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ASRDI OXYGEN TECHNOLOGY SURVEY

Volume IV: Low Temperature Measurement

SPARKS

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Volume IV:

Low Temperature Measurement

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PREFACE

This publication is part of an oxygen safety review in progress by the NASA Aerospace Safety Research and Data Institute (ASRDI). The objectives of the review include:

1. Recommendations to improve NASA oxygen handling practices by comparing NASA and contractor oxygen systems including the design, inspection, operation, maintenance and emergency procedures.

2. Assessment of the vulnerability to failure of oxygen equipment from a variety of sources so that hazards may be defined and remedial measures formulated.

3. Contributions to safe oxygen handling techniques through research.

4. Formulation of criteria and standards on all aspects of oxygen handling, storage, and disposal.

This special publication summarizes the current state of the art in temperature measurement in the general region between the triple point and critical point of oxygen (approximately 50 - 150 K). The three basic instrument types, resistance, thermocouples and filled thermometers are described. Calibration methods are discussed as well as tables and analytical data representations. The survey includes details of thermometer mounting and use as well as information on associated instrumentation. The relationship of the IPTS-68 temperature scale to previously used scales is also covered. Throughout the survey problem areas are identified and recommendations for further work are listed.

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FOREWORD

The specific goal of this review is to present up to date information on temperature measurement between the triple and critical point of oxygen. Temperature transducers which can be used in this range are treated over their entire range of usefulness. Three broad types of thermometer are considered -- resistance thermometers, thermocouples, and filled systems. In particular, platinum, indium, copper, germanium, carbon, and thermistor resistance thermometers are considered; thermocouple standard types E, K, T, and J plus various combinations utilizing Au-Co and Au-Fe alloys are considered; vapor pressure systems utilizing He, H_2, Ne, N_2, and O_2 as fill substances are discussed. Methods of low temperature thermometry are presented along with methods of calibration and analytical representation. Reference data are given in terms of Cragoe Z functions for indium and copper resistance thermometers and resistance ratios for carbon. Reference tables are included for each thermocouple type along with the power series coefficients necessary to generate the tabular data. Tabular vapor pressure data and analytical functions for each fill gas are also included. The relationship of the IPTS-68 temperature scale to previously used scales is discussed.

I would like to thank many of my colleagues for valuable discussions during the preparation of this volume. In particular, I appreciate the cooperation of Dr. R. L. Powell for the use of information now being published in NBS Monograph 125 and T. R. Strobridge for discussions of vapor pressure thermometry. I am indebted to ASRDI Project Manager Paul Ordin of the NASA-Lewis Research Center for his support and many helpful suggestions during the course of this work.

Larry L. Sparks

KEY WORDS

Calibration; cryogenics; liquid helium; liquid hydrogen; liquid neon; liquid nitrogen; liquid oxygen; reference data; resistance thermometers; thermocouples; thermometry; vapor pressure.

TABLE OF CONTENTS

List of Figures

List of Figures (continued)

List of Tables

List of Tables (continued)

INTRODUCTION

The use of cryogenic liquids as refrigerants and propellants has increased tremendously in the last ten to fifteen years. With the massive space program initiated in the 1960's as a significant impetus, cryogenics has reached into the fields of medicine, industry, agriculture, food processing, and others. These new uses of cryogenic liquids together with continuing space, military, and scientific research create a demand for compiled sources of information in such areas as temperature, pressure, and flow measurement.

The specific goal of this report is to present state of the art information on temperature measurement between the triple point and critical point of liquid oxygen. However, since this temperature range would be unnecessarily restrictive for most of the thermometers to be discussed, the criterion selected here is that all transducers which may reasonably be employed in the liquid oxygen (LO_2) temperature range will be considered. The temperature range for each transducer will be the appropriate full range for the particular thermometer.

The discussion of vapor pressure thermometry constitutes an exception to the "use in the LO_2 range" rule in that He, H_2, Ne, N_2, and O_2 will be considered as fill substances.

The discussion of each thermometer or type of thermometer will include, as nearly as possible, the following information:

1) useful temperature range,
2) general and particular methods of construction and the advantages of each type,
3) specifications (accuracy, reproducibility, response time, etc.),
4) associated instrumentation,
5) calibrations and procedures, and
6) analytical representations.

An extremely important part of any compilation such as this is the reference section. An author index has been included to supplement the reference section. In addition, a subject index identifying the major areas of discussion and associated pages, tables, figures, and references is included.

Certain previous review papers [1, 2, 3, 4] are so generally useful in the field of low temperature thermometry that many of the thoughts presented here must ultimately be credited to them. No further attempt will be made to cite these works except in the case of specific information.

TEMPERATURE AND TEMPERATURE SCALES

The concept of temperature is most properly based on the cyclic operation of a reversible heat engine. Temperature, then, is established by the laws of thermodynamics and is independent of the properties of the working medium. Thermodynamic arguments can be made which show that temperature is something which is proportional to the heat absorbed or evolved along the isotherms of a reversible Carnot cycle [5]. Unfortunately, this most basic approach is of little use in actually establishing an absolute temperature scale, because we have not been able to approach the reversible engine requirement. Other fundamental instruments (thermometers which in theory are independent of the working medium) such as optical pyrometers, velocity of sound thermometers, and constant volume gas thermometers have been utilized to approximate the thermodynamic scale. Of particular importance in this discussion are the acoustical and constant volume gas thermometers. The approximation involved in both of these systems is that of real gas properties becoming ideal gas properties as the density approaches zero. Using thermodynamics and kinetic theory [6, 7], temperature, as determined on the ideal gas scale, can be shown to be proportional to temperature on the absolute thermodynamic scale. Historically, constant volume gas thermometry has provided a practical link between empirical thermometers (thermometers whose characteristics depend on real materials) and the thermodynamic temperature scale. In a practical sense, however, use of the fundamental thermometers is limited to special situations. In general, only the national laboratories and a few universities have the capability of using these instruments at a state of the art level. Their primary use has been to transfer the best estimate of the thermodynamic scale to a few precision empirical thermometers. These transfer standards are, in turn, used to calibrate the many working thermometers by the comparison method.

As instrumentation and techniques improve, temperature scales become better approximations of the ideal thermodynamic scale. The history of the international attempt to establish a common temperature scale that represents the thermodynamic scale as nearly as possible has been thoroughly discussed [8]. A brief overview of the situation leading to the present International Practical Temperature Scale (IPTS-68) is presented here.

In 1927, the General Conference on Weights and Measures adopted the first internationally accepted temperature scale for temperatures above -190°C [9]. Minor revisions to the scale, including making the normal boiling point (n.b.p.) of liquid oxygen the lower limit, were made in 1948. There was a text revision in 1960 [10]; the revision added the word PRACTICAL to the official name for the first time. The scale was thus represented by IPTS-48 rather than ITS-48. No internationally accepted scale existed for temperatures below the n.b.p. of oxygen. Several laboratories developed and maintained their own standards for the temperatures not covered by IPTS-48. In 1968, the General Conference adopted IPTS-68 [11], the latest revision of the practical temperature scale. Of major importance in this revision was the extension of the scale to 13.81 K. Changes in several of the fixed points for IPTS-68 are compared to those of previous scales in table 1.

As mentioned previously, before IPTS-68 was available, several laboratories established their own scales for temperatures below 90 K. One of the most widely used in the United States was established by Hoge and Brickwedde [12] of the National Bureau of Standards. They compared platinum resistance thermometers to a helium gas thermometer in the range from 10 to 90 K. They used 90.19 K as the best value for the n.b.p. of oxygen; this scale was designated NBS-39. In 1955 the scale was changed by assuming a value of 90.18 K for the n.b.p. of oxygen. The resulting NBS scale was used by NBS as the standard in this range until 1968. In 1961, Barber [13] established a similar scale at the National Physical Laboratory in England. As was the case with the NBS-39 scale, the fundamental thermometer was a constant volume gas thermometer and the transfer standards were platinum resistance thermometers. The range of this scale, NPL-61, is from 10 to 90 K, and the n.b.p. of oxygen was taken to be 90.18 K. In 1953 Moessen, et al., [14] of Pennsylvania State University established the 10-90 K scale known as PSU-54. Constant volume helium gas thermometry was again used to calibrate platinum resistance thermometer transfer standards. The n.b.p. of oxygen for this scale was 90.154 K. The final widely used 10-90 K scale was established by Borovik-Romanov, et al., [15] in 1954. This scale, PRMI-54, was used as the Russian national scale with the n.b.p. of oxygen as 90.19 K. In 1965 Orlova, et al., [16] redetermined the n.b.p. of oxygen to be 90.165 K. Table 2 [17] compares these 10-90 K temperature scales to IPTS-68. The tabular values given in this table may be used to base "pre IPTS-68 data" on IPTS-68 for temperatures below 90 K. Above 90 K temperatures based in IPTS-48 may be converted to IPTS-68 by using the differences given in table 3 [11]. Both tables 2 and 3 give the deviations in the form $T_{68} - T_X = \Delta T$. T_X represents any one of the 10-90 K scales in table 2 and IPTS-48 in table 3. For a table with a finer grid of temperatures than given in table 3, the reader is referred to Douglas [18]. He has used three analytical expressions to represent $T_{68} - T_{48}$ and

$$\frac{d(T_{68} - T_{48})}{d\,T_{68}}$$

between 90 K and 10,000 K. The values arrived at using his expressions for $T_{68} - T_{48}$ agree exactly with those given in table 3. The analytical expression given by Douglas for temperatures between 90.188 and 273.15 K is

$$T_{68} - T_{48} = \frac{A_1[1 + A_2 t_{68} + A_3 t_{68}^2 + A_4(100 - t_{68})\, t_{68}^3 - W_t^*]}{1 + A_5 t_{68} + A_6(75 - t_{68}) t_{68}^2}$$

where W_t^* is the reference function $W_{CCT-68}(T_{68})$ given in [11], and t_{68} represents temperatures in degrees Celsius on IPTS-68. The coefficients for this equation are:

$$A_1 = 250.97$$

$$A_2 = 3.9845170 \times 10^{-3}$$

$$A_3 = -5.855019 \times 10^{-7}$$

$$A_4 = 4.35717 \times 10^{-12}$$

$$A_5 = -2.9389 \times 10^{-4}$$

$$A_6 = 4.3741 \times 10^{-9} .$$

A temperature scale between 2 and 20 K, based on velocity of sound measurements was established in 1965 and 1966 by Cataland and Plumb [19, 20]. This scale is officially known as NBS P 2-20 (1965). In the temperature range where they overlap (13.81 K up to 20 K), NBS P 2-20 (1965) and IPTS-68 differ as shown in table 4. The scale recommended by the International Committee for Weights and Measures (CIPM) for temperatures between 1 and 5.2 K is known as the 1958 He^4 scale of temperatures [21].

SELECTION OF THERMOMETER

The problem of choosing the proper thermometer for a given situation is often a series of compromises. In most engineering situations, temperature measurement is not the primary reason for the test, and the design criteria are based on other requirements. The basic questions which should be considered, however, apply to all systems in which temperature measurements are to be made. Costly mistakes can often be avoided if questions such as these are considered before the choice of the transducer is made.

1) What is the temperature range of interest? This seems to be straightforward enough. However, what is the probability of occasionally having to extend the temperature range? Is double instrumentation justified to cover the entire range or will a single type of transducer suffice with some loss of sensitivity and/or accuracy in certain ranges?

2) How accurate must the results be? Realize that, in general, greater accuracy requires more sophisticated transducers, instruments, and calibrations. Is accuracy and/or precision the real requirement?

3) What instrumentation is available or can be acquired? Selection of the optimum instruments to complement the situation and transducer depend on accuracy, physical size and ruggedness, time response, and time required to make a reading. Cost and delivery time may have to be considered.

4) Is the physical size of the thermometer important either from a space or heat capacity point of view? The time response of a transducer is proportional to its heat capacity (among other things).

5) Will hostile environments be encountered before or during operation? In the cryogenic temperature range sensor-environment compatibility is not as critical as it is at higher temperatures; however, even though chemical reactions are much slower at low temperatures, oxygen does promote increased reactivity. The system designer should also consider situations where high temperatures may be encountered even briefly. System bake out, soldering, welding, etc., can damage low temperature thermometers and calibrations.

6) How rugged must the thermometers be considering g-forces, vibration, thermal shock, handling, etc.?

7) How is thermal contact to the specimen to be accomplished?

8) What calibrations are necessary in order to achieve the desired accuracy with particular types of thermometers? Are analytical representations available which are consistent with the desired method of analysis?

9) How important is it that the thermometers be interchangeable at some later date?

There may very well be other considerations for particular situations. The questions (and more importantly the answers) are interrelated which ultimately leads to the compromises mentioned earlier. Frequently there will be one overriding consideration which will allow only a particular type of thermometer.

As each type of thermometer is discussed below, specific information for each of these areas of concern will be presented when available. The summary section will contain comparisons between different types of thermometers and general conclusions about the principal advantages and disadvantages of each type of thermometer.

THERMOMETER TYPES TO BE CONSIDERED

The general types of temperature transducers to be considered here are resistance, thermoelectric, and filled systems. A recent compilation of the commercial availability of thermometers is given in [22].

Thermometers depending on resistance changing as a function of temperature may be divided into two groups -- metallic and nonmetallic. Active thermometer elements of platinum, indium, and copper are the most commonly used metallic thermometers while carbon and germanium are the most commonly used non-metallic resistance thermometers. Thermistors, resistors made of sintered metal oxides, will be included in the nonmetal group. Several other metals and nonmetals have received much more limited use and will be discussed only briefly.

Thermoelectric thermometers will be considered in detail from both materials and methods points of view. Complete calibration tables and analytic functions will be given for the standard types[1] Chromel vs. constantan (Type E), Chromel vs. Alumel (Type K), iron vs. constantan (Type J), and copper vs. constantan (Type T). A discussion of the nominal compositions, the standardized letter designations, and the registered trade names is given in Appendix A. Tables and functions will also be given for the non-standard gold-iron alloy combinations. Tables only will be given for gold-cobalt alloy combinations.

The third main type of thermometer, filled systems, includes vapor pressure and constant volume gas thermometers. The principles of each type will be presented, along with temperature versus vapor pressure data. Precision constant volume gas thermometry is beyond the scope of this paper; references are given which include techniques and design considerations for this fundamental type thermometer. Practical gas thermometry, precision constant volume gas thermometry with relatively simple equipment and techniques, can be used and is discussed. As would be expected, the accuracy is at least an order of magnitude less than that of the precision type.

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[1] The letter designations for thermocouples are explained in Appendix A. The names Chromel and Alumel are registered trade names of the Hoskins Manufacturing Co., and are used here as an aid to the reader. Any material manufactured in compliance with an established standard is equally suitable.

A fourth catch-all category could be included to better represent all possible methods of cryogenic temperature measurement. It would, however, be an injustice to the many ingeneous methods of temperature measurement to present a cursory discussion of their principles and characteristics. Instead, some of the "other types" will be mentioned with the hope that the included references will allow the interested reader to find the necessary details for each particular type. Characteristics of some of these thermometers will be used for purposes of comparison in the summary section.

1) Pyroelectric thermometers [23, 24, 25, 26] are capable of detecting extremely small temperature changes in the 4 to 300 K temperature range.

2) Gallium arsenide junction diode thermometers [27, 28, 29, 30, 31] have a useable sensitivity between 1 and 300 K. Silicon junction diode thermometers have also been used [32].

3) Nuclear quadrupole resonance thermometers [33, 34] are capable of precisions of ± 1 mK between 50 and 297 K and are only slightly less precise between 12 and 50 K.

4) Inductance thermometers [35] generate a temperature dependent frequency which can be transmitted over long distances.

5) Ceramic thermometers [36, 37] are relatively new but are already available commercially. Operating range for these thermometers is 1.7 K to 300 K, and they have no magnetic field dependence.

TECHNIQUES OF LOW TEMPERATURE THERMOMETRY

One of the problems in temperature measurement in general, and cryogenic temperature measurement in particular, is establishing thermal contact between the thermometer and the specimen. Ideally, thermal contact will establish the thermometer at the temperature that the specimen would be at if the thermometer didn't exist. In reality of course, energy is transferred both from the specimen to the thermometer and vice versa. The practical solution to the problem is to make the thermal contact between the specimen and the thermometer as good as possible and then calculate the effect of energy flow into the specimen-thermometer system.

Consider the energy flow through the wires to the thermometer and, therefore, to the specimen. Thermal anchoring (tempering) of the wires to a heat sink whose temperature is near that of the specimen will allow the energy to dissipate before it can affect the measured temperature. The additional problem of electrical isolation through the thermal contact is generally present. Three recent papers discuss thermal anchoring to solids [38, 39, 40], and a fourth paper [41] concerns thermal anchoring in liquids. Hust [38] develops a rather general approach for determining the required tempering length for wires or rods in a vacuum. The required length is a function of wire material and size, insulation, temperatures to be encountered, and how closely the temperature of the wire must match that of the heat sink. Table 5, condensed from Hust's paper, presents required tempering lengths for various sizes of copper and constantan wire. The conditions applied to the situation shown in figure 1 and used to arrive at table 5 were as follows: (1) $T_3 - T_s = 0.001$ K, (2) $t = d_e$ = wire diameter, and (3) thermal conductivity of the adhesive is $\lambda(4K) = 0.01$ W/m·K, $\lambda(20\ K) = 0.02$ W/m·K, and $\lambda(78\ K) = 0.05$ W/m·K. Copper and constantan were chosen for the example because they represent the extremes of the wires likely to be used in cryogenic thermometry. Heat transfer calculations require knowledge of the thermal conductivity of wires, electrical insulators, greases, and adhesives. Values for common wires are shown in figure 2. The values of thermal conductivity shown in figure 2 were obtained as follows: Au - 0.03 at % Fe, [42]; Au - 0.07 at % Fe estimated from [42], composition change, and Nordheim's rule; TP (copper) and TN (constantan) [43]; JP (iron) [44]; Au - 2.1 at % Co [45] data extrapolated to 300 K; KP and KN data estimated from data on other nickel alloys [46].

Thermal conductivities of greases which are frequently used as contact agents in low temperature thermometry are given for various temperature ranges by Denner [47], and Kreitman, et al., [48, 49, 50]. Denner's paper also has the thermal conductivities of several adhesives, electrical insulators, and solders; Ashworth, et al., [51] gives the thermal conductivity of nylon. McTaggert, et al., [52] has determined the thermal conductivity of G.E. 7031 varnish[2]. A tabulation of the thermal conductivities of Apiezon N[3] and G.E. 7031 from papers by Ashworth and McTaggert is given in table 6.

A second mode of transferring energy into a thermometer-specimen system is via joule heating in the wire leads and thermometer itself. In the case of resistance thermometers, the power generated is I^2R. This power must be dissipated through the thermometer leads and into the specimen. In gas filled resistance thermometers

[2,3] The use of specific tradenames is necessary in order to properly apply the results presented in the referenced papers. Their use in no way implies any approval, endorsement, or recommendation by the National Bureau of Standards. G.E. 7031 is General Electric Companies' identification for a thermosetting adhesive varnish, and Apiezon N grease is the tradename of the Metropolitan-Vickers Electrical Company, Ltd.

a temperature gradient is established between the active element and the protective case. The gradient depends upon the particular construction of the thermometer and will be discussed in more detail in the section on resistance thermometry. Let it suffice here to say that the specific heat of most materials decreases with temperature, e.g., C_p (300 K)/C_p (20 K) = 18 for platinum, 50 for copper, and 77 for nickel. Joule heating can become important especially at very low temperatures. The Peltier heating or cooling associated with the flow of current between dissimilar metals is generally negligibly small; it will be discussed in the section on thermoelectric thermometry.

The signals encountered are often quite small due to relatively low sensitivities associated with low temperature thermometry. In the measurement of such voltages, one must be careful to avoid the effects of improper shielding or grounding. If more than one ground is present, loop currents are set up introducing spurious voltages in the signal path. Most modern low level dc amplifiers have excellent 60 Hz ac rejection; however, ac pickup may cause a low frequency beat with a chopper amplifier or may be sufficient to saturate the amplifier, resulting in a steady shift in its output. The following procedures for low level dc circuits are recommended:

1) Operate either at floating potential or with one ground preferably at the input of the amplifier.

2) Use extension cables that have a high rejection of electromagnetic, as well as static, noise. Twisted leads decrease the flux pickup area, and commercially available weave patterns [53] cause cancellation of pickup noise. The leads should be encased in a shield grounded at only one point. The normal copper shielding does not adequately shield low frequency noise, e.g., 60 Hz. Cables that have ferromagnetic material for shielding are preferable. Cables and wire junctions can also be placed in iron conduits or boxes to provide additional electromagnetic shielding.

A treatment of problems associated with instrumentation shielding and grounding is given by Morrison [54].

One of the principles of thermocouple thermometry is the law of intermediate materials. This law states, basically, that there will be no thermally generated voltage when dissimilar metals are joined unless the joint exists in a temperature gradient. Applying this to wiring in general, wherever a junction is made of dissimilar metals, it must be made isothermal, or it will contribute a spurious voltage to the thermometer signal. Solder junctions fall into this category since the wire-solder-wire combination forms a dissimilar metals situation even when the two wires are the same. When copper to copper junctions are made, a special solder (~ 70% cadmium + ~ 30% tin) which nearly matches copper thermoelectrically is recommended. It has been reported that such junctions tend to break down when cycled to low temperatures; however, the author has not observed any such breakdown using the low thermal solder. One can also make junctions by spot welding, either with an electrical discharge welder or with a small torch. In some apparatus, junctions are made by simply twisting the leads together. All of these methods of forming junctions have unique applications and can be used successfully if done with care.

Electrical feed-throughs must frequently be used to bring wires from one environment to another. Large temperature gradients may exist in the area of the feed-through; this increases the possibility of spurious voltages. There are two basic types of feed-throughs: continuous wire and junction type. Figure 3(a) shows the essential design of two commercially available units. Specifications of materials, sizes, wire capacity, and pressure rating vary considerably, allowing most design criteria to be satisfied. Figure 3(b) shows one of the many "potting" methods which may be used for "in-house" feed-throughs. The cup and reservoir approach is particularly simple and effective as an ambient temperature seal. If black sealing wax is used in the reservoir, the seal is easy to remake with a new set of wires. Use of the continuous type eliminates the necessity of a junction or at least allows the junction to be made at ambient temperature where large gradients don't exist. Along the same line, any disconnect plugs should be isothermal, and the number kept to a minimum. The important principle to remember when designing a temperature measuring system is to make as few junctions as possible and where they must be made make them as isothermal as possible.

If switches are used in low level circuits, they need to be of the appropriate quality to prevent degradation of the signal-to-noise ratio. For manual operation, low-resistance rotary switches have proven completely satisfactory if enclosed in metal cabinets. For automatic switching operations, enclosed gold or silver plated switches have usually been satisfactory; they typically have about 1 microvolt transient noise and therefore introduce excessive noise if switched faster than about once per second. For either manual or automatic usage, switches should be thermally isolated since large thermal voltages may be generated at the junctions of the wires and the switch components.

MATERIAL COMPATIBILITY IN OXYGEN

A primary concern in the design and use of oxygen containing systems is the compatibility of construction materials. Although a considerable amount of research has and is now being done in this area, there are no infallible criteria to follow on such crucial aspects as ignition sources and ignition temperatures of specific materials. Ignition sources may be any energy source which is capable of raising the temperature of a critical volume of combustible material to its ignition temperature. Included in this category are electrical discharge, shock from a falling object or vibration, adiabatic pressurization, and hot metals such as molten electrical wires. When coupled with the fact that virtually all metals, (with the possible exceptions of gold and platinum), plastics, organic compounds, and polymers are combustible in the presence of pure oxygen, the magnitude of the materials compatibility problem can be appreciated.

