.499	2.569	2.639	2.710	2.782	2.854	2.928	3.002	3.078	3.154
800	3.154	3.230	3.308	3.386	3.466	3.546	3.626	3.708	3.790	3.873	3.957
900	3.957	4.041	4.127	4.213	4.299	4.387	4.475	4.564	4.653	4.743	4.834
1000	4.834	4.926	5.018	5.111	5.205	5.299	5.394	5.489	5.585	5.682	5.780
1100	5.780	5.878	5.976	6.075	6.175	6.276	6.377	6.478	6.580	6.683	6.786
1200	6.786	6.890	6.995	7.100	7.205	7.311	7.417	7.524	7.632	7.740	7.848
1300	7.848	7.957	8.066	8.176	8.286	8.397	8.508	8.620	8.731	8.844	8.956
1400	8.956	9.069	9.182	9.296	9.410	9.524	9.639	9.753	9.868	9.984	10.099
1500	10.099	10.215	10.331	10.447	10.563	10.679	10.796	10.913	11.029	11.146	11.263
1600	11.263	11.380	11.497	11.614	11.731	11.848	11.965	12.082	12.199	12.316	12.433
1700	12.433	12.549	12.666	12.782	12.898	13.014	13.130	13.246	13.361	13.476	13.591
1800	13.591	13.706	13.820								

Temperature Ranges and Coefficients of Equations Used to Compute the Above Table

The equations are of the form: $E = c_0 + c_1t + c_2t^2 + c_3t^3 + \ldots c_nt^n$, where E is the emf in millivolts, t is the temperature in degrees Celsius (ITS-90), and c_0, c_1, c_2, c_3, *etc.* are the coefficients. These coefficients are extracted from NIST Monograph 175.

		0 °C to 630.615 °C	630.615 °C to 1820 °C
c_0	=	0.000 000 000 0 . . .	−3.893 816 862 1 . . .
c_1	=	$-2.465\,081\,834\,6 \times 10^{-4}$	$2.857\,174\,747\,0 \times 10^{-2}$
c_2	=	$5.904\,042\,117\,1 \times 10^{-6}$	$-8.488\,510\,478\,5 \times 10^{-5}$
c_3	=	$-1.325\,793\,163\,6 \times 10^{-9}$	$1.578\,528\,016\,4 \times 10^{-7}$
c_4	=	$1.566\,829\,190\,1 \times 10^{-12}$	$-1.683\,534\,486\,4 \times 10^{-10}$
c_5	=	$-1.694\,452\,924\,0 \times 10^{-15}$	$1.110\,979\,401\,3 \times 10^{-13}$
c_6	=	$6.299\,034\,709\,4 \times 10^{-19}$	$-4.451\,543\,103\,3 \times 10^{-17}$
c_7	=	. . . .	$9.897\,564\,082\,1 \times 10^{-21}$
c_8	=	. . . .	$-9.379\,133\,028\,9 \times 10^{-25}$

TABLE 10.3 -- *Type B thermocouples: emf-temperature (°F) reference table.*

Thermocouple emf as a Function of Temperature in Degrees Fahrenheit[a]

emf in Millivolts — Reference Junctions at 32 °F

°F	0	10	20	30	40	50	60	70	80	90	100
0					−0.001	−0.002	−0.002	−0.003	−0.002	−0.002	−0.001
100	−0.001	0.000	0.002	0.004	0.006	0.009	0.012	0.015	0.019	0.023	0.027
200	0.027	0.032	0.037	0.043	0.049	0.055	0.061	0.068	0.075	0.083	0.090
300	0.090	0.099	0.107	0.116	0.125	0.135	0.145	0.155	0.165	0.176	0.187
400	0.187	0.199	0.211	0.223	0.235	0.248	0.261	0.275	0.288	0.303	0.317
500	0.317	0.332	0.347	0.362	0.378	0.394	0.411	0.427	0.444	0.462	0.479
600	0.479	0.497	0.516	0.534	0.553	0.572	0.592	0.612	0.632	0.653	0.673
700	0.673	0.694	0.716	0.738	0.760	0.782	0.805	0.828	0.851	0.875	0.898
800	0.898	0.923	0.947	0.972	0.997	1.022	1.048	1.074	1.100	1.127	1.154
900	1.154	1.181	1.208	1.236	1.264	1.293	1.321	1.350	1.379	1.409	1.439
1000	1.439	1.469	1.499	1.530	1.561	1.592	1.624	1.655	1.687	1.720	1.752
1100	1.752	1.785	1.818	1.852	1.886	1.920	1.954	1.988	2.023	2.058	2.094
1200	2.094	2.129	2.165	2.201	2.237	2.274	2.311	2.348	2.385	2.423	2.461
1300	2.461	2.499	2.538	2.576	2.615	2.654	2.694	2.734	2.774	2.814	2.854
1400	2.854	2.895	2.936	2.978	3.019	3.061	3.103	3.145	3.188	3.230	3.273
1500	3.273	3.317	3.360	3.404	3.448	3.492	3.537	3.581	3.626	3.672	3.717
1600	3.717	3.763	3.809	3.855	3.901	3.948	3.994	4.041	4.089	4.136	4.184
1700	4.184	4.232	4.280	4.328	4.377	4.426	4.475	4.524	4.574	4.623	4.673
1800	4.673	4.723	4.774	4.824	4.875	4.926	4.977	5.028	5.080	5.132	5.184
1900	5.184	5.236	5.288	5.341	5.394	5.447	5.500	5.553	5.607	5.661	5.715
2000	5.715	5.769	5.823	5.878	5.932	5.987	6.042	6.098	6.153	6.209	6.264
2100	6.264	6.320	6.377	6.433	6.490	6.546	6.603	6.660	6.718	6.775	6.833
2200	6.833	6.890	6.948	7.006	7.065	7.123	7.182	7.240	7.299	7.358	7.417
2300	7.417	7.477	7.536	7.596	7.656	7.716	7.776	7.836	7.897	7.957	8.018
2400	8.018	8.079	8.140	8.201	8.262	8.323	8.385	8.446	8.508	8.570	8.632
2500	8.632	8.694	8.756	8.819	8.881	8.944	9.006	9.069	9.132	9.195	9.258
2600	9.258	9.321	9.385	9.448	9.511	9.575	9.639	9.702	9.766	9.830	9.894
2700	9.894	9.958	10.022	10.086	10.150	10.215	10.279	10.344	10.408	10.473	10.537
2800	10.537	10.602	10.666	10.731	10.796	10.861	10.925	10.990	11.055	11.120	11.185
2900	11.185	11.250	11.315	11.380	11.445	11.510	11.575	11.640	11.705	11.770	11.835
3000	11.835	11.900	11.965	12.030	12.095	12.160	12.225	12.290	12.355	12.420	12.484
3100	12.484	12.549	12.614	12.679	12.743	12.808	12.872	12.937	13.001	13.066	13.130
3200	13.130	13.194	13.259	13.323	13.387	13.451	13.515	13.579	13.642	13.706	13.769
3300	13.769										

[a]The emf values in this table were computed from the equations given on the facing page, after converting the desired temperature in °F to its equivalent in °C by the conversion formula given in Section 10.3.1.

TABLE 10.4 -- *Type E thermocouples: emf-temperature (°C) reference table and equations.*

Thermocouple emf as a Function of Temperature in Degrees Celsius (ITS-90)

emf in Millivolts **Reference Junctions at 0 °C**

°C	0	−10	−20	−30	−40	−50	−60	−70	−80	−90	−100
−200	−8.825	−9.063	−9.274	−9.455	−9.604	−9.718	−9.797	−9.835			
−100	−5.237	−5.681	−6.107	−6.516	−6.907	−7.279	−7.632	−7.963	−8.273	−8.561	−8.825
0	0.000	−0.582	−1.152	−1.709	−2.255	−2.787	−3.306	−3.811	−4.302	−4.777	−5.237

°C	0	10	20	30	40	50	60	70	80	90	100
0	0.000	0.591	1.192	1.801	2.420	3.048	3.685	4.330	4.985	5.648	6.319
100	6.319	6.998	7.685	8.379	9.081	9.789	10.503	11.224	11.951	12.684	13.421
200	13.421	14.164	14.912	15.664	16.420	17.181	17.945	18.713	19.484	20.259	21.036
300	21.036	21.817	22.600	23.386	24.174	24.964	25.757	26.552	27.348	28.146	28.946
400	28.946	29.747	30.550	31.354	32.159	32.965	33.772	34.579	35.387	36.196	37.005
500	37.005	37.815	38.624	39.434	40.243	41.053	41.862	42.671	43.479	44.286	45.093
600	45.093	45.900	46.705	47.509	48.313	49.116	49.917	50.718	51.517	52.315	53.112
700	53.112	53.908	54.703	55.497	56.289	57.080	57.870	58.659	59.446	60.232	61.017
800	61.017	61.801	62.583	63.364	64.144	64.922	65.698	66.473	67.246	68.017	68.787
900	68.787	69.554	70.319	71.082	71.844	72.603	73.360	74.115	74.869	75.621	76.373
1000	76.373										

Temperature Ranges and Coefficients of Equations Used to Compute the Above Table

The equations are of the form: $E = c_0 + c_1t + c_2t^2 + c_3t^3 + \ldots c_nt^n$, where E is the emf in millivolts, t is the temperature in degrees Celsius (ITS-90), and c_0, c_1, c_2, c_3, *etc.* are the coefficients. These coefficients are extracted from NIST Monograph 175.

		−270 °C to 0 °C	0 °C to 1000 °C
c_0	=	0.000 000 000 0 . . .	0.000 000 000 0 . . .
c_1	=	$5.866\,550\,870\,8 \times 10^{-2}$	$5.866\,550\,871\,0 \times 10^{-2}$
c_2	=	$4.541\,097\,712\,4 \times 10^{-5}$	$4.503\,227\,558\,2 \times 10^{-5}$
c_3	=	$-7.799\,804\,868\,6 \times 10^{-7}$	$2.890\,840\,721\,2 \times 10^{-8}$
c_4	=	$-2.580\,016\,084\,3 \times 10^{-8}$	$-3.305\,689\,665\,2 \times 10^{-10}$
c_5	=	$-5.945\,258\,305\,7 \times 10^{-10}$	$6.502\,440\,327\,0 \times 10^{-13}$
c_6	=	$-9.321\,405\,866\,7 \times 10^{-12}$	$-1.919\,749\,550\,4 \times 10^{-16}$
c_7	=	$-1.028\,760\,553\,4 \times 10^{-13}$	$-1.253\,660\,049\,7 \times 10^{-18}$
c_8	=	$-8.037\,012\,362\,1 \times 10^{-16}$	$2.148\,921\,756\,9 \times 10^{-21}$
c_9	=	$-4.397\,949\,739\,1 \times 10^{-18}$	$-1.438\,804\,178\,2 \times 10^{-24}$
c_{10}	=	$-1.641\,477\,635\,5 \times 10^{-20}$	$3.596\,089\,948\,1 \times 10^{-28}$
c_{11}	=	$-3.967\,361\,951\,6 \times 10^{-23}$	. . . .
c_{12}	=	$-5.582\,732\,872\,1 \times 10^{-26}$	. . . .
c_{13}	=	$-3.465\,784\,201\,3 \times 10^{-29}$	. . . .

TABLE 10.5 -- *Type E thermocouples: emf-temperature (°F) reference table.*

Thermocouple emf as a Function of Temperature in Degrees Fahrenheit[a]

emf in Millivolts **Reference Junctions at 32 °F**

°F	0	−10	−20	−30	−40	−50	−60	−70	−80	−90	−100
−400	−9.604	−9.672	−9.729	−9.775	−9.809	−9.830					
−300	−8.404	−8.561	−8.710	−8.852	−8.986	−9.112	−9.229	−9.338	−9.436	−9.525	−9.604
−200	−6.472	−6.692	−6.907	−7.116	−7.319	−7.516	−7.707	−7.891	−8.069	−8.240	−8.404
−100	−3.976	−4.248	−4.515	−4.777	−5.035	−5.287	−5.535	−5.777	−6.014	−6.246	−6.472
0	−1.026	−1.339	−1.648	−1.953	−2.255	−2.552	−2.846	−3.135	−3.420	−3.700	−3.976

°F	0	10	20	30	40	50	60	70	80	90	100
0	−1.026	−0.709	−0.389	−0.065	0.262	0.591	0.924	1.259	1.597	1.938	2.281
100	2.281	2.628	2.977	3.330	3.685	4.042	4.403	4.766	5.131	5.500	5.871
200	5.871	6.244	6.620	6.998	7.379	7.762	8.147	8.535	8.924	9.316	9.710
300	9.710	10.106	10.503	10.903	11.305	11.708	12.113	12.520	12.929	13.339	13.751
400	13.751	14.164	14.579	14.995	15.413	15.831	16.252	16.673	17.096	17.520	17.945
500	17.945	18.371	18.798	19.227	19.656	20.086	20.517	20.950	21.383	21.817	22.252
600	22.252	22.687	23.124	23.561	23.999	24.437	24.876	25.316	25.757	26.198	26.640
700	26.640	27.082	27.525	27.969	28.413	28.857	29.302	29.747	30.193	30.639	31.086
800	31.086	31.533	31.980	32.427	32.875	33.323	33.772	34.220	34.669	35.118	35.567
900	35.567	36.016	36.466	36.915	37.365	37.815	38.265	38.714	39.164	39.614	40.064
1000	40.064	40.513	40.963	41.412	41.862	42.311	42.760	43.209	43.658	44.107	44.555
1100	44.555	45.004	45.452	45.900	46.347	46.794	47.241	47.688	48.135	48.581	49.027
1200	49.027	49.472	49.917	50.362	50.807	51.251	51.695	52.138	52.581	53.024	53.466
1300	53.466	53.908	54.350	54.791	55.232	55.673	56.113	56.553	56.992	57.431	57.870
1400	57.870	58.308	58.746	59.184	59.621	60.058	60.494	60.930	61.366	61.801	62.236
1500	62.236	62.670	63.104	63.538	63.971	64.403	64.835	65.267	65.698	66.129	66.559
1600	66.559	66.989	67.418	67.846	68.274	68.701	69.128	69.554	69.979	70.404	70.828
1700	70.828	71.252	71.675	72.097	72.518	72.939	73.360	73.780	74.199	74.618	75.036
1800	75.036	75.454	75.872	76.289							

[a]The emf values in this table were computed from the equations given on the facing page, after converting the desired temperature in °F to its equivalent in °C by the conversion formula given in Section 10.3.1.

TABLE 10.6 -- *Type J thermocouples: emf-temperature (°C) reference table and equations.*

Thermocouple emf as a Function of Temperature in Degrees Celsius (ITS-90)

emf in Millivolts — Reference Junctions at 0 °C

°C	0	−10	−20	−30	−40	−50	−60	−70	−80	−90	−100
−200	−7.890	−8.095									
−100	−4.633	−5.037	−5.426	−5.801	−6.159	−6.500	−6.821	−7.123	−7.403	−7.659	−7.890
0	0.000	−0.501	−0.995	−1.482	−1.961	−2.431	−2.893	−3.344	−3.786	−4.215	−4.633

°C	0	10	20	30	40	50	60	70	80	90	100
0	0.000	0,507	1.019	1.537	2.059	2.585	3.116	3.650	4.187	4.726	5.269
100	5.269	5.814	6.360	6.909	7.459	8.010	8.562	9.115	9.669	10.224	10.779
200	10.779	11.334	11.889	12.445	13.000	13.555	14.110	14.665	15.219	15.773	16.327
300	16.327	16.881	17.434	17.986	18.538	19.090	19.642	20.194	20.745	21.297	21.848
400	21.848	22.400	22.952	23.504	24.057	24.610	25.164	25.720	26.276	26.834	27.393
500	27.393	27.953	28.516	29.080	29.647	30.216	30.788	31.362	31.939	32.519	33.102
600	33.102	33.689	34.279	34.873	35.470	36.071	36.675	37.284	37.896	38.512	39.132
700	39.132	39.755	40.382	41.012	41.645	42.281	42.919	43.559	44.203	44.848	45.494
800	45.494	46.141	46.786	47.431	48.074	48.715	49.353	49.989	50.622	51.251	51.877
900	51.877	52.500	53.119	53.735	54.347	54.956	55.561	56.164	56.763	57.360	57.953
1000	57.953	58.545	59.134	59.721	60.307	60.890	61.473	62.054	62.634	63.214	63.792
1100	63.792	64.370	64.948	65.525	66.102	66.679	67.255	67.831	68.406	68.980	69.553
1200	69.553										

Temperature Ranges and Coefficients of Equations Used to Compute the Above Table

The equations are of the form: $E = c_0 + c_1t + c_2t^2 + c_3t^3 + ... c_nt^n$, where E is the emf in millivolts, t is the temperature in degrees Celsius (ITS-90), and c_0, c_1, c_2, c_3, *etc.* are the coefficients. These coefficients are extracted from NIST Monograph 175.

		−210 °C to 760 °C	760 °C to 1200 °C
c_0	=	0.000 000 000 0 . . .	2.964 562 568 1 X 10^{2}
c_1	=	5.038 118 781 5 X 10^{-2}	−1.497 612 778 6 . . .
c_2	=	3.047 583 693 0 X 10^{-5}	3.178 710 392 4 X 10^{-3}
c_3	=	−8.568 106 572 0 X 10^{-8}	−3.184 768 670 1 X 10^{-6}
c_4	=	1.322 819 529 5 X 10^{-10}	1.572 081 900 4 X 10^{-9}
c_5	=	−1.705 295 833 7 X 10^{-13}	−3.069 136 905 6 X 10^{-13}
c_6	=	2.094 809 069 7 X 10^{-16}	....
c_7	=	−1.253 839 533 6 X 10^{-19}	....
c_8	=	1.563 172 569 7 X 10^{-23}	....

TABLE 10.7 -- *Type J thermocouples: emf-temperature (°F) reference table.*

Thermocouple emf as a Function of Temperature in Degrees Fahrenheit[a]

emf in Millivolts — Reference Junctions at 32 °F

°F	−0	−10	−20	−30	−40	−50	−60	−70	−80	−90	−100
−300	−7.519	−7.659	−7.791	−7.915	−8.030						
−200	−5.760	−5.962	−6.159	−6.351	−6.536	−6.716	−6.890	−7.058	−7.219	−7.373	−7.519
−100	−3.493	−3.737	−3.978	−4.215	−4.449	−4.678	−4.903	−5.125	−5.341	−5.553	−5.760
0	−0.886	−1.158	−1.428	−1.695	−1.961	−2.223	−2.483	−2.740	−2.994	−3.245	−3.493

°F	0	10	20	30	40	50	60	70	80	90	100
0	−0.886	−0.611	−0.334	−0.056	0.225	0.507	0.791	1.076	1.364	1.652	1.942
100	1.942	2.234	2.527	2.821	3.116	3.412	3.709	4.007	4.306	4.606	4.907
200	4.907	5.209	5.511	5.814	6.117	6.421	6.726	7.031	7.336	7.642	7.949
300	7.949	8.255	8.562	8.869	9.177	9.485	9.793	10.101	10.409	10.717	11.025
400	11.025	11.334	11.642	11.951	12.260	12.568	12.877	13.185	13.494	13.802	14.110
500	14.110	14.418	14.727	15.035	15.343	15.650	15.958	16.266	16.573	16.881	17.188
600	17.188	17.495	17.802	18.109	18.416	18.722	19.029	19.336	19.642	19.949	20.255
700	20.255	20.561	20.868	21.174	21.480	21.787	22.093	22.400	22.706	23.013	23.320
800	23.320	23.627	23.934	24.241	24.549	24.856	25.164	25.473	25.781	26.090	26.400
900	26.400	26.710	27.020	27.330	27.642	27.953	28.266	28.579	28.892	29.206	29.521
1000	29.521	29.836	30.153	30.470	30.788	31.106	31.426	31.746	32.068	32.390	32.713
1100	32.713	33.037	33.363	33.689	34.016	34.345	34.674	35.005	35.337	35.670	36.004
1200	36.004	36.339	36.675	37.013	37.352	37.692	38.033	38.375	38.718	39.063	39.408
1300	39.408	39.755	40.103	40.452	40.801	41.152	41.504	41.856	42.210	42.564	42.919
1400	42.919	43.274	43.631	43.988	44.346	44.705	45.064	45.423	45.782	46.141	46.500
1500	46.500	46.858	47.216	47.574	47.931	48.288	48.644	48.999	49.353	49.707	50.060
1600	50.060	50.411	50.762	51.112	51.460	51.808	52.154	52.500	52.844	53.188	53.530
1700	53.530	53.871	54.211	54.550	54.888	55.225	55.561	55.896	56.230	56.564	56.896
1800	56.896	57.227	57.558	57.888	58.217	58.545	58.872	59.199	59.526	59.851	60.177
1900	60.177	60.501	60.826	61.149	61.473	61.796	62.118	62.441	62.763	63.085	63.406
2000	63.406	63.728	64.049	64.370	64.691	65.012	65.333	65.654	65.974	66.295	66.615
2100	66.615	66.935	67.255	67.575	67.895	68.214	68.534	68.853	69.171	69.490	

[a]The emf values in this table were computed from the equations given on the facing page, after converting the desired temperature in °F to its equivalent in °C by the conversion formula given in Section 10.3.1.

TABLE 10.8 -- *Type K thermocouples: emf-temperature (°C) reference table and equations.*

Thermocouple emf as a Function of Temperature in Degrees Celsius (ITS-90)

emf in Millivolts — Reference Junctions at 0 °C

°C	0	−10	−20	−30	−40	−50	−60	−70	−80	−90	−100
−200	−5.891	−6.035	−6.158	−6.262	−6.344	−6.404	−6.441	−6.458			
−100	−3.554	−3.852	−4.138	−4.411	−4.669	−4.913	−5.141	−5.354	−5.550	−5.730	−5.891
0	0.000	−0.392	−0.778	−1.156	−1.527	−1.889	−2.243	−2.587	−2.920	−3.243	−3.554

°C	0	10	20	30	40	50	60	70	80	90	100
0	0.000	0.397	0.798	1.203	1.612	2.023	2.436	2.851	3.267	3.682	4.096
100	4.096	4.509	4.920	5.328	5.735	6.138	6.540	6.941	7.340	7.739	8.138
200	8.138	8.539	8.940	9.343	9.747	10.153	10.561	10.971	11.382	11.795	12.209
300	12.209	12.624	13.040	13.457	13.874	14.293	14.713	15.133	15.554	15.975	16.397
400	16.397	16.820	17.243	17.667	18.091	18.516	18.941	19.366	19.792	20.218	20.644
500	20.644	21.071	21.497	21.924	22.350	22.776	23.203	23.629	24.055	24.480	24.905
600	24.905	25.330	25.755	26.179	26.602	27.025	27.447	27.869	28.289	28.710	29.129
700	29.129	29.548	29.965	30.382	30.798	31.213	31.628	32.041	32.453	32.865	33.275
800	33.275	33.685	34.093	34.501	34.908	35.313	35.718	36.121	36.524	36.925	37.326
900	37.326	37.725	38.124	38.522	38.918	39.314	39.708	40.101	40.494	40.885	41.276
1000	41.276	41.665	42.053	42.440	42.826	43.211	43.595	43.978	44.359	44.740	45.119
1100	45.119	45.497	45.873	46.249	46.623	46.995	47.367	47.737	48.105	48.473	48.838
1200	48.838	49.202	49.565	49.926	50.286	50.644	51.000	51.355	51.708	52.060	52.410
1300	52.410	52.759	53.106	53.451	53.795	54.138	54.479	54.819			

Temperature Ranges and Coefficients of Equations Used to Compute the Above Table

The equations are of the form: $E = c_0 + c_1t + c_2t^2 + c_3t^3 + \ldots c_nt^n$, where E is the emf in millivolts, t is the temperature in degrees Celsius (ITS-90), and c_0, c_1, c_2, c_3, *etc.* are the coefficients. In the 0 °C to 1372 °C range there is also an exponential term that must be evaluated and added to the equation. The exponential term is of the form: $c_0 e^{c_1 (t - 126.9686)^2}$, where t is the temperature in °C, e is the natural logarithm base, and c_0 and c_1 are the coefficients. These coefficients are extracted from NIST Monograph 175.

		−270 °C to 0 °C	0 °C to 1372 °C	0 °C to 1372 °C (exponential term)
c_0	=	0.000 000 000 0 . . .	$-1.760\,041\,368\,6 \times 10^{-2}$	$1.185\,976 \times 10^{-1}$
c_1	=	$3.945\,012\,802\,5 \times 10^{-2}$	$3.892\,120\,497\,5 \times 10^{-2}$	$-1.183\,432 \times 10^{-4}$
c_2	=	$2.362\,237\,359\,8 \times 10^{-5}$	$1.855\,877\,003\,2 \times 10^{-5}$	....
c_3	=	$-3.285\,890\,678\,4 \times 10^{-7}$	$-9.945\,759\,287\,4 \times 10^{-8}$	....
c_4	=	$-4.990\,482\,877\,7 \times 10^{-9}$	$3.184\,094\,571\,9 \times 10^{-10}$	....
c_5	=	$-6.750\,905\,917\,3 \times 10^{-11}$	$-5.607\,284\,488\,9 \times 10^{-13}$	....
c_6	=	$-5.741\,032\,742\,8 \times 10^{-13}$	$5.607\,505\,905\,9 \times 10^{-16}$	....
c_7	=	$-3.108\,887\,289\,4 \times 10^{-15}$	$-3.202\,072\,000\,3 \times 10^{-19}$	....
c_8	=	$-1.045\,160\,936\,5 \times 10^{-17}$	$9.715\,114\,715\,2 \times 10^{-23}$	....
c_9	=	$-1.988\,926\,687\,8 \times 10^{-20}$	$-1.210\,472\,127\,5 \times 10^{-26}$	....
c_{10}	=	$-1.632\,269\,748\,6 \times 10^{-23}$	....	....

TABLE 10.9 -- *Type K thermocouples: emf-temperature (°F) reference table.*

Thermocouple emf as a Function of Temperature in Degrees Fahrenheit[a]

emf in Millivolts **Reference Junctions at 32 °F**

°F	0	−10	−20	−30	−40	−50	−60	−70	−80	−90	−100
−400	−6.344	−6.380	−6.409	−6.431	−6.446	−6.456					
−300	−5.632	−5.730	−5.822	−5.908	−5.989	−6.064	−6.133	−6.195	−6.251	−6.301	−6.344
−200	−4.381	−4.527	−4.669	−4.806	−4.939	−5.067	−5.190	−5.308	−5.421	−5.529	−5.632
−100	−2.699	−2.884	−3.065	−3.243	−3.417	−3.587	−3.754	−3.917	−4.076	−4.231	−4.381
0	−0.692	−0.905	−1.114	−1.322	−1.527	−1.729	−1.929	−2.126	−2.320	−2.511	−2.699
°F	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
0	−0.692	−0.478	−0.262	−0.044	0.176	0.397	0.619	0.843	1.068	1.294	1.521
100	1.521	1.749	1.977	2.207	2.436	2.667	2.897	3.128	3.359	3.590	3.820
200	3.820	4.050	4.280	4.509	4.738	4.965	5.192	5.419	5.644	5.869	6.094
300	6.094	6.317	6.540	6.763	6.985	7.207	7.429	7.650	7.872	8.094	8.316
400	8.316	8.539	8.761	8.985	9.208	9.432	9.657	9.882	10.108	10.334	10.561
500	10.561	10.789	11.017	11.245	11.474	11.703	11.933	12.163	12.393	12.624	12.855
600	12.855	13.086	13.318	13.549	13.782	14.014	14.247	14.479	14.713	14.946	15.179
700	15.179	15.413	15.647	15.881	16.116	16.350	16.585	16.820	17.055	17.290	17.526
800	17.526	17.761	17.997	18.233	18.469	18.705	18.941	19.177	19.414	19.650	19.887
900	19.887	20.123	20.360	20.597	20.834	21.071	21.308	21.544	21.781	22.018	22.255
1000	22.255	22.492	22.729	22.966	23.203	23.439	23.676	23.913	24.149	24.386	24.622
1100	24.622	24.858	25.094	25.330	25.566	25.802	26.037	26.273	26.508	26.743	26.978
1200	26.978	27.213	27.447	27.681	27.915	28.149	28.383	28.616	28.849	29.082	29.315
1300	29.315	29.548	29.780	30.012	30.243	30.475	30.706	30.937	31.167	31.398	31.628
1400	31.628	31.857	32.087	32.316	32.545	32.774	33.002	33.230	33.458	33.685	33.912
1500	33.912	34.139	34.365	34.591	34.817	35.043	35.268	35.493	35.718	35.942	36.166
1600	36.166	36.390	36.613	36.836	37.059	37.281	37.504	37.725	37.947	38.168	38.389
1700	38.389	38.610	38.830	39.050	39.270	39.489	39.708	39.927	40.145	40.363	40.581
1800	40.581	40.798	41.015	41.232	41.449	41.665	41.881	42.096	42.311	42.526	42.741
1900	42.741	42.955	43.169	43.382	43.595	43.808	44.020	44.232	44.444	44.655	44.866
2000	44.866	45.077	45.287	45.497	45.706	45.915	46.124	46.332	46.540	46.747	46.954
2100	46.954	47.161	47.367	47.573	47.778	47.983	48.187	48.391	48.595	48.798	49.000
2200	49.000	49.202	49.404	49.605	49.806	50.006	50.206	50.405	50.604	50.802	51.000
2300	51.000	51.198	51.395	51.591	51.787	51.982	52.177	52.371	52.565	52.759	52.952
2400	52.952	53.144	53.336	53.528	53.719	53.910	54.100	54.289	54.479	54.668	54.856
2500	54.856										

[a]The emf values in this table were computed from the equations given on the facing page, after converting the desired temperature in °F to its equivalent in °C by the conversion formula given in Section 10.3.1.