The most obvious sources of energy which appear due to temperature transducers are electrical discharge and hot wires. With the exception of the junction diode thermometers, all of the thermometers used at low temperatures are low voltage devices; the energy envolved is not, under ordinary circumstances, enough to promote ignition in metals. Care must be taken, however, that the currents involved are not sufficient to cause excessive heating in the small wires often used in cryogenic thermometry. The real danger results from the use of electrical insulations, thermal contact agents, adhesives, and residual impurities in the form of grease, dirt, etc.

No attempt will be made here to give the degree of compatibility of the many materials found in the various thermometers being considered. Rather, the reader is referred to papers by Clark, et al., [55] and Hust, et al., [56]. These papers contain compatibility information on materials and extensive lists of references.

RESISTANCE THERMOMETERS

The fact that the electrical resistivity of certain materials varies as a function of temperature is the basis for one of the major approaches to determining temperature. Within this major group are two sub-groups--metals and nonmetals.

Metals are characterized by a positive dR/dT while nonmetals are similarly characterized by a negative dR/dT. Both types of thermometers have been widely used for measuring cryogenic temperatures, and both types have typical strong and weak points. Metals exhibit decreasing sensitivity below certain temperatures which ordinarily limits their use to the range where $T \geqslant 10$ K. The sensitivity of nonmetals, on the other hand, increases at lower temperatures giving them the advantage when $T \leqslant 20$ K.

One of two general methods is usually used to determine the electrical resistance of a temperature transducer. A schematic illustrating the standard four lead potentiometric method is shown in figure 4(a). Two voltage readings are necessary in order to determine the thermometer resistance, R_X. The voltage across the standard resistor, R_S, in series with the thermometer allows the thermometer current to be calculated. Resistance of the thermometer is then given by

$$R_X = \frac{V_X R_S}{V_S} .$$

In order to cancel possible spurious voltages in the potential leads, the direction of current flow must be reversed and a similar pair of voltage readings taken. The resistance of the thermometer is then given by

$$R = \frac{R_X(\text{current forward}) + R_X(\text{current reversed})}{2} .$$

This procedure involves four voltage measurements and consequently is best applied to systems with nearly constant temperatures. Figure 4(b) illustrates another method which involves measuring the voltage drop across a known resistor, R_S, and across the unknown, R_X. The ratio of these numbers allows R_X to be computed, i.e.,

$$R_X = R_S \frac{V_X}{V_S} .$$

This method allows the accurate determinations of R_X from precise but not necessarily accurate determinations of V_X and V_S, e.g., the working current in a potentiometer would not need to be standardized. The second general method is to determine the thermometer resistance directly using one of several possible bridge circuits. Four of the more common circuits are shown in figure 5. The bridge shown in figure 5(a) is often used with two lead thermometers and has no lead or contact resistance compensation since both leads are in the same arm of the bridge as the unknown resistance. The resistance determined will include the resistance of the leads L_1 and L_2, i.e.,

$$R = R_X + R_{L1} + R_{L2} .$$

Figure 5(b) utilizes three thermometer leads which compensates for the lead resistance to the extent that $R_{L1} = R_{L3}$. These resistances appear in different arms of the bridge so that

$$R = R_X + R_{L3} - R_{L1} \approx R_X .$$

Figure 5(c) represents the basic design of the much used Mueller bridge. This configuration requires two readings, but does eliminate the effect of the leads. The temperature of the leads must remain the same for both readings. The required pair of readings would be:

$$R_1 = R_X + R_{L1} - R_{L4}$$

and

$$R_2 = R_X + R_{L4} - R_{L1} .$$

Averaging R_1 and R_2 results in the cancellation of the lead resistance. A fourth bridge, figure 5(d), is known as the Kelvin double bridge. In principle, this circuit allows complete lead compensation and is frequently used to measure four terminal resistances of less than 1 ohm. If

$$R_4 = R_{L4} + r_4, \quad R_3 = R_{L3} + r_3, \quad R_2 = R_{L2} + r_2, \text{ and } R_1 = R_{L1} + r_1,$$

then

$$R_X = R_S \frac{R_3}{R_4} + \frac{R_2 r_c}{R_1 + R_2 + r_c} \left(\frac{R_3}{R_4} - \frac{R_1}{R_2}\right).$$

If the value of r_c and the difference ratio

$$\left(\frac{R_3}{R_4} - \frac{R_1}{R_2}\right)$$

are made small enough, the second term can be neglected and

$$R_X = R_S \frac{R_3}{R_4} .$$

Further details on the circuits outlined above [57, 58] and descriptions of special circuits developed for particular applications abound in the literature. The review paper by Daneman, et al., [59] contain, extensive references to such developments.

Metals

The resistivity of a metal, as given by Matthiessen's rule, is made up of two terms so that

$$\rho_{Total} = \rho_i(T) + \rho_o .$$

ρ_o, the residual resistivity, is constant and is due to electron scattering by impurities and lattice defects. $\rho_i(T)$, the intrinsic resistivity, is an increasing function of temperature and is due to electron scattering by lattice vibrations. Lattice vibrations and therefore temperature sensitivity persist to lower temperatures in metals which have lower Debye temperatures. The Debye characteristic temperature is defined as:

$$\theta_D = \frac{h\nu_{MAX}}{k}$$

where h is Planck's constant, k is Boltzmann's constant, and ν_{MAX} is the maximum lattice frequency allowable in a particular lattice (ν_{MAX} may be thought of as corresponding to the wavelength just greater than the atomic spacing). The Bloch-Grüneisen relationship for the temperature dependent resistivity is

$$\rho_i \propto \frac{T^5}{\theta_D^6}$$

for low temperatures. In general, heavy loosely packed materials have long minimum wavelengths which means that ν_{MAX} and θ_D are low and R_i is high. For example, θ_D(lead) = 88 K, θ_D(indium) = 110 K, θ_D(platinum) = 225 K, and θ_D(copper) = 310 K [60]. Other properties being equal, the metal with the lowest θ_D would make the best thermometer element for lower temperatures.

Matthiessen's rule is not exact. It has been shown [61] that there is a third term in the expression of ρ_{Total} which is temperature dependent. This deviation also depends on crystal imperfections. Accurate interpolation of thermometer resistances must take this deviation into account as will be discussed later in the section on calibration of resistance thermometers.

Although platinum is by far the most common metal used in low temperature thermometry, others such as indium and copper have been used to some extent. Important properties of a metal being considered for use in low temperature resistance thermometers are chemical inertness, ductility, availability in highly purified state, and as mentioned above, thermal sensitivity to low temperatures (θ_D as low as possible).

Nonmetals

Basically, semiconductors differ from metals in that there is an energy gap between the valence band and the conduction band. For a complete discussion of the conduction properties of a semiconductor see Kittel [62]. A very cursory treatment of the subject is more appropriate here.

The energy levels existing in a pure semiconductor are as shown in figure 6(a). At absolute zero, the valence band is completely full, the conduction band is completely empty, and the crystal behaves as an insulator. The resistivity is given by

$$\rho = A \exp E_c/2kT.$$

As the temperature increases to a certain level, sufficient thermal energy is added to allow some electrons to jump to the conduction band. Both the electron in the conduction band and the hole in the valence band contribute to the overall conduction. This temperature dependent conductivity is known as intrinsic conductivity. Addition of impurities such as arsenic or boron to the crystal creates energy levels as shown in figure 6(b). Resistivity remains a function of temperature, but the energy gaps E_D and E_A are seen to be much smaller than E_C and therefore require less thermal energy to affect the conduction properties. Donor impurities give up electrons to the conduction band while acceptor impurities take electrons from the valence band. When donor impurities are dominant over acceptor impurities, the conduction is primarily by electrons in the conduction band; the resulting semiconductor is referred to as n-type. When acceptor impurities are dominant, conduction is primarily due to "holes" in the valence band; this type of semiconductor is known as p-type. The complex conduction processes involved in semiconductors makes general analytical representation of R versus T difficult. This is one of the drawbacks to the use of doped germanium crystals in thermometry, and will be discussed in more detail later.

Thermistors are semiconducting resistors made up of sintered metallic oxides. The temperature dependent behavior of thermistors is similar to that of the semiconductors discussed above. Manufacturing processes allow the tailoring of thermistors to be useful over a wide range of temperatures.

For our purposes, carbon will be considered a semiconductor since its general thermometric characteristics fall in this category, e.g., $dR/dT<0$. Carbon resistors have for some time been one of the most used cryogenic thermometers for temperatures below 20 K. They are cheap, rugged, and have a high sensitivity to temperature change at low temperatures. Carbon is used in the form of common radio type resistors, colloidal suspensions painted on various substrates, and more recently, vacuum deposited thin films. The analytical representation of carbon thermometers is relatively simple, belying the complicated conduction process. Variations of

$$\log R = A + B/T$$

are generally used to represent resistance - temperature relationships.

Platinum

Platinum resistance thermometers (PRT's) are probably the most accurate and reproducible empirical thermometers available over a wide range of temperatures. This is attested to by the fact that IPTS-68 uses a PRT to define the scale between the fixed points from 13.81 K to 630.74°C. With special effort the useable range for PRT's can be extended down to 2 K with an accuracy of about 10 mK. A discrimination of less than 5 mK from 2 to 4 K and 2 mK from 4 to 10 K is possible [63, 64, 65, 66]. It must be stressed that these numbers represent the state of the art in instrumentation, in thermometers, and in techniques at these temperatures. In addition, special calibration and analytical representations are also required. At the other end of the temperature range, precision PRT's have been developed for use as high as 1100°C [67, 68, 69]. Long term stability due to impurity contamination and breakdown of electrical insulating properties of support material are major problem areas.

Measurements in the range from 20 K to 450°C are made routinely with a high degree of accuracy and with a number of different commercially available thermometers. The sensitivity of a typical precision PRT is shown in figure 7.

Annealing of the thermometer is basic to achieving a reproducible unit. In order to achieve electrical stability, the thermometer must be annealed at a temperature which is at least as high as that at which the thermometer will be used. Corruccini [70] found that annealing procedures differ depending upon the amount of cold work and purity of the platinum. The ITS-48 recommends an annealing temperature of 450°C for standard resistance thermometers [71]. In any case, slow cooling is required since rapid cooling from a high temperature traps lattice defects and changes the electrical properties.

PRT's are available in many configurations and can be commercially fabricated for special applications at additional cost. The following discussion is going to divide PRT's into two classes -- laboratory and industrial; the division may be rather arbitrary. The separation will be based primarily on how the active element is supported and on its purity. The industrial class will also include platinum film resistors.

In 1932, Meyers [72] designed a PRT, figure 8(a), which consisted of a coiled helix of fine platinum wire on a mica cross support. Another Meyers design [73] features a single coil of platinum on a mica support as seen in figure 8(b). Barber has designed two capsule type PRT's [74, 75], one of which is shown in figure 8(c) and makes use of a freely suspended helix of platinum in a glass support tube. Although different in detail, all of these thermometers make use of a protective sheath, some kind of coiling of the sensitive element in order to get the length to area ratio up, a suspension scheme intended to retain the strain free properties of annealed platinum, and a filling gas [74, 76] to increase the thermal conductivity to the sensitive element.

IPTS-68 defines the reference thermometer as a strain free PRT with $W \equiv R(373.15)/R(273.15)$ not less than 1.39250. Another relationship frequently used to compare the degree of purity and strain of PRT's is

$$\alpha \equiv \frac{R_{100°C} - R_{0°C}}{100\ R_{0°C}} \quad .$$

An IPTS-68 requirement is that $\alpha \geqq 0.003925$. Laboratory thermometers with the essential designs discussed above and which meet the α requirements are available commercially. Both long stem and capsule types of sheaths are available. The nature of the strain free suspension makes these thermometers susceptible to strain from moderate g-forces or vibrations [77]. The resistance of a strain free capsule thermometer is reproducible to better than the equivalent of 1 mK. The time response of this type of thermometer varys from 2 to 7 seconds depending on the thermometer fill gas and the conditions of the measurement. Ordinarily PRT's such as this are used in static or slowly changing environments.

The size of these precision thermometers is relatively large, e.g., ~5.7 mm diameter, ~ 6 cm long, and weight about 5 gm. A much smaller precision PRT, ~ 4 mm diameter, ~ 1.3 cm long, ~ 1.1 gm, has been developed and is available commercially. It was found that after several thermal shocks from ambient to liquid helium temperature, the resistance at the triple point of water became stable to within about 0.0004Ω [78]. This is the temperature equivalent of 1 mK for these $R_o \cong 100\Omega$ resistors.

Calibration of these smaller thermometers indicated an $\alpha > 0.003925$ which is the requirement for a standard thermometer. Below 90 K, however, R_T/R_{273} drops more rapidly than for the larger PRT's [79]. This means that the similarity requirement is not met and the Cragoe Z function interpolation cannot be applied using the calibration of a capsule type thermometer (Cragoe Z functions will be discussed later in the section on calibration of PRT's).

Industrial PRT's are available for a wide range of applications. These thermometers are, in general, less precise than the laboratory resistors just discussed. The ruggedness of these units is achieved by more rigid support of the sensitive elements. Differential thermal contraction between the supporting material and the platinum element strain the platinum and, therefore, change the electrical properties. Available design features vary to such an extent that only general features can be discussed here. Several excellent company bulletins are available which discuss these in great detail.

There are two basic designs -- immersion probes and surface temperature sensors. The immersion probes feature a high purity platinum wire encapsulated in ceramic, figure 9(a), or securely attached to a support frame. R_o values are usually in the 100 to 1000Ω range. The recommended temperature range is from ~ 10 K up to 250°C and higher in cases where the supporting material is such that the platinum will not suffer contamination. Features such as repeatability after thermal shocks, time response in different environments, interchangeability, and mechanical shock tolerance differ between companies and specific designs. For the most part, the specifications below represent typical values which might be used in preliminary designs. Exact specifications must necessarily come from the manufacturer. The repeatability of the typical immersion sensor is usually certified to be about ± 0.1°C at the ice point after several thermal cyclings to cryogenic temperatures. For most thermometers this repeatability figure is conservative. The time response is particularly difficult to assess in a general way because it depends critically upon the design and on the method of testing. Flowing water, oil, or cryogenic liquids are often used as the test medium. The time response of the capsule type PRT was previously given as 2 to 7 seconds, which meant that in this time the sensor had reached the equilibrium temperature of the system (ignoring I^2R heating). In the case of the industrial PRT, dynamic systems are frequently encountered. Convention has been to define the time response of a thermometer to be the time it takes the sensor to reach 63.2% of the temperature of a step function temperature change. With this definition of the time constant, a typical range of values for this type of resistor is 0.1 to 3 seconds. Interchangeability is measured in terms of errors involved when more than one thermometer is used with a single R versus T relationship. This becomes a major concern in operations where control resistors must be replaceable without system interruption, and where data reduction and calibration expense must be minimized. Interchangeability is ordinarily specified at a given temperature, i.e., the resistance of the thermometers will not vary more than a specified amount at a certain temperature. Immersion type sensors may generally be specified to have the same ice point resistance to within an equivalent of about ± 1.5°C; surface sensors show slightly worse interchangeability, ± 4 to 5° at 0°C. Some manufacturers provide different grades of interchangeability for particular models. Even after specifying a particular resistance value at a given temperature, the slope of R versus T, which depends on purity and strain, may vary from one thermometer to another. This slope variation is reflected in the specifications shown in company manuals where it is seen that $\Delta T = (T_x - T_{ref})$ increases both above and below the R matching point. A ruggedness specification by NASA [80] for a particular requirement is given as (1) 50 g's or 0.5 inch double amplitude (smaller of the two) from 20 to 2000 Hz for 15 minutes, (2) impact shock of 100 g's for 10 millisecond triangular wave, and (3) velocity loading > 100 ft/second of liquid hydrogen. Manufacturer's specifications are generally along the same lines; the values, of course, vary with the particular type of construction.

The second type of industrial sensor is broadly known as a surface temperature sensor. The general design is as shown in figure 9(b). The principal advantages of these thermometers are that they are small, typically 0.25 cm x 1.3 cm x 1.3 cm with perhaps a factor of 2 variation in any dimension. Their geometry is such that they make good thermal contact with surfaces of various shapes. Sensors are available for clamping around small tubing, fitting into milled slots, clamping under bolt heads, soldering, welding, and cementing. Custom design capability is high in this general type of resistor.

Both the immersion and the surface sensors are available in versions which have built in bridge circuits. These bridge circuits allow adjustments to be made on individual sensors to increase the interchangeability. Two, three, and four lead configurations are available in both the surface and immersion sensors.

Calibration of Platinum Resistance Thermometers

The interpolating instrument for IPTS-48 and IPTS-68 is the platinum resistance thermometer for temperatures below 630.74°C. IPTS-48 used the Callendar equation [81],

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

as the interpolating equation above 0° C and the Callendar-Van Dusen modification [82]

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

for interpolation between 0° C and 90 K. Below 90 K there was no adequate analytical representation; thermometers were calibrated at 16 points by comparison to standard platinum resistance thermometers at the National Bureau of Standards. Adoption of IPTS-68 has eliminated the need for the Callendar-Van Dusen equation above 90 K and has provided analytical relationships which allow thermometers to be calibrated on the IPTS-68 between 13.81 K and 90.188 K. Practically, however, it remains very difficult for a laboratory to calibrate a platinum resistance thermometer since seven fixed points between 13.81 K and 273.15 K are required. It remains imperative that there exist methods of calibration which may reasonably be carried out.

One such procedure has been developed which makes use of an existing precision calibration and Matthiessen's rule. Cragoe [83] proposed the following universal function which would represent all resistors of the same type

$$Z(T) = \frac{R_T - R_1}{R_2 - R_1}$$

Development of this function requires that Matthiessen's rule be obeyed for the temperature range in question, i.e., $R_T = R_i(T) + R_0$. The procedure used would be to establish the Z(T) for the standard thermometer, keeping in mind that only the calibration for such a thermometer is necessary, not the thermometer itself. Calibration of the unknown thermometer at two fixed points, i.e., R_{1x} at T_1 and R_{2x} at T_2, allows one to write

$$Z_x(T) = \frac{R_{x,T} - R_{x,T1}}{R_{x,T2} - R_{x,T1}} = Z_{STD}(T).$$

A form which is convenient for constructing a table of R_x versus T for the unknown thermometer X is

$$R_{x,T}^{C} = R_{x,T1} + \alpha_x(R_{A,T} - R_{A,T1})$$

where

$$\alpha_x = \frac{R_{x,T2} - R_{x,T1}}{R_{A,T2} - R_{A,T1}} .$$

The subscript A denotes the thermometer for which the calibration is available, and the superscript C indicates a value calculated using Cragoe's assumption that Matthiessen's rule is exact.

Corruccini [84] has done calculations on several precision capsule type platinum thermometers with full NBS calibrations in order to check the errors involved in using this approach on this type of thermometer. His results for this type of interpolation are indicated by a "C" in table 7. As the temperature range, $(T_2 - T_1)$, becomes smaller, deviations from Matthiessen's rule decrease and the accuracy of the interpolation via Z functions gets better. An indication of this trend is seen in the two intervals where interpolation was done with Cragoe's functions.

Sinclair, et al., [80, 85] has applied the Cragoe Z approach to platinum resistance thermometers which were not of the precision capsule type. The thermometers were the compact high resistance units which are available commercially. Room temperature resistance ranged from 200 to 5000 ohms at room temperature as compared to 25.5 ohms for the precision units tested by Corruccini. For the two ranges, $T_1 = 20.2$ K to $T_2 = 77.4$ K, and $T_1 = 77.4$ K to $T_2 = 273.15$ K, the deviations from the standard thermometer were not more than 40 mK. Deviations as high as 150 mK were found when this approach was applied in the range $T_1 = 4.2$ K to $T_2 = 20.2$ K.

Deviations from Matthiessen's rule have a characteristic shape. Corruccini [84, 86] has taken advantage of this fact to establish a more accurate method of interpolation of platinum resistance thermometers. This method requires three fixed point calibrations of the unknown thermometer and calibration tables for two similar platinum thermometers. In comparing this method with the Cragoe Z method, it is seen that one extra calibration table and one extra fixed point calibration are needed.

We have previously written

$$R^{C}_{x,T} = R_{x,T1} + \alpha_x(R_{A,T} - R_{A,T1}) \,.$$

If we now include the correction term for the deviation from Matthiessen's rule and denote the value so calculated as $R^{M}_{x,T}$ we can write

$$R^{M}_{x,T} = R^{C}_{x,T} - \beta_x(R^{C}_{B,T} - R_{B,T})$$

where

$$\beta_x = \frac{R^{C}_{x,T3} - R_{x,T3}}{R^{C}_{B,T3} - R_{B,T3}} \,.$$

Corruccini's results for this type of interpolation are shown in table 7 and are indicated by an M. The $R^{M}_{x,T}$ values for $T > 90$ K and determined with $T_1 = 90$ K, $T_2 = 200$ K and $T_3 = 273.15$ K are within 0.6 mK of the values given by the Callendar-Van Dusen equation which requires four calibration points.

Indium

As mentioned previously, the desirable characteristics of a resistance thermometer element include availability in high purity, ductility, chemical inertness, and for low temperature ($T < 20$ K) a low Debye characteristic temperature.

Indium appears to fit the requirements rather well, e.g., $R_{4.2}/R_{273} \cong 10^{-4}$ ($\cong 10^{-3}$ for platinum), is extremely soft and malleable, and $\theta_D(\mathrm{In}) \cong 100$ K. This θ_D allows the lattice vibrations in the high purity material to dominate the total resistance down to the superconducting transition temperature (~ 3.4 K). White, et al., [87, 88] have constructed and tested a total of 4 indium resistance thermometers. Their first two thermometers, $R_4/R_{295} \approx 10^{-4}$, had $R(295\ \mathrm{K}) \cong 0.3$ ohm which limited the accuracy of their measurements. A table of Cragoe Z functions was constructed for the two thermometers between 3.5 K and 300 K. The Z functions [87] are given in table 8.

White, et al., later constructed and tested two additional indium thermometers with $R_{295\ K} \cong 4\Omega$; these measurements resulted in more accurate results, but didn't affect the Z functions computed from the first set of tests. One of the two final thermometers tested was wound on an indium rod while the other was mounted on a mica cross much as in the precision PRT construction. The effect of indium's anisotropic expansion was seen when the resistance of the "indium rod thermometer" changed with thermal cycling.

White, et al., found that their data, shown in figure 10, were fit reasonably well by $R_T/R_{273} = A + BT + CT^2$ for temperatures above 100 K; for temperatures between 100 K and 40 K, $R_T/R_{273} = A + BT$; and for temperatures below 10 K, $R_T = A + BT^5$.

Orlova, et al., [89], Yates, et al., [90], and Kos, et al., [91] constructed and tested several indium thermometers with higher absolute resistances. Construction details for the thermometers are included in the respective papers. The purity of the indium wire used by Orlova was given as $R_4/R_{273} = 2$ to 4×10^{-4}, the wire used by Yates contained less than 6 ppm impurity, and the 0.254 mm diameter wire used by Kos was 99.999% pure. In representing his results, Orlova found the $R = A + BT^5$ as suggested by White, et al., to give temperature uncertainties of 0.2 K at liquid helium temperatures. Applying the Z functions given by White, he found that at 3.5 K the error for his thermometer was 40 mK and as the temperature was increased the error decreased to 20 to 30 mK. Kos also found White's Z function insufficient for accurate thermometry. It is suggested by Orlova that the best approach might be to determine a $W = R_4/R_{273}$ as has been done for platinum and then devise a method of adapting this W to an individual thermometer by calibrating at a few fixed points.