TABLE 10.10 -- *Type N thermocouples: emf-temperature (°C) reference table and equations.*

Thermocouple emf as a Function of Temperature in Degrees Celsius (ITS-90)

emf in Millivolts | Reference Junctions at 0 °C

°C	0	−10	−20	−30	−40	−50	−60	−70	−80	−90	−100
−200	−3.990	−4.083	−4.162	−4.226	−4.277	−4.313	−4.336	−4.345			
−100	−2.407	−2.612	−2.808	−2.994	−3.171	−3.336	−3.491	−3.634	−3.766	−3.884	−3.990
0	0.000	−0.260	−0.518	−0.772	−1.023	−1.269	−1.509	−1.744	−1.972	−2.193	−2.407

°C	0	10	20	30	40	50	60	70	80	90	100
0	0.000	0.261	0.525	0.793	1.065	1.340	1.619	1.902	2.189	2.480	2.774
100	2.774	3.072	3.374	3.680	3.989	4.302	4.618	4.937	5.259	5.585	5.913
200	5.913	6.245	6.579	6.916	7.255	7.597	7.941	8.288	8.637	8.988	9.341
300	9.341	9.696	10.054	10.413	10.774	11.136	11.501	11.867	12.234	12.603	12.974
400	12.974	13.346	13.719	14.094	14.469	14.846	15.225	15.604	15.984	16.366	16.748
500	16.748	17.131	17.515	17.900	18.286	18.672	19.059	19.447	19.835	20.224	20.613
600	20.613	21.003	21.393	21.784	22.175	22.566	22.958	23.350	23.742	24.134	24.527
700	24.527	24.919	25.312	25.705	26.098	26.491	26.883	27.276	27.669	28.062	28.455
800	28.455	28.847	29.239	29.632	30.024	30.416	30.807	31.199	31.590	31.981	32.371
900	32.371	32.761	33.151	33.541	33.930	34.319	34.707	35.095	35.482	35.869	36.256
1000	36.256	36.641	37.027	37.411	37.795	38.179	38.562	38.944	39.326	39.706	40.087
1100	40.087	40.466	40.845	41.223	41.600	41.976	42.352	42.727	43.101	43.474	43.846
1200	43.846	44.218	44.588	44.958	45.326	45.694	46.060	46.425	46.789	47.152	47.513
1300	47.513										

Temperature Ranges and Coefficients of Equations Used to Compute the Above Table

The equations are of the form: $E = c_0 + c_1t + c_2t^2 + c_3t^3 + \ldots c_nt^n$, where E is the emf in millivolts, t is the temperature in degrees Celsius (ITS-90), and c_0, c_1, c_2, c_3, *etc.* are the coefficients. These coefficients are extracted from NIST Monograph 175.

		−270 °C to 0 °C	0 °C to 1300 °C
c_0	=	0.000 000 000 0 . . .	0.000 000 000 0 . . .
c_1	=	$2.615\,910\,596\,2 \times 10^{-2}$	$2.592\,939\,460\,1 \times 10^{-2}$
c_2	=	$1.095\,748\,422\,8 \times 10^{-5}$	$1.571\,014\,188\,0 \times 10^{-5}$
c_3	=	$-9.384\,111\,155\,4 \times 10^{-8}$	$4.382\,562\,723\,7 \times 10^{-8}$
c_4	=	$-4.641\,203\,975\,9 \times 10^{-11}$	$-2.526\,116\,979\,4 \times 10^{-10}$
c_5	=	$-2.630\,335\,771\,6 \times 10^{-12}$	$6.431\,181\,933\,9 \times 10^{-13}$
c_6	=	$-2.265\,343\,800\,3 \times 10^{-14}$	$-1.006\,347\,151\,9 \times 10^{-15}$
c_7	=	$-7.608\,930\,079\,1 \times 10^{-17}$	$9.974\,533\,899\,2 \times 10^{-19}$
c_8	=	$-9.341\,966\,783\,5 \times 10^{-20}$	$-6.086\,324\,560\,7 \times 10^{-22}$
c_9	=	. . . .	$2.084\,922\,933\,9 \times 10^{-25}$
c_{10}	=	. . . .	$-3.068\,219\,615\,1 \times 10^{-29}$

TABLE 10.11 -- *Type N thermocouples: emf-temperature (°F) reference table.*

Thermocouple emf as a Function of Temperature in Degrees Fahrenheit[a]

emf in Millivolts | **Reference Junctions at 32 °F**

°F	0	−10	−20	−30	−40	−50	−60	−70	−80	−90	−100
−400	−4.277	−4.299	−4.316	−4.330	−4.339	−4.344					
−300	−3.820	−3.884	−3.945	−4.001	−4.054	−4.102	−4.145	−4.185	−4.220	−4.251	−4.277
−200	−2.974	−3.074	−3.171	−3.264	−3.354	−3.441	−3.524	−3.604	−3.679	−3.752	−3.820
−100	−1.821	−1.947	−2.072	−2.193	−2.313	−2.430	−2.544	−2.656	−2.765	−2.871	−2.974
0	−0.461	−0.603	−0.744	−0.884	−1.023	−1.160	−1.296	−1.430	−1.562	−1.692	−1.821

°F	0	10	20	30	40	50	60	70	80	90	100
0	−0.461	−0.318	−0.174	−0.029	0.116	0.261	0.407	0.555	0.703	0.853	1.004
100	1.004	1.156	1.309	1.463	1.619	1.776	1.934	2.093	2.253	2.415	2.577
200	2.577	2.741	2.906	3.072	3.240	3.408	3.578	3.748	3.920	4.093	4.267
300	4.267	4.442	4.618	4.795	4.973	5.152	5.332	5.512	5.694	5.877	6.060
400	6.060	6.245	6.430	6.616	6.803	6.991	7.179	7.369	7.559	7.750	7.941
500	7.941	8.134	8.327	8.520	8.715	8.910	9.105	9.302	9.499	9.696	9.895
600	9.895	10.093	10.293	10.493	10.693	10.894	11.096	11.298	11.501	11.704	11.907
700	11.907	12.111	12.316	12.521	12.726	12.932	13.139	13.346	13.553	13.760	13.969
800	13.969	14.177	14.386	14.595	14.804	15.014	15.225	15.435	15.646	15.857	16.069
900	16.069	16.281	16.493	16.705	16.918	17.131	17.344	17.558	17.772	17.986	18.200
1000	18.200	18.414	18.629	18.844	19.059	19.274	19.490	19.705	19.921	20.137	20.353
1100	20.353	20.570	20.786	21.003	21.220	21.437	21.654	21.871	22.088	22.305	22.523
1200	22.523	22.740	22.958	23.176	23.393	23.611	23.829	24.047	24.265	24.483	24.701
1300	24.701	24.919	25.137	25.356	25.574	25.792	26.010	26.229	26.447	26.665	26.883
1400	26.883	27.102	27.320	27.538	27.756	27.975	28.193	28.411	28.629	28.847	29.065
1500	29.065	29.283	29.501	29.719	29.937	30.154	30.372	30.590	30.807	31.025	31.242
1600	31.242	31.459	31.677	31.894	32.111	32.328	32.545	32.761	32.978	33.195	33.411
1700	33.411	33.627	33.844	34.060	34.276	34.491	34.707	34.923	35.138	35.353	35.568
1800	35.568	35.783	35.998	36.213	36.427	36.641	36.855	37.069	37.283	37.497	37.710
1900	37.710	37.923	38.136	38.349	38.562	38.774	38.986	39.198	39.410	39.622	39.833
2000	39.833	40.044	40.255	40.466	40.677	40.887	41.097	41.307	41.516	41.725	41.935
2100	41.935	42.143	42.352	42.560	42.768	42.976	43.184	43.391	43.598	43.805	44.012
2200	44.012	44.218	44.424	44.629	44.835	45.040	45.245	45.449	45.653	45.857	46.060
2300	46.060	46.263	46.466	46.668	46.870	47.071	47.272	47.473			

[a] The emf values in this table were computed from the equations given on the facing page, after converting the desired temperature in °F to its equivalent in °C by the conversion formula given in Section 10.3.1.

TABLE 10.12 -- *Type R thermocouples: emf-temperature (°C) reference table and equations.*

Thermocouple emf as a Function of Temperature in Degrees Celsius (ITS-90)

emf in Millivolts — Reference Junctions at 0 °C

°C	0	−10	−20	−30	−40	−50	−60	−70	−80	−90	−100
0	0.000	−0.051	−0.100	−0.145	−0.188	−0.226					

°C	0	10	20	30	40	50	60	70	80	90	100
0	0.000	0.054	0.111	0.171	0.232	0.296	0.363	0.431	0.501	0.573	0.647
100	0.647	0.723	0.800	0.879	0.959	1.041	1.124	1.208	1.294	1.381	1.469
200	1.469	1.558	1.648	1.739	1.831	1.923	2.017	2.112	2.207	2.304	2.401
300	2.401	2.498	2.597	2.696	2.796	2.896	2.997	3.099	3.201	3.304	3.408
400	3.408	3.512	3.616	3.721	3.827	3.933	4.040	4.147	4.255	4.363	4.471
500	4.471	4.580	4.690	4.800	4.910	5.021	5.133	5.245	5.357	5.470	5.583
600	5.583	5.697	5.812	5.926	6.041	6.157	6.273	6.390	6.507	6.625	6.743
700	6.743	6.861	6.980	7.100	7.220	7.340	7.461	7.583	7.705	7.827	7.950
800	7.950	8.073	8.197	8.321	8.446	8.571	8.697	8.823	8.950	9.077	9.205
900	9.205	9.333	9.461	9.590	9.720	9.850	9.980	10.111	10.242	10.374	10.506
1000	10.506	10.638	10.771	10.905	11.039	11.173	11.307	11.442	11.578	11.714	11.850
1100	11.850	11.986	12.123	12.260	12.397	12.535	12.673	12.812	12.950	13.089	13.228
1200	13.228	13.367	13.507	13.646	13.786	13.926	14.066	14.207	14.347	14.488	14.629
1300	14.629	14.770	14.911	15.052	15.193	15.334	15.475	15.616	15.758	15.899	16.040
1400	16.040	16.181	16.323	16.464	16.605	16.746	16.887	17.028	17.169	17.310	17.451
1500	17.451	17.591	17.732	17.872	18.012	18.152	18.292	18.431	18.571	18.710	18.849
1600	18.849	18.988	19.126	19.264	19.402	19.540	19.677	19.814	19.951	20.087	20.222
1700	20.222	20.356	20.488	20.620	20.749	20.877	21.003				

Temperature Ranges and Coefficients of Equations Used to Compute the Above Table

The equations are of the form: $E = c_0 + c_1t + c_2t^2 + c_3t^3 + ... c_nt^n$, where E is the emf in millivolts, t is the temperature in degrees Celsius (ITS-90), and c_0, c_1, c_2, c_3, *etc.* are the coefficients. These coefficients are extracted from NIST Monograph 175.

		−50 °C to 1064.18 °C	1064.18 °C to 1664.5 °C	1664.5 °C to 1768.1 °C
c_0	=	0.000 000 000 00 . . .	2.951 579 253 16 . . .	1.522 321 182 09 X 10^{2}
c_1	=	5.289 617 297 65 X 10^{-3}	−2.520 612 513 32 X 10^{-3}	−2.688 198 885 45 X 10^{-1}
c_2	=	1.391 665 897 82 X 10^{-5}	1.595 645 018 65 X 10^{-5}	1.712 802 804 71 X 10^{-4}
c_3	=	−2.388 556 930 17 X 10^{-8}	−7.640 859 475 76 X 10^{-9}	−3.458 957 064 53 X 10^{-8}
c_4	=	3.569 160 010 63 X 10^{-11}	2.053 052 910 24 X 10^{-12}	−9.346 339 710 46 X 10^{-15}
c_5	=	−4.623 476 662 98 X 10^{-14}	−2.933 596 681 73 X 10^{-16}	. . . .
c_6	=	5.007 774 410 34 X 10^{-17}	. . . .	. . . .
c_7	=	−3.731 058 861 91 X 10^{-20}	. . . .	. . . .
c_8	=	1.577 164 823 67 X 10^{-23}	. . . .	. . . .
c_9	=	−2.810 386 252 51 X 10^{-27}	. . . .	. . . .

TABLE 10.13 -- *Type R thermocouples: emf-temperature (°F) reference table.*

Thermocouple emf as a Function of Temperature in Degrees Fahrenheit[a]

emf in Millivolts | Reference Junctions at 32 °F

°F	0	−10	−20	−30	−40	−50	−60	−70	−80	−90	−100
0	−0.090	−0.116	−0.141	−0.165	−0.188	−0.210					

°F	0	10	20	30	40	50	60	70	80	90	100
0	−0.090	−0.063	−0.035	−0.006	0.024	0.054	0.086	0.118	0.151	0.184	0.218
100	0.218	0.254	0.289	0.326	0.363	0.400	0.439	0.478	0.517	0.557	0.598
200	0.598	0.639	0.681	0.723	0.766	0.809	0.853	0.897	0.941	0.986	1.032
300	1.032	1.078	1.124	1.171	1.218	1.265	1.313	1.361	1.410	1.459	1.508
400	1.508	1.558	1.607	1.658	1.708	1.759	1.810	1.861	1.913	1.965	2.017
500	2.017	2.070	2.122	2.175	2.229	2.282	2.336	2.390	2.444	2.498	2.553
600	2.553	2.608	2.663	2.718	2.773	2.829	2.885	2.941	2.997	3.054	3.110
700	3.110	3.167	3.224	3.281	3.339	3.396	3.454	3.512	3.570	3.628	3.686
800	3.686	3.745	3.803	3.862	3.921	3.980	4.040	4.099	4.159	4.219	4.279
900	4.279	4.339	4.399	4.459	4.520	4.580	4.641	4.702	4.763	4.824	4.886
1000	4.886	4.947	5.009	5.071	5.133	5.195	5.257	5.320	5.382	5.445	5.508
1100	5.508	5.571	5.634	5.697	5.761	5.824	5.888	5.952	6.016	6.080	6.144
1200	6.144	6.209	6.273	6.338	6.403	6.468	6.533	6.598	6.664	6.730	6.795
1300	6.795	6.861	6.927	6.994	7.060	7.126	7.193	7.260	7.327	7.394	7.461
1400	7.461	7.529	7.596	7.664	7.732	7.800	7.868	7.936	8.005	8.073	8.142
1500	8.142	8.211	8.280	8.349	8.418	8.488	8.557	8.627	8.697	8.767	8.837
1600	8.837	8.908	8.978	9.049	9.120	9.191	9.262	9.333	9.404	9.476	9.547
1700	9.547	9.619	9.691	9.763	9.835	9.908	9.980	10.053	10.126	10.198	10.271
1800	10.271	10.345	10.418	10.491	10.565	10.638	10.712	10.786	10.860	10.934	11.009
1900	11.009	11.083	11.158	11.233	11.307	11.382	11.457	11.533	11.608	11.683	11.759
2000	11.759	11.834	11.910	11.986	12.062	12.138	12.214	12.291	12.367	12.443	12.520
2100	12.520	12.597	12.673	12.750	12.827	12.904	12.981	13.058	13.135	13.213	13.290
2200	13.290	13.367	13.445	13.522	13.600	13.677	13.755	13.833	13.911	13.989	14.066
2300	14.066	14.144	14.222	14.300	14.379	14.457	14.535	14.613	14.691	14.770	14.848
2400	14.848	14.926	15.005	15.083	15.161	15.240	15.318	15.397	15.475	15.553	15.632
2500	15.632	15.710	15.789	15.867	15.946	16.024	16.103	16.181	16.260	16.338	16.417
2600	16.417	16.495	16.574	16.652	16.731	16.809	16.887	16.966	17.044	17.122	17.200
2700	17.200	17.279	17.357	17.435	17.513	17.591	17.669	17.747	17.825	17.903	17.981
2800	17.981	18.059	18.137	18.214	18.292	18.369	18.447	18.524	18.602	18.679	18.756
2900	18.756	18.834	18.911	18.988	19.065	19.141	19.218	19.295	19.372	19.448	19.525
3000	19.525	19.601	19.677	19.753	19.829	19.905	19.981	20.056	20.132	20.207	20.281
3100	20.281	20.356	20.430	20.503	20.576	20.649	20.721	20.792	20.863	20.933	21.003
3200	21.003	21.071									

[a]The emf values in this table were computed from the equations given on the facing page, after converting the desired temperature in °F to its equivalent in °C by the conversion formula given in Section 10.3.1.

TABLE 10.14 -- *Type S thermocouples: emf-temperature (°C) reference table and equations.*

Thermocouple emf as a Function of Temperature in Degrees Celsius (ITS-90)

emf in Millivolts — Reference Junctions at 0 °C

°C	0	−10	−20	−30	−40	−50	−60	−70	−80	−90	−100
0	0.000	−0.053	−0.103	−0.150	−0.194	−0.236					

°C	0	10	20	30	40	50	60	70	80	90	100
0	0.000	0.055	0.113	0.173	0.235	0.299	0.365	0.433	0.502	0.573	0.646
100	0.646	0.720	0.795	0.872	0.950	1.029	1.110	1.191	1.273	1.357	1.441
200	1.441	1.526	1.612	1.698	1.786	1.874	1.962	2.052	2.141	2.232	2.323
300	2.323	2.415	2.507	2.599	2.692	2.786	2.880	2.974	3.069	3.164	3.259
400	3.259	3.355	3.451	3.548	3.645	3.742	3.840	3.938	4.036	4.134	4.233
500	4.233	4.332	4.432	4.532	4.632	4.732	4.833	4.934	5.035	5.137	5.239
600	5.239	5.341	5.443	5.546	5.649	5.753	5.857	5.961	6.065	6.170	6.275
700	6.275	6.381	6.486	6.593	6.699	6.806	6.913	7.020	7.128	7.236	7.345
800	7.345	7.454	7.563	7.673	7.783	7.893	8.003	8.114	8.226	8.337	8.449
900	8.449	8.562	8.674	8.787	8.900	9.014	9.128	9.242	9.357	9.472	9.587
1000	9.587	9.703	9.819	9.935	10.051	10.168	10.285	10.403	10.520	10.638	10.757
1100	10.757	10.875	10.994	11.113	11.232	11.351	11.471	11.590	11.710	11.830	11.951
1200	11.951	12.071	12.191	12.312	12.433	12.554	12.675	12.796	12.917	13.038	13.159
1300	13.159	13.280	13.402	13.523	13.644	13.766	13.887	14.009	14.130	14.251	14.373
1400	14.373	14.494	14.615	14.736	14.857	14.978	15.099	15.220	15.341	15.461	15.582
1500	15.582	15.702	15.822	15.942	16.062	16.182	16.301	16.420	16.539	16.658	16.777
1600	16.777	16.895	17.013	17.131	17.249	17.366	17.483	17.600	17.717	17.832	17.947
1700	17.947	18.061	18.174	18.285	18.395	18.503	18.609				

Temperature Ranges and Coefficients of Equations Used to Compute the Above Table

The equations are of the form: $E = c_0 + c_1t + c_2t^2 + c_3t^3 + \dots c_nt^n$, where E is the emf in millivolts, t is the temperature in degrees Celsius (ITS-90), and c_0, c_1, c_2, c_3, *etc.* are the coefficients. These coefficients are extracted from NIST Monograph 175.

		−50 °C to 1064.18 °C	1064.18 °C to 1664.5 °C	1664.5 °C to 1768.1 °C
c_0	=	0.000 000 000 00 . . .	1.329 004 440 85 . . .	1.466 282 326 36 X 10^{2}
c_1	=	5.403 133 086 31 X 10^{-3}	3.345 093 113 44 X 10^{-3}	−2.584 305 167 52 X 10^{-1}
c_2	=	1.259 342 897 40 X 10^{-5}	6.548 051 928 18 X 10^{-6}	1.636 935 746 41 X 10^{-4}
c_3	=	−2.324 779 686 89 X 10^{-8}	−1.648 562 592 09 X 10^{-9}	−3.304 390 469 87 X 10^{-8}
c_4	=	3.220 288 230 36 X 10^{-11}	1.299 896 051 74 X 10^{-14}	−9.432 236 906 12 X 10^{-15}
c_5	=	−3.314 651 963 89 X 10^{-14}	. . . .	. . . .
c_6	=	2.557 442 517 86 X 10^{-17}	. . . .	. . . .
c_7	=	−1.250 688 713 93 X 10^{-20}	. . . .	. . . .
c_8	=	2.714 431 761 45 X 10^{-24}	. . . .	. . . .

TABLE 10.15 -- *Type S thermocouples: emf-temperature (°F) reference table.*

Thermocouple emf as a Function of Temperature in Degrees Fahrenheit[a]

emf in Millivolts **Reference Junctions at 32 °F**

°F	0	−10	−20	−30	−40	−50	−60	−70	−80	−90	−100
0	−0.092	−0.119	−0.145	−0.170	−0.194	−0.218					

°F	0	10	20	30	40	50	60	70	80	90	100
0	−0.092	−0.064	−0.035	−0.006	0.024	0.055	0.087	0.119	0.153	0.186	0.221
100	0.221	0.256	0.292	0.328	0.365	0.402	0.440	0.479	0.518	0.557	0.597
200	0.597	0.638	0.679	0.720	0.762	0.804	0.847	0.889	0.933	0.977	1.021
300	1.021	1.065	1.110	1.155	1.200	1.246	1.292	1.338	1.385	1.431	1.478
400	1.478	1.526	1.573	1.621	1.669	1.718	1.766	1.815	1.864	1.913	1.962
500	1.962	2.012	2.062	2.111	2.162	2.212	2.262	2.313	2.364	2.415	2.466
600	2.466	2.517	2.568	2.620	2.672	2.723	2.775	2.827	2.880	2.932	2.985
700	2.985	3.037	3.090	3.143	3.196	3.249	3.302	3.355	3.409	3.462	3.516
800	3.516	3.570	3.623	3.677	3.731	3.786	3.840	3.894	3.949	4.003	4.058
900	4.058	4.113	4.167	4.222	4.277	4.332	4.388	4.443	4.498	4.554	4.610
1000	4.610	4.665	4.721	4.777	4.833	4.889	4.945	5.001	5.058	5.114	5.171
1100	5.171	5.227	5.284	5.341	5.398	5.455	5.512	5.569	5.627	5.684	5.741
1200	5.741	5.799	5.857	5.915	5.972	6.030	6.089	6.147	6.205	6.264	6.322
1300	6.322	6.381	6.439	6.498	6.557	6.616	6.675	6.735	6.794	6.853	6.913
1400	6.913	6.973	7.032	7.092	7.152	7.212	7.273	7.333	7.393	7.454	7.514
1500	7.514	7.575	7.636	7.697	7.758	7.819	7.881	7.942	8.003	8.065	8.127
1600	8.127	8.189	8.250	8.312	8.375	8.437	8.499	8.562	8.624	8.687	8.749
1700	8.749	8.812	8.875	8.938	9.001	9.065	9.128	9.192	9.255	9.319	9.382
1800	9.382	9.446	9.510	9.574	9.638	9.703	9.767	9.831	9.896	9.961	10.025
1900	10.025	10.090	10.155	10.220	10.285	10.350	10.416	10.481	10.547	10.612	10.678
2000	10.678	10.743	10.809	10.875	10.941	11.007	11.073	11.139	11.205	11.272	11.338
2100	11.338	11.404	11.471	11.537	11.604	11.670	11.737	11.804	11.870	11.937	12.004
2200	12.004	12.071	12.138	12.205	12.272	12.339	12.406	12.473	12.540	12.607	12.675
2300	12.675	12.742	12.809	12.876	12.944	13.011	13.078	13.146	13.213	13.280	13.348
2400	13.348	13.415	13.483	13.550	13.617	13.685	13.752	13.820	13.887	13.955	14.022
2500	14.022	14.089	14.157	14.224	14.292	14.359	14.426	14.494	14.561	14.629	14.696
2600	14.696	14.763	14.830	14.898	14.965	15.032	15.099	15.166	15.233	15.300	15.367
2700	15.367	15.434	15.501	15.568	15.635	15.702	15.769	15.835	15.902	15.969	16.035
2800	16.035	16.102	16.168	16.235	16.301	16.367	16.434	16.500	16.566	16.632	16.698
2900	16.698	16.764	16.829	16.895	16.961	17.026	17.092	17.157	17.223	17.288	17.353
3000	17.353	17.418	17.483	17.548	17.613	17.678	17.742	17.807	17.871	17.935	17.998
3100	17.998	18.061	18.124	18.187	18.248	18.310	18.371	18.431	18.491	18.551	18.609
3200	18.609	18.667									

[a]The emf values in this table were computed from the equations given on the facing page, after converting the desired temperature in °F to its equivalent in °C by the conversion formula given in Section 10.3.1.

TABLE 10.16 -- *Type T thermocouples: emf-temperature (°C) reference table and equations.*

Thermocouple emf as a Function of Temperature in Degrees Celsius (ITS-90)

emf in Millivolts | Reference Junctions at 0 °C

°C	0	−10	−20	−30	−40	−50	−60	−70	−80	−90	−100
−200	−5.603	−5.753	−5.888	−6.007	−6.105	−6.180	−6.232	−6.258			
−100	−3.379	−3.657	−3.923	−4.177	−4.419	−4.648	−4.865	−5.070	−5.261	−5.439	−5.603
0	0.000	−0.383	−0.757	−1.121	−1.475	−1.819	−2.153	−2.476	−2.788	−3.089	−3.379

°C	0	10	20	30	40	50	60	70	80	90	100
0	0.000	0.391	0.790	1.196	1.612	2.036	2.468	2.909	3.358	3.814	4.279
100	4.279	4.750	5.228	5.714	6.206	6.704	7.209	7.720	8.237	8.759	9.288
200	9.288	9.822	10.362	10.907	11.458	12.013	12.574	13.139	13.709	14.283	14.862
300	14.862	15.445	16.032	16.624	17.219	17.819	18.422	19.030	19.641	20.255	20.872
400	20.872										

Temperature Ranges and Coefficients of Equations Used to Compute the Above Table

The equations are of the form: $E = c_0 + c_1t + c_2t^2 + c_3t^3 + \ldots c_nt^n$, where E is the emf in millivolts, t is the temperature in degrees Celsius (ITS-90), and c_0, c_1, c_2, c_3, *etc.* are the coefficients. These coefficients are extracted from NIST Monograph 175.

		−270 °C to 0 °C	0 °C to 400 °C
c_0	=	0.000 000 000 0 . . .	0.000 000 000 0 . . .
c_1	=	$3.874\,810\,636\,4 \times 10^{-2}$	$3.874\,810\,636\,4 \times 10^{-2}$
c_2	=	$4.419\,443\,434\,7 \times 10^{-5}$	$3.329\,222\,788\,0 \times 10^{-5}$
c_3	=	$1.184\,432\,310\,5 \times 10^{-7}$	$2.061\,824\,340\,4 \times 10^{-7}$
c_4	=	$2.003\,297\,355\,4 \times 10^{-8}$	$-2.188\,225\,684\,6 \times 10^{-9}$
c_5	=	$9.013\,801\,955\,9 \times 10^{-10}$	$1.099\,688\,092\,8 \times 10^{-11}$
c_6	=	$2.265\,115\,659\,3 \times 10^{-11}$	$-3.081\,575\,877\,2 \times 10^{-14}$
c_7	=	$3.607\,115\,420\,5 \times 10^{-13}$	$4.547\,913\,529\,0 \times 10^{-17}$
c_8	=	$3.849\,393\,988\,3 \times 10^{-15}$	$-2.751\,290\,167\,3 \times 10^{-20}$
c_9	=	$2.821\,352\,192\,5 \times 10^{-17}$	. . . .
c_{10}	=	$1.425\,159\,477\,9 \times 10^{-19}$	. . . .
c_{11}	=	$4.876\,866\,228\,6 \times 10^{-22}$	. . . .
c_{12}	=	$1.079\,553\,927\,0 \times 10^{-24}$	. . . .
c_{13}	=	$1.394\,502\,706\,2 \times 10^{-27}$	. . . .
c_{14}	=	$7.979\,515\,392\,7 \times 10^{-31}$	. . . .

TABLE 10.17 -- *Type T thermocouples: emf-temperature (°F) reference table.*

Thermocouple emf as a Function of Temperature in Degrees Fahrenheit[a]

emf in Millivolts **Reference Junctions at 32 °F**

°F	0	−10	−20	−30	−40	−50	−60	−70	−80	−90	−100
−400	−6.105	−6.150	−6.187	−6.217	−6.240	−6.254					
−300	−5.341	−5.439	−5.532	−5.620	−5.705	−5.785	−5.860	−5.930	−5.994	−6.053	−6.105
−200	−4.149	−4.286	−4.419	−4.548	−4.673	−4.794	−4.912	−5.025	−5.135	−5.240	−5.341
−100	−2.581	−2.754	−2.923	−3.089	−3.251	−3.410	−3.565	−3.717	−3.865	−4.009	−4.149
0	−0.675	−0.879	−1.081	−1.279	−1.475	−1.667	−1.857	−2.043	−2.225	−2.405	−2.581
°F	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
0	−0.675	−0.467	−0.256	−0.043	0.173	0.391	0.611	0.834	1.060	1.288	1.519
100	1.519	1.752	1.988	2.227	2.468	2.712	2.958	3.207	3.459	3.712	3.968
200	3.968	4.227	4.487	4.750	5.015	5.282	5.551	5.823	6.096	6.371	6.648
300	6.648	6.928	7.209	7.492	7.777	8.064	8.352	8.643	8.935	9.229	9.525
400	9.525	9.822	10.122	10.423	10.725	11.029	11.335	11.643	11.951	12.262	12.574
500	12.574	12.887	13.202	13.518	13.836	14.155	14.476	14.797	15.121	15.445	15.771
600	15.771	16.098	16.426	16.756	17.086	17.418	17.752	18.086	18.422	18.759	19.097
700	19.097	19.437	19.777	20.118	20.460	20.803					

[a]The emf values in this table were computed from the equations given on the facing page, after converting the desired temperature in °F to its equivalent in °C by the conversion formula given in Section 10.3.1.

TABLE 10.18—*Type B thermocouples: coefficients (c_i) of polynomials for the computation of temperatures in °C as a function of the thermocouple emf in various temperature and emf ranges.*

Temperature Range:	250 °C to 700 °C	700 °C to 1820 °C
emf Range:	0.291 mV to 2.431 mV	2.431 mV to 13.820 mV
c_0 =	9.842 332 1 X 10^1	2.131 507 1 X 10^2
c_1 =	6.997 150 0 X 10^2	2.851 050 4 X 10^2
c_2 =	−8.476 530 4 X 10^2	−5.274 288 7 X 10^1
c_3 =	1.005 264 4 X 10^3.	9.916 080 4 . . .
c_4 =	−8.334 595 2 X 10^2	−1.296 530 3 . . .
c_5 =	4.550 854 2 X 10^2	1.119 587 0 X 10^{-1}
c_6 =	−1.552 303 7 X 10^2	−6.062 519 9 X 10^{-3}
c_7 =	2.988 675 0 X 10^1	1.866 169 6 X 10^{-4}
c_8 =	−2.474 286 0 . . .	−2.487 858 5 X 10^{-6}

NOTE—The above coefficients are extracted from NIST Monograph 175 and are for an expression of the form shown in Section 10.3.2. They yield approximate values of temperature that agree within ± 0.03 °C with the values given in Table 10.2.

TABLE 10.19—*Type E thermocouples: coefficients (c_i) of polynomials for the computation of temperatures in °C as a function of the thermocouple emf in various temperature and emf ranges.*

Temperature Range:	−200 °C to 0 °C	0 °C to 1000 °C
emf Range:	−8.825 mV to 0.0 mV	0.0 mV to 76.373 mV
c_0 =	0.000 000 0 . . .	0.000 000 0 . . .
c_1 =	1.697 728 8 X 10^1	1.705 703 5 X 10^1
c_2 =	−4.351 497 0 X 10^{-1}	−2.330 175 9 X 10^{-1}
c_3 =	−1.585 969 7 X 10^{-1}	6.543 558 5 X 10^{-3}
c_4 =	−9.250 287 1 X 10^{-2}	−7.356 274 9 X 10^{-5}
c_5 =	−2.608 431 4 X 10^{-2}	−1.789 600 1 X 10^{-6}
c_6 =	−4.136 019 9 X 10^{-3}	8.403 616 5 X 10^{-8}
c_7 =	−3.403 403 0 X 10^{-4}	−1.373 587 9 X 10^{-9}
c_8 =	−1.156 489 0 X 10^{-5}	1.062 982 3 X 10^{-11}
c_9 =	. . . .	−3.244 708 7 X 10^{-14}

NOTE—The above coefficients are extracted from NIST Monograph 175 and are for an expression of the form shown in Section 10.3.2. They yield approximate values of temperature that agree within ± 0.02 °C with the values given in Table 10.4.

TABLE 10.20—*Type J thermocouples: coefficients (c_i) of polynomials for the computation of temperatures in °C as a function of the thermocouple emf in various temperature and emf ranges.*

Temperature Range:	−210 °C to 0 °C	0 °C to 760 °C	760 °C to 1200 °C
emf Range:	−8.095 mV to 0.0 mV	0.0 mV to 42.919 mV	42.919 mV to 69.553 mV
c_0 =	0.000 000 0 . . .	0.000 000 . . .	$-3.113\ 581\ 87 \times 10^{3}$
c_1 =	$1.952\ 826\ 8 \times 10^{1}$	$1.978\ 425 \times 10^{1}$	$3.005\ 436\ 84 \times 10^{2}$
c_2 =	−1.228 618 5 . . .	$-2.001\ 204 \times 10^{-1}$	−9.947 732 30 . . .
c_3 =	−1.075 217 8 . . .	$1.036\ 969 \times 10^{-2}$	$1.702\ 766\ 30 \times 10^{-1}$
c_4 =	$-5.908\ 693\ 3 \times 10^{-1}$	$-2.549\ 687 \times 10^{-4}$	$-1.430\ 334\ 68 \times 10^{-3}$
c_5 =	$-1.725\ 671\ 3 \times 10^{-1}$	$3.585\ 153 \times 10^{-6}$	$4.738\ 860\ 84 \times 10^{-6}$
c_6 =	$-2.813\ 151\ 3 \times 10^{-2}$	$-5.344\ 285 \times 10^{-8}$	. . . .
c_7 =	$-2.396\ 337\ 0 \times 10^{-3}$	$5.099\ 890 \times 10^{-10}$	. . . .
c_8 =	$-8.382\ 332\ 1 \times 10^{-5}$	. . . .	. . . .

NOTE—The above coefficients are extracted from NIST Monograph 175 and are for an expression of the form shown in Section 10.3.2. They yield approximate values of temperature that agree within ± 0.05 °C with the values given in Table 10.6.

TABLE 10.21—*Type K thermocouples: coefficients (c_i) of polynomials for the computation of temperatures in °C as a function of the thermocouple emf in various temperature and emf ranges.*

Temperature Range:	−200 °C to 0 °C	0 °C to 500 °C	500 °C to 1372 °C
emf Range:	−5.891 mV to 0.0 mV	0.0 mV to 20.644 mV	20.644 mV to 54.886 mV
c_0 =	0.000 000 0 . . .	0.000 000 0 . . .	$-1.318\ 058 \times 10^{2}$
c_1 =	$2.517\ 346\ 2 \times 10^{1}$	$2.508\ 355 \times 10^{1}$	$4.830\ 222 \times 10^{1}$
c_2 =	−1.166 287 8 . . .	$7.860\ 106 \times 10^{-2}$	−1.646 031 . . .
c_3 =	−1.083 363 8 . . .	$-2.503\ 131 \times 10^{-1}$	$5.464\ 731 \times 10^{-2}$
c_4 =	$-8.977\ 354\ 0 \times 10^{-1}$	$8.315\ 270 \times 10^{-2}$	$-9.650\ 715 \times 10^{-4}$
c_5 =	$-3.734\ 237\ 7 \times 10^{-1}$	$-1.228\ 034 \times 10^{-2}$	$8.802\ 193 \times 10^{-6}$
c_6 =	$-8.663\ 264\ 3 \times 10^{-2}$	$9.804\ 036 \times 10^{-4}$	$-3.110\ 810 \times 10^{-8}$
c_7 =	$-1.045\ 059\ 8 \times 10^{-2}$	$-4.413\ 030 \times 10^{-5}$	. . . .
c_8 =	$-5.192\ 057\ 7 \times 10^{-4}$	$1.057\ 734 \times 10^{-6}$	. . . .
c_9 =	. . . .	$-1.052\ 755 \times 10^{-8}$	. . . .

NOTE—The above coefficients are extracted from NIST Monograph 175 and are for an expression of the form shown in Section 10.3.2. They yield approximate values of temperature that agree within ± 0.05 °C with the values given in Table 10.8.

TABLE 10.22—*Type N thermocouples: coefficients (c_i) of polynomials for the computation of temperatures in °C as a function of the thermocouple emf in various temperature and emf ranges.*

Temperature Range:	−200 °C to 0 °C	0 °C to 600 °C	600 °C to 1300 °C
emf Range:	−3.990 mV to 0.0 mV	0.0 mV to 20.613 mV	20.613 mV to 47.513 mV
c_0 =	0.000 000 0 . . .	0.000 00 . . .	1.972 485 X 10^1
c_1 =	3.843 684 7 X 10^1	3.868 96 X 10^1	3.300 943 X 10^1
c_2 =	1.101 048 5 . . .	−1.082 67 . . .	−3.915 159 X 10^{-1}
c_3 =	5.222 931 2 . . .	4.702 05 X 10^{-2}	9.855 391 X 10^{-3}
c_4 =	7.206 052 5 . . .	−2.121 69 X 10^{-6}	−1.274 371 X 10^{-4}
c_5 =	5.848 858 6 . . .	−1.172 72 X 10^{-4}	7.767 022 X 10^{-7}
c_6 =	2.775 491 6 . . .	5.392 80 X 10^{-6}	. . . .
c_7 =	7.707 516 6 X 10^{-1}	−7.981 56 X 10^{-8}	. . . .
c_8 =	1.158 266 5 X 10^{-1}	. . . .	. . . .
c_9 =	7.313 886 8 X 10^{-3}	. . . .	. . . .

NOTE—The above coefficients are extracted from NIST Monograph 175 and are for an expression of the form shown in Section 10.3.2. They yield approximate values of temperature that agree within ± 0.04 °C with the values given in Table 10.10.

TABLE 10.23—*Type R thermocouples: coefficients (c_i) of polynomials for the computation of temperatures in °C as a function of the thermocouple emf in various temperature and emf ranges.*

Temperature Range:	−50 °C to 250 °C	250 °C to 1200 °C	1064 °C to 1664.5 °C	1664.5 °C to 1768.1 °C
emf Range:	−0.226 mV to 1.923 mV	1.923 mV to 13.228 mV	11.361 mV to 19.739 mV	19.739 mV to 21.103 mV
c_0 =	0.000 000 0 . . .	1.334 584 505 X 10^1	−8.199 599 416 X 10^1	3.406 177 836 X 10^4
c_1 =	1.889 138 0 X 10^2	1.472 644 573 X 10^2	1.553 962 042 X 10^2	−7.023 729 171 X 10^3
c_2 =	−9.383 529 0 X 10^1	−1.844 024 844 X 10^1	−8.342 197 663 . . .	5.582 903 813 X 10^2
c_3 =	1.306 861 9 X 10^2	4.031 129 726 . . .	4.279 433 549 X 10^{-1}	−1.952 394 635 X 10^1
c_4 =	−2.270 358 0 X 10^2	−6.249 428 360 X 10^{-1}	−1.191 577 910 X 10^{-2}	2.560 740 231 X 10^{-1}
c_5 =	3.514 565 9 X 10^2	6.468 412 046 X 10^{-2}	1.492 290 091 X 10^{-4}	. . . .
c_6 =	−3.895 390 0 X 10^2	−4.458 750 426 X 10^{-3}	. . . .	. . . .
c_7 =	2.823 947 1 X 10^2	1.994 710 149 X 10^{-4}	. . . .	. . . .
c_8 =	−1.260 728 1 X 10^2	−5.313 401 790 X 10^{-6}	. . . .	. . . .
c_9 =	3.135 361 1 X 10^1	6.481 976 217 X 10^{-8}	. . . .	. . . .
c_{10} =	−3.318 776 9 . . .	. . . .	. . . .	. . . .

NOTE—The above coefficients are extracted from NIST Monograph 175 and are for an expression of the form shown in Section 10.3.2. They yield approximate values of temperature that agree within ± 0.02 °C with the values given in Table 10.12.

TABLE 10.24—*Type S thermocouples: coefficients (c_i) of polynomials for the computation of temperatures in °C as a function of the thermocouple emf in various temperature and emf ranges.*

Temperature Range:	−50 °C to 250 °C	250 °C to 1200 °C	1064 °C to 1664.5 °C	1664.5 °C to 1768.1 °C
emf Range:	−0.235 mV to 1.874 mV	1.874 mV to 11.950 mV	10.332 mV to 17.536 mV	17.536 mV to 18.693 mV
c_0 =	0.000 000 00 . . .	$1.291\ 507\ 177 \times 10^{1}$	$-8.087\ 801\ 117 \times 10^{1}$	$5.333\ 875\ 126 \times 10^{4}$
c_1 =	$1.849\ 494\ 60 \times 10^{2}$	$1.466\ 298\ 863 \times 10^{2}$	$1.621\ 573\ 104 \times 10^{2}$	$-1.235\ 892\ 298 \times 10^{4}$
c_2 =	$-8.005\ 040\ 62 \times 10^{1}$	$-1.534\ 713\ 402 \times 10^{1}$	−8.536 869 453 . . .	$1.092\ 657\ 613 \times 10^{3}$
c_3 =	$1.022\ 374\ 30 \times 10^{2}$	3.145 945 973 . . .	$4.719\ 686\ 976 \times 10^{-1}$	$-4.265\ 693\ 686 \times 10^{1}$
c_4 =	$-1.522\ 485\ 92 \times 10^{2}$	$-4.163\ 257\ 839 \times 10^{-1}$	$-1.441\ 693\ 666 \times 10^{-2}$	$6.247\ 205\ 420 \times 10^{-1}$
c_5 =	$1.888\ 213\ 43 \times 10^{2}$	$3.187\ 963\ 771 \times 10^{-2}$	$2.081\ 618\ 890 \times 10^{-4}$	. . . .
c_6 =	$-1.590\ 859\ 41 \times 10^{2}$	$-1.291\ 637\ 500 \times 10^{-3}$	. . . .	. . . .
c_7 =	$8.230\ 278\ 80 \times 10^{1}$	$2.183\ 475\ 087 \times 10^{-5}$	. . . .	. . . .
c_8 =	$-2.341\ 819\ 44 \times 10^{1}$	$-1.447\ 379\ 511 \times 10^{-7}$	. . . .	. . . .
c_9 =	2.797 862 60 . . .	$8.211\ 272\ 125 \times 10^{-9}$	. . . .	. . . .

NOTE—The above coefficients are extracted from NIST Monograph 175 and are for an expression of the form shown in Section 10.3.2. They yield approximate values of temperature that agree within ± 0.02 °C with the values given in Table 10.14.

TABLE 10.25—*Type T thermocouples: coefficients (c_i) of polynomials for the computation of temperatures in °C as a function of the thermocouple emf in various temperature and emf ranges.*

Temperature Range:	−200 °C to 0 °C	0 °C to 400 °C
emf Range:	−5.603 mV to 0.0 mV	0.0 mV to 20.872 mV
c_0 =	0.000 000 0 . . .	0.000 000 . . .
c_1 =	$2.594\ 919\ 2 \times 10^{1}$	$2.592\ 800 \times 10^{1}$
c_2 =	$-2.131\ 696\ 7 \times 10^{-1}$	$-7.602\ 961 \times 10^{-1}$
c_3 =	$7.901\ 869\ 2 \times 10^{-1}$	$4.637\ 791 \times 10^{-2}$
c_4 =	$4.252\ 777\ 7 \times 10^{-1}$	$-2.165\ 394 \times 10^{-3}$
c_5 =	$1.330\ 447\ 3 \times 10^{-1}$	$6.048\ 144 \times 10^{-5}$
c_6 =	$2.024\ 144\ 6 \times 10^{-2}$	$-7.293\ 422 \times 10^{-7}$
c_7 =	$1.266\ 817\ 1 \times 10^{-3}$	. . . .

NOTE—The above coefficients are extracted from NIST Monograph 175 and are for an expression of the form shown in Section 10.3.2. They yield approximate values of temperature that agree within ± 0.04 °C with the values given in Table 10.16.

applications. If greater precision is required, reference tables giving emf values to four decimal places for each degree of temperature are given in NIST Monograph 175 [*3*]. Furthermore, equations for computing temperature-emf relationships for the various thermocouple types with greater temperature resolution are presented in the next Section.

10.3 Computation of Temperature-Emf Relationships

10.3.1 Equations Used to Derive the Reference Tables

The emf values of each of the eight thermocouple types given in Tables 10.2 to 10.17 are generated by power series equations according to Ref *3*. The equations give the thermocouple emf, in millivolts, as a function of the temperature in degrees Celsius (ITS-90). The coefficients and temperature ranges of the equations used for each thermocouple type are listed on the same page as the degrees Celsius reference table (the even numbered tables). The reference tables which give temperatures in degrees Fahrenheit (t_f) were computed using these same equations and the conversion formula

$$t_f = (9/5)t_{90} + 32$$

where t_{90} is value of the temperature in degrees Celsius (ITS-90).

10.3.2 Polynomial Approximations Giving Temperature as a Function of the Thermocouple Emf

The equations presented in Section 10.3.1 are useful for generating reference tables, but they are not well suited for calculating temperatures from values of thermocouple emf. While temperatures may be obtained from emf by iteration of such equations, it is much more convenient to use equations that give temperature as a function of thermocouple emf for this purpose.

Tables 10.18 to 10.25 give the coefficients of polynomial approximations that express temperature, in degrees Celsius (ITS-90), as a function of emf for each of the eight thermocouple types in various temperature and emf ranges. These polynomial approximations were extracted from Ref *3*, and they are based on reference junctions at 0°C. They yield approximate values of temperature that agree to at least ±0.06°C, over the temperature range specified, with the values given by the appropriate reference table in Section 10.2. The coefficients given in Tables 10.18 to 10.25 are for an expression of the form

$$t = c_0 + c_1E + c_2E^2 + c_3E^3 + \ldots c_iE^i$$

where

t = temperature in degrees Celsius (ITS-90),
E = thermocouple emf in millivolts, and
c_0, c_1, c_2, c_3, etc. = coefficients.

10.4 References

[*1*] Belecki, N. B., Dziuba, R. F., Field, B. F., and Taylor, B. N., "Guidelines for Implementing the New Representations of the Volt and Ohm Effective January 1, 1990," NIST Technical Note 1263, National Institute of Standards and Technology, 1989.

[*2*] Preston-Thomas, H., "The International Temperature Scale of 1990 (ITS-90)," *Metrologia,* Vol. 27, No. 1, 1990, pp. 3–10; *Metrologia,* Vol. 27, No. 2, 1990, p. 107 and Appendix II of this publication.

[*3*] Burns, G. W., Scroger, M. G., Strouse, G. F., Croarkin, M. C., and Guthrie, W. F., "Temperature-Electromotive Force Reference Functions and Tables for the Letter-Designated Thermocouple Types Based on the ITS-90," NIST Monograph 175, National Institute of Standards and Technology, 1993.

Chapter 11—Cryogenics

11.1 General Remarks

The discussion in this chapter very loosely interprets the cryogenic temperature range to include temperatures from 280 K down to absolute zero, 0 K. Many aspects of thermocouple usage are the same at cryogenic temperatures as they are at higher temperatures; for example, the basic principles, as discussed in Chapter 2, the material descriptions and precautions in Chapter 3, and the measurement systems in Chapter 6, apply to both high and low temperatures. There are, however, significant differences in selection of wire size, insulations, and methods of practical usage [*1,2*]. Some significant high-temperature problems such as oxidation, reduction, migration, and annealing are not present to the same degree in low-temperature applications.

Successful use of thermocouples for absolute or differential temperature measurement at low temperatures requires that particular attention be paid to thermocouple sensitivity and to the thermoelectric effects of dilute impurities, strain, and inhomogeneity. Sensitivity, denoted by the Seebeck coefficient, decreases with decreasing temperature. In the cryogenic temperature range this amplifies the relative importance of chemical and physical imperfections in the thermocouple wires. The requirements for the associated electronics and signal maintenance become more stringent as the temperature and thermoelectric sensitivity decrease. Another consideration for low-temperature systems is that the heat capacity of materials decreases with decreasing temperature. This frequently causes the heat leak into a system to be a major concern, since a small input of energy can affect the temperature being measured as well as the economics of running an experimental apparatus. Heat leak is minimized by using long, small-diameter wires with high thermal resistance to communicate between high and low temperatures. Unfortunately, long, small-diameter alloy wires are difficult to work with, tend to be more thermoelectrically inhomogeneous, and are strained easily by unmatched rates of thermal expansion of materials in the system.

An increasingly important subset of temperature measurement at low temperatures involves magnetic-field environments. In spite of the difficulties involved, their size, low heat capacity, time response, and ability to measure temperature differences make thermocouples attractive in certain situations. A major problem arises from the fact that the Seebeck coefficient is not only a function of temperature but also of the field strength and orientation of the field relative to the wire axis. At temperatures near 4 K and magnetic-field strength of 12 T, the effect on the emf output is approximately 90% for KP versus AuFe thermocouples [*3*] and 14% for Type E [*4*]. For very low temperatures the applications will be limited to situations that allow in situ calibration as a function of field strength and temperature. The development of superconductors with high-transition temperatures may allow expanded use of thermocouples since the effect of the magnetic field decreases as the temperature increases. At the present time magnetic field effect data are limited to temperatures below 50 K. It is encouraging to note, however, that the effect on Type E emf at 12 T and 45 K is about 2%.

11.2 Materials

Sensitivity is ordinarily given first consideration in the selection of a thermocouple pair to use in low-temperature applications. Three of the letter-designated types are considered to be adequate for use down to approximately 40 K. Other standardized pairs are useable but tend to suffer from lack of sensitivity, lot-to-lot variations, and dependence on dilute impurities. Type E is recommended for use at temperatures above about 40 K. As seen in Figure 11.1, the sensitivity of Type E is higher in this range than it is for Types T and K; the effect of inhomogeneities is about the same for Type E as for the others and both EP and EN are highly alloyed materials with high thermal resistance.

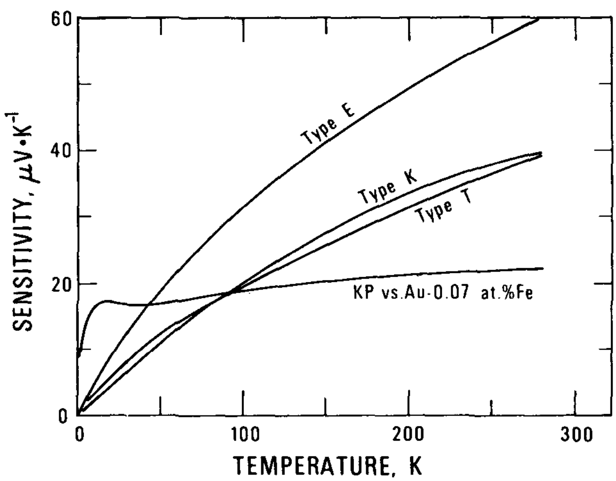

FIG. 11.1—*Seebeck coefficients for Types E, K, T, and KP versus Au-0.07 Fe.*

For temperatures below about 40 K, reduced sensitivity limits the usefulness of the standardized thermocouple types. Two alloys which retain useable sensitivities below 40 K have been used extensively as the negative materials in combination with positive materials such as copper, "normal" silver (silver-0.37 atomic percent gold), and KP (or EP); these are silver-2.1 atomic percent cobalt and gold-0.07 atomic percent iron. Gold-cobalt is a supersaturated solid solution in which the Co migrates to the grain boundaries, even at room temperature. This causes the thermocouple calibration to shift with time and ultimately restricts use of this alloy to situations where long-term stability is not critical. The gold-iron alloy, on the other hand, is metallurgically stable, retains a useable sensitivity at temperatures below 4 K, and exhibits nearly linear dependence of sensitivity on temperature above 50 K.

11.3 Reference Tables (for use below 280 K)

Reference tables for the standardized thermocouple Types E, K, and T are given in Tables 11.1 through 11.3 [*5*]. These data are also included in Chapter 10 in a different format as part of an extended-range reference set [*6*]. Table 11.4 provides low-temperature tables for KP versus gold-0.07 atomic percent iron [*7*]. The values presented in these tables are thermoelectric voltage, Seebeck coefficient, and derivative of the Seebeck coefficient, all given as functions of temperature. These tables are based on ITS-90 [*9*] and the SI volt [*8*] as modified from the original tables [*5–7*]. The original tables were based on IPTS-68 for temperatures above 20 K and P2-20 (1965) for temperatures between 4 and 20 K.

TABLE 11.1—*Type E thermocouple: thermoelectric voltage, E(T), Seebeck coefficient, S(T), and derivative of the Seebeck coefficient, dS/dT.*

T, K	E, μV	S, μV/K	dS/dT, nV/K²	T, K	E, μV	S, μV/K	dS/dT, nV/K²
				35	258.32	13.838	341.5
				36	272.33	14.178	339.5
				37	286.68	14.517	337.3
3	2.07	1.489	509.2	38	301.36	14.853	335.1
4	3.81	1.988	489.2	39	316.38	15.187	332.9
5	6.04	2.468	471.7	40	331.74	15.518	330.5
6	8.74	2.932	456.3	41	347.42	15.848	328.2
7	11.90	3.381	442.9	42	363.43	16.175	325.7
8	15.50	3.818	431.2	43	379.77	16.499	323.3
9	19.53	4.244	421.0	44	396.43	16.821	320.8
10	23.98	4.661	412.2	45	413.41	17.141	318.3
11	28.85	5.069	404.5	46	430.71	17.458	315.7
12	34.12	5.470	397.9	47	448.33	17.772	313.1
13	39.79	5.865	392.1	48	466.25	18.084	310.5
14	45.85	6.255	387.2	49	484.49	18.393	307.9
15	52.30	6.640	382.8	50	503.04	18.700	305.3
16	59.13	7.021	379.1	51	521.89	19.004	302.8
17	66.34	7.398	375.9	52	541.05	19.306	300.2
18	73.92	7.772	373.0	53	560.50	19.604	297.6
19	81.88	8.144	370.5	54	580.26	19.901	295.1
20	90.21	8.513	368.2	55	600.30	20.195	292.5
21	98.91	8.881	366.1	56	620.64	20.486	290.0
22	107.97	9.246	364.2	57	641.27	20.775	287.5
23	117.40	9.609	362.4	58	662.19	21.061	285.1
24	127.19	9.971	360.8	59	683.40	21.345	282.7
25	137.34	10.331	359.1	60	704.88	21.626	280.3
26	147.85	10.689	357.5	61	726.65	21.905	278.0
27	158.72	11.046	355.9	62	748.69	22.182	275.7
28	169.94	11.401	354.3	63	771.01	22.457	273.5
29	181.52	11.754	352.6	64	793.60	22.729	271.3
30	193.45	12.106	350.9	65	816.47	22.999	269.1
31	205.73	12.456	349.2	66	839.60	23.267	267.0
32	218.36	12.804	347.4	67	863.00	23.533	265.0
33	231.33	13.151	345.5	68	886.67	23.797	263.0
34	244.66	13.495	343.5	69	910.60	24.059	261.0

TABLE 11.1—*Type E thermocouple: thermoelectric voltage, E(T), Seebeck coefficient, S(T), and derivative of the Seebeck coefficient, dS/dT (continued).*

T, K	E, μV	S, μV/K	dS/dT, nV/K²	T, K	E, μV	S, μV/K	dS/dT, nV/K²
70	934.79	24.319	259.1	105	1933.70	32.503	213.8
71	959.23	24.578	257.2	106	1966.31	32.716	212.8
72	983.94	24.834	255.4	107	1999.14	32.929	211.9
73	1008.90	25.088	253.7	108	2032.17	33.140	210.9
74	1034.12	25.341	251.9	109	2065.42	33.350	210.0
75	1059.58	25.592	250.3	110	2098.87	33.560	209.0
76	1085.30	25.842	248.6	111	2132.54	33.768	208.1
77	1111.27	26.090	247.0	112	2166.41	33.976	207.2
78	1137.48	26.336	245.5	113	2200.49	34.183	206.2
79	1163.94	26.581	244.0	114	2234.77	34.389	205.3
80	1190.64	26.824	242.5	115	2269.26	34.593	204.4
81	1217.59	27.066	241.1	116	2303.96	34.797	203.5
82	1244.77	27.306	239.7	117	2338.86	35.000	202.6
83	1272.20	27.545	238.3	118	2373.96	35.203	201.7
84	1299.86	27.783	237.0	119	2409.26	35.404	200.8
85	1327.76	28.019	235.7	120	2444.77	35.604	199.9
86	1355.90	28.254	234.4	121	2480.47	35.804	199.1
87	1384.27	28.488	233.1	122	2516.37	36.002	198.2
88	1412.87	28.720	231.9	123	2552.48	36.200	197.3
89	1441.71	28.952	230.7	124	2588.77	36.397	196.5
90	1470.78	29.182	229.5	125	2625.27	36.593	195.6
91	1500.07	29.411	228.4	126	2661.96	36.788	194.8
92	1529.60	29.638	227.2	127	2698.85	36.983	194.0
93	1559.35	29.865	226.1	128	2735.93	37.176	193.2
94	1589.33	30.091	225.0	129	2773.20	37.369	192.3
95	1619.53	30.315	224.0	130	2810.66	37.561	191.5
96	1649.96	30.539	222.9	131	2848.32	37.752	190.7
97	1680.61	30.761	221.8	132	2886.17	37.942	189.9
98	1711.48	30.982	220.8	133	2924.20	38.132	189.2
99	1742.57	31.203	219.8	134	2962.43	38.321	188.4
100	1773.88	31.422	218.7	135	3000.85	38.509	187.6
101	1805.41	31.640	217.7	136	3039.45	38.696	186.8
102	1837.16	31.857	216.7	137	3078.24	38.882	186.1
103	1869.13	32.073	215.7	138	3117.21	39.068	185.4
104	1901.31	32.289	214.8	139	3156.37	39.253	184.6