Swenson [92] found a discontinuity in the R versus T of indium at 210 K. This discontinuity was not observed by either White or Orlova. A possible explanation could be that Swenson's specimen $R_4/R_{273} \cong 10^{-3}$ was more impure than the others.

It would appear that with sufficient development, indium could be a resistance thermometer with good sensitivity between 300 K and 3.4 K. Work in the area of analytical representation is a major thermometric deficiency at this time; there appears to be no basic reason that this couldn't be resolved to approach the PRT level of uncertainty.

Copper

Copper is frequently used as the active element in thermometers of "in-house" construction. It offers such advantages as being cheap, having a nearly linear resistance temperature relationship, being ductile, and being available in most laboratories.

The main disadvantages are that copper oxidizes at relatively low temperatures, and compared to platinum, is not very stable or reproducible. Dauphinee, et al., [93] examined eleven copper resistance thermometers, made from commercial, enameled copper wire, between the temperatures of 20 and 320 K. They established the temperature-resistance relationship given in table 9. White [60] has used this data to arrive at the Z functions

$$Z = \frac{R_T - R_{4.2}}{R_{273} - R_{4.2}}$$

given in table 10. If the wire used has a ratio of

$$\frac{R_{273}}{R_4} \cong 100,$$

the Z functions presented here will probably result in an accuracy of about ± 0.1 K. Dauphinee found that by calibrating a single thermometer at the n.b.p. of hydrogen and at the ice point he could adjust the R/R_o values given in the table to represent his test thermometer to within ± 25 mK throughout the range.

Carbon

Carbon resistors in the form of standard radio type resistors, colloidal suspensions and, more recently, evaporated films have been widely used as temperature sensing devices and as liquid level sensors [94]. All exhibit the general characteristic negative temperature coefficient of resistance. The bulk of the use of carbon resistance thermometers is for temperatures at and below 20 K. Their use at higher temperatures is limited because of decreasing sensitivity, reported stability problems, and competition with metallic resistors. By far the most used form of the carbon thermometer is the standard radio type. An R versus T plot for a 270Ω, 0.1 watt resistor is shown in figure 11. They are available from several commercial sources in a wide selection of absolute values and wattage ratings. In general, the 0.1 to 1 watt resistors with room temperature resistances of 10 to 500Ω are most used. The advantages of these resistors are that they are physically small, rugged, cheap, and are the least sensitive of the resistance thermometers to magnetic fields.

The reproducibility of carbon resistors upon thermal cycling has traditionally been questioned. Since carbons exhibit graphite like behavior in varying degrees, it is possible that any lack of reproducibility could be due to the anisotropic electrical conductivity and thermal expansion observed in graphite [95]. Several investigations of commercial resistors of various types indicate that carbon resistors are reproducible to about 0.1% or ± 4 mK at 4 K when cycled between room temperature and liquid helium temperature [96]. Plumb, et al., [97, 98] found the reproducibility to be at least this good, but that there was long term drift when exposed to liquid helium temperatures for extended periods of time. This drift amounted to an increase in resistance equivalent to about 4 mK. Johnson, et al., [99] also observed this drift and concluded that the lack of reproducibility was due to the active resistive element itself, (intrinsic) and not a thermal strain effect which would eventually saturate. Further, the nonreproducibility is probably due to the drift characteristic of the thermometer and not the thermal shock effect. In order to obtain reproducibilities on the order discussed above, care must be taken not to change the resistors characteristics by heating with a soldering gun, baking, etc. [100]. Effects of heating carbon resistors is discussed in detail in [99].

Clement, et al., [96] found that over the temperature range of 2 - 20 K, they could fit resistors with a wide variety of nominal room temperature resistances with the empirical relationship

$$\log R + \frac{K}{\log R} = A + \frac{B}{T} .$$

Temperatures calculated from this equation agreed to within ± 0.5 K for all resistors tested. Schulte [101] used this equation to arrive at the resistance ratios shown in table 11 (R_{295} = 265.22Ω). For the resistors tested, he found the following variations in the calculated and experimental ratios: ± 6.8% at 4.2 K, ± 2.2% at 20.3 K and ± 0.25% at 77.4 K. These variations correspond to temperature uncertainties of ± 110 mK, ± 500 mK, and ± 500 mK, respectively. The coefficients used by Schulte were A = 4.478, B = 3.091, and K = 5.004. It is well known that the R - T characteristics of different brands of resistors vary. Application of the data in this table should be applied only to the brand, wattage, and nominal resistance value used by Schulte. Even then, the resistor to be used should be calibrated at 4.2 K and room temperature and the ratio of these resistances should agree to within 6.8% of the table ratio. Other appraches to representing the temperature resistance characteristics are found in [102, 103, 104].

Germanium

Semiconducting materials germanium and silicon exhibit useful R versus T characteristics at low temperatures. The primary range for these thermometers is for T < 20 K; they can, however, be used up to 100 K with decreased sensitivity. The R versus T characteristics of several germanium commercial units are shown in figure 12. The bulk of the development work has been done on the germanium resistance thermometers. Commercial units are available in both 2 and 4 lead configurations as shown in figure 13(a).

These thermometers are small (typical size is approximately 1.3 cm long and 0.3 cm in diameter) and have small mass with a resulting time constant on the order of 0.1 second. As seen in figure 13, the leads which actually contact the germanium crystal are very small. This results in the instruments being relatively easy to burn out if the measuring current is too high. Most models use 1 μ A for $T < 2$ K, 10 μ A for $2 < T \leq 15$ K, 100 μ A for 15 K $< T \leq$ 40 K, and 1 mA for 40 K $< T <$ 100 K.

These thermometers are generally used in a potentiometric circuit such as the one shown in figure 13(b). In order to eliminate spurious emf's, the average of a forward-reverse set of measurements is recommended for very accurate work.

The reproducibility of doped single crystal germanium thermometers (GRT's) has been established on units from various sources by various labs [105, 106, 107]. The reproducibility of the thermometers at 4 K is as good as the current ability to check them, i.e., typically a few tenths of a millidegree.

The conduction processes and effect of various controlled impurities are discussed by Blakemore [108]. It is noted here that by changing the type and amount of impurity, the thermometer can be made to have an optimum range of usefulness. Commercial units are available for use in several different ranges.

The major disadvantage associated with the use of germanium thermometers is the lack of a simple analytical representation. Each thermometer must be calibrated by comparison at many points in the range of interest if the inherent reproducibility of the thermometer is to be utilized.

A polynomial of the form

$$\log R = \sum_{j=0}^{m} A_j (\log_{10} T)^i$$

has been proposed [109]. In this paper Blakemore finds that application of this polynomial over the entire range from 1 - 100 K results in oscillations amounting to 0.3% of the absolute temperature. If the range is divided, $T < 20$ K and $T > 20$ K, these oscillations are reduced to a few parts in 10^4 of temperature. Other schemes of representation have been developed and are important because they present the user with easier functions to deal with even though the ultimate accuracy may suffer [110, 111, 112].

Thermistors

Thermistors (thermally sensitive resistors) are essentially resistors made up of metal oxides. Frequently used materials are nickel, manganese, and cobalt oxides. The temperature-resistance relationship for this type of resistor has a negative slope much like the carbon or germanium resistors. The fact that these resistors are becoming increasingly popular in measurement and control circuits is attested to by the number of companies selling them [22]. The reasons for the increasing use are in part: (1) they are small which tends to make the time response significantly less than 1 second, (2) they are typically high resistance units which reduces the overall effect of lead resistances, and (3) their temperature-resistance characteristics are dependent on materials and procedures which allow thermometers to be developed which are particularly sensitive in limited ranges of temperature.

There are, of course, disadvantages also. Items (2) and (3) above may be considered as disadvantages as well as advantages: any one thermistor is not usable over a wide range of temperatures due to its resistance becoming exceedingly high. The analytical representation of the resistance versus temperature characteristics are represented by

$$\rho = A \exp \frac{B}{T}$$

for short ranges of temperature [113]. Reproducibilities are also experimentally determined by Sachse [113] and were found to be about ± 30 mK after cycling between room temperature and liquid oxygen. After 1000 cyclings, the error was on the order of tenths of degrees. Sachse discusses the commercially available types of resistors and Droms [114] presents a detailed study of bridge circuits to be used with this type of resistor.

THERMOCOUPLES

In 1823, Seebeck found that when two dissimilar wires were joined at both ends and subjected to a temperature gradient between the two junctions, a current would flow. This phenomenon now bears his name - Seebeck effect. A bit later Peltier found that when electrical current flows across a junction of dissimilar metals heat was either liberated or absorbed. The Peltier heat is given by $\pi = TS$ [115] where T is the absolute temperature and S is the absolute thermopower. Except in the case where one of the thermocouple materials is superconducting, S is actually the net thermopower of the materials making up the junction, i.e., $S = S_{12} = S_1 - S_2$. Kelvin (Sir William Thomson) analyzed the Seebeck circuit treating it as a reversible heat engine, with the Peltier voltage as the driving force. He discovered that an additional reversible effect was needed because the observed thermal voltage is not proportional to the temperature difference. The second reversible phenomenon was found to exist in a homogeneous conductor when an electrical and thermal gradient were simultaneously applied. Heat is liberated or absorbed at different points depending upon the material and the relationship between heat flow and electrical current flow. This effect is different than the Peltier effect in that it occurs in a continuous, homogeneous conductor. The Thomson heat, μ, is given as $T \frac{dS}{dT}$ [115] where S and T have the same meanings as in the Peltier coefficient. If the Thomson coefficient is known, one may compute the absolute thermopower of a material using

$$S(T) = S(T) - S(0) = \int_0^T \frac{\mu}{T} \, dT.$$

Borelius, et al., [116, 117] determined μ from calorimetric methods for lead. More recent discussions concerning the accuracy of these measurements are given in [118, 119].

Sign conventions have been adopted in order to determine the direction of current flow, Peltier heating (or cooling), and Thomson heating (or cooling). The most important of these phenomena from a thermometry point of view is the direction of current flow. The convention is that if current flows from material A to material B at the cooler of the two junctions, then material A is thermoelectrically positive with respect to material B as shown in figure 14(a).

For the materials used in thermometry, the Peltier heating effect is small as shown in the following example: Peltier coefficient $\pi = TS$ is in joules per coulomb. We must have current flow in order to generate the Peltier heat so assume that a voltmeter of reasonably low resistance is used to measure the Seebeck voltage. The total circuit resistance will be assumed to be 150Ω. The warm junction will be taken as 0°C (273.15 K) and the cold junction will be taken at 76.15 K (-197°C). Further, assume that the thermocouple being used is made up of copper and constantan. The emf generated will be 5555 μV which results in a circuit current of $I = \frac{5555\ \mu V}{150\Omega} = 37.03\ \mu A$.

$$\text{coulombs (C)} = I(A) \times \text{time (s)}$$

$$\frac{1C}{37\ \mu A} = 2.7 \times 10^4 \text{ s.}$$

If we concern ourselves with the cooler of the junctions,

$$\pi = 76.15\ \mathrm{K} \times 16.14\,\frac{\mu\mathrm{V}}{\mathrm{K}} = 1229.1\,\frac{\mu\mathrm{J}}{\mathrm{C}}$$

or 1 coulomb liberates 1229.1 μJ

or 0.000294 cal

and the power will be

$$\frac{0.000294\ \mathrm{cal}}{2.7 \times 10^{4}\ \mathrm{s}} = 1.1 \times 10^{-8}\ \frac{\mathrm{cal}}{\mathrm{s}}\ .$$

The effect of the Thomson heat is much smaller and can only be detected when large currents are used; consequently, it will not be considered further.

A gradient approach [120] to thermocouple circuit analysis will be introduced at this point. This method of analyzing thermocouple circuits is extremely useful when analyzing thermocouple systems. A simple E (thermal voltage) versus T plot is made. Frequently the relative relationships between thermopowers of materials can be used, e.g., EP (a nickel-chromium alloy - see Appendix A for more detailed material explanation) has a very positive slope, copper has a slightly positive slope, and EN (a copper-nickel alloy) has a negative slope. Assuming that the slope of each material is a straight line (this isn't at all necessary), the thermoelectric circuit shown in figure 15(a) could be represented graphically as in figure 15(b).

There are three basic empirical laws which govern the use of thermocouples as thermometers [121]. They may be stated as follows: (1) law of the homogeneous circuit. No current will flow in a thermoelectric circuit such as figure 14(a) if material A and B are identical regardless of the magnitude of the temperature gradient or its distribution along the wires. The first law, as seen graphically, is given in figure 16(a). (2) Law of intermediate materials. This law states that a third material, introduced into the thermoelectric circuit as shown in figure 14(b), will have no thermoelectric effect if it exists entirely in an isothermal region. This law may be shown graphically as shown in figure 16(b). (3) Law of intermediate temperatures. This law states that if a thermocouple pair generates a voltage E_1, when its junctions are at T_1 and T_2, and a voltage E_2 when its junctions are at T_2 and T_3, then it will generate the voltage $E_{12} = E_1 + E_2$ when its junctions are at T_1 and T_3.

A full understanding of these three basic empirical laws will allow successful temperature measurement with thermocouples. For instance, application of the second law assures us that a feed-through or disconnect (being an intermediate material) will produce no thermoelectric effect if it is isothermal.

The types of thermocouples used in low temperature thermometry are the standardized types Chromel versus constantan (type E), Chromel versus Alumel (type K), copper versus constantan (type T), and combinations utilizing dilute noble metal alloys as the negative thermoelements. The base metal thermocouples, types E, K, and T, do not have specified chemical compositions. Rather, any pair of thermocouple materials that satisfy the limits set forth in table 12 [122] may be used. Limits of error for temperatures below 0°C have not been established for types E and K. As noted in Appendix A, KP = EP and EN = TN. Further discussions of the standardized materials are given in [123, 124]. The nominal make-up of these wires is given in Appendix A.

The increasing use of liquid hydrogen and liquid helium in the scientific and aerospace communities has created a demand for specialized thermometry below, say, 25 K. Ordinary thermocouple combinations are only marginally acceptable due to their low sensitivity in this range. Dilute alloys of noble metals and transition metals, however, do form thermoelements with relatively high temperature sensitivity below 25 K; <u>Au</u>-2.1 at % (atomic percent) Co is perhaps the best known of this type. Unfortunately, the <u>gold</u>-cobalt alloy forms a supersaturated solid solution; cobalt tends to migrate to the grain boundaries even at room temperature [125]. This migration changes the thermoelectric properties and reduces the worth of this material as a thermoelement. Another family of alloys of this type are alloys of iron in gold. These alloys are metallurgically stable and exhibit extremely useful thermoelectric properties at very low temperatures. A differential thermocouple made with <u>Au</u>-0.02, 0.03, or 0.07 at % Fe as the negative element and copper, "normal" silver (<u>Ag</u>-0.37 at % Au), or KP as the positive element provides a usable sensitivity even below 4 K.

<u>Type E</u>

The history of type E is not well documented; the first published calibration that we are aware of was by Shenker, et al., [126]. Their tables were calculated from data on KP and TN versus reference platinum from earlier NBS Research papers. This type of thermocouple has the highest Seebeck coefficient (S) of the three standardized types both above and below 0°C. In addition to this, both elements of this thermocouple have low thermal conductivity, reasonable homogeneity, and they resist corrosion in moist atmospheres. A word of warning concerning the unfortunate ambiguity over the material referred to as constantan. Iron versus constantan (JP versus JN) is an often used combination. The negative element, JN, is not the same material as EN (or TN) and cannot generally be used interchangeably.

Type E thermocouples are recommended by the ASTM [127] for use in the temperature range from -250°C to 871°C in oxidizing or inert atmospheres. The negative thermoelement is subject to deterioration above about 871°C, but the thermocouple may be used up to 1000°C for short periods. The following restrictions should be placed on the use of type E:

> They should not be used in sulphurous, reducing, or alternately reducing and oxidizing atmospheres unless suitably protected with protecting tubes. They should not be used in vacuum (at high temperatures) for extended times because the chromium in the positive thermoelement vaporizes out of solution and alters the calibration. They should also not be used in atmospheres that promote "green-rot" corrosion (those with low, but not negligible, oxygen content).

Neither thermoelement of type E thermocouples is very sensitive to minor changes in composition or impurity level because both are already heavily alloyed. Similarly they are also not extremely sensitive to minor differences in heat treatment (provided that the treatment does not violate any of the restrictions mentioned above). For most general applications they may be used with the heat treatment routinely given by the wire manufacturers. However, when the highest accuracy is sought, additional preparatory heat treatments may be required in order to enhance their performance. Details on this and other phases of the use and behavior of type EP (or KP) thermoelements are given by Potts, et al., [128].

Type K

The first industry-wide reference tables for type K thermocouples were developed by Roeser [129]. He based his experimental work on a large number of specimens above 0°C; however, there was only one manufacturer of the KP and KN materials at the time. His work below 0°C is based on only two type K thermocouples. Shenker, et al., [126] revised the early tables to base them on the then current temperature scale and electrical units.

The sensitivity of the type K thermocouples is only about one half that of the type E combination at 20 K (4.1 μV/K compared to 8.5 μV/K). The negative element is also a bit more inhomogeneous than that of the EN element. Both materials have low thermal conductivity and are corrosion resistant in moist atmospheres.

Type K thermocouples are recommended by the ASTM [127] for continuous use at temperatures within the range -250°C to 1260°C in oxidizing or inert atmospheres. Both the KP and the KN thermoelements are subject to oxidation when used in air above about 850°C, but even so, type K thermocouples may be used at temperatures up to about 1350°C for short periods with only small changes in calibration. When oxidation occurs, it normally leads to a gradual increase in the thermoelectric voltage with time. The magnitude of the change in the thermoelectric voltage will depend upon such factors as the temperatures, time at temperature, diameter of thermoelement and conditions of use. The thermoelectric instability of type K thermocouples in air at elevated temperatures has been carefully studied [128, 130, 131], and these works should be consulted for details. The following restrictions should be placed on the use of type K:

> They should not be used in sulphurous, reducing, or alternately reducing and oxidizing atmospheres unless suitably protected with protecting tubes. They should not be used in vacuum (at high temperatures) for extended times because the chromium in the positive thermoelement vaporizes out of solution and alters the calibration. They should also not be used in atmospheres that promote "green-rot" corrosion (those with low, but not negligible, oxygen content).

Neither thermoelement of type K thermocouple is very sensitive to minor changes in composition or impurity level because both are already heavily alloyed. Similarly they are also not extremely sensitive to minor differences in heat treatment (provided that treatment does not violate any of the restrictions mentioned above). For most general applications they may be used with the heat treatment routinely given by the wire manufacturer. However, when extreme accuracy is sought, the thermoelements may require additional preparatory heat treatments in order to achieve the desired results. Details on this and other phases of the use and behavior of type K thermocouples are given in [128, 132, 133].

Type T

This thermocouple type is one of the older and more popular combinations, and is the only one of the standardized types for which limits of error below 0°C have been established. A word of warning concerning the unfortunate ambiguity over the material referred to as constantan. Iron versus constantan (JP versus JN) is an often used combination. The negative element, JN, is not the same material as TN (or EN) and cannot generally be used interchangeably.

Reference tables for type T were first prepared by Roeser, et al., [134]. Later these tables were modified to represent the combination better below 0°C [135] and to base the work on the then current temperature scale [126].

Type T thermocouples are recommended by the ASTM [127] for use in the temperature range from -184°C to 371°C in vacuum or in oxidizing, reducing or inert atmospheres. Later research [136, 137] indicates that they can be used down to about 20 K. There are, however, several reasons for not using type T at very low temperatures. (1) The sensitivity of type T at 20 K is lower than that of type E (4.6 μV/K compared to 8.5 μV/K). (2) The thermoelectric properties of the TP element become quite dependent upon trace impurities of iron at temperatures below about 76 K. (3) The thermal conductivity of the TP element is much higher than that of the alloys involved in the type E and K combinations as is seen in figure 2.

Gold-iron Alloy Thermocouples

The fact that trace amounts of transition elements in noble metal solvents causes anomalous thermoelectric properties has been known for some time. Borelius, et al., [138, 139] determined the thermoelectric sensitivity of many dilute alloys of copper, silver, gold, and platinum in 1932. The electrical resistivity and thermopower of these alloys are of interest because of the unusual electron scattering which must be present to cause the peculiar behavior. Much of the work done on dilute alloys has, therefore, been to understand the bulk transport properties involved. Development of the gold-iron alloys for use in low temperature thermocouple thermometry didn't really begin until after 1960 when Berman, et al., [140] tested Au-0.02 at % Fe for possible use in their thermal conductivity apparatus.

Several necessary thermoelectric properties have been determined for the gold-iron alloys, e.g., reproducibility after repeated thermal cycling [141], behavior in a magnetic field [42], and the effect of heat treatment [142, 143]. The number of investigations concerning these properties is small and the conclusions could, therefore, be representative of particular materials rather than a general material. The consensus is, however, that sufficient information is available to establish the gold-iron alloys as the most promising thermoelement available for use at very low temperatures.

There have been four extended range calibrations of gold-iron alloys published in the literature [142, 143, 144, 145]. The types of wire commercially available in this country are the 0.02 and 0.07 at % alloys of iron in gold. The calibration effort of NBS-Boulder has been on these two alloys while 0.03 at % iron in gold is frequently used in England. The annealing procedure for the gold-iron alloys is rather critical as illustrated in the comparison of sensitivity data by Sparks [144] and Rosenbaum [142] in figures 17 and 18. The anneal used by Sparks was 350°C in air for 20 minutes. If the anneal temperature exceeds about 350°C in air, the iron will begin to oxidize resulting in a much reduced thermopower [146]. Higher anneal temperatures are possible in vacuum; however, since the anneal is for purposes of stress relief, the 350°C temperature should be adequate. It is reported [140] that the repeatability of a single piece of gold-iron wire is around 0.2%. The variability between wires from different manufacturers and different melts is indicated in figure 19 which shows the experimentally determined differences among 7 specimens of Au-0.07 at % Fe wire. Reference [144] should be consulted for the details concerning this figure.

Other Materials

As mentioned previously, Au-2.1 at % Co was used extensively as a low temperature thermoelement before its instability [125] became known. Above 18 K a KP versus gold-cobalt thermocouple has better sensitivity than any of the gold-iron combinations. For this reason this alloy is still used in situations where accuracy is of secondary importance, when frequent calibrations can be made, or when it is used as a controlling element. For example, if one wishes the temperature of two bodies to be identical (zero output from a differential thermocouple), the absolute calibration doesn't make any difference; only the sensitivity is important. Calibration tables will be given later for gold-cobalt alloy combinations with the understanding of their limitations.

Another standardized type which is seldom used at low temperatures is type J. Type J is iron (JP) versus constantan (JN). As mentioned in the discussion of types T and E, this "constantan" is not the same as the constantan referred to as TN (or EN). Type J thermocouples are recommended by ASTM [127] for use in the range 0° to 760°C in vacuum, oxidizing, reducing, or inert atmospheres. They are not recommended for sub-zero usage. The fitting functions to be given later for this type are based on the work of Corruccini, et al., [147], revised to IPTS-68 temperature scale.

Thermocouple Reference Data

Tabular data for thermocouple types E, K, and T for the temperature range 0 to 280 K are from [136]. These data are found in tables 13, 14, and 15, respectively. Data for KP versus Au-0.07 at % Fe (table 16), KP versus Au-0.02 at % Fe (table 17), Cu (TP) versus Au-0.07 at % Fe (table 18), Cu versus Au-0.02 at % Fe (table 19), normal silver (Ag-0.37 at % Au) versus Au-0.07 at % Fe (table 20), and normal silver versus Au-0.02 at % Fe (table 21) are from [144]. All of these tables are based on experimental data from the recently completed thermocouple thermometry program at NBS Boulder. The experimental range for the data is $5 \leq T \leq 280$ K. Any extension of the power series representation for $T > 280$ K is an extrapolation and all of the uncertainties inherent in such extensions of experimental data must apply. Extension of the data to $T < 5$ K is more acceptable since the constraint $E = 0 \mu V$ when $T = 0$ K was used in the original fit.