TABLE 11.1—*Type E thermocouple: thermoelectric voltage, E(T), Seebeck coefficient, S(T), and derivative of the Seebeck coefficient, dS/dT (continued).*

T, K	E, μV	S, μV/K	dS/dT, nV/K²	T, K	E, μV	S, μV/K	dS/dT, nV/K²
140	3195.72	39.437	183.9	175	4683.92	45.475	161.8
141	3235.25	39.621	183.2	176	4729.47	45.637	161.3
142	3274.96	39.804	182.5	177	4775.19	45.798	160.7
143	3314.86	39.986	181.8	178	4821.07	45.958	160.1
144	3354.93	40.167	181.1	179	4867.10	46.118	159.5
145	3395.19	40.348	180.4	180	4913.30	46.277	158.9
146	3435.63	40.528	179.7	181	4959.66	46.435	158.3
147	3476.25	40.707	179.0	182	5006.17	46.593	157.7
148	3517.04	40.886	178.4	183	5052.84	46.751	157.1
149	3558.02	41.064	177.7	184	5099.67	46.907	156.5
150	3599.17	41.242	177.1	185	5146.66	47.064	155.9
151	3640.50	41.418	176.4	186	5193.80	47.219	155.3
152	3682.01	41.594	175.8	187	5241.10	47.374	154.7
153	3723.69	41.770	175.1	188	5288.55	47.529	154.1
154	3765.55	41.945	174.5	189	5336.15	47.682	153.4
155	3807.58	42.119	173.9	190	5383.91	47.835	152.8
156	3849.78	42.292	173.2	191	5431.83	47.988	152.2
157	3892.16	42.465	172.6	192	5479.89	48.140	151.6
158	3934.71	42.638	172.0	193	5528.10	48.291	151.0
159	3977.44	42.809	171.4	194	5576.47	48.442	150.4
160	4020.33	42.980	170.8	195	5624.99	48.592	149.8
161	4063.40	43.151	170.2	196	5673.66	48.742	149.2
162	4106.63	43.321	169.6	197	5722.47	48.891	148.6
163	4150.04	43.490	169.0	198	5771.44	49.039	148.0
164	4193.61	43.659	168.4	199	5820.55	49.187	147.4
165	4237.36	43.827	167.8	200	5869.81	49.334	146.8
166	4281.27	43.994	167.2	201	5919.22	49.480	146.2
167	4325.35	44.161	166.6	202	5968.77	49.626	145.7
168	4369.59	44.328	166.0	203	6018.47	49.772	145.1
169	4414.00	44.493	165.4	204	6068.31	49.916	144.5
170	4458.58	44.658	164.8	205	6118.30	50.061	143.9
171	4503.32	44.823	164.2	206	6168.43	50.204	143.3
172	4548.22	44.987	163.6	207	6218.71	50.347	142.7
173	4593.29	45.150	163.0	208	6269.13	50.490	142.2
174	4638.52	45.313	162.4	209	6319.69	50.632	141.6

TABLE 11.1—*Type E thermocouple: thermoelectric voltage, E(T), Seebeck coefficient, S(T), and derivative of the Seebeck coefficient, dS/dT (continued).*

T, K	E, μV	S, μV/K	dS/dT, nV/K²	T, K	E, μV	S, μV/K	dS/dT, nV/K²
210	6370.39	50.773	141.0	245	8230.04	55.397	124.7
211	6421.23	50.914	140.4	246	8285.50	55.521	124.4
212	6472.22	51.054	139.9	247	8341.08	55.645	124.1
213	6523.34	51.193	139.3	248	8396.79	55.769	123.8
214	6574.60	51.332	138.8	249	8452.62	55.893	123.6
215	6626.01	51.471	138.2	250	8508.57	56.017	123.3
216	6677.55	51.609	137.7	251	8564.65	56.140	123.0
217	6729.22	51.746	137.1	252	8620.85	56.262	122.6
218	6781.04	51.883	136.6	253	8677.18	56.385	122.3
219	6832.99	52.019	136.0	254	8733.62	56.507	122.0
220	6885.08	52.155	135.5	255	8790.19	56.629	121.6
221	6937.30	52.290	135.0	256	8846.88	56.750	121.2
222	6989.66	52.425	134.5	257	8903.69	56.871	120.7
223	7042.15	52.559	134.0	258	8960.62	56.992	120.2
224	7094.78	52.693	133.4	259	9017.67	57.112	119.7
225	7147.54	52.826	132.9	260	9074.84	57.231	119.0
226	7200.43	52.959	132.4	261	9132.13	57.350	118.2
227	7253.45	53.091	132.0	262	9189.54	57.467	117.3
228	7306.61	53.223	131.5	263	9247.07	57.584	116.3
229	7359.90	53.354	131.0	264	9304.71	57.700	115.1
230	7413.32	53.485	130.5	265	9362.47	57.814	113.7
231	7466.87	53.615	130.1	266	9420.34	57.927	112.1
232	7520.55	53.745	129.6	267	9478.32	58.039	110.3
233	7574.36	53.874	129.2	268	9536.42	58.148	108.2
234	7628.30	54.003	128.8	269	9594.62	58.255	105.7
235	7682.36	54.132	128.3	270	9652.93	58.359	102.8
236	7736.56	54.260	127.9	271	9711.34	58.460	99.6
237	7790.88	54.388	127.5	272	9769.85	58.558	95.8
238	7845.34	54.515	127.2	273	9828.45	58.652	91.5
239	7899.91	54.642	126.8				
240	7954.62	54.769	126.4				
241	8009.45	54.895	126.1				
242	8064.41	55.021	125.7				
243	8119.49	55.146	125.4				
244	8174.70	55.272	125.1				

TABLE 11.2—*Type T thermocouple: thermoelectric voltage, E(T), Seebeck coefficient, S(T), and derivative of the Seebeck coefficient, dS/dT.*

T, K	E, μV	S, μV/K	dS/dT, nV/K²	T, K	E, μV	S, μV/K	dS/dT, nV/K²
				35	170.13	9.147	224.9
				36	179.39	9.370	222.0
				37	188.87	9.591	219.1
3	0.91	0.950	391.7	38	198.57	9.808	216.0
4	2.05	1.325	359.9	39	208.48	10.023	212.9
5	3.55	1.671	333.6	40	218.61	10.234	209.6
6	5.39	1.994	312.1	41	228.95	10.442	206.4
7	7.53	2.297	294.6	42	239.49	10.647	203.1
8	9.98	2.584	280.7	43	250.24	10.848	199.8
9	12.70	2.859	269.6	44	261.19	11.046	196.5
10	15.69	3.124	261.1	45	272.33	11.241	193.3
11	18.94	3.382	254.7	46	283.67	11.433	190.0
12	22.45	3.634	249.9	47	295.20	11.621	186.9
13	26.21	3.882	246.5	48	306.91	11.807	183.8
14	30.22	4.128	244.2	49	318.81	11.989	180.8
15	34.47	4.371	242.8	50	330.89	12.168	177.9
16	38.96	4.614	242.0	51	343.15	12.345	175.0
17	43.69	4.855	241.7	52	355.58	12.518	172.3
18	48.67	5.097	241.7	53	368.18	12.689	169.7
19	53.89	5.339	241.9	54	380.96	12.858	167.2
20	59.35	5.581	242.2	55	393.90	13.024	164.8
21	65.05	5.823	242.4	56	407.00	13.187	162.5
22	70.99	6.066	242.6	57	420.27	13.349	160.3
23	77.18	6.308	242.6	58	433.70	13.508	158.3
24	83.61	6.551	242.4	59	447.29	13.665	156.4
25	90.28	6.793	242.0	60	461.03	13.821	154.6
26	97.20	7.035	241.4	61	474.93	13.975	152.9
27	104.35	7.276	240.5	62	488.98	14.127	151.3
28	111.75	7.516	239.4	63	503.18	14.277	149.8
29	119.38	7.754	238.0	64	517.53	14.426	148.4
30	127.26	7.992	236.3	65	532.03	14.574	147.2
31	135.37	8.227	234.5	66	546.68	14.721	146.0
32	143.71	8.461	232.4	67	561.47	14.866	144.9
33	152.29	8.692	230.0	68	576.41	15.010	143.9
34	161.09	8.921	227.5	69	591.49	15.154	143.0

TABLE 11.2—*Type T thermocouple: thermoelectric voltage, E(T), Seebeck coefficient, S(T), and derivative of the Seebeck coefficient, dS/dT (continued).*

T, K	E, μV	S, μV/K	dS/dT, nV/K²	T, K	E, μV	S, μV/K	dS/dT, nV/K²
70	606.72	15.296	142.1	105	1225.79	20.013	129.5
71	622.09	15.438	141.4	106	1245.86	20.142	129.3
72	637.59	15.579	140.7	107	1266.07	20.271	129.0
73	653.24	15.720	140.0	108	1286.41	20.400	128.7
74	669.03	15.859	139.4	109	1306.87	20.529	128.4
75	684.96	15.998	138.9	110	1327.46	20.657	128.2
76	701.03	16.137	138.3	111	1348.18	20.785	127.9
77	717.24	16.275	137.9	112	1369.03	20.913	127.7
78	733.58	16.413	137.4	113	1390.01	21.040	127.4
79	750.06	16.550	137.0	114	1411.11	21.168	127.2
80	766.68	16.687	136.7	115	1432.35	21.295	127.0
81	783.43	16.823	136.3	116	1453.70	21.422	126.7
82	800.33	16.959	136.0	117	1475.19	21.548	126.5
83	817.35	17.095	135.7	118	1496.80	21.675	126.3
84	834.52	17.231	135.4	119	1518.54	21.801	126.1
85	851.82	17.366	135.1	120	1540.40	21.927	125.9
86	869.25	17.501	134.8	121	1562.39	22.053	125.8
87	886.82	17.636	134.5	122	1584.51	22.179	125.6
88	904.52	17.770	134.2	123	1606.75	22.304	125.4
89	922.36	17.904	134.0	124	1629.12	22.429	125.3
90	940.33	18.038	133.7	125	1651.61	22.555	125.1
91	958.43	18.172	133.4	126	1674.23	22.680	125.0
92	976.67	18.305	133.2	127	1696.97	22.804	124.8
93	995.04	18.438	132.9	128	1719.83	22.929	124.7
94	1013.55	18.571	132.6	129	1742.83	23.054	124.6
95	1032.18	18.703	132.4	130	1765.94	23.178	124.4
96	1050.95	18.835	132.1	131	1789.18	23.303	124.3
97	1069.85	18.967	131.8	132	1812.55	23.427	124.2
98	1088.89	19.099	131.5	133	1836.04	23.551	124.1
99	1108.05	19.230	131.2	134	1859.65	23.675	124.0
100	1127.35	19.361	131.0	135	1883.39	23.799	123.8
101	1146.78	19.492	130.7	136	1907.25	23.923	123.7
102	1166.33	19.623	130.4	137	1931.23	24.047	123.6
103	1186.02	19.753	130.1	138	1955.34	24.170	123.5
104	1205.84	19.883	129.8	139	1979.57	24.294	123.4

TABLE 11.2—*Type T thermocouple: thermoelectric voltage, E(T), Seebeck coefficient, S(T), and derivative of the Seebeck coefficient, dS/dT (continued).*

T, K	E, μV	S, μV/K	dS/dT, nV/K²	T, K	E, μV	S, μV/K	dS/dT, nV/K²
140	2003.93	24.417	123.2	175	2932.71	28.608	115.2
141	2028.41	24.540	123.1	176	2961.38	28.723	115.0
142	2053.01	24.663	123.0	177	2990.16	28.838	114.7
143	2077.73	24.786	122.8	178	3019.05	28.953	114.4
144	2102.58	24.909	122.7	179	3048.06	29.067	114.2
145	2127.55	25.031	122.6	180	3077.19	29.181	113.9
146	2152.64	25.154	122.4	181	3106.42	29.295	113.7
147	2177.86	25.276	122.2	182	3135.78	29.409	113.4
148	2203.20	25.398	122.1	183	3165.24	29.522	113.2
149	2228.65	25.520	121.9	184	3194.82	29.635	113.0
150	2254.24	25.642	121.7	185	3224.51	29.748	112.8
151	2279.94	25.764	121.5	186	3254.32	29.860	112.5
152	2305.76	25.885	121.3	187	3284.23	29.973	112.3
153	2331.71	26.006	121.1	188	3314.26	30.085	112.1
154	2357.78	26.127	120.9	189	3344.40	30.197	111.9
155	2383.96	26.248	120.6	190	3374.66	30.309	111.7
156	2410.27	26.369	120.4	191	3405.02	30.421	111.5
157	2436.70	26.489	120.2	192	3435.50	30.532	111.3
158	2463.25	26.609	119.9	193	3466.08	30.643	111.1
159	2489.92	26.729	119.7	194	3496.78	30.754	110.9
160	2516.71	26.848	119.4	195	3527.59	30.865	110.8
161	2543.61	26.968	119.1	196	3558.51	30.976	110.6
162	2570.64	27.087	118.9	197	3589.54	31.086	110.4
163	2597.79	27.205	118.6	198	3620.69	31.197	110.2
164	2625.05	27.324	118.3	199	3651.94	31.307	110.0
165	2652.44	27.442	118.0	200	3683.30	31.417	109.8
166	2679.94	27.560	117.8	201	3714.77	31.526	109.6
167	2707.55	27.677	117.5	202	3746.35	31.636	109.4
168	2735.29	27.795	117.2	203	3778.04	31.745	109.2
169	2763.14	27.912	116.9	204	3809.84	31.854	109.0
170	2791.11	28.029	116.6	205	3841.75	31.963	108.7
171	2819.20	28.145	116.3	206	3873.77	32.072	108.5
172	2847.40	28.261	116.1	207	3905.89	32.180	108.3
173	2875.72	28.377	115.8	208	3938.13	32.288	108.0
174	2904.16	28.493	115.5	209	3970.47	32.396	107.8

TABLE 11.2—*Type T thermocouple: thermoelectric voltage, E(T), Seebeck coefficient, S(T), and derivative of the Seebeck coefficient, dS/dT (continued).*

T, K	E, μV	S, μV/K	dS/dT, nV/K²	T, K	E, μV	S, μV/K	dS/dT, nV/K²
210	4002.92	32.504	107.5	245	5204.29	36.093	99.0
211	4035.48	32.611	107.3	246	5240.44	36.192	98.9
212	4068.14	32.718	107.0	247	5276.68	36.290	98.8
213	4100.91	32.825	106.7	248	5313.02	36.389	98.7
214	4133.79	32.932	106.4	249	5349.45	36.488	98.6
215	4166.77	33.038	106.1	250	5385.99	36.586	98.5
216	4199.87	33.144	105.8	251	5422.63	36.685	98.3
217	4233.06	33.249	105.5	252	5459.36	36.783	98.1
218	4266.36	33.355	105.2	253	5496.19	36.881	97.9
219	4299.77	33.460	104.8	254	5533.12	36.979	97.6
220	4333.28	33.564	104.5	255	5570.15	37.076	97.3
221	4366.90	33.669	104.2	256	5607.28	37.173	97.0
222	4400.62	33.773	103.9	257	5644.50	37.270	96.6
223	4434.45	33.877	103.6	258	5681.82	37.366	96.1
224	4468.37	33.980	103.2	259	5719.23	37.462	95.6
225	4502.41	34.083	102.9	260	5756.74	37.558	95.0
226	4536.54	34.186	102.6	261	5794.34	37.652	94.3
227	4570.78	34.288	102.3	262	5832.04	37.746	93.6
228	4605.12	34.390	102.0	263	5869.84	37.839	92.9
229	4639.56	34.492	101.7	264	5907.72	37.932	92.1
230	4674.10	34.594	101.4	265	5945.70	38.024	91.3
231	4708.74	34.695	101.2	266	5983.77	38.115	90.5
232	4743.49	34.796	100.9	267	6021.93	38.205	89.8
233	4778.34	34.897	100.7	268	6060.18	38.294	89.1
234	4813.28	34.997	100.4	269	6098.52	38.383	88.5
235	4848.33	35.098	100.2	270	6136.94	38.471	88.0
236	4883.48	35.198	100.0	271	6175.46	38.559	87.8
237	4918.73	35.298	99.9	272	6214.06	38.647	87.9
238	4954.07	35.398	99.7	273	6252.75	38.735	88.3
239	4989.52	35.497	99.6				
240	5025.07	35.597	99.4				
241	5060.72	35.696	99.3				
242	5096.46	35.795	99.2				
243	5132.31	35.895	99.1				
244	5168.25	35.994	99.0				

TABLE 11.3—*Type K thermocouple: thermoelectric voltage, E(T), Seebeck coefficient, S(T), and derivative of the Seebeck coefficient, dS/dT.*

T, K	E, μV	S, μV/K	dS/dT, nV/K²	T, K	E, μV	S, μV/K	dS/dT, nV/K²
				35	128.93	7.509	221.5
				36	136.55	7.730	220.7
				37	144.39	7.950	220.0
3	1.40	0.710	167.9	38	152.45	8.170	219.2
4	2.20	0.881	174.0	39	160.73	8.388	218.3
5	3.17	1.057	179.6	40	169.23	8.606	217.4
6	4.31	1.240	184.7	41	177.94	8.823	216.5
7	5.65	1.427	189.5	42	186.87	9.039	215.5
8	7.17	1.618	193.8	43	196.02	9.254	214.5
9	8.89	1.814	197.8	44	205.38	9.468	213.6
10	10.80	2.014	201.4	45	214.96	9.681	212.5
11	12.91	2.217	204.7	46	224.75	9.893	211.5
12	15.23	2.423	207.6	47	234.74	10.104	210.5
13	17.76	2.632	210.3	48	244.95	10.314	209.4
14	20.50	2.844	212.7	49	255.37	10.523	208.4
15	23.45	3.057	214.8	50	266.00	10.731	207.3
16	26.62	3.273	216.7	51	276.83	10.938	206.3
17	30.00	3.491	218.4	52	287.87	11.144	205.2
18	33.60	3.710	219.8	53	299.12	11.348	204.2
19	37.42	3.930	221.0	54	310.57	11.552	203.1
20	41.46	4.152	222.1	55	322.22	11.755	202.1
21	45.72	4.374	222.9	56	334.08	11.956	201.0
22	50.21	4.598	223.6	57	346.14	12.157	200.0
23	54.92	4.822	224.1	58	358.39	12.356	198.9
24	59.85	5.046	224.5	59	370.85	12.554	197.9
25	65.01	5.270	224.7	60	383.50	12.752	196.9
26	70.39	5.495	224.8	61	396.35	12.948	195.9
27	76.00	5.720	224.8	62	409.40	13.144	194.9
28	81.83	5.945	224.7	63	422.64	13.338	193.9
29	87.89	6.169	224.5	64	436.07	13.532	193.0
30	94.17	6.394	224.2	65	449.70	13.724	192.0
31	100.68	6.618	223.8	66	463.52	13.916	191.1
32	107.41	6.841	223.3	67	477.53	14.106	190.1
33	114.36	7.064	222.8	68	491.73	14.296	189.2
34	121.53	7.287	222.1	69	506.12	14.485	188.3

TABLE 11.3—*Type K thermocouple: thermoelectric voltage, E(T), Seebeck coefficient, S(T), and derivative of the Seebeck coefficient, dS/dT (continued).*

T, K	E, μV	S, μV/K	dS/dT, nV/K²	T, K	E, μV	S, μV/K	dS/dT, nV/K²
70	520.70	14.673	187.4	105	1143.42	20.768	162.6
71	535.47	14.859	186.5	106	1164.26	20.930	162.0
72	550.42	15.046	185.7	107	1185.27	21.092	161.4
73	565.56	15.231	184.8	108	1206.45	21.253	160.8
74	580.88	15.415	184.0	109	1227.78	21.413	160.2
75	596.39	15.599	183.1	110	1249.27	21.573	159.6
76	612.08	15.782	182.3	111	1270.93	21.732	159.1
77	627.95	15.963	181.5	112	1292.74	21.891	158.5
78	644.01	16.145	180.7	113	1314.71	22.049	157.9
79	660.24	16.325	179.9	114	1336.84	22.207	157.3
80	676.66	16.504	179.2	115	1359.12	22.364	156.7
81	693.25	16.683	178.4	116	1381.56	22.520	156.2
82	710.02	16.861	177.7	117	1404.16	22.676	155.6
83	726.97	17.039	176.9	118	1426.92	22.832	155.0
84	744.10	17.215	176.2	119	1449.83	22.986	154.4
85	761.40	17.391	175.5	120	1472.89	23.140	153.9
86	778.88	17.566	174.8	121	1496.11	23.294	153.3
87	796.53	17.740	174.1	122	1519.48	23.447	152.7
88	814.36	17.914	173.4	123	1543.00	23.599	152.1
89	832.36	18.087	172.7	124	1566.68	23.751	151.6
90	850.54	18.260	172.0	125	1590.50	23.903	151.0
91	868.88	18.431	171.3	126	1614.48	24.053	150.4
92	887.40	18.602	170.7	127	1638.61	24.203	149.8
93	906.09	18.773	170.0	128	1662.89	24.353	149.3
94	924.94	18.942	169.4	129	1687.31	24.502	148.7
95	943.97	19.111	168.7	130	1711.89	24.650	148.1
96	963.17	19.280	168.1	131	1736.62	24.798	147.5
97	982.53	19.448	167.5	132	1761.49	24.945	147.0
98	1002.06	19.615	166.8	133	1786.51	25.092	146.4
99	1021.76	19.781	166.2	134	1811.67	25.238	145.8
100	1041.62	19.947	165.6	135	1836.98	25.384	145.2
101	1061.65	20.112	165.0	136	1862.44	25.529	144.7
102	1081.85	20.277	164.4	137	1888.04	25.673	144.1
103	1102.21	20.441	163.8	138	1913.78	25.817	143.5
104	1122.73	20.605	163.2	139	1939.67	25.960	142.9

TABLE 11.3—*Type K thermocouple: thermoelectric voltage, E(T), Seebeck coefficient, S(T), and derivative of the Seebeck coefficient, dS/dT (continued).*

T, K	E, μV	S, μV/K	dS/dT, nV/K²	T, K	E, μV	S, μV/K	dS/dT, nV/K²
140	1965.70	26.103	142.3	175	2962.24	30.719	121.2
141	1991.88	26.245	141.7	176	2993.02	30.840	120.6
142	2018.19	26.386	141.2	177	3023.92	30.960	119.9
143	2044.65	26.527	140.6	178	3054.94	31.080	119.3
144	2071.25	26.667	140.0	179	3086.08	31.199	118.7
145	2097.98	26.807	139.4	180	3117.34	31.317	118.0
146	2124.86	26.946	138.8	181	3148.71	31.435	117.4
147	2151.88	27.085	138.2	182	3180.21	31.552	116.8
148	2179.03	27.223	137.6	183	3211.82	31.669	116.1
149	2206.32	27.360	137.0	184	3243.55	31.784	115.5
150	2233.75	27.497	136.4	185	3275.39	31.900	114.8
151	2261.31	27.633	135.9	186	3307.34	32.014	114.2
152	2289.02	27.768	135.3	187	3339.41	32.128	113.5
153	2316.85	27.903	134.7	188	3371.60	32.241	112.9
154	2344.82	28.038	134.1	189	3403.90	32.354	112.2
155	2372.93	28.171	133.5	190	3436.31	32.466	111.6
156	2401.16	28.305	132.9	191	3468.83	32.577	110.9
157	2429.54	28.437	132.3	192	3501.46	32.687	110.3
158	2458.04	28.569	131.7	193	3534.20	32.797	109.6
159	2486.67	28.700	131.1	194	3567.05	32.907	109.0
160	2515.44	28.831	130.5	195	3600.02	33.015	108.3
161	2544.34	28.961	129.9	196	3633.09	33.123	107.7
162	2573.36	29.091	129.2	197	3666.26	33.231	107.0
163	2602.52	29.220	128.6	198	3699.55	33.337	106.3
164	2631.80	29.348	128.0	199	3732.94	33.443	105.7
165	2661.21	29.476	127.4	200	3766.43	33.549	105.0
166	2690.75	29.603	126.8	201	3800.03	33.653	104.4
167	2720.42	29.730	126.2	202	3833.74	33.757	103.7
168	2750.21	29.855	125.6	203	3867.55	33.861	103.0
169	2780.13	29.981	124.9	204	3901.46	33.964	102.4
170	2810.17	30.105	124.3	205	3935.48	34.066	101.7
171	2840.34	30.229	123.7	206	3969.59	34.167	101.1
172	2870.63	30.353	123.1	207	4003.81	34.268	100.4
173	2901.05	30.475	122.5	208	4038.13	34.368	99.7
174	2931.58	30.598	121.8	209	4072.54	34.467	99.1

TABLE 11.3—*Type K thermocouple: thermoelectric voltage, E(T), Seebeck coefficient, S(T), and derivative of the Seebeck coefficient, dS/dT (continued).*

T, K	E, µV	S, µV/K	dS/dT, nV/K²	T, K	E, µV	S, µV/K	dS/dT, nV/K²
210	4107.06	34.566	98.4	245	5372.59	37.624	76.6
211	4141.68	34.664	97.8	246	5410.25	37.700	76.0
212	4176.39	34.761	97.1	247	5447.99	37.776	75.4
213	4211.20	34.858	96.5	248	5485.80	37.851	74.7
214	4246.11	34.954	95.8	249	5523.69	37.925	74.1
215	4281.11	35.050	95.2	250	5561.65	37.999	73.4
216	4316.20	35.145	94.5	251	5599.69	38.072	72.7
217	4351.40	35.239	93.9	252	5637.80	38.144	72.0
218	4386.68	35.332	93.2	253	5675.98	38.216	71.3
219	4422.06	35.425	92.6	254	5714.23	38.287	70.5
220	4457.53	35.518	91.9	255	5752.55	38.357	69.7
221	4493.10	35.609	91.3	256	5790.94	38.426	68.9
222	4528.75	35.700	90.7	257	5829.40	38.495	68.1
223	4564.50	35.791	90.0	258	5867.93	38.562	67.3
224	4600.33	35.880	89.4	259	5906.52	38.629	66.4
225	4636.26	35.969	88.8	260	5945.19	38.695	65.4
226	4672.27	36.058	88.2	261	5983.91	38.760	64.4
227	4708.37	36.146	87.6	262	6022.71	38.824	63.4
228	4744.56	36.233	86.9	263	6061.56	38.887	62.3
229	4780.84	36.320	86.3	264	6100.48	38.948	61.2
230	4817.20	36.406	85.7	265	6139.46	39.009	60.0
231	4853.65	36.491	85.1	266	6178.50	39.068	58.7
232	4890.18	36.576	84.5	267	6217.59	39.126	57.4
233	4926.80	36.660	83.9	268	6256.75	39.183	56.0
234	4963.50	36.744	83.3	269	6295.96	39.238	54.5
235	5000.29	36.827	82.7	270	6335.23	39.292	52.9
236	5037.16	36.909	82.1	271	6374.54	39.344	51.2
237	5074.11	36.991	81.5	272	6413.91	39.395	49.4
238	5111.14	37.072	80.9	273	6453.33	39.443	47.5
239	5148.25	37.153	80.3				
240	5185.44	37.233	79.7				
241	5222.72	37.312	79.1				
242	5260.07	37.391	78.5				
243	5297.50	37.469	77.9				
244	5335.01	37.547	77.3				

TABLE 11.4—*KP or EP versus gold-0.07 atomic percent iron thermocouple: thermoelectric voltage, Seebeck coefficient, and derivative of the Seebeck coefficient.*

T, K	E, μV	S, μV/K	dS/dT, nV/K²	T, K	E, μV	S, μV/K	dS/dT, nV/K²
				35	545.40	16.462	-9.5
				36	561.86	16.455	-5.0
				37	578.31	16.452	-0.6
3	28.02	11.372	1153.3	38	594.76	16.454	3.6
4	39.94	12.438	981.2	39	611.22	16.459	7.6
5	52.84	13.341	829.5	40	627.68	16.469	11.3
6	66.58	14.103	696.1	41	644.16	16.482	14.9
7	81.01	14.739	579.2	42	660.65	16.499	18.2
8	96.02	15.266	477.2	43	677.16	16.518	21.3
9	111.51	15.698	388.5	44	693.69	16.541	24.1
10	127.39	16.047	311.9	45	710.24	16.566	26.7
11	143.58	16.325	245.9	46	726.82	16.594	29.0
12	160.02	16.542	189.5	47	743.43	16.624	31.2
13	176.65	16.707	141.6	48	760.07	16.657	33.1
14	193.42	16.828	101.2	49	776.74	16.691	34.8
15	210.29	16.911	67.4	50	793.45	16.726	36.3
16	227.23	16.964	39.5	51	810.20	16.763	37.6
17	244.21	16.992	16.8	52	826.98	16.801	38.7
18	261.21	17.000	-1.5	53	843.80	16.840	39.7
19	278.20	16.991	-15.8	54	860.66	16.881	40.6
20	295.18	16.969	-26.7	55	877.56	16.921	41.3
21	312.14	16.938	-34.7	56	894.50	16.963	41.9
22	329.06	16.900	-40.3	57	911.49	17.005	42.4
23	345.94	16.858	-43.7	58	928.51	17.048	42.8
24	362.77	16.814	-45.3	59	945.58	17.091	43.1
25	379.56	16.768	-45.5	60	962.70	17.134	43.3
26	396.31	16.723	-44.4	61	979.85	17.177	43.5
27	413.01	16.680	-42.3	62	997.05	17.221	43.6
28	429.67	16.639	-39.4	63	1014.29	17.264	43.7
29	446.29	16.601	-36.0	64	1031.58	17.308	43.7
30	462.87	16.567	-32.0	65	1048.91	17.352	43.7
31	479.43	16.537	-27.8	66	1066.28	17.395	43.6
32	495.95	16.512	-23.3	67	1083.70	17.439	43.6
33	512.45	16.491	-18.7	68	1101.16	17.483	43.5
34	528.93	16.474	-14.1	69	1118.66	17.526	43.4

TABLE 11.4—*KP or EP versus gold-0.07 atomic percent iron thermocouple: thermoelectric voltage, Seebeck coefficient, and derivative of the Seebeck coefficient (continued).*

T,K	E, μV	S, μV/K	dS/dT, nV/K²	T,K	E, μV	S, μV/K	dS/dT, nV/K²
70	1136.21	17.569	43.3	105	1776.71	18.995	36.9
71	1153.80	17.613	43.2	106	1795.73	19.032	36.6
72	1171.44	17.656	43.1	107	1814.78	19.068	36.3
73	1189.12	17.699	43.0	108	1833.86	19.104	36.0
74	1206.84	17.742	42.8	109	1852.99	19.140	35.6
75	1224.60	17.785	42.7	110	1872.14	19.176	35.3
76	1242.40	17.827	42.6	111	1891.34	19.211	35.0
77	1260.25	17.870	42.5	112	1910.57	19.246	34.6
78	1278.14	17.912	42.3	113	1929.83	19.280	34.3
79	1296.08	17.954	42.2	114	1949.13	19.314	33.9
80	1314.05	17.997	42.1	115	1968.46	19.348	33.6
81	1332.07	18.039	42.0	116	1987.82	19.381	33.2
82	1350.13	18.081	41.8	117	2007.22	19.414	32.9
83	1368.23	18.122	41.7	118	2026.65	19.447	32.6
84	1386.37	18.164	41.6	119	2046.11	19.480	32.2
85	1404.56	18.205	41.4	120	2065.61	19.512	31.9
86	1422.79	18.247	41.3	121	2085.14	19.543	31.6
87	1441.05	18.288	41.1	122	2104.70	19.575	31.3
88	1459.36	18.329	41.0	123	2124.29	19.606	31.0
89	1477.71	18.370	40.8	124	2143.91	19.637	30.7
90	1496.10	18.411	40.6	125	2163.56	19.667	30.4
91	1514.53	18.451	40.5	126	2183.24	19.697	30.1
92	1533.00	18.492	40.3	127	2202.96	19.727	29.8
93	1551.52	18.532	40.1	128	2222.70	19.757	29.5
94	1570.07	18.572	39.9	129	2242.47	19.786	29.2
95	1588.66	18.611	39.6	130	2262.27	19.815	29.0
96	1607.29	18.651	39.4	131	2282.10	19.844	28.7
97	1625.96	18.690	39.2	132	2301.96	19.873	28.5
98	1644.67	18.729	38.9	133	2321.85	19.901	28.2
99	1663.42	18.768	38.7	134	2341.76	19.929	28.0
100	1682.21	18.807	38.4	135	2361.70	19.957	27.8
101	1701.03	18.845	38.1	136	2381.68	19.985	27.5
102	1719.90	18.883	37.8	137	2401.67	20.012	27.3
103	1738.80	18.921	37.5	138	2421.70	20.040	27.1
104	1757.74	18.958	37.2	139	2441.75	20.067	26.9

TABLE 11.4—*KP or EP versus gold-0.07 atomic percent iron thermocouple: thermoelectric voltage, Seebeck coefficient, and derivative of the Seebeck coefficient (continued).*

T,K	E, μV	S, μV/K	dS/dT, nV/K²	T,K	E, μV	S, μV/K	dS/dT, nV/K²
140	2461.83	20.093	26.7	175	3180.19	20.919	20.4
141	2481.94	20.120	26.5	176	3201.12	20.939	20.3
142	2502.07	20.146	26.3	177	3222.07	20.960	20.1
143	2522.23	20.173	26.2	178	3243.04	20.980	19.9
144	2542.42	20.199	26.0	179	3264.03	20.999	19.7
145	2562.63	20.225	25.8	180	3285.03	21.019	19.6
146	2582.87	20.250	25.6	181	3306.06	21.039	19.4
147	2603.13	20.276	25.4	182	3327.11	21.058	19.3
148	2623.42	20.301	25.3	183	3348.18	21.077	19.1
149	2643.73	20.326	25.1	184	3369.27	21.096	19.0
150	2664.07	20.351	24.9	185	3390.37	21.115	18.8
151	2684.44	20.376	24.8	186	3411.50	21.134	18.7
152	2704.82	20.401	24.6	187	3432.64	21.152	18.6
153	2725.24	20.425	24.4	188	3453.80	21.171	18.4
154	2745.67	20.450	24.2	189	3474.98	21.189	18.3
155	2766.14	20.474	24.1	190	3496.18	21.207	18.2
156	2786.62	20.498	23.9	191	3517.40	21.226	18.1
157	2807.13	20.522	23.7	192	3538.63	21.244	18.0
158	2827.67	20.545	23.5	193	3559.88	21.261	17.8
159	2848.22	20.569	23.4	194	3581.15	21.279	17.7
160	2868.80	20.592	23.2	195	3602.44	21.297	17.6
161	2889.41	20.615	23.0	196	3623.75	21.315	17.5
162	2910.03	20.638	22.8	197	3645.07	21.332	17.4
163	2930.68	20.661	22.6	198	3666.41	21.349	17.3
164	2951.35	20.683	22.5	199	3687.77	21.367	17.2
165	2972.05	20.706	22.3	200	3709.14	21.384	17.1
166	2992.77	20.728	22.1	201	3730.54	21.401	17.0
167	3013.50	20.750	21.9	202	3751.95	21.418	16.9
168	3034.27	20.772	21.7	203	3773.37	21.435	16.8
169	3055.05	20.793	21.5	204	3794.82	21.452	16.7
170	3075.85	20.815	21.3	205	3816.28	21.468	16.6
171	3096.68	20.836	21.2	206	3837.75	21.485	16.5
172	3117.52	20.857	21.0	207	3859.25	21.501	16.4
173	3138.39	20.878	20.8	208	3880.76	21.518	16.3
174	3159.28	20.899	20.6	209	3902.28	21.534	16.1

TABLE 11.4—*KP or EP versus gold-0.07 atomic percent iron thermocouple: thermoelectric voltage, Seebeck coefficient, and derivative of the Seebeck coefficient (continued).*

T,K	E, μV	S, μV/K	dS/dT, nV/K²	T,K	E, μV	S, μV/K	dS/dT, nV/K²
210	3923.82	21.550	16.0	245	4686.39	21.981	9.3
211	3945.38	21.566	15.8	246	4708.38	21.990	9.3
212	3966.95	21.582	15.7	247	4730.37	21.999	9.3
213	3988.54	21.550	15.5	248	4752.38	22.009	9.4
214	4010.15	21.613	15.3	249	4774.39	22.018	9.5
215	4031.77	21.628	15.2	250	4796.41	22.028	9.6
216	4053.40	21.643	15.0	251	4818.45	22.037	9.8
217	4075.06	21.658	14.8	252	4840.49	22.047	10.0
218	4096.72	21.672	14.6	253	4862.54	22.057	10.1
219	4118.40	21.687	14.3	254	4884.60	22.068	10.3
220	4140.09	21.701	14.1	255	4906.68	22.078	10.5
221	4161.80	21.715	13.9	256	4928.76	22.089	10.7
222	4183.52	21.729	13.6	257	4950.85	22.099	10.9
223	4205.26	21.742	13.4	258	4972.96	22.110	11.1
224	4227.01	21.756	13.1	259	4995.07	22.122	11.3
225	4248.77	21.769	12.9	260	5017.20	22.133	11.4
226	4270.55	21.781	12.6	261	5039.34	22.145	11.6
227	4292.33	21.794	12.3	262	5061.49	22.156	11.6
228	4314.13	21.806	12.1	263	5083.65	22.168	11.7
229	4335.95	21.818	11.8	264	5105.83	22.179	11.6
230	4357.77	21.830	11.6	265	5128.01	22.191	11.5
231	4379.61	21.841	11.3	266	5150.21	22.203	11.4
232	4401.45	21.852	11.1	267	5172.42	22.214	11.1
233	4423.31	21.863	10.8	268	5194.64	22.225	10.8
234	4445.18	21.874	10.6	269	5216.87	22.235	10.3
235	4467.06	21.885	10.4	270	5239.11	22.245	9.7
236	4488.95	21.895	10.2	271	5261.36	22.255	9.1
237	4510.85	21.905	10.0	272	5283.62	22.263	8.3
238	4532.76	21.915	9.8	273	5305.88	22.271	7.4
239	4554.68	21.924	9.7	274	5328.16	22.278	6.4
240	4576.61	21.934	9.5	275	5350.44	22.284	5.3
241	4598.55	21.944	9.4	276	5372.73	22.289	4.1
242	4620.49	21.953	9.3	277	5395.02	22.292	2.9
243	4642.45	21.962	9.3	278	5417.31	22.295	1.5
244	4664.42	21.971	9.3	279	5439.61	22.295	0.2

11.4 References

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Chapter 12—Temperature Measurement Uncertainty

12.1 The General Problem

Every measurement has associated with it an error. This is a real certain value which exists but cannot be known. It is different from the uncertainty of the measurement, which reflects only our lack of understanding of the error. This chapter deals primarily with the uncertainty.

An error may be caused by a mistake or by a broken instrument as well as by the usual variation in parameters affecting the temperature measurement. A *mistake,* like connecting a Type E thermocouple to a Type K instrument or using a broken instrument, in which perhaps a reference diode has failed, is regrettable but cannot be analyzed by the mathematics of measurement errors. Hence, these events are not treated herein.

Aside from mistakes and broken instruments, common opportunities for measurement error are apparent in a simple example: If a pot of water is to be heated to 57.2°C (135°F) a suitable thermometer is inserted and a reading is taken. If another reading is taken, it will not be the same unless the measuring technique is insensitive. Further checks with other thermometers, or at different points in the pot, or by an assistant will probably yield as many different answers as the number of measurements made. This variation is to be expected: it reflects the statistical uncertainty of the measurement. It may not represent a problem. If the hot water is to be used as a chemical reagent in a process which is temperature sensitive, knowledge of the temperature within a few tenths of a degree may be necessary. The error now needs to be estimates as well as its uncertainty.

As in all statistical analysis, the credibility of the analysis is enhanced by its success in predicting. When the analyst predicts a variability which is grossly different from that observed in testing, his judgment is flawed. Either his model or his analysis is wrong. Statistics do not lie, but they can mislead, either accidentally or by intent.

In the discussion which follows, no attempt will be made to teach statistics. This topic has been covered more than adequately by Benedict [*1*], Chatfield [*2*], Spiegel [*3*], Abernethy [*4*], and the ASTM Committee E11 on Statistical Techniques [*5*]. The reader who wants to apply these tools should study some of the references if he is not familiar with their use.

12.2 Tools of the Trade

The language of measurement uncertainty is largely the language of statistics, and it is often misunderstood. Statistical terms, like legal terms, are very precise in their meaning, and he who uses them carelessly does so not only at his own risk but also at that of the reader. The following terms are discussed here in the context of thermocouple measurements.

12.2.1 Average and Mean

The terms *average* and *mean* are synonymous and are defined by the equation

$$\text{average } X = \Sigma X_i/n, \text{ denoted } \overline{X}$$

where n is the number of measurements of X_i. The definition "$\overline{X} = (X\max + X\min)/2$," though commonly used in other applications, has no place in a discussion of measurement uncertainty. The symbol $\overline{X}$ is used for the average of a set of measurements; μ is the average of the total (infinite) population from which the sample is drawn.

The term *across* is introduced at this point. Like many statistical terms, an average is always taken across a specific group of data. The average across a series of readings (subset) will differ from the average across another subset, and from the average of the total population, which is seldom known. The group of data being averaged must always be defined.

12.2.2 Normal or Gaussian Distribution

The *Normal or Gaussian distribution* is defined by the formula

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}}\, e^{-[(x-\mu)^2/(2\sigma^2)]}$$

where σ is the standard deviation of the total (infinite) population. In the analysis of measurement uncertainty, this formula is seldom used directly, but it defines the dispersion that usually exists in real physical data sampled in a random manner. The careful investigator will always check the normality of his test data before applying normal statistics to it. A visual check is often sufficient, especially with the aid of probability-plot paper (See 12.3.4).

12.2.3 Standard Deviation and Variance

The *standard deviation* and *variance* of the total population are measures of the precision or scatter of normally distributed data, that is, the extent to which such data depart from the mean. The variance is the sum of the squares of the deviations of the individual measurements from the mean, divided by the degrees of freedom. The standard deviation is the square root of the variance. With a sample of real data, an estimate of the standard deviation is s defined as

$$s = \sqrt{\frac{\Sigma(X_i - \overline{X})^2}{n - 1}}$$

Obviously, the variance, s^2, is the same equation without the radical. The impact of moderately priced personal calculators on these evaluations is clear. Statistical calculations, too tedious to perform longhand, can be handled easily on such calculators.

12.2.4 Bias, Precision, and Uncertainty

Bias, precision, and *uncertainty* are the key terms for describing defects in measurement. These terms can be confusing at times because of careless use. *Precision* is the scatter, usually random, between measurements in the same set, or between an individual average and the true value of the parameter. *Bias* is the systematic difference between the individual averages of two or more sets. *Uncertainty* is a less rigorous term which tries to combine bias and precision into a single term for talking purposes. It is defined by Abernethy [*4*], as $\pm(b + t_{95}s)$, where b is the best estimate of the limit of uncorrected bias, s is the precision, and t_{95} is the 95th percentile value of the two-tailed Student t distribution. In words, it is the largest error which can reasonably be expected. An important rule to be observed is that an uncertainty statement should never be made without including: (1) bias, (2) precision, (3) degrees of freedom, and (4) confidence interval. Opportunity for confusion lies in the fact that a component of uncertainty can "move" between bias and precision depending on what uncertainty is being assessed. For example, the bias between reels of thermocouple wire becomes reel-to-reel precision when evaluating the uncertainty of K thermocouple measurements in general. The extent to which this element can be "corrected out" of the uncertainty of the smaller set depends on the extent of calibration activities. The importance of identifying the components of the uncertainty statement is evident.

Degrees of freedom (df) is a term which is used in many of the equations of uncertainty, and relates to the size of the data sample on which the calculations are based. Chatfield [*2*] defines it as the number of independent comparisons available. For example in the formula for the average there are n degrees of freedom. In the formula for standard deviation there are only $(n - 1)$, since there is only one difference between two values, one degree of freedom is lost. Similarly the constants in a regression equation each consume one degree of freedom as shown in paragraph 12.3.5.

12.2.5 Precision of the Mean

The *precision of the mean* is an important concept in temperature measurement. As the number of independent measurements of the same temperature is increased, the uncertainty of our knowledge of the true mean decreases, specifically by the square root of the number of measurements.

$$s_{\text{mean}} = \frac{s}{\sqrt{n}}$$

where n is the number of independent measurements. This can be applied to the time average, space average, production norm, or to any other set. For discussion see paragraph 12.3.3.

12.2.6 Regression Line or Least-Square Line

A *regression line* or *least-squares line* represents the equation obtained by a process which minimizes the sum of the squares of the displacements of the individual data points in a set from the curve the equation describes. The regression may be a straight line or a polynomial, exponential, or any other basic form (see Section 12.3.5).

12.3 Typical Applications

12.3.1 General Considerations

The discussions herein will be confined to Type K, because of the availability of a statistically significant quantity of data for this thermocouple type. The same statistical concepts can be applied to other types.

ASTM E 230 describes the temperature-emf characteristics of Type K wire. The "limits of error" stated in this standard are definitive, not statistical. Wire which does not conform to the stated limits is simply not Type K. Further, the limits of error are defined as referring only to new wire as delivered, and not to include the effects of insulating, sheathing, or exposure to operating conditions of the application. The statistical treatment discussed herein is, in a large part, similarly limited.

Topics to be discussed include: (1) the improvement in uncertainty which can be realized by calibration of individual thermocouples; (2) the use of the precision of the mean of several thermocouples; (3) probability plots; and (4) the use of regression analysis to separate variations due to assignable cause from random variations.

12.3.2 Wire Calibration

The Type K temperature-emf relationship, described by algorithms and tables presented in NIST Monograph 175 [*8*] and ASTM E 230, is based on empirical data developed by NIST and its predecessor NBS from experimental data on real Type K thermocouples from several sources and including several sizes of wire. In other words, these documents present statistical information believed to represent the typical Type K thermocouple. Whether or not the deviations of the individual thermocouples tested from the algorithm were distributed normally is not known. We also do not know the scatter of these data about the K-curve.

Sanders [*7*] presents observations on incoming inspection calibrations performed by a large user of 20-28 B&S gage Type K wire with "soft" insulation. A small quantity of sheathed wire was considered separately. An analysis of variance was made to assess the effect of various insulations, cable makeup, vendors, and wire gages on the precision or bias of the calibration. The only significant influence was that of wire gage. The data are shown in Table 12.1. Precision is stated as two-standard deviations.

From these data it is clear that, first, the typical wire received by this user is systematically different from the K-curve as shown in Fig. 12.1, probably because of the difference in the range of sizes tested by the NIST and this user. Thus, if he plans to use thermocouples made from this wire without further calibration, he would be advised to modify the K-curve by the bias curve of Table 12.1. Secondly, if he uses this modified curve, he can expect that such couples individually will vary from the curve by the precision shown in the table, which is substantially less than the ±2 deg permitted by ASTM E 230. If he does not correct for the bias, he can expect the true value

TABLE 12.1—*Accuracy of unsheathed thermocouples.*

Temperature °F, T	Bias °F, b	Overall Precision °F, $t_{95}s$	In-Reel Precision °F, $t_{95}s$	Uncertainty °F, U
0	0.28	±0.09	±0.08	0.37
32	0.00	±0.06	±0.06	0.06
65	−0.16	±0.18	±0.06	0.34
100	−0.14	±0.29	±0.08	0.43
150	−0.10	±0.51	±0.11	0.61
200	0.00	±0.68	±0.11	0.68
250	0.26	±0.96	±0.15	1.22
300	0.47	±0.09	±0.18	1.56
350	0.13	±1.30	±0.20	1.43
400	−0.15	±1.40	±0.24	1.55
450	−0.41	±1.48	±0.28	1.89
500	−0.91	±1.33	±0.38	2.24

NOTE—Temperature °C = 5/9 (°F-32).
Interval °C = 5/9 °F.

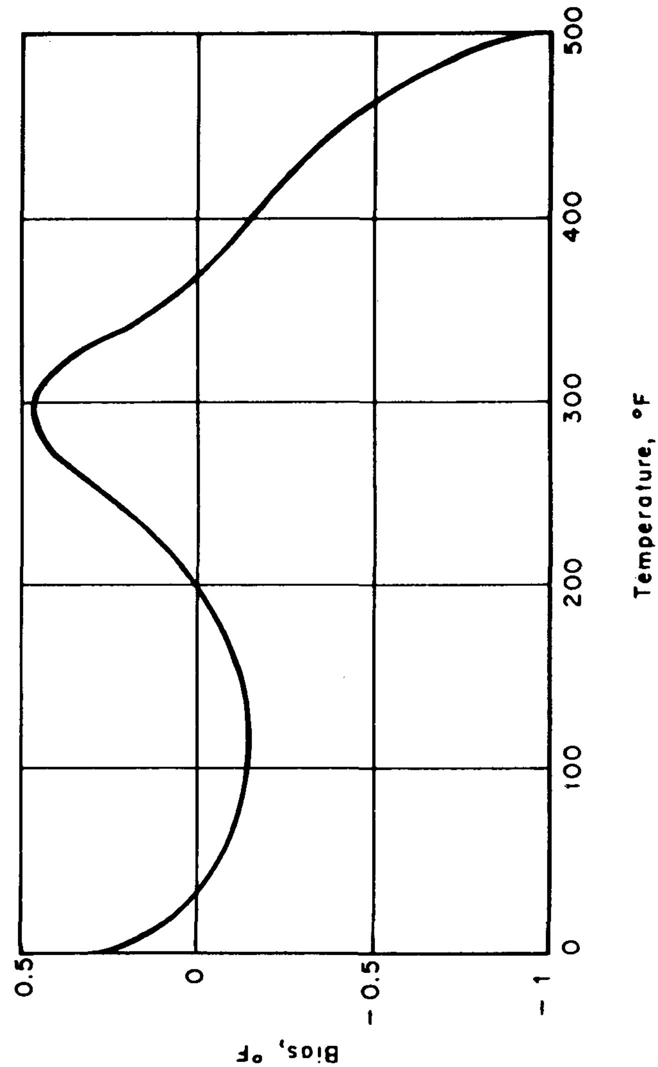

FIG. 12.1—*Bias of a typical Type K wire [temperature °C = 5/9 (°F − 32); bias °C = 5/9 °F].*

TABLE 12.2—*Accuracy of sheathed thermocouples.*

Temperature °F, T	Bias °F, b	Overall Precision °F, $t_{95}s$	In-Reel Precision °F, $t_{95}s$	Uncertainty °F, U
100	−0.13	±0.37	±0.10	0.50
150	+0.01	±0.50	±0.14	0.51
200	+0.35	±0.70	±0.30	1.05
250	+0.82	±1.12	±0.42	1.94
300	+1.09	±1.36	±0.52	2.45
350	+0.78	±1.45	±0.61	2.23
400	+0.65	±1.51	±0.68	2.16
450	+0.74	±1.57	±0.90	2.31
500	+0.69	±1.40	±0.96	2.09

NOTE—Temperature °C = 5/9 (°F − 32).
Interval °C = 5/9°F.

to lie between the bounds of total uncertainty listed in the table, which is slightly in excess of the specification.

Sanders further concludes that the reel-to-reel precision, as expected, is worse than the precision within a reel; that is, that thermocouples, whose readings are to be compared should be made, if possible, from the same reel of wire, especially if individual calibrations are not performed. If a piece of thermocouple wire is calibrated and then the junction is cut off in order to fabricate a probe, the calibration will be valid within 0.03°C (0.05°F) for that probe if the new junction is within a few centimeters (inches) of the calibration junction. If it is more than a few centimeters (inches) away, the full in-reel precision will be developed. Similar calibration data for a limited sample of sheathed wire are given in Table 12.2, for comparison only.

The material discussed in the previous table represents a large, but specific, subset of small gage Type K wire below 260°C (500°F). Similar tests on a different data subset should be expected to vary to some extent, depending upon sample and measurement differences. However, the basic conclusions should hold, that the uncertainty can be reduced by batch calibration and further reduced by specific calibrations.

Drifts in calibration with use may be observed with Type K under some operating conditions. The analysis discussed is still valid for Type K and other temperature sensors (see last paragraph of Section 12.3.5).

12.3.3 Means and Profiles

In all areas of human knowledge, iteration is one of the most respected ways to stress or reinforce an observation. If the results of an experiment are in doubt, it is repeated. It is not surprising, then, that the mean of several readings of a temperature, or of the readings of several sensors, or of the temperature-emf characteristics of a pair of alloy ingots affords more confidence than a single reading. Statistics provides the means to quantify this increase in confidence. Like all tools, the statistics must be properly used.

In the development of a turbine engine, the gas temperature at a particular axial section may be measured by one hundred or more sensors. For component efficiency studies the mean temperature at this section is a needed parameter. To assess incremental inprovement in performance after a change in configuration, the uncertainty of this temperature can be quite critical. When a single probe is used, several error components exist. First, and usually dominant, is the temperature variation in space and time at different points across the section. Another error component is the degree to which the kinetic energy of the gas stream is not converted to junction temperature (aerodynamic recovery). Others include manufacturing tolerances, conduction errors, and wire calibration. The latter is usually minimized by calibration.

If 100 thermocouples are used, the precision due to the space profile, manufacturing tolerances, and calibration are reduced by $\sqrt{n} = 10$, because of the improved precision of the mean section temperature. Now when the mean temperature before and after a change in configuration are compared, the minimum significant change in observed performance is reduced by an order of magnitude. Note that the same improvement does not apply to the individual measurements in the set.

Further information may be derived from the same data for different purposes. The performance of the engine may be affected by the uniformity of the gas temperature across the section, which is quantified by the standard deviation of the individual temperature. This will also predict the maximum existing temperature whether measured or not, which will affect the life of metal parts. A check of the normality of the data may show that a pattern exists, related to the location of the struts or airfoils.

It is important to realize the significance of the precision of the mean. It does no good to improve the precision of measurement of the mean unless the mean is the parameter of concern. For example, in calibration an array of thermocouples is frequently used to establish the degree of spatial uniformity of temperatures in a liquid bath to be used to calibrate thermocouples. The standard deviation of the measurements is a measure of uniformity, but not of uncertainty of the local bath temperatures. Specifically

$$T_i = \overline{T} \pm ts, \text{ not } \overline{T} \pm ts/\sqrt{n}$$

where

T_i = local temperature at the location of the test sensor,
$\overline{T}$ = mean of temperature measurements,
s = standard deviation of temperature measurements, and
t = Student's t.

12.3.4 Probability Paper

Paragraph 12.2.2 refers to the normality of data and the need to ensure that data are normally distributed before applying the mathematics of classical statistics. Actually, the determination of this property can directly reveal some anomalies and possible assignable causes, and lead to improved accuracy.

The normal or Gaussian distribution, plotted as error versus frequency of occurrence, yields the familiar "bell-shaped" curve. The integral of this curve, plotting error versus cumulative frequency, is an ogive. If the frequency axis of the ogive is properly warped, a special "probability paper" is created, on which normally distributed data plot as a straight line which is easily evaluated by eye as to its straightness. Figure 12.2 reproduces this probability plot, which is commerically available from several sources.

When the data are properly ranked and plotted on prob-plot paper, the nature of any existing nonnormalities is often revealed. Data from a population for which the "bell-shaped" error distribution is skewed to the left or right will plot concave upward or downward, respectively. One of the more common revelations is that the data are bimodal or polymodal. Such data will appear as a series of line segments of different slopes. This indicates that

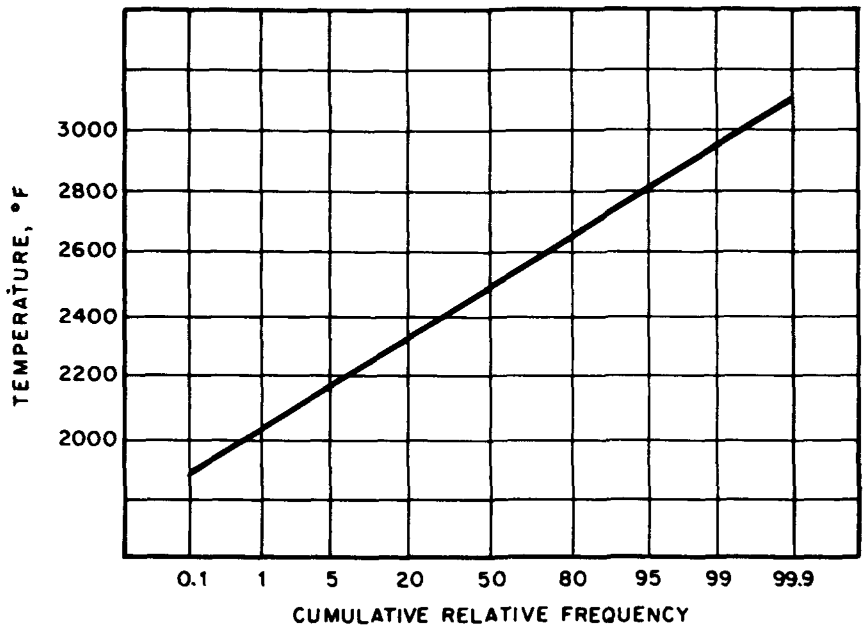

FIG. 12.2—*Typical probability plot* [°C = 5/9 (°F−32)].

the data come from more than one subset, having different standard deviations or means or both. Data which are flatter or more peaked will yield plots which are similar to polymodal.