Figure 20 is a graphical comparison of the Seebeck voltages for types E, K, T, and KP versus Au-0.07 at % Fe. The Seebeck coefficients for these combinations are given in figure 21. The Seebeck coefficients for copper (TP) and normal silver versus both Au-0.07 at % Fe and Au-0.02 at % Fe are given in figures 22 and 23 respectively.

In order to facilitate computerized reduction of data, the power series coefficients used to generate the calibration tables are given in table 22. The Seebeck voltage in microvolts as a function of the temperature in degrees K, 0 K reference temperature, is represented by

$$E = \sum_{i=1}^{N} B_i T^i$$

where N represents the number of coefficients for the particular combination. As an example of the application of a series like the one above, consider a thermocouple pair whose temperature-voltage output is represented by a four term (N=4) power series in the temperature range $T_L \leq T \leq T_H$. The thermal voltage expansion as a function of temperature would be given by

$$E = \sum_{i=1}^{4} B_i T^i = B_1 T + B_2 T^2 + B_3 T^3 + B_4 T^4 .$$

This relationship would represent the thermocouple for $T_L \leq T \leq T_H$. It is necessary to use all of the coefficients given for each thermocouple, e.g., table 22 indicates that 14 coefficients must be used to represent type T.

Data in degrees Celsius, 0 °C reference temperature, may be generated using the power series coefficients given in tables 23 through 26. The coefficients used below 0 °C represent the same data as the coefficients given in table 22. Above 0 °C the coefficients represent data from [148]. Coefficients for type J thermocouples as they appear in [148] are given in table 26. Note that for temperatures above 0 °C, the type K representation is by a power series plus a three term exponential.

Tables 27 through 29 [149] contain reference data for thermocouple combinations KP versus Au-2.1 at % Co, Cu (TP) versus Au-2.1 at % Co, and normal silver versus Au-2.1 at % Co, respectively. These tables have not been based on IPTS-68; due to the metallurgical instability of these alloys no experimental work was done on these combinations in the recent NBS calibration program described in [136]. The temperature scales used in these tables were IPTS-48 above 90 K and NBS-55 below 90 K. Corrections given in tables 2 and 3 may be used to base these data on IPTS-68 if desired.

Thermocouple Selection Guidelines

Accurate cryogenic thermocouple thermometry is possible only if care is taken in:

(a) material (thermocouple) selection,

(b) thermocouple calibration, and

(c) general experimental design and measurement technique.

The selection of the proper thermocouple for use in a particular situation is based upon many considerations. Probably the most important at high temperatures is compatibility of the environment with the thermocouple material and its insulation. At low temperatures this is also important, but it is generally not a problem. This criterion, satisfied in essentially the same way as at high temperatures, is treated in detail in the literature [124, 127]. Insulations commonly available are enamel, polyethylene, polytetrafluoroethylene, polymide, and spun glass. Combinations of glass and one of the others are also frequently available. Probably the most durable, but also most difficult to remove, is polyimide. Wires can also be obtained without insulation for use in special situations.

Another important consideration in the selection of the best thermocouple combination for a given task is the physical and chemical inhomogeneity of the wire. No thermal voltage is developed when a loop of homogeneous wire is subjected to a temperature gradient (first law of thermoelectricity). Similarly, no voltage is generated when two identical wires are joined and the pair of wires is placed in a temperature gradient. The problem in practical thermometry is, however, that the ideal characteristics "homogeneous" and "identical" are not sufficiently well approximated for real thermocouple materials. Actually, a loop of wire placed in a large temperature gradient will usually produce a thermoelectric voltage, sometimes as large as ten microvolts for poor materials [150, 151, 152]. If wire from one spool is connected to wire from a different spool of the same nominal composition, their junction placed in a cryogenic fluid, and the free ends held at room temperature, then a significant voltage may result: we have observed readings as large as hundreds of microvolts for poorly controlled alloys. These variable spurious voltages caused by inhomogeneities, physical imperfections, and chemical impurities are one source of imprecision and inaccuracy in thermocouple systems.

Thermocouple Testing

Experimental methods described below allow selection of materials that are most homogeneous and therefore have the smallest amount of spurious voltages. The tests also provide data necessary for making realistic error analyses.

For descriptive convenience we have divided inhomogeneities into four categories based on their distance of separation:

(1) Short-range inhomogeneities occur in a single wire and are separated by less than five meters, often being within a few centimeters of each other.

(2) Medium-range inhomogeneities occur in wires that are from a single spool but are more than five meters apart.

(3) Long-range inhomogeneities are found in wires that are from the same general stock but are from different spools.

(4) Inter-lot variations in chemical composition, thermal treatment, and handling occur in materials produced by different manufacturers, or even in wire produced by the same manufacturer at different times.

The latter categories of inhomogeneities lead to much larger spurious voltages in cryogenic systems. Well-prepared thermocouple wire can have short-range inhomogenity effects as low as 0.1 microvolt; poorly controlled alloys often have inter-lot variations as large as 100 microvolts.

Three types of probes, shown in figure 24, can be used to investigate the various effects of the four categories of inhomogeneities. The first probe configuration, shown in figure 24(a), consists of a single wire about 4 or 5 meters long, part of which is attached to a plastic tube. It need not have a large number of coils, even straight lengths of wire are often satisfactory. Such a probe is used to test for short-range inhomogeneities. The second probe configuration, shown in figure 24(b), consists of two wires, each 2 or 3 meters long, that are coiled on a plastic tube and joined at the bottom. This probe is used to test for the last three categories of inhomogeneities. The essential difference between the two types of probes (besides the junction) is in their manner of thermal tempering: the second type has tightly wound coils of wire near the junction in order to prevent a thermal gradient across the junction, which often contains dissimilar materials.

For both types of probes the ends of the wires are connected to a potentiometer or high-resistance voltmeter; the probes are then dipped into dewars containing cryogenic fluids, usually liquid helium or nitrogen. The first type of probe is dipped in two different manners, one way for static tests, another way for dynamic tests.

For static short-range inhomogeneity tests the probes are immersed to a given depth in the cryogenic fluid and the temperature gradient is allowed to come to equilibrium before readings are taken. In order to obtain more representative values, readings are usually taken at several different liquid levels for each test.

For dynamic short-range inhomogeneity tests the probes are lowered into the fluid at a constant speed. Erratic output voltages are usually observed in these tests because large temperature gradients are developed over different, relatively short lengths of wire as the depth of immersion is changed. The magnitude of the output depends on the type of thermocouple wire, the specific specimen, and to some extent, the rate of immersion. Since comparable results are desired, a constant immersion rate should be used. We have arbitrarily selected 0.5 meter per minute for our tests.

The dynamic, short-range tests are sensitive because large temperature gradients are established over short sections of wire which may contain significant chemical and physical defects. The thermal gradients in the static short-range tests are smaller because of thermal diffusion. This results in spurious voltages which are correspondingly smaller. The static tests are therefore less sensitive indicators of inhomogeneities but more indicative of spurious voltages to be expected in practice. Short-range inhomogeneity tests give a good preliminary estimate of the imprecision that can be expected for temperature measurements in an actual cryogenic system. Results from dynamic tests are most applicable to systems with rapidly fluctuating temperatures or liquid levels; results from static tests are most appropriate for stable cryogenic systems like the typical laboratory cryostat. Wire that exhibits unusually high spurious thermal voltages can be detected and rejected before costly installation.

For tests on medium-or long-range inhomogeneities, or inter-lot variations, the probe configuration shown in figure 24(b) is used. The only differences are in the methods for selection of wires that will be assembled in the test rig. The selection criteria are simply those implied in the basic definitions of the three categories of inhomogeneities. The manner of joining the wires is not critical as long as good electrical contact is obtained and the materials are not mechanically or thermally strained more than a few centimeters away from the junction. The assembled probes are dipped into a cryogenic fluid in the same manner as in static short-range inhomogeneity tests.

Medium-and long-range inhomogeneity tests are useful for determining the variations that may occur in a selected lot of thermocouple wire. The medium-range inhomogeneity tests are especially useful for systems that include thermocouples made from consecutive lengths of wire. The deviations in voltage usually become progressively larger as the original positions of the wires become more widely separated. It is good practice to thermoelectrically compare the front and back ends of a spool, or lot of material, to determine if variations of the material are within acceptable limits. If the material is sufficiently homogeneous, then a single calibration will suffice for all thermocouples made from that spool. If the material varies beyond acceptable limits, then additional calibrations become necessary for each separate part of the spool or lot. In the limits of relatively inhomogeneous material or extremely accurate measurement systems, separate calibrations should be made for each length of wire.

Tests for inter-lot variations are necessary if wires from different melts or from different manufacturers are going to be used. Inter-lot variations can be very large: hundreds of microvolts have been observed for nominally "identical" material received from different manufacturers. Even material received from the same manufacturer at different times can have large variations, up to about 40 microvolts. Because of these variations, it is best to have all thermocouples in a system made from one lot, preferably one spool, of material. To insure this, enough wire should be ordered at the beginning of construction of a thermocouple system to allow repair or replacement of all initial thermocouples.

We have determined the spurious voltages caused by the first three categories of inhomogeneities for several of the thermocouple materials used at low temperatures. Results obtained with both types of probes on five different materials are summarized in table 30. Short-range inhomogeneity results were obtained by using probe type 1; the other results, by using the type 2 probe with a junction in the wires. The numbers quoted are the average of the maximum values which were found for several spools from the same manufacturer.

The calibration procedure necessary to make use of a particular thermocouple depends on the application. If temperature differences are needed only to about 10%, one can probably accomplish this by using general calibration tables. These are tables which refer to a general type of thermocouple, not to a particular wire or spool of wire. To obtain a more exact calibration, one must measure the emfs of this thermocouple at selected temperatures. The emf difference between a particular thermocouple and the standard table is often small and nearly linear in temperature, so that only a few points, sometimes only two, are necessary.

The calibration of a thermocouple is done with a type 3 probe shown in figure 24 (c). This probe would normally be used to obtain the thermoelectric emfs between a series of pairs of fixed points. These emfs would then be used in conjunction with a standard reference table to form a new and more accurate table for that specific thermocouple. Such a calibration may be accurate to a few millidegrees if the wire has been thoroughly homogenized and is free of physical defects. Before calibrating wire for highly accurate or precise applications, one should perform the tests discussed in the previous section to determine the effect of the inhomogeneities in the wire. If one needs 0.01 K precision, or better, it will be necessary to do extremely careful in-place calibration against a calibrated thermometer such as a platinum or germanium resistance thermometer.

In conjunction with the establishment of standard reference tables for low temperature thermocouples, a standard reference material (Ag-28 at % Au) has been developed [153]. This material is recommended for use at low temperatures, along with platinum, to standardize thermocouple materials which match these standard reference tables more uniformly than was possible in the past.

FILLED SYSTEMS

Vapor Pressure Thermometers

Vapor pressure thermometry makes use of the non-linear relationship between the vapor pressure and the temperature of the saturated liquid and saturated vapor phases of a pure gas. Advantages of this type of thermometry are that it is sensitive, can have good time response, is not affected by magnetic fields, and needs no calibration. The primary disadvantage is that it can be used only between the triple point and critical point of the fill liquid. The ranges of use and approximate sensitivities are shown in table 31. It is seen from this table that there are gaps in the measurable ranges from 5.2 K up to 13.8 K and another from 44.4 K up to 54.35 K.

There are many different analytical representations of the vapor pressure-temperature relationship for each of the gases used in vapor pressure thermometry. A critical and comparative analysis of these equations is beyond the scope of this paper. To further complicate the situation, some of the useful data are based on temperature scales other than IPTS-68. Helium vapor pressure is a special case lying outside the range of IPTS-68. After due consideration, the best tact for presenting the data needed in vapor pressure thermometry seems to be as follows: (1) the tabular vapor pressure-temperature data will be presented as it is in the referenced papers, (2) the temperature scale(s) used in the tables will be noted, and, (3) the analytical representations will be given as in the referenced papers.

The saturation properties and thermodynamic properties of He^4 are given by McCarty [154]. The vapor pressure versus temperature relationship is shown in table 32. The lambda point is at 2.177 K, the critical point at 5.201 K, and the n.b.p. at 4.224 K. Analytical representation of these data is given by

$$\ln P = \sum_{i=1}^{10} A_i T^{(2-i)} .$$

Pressure is in microns, temperature in kelvins. The coefficients for this series are given in table 33. The temperatures used in this representation are $T_{58} + 0.001 + 0.002 \times T_{58}$, where T_{58} indicates temperatures on the 1958 helium vapor pressure-temperature scale [21].

Saturation and thermodynamic properties for equilibrium hydrogen (0.21% ortho, 99.79% para) are given by Roder, et al., [155]. The vapor pressure versus temperature relationship is shown in table 34. The triple point is at 13.803 K, the n.b.p. at 20.268 K, and the critical point at 32.976 K. The temperatures used in this table are based on the NBS-55 scale; these temperatures may be based on IPTS-68 by using the data in table 2. The analytical representation for this table is given in three ranges by the following equations [156]: For temperatures between 13.803 K and 21 K

$$\log P = A_1 + \frac{A_2}{T_{55}} + A_3 T_{55},$$

between 20.268 K and 29 K

$$\log P_a = A_4 + \frac{A_5}{T_{55} + A_6} + A_7 T_{55},$$

and between 29 K and 32.976

$$P = P_a + A_8(T_{55} - 29)^3 + A_9(T_{55} - 29)^5 + A_{10}(T_{55} - 29)^7 .$$

Pressure is in atmospheres, temperature in kelvins. The coefficients for all three equations are given in the HYDROGEN column of table 33. In order to use these functions on IPTS-68, $T_{55} = T_{68} - \Delta T$ must be used (the ΔT are found in table 2).

The saturation properties of neon as determined by Grilly and by McCarty, et al., [157, 158] are shown in table 35. The triple point is at 24.54 K, the n.b.p. at 27.09 K, and the critical point at 44.40 K. The temperatures used in this table are based on the NBS-55 scale; these temperatures may be based on IPTS-68 by using the data in table 2. The analytical representation for this table is given by

$$\log P = A_1 + \frac{A_2}{T_{55}} + A_3 T_{55} + A_4 T_{55}^2 .$$

Pressure is given in mm Hg, temperature in kelvins. The coefficients for this equation are given in table 33. In order to use this function on the IPTS-68 scale, $T_{55} = T_{68} - \Delta T$ from table 2 must be used. The thermodynamic properties of neon are found in McCarty, et al., [159].

Saturation and thermodynamic properties of nitrogen are given by Jacobsen [160]. The vapor pressure versus temperature relationship is shown in table 36. The triple point is at 63.148 K, the n.b.p. at 77.347 K, and the critical point at 126.2 K. The analytical representation of these data is given by

$$\ell n\, P = \frac{A_1}{T} + A_2 + A_3 T + A_4 (T_c - T)^{1.95} + A_5 T^3 + A_6 T^4$$

$$+ A_7 T^5 + A_8 T^6 + A_9 \ell n(T).$$

Pressure is in atmospheres, temperatures in kelvins. The coefficients used are given in table 33. These data are based on IPTS-68.

Saturation and thermodynamic properties of oxygen are given by Roder, et al., [161]. The vapor pressure versus temperature relationship is shown in table 37. The triple point is at 54.351 K, the n.b.p. at 90.18 K, and the critical point at 154.576 K. The analytical representation of these data is given by

$$\ell n\, P = A_1 + A_2 T + A_3 T^2 + A_4 T^3 + A_5 T^4 + A^6 T^5$$

$$+ A_7 T^6 + A_8 T^7.$$

Pressure is in atmospheres, temperature in kelvins. The coefficients for this equation are given in table 33. These data are based on NBS-55 for temperatures below 91 K and IPTS-48 for temperatures above 91 K. As discussed in the hydrogen vapor pressure paragraph, $T_{55 \text{ or } 48} = T_{68} - \Delta T$ must be used in order to base the results on IPTS-68.

In reviewing the open literature, the author finds little information on the "nuts and bolts" design of vapor pressure systems — the reason being, perhaps, that it is straightforward enough to allow design and use from basic principles. There are, however, pitfalls which might best be shown in the development of a basic approach to design.

The most simple vapor pressure-temperature determination is made by measuring the pressure over a liquid surface where the liquid may or may not be confined.

This situation is shown in figure 25(a). The temperature measured in this way may be significantly different than the temperature in the bulk liquid [80, 162, 163]. Also, the purity of the fluid in a situation such as this may be questionable. The vapor pressure measured will represent the total pressure which is in turn made up of the partial pressures of all gases present, i.e., $P_{total} = P_{fill\ fluid} + P_{residual\ gases}$.

Vapor pressure systems built specifically for temperature measurement are represented schematically in figure 25(b). The accuracy of a system such as this is limited by the pressure measurement accuracy, pressure temperature relationship for the fill substance, and the purity of the fill substance. In most applications, the purity and pressure measurement are the real limiting factors. The vapor bulb system should be carefully cleaned, and then evacuated and heated to remove residual gases.

The vapor pressure of liquid helium is only negligibly affected by impurities. Only residual helium affects the vapor pressure of hydrogen. However, the ortho-para concentration is important in hydrogen [164]. The vapor pressure of the nitrogen and oxygen are significantly altered by impurities; the primary impurities are oxygen in nitrogen and vice versa. Chemical preparation or high purity cylinder gas is recommended when either are used as fill gases.

The temperature indicated by a vapor pressure measurement will be affected by the coldest spot in the system. The bulb must be the coldest part of the system; otherwise, vacuum insulation or electrical heating must be used on the connecting line. If this is not done, or precautions taken to insure a homogeneous temperature distribution in the bath, a temperature which is different than the bulb temperature will be encountered at the liquid surface.

It is very easy to get erroneous readings from "over-fill" and "fade-out". "Over-fill" is the condition where sufficient gas has condensed to completely fill the vapor bulb. The temperature indicated in such a situation will be the temperature of the liquid vapor interface. The level of the interface in the connecting tube will be determined by the heat flow into the system. "Fade-out" is the condition occurring when the liquid phase no longer exists at the temperature and pressure of the system. In such a case, the vapor pressure system becomes a gas thermometer. This situation is illustrated for temperatures greater than T_f in figure 26. This condition is particularly treacherous because there is no obvious transition, and the pressure read out will not appear vastly different. Proper design for particular ranges of use can eliminate concern over these problems.

A general approach to system design might be as follows [165] where the volumes are defined in figure 25(b):

(1). Determine the temperature range to be used.

$T_{BH} \equiv$ highest bulb temperature

$T_{BL} \equiv$ lowest bulb temperature

(2) Using either the specific volumes or densities (1/specific volume), establishing the constant mass relationship

$$M_{BH} = X_{BH} V_B \rho_{L, BH} + (1 - X_{BH}) V_B \rho_{V, BH} + \rho_{G1, A} V_A$$

where X is the fraction of the bulb filled with liquid at the highest bulb temperature (BH), (1 - X) is the fraction of the bulb filled with saturated vapor at T_{BH}, $\rho_{G1, A}$ is the density of the gas at system pressure and ambient temperature (T_A), and $V_A \cong V_A + V_C$. A similar equation for T_{BL} may be written

$$M_{BL} = X_{BL} V_B \rho_{L, BL} + (1 - X_{BL}) V_B \rho_{V, BL} + \rho_{G2, A} V_A .$$

Since the mass of the system is constant, $M_{BL} = M_{BH}$ and

$$\frac{V_A}{V_B} = \frac{X_{BL}\rho_{L, BL} - X_{BH}\rho_{L, BH} + (1 - X_{BL})\rho_{V, BL} - (1 - X_{BH})\rho_{V, BH}}{\rho_{G1, A} - \rho_{G2, A}}$$

(3) Select either volume A or B. Often the capillary and gage volume are relatively fixed. Since the ratio of V_A/V_B is known from the preceding equation, both volumes are now known. Substitution of V_A and V_B into either of the mass relationships will determine the mass of the gas in the system.

(4) The relationship $\frac{\text{mass}}{\text{volume}}$ = density is used to find the density of the gas in the system.

(5) Tables of the thermodynamic properties of gases contain data relating ρ, T, and P. At a given fill temperature and computed density, the required fill pressure may be determined.

Thermodynamic properties of gases have been referenced earlier, but for convenience they will be cited again: He^4,[154]; H_2,[155]; Ne, [158]; N_2,[160]; and O_2,[161]. One of the thermodynamic parameters needed in the mass equations is the density of the gas at a given pressure and at the temperature of the warm volume which is generally about 295 K. $\rho(P, T)$, where T = 295 K, is given for some of the gases and not for others. The ideal gas law may be used for determining this value.

$$PV = nRT$$

or

$$\frac{n}{V} = \frac{P}{RT} .$$

As an example of the calculation which may be needed consider P = 1 atm = 1013200 dyn/cm^2, T = 295 K, R = 8.3144 x 10^7 dyn cm K^{-1} mol^{-1}. Then,

$$\frac{n}{V} = 4.1309 \times 10^{-5} \frac{\text{mol}}{\text{cm}^3} .$$

For He,

$$\frac{n}{V} = 4.1309 \times 10^{-5} \frac{\text{mol}}{\text{cm}^3} \times \frac{4\text{g}}{1 \text{ mol}} = 1.65236 \times 10^{-4} \frac{\text{g}}{\text{cm}^3} .$$

Using linear interpolation in the 1 atm isobar table from [154], ρ = 1.65273 x 10^{-4} g/cm^3. This magnitude of error is of little consequence since the value is only used in determining the fill pressure.

The pressure measuring equipment used in vapor pressure thermometry may be a pressure-electrical transducer, dial type pressure gage, or manometry. Precision pressure measurements with mercury manometers are discussed in [166].

The response time of a vapor pressure system depends on the rate that the system can transfer energy to and from the bath, and on the specific heat of the bulb. A small bulb with light, highly conductive walls would require a minimum of energy from the bath in order to alter the vapor pressure. A high ratio of outside surface area to bulb volume promotes good heat transfer characteristics. A well designed system in a moving liquid environment can have a response time (63.2% of temperature step function) of less than 0.1 second.

Gas Thermometers

Precision gas thermometry falls in the category of fundamental thermometers rather than empirical thermometers. It is much too demanding for common use. Indeed, only a handful of the national laboratories and universities are able to do precision gas thermometry. Although by no means complete, the following references will supply the interested reader with basic information and many excellent references for constant volume helium gas thermometry [167, 168, 169, 170, 171, 172] and [173, 174] for hydrogen gas thermometry.

Gas thermometry of a less precise nature is frequently used in practical temperature measurements. Figure 25(b), used in the discussion on vapor pressure thermometers, may be used also in gas thermometry. In this case, a fill gas must be used which will not condense at the lowest temperature to be encountered. Boyles' law states that for a constant mass of gas, PV = RT or PV/T = R, the universal gas constant. If a system such as that shown in figure 25(b) is filled to a pressure of P_f at T_f and $V_A \cong V_A + V_C$ then

$$\frac{P_f V_A}{T_f} + \frac{P_f V_B}{T_f} = \frac{P_T V_B}{T} + \frac{P_T V_A}{T_f} .$$

(It is assumed that the fill temperature is the same as the operating temperature of the auxilary volume, i.e., $T_f = T_{room}$). This equation may be arranged

$$\frac{1}{P_T} \quad P_f(V_A + V_B) = \frac{1}{T} \quad V_B T_f + V_A .$$

If the volumes are known, the temperature results directly from the measurement of pressure. If the volumes are not known, they may be determined by measuring the pressure at two calibration temperatures. Varying the ratio of V_A to V_B allows the sensitivity of the thermometer to be changed. Good low temperature sensitivity may be obtained by making V_A/V_B large. A high ratio means that only at very cold temperatures will an appreciable amount of gas be in the bulb; this condition also causes the thermometer to be sensitive to ambient temperature fluctuations. If V_A/V_B is made very small, sensitivity of the system becomes approximately constant throughout the temperature range. White [60] and Coxon [175] discuss corrections and precautions which must be applied to practical gas thermometer systems in order to achieve maximum accuracy. Inaccuracies of a few parts in a thousand are possible with reasonable care. Factors affecting the accuracy such as shrinkage of the cold volume, capillary tube effects, and ambient temperature are discussed by Holten [176]. This paper also deals with the dynamic response of gas thermometers and methods of reducing response time. Time responses of less than 0.5 seconds have been achieved under specific conditions.