Figure 12.3 shows a straight line of finite slope, terminated at the top by a segment of zero slope. In real data the transition may be less sharp. A possible conclusion from this plot, unless there is an *a priori* reason to expect nonnormal temperature distribution, the highest temperatures which occurred were not measured.

The plot shows hypothetical temperature readings across an engine section or a furnace. The curve reveals the mean temperature to have been 2500 deg (the 50th percentile), and there should have been 10 readings in excess of 2900 and one in excess of 3000. Perhaps these sensors were burned out (truncation). Perhaps the experimenter thought he had reason to doubt any readings as high as 2900 (editing or false outlier rejection). Or perhaps there were no thermocouples located at the hottest spots (sampling error). But the evidence is clear, the probability of existence of temperatures above 3000 is high and cannot be rejected lightly. If the data are taken from 1000 successive readings of a single thermocouple, the reasoning is the same and the conclusions equally valid in the time domain. The highest temperature need not be seen. They must have occurred.

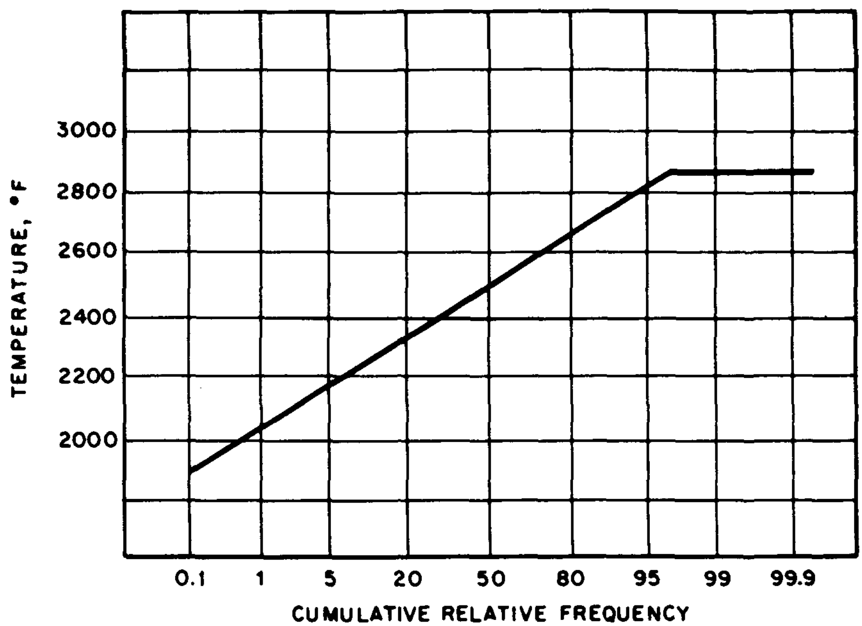

FIG. 12.3—*Typical probability plot—truncated data* [°C = 5/9 (°F−32)].

12.3.5 Regression Analyses

Regression analysis is used statistically to express a set of data in an analytical relationship. This relationship can be used to predict values of the dependent variable at values of the independent variable between those for which test data exists. The technique can also help to smooth the curve of test data, based on knowledge of the process beyond the mere statistics, for example, we may know from physical facts that the true relation is linear, polynomial, or exponential, and need only to determine a few data points to define it. Redundant data points beyond the number of constants to be derived are required to provide degrees of freedom in order to establish confidence in the constants. This confidence is an expression of the "goodness of fit" of the curve and is called the standard error of estimate (SEE) expressed by

$$\text{SEE} = \sqrt{\frac{\Sigma(Y_i - Y_{ci})^2}{n - (1 + q)}}$$

where

Y_{ci} = predicted value of $Y_i = f(X_i)$,
Y_i = measured value of Y_i at X_i,
n = number of data points, and
q = order of the derived equation.

The same SEE is used to assess the scatter of the data points around the curve. Obviously, if the scatter of the original data is large, this fact will be reflected in a large SEE of the curve, which implies a large uncertainty in the constants. Conversely, experimental data closely grouped around a simple, well-defined regression curve will produce a low value of SEE which indicates the precision of both the coefficients and the test data.

Care must be taken to avoid over fitting a curve to experimental data. Most physical relationships can be expressed with relatively few constants, for example, a low order polynomial. Any set of data, on the other hand, can be perfectly fitted by a polynomial with a number of constants equal to the number of data points. Such a fit will be generally meaningless. The SEE will have increased because of the decrease in the degrees of freedom (denominator), and the equation will perfectly describe what is already known, while becoming worthless to predict intermediate values. (Extrapolated values should never be predicted.) A very interesting account of the regression of the temperature-emf tables is given in NBS-125 [*6*] and the references contained therein. In this unusual case the large quantity of data (degrees of freedom) permits regression to as much as a 14th order equation to reduce the SEE to the order of one microvolt, while retaining sufficient degrees of freedom.

Regression analysis is one of several techniques which can be used to identify a causal relationship between two variables. Other techniques such as correlation and analysis of variance (ANOVA) are somewhat more sophisticated and are discussed by Chatfield [2].

Thermocouples often are accused of drifting with time in use. A series of data points representing time versus error determined by reference to noble metal thermocouples, resistance thermometer, optical pyrometer, or other alternate technique, will show a scatter for one or more experimental reasons between the points. One way to decide whether the error is a linear function of time is to determine the coefficients of a linear regression of the data. If there is no linear relationship, the SEE will approximate the standard deviation; if the points all fall on a straight line, it will be zero.

12.4 References

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Chapter 13—Terminology*

absolute Seebeck coefficient, *n*—the Seebeck coefficient of a homogeneous segment of a conducting material of a single thermoelectric type, independent of other materials. (Compare with *relative Seebeck coefficient.* See *absolute Seebeck emf.*)

absolute Seebeck emf, *n*—the net Seebeck emf across a segment of a single electrically conducting material of one nominal type. (See *absolute Seebeck coefficient.*)

absolute temperature, *n*—temperature measured on the *Kelvin Thermodynamic Temperature Scale.* (See *KTTS.*)

absolute zero temperature, *n*—the physically unrealizable origin of the thermodynamic temperature scale that represents the theoretical lowest temperature state of matter, **0 K.** (See *absolute temperature.*)

Discussion: Entropy and all thermoelectric effects are presumed to vanish at this theoretical temperature that has been approached within 10^{-7} K.

accuracy, *n—qualitative,* the degree of agreement between a measured value and a corresponding reference value defined as true. (See also *uncertainty, bias, precision.*)

Discussion: For quantitative measure use *measurement uncertainty.*

ANSI, *n*—the *American National Standards Association,* an organization nationally sanctioned to formally represent the United States in international standards affairs.

bead, *n—of a thermocouple,* the mass of conducting material formed by the fusion, brazing, or soldering of dissimilar thermoelements in fabricating the junction of a thermocouple. (Compare with *junction.*)

Discussion: The bead is not the intended source of Seebeck emf in thermoelectric measurement. However, this incidental conducting material, if interposed between thermoelements and not kept isothermal, will produce a spurious Seebeck emf that degrades accuracy in thermoelectric thermometry.

bias, *n—qualitative,* deviation of a measured or observed value from a particular related reference value. (Compare with *uncertainty bias.*)

calibrate, *v—in measurement,* to determine the values of indication, output, scaling, or response of a particular measuring means with respect to a reference of stated adequate uncertainty. (Compare with *certify, characterize, graduate, qualify, validate.*)

Discussion: Motivation for calibration may be to adjust, confirm, correct, or document measurement characteristics to allow measurement with a particular instrument to an established uncertainty.

calibration, *n—in measurement,* for a sensor or system, the expression of the relation between a measurand and corresponding values of a sensing variable used to measure it as determined by comparison with an identified reference.

calibration drift, *n—in thermoelectric thermometry,* a usually irreversible progressive or irregular change in Seebeck coefficient of a segment of thermoelement that results from migration of constituents, transmutation, surface composition change, etc., caused by an environment of excessive temperature, temperature gradient, radiation, chemical, or other environmental exposure, usually during application. (Compare with *calibration shift.* See also *Seebeck instability.*)

*For consensus standard definitions adopted by ASTM Committee E20 on Thermometry see Standard E 344 "Terminology Relating to Thermometry and Hydrometry."

calibration point, *n—in thermoelectric thermometry,* a temperature at which a thermocouple calibration is stated or for which it is required.

calibration shift, *n—in thermoelectric thermometry,* a usually abrupt, sometimes reversible, systematic change in Seebeck coefficient of a segment of a thermoelement that results from a metallurgical transition of a material or alloy at a characteristic pressure, inelastic strain, temperature, or other physical threshold. (Compare with *calibration drift, Seebeck instability.*)

Discussion: Reversible shifts, as from work hardening, may often be reversed by annealing at appropriate temperatures and in protective environments.

CCT, *n*—the Comité Consultatif de Thermométrie of the CIPM (the Consultative Committee of Thermometry), an international group of thermal metrologists charged with developing thermometry standards such as the *ITS-90* temperature scale.

Celsius temperature scale, *n*—one that is implicit in the *ITS-90* and on which the degree is represented by °C, and at a pressure of 101325 Pa (1 atm), **0°C** is near the water freezing point and **100°C** is near the water boiling point. (see also *temperature scale.*)

Discussion: The magnitude of the Celsius degree and the Kelvin are the same. The Celsius scale supersedes the centigrade scale. Temperatures on the Celsius Temperature Scale are related to the *ITS-90* by

$$t_c, °\text{C} = \text{T, K} - 273.15 \text{ K}$$

centigrade—Obsolete. (See **Celsius temperature scale.**)

certify, *v—in measurement,* to attest by written or printed statement that an item is as specified or that a test result is valid and accurate as stated. (Compare with *calibrate, qualify, validate, verify.*)

characterize, *v—in measurement,* to establish representative normal properties of a class of subject. (Compare with *calibrate.*)

Discussion: Thermocouple materials of standardized type are characterized to establish a general relationship between Seebeck coefficient or emf and temperature that is representative of all normal materials of that type within some tolerance.

CIPM, *n*—the Comité International des Poids et Mesures (International Committee of Weights and Measures) a U.S. recognized international cooperative body that establishes and promulgates measurement standards for uniform use worldwide.

coaxial thermocouple, *n*—a tubular thermoelement and an enclosed dissimilar thermoelement that are coupled at one end to form a junction and are insulated elsewhere. (Compare with *sheathed thermoelement.*)

cold junction, n—Deprecated term. Use **reference junction.**

compensating extension leads, *n—in thermoelectric thermometry,* paired thermoelements of dissimilar materials of which each is different in thermoelectric type from the thermoelement to which it is to be joined but which have, as a pair over a limited temperature range near ambient temperature, a relative Seebeck coefficient that is similar to that of the thermocouple type to which they are to be electrically connected. (See also *matching extension lead; thermocouple extension lead.*)

connection head, *n*—a protective enclosure for the terminals of a metal-sheathed sensor.

convention, *n*—a somewhat uniform community practice followed without formal agreement and without formal authority. (Compare with *standard.*)

cryogenic, *adj—in thermometry,* usually relating to temperatures that are substantially below the icepoint.

Discussion: "Cryogenic" often is applied to the temperature range of 90 K or lower (the boiling point of liquid oxygen at 101325 Pa, 1 atm.)

decalibrate, *v—qualitative,* to change, and usually to degrade, the accuracy of a measurement device or system from an established uncertainty. (See also *calibration drift, calibration shift, Seebeck instability.*)

defining fixed point, *n*—a reproducible and physically realizable temperature with assigned values standardized for definition of discrete points on temperature scales such as the ITS-90. (See also *secondary fixed point.*)

degree, *n—in thermometry,* the unit measure of temperature on most temperature scales. (Compare with *kelvin.*)

differential thermocouple, *n—in thermoelectric thermometry,* a thermocouple assembly intended for the direct measurement of the approximate temperature difference between two measuring junctions that are simultaneously at different temperatures.

dissimilar materials, *n—in thermoelectric thermometry,* two or more materials, each of which is substantially different in Seebeck characteristics from the other. (See also *similar materials.*)

Discussion: Dissimilar materials may be of identical chemical composition but of very different thermoelectric characteristics due to metallurgic state, dimension, etc.

electrical conducting material, *n—in thermoelectricity,* any material in a physical state that allows electrical charge to be moved freely.

Discussion: Such materials are classified according to the relative mobility of charge as superconductor, normal conductor, or semiconductor, etc. Conduction can occur through electronic, ionic, or electrolytic mechanisms in bulk or powdered solids, liquids, or gases. The Seebeck effect can occur in any conducting material over some temperature range.

electromotive force (emf), [V], *n*—a difference in simultaneous electrical potential between two locations.

extension wire, *n—in thermoelectric thermometry,* extension leads in the form of wire.

Discussion: thermoelectric extension leads are often in the form of ribbon, foil, bar, or deposited film.

extension leads, *n—in electricity,* electrical conductors, usually electrically insulated and flexible, intended for interconnecting components of a circuit. (See *compensating extension leads, matched extension leads.*)

extension leads, *n—in thermoelectric thermometry,* paired dissimilar thermoelements, usually electrically insulated and flexible, intended for interconnecting components of a thermoelectric circuit. (See *compensating extension leads, matched extension leads, pigtail leads.*)

Discussion: All extension leads must be recognized as thermoelements, not simply as electrical leads, that normally contribute a small portion of the Seebeck emf in a temperature measurement.

extension lead error, *n—in thermoelectric thermometry,* error introduced by incorrect Seebeck emf from extension leads. (See *extension leads, compensating leads.*)

Discussion: Such error can occur because, under the conditions of use, the extension leads have a relative Seebeck coefficient different from the thermocouple with which they are used or because the temperatures of incidental junctions between primary and extension thermoelements are not properly matched.

Fahrenheit temperature scale, *n*—the common temperature scale now used mostly in the United States in engineering and in public life with the degree denoted by °F. (See *temperature scale.*)

Discussion: The relation between the Celsius and Fahrenheit temperature scales is

$$t_c, °C = (t_f, °F - 32, °F)/1.8$$

fixed point, *n—in thermometry,* a reproducible and realizable characteristic temperature of equilibrium between different phases of a reference material under standard conditions. (See also *ice point, freezing point, melting point, water triple point.*)

fixed point reference, *n—in thermometry,* a device used to realize a thermometric *fixed point.*

freezing point, *n—in thermometry,* the temperature of a two-phase material at a pressure of 101325 Pa (1 atm) while it passes from liquid to solid state.

Discussion: For a pure material, the temperatures of freezing and melting have the same value.

graduate, *v—in measurement,* to mark in a sequence of intervals.

material gradient, *n—in thermoelectricity,* the rate of change of Seebeck coefficient with position in an isothermal inhomogeneous material. (See *Peltier effect.*)

ground, *n—in electrical measurement,* an electrical potential reference point, usually at the potential of the local earth.

grounded junction, *n*—one in electrical contact with circuit ground reference either directly or else indirectly through a grounded conducting sheath. (Compare with *isolated junction.* See also *junction, junction class.*)

Discussion: The term is very often applied to junctions that are merely electrically common with their sheath even if that sheath is isolated from reference ground.

hot junction, n—Deprecated term. (Use **measuring junction.**)

ice point, *n—in thermometry,* the temperature of air-saturated water coexisting at equilibrium in liquid and solid phases at a pressure of 101325 Pa, 1 atm.

Discussion: The value of the ice point is approximately **0°C** on the *Celsius temperature scale,* **32°F** on the *Fahrenheit temperature scale,* and **273.15 K** on the *ITS-90* and *KTTS.*)

incidental junction, *n—in thermoelectric thermometry,* one that occurs at splices between materials that may be nominally alike but are significantly dissimilar in Seebeck coefficient and that is used neither as a measuring nor a reference junction.

Discussion: The temperatures of incidental junctions around a circuit must be deliberately controlled to avoid temperature error.

inhomogeneity, *n*—variation of the value of a property as a function of position within it at a fixed time. (See *Seebeck inhomogeneity.*)

isolated junction, *n*—one that is not common with electrical reference ground. (Compare with *grounded junction.*)

instability, *n*—anomalous variation with time of an indication or a property. (See also *Seebeck instability.*)

Discussion: Examples are varying temperature indications by a thermometer with the sensing element always at the same temperature or progressive changes in the Seebeck coefficient of a thermoelement independent of temperature.

insulation resistance, *n—of sheathed thermocouple material,* the electrical shunting resistance between a pair of isolated thermoelements or between a thermoelement and its sheath from which it is intended to be isolated.

Discussion: The shunt resistance varies inversely with the length.

interlaboratory comparison test, *n—in measurement,* a test to compare between two or more organizations the results of procedures to accomplish a common objective each using their own usual practices and apparatus. (Compare with *round-robin test.*)

intrinsic thermocouple, *n*—one in which the two thermoelements separately are joined to the electrically conductive subject of measurement so that the test subject itself becomes an intermediate thermoelement in series between the primary thermoelements.

Discussion: This configuration achieves intimate contact with the surface and reduces response time in fast transient measurement. However, varying differences of temperature between the two points of attachment can result in significant error.

IPTS-48, *n*—the International Practical Temperature Scale adopted by the 11th General Conference on Weights and Measures in 1960 and replaced in 1968 by the IPTS-68 (Obsolete, see *ITS-90.*)

IPTS-68, *n*—the International Practical Temperature Scale of 1968 the temperature scale adopted by the 13th General Conference on Weights and Measures in 1968 (Obsolete, superseded by *ITS-90.*)

isolated junction, *n*—one not in electrical contact with any protective electrically conductive enclosure or structure, or with electrical reference ground. (Compare with *exposed junction, grounded junction, protected junction.* See also *junction class.*)

Discussion: Electrical isolation of the measuring junction and other portions of the thermocouple from earth or reference ground is often required to avoid noise from ground loops, particularly in transient temperature measurement.

isothermal, *adj*—everywhere at the same temperature at the same time.

ITS-90, *n*—The International Temperature Scale of 1990 that superseded the *IPTS-68* on 1 January 1990. (See also *Celsius temperature scale, defining fixed points, KTTS.*)

Discussion: This scale is a physical approximation of the linear *Kelvin Thermodynamic Temperature Scale.* Cardinal values of both scales are **0 K** and the triple point of water, assigned the value **273.16 K.** The *ITS-90* is defined by seventeen realizable fixed points assigned standardized values by the *CCT* to well-approximate the *KTTS.* It is interpolated continuously between these points by prescribed instruments.

joint, *n—in thermoelectric thermometry,* any deliberate electrical connection or splice between conducting materials that have essentially similar Seebeck coefficients over the temperature range of application. (Compare with *junction.*)

junction, *n—in thermoelectric thermometry,* any electrical interface between conducting materials that have significantly different Seebeck coefficients. (Compare with *bead, joint.*)

junction class, *n—in thermoelectric thermometry,* the electrical connectivity of a junction. (Compare with *junction style.* See *exposed junction, grounded junction, isolated junction.*)

Discussion: **Class U** junctions are electrically isolated from conductive sheaths and from reference ground; **Class G** junctions are electrically connected to their protective sheath. In common usage, Class G junctions are often called "grounded" junctions even when not electrically common with reference ground.

junction style, *n*—the mechanical and geometric aspects of a thermocouple at a junction. (See *junction, thermocouple.*)

Discussion: Thermocouple junctions are coupled thermally and mechanically to the subject of measurement in a variety of ways to aid measurement. Examples are: reduced diameter junction, exposed junction, etc.

kelvin, *n*—the unit measure of temperature, **1/273.16** of the temperature span between **0 K** and the water triple point, on the **ITS-90** and the **KTTS**; denoted by the symbol "[space] **K**" without degree mark. (See also **Celsius, ITS-90.**)

KTTS, *n*—the linear **Kelvin Thermodynamic Temperature Scale** defined by the two points: *absolute zero,* assigned the value **0 K,** and the *water triple point,* assigned the value **273.16 K** with the unit measure of temperature denoted by "**[space] K.**" (See *absolute temperature, absolute zero temperature, ITS-90, water triple point.*)

leads, *n—in electricity,* electrical conductors, usually flexible, intended for interconnecting parts of a circuit. (See *compensating extension leads, extension leads, matched extension leads.*)

Discussion: The distinction between **lead,** the electrical component, and **lead (Pb),** the material element, is usually clear in context. Where confusion is likely, use the chemical symbol, **Pb.**

liquid-in-glass thermometer, *n*—a temperature measuring instrument whose indications are based on the temperature coefficient of expansion of a liquid relative to that of its containing glass envelope.

loop resistance, *n—in thermoelectric thermometry,* the total resistance of a complete series thermoelectric circuit measured at its terminals or the combined resistance of separate thermoelements as if connected in such a circuit.

Discussion: Where a thermocouple circuit is not isothermal during resistance measurement, indicated resistance measurements must be corrected, as by measuring in alternate polarity and averaging, to compensate for Seebeck emf. Otherwise very large errors in indicated loop resistance can occur.

matching extension leads, *n—in thermoelectric thermometry,* a pair of dissimilar conductors of which each is nominally the same in thermoelectric type as the thermoelement to which it is to be joined and so has, individually and as a pair over a broad temperature range of use, a relative Seebeck coefficient that is nominally like that of the thermocouple type to which it is to be electrically connected. (Compare with *compensating extension leads.* See also *thermocouple extension leads.*)

measurement uncertainty, *n*—The paired measures, *uncertainty bias* and *uncertainty precision,* stated separately, that jointly express an estimate of the departure of the mean of a set of measurements from an exact representation of a defined reference value.

measurement standard, *n*—a natural physical constant, property, material, artifact, or item that has been formally established or certified as a reference by an identified authoritative body. (Compare with *measurement reference.*)

measuring junction, *n—in thermoelectric thermometry,* a junction, the temperature of which is to be deduced from the net Seebeck potential and the known temperature of reference junctions. (Compare with *reference junction.* See also *junction class.*)

melting point, *n*—the temperature of a two-phase material at a pressure of 101325 Pa (1 atm) as it passes from solid to liquid state.

Discussion: For the most pure materials, the temperatures of freezing and melting have the same value.

MIMS, *adj—in thermoelectric thermometry,* mineral-insulated metal-sheathed.

MIMS construction, *n—in thermoelectric thermometry,* thermoelements embedded within a tubular sheath in densely compacted ceramic insulation.

Discussion: The high purity metal oxide or ceramic insulation material is densely compressed by drawing or else by swaging the sheath tightly around the insulation crushing it reduced diameter.

NBS, *n*—Superseded. The United States **National Bureau of Standards,** the national metrology agency renamed *NIST* in August 1989.

net Seebeck emf, *n—in thermoelectric thermometry,* the algebraic sum of Seebeck emfs presented at the terminals of a series open circuit without regard to special pairing of dissimilar materials, temperature distribution, or circuit configuration. (Compare with *relative Seebeck emf.*)

NIST, *n*—The United States **National Institute for Standards and Technology,** the agency responsible for the establishment and promulgation of U.S. national reference standards. (See *NBS*)

open-circuit emf, *n*—The net source potential difference observed at the terminals of a circuit measured under conditions of zero current.

Peltier coefficient, π, *n*—the rate of heat transfer per unit current per unit time at a junction or material property gradient due to the Peltier effect.
Discussion: While the Peltier coefficient can be expressed alternately with units of volts, it is not an emf. See *Seebeck emf.*

Peltier effect, *n*—the exchange of heat between an electric conductor and its environment local to an isothermal junction between dissimilar materials or a *material gradient* as it is traversed by electric current.

Peltier emf, n—Disparaged term. (See **Seebeck emf.**)

Peltier heat, *n*—heat exchanged between the environment and a thermoelectric junction due to the Peltier effect.

pigtail leads, *n—in thermoelectric thermometry,* short flexible extension leads that are joined as a part of a thermocouple assembly or thermoelectric device for convenience in interconnection and handling. (See *extension leads, compensating extension leads, matched extension leads.*)

potentiometer, *n—in thermoelectric thermometry,* a device for measuring an open-circuit emf by null comparison to a standard emf reference.

precision, *n—qualitative,* the dispersion between values from a set of repeated measurements of the same quantity. (See *uncertainty precision.*)

precision index, s, *n*—A quantitative measure of the imprecision of a set of values expressed as the sample standard deviation, calculated by

$$s = \left[\frac{1}{N-1}\sum_{i=1}^{i=N}(X(i) - X_m)^2\right]^{1/2}$$

where

N = number of values in the set,
$X(i)$ = values of the samples, and
X_m = arithmetic mean (average) of values of the samples.

(See also *repeatability, uncertainty precision.*)
Discussion: The precision index can be expressed directly in physical units like the set of observed values; relatively, normalized to some stated value such as X_m; or else as a percentage of X_m. The square of precision index is the statistical *variance* measure of imprecision. This measure is appropriate for uncertainty of normal distribution.

primary reference standard, *n*—a material, apparatus, device, or other artifact used as the highest level of calibration authority within a calibration system.
Discussion: In the United States, if a primary reference standard is available, it is usually maintained or certified by the *NIST.*

primary standard thermocouple, *n*—one qualified as a *primary reference standard.*

protected junction, *n*—one mechanically separated from the subject of thermometry and from a mechanically or chemically harmful environment by a protective covering. (Compare, with *isolated junction, exposed junction.*)

protecting tube, *n—in thermoelectric thermometry,* a tubular enclosure to isolate a thermocouple from a harmful mechanical or chemical environment.

Pt-27, *n*—the *NBS* platinum reference standard for thermoelectric and resistance thermometry that was replaced by *Pt-67* in 1973.

Pt-67, *n*—The certified high purity platinum reference material standardized and distributed as SRM 1967 by the *NIST* for thermoelectric, resistance, and other reference.

Comment: The material is often used as a thermoelectric reference material against which the relative Seebeck emf of other materials are measured. (See also Pt-27.)

qualify, *v*—to assure by test that a subject is initially suited and that it remains suited to a particular purpose within explicit requirements. (Compare with *calibrate, certify, characterize, validate.*)

range, *n*—the span between limits within which a quantity is measured or a device is operated.

real junction, *n—in thermoelectric thermometry,* an actual physical junction. (Compare with *virtual junction.* See also, *junction.*)

reference, *n*—any natural or artifact material, physical state, value, object or device used as a norm to which others are compared. (Compare with *measurement standard.*)

reference junction, *n—in thermoelectric thermometry,* any junction maintained at a known or independently monitored temperature as a reference for thermoelectric thermometry. (Compare with *measuring junction.*)

Discussion: A thermocouple has no reference junction(s) until it is joined to other circuit elements to form junctions and until the reference temperature is established.

reference junction error, *n—in thermoelectric thermometry,* the temperature error introduced because paired reference junctions of a thermoelectric thermometer are not maintained at the same temperature or else the actual temperature of the reference junctions is not accurately applied as a correction to the reference value. (See also *extension lead error.*)

refractory thermocouple, *n*—one of which neither thermoelement has a melting point below 2208.16 K. (the melting point of Pt60/Rh40.)

relative Seebeck coefficient, *n*—the net effective Seebeck coefficient between two homogeneous segments of electrical conductors that are arranged electrically in series and that have their corresponding end points at the same two temperatures. (Compare with *absolute Seebeck coefficient.* See also *relative Seebeck emf.*)

relative Seebeck emf, *n*—the net Seebeck emf between two homogeneous thermoelements that are arranged electrically in series and that have their corresponding endpoints at the same two temperatures. (See also *relative Seebeck coefficient, net Seebeck emf.*)

Discussion: Usually, it is the relative Seebeck emf for a pair of dissimilar materials with one endpoint at 0°C and the other at the temperature of the measuring junction that is presented as a table relating emf and temperature for a thermocouple type. Pairs of materials have a relative Seebeck emf even if not in a physical circuit.

repeat, *v—in measurement,* to perform a test more than once under similar but not necessarily duplicate conditions. (Compare with *replicate.*)

repeatability, *n*—the *uncertainty precision* of a set of measurements made on corresponding subjects, by the same worker, with the same equipment and procedures, under like conditions. (See *precision, repetition, replication.* Compare with *reproducibility.*)

Discussion: The mean value of a single set of repeatability measurements is not a measure of reproducibility. Rather, it reflects an *uncertainty bias* relative to a normal value that might be estimated by round-robin tests for reproducibility from which uncertainty could be estimated.

replicate, *v—in measurement,* to perform a test, such as a *round-robin test* or *interlaboratory comparison test,* more than once duplicating all relevant factors. (Compare with *repeat.*)

reproducibility, *n—in measurement,* the *uncertainty precision* of the set of mean values from a group of separate *repeatability* tests, each set made on corresponding subjects, under like conditions and procedures, but by different observers, with different equipment, at different times, or at different locations, or under different conditions, etc. (See *uncertainty precision, uncertainty bias, repeatability.*)

Discussion: The overall *uncertainty bias* of the set of individual uncertainty biases from all repeatability tests of a *round-robin test* is an estimate of the normal value of the method or procedure. This overall uncertainty bias is the reference value for estimating the uncertainty bias of a single set of individual reproducibility tests. The estimated uncertainty of a procedure or method is often represented by reproducibility as the precision index and the mean of individual repeatability biases as the uncertainty bias.

round-robin test, *n—in measurement,* a coordinated series of tests performed independently but replicated for comparison between results from more than two observers, organizations, devices, or all of these in order to validate a test method or device, to determine representative values and their uncertainty, or to test reproducibility. (See also *interlaboratory comparison test, repetition, replication.*)

secondary reference standard, *n*—a currently certified or qualified material, apparatus, device, or other artifact used to transfer values form a primary reference standard to a lower level measurement device by comparison calibration.

secondary standard thermocouple, *n*—one qualified as a *secondary reference standard.*

Seebeck coefficient, σ, **[V/Θ],** *n*—the increment of thermoelectric emf produced by a small temperature difference across homogeneous segments of individual or paired thermoelements, expressed by

$$\sigma(\mathrm{T}) = \lim_{\Delta \mathrm{T} \to 0} \frac{\Delta E_s(\mathrm{T})}{\Delta \mathrm{T}}$$

(See also *absolute Seebeck coefficient, relative Seebeck coefficient.*)

Discussion: When the Seebeck emf is graphed versus temperature, the value of the slope of the curve at a temperature represents the value of the Seebeck coefficient at that temperature.

Seebeck effect, *n*—the occurrence of a thermoelectric emf as a result only of a temperature gradient in an electrically conducting material.

Discussion: The Seebeck effect is related thermodynamically to the Peltier and Thomson effects but it is only the Seebeck effect that produces the thermoelectric emf that is used in thermometry. The effect occurs in liquids as well as solids and in ionic as well as electronic conductors and semiconductors. The thermoelectric effect is distinct from the pyroelectric effect that also thermally produces an emf from distortion of the atomic structure of atoms due to a temperature gradient and that also is used in thermometry.

Seebeck emf, *n*—any emf resulting from the Seebeck effect. (See *absolute Seebeck emf, relative Seebeck emf, net Seebeck emf.*)

Discussion: The Seebeck emf is a motive electrical force of a source. Its full value is observable at the terminals of a circuit only under open circuit conditions. The net terminal voltage of a thermocouple is the Seebeck emf reduced by resistance in circuits when current is allowed to flow.

Seebeck inhomogeneity, *n*—*in thermoelectric thermometry,* the variation with position along a circuit path of the temperature-dependent Seebeck coefficient of a stable thermoelement at a particular time, expressed by

$$\delta\sigma(X) = \sigma(X, \mathrm{T}) - \sigma_r(\mathrm{T})$$

Discussion: the Seebeck coefficient reference function, σ_r, must be defined, as suited to the purpose of the homogeneity measure, as a time-independent function of temperature for the nominal material.

Seebeck instability, *n*—the anomolous variation with time, t, of the Seebeck coefficient at a fixed location X_0, relative to the coefficient at a reference time, t_r, expressed as

$$\delta\sigma(t) = \sigma(t, X_0) - \sigma(t_r, X_0)$$

(See also *thermocouple drift, thermocouple shift.*)

sensing element, *n*—*in measurement,* the portion of a measuring instrument that detects the value of the measurand. (Compare with *transducing element.*)

Discussion: In thermoelectric thermometry, the parts of a thermocouple assembly that sense temperature are the junctions. The Seebeck emf, observed as a measure of temperature, is produced in nonisothermal segments of the thermoelements, not in the junctions.

sheathed thermocouple, *n*—one of *MIMS* construction.

sheathed thermocouple material, *n*—material of MIMS construction with dissimilar thermoelements electrically isolated from their sheath and without junctions.

Discussion: Such material is supplied in bulk form for user fabrication into finished thermocouples.

sheathed thermoelement, *n*—a single thermoelement of MIMS construction and for which the sheath is not intended to serve as a thermoelement. (Compare with *coaxial thermocouple.*)

similar materials, *n*—*in thermoelectric thermometry,* two or more materials that are sufficiently alike in Seebeck characteristics to be interchangeable in a particular application. (See also *dissimilar materials.*)

Discussion: Few materials are strictly identical but many may be alike within an acceptable tolerance for some use. Two similar materials may be of much different chemical composition and may have very different environmental limitations.)

standard, *adj*—complying with a particular specification, or designation that has been formally established or certified by an identified authoritative body. (Compare with *reference, convention.*)

standard, *n*—a document, or practice such as a specification, procedure, naming, coding, or designation that has been formally established or certified by an identified authoritative body. (Compare with *reference.*)

standard platinum resistance thermometer, SPRT, *n*—an accurate stable resistance thermometer of special design and construction that is qualified as a temperature interpolating instrument for realizing the *ITS-90.*

step response, *n*—the characteristic output waveform from a device or system that results from imposing a sustained step change of input value. (See also *step response time, time constant.*)

step response time, *n*—the time interval between the instant a sensing element or system is exposed to a step change of the value of input to the time that the output indication attains some defined response criteria. (Compare with *time constant.*)

Discussion: The *response time* is a general term for which the criteria must be specifically stated. *Time constant,* however, is particular kind of step response time that *mathematically* relates specifically to first-order systems only.

superconductor, *n*—*in thermoelectric thermometry,* a material, the Seebeck coefficient and emf of which vanish (below some critical value of magnetic field) for all temperatures below some critical temperature, T_c.

Discussion: Over the small very low temperature range of superconductivity adjacent to 0 K, these materials can be used as a null reference thermoelement to allow the direct observation of the absolute Seebeck emf of other paired thermoelements. Null reference application is limited presently to temperatures below about **120 K.**

temperature difference, [Θ], *n*—the simultaneous net temperature interval between two separate points. (Compare with *temperature gradient.*)

temperature gradient, [Θ/L], *n*—the rate of change of temperature with position at a particular location and time. (Compare with *temperature difference, material gradient.*)

Discussion: This commonplace term is very often misused as a synonym for *temperature difference* or *temperature distribution* that are very different concepts.)

temperature scale, *n*—a formal series of related temperature values graduated for measurement.

thermal emf, n—Disparaged term. (Use **Seebeck emf.**)

Discussion: The term is intended usually to be synonymous with Seebeck emf but is ambiguous as both the magneto-thermoelectric Nearnst effect and the pyroelectric effect also thermally produce emfs.

thermocouple, *n*—*in thermometry,* two dissimilar thermoelements electrically isolated from each other except where electrically coupled at a common connection. (Compare with *thermocouple assembly.* See also *bead, junction.*)

thermocouple assembly, *n*—*in thermometry,* a fabrication of one or more thermocouples and auxiliary parts such as extension thermoelements, reference junctions, insulators, protective sheath, and connectors, but excluding signal conditioning components such as reference junction compensator, transmitter, or amplifier.

thermocouple cable, *n*—two or more insulated thermocouple pairs, usually of extension lead material, assembled within a common protective jacket.

Discussion: Each pair may be twisted and electrically shielded and jacketed, and the entire assembly may be contained within one or more shields for electrical noise isolation and within an overall jacket. The jackets may be of elastomeric materials chosen for protection against mechanical abrasion or chemical environment.

thermocouple circuit, *n*—an electrical circuit that includes thermocouple junctions.

thermocouple connector, *n*—*in thermoelectric thermometry,* a device for electrically quick-connecting one or more thermoelements of an assembly and made from contact materials with Seebeck coefficients similar to those of the thermoelements to be connected.

thermocouple element, n—Disparaged term. Use **thermoelement.**

thermocouple gland, *n*—a pressure-tight feed-through that allows continuous pieces of sheathed thermocouple materials to pass through a wall without interruption of the sheath or thermoelements.

thermocouple head, *n*—a compact enclosure for strain relieving and protecting the terminal splices between thermocouple assemblies and their extension leads.

thermocouple probe, *n*—a thermocouple assembly that has a measuring junction of specialized design, adapted to the thermometry of particular kinds of subjects, often associated with a handle that facilitates use.

thermocouple style, *n*—the geometric, mechanical, and physical design of a thermocouple assembly without regard to material. (See thermocouple type.)
Discussion: Style refers to the junction kind, protection, insulation, circuit, etc.

thermocouple type, *n*—a nominal thermoelectric class of thermoelement materials that, used as a pair, have a normal relation and tolerance between relative Seebeck emf and temperature, physical characteristics, and an assigned type letter designator and color code defined in the United States by *ANSI* standard and described by ASTM E 230 and ASTM E 1223.

thermoelectric circuit, *n*—any electrical circuit that includes interconnected dissimilar materials.

thermoelectric thermometer, *n—in thermometry,* a thermocouple assembly together with signal conditioning and indicating devices required to produce a temperature measurement using the Seebeck effect.

thermoelectric thermometry, *n*—temperature measurement that uses the Seebeck effect as the transducing principle.

thermoelectric power, *n—in energy generation,* electromotive energy produced by conversion from thermal form to electrical form by means of the Seebeck effect.
Discussion: The Seebeck effect is widely used in the generation of electrical power from solar, nuclear, and fossil fuel heat sources where the very low efficiency of energy conversion is tolerable.

thermoelectric power, *n—In thermoelectric thermometry,* a deprecated term. Use **Seebeck coefficient.** (See also *thermopower.*)
Discussion: This very commonly used archaic term is disparaged because it conflicts with the more logical contemporary use to describe electrical motive energy generated by thermoelectric means.

thermoelectric thermometry, *n*—the measurement of temperature using the Seebeck effect as the transducing principle.

thermoelectric pyrometer, *n*—any device for measuring temperatures into a high temperature range using the Seebeck effect.

thermoelement, *n—in thermoelectric thermometry,* an electrical conducting circuit component of a single nominal material type that functions as a source of Seebeck emf.

thermopile, *n*—two or more thermocouples connected in series, in parallel, or both.
Discussion: series or parallel thermopile arrangements are used in thermometry for increasing voltage or current output for a given temperature difference between measuring and reference junctions, or for estimating a spatial average temperature over several junction locations.

thermopower, n—Deprecated term. (See *thermoelectric power, Seebeck coefficient.*)

thermowell, *n*—a pressure-tight closed-end tube of special thermometric design for the mechanical and chemical protection of a temperature sensor during measurement.

Thomson coefficient, τ, *n*—The time rate of Thomson heat exchanged due the Thomson effect per unit temperature gradient per unit current.
Discussion: In thermoelectric thermometry, the Thomson coefficient is of practical importance primarily as used to experimentally determine the absolute Seebeck coefficient for individual thermoelements.

Thomson effect, *n*—the thermoelectric transfer of heat between an electrical conductor and its immediate environment local to a nonisothermal segment wherever electric current traverses a *temperature gradient.*

Thomson emf, n—Deprecated term. (See **Thomson effect, Seebeck emf.**)
Discussion: The Thomson effect concerns only a heat exchange resulting from electric current interacting with a *temperature gradient.* The Thomson effect does not produce an emf.

Thomson heat, *n*—heat exchanged due to the Thomson effect.

time constant, *n—in measurement,* the time interval between the initial exposure of a first-order sensing element or system to a step change of input and the time the response changes to within $1/e$ (**36.79%**) of its eventual asymptotic value in response to that input alone. (See also *step response time.*)
Discussion: A first-order system is one that responds as a simple exponential function. Few real temperature sensors (for example, some simple bare thermocouple junctions) exhibit the first-order response for which the characteristic value has particular mathematical significance.

total temperature, *n—in thermometry of fluids,* the combination of static and kinetic temperature that represent nondirected and directed energy flow, respectively.

transducing element, *n—in measurement,* the portion of a measuring device that converts energy from the form of the measurand (for example, temperature) to the form for observation (for example, emf). (Compare with *sensing element.*)
Discussion: In a thermoelectric thermometer, the Seebeck emf generated is defined by temperatures "sensed" at discrete locations by junctions. But, the distributed emf is produced only in nonisothermal segments of the thermoelements. Sensing locations (junctions) are usually separated apart from the transducing portions of the circuit. In contrast, a resistive thermometer senses and transduces at the same place, throughout the volume of the essentially localized resistive element, so the sensing and transducing elements are the same.

triple point, *n—in thermometry,* the fixed-point temperature of a material in equilibrium simultaneously in solid, liquid, and vapor phases. (See also *fixed point, water triple point.*)
Discussion: Many materials experience more than one triple point at different combinations of the variables.

uncertainty, *n—qualitative in measurement,* the measure of measurement inaccuracy. (See *measurement uncertainty.*)

uncertainty bias, *n—in measurement,* the quantitative deviation of the mean of values of a defined set from an identified reference value. (Compare with *bias.* See also *measurement uncertainty, uncertainty precision.*)

uncertainty precision, *n—in measurement,* the quantitative degree of dispersion between the individual values of a defined set. (See *measurement uncertainty, precision index, uncertainty bias.*)
Discussion: Precision can be expressed by a variety of measures. The preferred measure for normally distributed errors is the precision index.)

validate, *v—in measurement,* to prove by test that a subject authentically performs its intended or purported function. (Compare with *certify, qualify, verify.*)
Discussion: Validation is a proof that addresses efficacy rather than degree of uncertainty, repeatability, or reproducibility.

verify, *n—in measurement,* to confirm that an assertion or proposition is correct. (Compare with *calibrate, certify, characterize, qualify, validate.*)

virtual junction, *n—in thermoelectric thermometry,* a location along a homogeneous thermoelement that marks a segment endpoint that (for purposes of analysis) functions as if it were a real thermocouple junction. (Compare with *real junction.* See *junction.*)

voltage, V, [V], *n*—the work required to move a unit charge through a circuit element from one point to another and measured as a difference between the electric potentials simultaneously at two points. (Compare with *electromotive force.*)
Discussion: Emf is a source motive force. Voltage across a circuit element can result from electromotive force, change of electric potential due to impedance, or a combination of these.

water triple point, *n—in thermometry,* the fixed-point temperature of pure water of natural isotopic composition in equilibrium simultaneously in solid, liquid, and vapor phases under its own vapor pressure. (See also *fixed point, defining fixed point.*)
Discussion: The temperature value of the unique water triple point is assigned the standard

value **273.16 K** as the only arbitrary value on the linear *KTTS* and *ITS-90* temperature scales. Water experiences more than one triple point at different forced combinations of the variables.

zone plate, *n—in thermoelectric thermometry,* a device for maintaining junctions and portions of thermoelectric circuits isothermal at fixed or monitored temperatures.

Appendix I

List of ASTM Standards Pertaining to Thermocouples

The following standards relating to thermoelectric thermometry may be of interest. All standards are periodically reviewed and updated as necessary and are published in Volume 14.03 of the *ASTM Annual Book of Standards.*

E 207 Method of Thermal EMF Test of Single Thermoelement Materials by Comparison with a Secondary Standard of Similar EMF-Temperature Properties
E 220 Method of Calibration of Thermocouples by Comparison Techniques
E 230 Temperature Electromotive Force (EMF) Tables for Standardized Thermocouples
E 235 Specification for Thermocouples, Sheathed, Type K, for Nuclear or Other High-Reliability Applications
E 344 Terminology Relating to Thermometry and Hydrometry
E 452 Test Method for Calibration of Refractory Metal Thermocouples Using an Optical Pyrometer
E 563 Practice for Preparation and Use of Freezing Point Reference Baths
E 574 Specification for Duplex, Base-Metal Thermocouple Wire with Glass Fiber or Silica Fiber Insulation
E 585 Specification for Sheathed Base-Metal Thermocouple Materials
E 601 Test Method for Comparing EMF Stability of Single-Element Base-Metal Thermocouple Materials in Air
E 608 Specification for Metal-Sheathed Base-Metal Thermocouples
E 633 Guide for Use of Thermocouples in Creep and Stress Rupture Testing to 1000°C (1800°F) in Air
E 696 Specification for Tungsten-Rhenium Alloy Thermocouple Wire
E 710 Method for Comparing EMF Stabilities of Base-Metal Thermoelements in Air Using Dual, Simultaneous, Thermal-EMF Indicators
E 780 Method for Measuring the Insulation Resistance of Sheathed Thermocouple Material at Room Temperature
E 839 Test Methods for Sheathed Thermocouples and Sheathed Thermocouple Material
E 988 Temperature-Electromotive Force (EMF) Tables for Tungsten-Rhenium Thermocouples

E 1129 Specification for Thermocouple Connectors
E 1159 Specification for Thermocouple Materials, Platinum-Rhodium Alloys, and Platinum
E 1223 Specification for Type N Thermocouple Wire
E 1350 Practice for Testing Sheathed Thermocouples Prior to, During, and After Installation

Appendix II

H. Preston-Thomas[1]

The International Temperature Scale of 1990 (ITS-90)* **

Introductory Note

The official French text of the ITS-90 is published by the BIPM as part of the Procès-verbaux of the Comité International des Poids et Mesures (CIPM). However, the English version of the text reproduced here has been authorized by the Comité Consultatif de Thermométrie (CCT) and approved by the CIPM.

The International Temperature Scale of 1990

The International Temperature Scale of 1990 was adopted by the International Committee of Weights and Measures at its meeting in 1989, in accordance with the request embodied in Resolution 7 of the 18th General Conference of Weights and Measures of 1987. This scale supersedes the International Practical Temperature Scale of 1968 (amended edition of 1975) and the 1976 Provisional 0.5 K to 30 K Temperature Scale.

[1]President of the Comité Consultatif de Thermométrie and Vice-President of the Comité International des Poids et Mesures Division of Physics, National Research Council of Canada, Ottawa, K1A 0S1 Canada.

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1. Units of Temperature

The unit of the fundamental physical quantity known as thermodynamic temperature, symbol T, is the kelvin, symbol K, defined as the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.[2]

Because of the way earlier temperature scales were defined, it remains common practice to express a temperature in terms of its difference from 273.15 K, the ice point. A thermodynamic temperature, T, expressed in this way is known as a Celsius temperature, symbol t, defined by

$$t/°\mathrm{C} = T/\mathrm{K} - 273.15 \tag{1}$$

The unit of Celsius temperature is the degree Celsius, symbol °C, which is by definition equal in magnitude to the kelvin. A difference of temperature may be expressed in kelvins or degrees Celsius.

The International Temperature Scale of 1990 (ITS-90) defines both International Kelvin Temperatures, symbol T_{90}, and International Celsius Temperatures, symbol t_{90}. The relation between T_{90} and t_{90} is the same as that between T and t, i.e.

$$t_{90}/°\mathrm{C} = T_{90}/\mathrm{K} - 273.15 \tag{2}$$

The unit of the physical quantity T_{90} is the kelvin, symbol K, and the unit of the physical quantity t_{90} is the degree Celsius, symbol °C, as is the case for the thermodynamic temperature T and the Celsius temperature t.

2. Principles of the International Temperature Scale of 1990 (ITS-90)

The ITS-90 extends upwards from 0.65 K to the highest temperature practicably measurable in terms of the Planck radiation law using monochromatic radiation. The ITS-90 comprises a number of ranges and subranges throughout each of which temperatures T_{90} are defined. Several of these ranges or subranges overlap, and where such overlapping occurs, differing definitions of T_{90} exist: these differing definitions have equal status. For measurements of the very highest precision there may be detectable numerical differences between measurements made at the same temperature but in accordance with differing definitions. Similarly, even using one definition, at a temperature between defining fixed points two acceptable interpolating instruments (e.g., resistance thermometers) may give detectably differing numerical values of T_{90}. In virtually all cases these differences are of negligible practical importance and are at the minimum level consistent with a scale of no more than reasonable complexity: for further information on this point, see "Supplementary Information for the ITS-90" (BIPM-1990).

[2]Comptes Rendus des Séances de la Treizième Conférence Générale des Poids et Mesures (1967–1968), Resolutions 3 and 4, p. 104.

The ITS-90 has been constructed in such a way that, throughout its range, for any given temperature the numerical value of T_{90} is a close approximation to the numerical value of T according to best estimates at the time the scale was adopted. By comparison with direct measurements of thermodynamic temperatures, measurements of T_{90} are more easily made, are more precise and are highly reproducible.

There are significant numerical differences between the values of T_{90} and the corresponding values of T_{68} measured on the International Practical Temperature Scale of 1968 (IPTS-68), see Fig. 1 and Table 6. Similarly there were differences between the IPTS-68 and the International Practical Temperature Scale of 1948 (IPTS-48), and between the International Temperature Scale of 1948 (ITS-48) and the International Temperature Scale of 1927 (ITS-27). See the Appendix and, for more detailed information, "Supplementary Information for the ITS-90."

3. Definition of the International Temperature Scale of 1990

Between 0.65 K and 5.0 K T_{90} is defined in terms of the vapor-pressure temperature relations of ^{3}He and ^{4}He.

Between 3.0 K and the triple point of neon (24.5561 K) T_{90} is defined by means of a helium gas thermometer calibrated at three experimentally realizable temperatures having assigned numerical values (defining fixed points) and using specified interpolation procedures.

Between the triple point of equilibrium hydrogen (13.8033 K) and the freezing point of silver (961.78°C) T_{90} is defined by means of platinum resistance thermometers calibrated at specified sets of defining fixed points and using specified interpolation procedures.

Above the freezing point of silver (961.78°C) T_{90} is defined in terms of a defining fixed point and the Planck radiation law.

The defining fixed points of the ITS-90 are listed in Table 1. The effects of pressure, arising from significant depths of immersion of the sensor or from other causes, on the temperature of most of these points are given in Table 2.

3.1 From 0.65 K to 5.0 K: Helium Vapor-Pressure Temperature Equations

In this range T_{90} is defined in terms of the vapor pressure p of ^{3}He and ^{4}He using equations of the form

$$T_{90}/K = A_0 + \sum_{i=1}^{9} A_i[(\ln(p/\mathrm{Pa}) - B)/C]^i \tag{3}$$

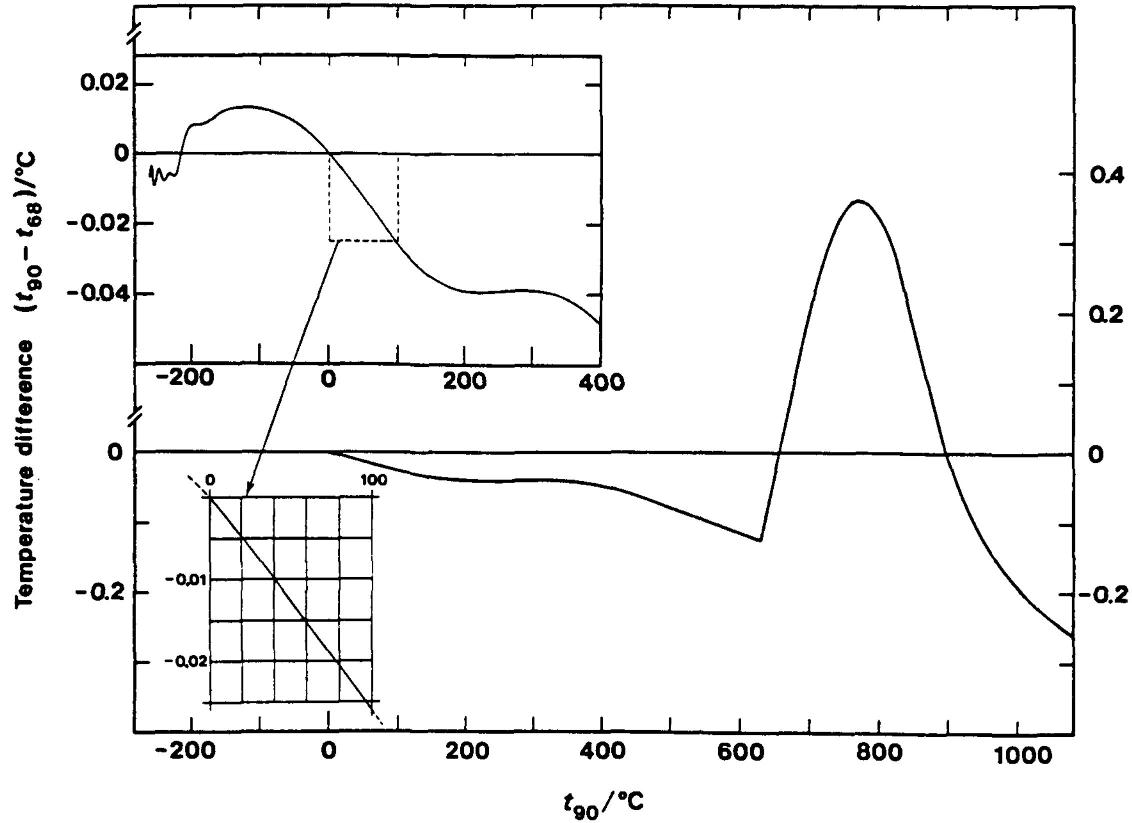

FIG. 1—*The differences* ($t_{90} - t_{68}$) *as a function of Celsius temperature* t_{90}.

TABLE 1—*Defining fixed points of the ITS-90.*

Number	Temperature		Substance[a]	State[b]	$W_r(T_{90})$
	T_{90}/K	t_{90}/°C			
1	3 to 5	−270.15 to −268.15	He	V	...
2	13.8033	−259.3467	e-H_2	T	0.001 190 07
3	≈17	≈−256.15	e-H_2 (or He)	V (or G)	...
4	≈20.3	≈−252.85	e-H_2 (or He)	V (or G)	...
5	24.5561	−248.5939	Ne	T	0.008 449 74
6	54.3584	−218.7916	O_2	T	0.091 718 04
7	83.8058	−189.3442	Ar	T	0.215 859 75
8	234.3156	−38.8344	Hg	T	0.844 142 11
9	273.16	0.01	H_2O	T	1.000 000 00
10	302.9146	29.7646	Ga	M	1.118 138 89
11	429.7485	156.5985	In	F	1.609 801 85
12	505.078	231.928	Sn	F	1.892 797 68
13	692.677	419.527	Zn	F	2.568 917 30
14	933.473	660.323	Al	F	3.376 008 60
15	1234.93	961.78	Ag	F	4.286 420 53
16	1337.33	1064.18	Au	F	...
17	1357.77	1084.62	Cu	F	...

[a] All substances except ^{3}He are of natural isotopic composition, e-H_2 is hydrogen at the equilibrium concentration of the ortho- and para-molecular forms.

[b] For complete definitions and advice on the realization of these various states, see "Supplementary Information for the ITS-90." The symbols have the following meanings: V: vapor pressure point; T: triple point (temperature at which the solid, liquid and vapor phases are in equilibrium); G: gas thermometer point; M, F: melting point, freezing point (temperature, at a pressure of 101 325 Pa, at which the solid and liquid phases are in equilibrium).

The values of the constants A_0, A_i, B, and C are given in Table 3 for ^{3}He in the range of 0.65 K to 3.2 K, and for ^{4}He in the ranges 1.25 K to 2.1768 K (the λ point) and 2.1768 K to 5.0 K.

3.2 From 3.0 K to the Triple Point of Neon (24.5561 K): Gas Thermometer

In this range T_{90} is defined in terms of a ^{3}He or a ^{4}He gas thermometer of the constant-volume type that has been calibrated at three temperatures. These are the triple point of neon (24.5561 K), the triple point of equilibrium hydrogen (13.8033 K), and a temperature between 3.0 K and 5.0 K. This last temperature is determined using a ^{3}He or a ^{4}He vapor pressure thermometer as specified in Sect. 3.1.

3.2.1 From 4.2 K to the Triple Point of Neon (24.5561 K) with ^{4}He as the Thermometric Gas—In this range T_{90} is defined by the relation

$$T_{90} = a + bp + cp^2 \tag{4}$$

TABLE 2—*Effect of pressure on the temperatures of some defining fixed points.*[a]

Substance	Assigned Value of Equilibrium Temperature T_{90}/K	Temperature with Pressure, $p\,(dT/dp)/(10^{-8}\,K\cdot Pa^{-1})$[b]	Variation with Depth, $l\,(dT/dl)/(10^{-3}\,K\cdot m^{-1})$[c]
e-Hydrogen (T)	13.8033	34	0.25
Neon (T)	24.5561	16	1.9
Oxygen (T)	54.3584	12	1.5
Argon (T)	83.8058	25	3.3
Mercury (T)	234.3156	5.4	7.1
Water (T)	273.16	−7.5	−0.73
Gallium	302.9146	−2.0	−1.2
Indium	429.7485	4.9	3.3
Tin	505.078	3.3	2.2
Zinc	692.677	4.3	2.7
Aluminium	933.473	7.0	1.6
Silver	1234.93	6.0	5.4
Gold	1337.33	6.1	10
Copper	1357.77	3.3	2.6

[a]The Reference pressure for melting and freezing points is the standard atmosphere (p_0 = 101 325 Pa). For triple points (T) the pressure effect is a consequence only of the hydrostatic head of liquid in the cell.
[b]Equivalent to millikelvins per standard atmosphere.
[c]Equivalent to millikelvins per meter of liquid.

where p is the pressure in the gas thermometer and a, b, and c are coefficients the numerical values of which are obtained from measurements made at the three defining fixed points given in Sect. 3.2, but with the further restriction that the lowest one of these points lies between 4.2 K and 5.0 K.