SUMMARY AND RECOMMENDATIONS

Measurement of cryogenic temperatures can be accomplished with several types of transducers as has been discussed above. Figure 27 summarizes the principal instruments which can be used between 4 and 300 K. Note that all but neon, hydrogen, and helium-4 vapor pressure instruments can be used in at least part of the temperature range between the triple point and the critical point of oxygen. The information presented in this figure is intended as a general guide, except in the cases of the vapor pressure instruments where it indicates the total range for each fill substance. Carbon and germanium resistance thermometers can be used above 100 K, platinum resistance thermometers can be used below 10 K, and thermocouple types T and R can be used below 20 K; however, extension of the ranges beyond the bounds indicated in the figure puts the transducer at a rather severe disadvantage. Figure 28 shows the comparative sensitivities of the resistance thermometers and the gallium arsenide junction thermometer (100μA forward current).

For temperatures above about 20 K, the metallic resistance thermometers are more sensitive than the nonmetallic resistance thermometers. Temperatures above 20 K can be measured routinely with industrial type PRT's with an accuracy of better than 100 mK and time responses somewhat better than 1 second. Accuracy at the millidegree level requires precision capsule type PRT's and careful calibration.

Carbon thermometers are generally used for low temperature measurements ($T < 80$ K) when accuracies of ± 0.1 K or ± 1% of temperature are needed. Millidegree accuracy is attainable using germanium resistance thermometers at temperatures below 20 K. The primary drawback to germanium thermometers is that no simple analytical representation is available which represents the resistance versus temperature characteristics even for a given class of doped germanium crystals. A many point comparison calibration is required if all the inherent stability of the resistor is to be utilized.

Thermocouple types E, K, T, and KP versus Au-0.02, 0.07 at % Fe can be used very well in the LO_2 range. If a gold-iron alloy is to be used above about 20 K, the positive thermoelement should be type KP. Use of the KP material allows the gold-iron alloys to be used from below the n.b.p. of helium up to room temperature. These couples have an extremely linear sensitivity above 20 K. Type E is recommended for general use when temperatures are not below 20 K.

Vapor pressure and gas thermometry offer sensitive methods of temperature measurement with the advantage that no calibration is necessary. Further advantages are that these transducers are not sensitive to magnetic fields or electric fields. In the case of vapor pressure thermometers, the time response may be made comparable to that of the resistance thermometers.

Throughout this paper, problem areas for specific thermometer types have been mentioned. In many cases additional research could eliminate some of the existing difficulties.

(1) General area of resistance thermometers: The anisotropic behavior of indium should be studied with the purpose of constructing reproducible thermometers. If sufficient similarity between thermometers could be achieved, Cragoe Z functions might allow precise R(T) from only a few calibration points. Other approaches to analytical representation should also be examined. Resistance thermometer construction in general could benefit from the development of better support materials and suspension techniques. The work being done on high temperature platinum resistance thermometers is representative of needed research in this area.

Carbon resistors have received a good deal of attention in their role as low temperature thermometers. However, the resistors used are designed for use in radio or similar circuits. Additional research on active element support and lead attachment would be beneficial. Thin film thermometers are perhaps most in need of further work. Standardized methods of deposition, materials, substrates, etc., are all needed. The desirable characteristics of fast time response, small size, ruggedness, and high sensitivity should warrant the needed basic development of these thermometers. Up to this time, the work on thin film thermometers has been highly empirical. Basic studies are needed to understand the transport properties of thin films for use as thermometers.

(2) General area of thermoelectric thermometry: Additional research is needed to develop materials for use in special applications such as very low temperatures, magnetic fields, nuclear environment, etc. The noble metal-transition metal alloys in particular need further examination. One goal of these investigations would be to determine whether or not the Au-0.02, 0.03, or 0.07 at % Fe alloys currently being used are optimized. Both concentration and different elements should be studied.

The National Bureau of Standards in Washington, D.C., provides a calibration service for thermocouples, PRT's and GRT's. Details of the service are available from the Temperature Section, PHYS-B228, National Bureau of Standards, Washington, D.C., 20234.

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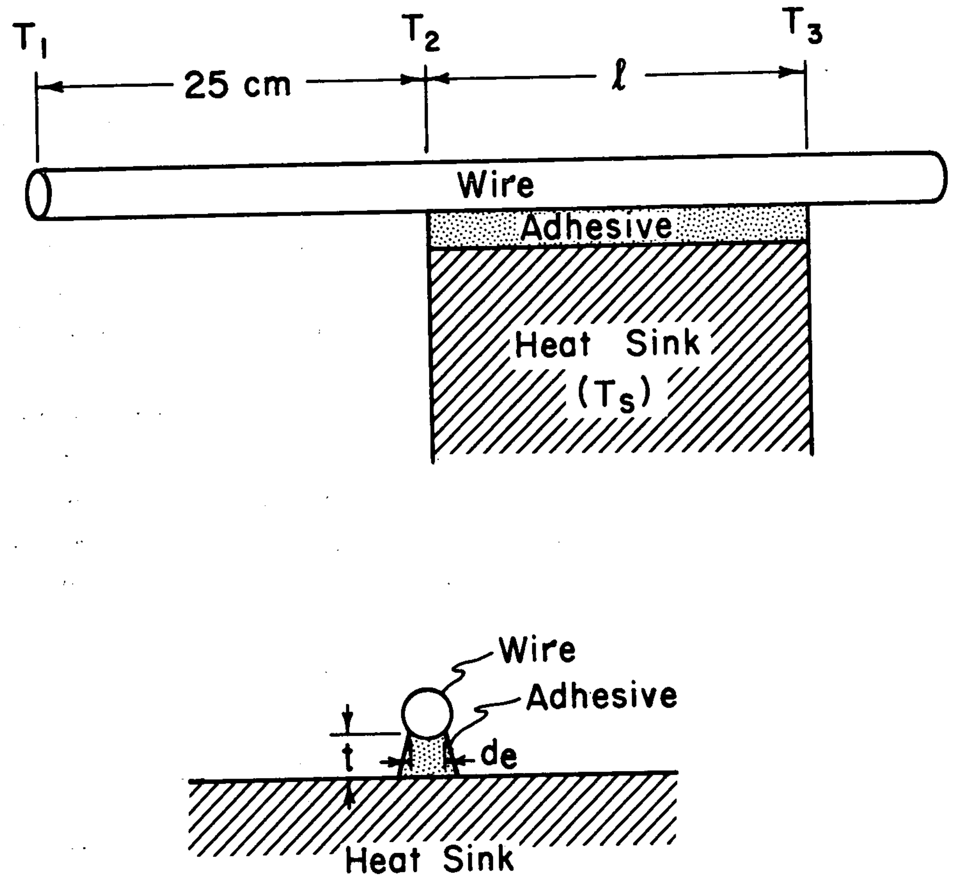


Figure 1. Thermal anchoring of wire to heat sink through adhesive.

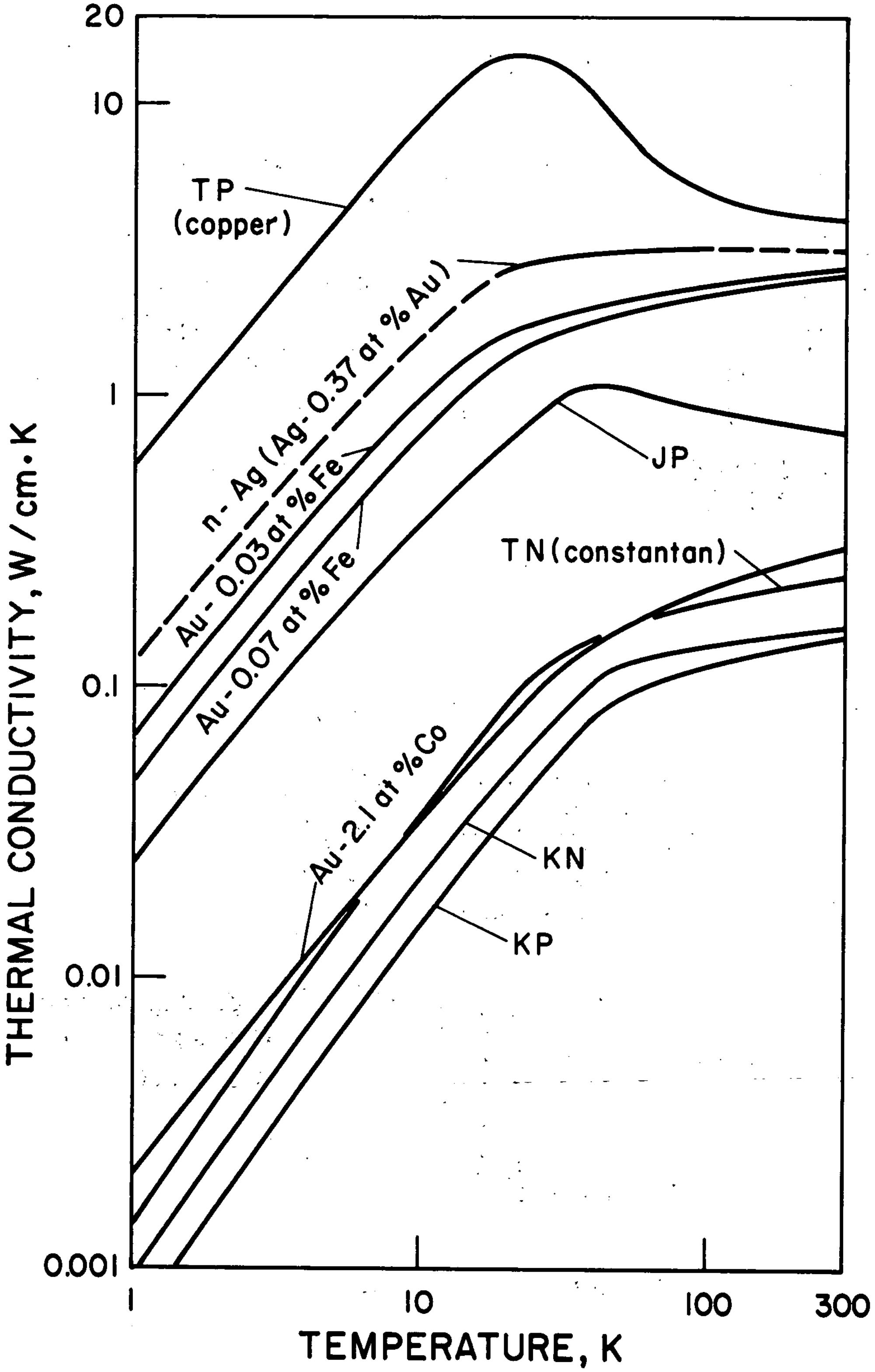
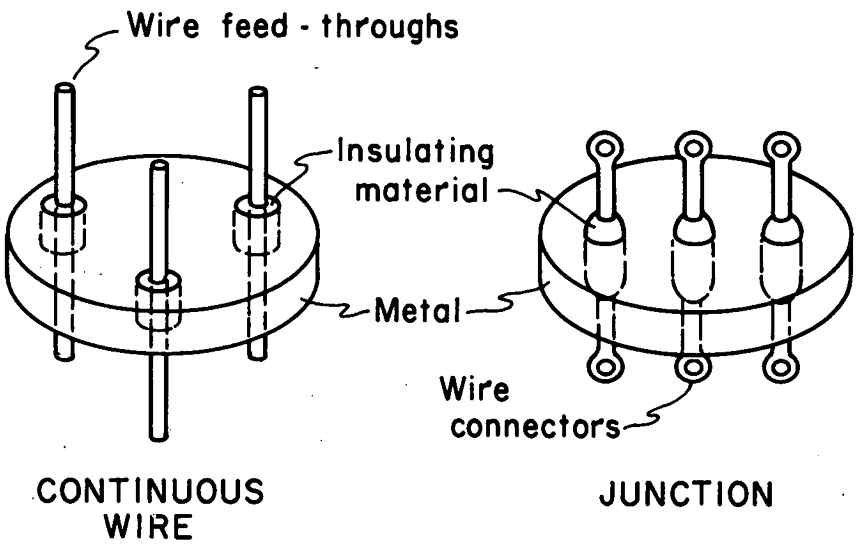


Figure 2. Thermal conductivity (W/cm•K) versus temperature (K) for materials frequently used in thermocouple thermometry.

a)



b)

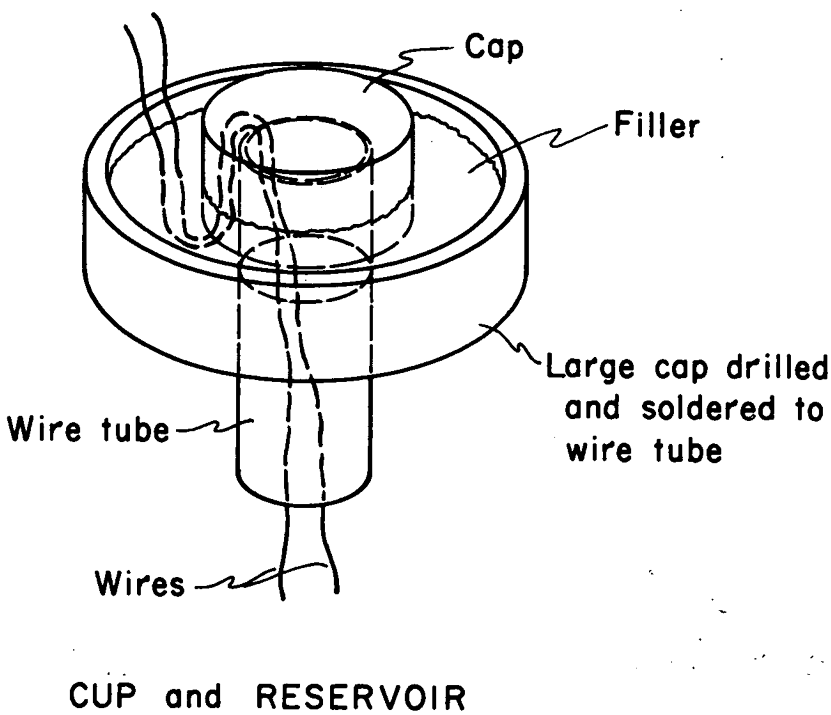


Figure 3. Schematic of electrical feed-throughs frequently used in low temperature cryostats.

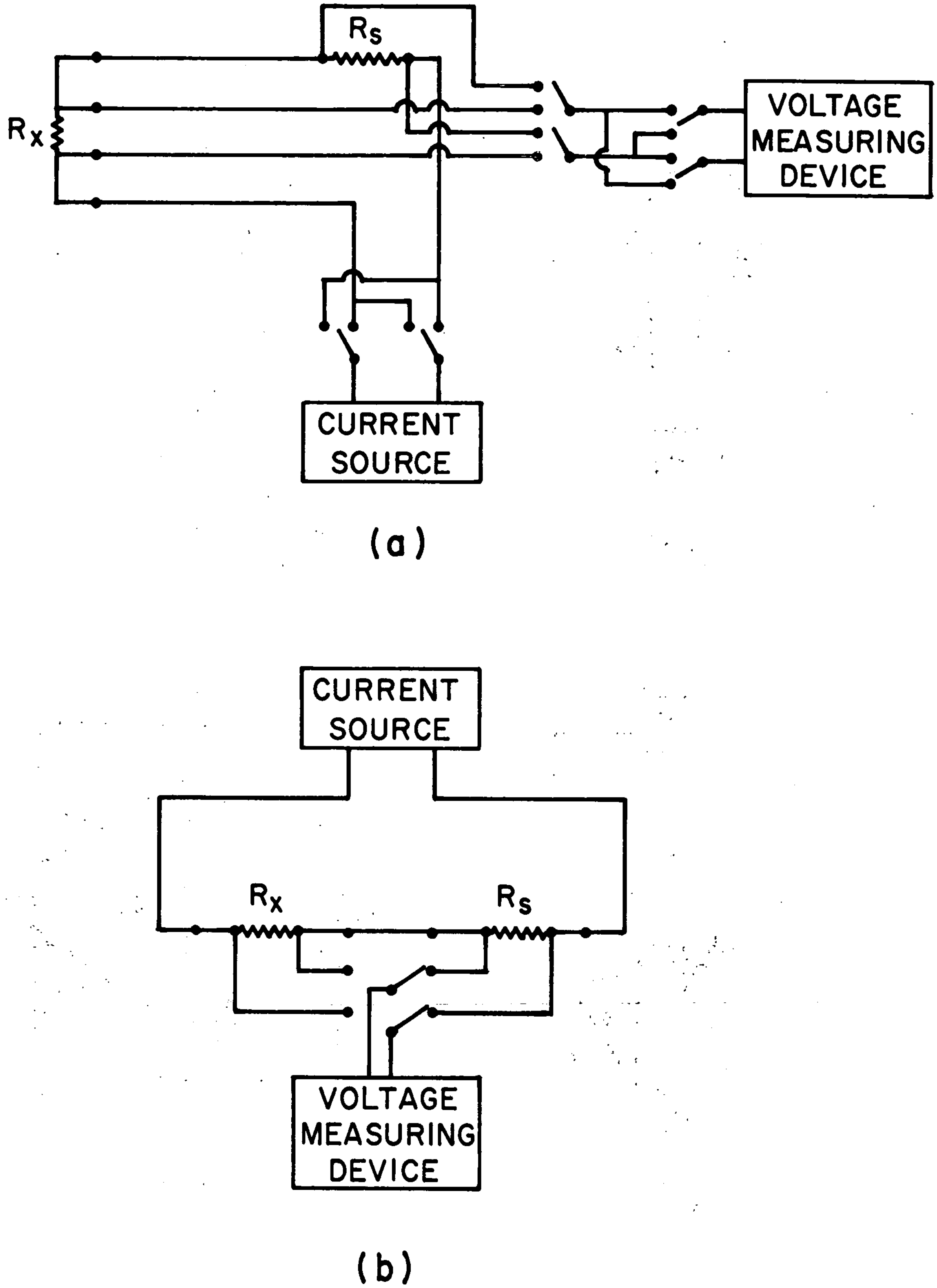


Figure 4. Schematic of potentiometric circuits used with resistance thermometers.

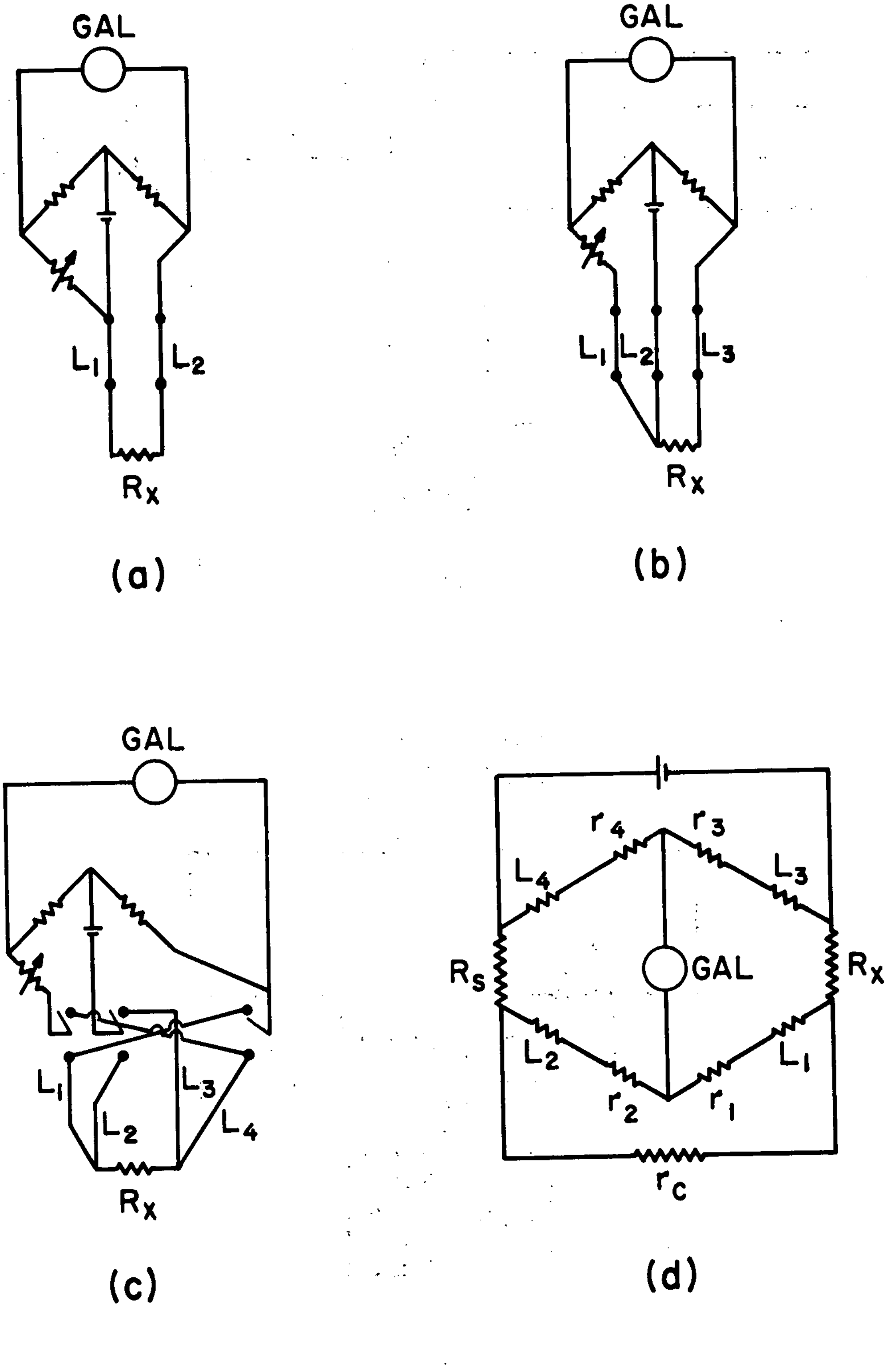


Figure 5. Schematic of bridge circuits used with resistance thermometers.