3.2.2 From 3.0 K to the Triple Point of Neon (24.5561 K) with ^3He or ^4He as the Thermometric Gas—For a ^3He gas thermometer, and for a ^4He

TABLE 3—*Values of the constants for the helium vapor pressure Eqs 3, and the temperature range for which each equation, identified by its set of constants, is valid.*

	^3He 0.65 K to 3.2 K	^4He 1.25 K to 2.1768 K	^4He 2.1768 K to 5.0 K
A_0	1.053 447	1.392 408	3.146 631
A_1	0.980 106	0.527 153	1.357 655
A_2	0.676 380	0.166 756	0.413 923
A_3	0.372 692	0.050 988	0.091 159
A_4	0.151 656	0.026 514	0.016 349
A_5	−0.002 263	0.001 975	0.001 826
A_6	0.006 596	−0.017 976	−0.00 4325
A_7	0.008 966	0.005 409	−0.00 4973
A_8	−0.004 770	0.013 259	0
A_9	−0.054 943	0	0
B	7.3	5.6	10.3
C	4.3	2.9	1.9

gas thermometer used below 4.2 K, the nonideality of the gas must be accounted for explicitly, using the appropriate second virial coefficient $B_3(T_{90})$ or $B_4(T_{90})$. In this range T_{90} is defined by the relation

$$T_{90} = \frac{a + bp + cp^2}{1 + B_x(T_{90})N/V} \quad (5)$$

where p is the pressure in the gas thermometer, a, b, and c are coefficients the numerical values of which are obtained from measurements at three defining temperatures as given in Sect. 3.2, N/V is the gas density with N being the quantity of gas, and V the volume of the bulb, x is 3 or 4 according to the isotope used, and the values of the second virial coefficients are given by the relations

For ^{3}He,

$$B(T_{90})/\text{m}^3\,\text{mol}^{-1} = \{16.69 - 336.98(T_{90}/\text{K})^{-1} + 91.04(T_{90}/\text{K})^{-2} - 13.82(T_{90}/\text{K})^{-3}\}10^{-6} \quad (6a)$$

For ^{4}He,

$$B_4(T_{90})/\text{m}^3\,\text{mol}^{-1} = \{16.708 - 374.05(T_{90}/\text{K})^{-1} - 383.53(T_{90}/\text{K})^{-2} + 1799.2(T_{90}/\text{K})^{-3} - 4033.2(T_{90}/\text{K})^{-4} + 3252.8(T_{90}/\text{K})^{-5}\}10^{-6} \quad (6b)$$

The accuracy with which T_{90} can be realized using Eqs 4 and 5 depends on the design of the gas thermometer and the gas density used. Design criteria and current good practice required to achieve a selected accuracy are given in "Supplementary Information for the ITS-90."

3.3 The Triple Point of Equilibrium Hydrogen (13.8033 K) to the Freezing Point of Silver (961.78°C): Platinum Resistance Thermometer

In this range T_{90} is defined by means of a platinum resistance thermometer calibrated at specified sets of defining fixed points, and using specified reference and deviation functions for interpolation at intervening temperatures.

No single platinum resistance thermometer can provide high accuracy, or is even likely to be usable, over all of the temperature range 13.8033 K to 961.78°C. The choice of temperature range, or ranges, from among those listed below for which a particular thermometer can be used is normally limited by its construction.

For practical details and current good practice, in particular concerning types of thermometer available, their acceptable operating ranges, probable accuracies, permissible leakage resistance, resistance values, and thermal treatment, see "Supplementary Information for the ITS-90." It is particularly important to take account of the appropriate heat treatments that should be followed each time a platinum resistance thermometer is subjected to a temperature above about 420°C.

Temperatures are determined in terms of the ratio of the resistance $R(T_{90})$ at a temperature T_{90} and the resistance $R(273.16\ \text{K})$ at the triple point of water. This ratio, $W(T_{90})$ is[3]

$$W(T_{90}) = R(T_{90})/R(273.16\ \text{K}) \tag{7}$$

An acceptable platinum resistance thermometer must be made from pure, strain-free platinum, and it must satisfy at least one of the following two relations

$$W(29.7646°\text{C}) \geq 1.118\,07 \tag{8a}$$

$$W(-38.8344°\text{C}) \leq 0.844\,235 \tag{8b}$$

An acceptable platinum resistance thermometer that is to be used up to the freezing point of silver must also satisfy the relation

$$W(961.78°\text{C}) \geq 4.2844 \tag{8c}$$

In each of the resistance thermometer ranges, T_{90} is obtained from $W_r(T_{90})$ as given by the appropriate reference function {Eqs 9*b* or 10*b*}, and the deviation $W(T_{90}) - W_r(T_{90})$. At the defining fixed points this deviation is obtained directly from the calibration of the thermometer: at intermediate temperatures it is obtained by means of the appropriate deviation function {Eqs 12, 13, and 14}.

(i)—For the range 13.8033 K to 273.16 K the following reference function is defined

$$\ln[W_r(T_{90})] = A_0 + \sum_{i=1}^{12} A_i \left[\frac{\ln(T_{90}/273.16\ \text{K}) + 1.5}{1.5}\right]^i \tag{9a}$$

An inverse function, equivalent to Eq 9*a* to within 0.1 mK, is

$$T_{90}/273.16\ \text{K} = B_0 + \sum_{i=1}^{15} B_i \left[\frac{W_r(T_{90})^{1/6} - 0.65}{0.35}\right]^i \tag{9b}$$

The values of the constants A_0, A_i, B_0, and B_i are given in Table 4.

A thermometer may be calibrated for use throughout this range or, using progressively fewer calibration points, for ranges with low temperature limits of 24.5561 K, 54.3584 K, and 83.8058 K, all having an upper limit of 273.16 K.

[3]Note that this definition of $W(T_{90})$ differs from the corresponding definition used in the ITS-27, ITS-48, IPTS-48, and IPTS-68: for all of these earlier scales $W(T)$ was defined in terms of a reference temperature of 0°C, which since 1954 has itself been defined as 273.15 K.

(ii)—For the range 0°C to 961.78°C the following reference function is defined

$$W_r(T_{90}) = C_0 + \sum_{i=1}^{9} C_i \left[\frac{T_{90}/\mathrm{K} - 754.15}{481} \right]^i \tag{10a}$$

An inverse function, equivalent to Eq 10*a* to within 0.13 mK is

$$T_{90}/\mathrm{K} - 273.15 = D_0 + \sum_{i=1}^{9} D_i \left[\frac{W_r(T_{90}) - 2.64}{1.64} \right]^i \tag{10b}$$

The values of the constants C_0, C_i, D_0, and D_i are given in Table 4.

A thermometer may be calibrated for use throughout this range or, using fewer calibration points, for ranges with upper limits of 660.323°C, 419.527°C, 231.928°C, 156.5985°C, or 29.7646°C, all having a lower limit of 0°C.

(iii)—A thermometer may be calibrated for use in the range 234.3156 K (−38.8344°C) to 29.7646°C, the calibration being made at these temperatures and at the triple point of water. Both reference functions {Eqs 9 and 10} are required to cover this range.

The defining fixed points and deviation functions for the various ranges are given below, and in summary form in Table 5.

TABLE 4—*The constants* A_0, A_i; B_0, B_i; C_0, C_i; D_0 *and* D_i *in the reference functions of Eqs* 9a; 9b; *10*a; *and 10*b *respectively.*

A_0	−2.135 347 29	B_0	0.183 324 722	B_{13}	−0.091 173 542
A_1	3.183 247 20	B_1	0.240 975 303	B_{14}	0.001 317 696
A_2	−1.801 435 97	B_2	0.209 108 771	B_{15}	0.026 025 526
A_3	0.717 272 04	B_3	0.190 439 972		
A_4	0.503 440 27	B_4	0.142 648 498		
A_5	−0.618 993 95	B_5	0.077 993 465		
A_6	−0.053 323 22	B_6	0.012 475 611		
A_7	0.280 213 62	B_7	−0.032 267 127		
A_8	0.107 152 24	B_8	−0.075 291 522		
A_9	−0.293 028 65	B_9	−0.056 470 670		
A_{10}	0.044 598 72	B_{10}	0.076 201 285		
A_{11}	0.118 686 32	B_{11}	0.123 893 204		
A_{12}	−0.052 481 34	B_{12}	−0.029 201 193		
C_0	2.781 572 54	D_0	439.932 854		
C_1	1.646 509 16	D_1	472.418 020		
C_2	−0.137 143 90	D_2	37.684 494		
C_3	0.006 497 67	D_3	7.472 018		
C_4	−0.002 344 44	D_4	2.920 828		
C_5	0.005 118 68	D_5	0.005 184		
C_6	0.001 879 82	D_6	−0.963 864		
C_7	−0.002 044 72	D_7	−0.188 732		
C_8	−0.000 461 22	D_8	0.191 203		
C_9	0.000 457 24	D_9	0.049 025		

TABLE 5—*Deviation functions and calibration points for platinum resistance thermometers in the various ranges in which they define* T_{90}.

a. Ranges with an Upper Limit of 273.16 K

Section	Lower Temperature Limit T/K	Deviation Functions	Calibration Points (see Table 1)
3.3.1	13.8033	$a[W(T_{90}) - 1] + b[W(T_{90}) - 1]^2 + \sum_{i=1}^{5} c_i[\ln W(T_{90})]^{i+n}$, $n = 2$	2–9
3.3.1.1	24.5561	As for 3.3.1 with $c_4 = c_5 = n = 0$	2, 5–9
3.3.1.2	54.3584	As for 3.3.1 with $c_2 = c_3 = c_4 = c_5 = 0, n = 1$	6–9
3.3.1.3	83.8058	$a[W(T_{90}) - 1] + b[W(T_{90}) - 1] \ln W(T_{90})$	7–9

b. Ranges with a Lower Limit of 0°C

Section	Upper Temperature Limit t/°C	Deviation Functions	Calibration Points (see Table 1)
3.3.2.[a]	961.78	$a[W(T_{90}) - 1] + b[W(T_{90}) - 1]^2 + c[W(T_{90}) - 1]^3 + d[W(T_{90}) - W(660.323°C)]^2$	9, 12–15
3.3.2.1	660.323	As for 3.3.2 with $d = 0$	9, 12–14
3.3.2.2	419.527	As for 3.3.2 with $c = d = 0$	9, 12, 13
3.3.2.3	231.928	As for 3.3.2 with $c = d = 0$	9, 11, 12
3.3.2.4	156.5985	As for 3.3.2 with $b = c = d = 0$	9, 11
3.3.2.5	29.7646	As for 3.3.2 with $b = c = d = 0$	9, 10

c. Range from 234.3156 K (−38.8344°C) to 29.7646°C

Section		Deviation Functions	Calibration Points
3.3.3		As for 3.3.2 with $c = d = 0$	8–10

[a]Calibration points 9, 12–14 are used with $d = 0$ for $t_{90} \leq 660.323$°C; the values of a, b, and c thus obtained are retained for $t_{90} > 660.323$°C, with d being determined from calibration point 15.

3.3.1 The Triple Point of Equilibrium Hydrogen (13.8033 K) to the Triple Point of Water (273.16 K)

The thermometer is calibrated at the triple points of equilibrium hydrogen (13.8033 K), neon (24.5561 K), oxygen (54.3584 K), argon (83.8058 K), mercury (234.3156 K), and water (273.16 K), and at two additional temperatures close to 17.0 K and 20.3 K. These last two may be determined either: by using a gas thermometer as described in Sect. 3.2, in which case the two temperatures must lie within the ranges 16.9 K to 17.1 K and 20.2 K to 20.4 K, respectively; or by using the vapor pressure-temperature relation of equilibrium hydrogen, in which case the two temperatures must lie within the ranges 17.025 K to 17.045 K and 20.26 K to 20.28 K, respectively, with the precise values being determined from Eqs 11*a* and 11*b* respectively

$$T_{90}/\mathrm{K} - 17.035 = (p/\mathrm{kPa} - 33.3213)/13.32 \qquad (11a)$$

$$T_{90}/\mathrm{K} - 20.27 = (p/\mathrm{kPa} - 101.292)/30 \qquad (11b)$$

The deviation function is[4]

$$W(T_{90}) - W_r(T_{90}) = a[W(T_{90}) - 1] + b[W(T_{90}) - 1]^2 + \sum_{i=1}^{5} c_i[\ln W(T_{90})]^{i+n} \qquad (12)$$

with values for the coefficients a, b, and c_i being obtained from measurements at the defining fixed points and with $n = 2$.

For this range and for the subranges 3.3.1.1 to 3.3.1.3 the required values of $W_r(T_{90})$ are obtained from Eq 9*a* or from Table 1.

3.3.1.1 The Triple Point of Neon (24.5561 K) to the Triple Point of Water (273.16 K)—The thermometer is calibrated at the triple points of equilibrium hydrogen (13.8033 K), neon (24,5561 K), oxygen (54,3584 K), argon (83.8058 K), mercury (234.3156 K), and water (273.16 K).

The deviation function is given by Eq 12 with values for the coefficients a, b, c_1, c_2, and c_3 being obtained from measurements at the defining fixed points and with $c_4 = c_5 = n = 0$.

3.3.1.2 The Triple Point of Oxygen (54.3584 K) to the Triple Point of Water (273.16 K)—The thermometer is calibrated at the triple points of oxygen (54.3584 K), argon (83.8058 K), mercury (234.3156 K), and water (273.16 K).

The deviation function is given by Eq 12 with values for the coefficients a, b, and c_1 being obtained from measurements at the defining fixed points, with $c_2 = c_3 = c_4 = c_5 = 0$ and with $n = 1$.

3.3.1.3 The Triple Point of Argon (83.8058 K) to the Triple Point of Water (273.16 K)—The thermometer is calibrated at the triple points of argon (83.8058 K), mercury (234.3156 K), and water (273.16 K).

The deviation function is

$$W(T_{90}) - W_r(T_{90}) = a[W(T_{90}) - 1] + b[W(T_{90}) - 1] \ln W(T_{90}) \qquad (13)$$

with the values of a and b being obtained from measurements at the defining fixed points.

3.3.2 From 0°C to the Freezing Point of Silver (961.78°C)

The thermometer is calibrated at the triple point of water (0.01°C), and at the freezing points of tin (231.928°C), zinc (419.527°C), aluminium (660.323°C), and silver (961.78°C).

[4]This deviation function (and also those of Eqs 13 and 14) may be expressed in terms of W_r rather than W; for this procedure see "Supplementary Information for ITS-90."

The deviation function is

$$W(T_{90}) - W_r(T_{90}) = a[W(T_{90}) - 1] + b[W(T_{90}) - 1]^2 + c[W(T_{90}) - 1]^3 + d[W(T_{90}) - W(660.323°\text{C})]^2 \quad (14)$$

For temperatures below the freezing point of aluminium $d = 0$, with the values of a, b, and c being determined from the measured deviations from $W_r(T_{90})$ at the freezing points of tin, zinc, and aluminium. From the freezing point of aluminium to the freezing point of silver the above values of a, b, and c are retained and the value of d is determined from the measured deviation from $W_r(T_{90})$ at the freezing point of silver.

For this range and for the subranges 3.3.2.1 to 3.3.2.5 the required values for $W_r(T_{90})$ are obtained from Eq 10*a* or from Table 1.

3.3.2.1 From 0°C to the Freezing Point of Aluminium (660.323°C)—The thermometer is calibrated at the triple point of water (0.01°C), and at the freezing points of tin (231.928°C), zinc (419.527°C), and aluminium (660.323°C).

The deviation function is given by Eq 14, with the values of a, b, and c being determined from measurements at the defining fixed points and with $d = 0$.

3.3.2.2 From 0°C to the Freezing Point of Zinc (419.527°C)—The thermometer is calibrated at the triple point of water (0.01°C), and at the freezing points of tin (231.928°C) and zinc (419.527°C).

The deviation function is given by Eq 14 with the values of a and b being obtained from measurements at the defining fixed points and with $c = d = 0$.

3.3.2.3 From 0°C to the Freezing Point of Tin (231.928°C)—The thermometer is calibrated at the triple point of water (0.01°C), and at the freezing points of indium (156.5985°C) and tin (231.928°C).

The deviation function is given by Eq 14 with the values of a and b being obtained from measurements at the defining fixed points and with $c = d = 0$.

3.3.2.4 From 0°C to the Freezing Point of Indium (156.5985°C)—The thermometer is calibrated at the triple point of water (0.01°C), and at the freezing point of indium (156.5985°C).

The deviation function is given by Eq 14 with the value of a being obtained from measurements at the defining fixed points and with $b = c = d = 0$.

3.3.2.5 From 0°C to the Melting Point of Gallium (29.7646°C)—The thermometer is calibrated at the triple point of water (0.01°C), and at the melting point of gallium (29.7646°C).

The deviation function is given by Eq 14 with the value of a being obtained from measurements at the defining fixed points and with $b = c = d = 0$.

3.3.3 The Triple Point of Mercury (−38.8344°C) to the Melting Point of Gallium (29.7646°C)

The thermometer is calibrated at the triple points of mercury (−38.8344°C), and water (0.01°C), and at the melting point of gallium (29.7646°C).

The deviation function is given by Eq 14 with the values of a and b being obtained from measurements at the defining fixed points and with $c = d = 0$.

The required values of $W_r(T_{90})$ are obtained from Eqs 9a and 10a for measurements below and above 273.16 K respectively, or from Table 1.

3.4 The Range Above the Freezing Point of Silver (961.78°C): Planck Radiation Law

Above the freezing point of silver the temperature T_{90} is defined by the equation

$$\frac{L_\lambda(T_{90})}{L_\lambda[T_{90}(\mathrm{X})]} = \frac{\exp(c_2[\lambda T_{90}(\mathrm{X})]^{-1}) - 1}{\exp(c_2[\lambda T_{90}]^{-1}) - 1} \tag{15}$$

where $T_{90}(\mathrm{X})$ refers to any one of the silver $\{T_{90}(\mathrm{Ag}) = 1234.93\ \mathrm{K}\}$, the gold $\{T_{90}(\mathrm{Au}) = 1337.33\ \mathrm{K}\}$, or the copper $\{T_{90}(\mathrm{Cu}) = 1357.77\ \mathrm{K}\}$ freezing points[5] and in which $L_\lambda(T_{90})$ and $L_\lambda[T_{90}(\mathrm{X})]$ are the spectral concentrations of the radiance of a blackbody at the wavelength (in vacuo) λ at T_{90} and at $T_{90}(\mathrm{X})$, respectively, and $c_2 = 0.014388\ \mathrm{m \cdot K}$.

For practical details and current good practice for optical pyrometry, see "Supplementary Information for the ITS-90" (BIPM-1990).

4. Supplementary Information and Differences from Earlier Scales

The apparatus, methods and procedures that will serve to realize the ITS-90 are given in "Supplementary Information for the ITS-90." This document also gives an account of the earlier International Temperature Scales and the numerical differences between successive scales that include, where practicable, mathematical functions for the differences $T_{90} - T_{68}$. A number of useful approximations to the ITS-90 are given in "Techniques for Approximating the ITS-90."

These two documents have been prepared by the Comité Consultatif de Thermométrie and are published by the BIPM; they are revised and updated periodically.

[5]The T_{90} values of the freezing points of silver, gold, and copper are believed to be self consistent to such a degree that the substitution of any one of them in place of one of the other two as the reference temperature $T_{90}(\mathrm{X})$ will not result in significant differences in the measured values of T_{90}.

The differences $T_{90} - T_{68}$ are shown in Fig. 1 and Table 6. The number of significant figures given in Table 6 allows smooth interpolations to be made. However, the reproducibility of the IPTS-68 is, in many areas, substantially worse than is implied by this number.

APPENDIX

The International Temperature Scale of 1927 (ITS-27)

The International Temperature Scale of 1927 was adopted by the seventh General Conference of Weights and Measures to overcome the practical difficulties of the direct realization of thermodynamic temperatures by gas thermometry, and as a universally acceptable replacement for the differing existing national temperature scales. The ITS-27 was formulated so as to allow measurements of temperature to be made precisely and reproducibly, with as close an approximation to thermodynamic temperatures as could be determined at that time. Between the oxygen boiling point and the gold freezing point it was based upon a number of reproducible temperatures, or fixed points, to which numerical values were assigned, and two standard interpolating instruments. Each of these interpolating instruments was calibrated at several of the fixed points, this giving the constants for the interpolating formula in the appropriate temperature range. A platinum resistance thermometer was used for the lower part and a platinum rhodium/platinum thermocouple for temperatures above 660°C. For the region above the gold freezing point, temperatures were defined in terms of the Wien radiation law: in practice, this invariably resulted in the selection of an optical pyrometer as the realizing instrument.

The International Temperature Scale of 1948 (ITS-48)

The International Temperature Scale of 1948 was adopted by the ninth General Conference. Changes from the ITS-27 were: the lower limit of the platinum resistance thermometer range was changed from -190°C to the defined oxygen boiling point of -182.97°C, and the junction of the platinum resistance thermometer range and the thermocouple range became the measured antimony freezing point (about 630°C) in place of 660°C; the silver freezing point was defined as being 960.8°C instead of 960.5°C; the gold freezing point replaced the gold melting point (1063°C); the Planck radiation law replaced the Wien law; the value assigned to the second radiation constant became 1.438×10^{-2} m · K in place of 1.432×10^{-2} m · K; the permitted ranges for the constants of the interpolation formulae for the standard resistance thermometer and thermocouple were modified; the limitation on λT for optical pyrometry ($\lambda T < 3 \times 10^{-3}$ m · K) was changed to the requirement that "visible" radiation be used.

The International Practical Temperature Scale of 1948 (Amended Edition of 1960) (IPTS-48)

The International Practical Temperature Scale of 1948, amended edition of 1960, was adopted by the eleventh General Conference: the tenth General Conference had already adopted the triple point of water as the sole point defining the kelvin, the unit of thermodynamic temperature. In addition to the introduction of the word "Practical", the modifications to the ITS-48 were: the triple point of water, defined as being 0.01 °C, replaced the melting point of ice as the calibration point in this region; the freezing point of zinc, defined as being 419.505 °C, became a preferred alternative to the sulfur boiling point (444.6°C) as a calibration point; the permitted ranges for the

TABLE 6—*Differences between ITS-90 and EPT-76, and between ITS-90 and IPTS-68 for specified values of* T_{90} *and* t_{90}.

					$(T_{90} - T_{76})$/mK					
T_{90}/K	0	1	2	3	4	5	6	7	8	9
0	...	...	...	...	...	−0.1	−0.2	−0.3	−0.4	−0.5
10	−0.6	−0.7	−0.8	−1.0	−1.1	−1.3	−1.4	−1.6	−1.8	−2.0
20	−2.2	−2.5	−2.7	−3.0	−3.2	−3.5	−3.8	−4.1		

					$(T_{90} - T_{68})$/K					
T_{90}/K	0	1	2	3	4	5	6	7	8	9
10	...	...	...	...	−0.006	−0.003	−0.004	−0.006	−0.008	−0.009
20	−0.009	−0.008	−0.007	−0.007	−0.006	−0.005	−0.004	−0.004	−0.005	−0.006
30	−0.006	−0.007	−0.008	−0.008	−0.008	−0.007	−0.007	−0.007	−0.006	−0.006
40	−0.006	−0.006	−0.006	−0.006	−0.006	−0.007	−0.007	−0.007	−0.006	−0.006
50	−0.006	−0.005	−0.005	−0.004	−0.003	−0.002	−0.001	0.000	0.001	0.002
60	0.003	0.003	0.004	0.004	0.005	0.005	0.006	0.006	0.007	0.007
70	0.007	0.007	0.007	0.007	0.007	0.008	0.008	0.008	0.008	0.008
80	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
90	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.009	0.009	0.009
T_{90}/K	0	10	20	30	40	50	60	70	80	90
100	0.009	0.011	0.013	0.014	0.014	0.014	0.014	0.013	0.012	0.012
200	0.011	0.010	0.009	0.008	0.007	0.005	0.003	0.001		

	$(t_{90} - t_{68})$/°C									
t_{90}/°C	0	−10	−20	−30	−40	−50	−60	−70	−80	−90
−100	0.013	0.013	0.014	0.014	0.014	0.013	0.012	0.010	0.008	0.008
0	0.000	0.002	0.004	0.006	0.008	0.009	0.010	0.011	0.012	0.012
t_{90}/°C	0	10	20	30	40	50	60	70	80	90
0	0.000	−0.002	−0.005	−0.007	−0.010	−0.013	−0.016	−0.018	−0.021	−0.024
100	−0.026	−0.028	−0.030	−0.032	−0.034	−0.036	−0.037	−0.038	−0.039	−0.039
200	−0.040	−0.040	−0.040	−0.040	−0.040	−0.040	−0.040	−0.039	−0.039	−0.039
300	−0.039	−0.039	−0.039	−0.040	−0.040	−0.041	−0.042	−0.043	−0.045	−0.046
400	−0.048	−0.051	−0.053	−0.056	−0.059	−0.062	−0.065	−0.068	−0.072	−0.075
500	−0.079	−0.083	−0.087	−0.090	−0.094	−0.098	−0.101	−0.105	−0.108	−0.112
600	−0.115	−0.118	−0.122	−0.125[a]	−0.08	−0.03	0.02	0.06	0.11	0.16
700	0.20	0.24	0.28	0.31	0.33	0.35	0.36	0.36	0.36	0.35
800	0.34	0.32	0.29	0.25	0.22	0.18	0.14	0.10	0.06	0.03
900	−0.01	−0.03	−0.06	−0.08	−0.10	−0.12	−0.14	−0.06	−0.17	−0.18
1000	−0.19	−0.20	−0.21	−0.22	−0.23	−0.24	−0.25	−0.25	−0.26	−0.26
t_{90}/°C	0	100	200	300	400	500	600	700	800	900
1000		−0.26	−0.30	−0.35	−0.39	−0.44	−0.49	−0.54	−0.60	−0.66
2000	−0.72	−0.79	−0.85	−0.93	−1.00	−1.07	−1.15	−1.24	−1.32	−1.41
3000	−1.50	−1.59	−1.69	−1.78	−1.89	−1.99	−2.10	−2.21	−2.32	−2.43

[a] A discontinuity in the first derivative of $(t_{90} - t_{68})$ occurs at a temperature of $t_{90} = 630.6$°C, at which $(t_{90} - t_{68}) = -0.125$°C.

constants of the interpolation formulae for the standard resistance thermometer and the thermocouple were further modified; the restriction to "visible" radiation for optical pyrometry was removed.

Inasmuch as the numerical values of temperature on the IPTS-48 were the same as on the ITS-48, the former was not a revision of the scale of 1948 but merely an amended form of it.

The International Practical Temperature Scale of 1968 (IPTS-68)

In 1968 the International Committee of Weights and Measures promulgated the International Practical Temperature Scale of 1968, having been empowered to do so by the thirteenth General Conference of 1967–1968. The IPTS-68 incorporated very extensive changes from the IPTS-48. These included numerical changes, designed to bring it more nearly in accord with thermodynamic temperatures, that were sufficiently large to be apparent to many users. Other changes were as follows: the lower limit of the scale was extended down to 13.81 K; at even lower temperatures (0.5 K to 5.2 K), the use of two helium vapor pressure scales was recommended; six new defining fixed points were introduced—the triple point of equilibrium hydrogen (13.81 K), an intermediate equilibrium hydrogen point (17.042 K), the normal boiling point of equilibrium hydrogen (20.28 K), the boiling point of neon (27.102 K), the triple point of oxygen (54.361 K), and the freezing point of tin (231.9681°C) which became a permitted alternative to the boiling point of water; the boiling point of sulfur was deleted; the values assigned to four fixed points were changed—the boiling point of oxygen (90.188 K), the freezing point of zinc (419.58°C), the freezing point of silver (961.93°C), and the freezing point of gold (1064.43°C); the interpolating formulae for the resistance thermometer range became much more complex; the value assigned to the second radiation constant c_2 became 1.4388×10^{-2} m · K; the permitted ranges of the constants for the interpolation formulae for the resistance thermometer and thermocouple were again modified.

The International Practical Temperature Scale of 1968 (Amended Edition of 1975) (IPTS-68)

The International Practical Temperature Scale of 1968, amended edition of 1975, was adopted by the fifteenth General Conference in 1975. As was the case for the IPTS-48 with respect to the ITS-48, the IPTS-68(75) introduced no numerical changes. Most of the extensive textural changes were intended only to clarify and simplify its use. More substantive changes were: the oxygen point was defined as the condensation point rather than the boiling point; the triple point of argon (83.798 K) was introduced as a permitted alternative to the condensation point of oxygen; new values of the isotopic composition of naturally occurring neon were adopted; the recommendation to use values of T given by the 1958 ^{4}He and 1962 ^{3}He vapor-pressure scales was rescinded.

The 1976 Provisional 0.5 K to 30 K Temperature Scale EPT-76

The 1976 Provisional 0.5 K to 30 K Temperature Scale was introduced to meet two important requirements: these were to provide means of substantially reducing the errors (with respect to corresponding thermodynamic values) below 27 K that were then known to exist in IPTS-68 and throughout the temperature ranges of the ^{4}He and ^{3}He vapor pressure scales of 1958 and 1962, respectively, and to bridge the gap between 5.2 K and 13.81 K in which there had not previously been an international scale. Other objectives in devising the ETP-76 were "that it should be thermodynamically smooth, that it should be continuous with the IPTS-68 at 27.1 K, and that is should agree with thermodynamic temperature T as closely as these two conditions allow." In contrast with the IPTS-68, and to ensure its rapid adoption, several methods of realizing the ETP-76 were approved. These included: using a thermodynamic interpolation instrument and one or more of eleven assigned reference points; taking differences from the IPTS-68 above 13.81 K; taking differences from helium vapor pressure scales below 5 K; and taking differences from certain well-established laboratory scales. Because there was a certain "lack of internal consistency" it was admitted that "slight ambiguities between realizations" might be introduced. However the advantages gained by adopting the EPT-76 as a working scale until such time as the IPTS-68 should be revised and extended were considered to outweigh the disadvantages.

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