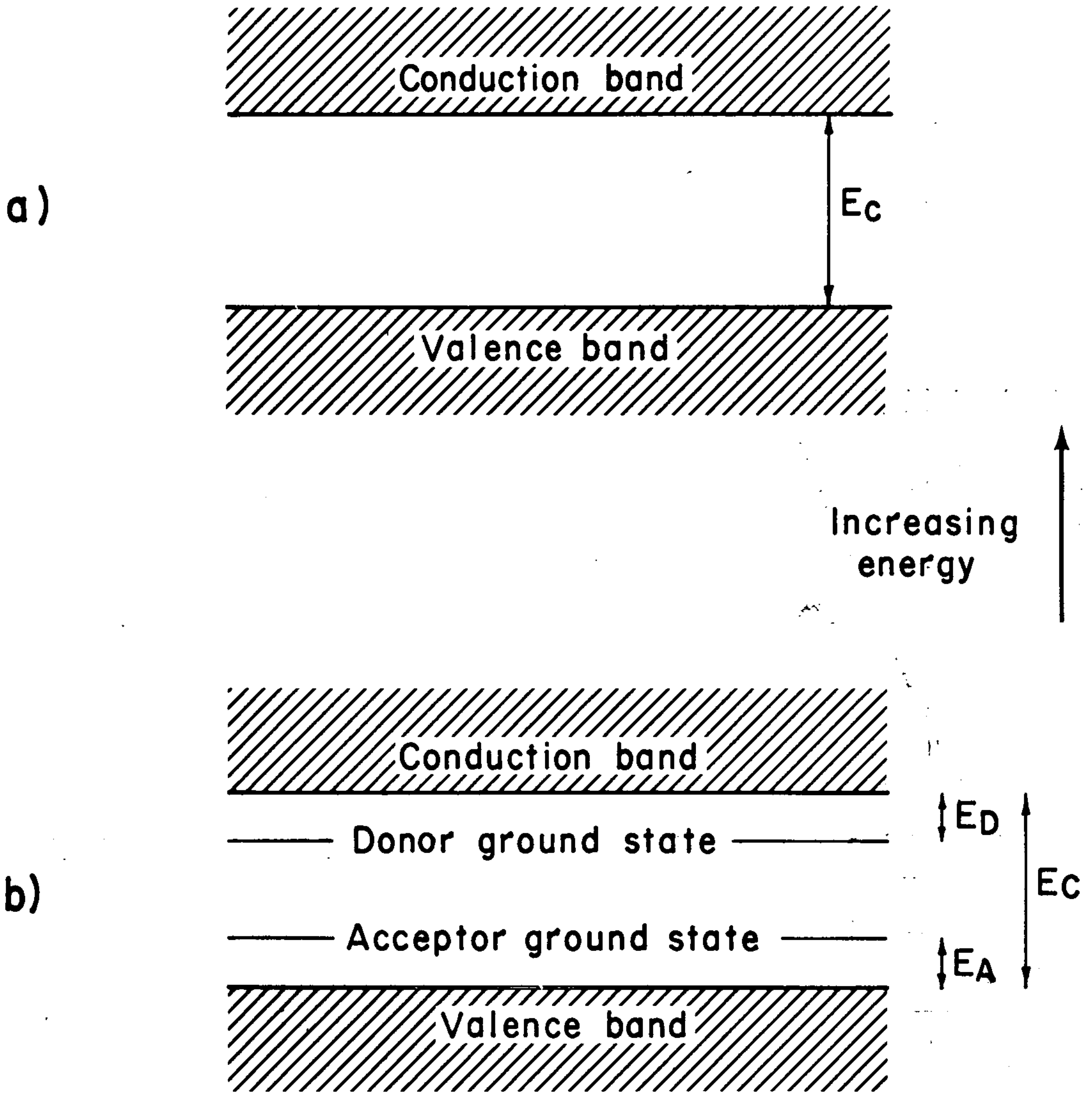


Figure 6. Energy levels of semiconductors.

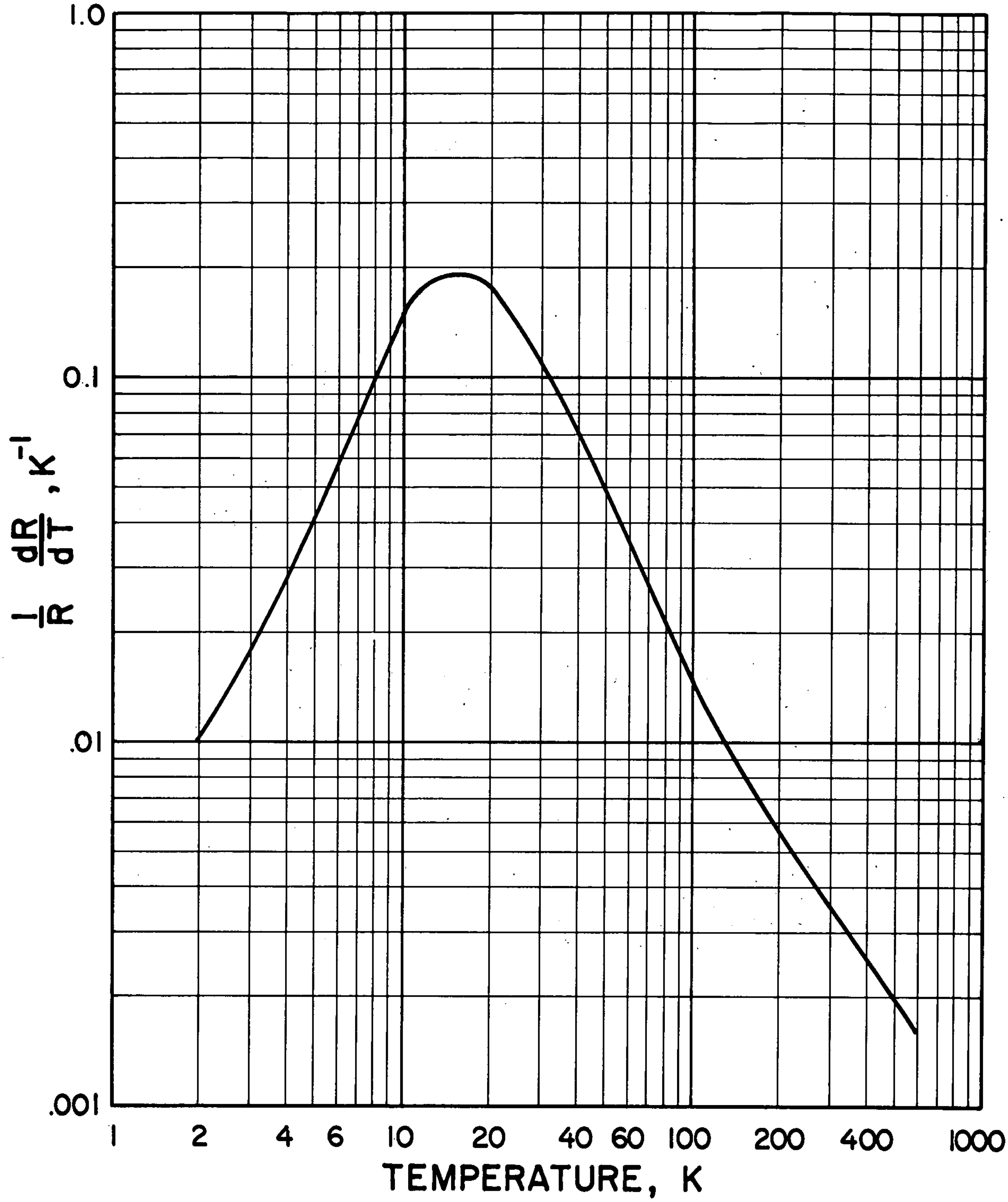


Figure 7. Temperature coefficient of resistance (K^{-1}) versus temperature (K) for high purity platinum.

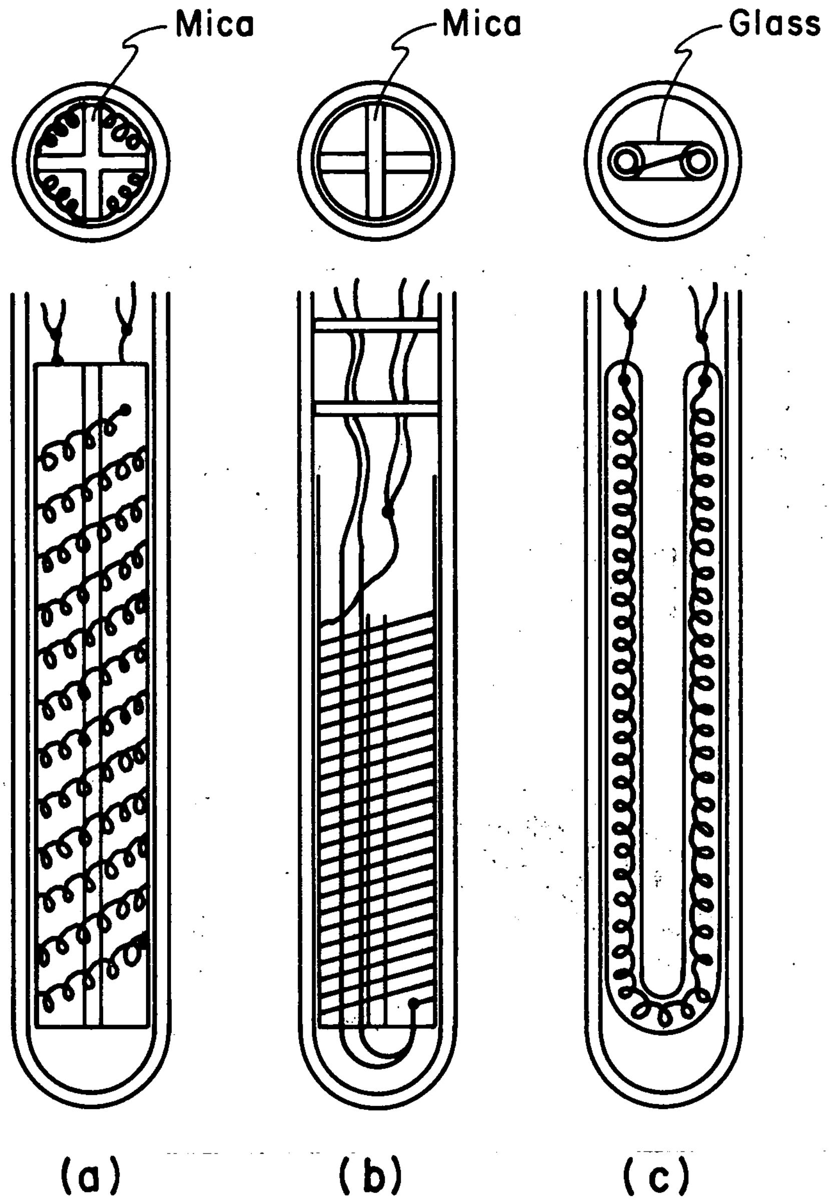


Figure 8. Schematic of capsule type platinum resistance thermometers.

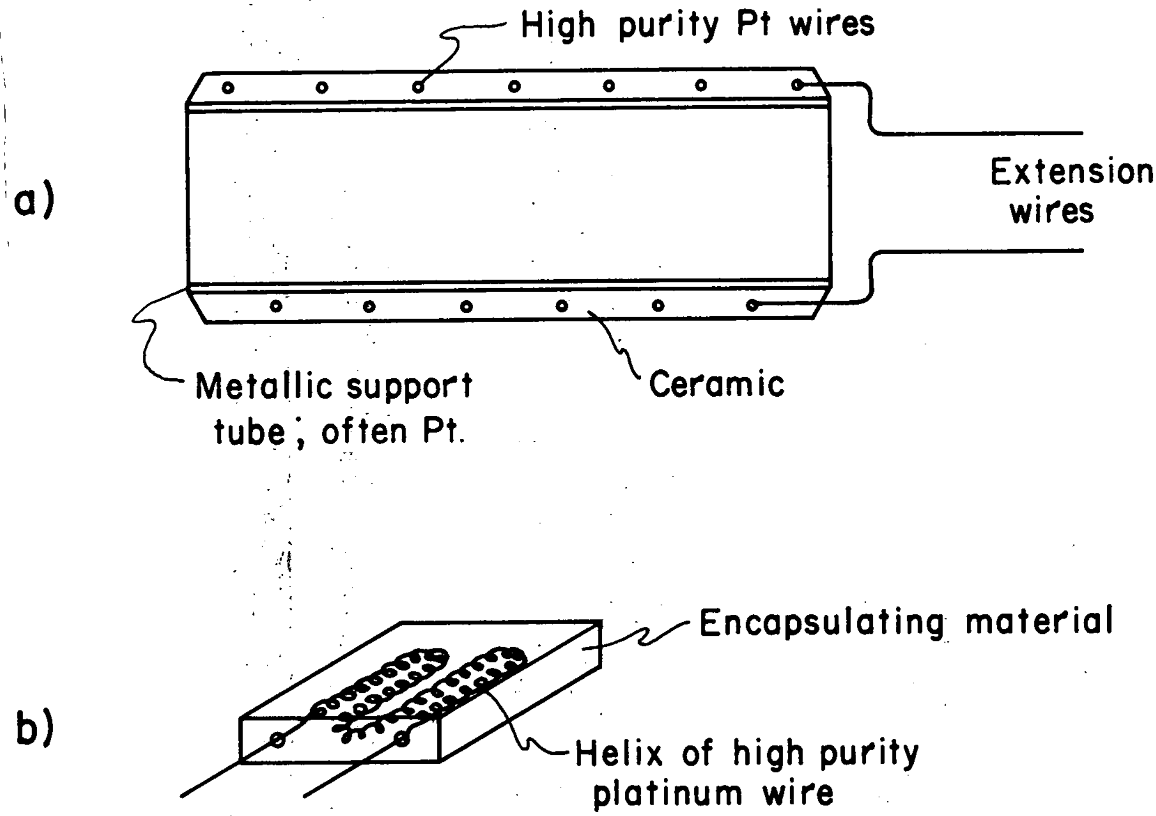


Figure 9. Schematic of industrial platinum resistance thermometers, (a) immersion type and (b) surface type.

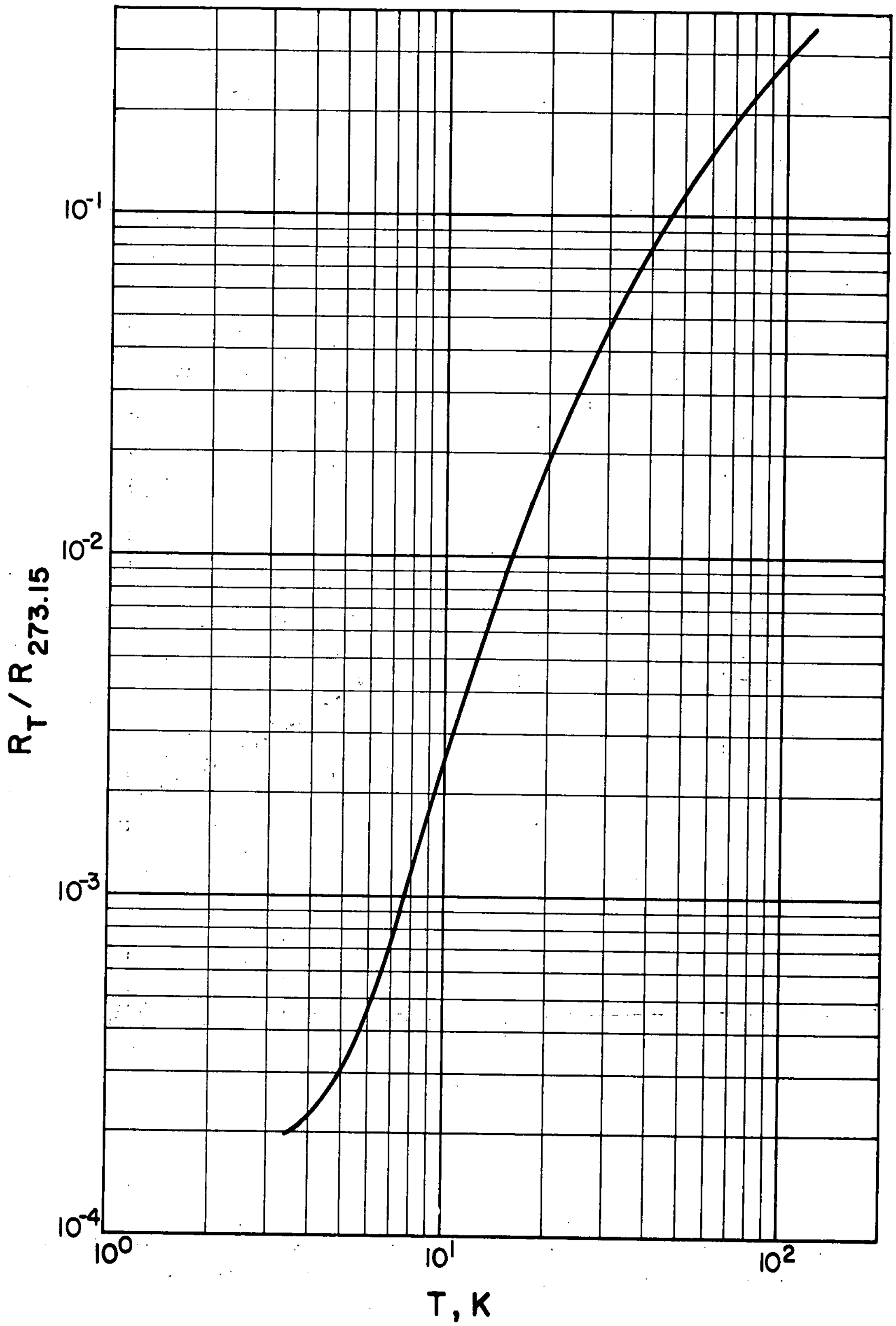


Figure 10. Resistance ratio, $R_T/R_{273.15}$, versus temperature (K) for indium.

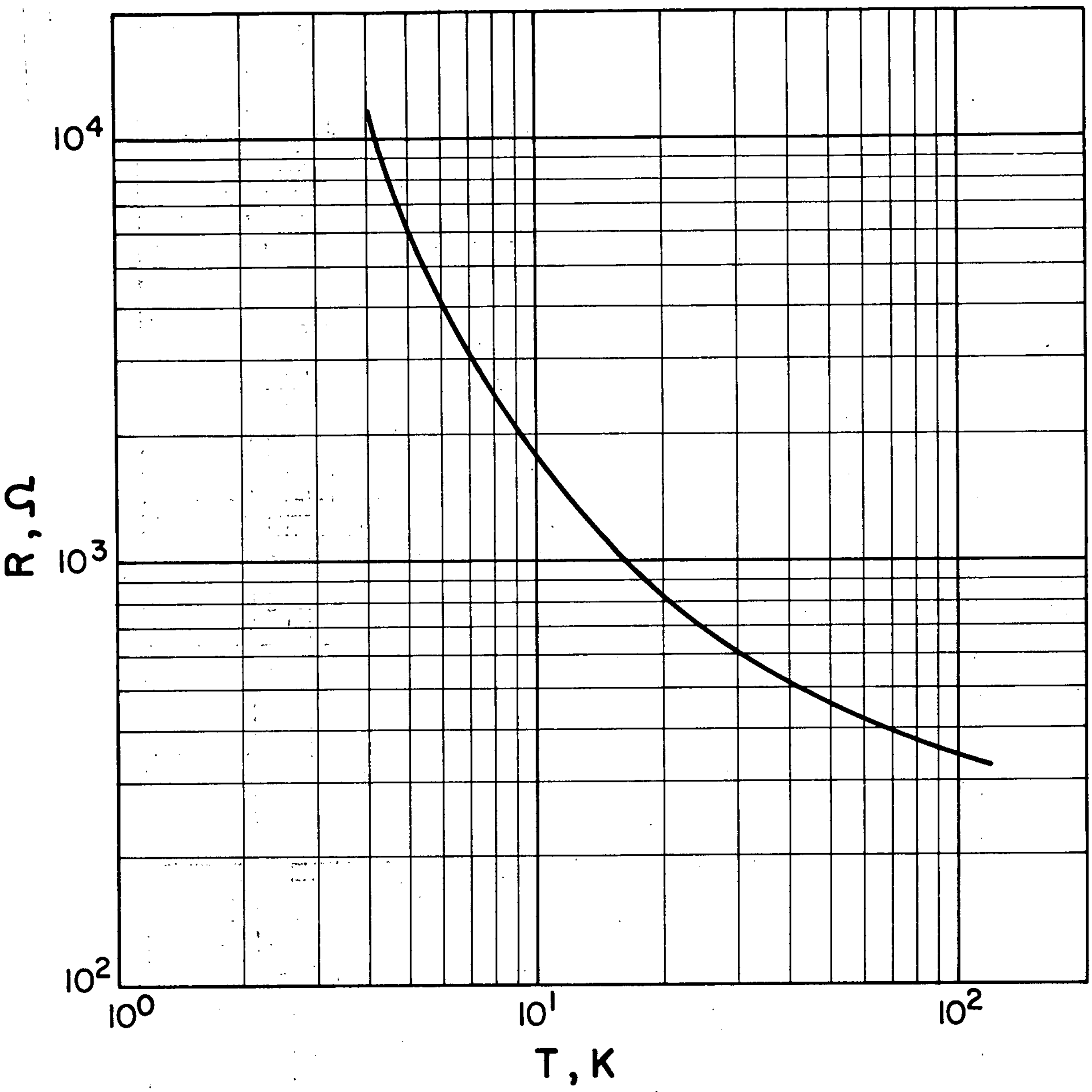


Figure 11. Resistance (Ω) versus temperature (K) for a commercially available 0.1 watt, 270 Ω carbon radio resistor.

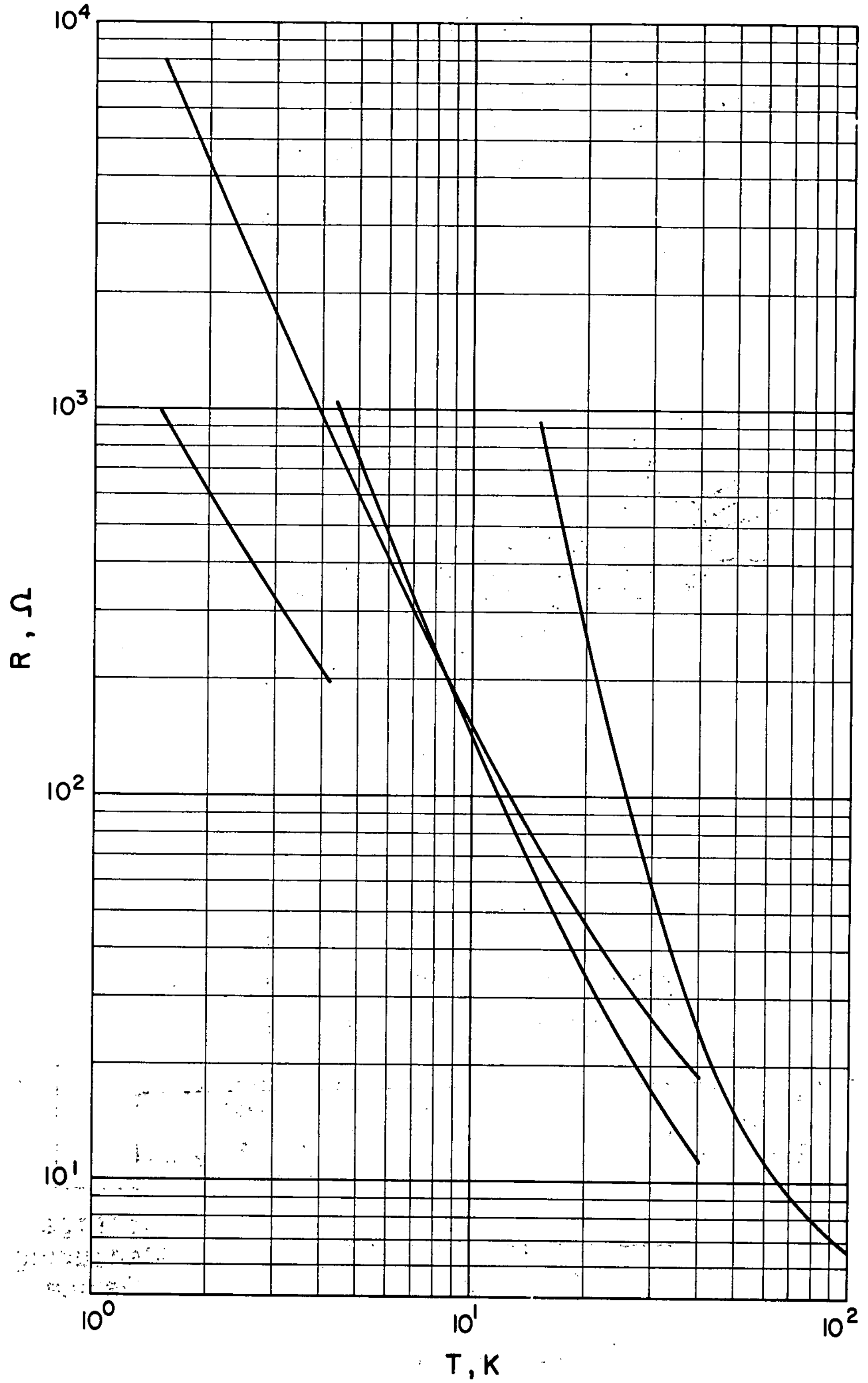


Figure 12. Resistance (Ω) versus temperature (K) for several types of commercially available germanium resistance thermometers.

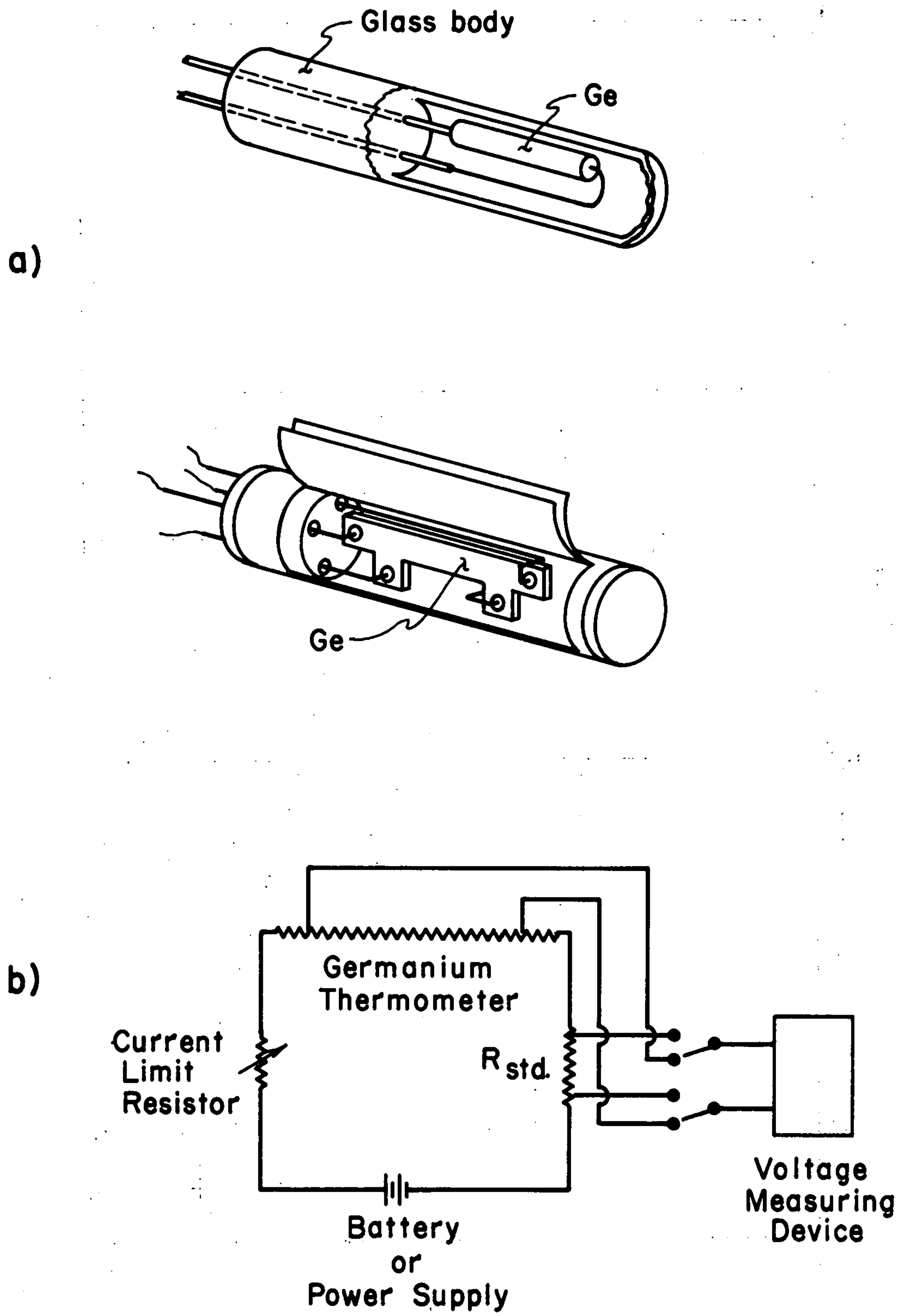


Figure 13. Schematic of (a) two types of commercially available germanium resistance thermometers, and (b) a circuit often used to determine temperatures with a germanium resistance thermometer.

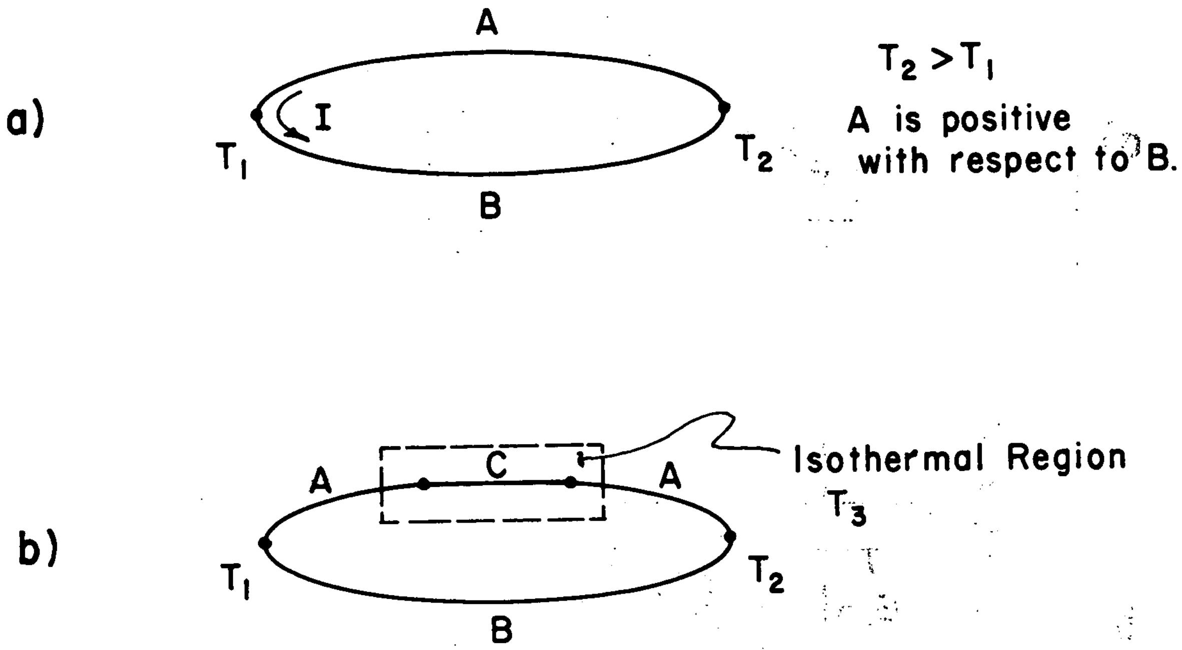
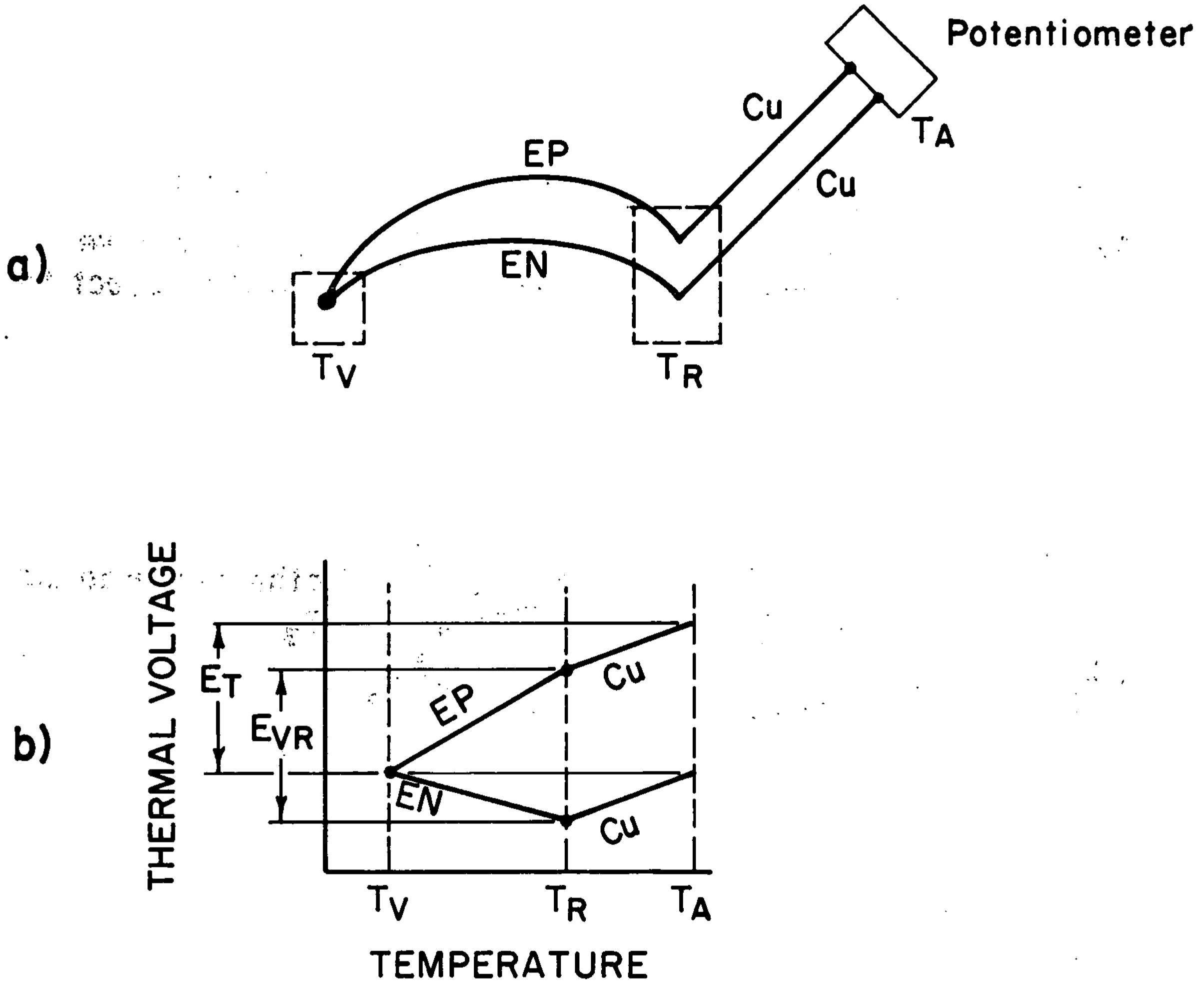


Figure 14. Schematic of two thermocouple circuits: (a) current flows from the positive to negative material at the cooler of the two junctions, (b) introduction of a third material "C" into an isothermal part of the thermocouple circuit has no effect on the output.



E_{VR} ≡ Thermal voltage generated by a Type E thermocouple temperature difference $T_R - T_V$.

E_T (= E_{VR}) ≡ Thermal voltage E_{VR} as transmitted to ambient temperature via Cu extension leads.

Figure 15. (a) Schematic of a type E thermocouple with copper extension wires. (b) Thermocouple output shown graphically.

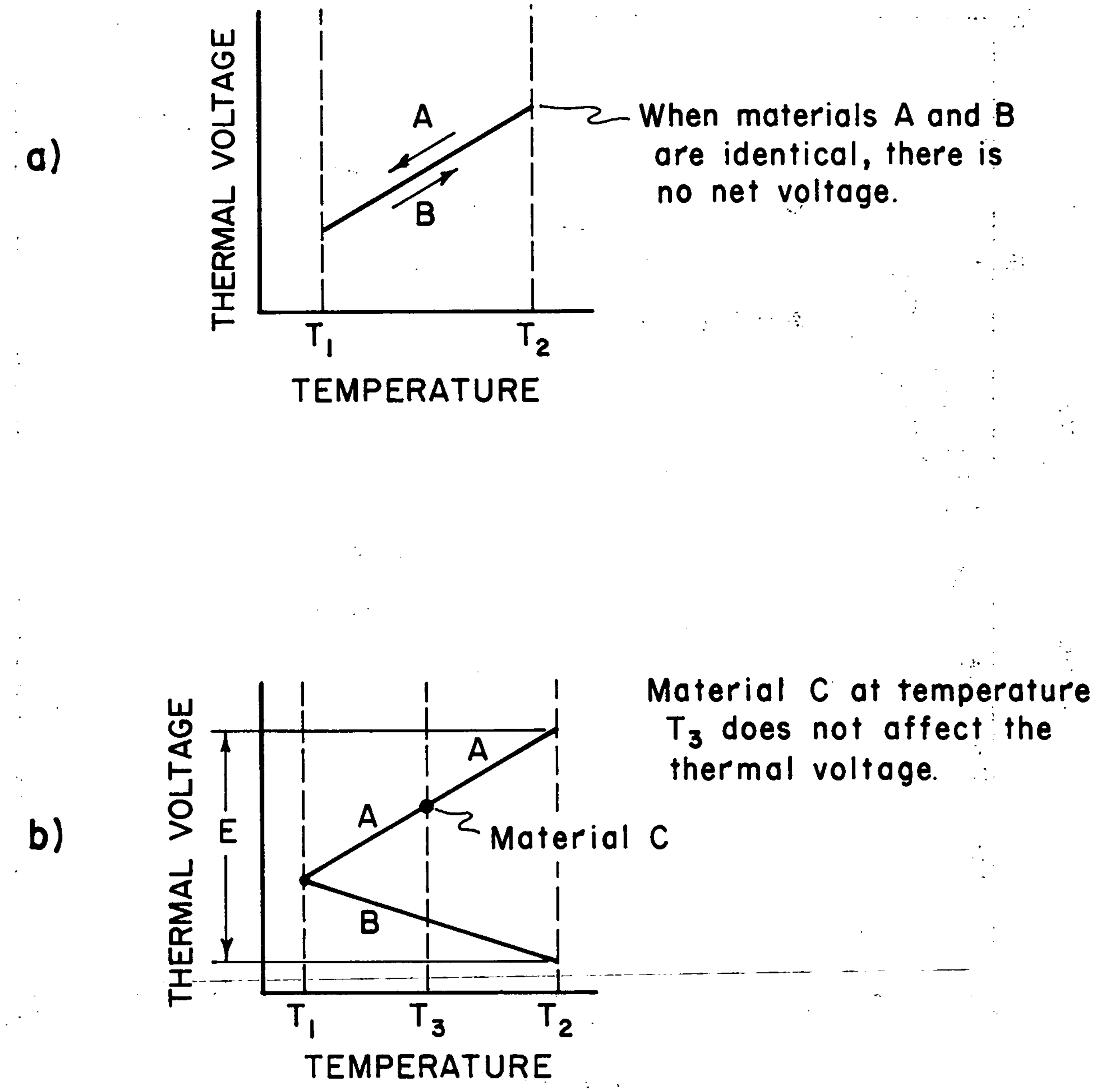


Figure 16. Graphic analysis of the first two laws of thermoelectricity. (a) Law of the homogeneous circuit -- no net measurable emf developed when materials A and B are identical. (b) Law of intermediate materials -- material "C" causes no change in the thermoelectric characteristics of the circuit because it is contained entirely in an isothermal region.

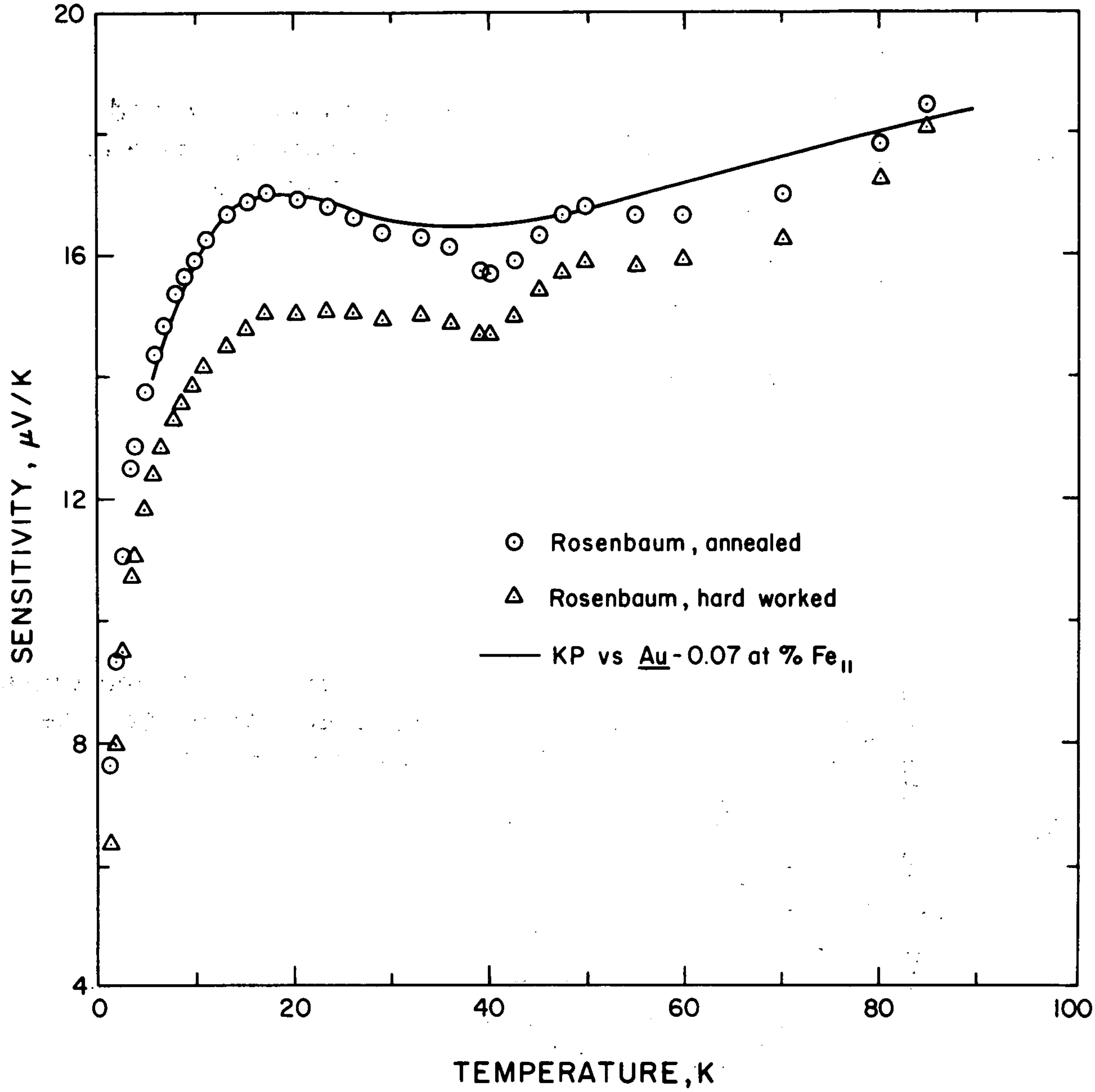


Figure 17. Comparison of Seebeck coefficients for KP versus Au-0.07 at % Fe in the annealed and unannealed state.

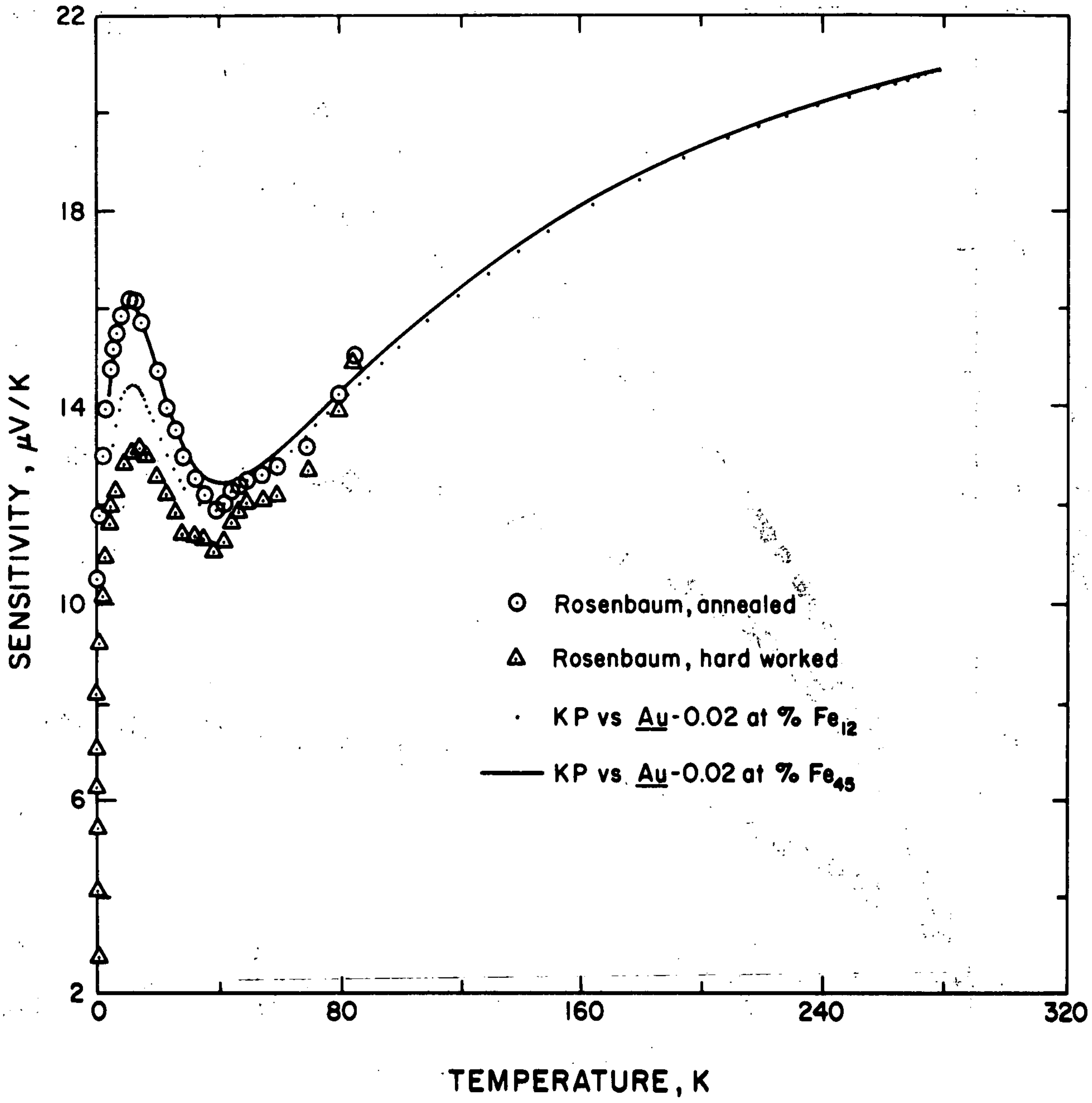


Figure 18. Comparison of Seebeck coefficients for KP versus Au-0.02 at % Fe in the annealed and unannealed state.

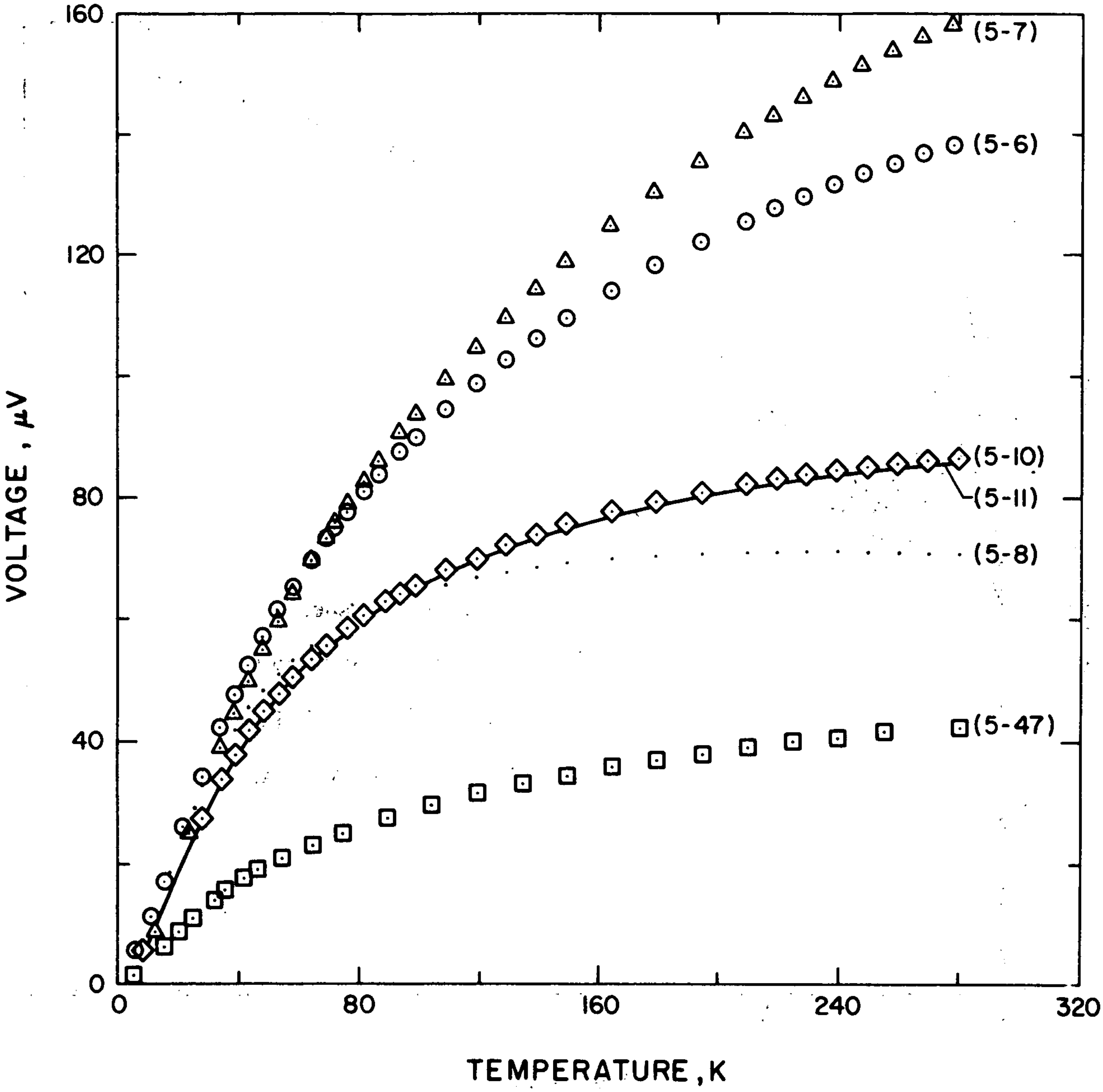


Figure 19. Thermoelectric differences between a particular Au-0.07 at % Fe specimen and six other Au-0.07 at % Fe specimens.

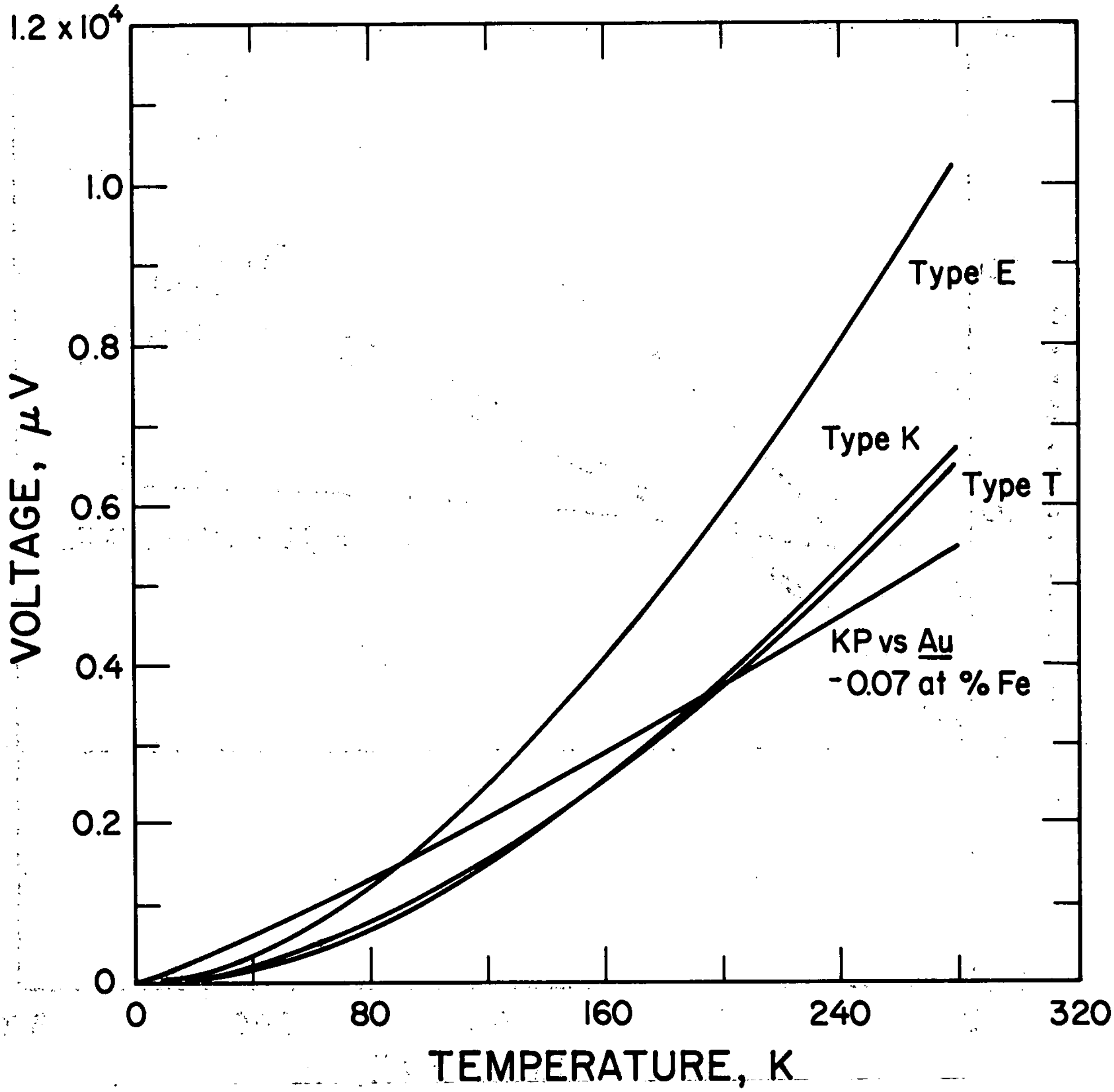


Figure 20. Thermoelectric voltage (μV) versus temperature (K) for thermocouple types E, K, T, and KP versus Au-0.07 at % Fe.

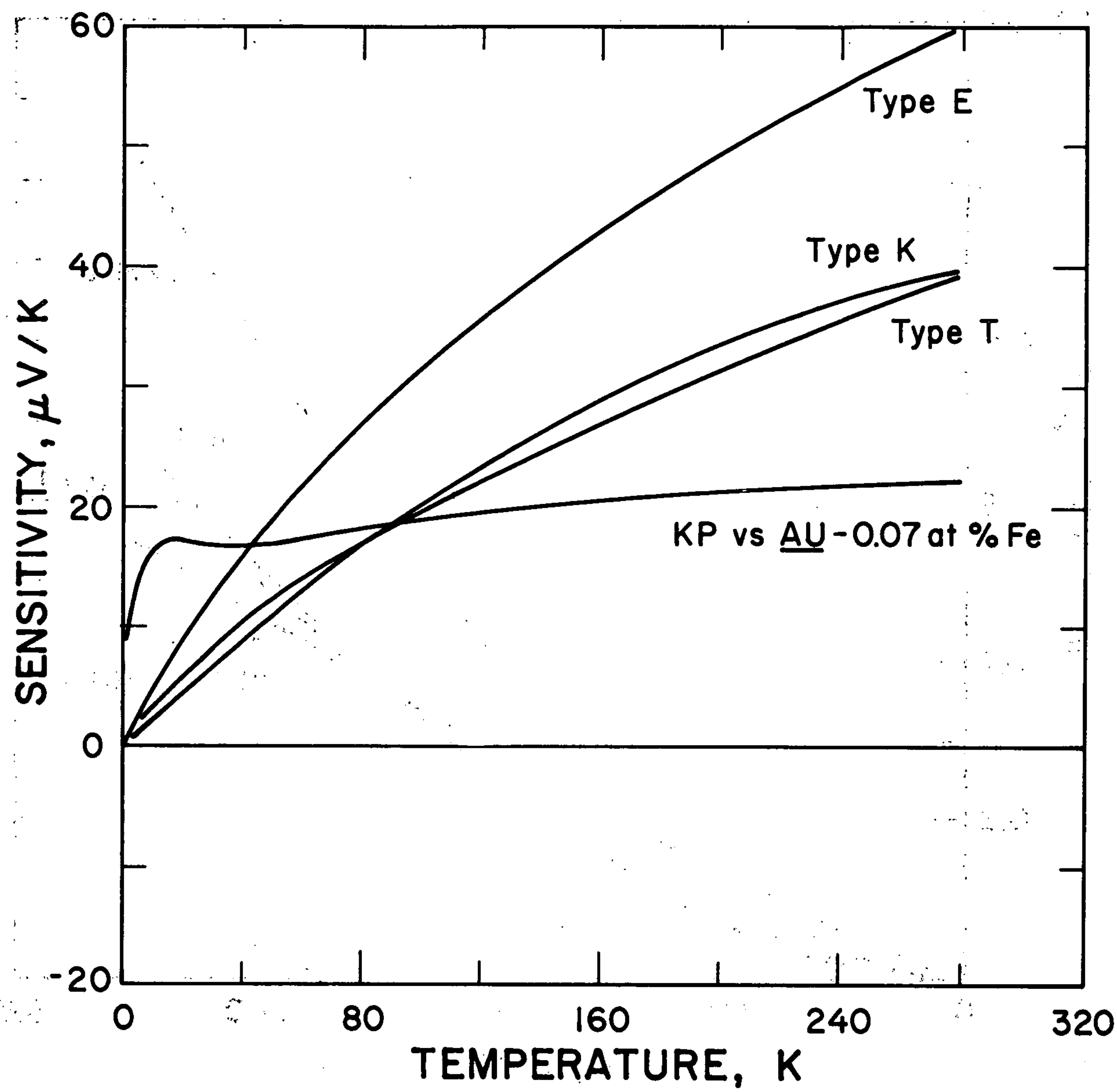


Figure 21. Thermoelectric sensitivity (μV/K) versus temperature (K) for thermocouple types E, K, T, and KP versus Au-0.07 at % Fe.

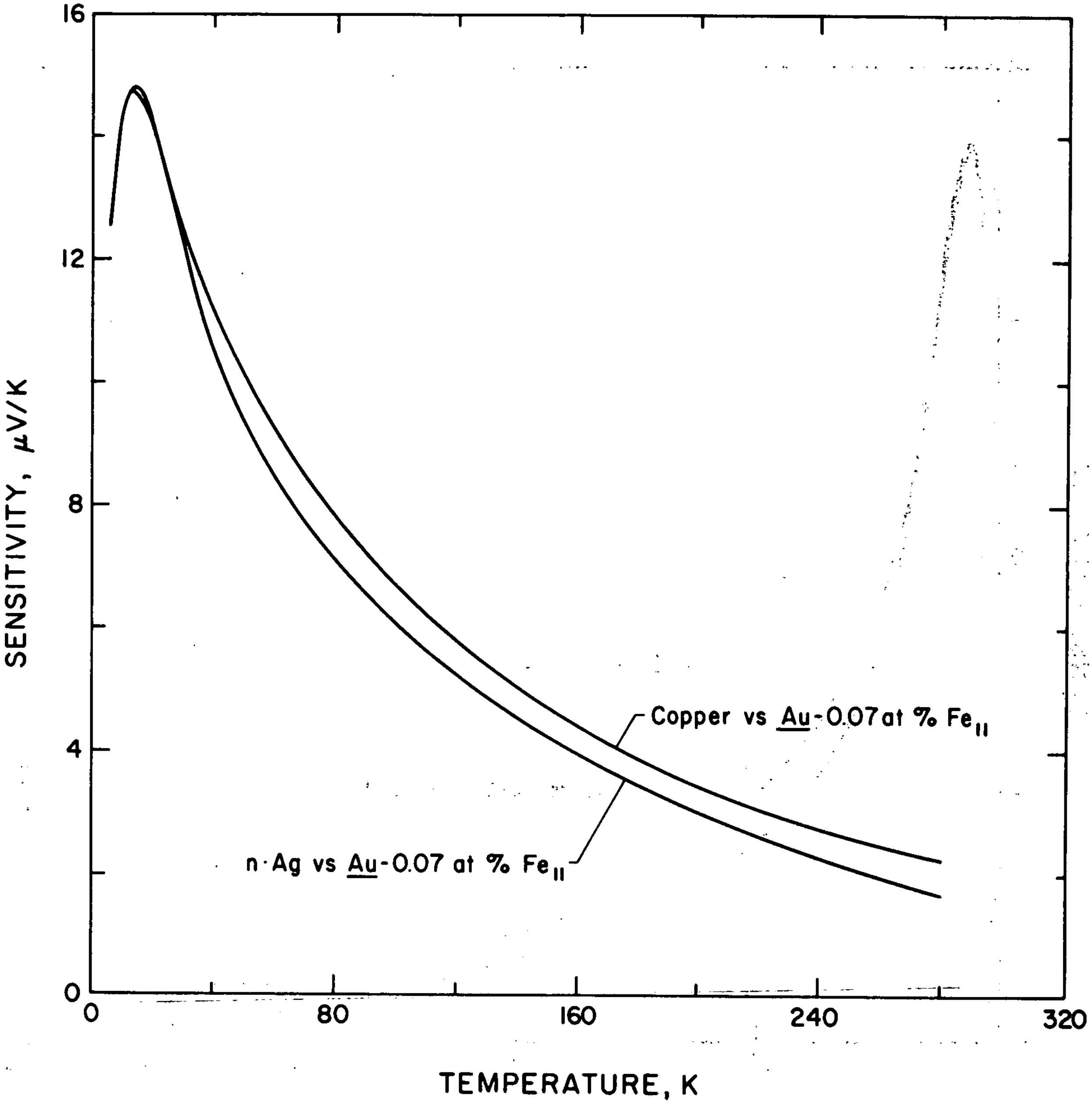


Figure 22. Thermoelectric sensitivity (μV/K) versus temperature (K) for copper and normal silver versus Au-0.07 at % Fe.

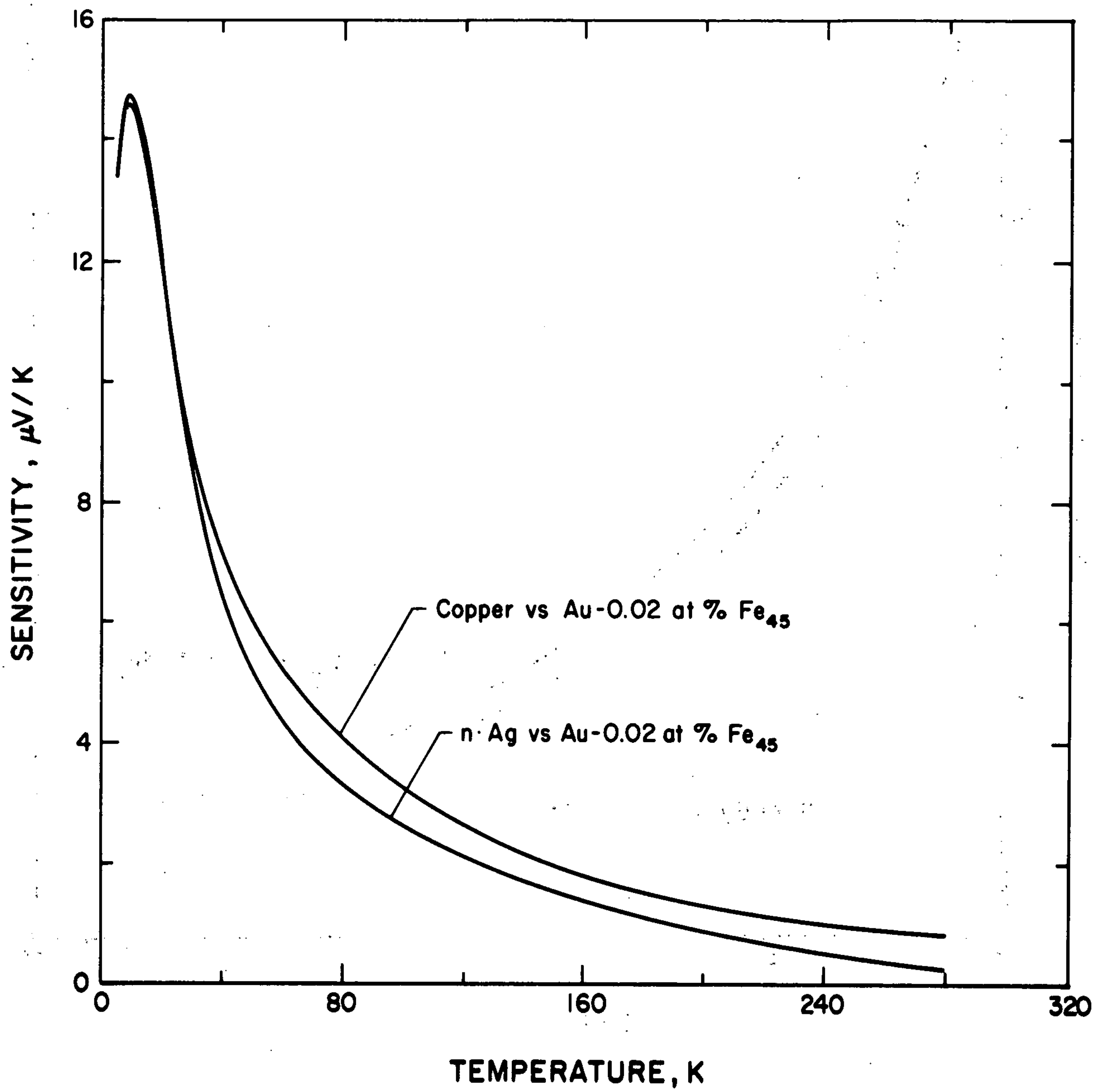


Figure 23. Thermoelectric sensitivity (μV/K) versus temperature for copper and normal silver versus Au-0.02 at % Fe.

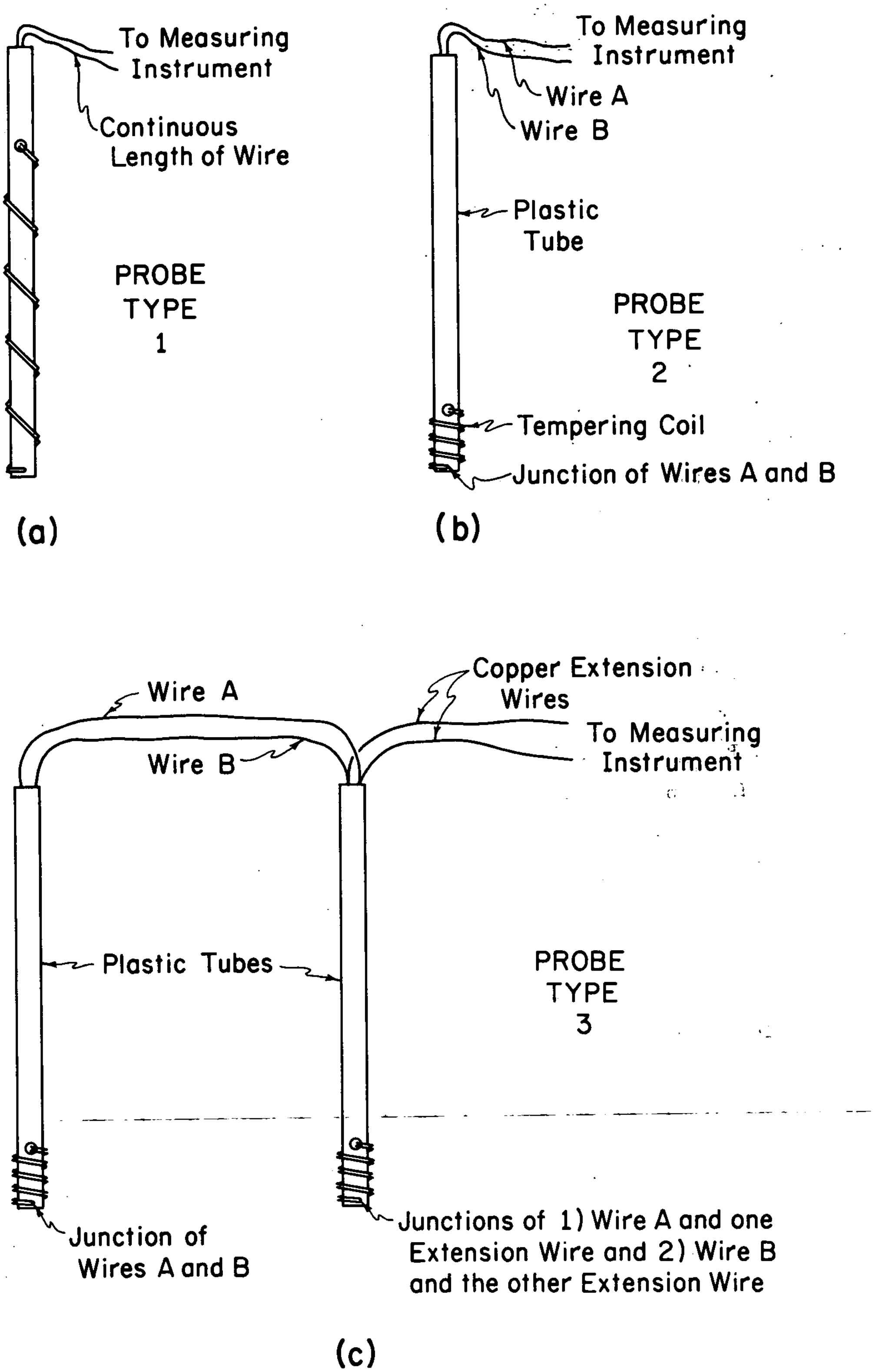


Figure 24. (a) Short-range inhomogeneity probe. (b) Medium-range, long-range, and inter-lot homogeneity probe. (c) Differential thermocouple probe.

a)

b)

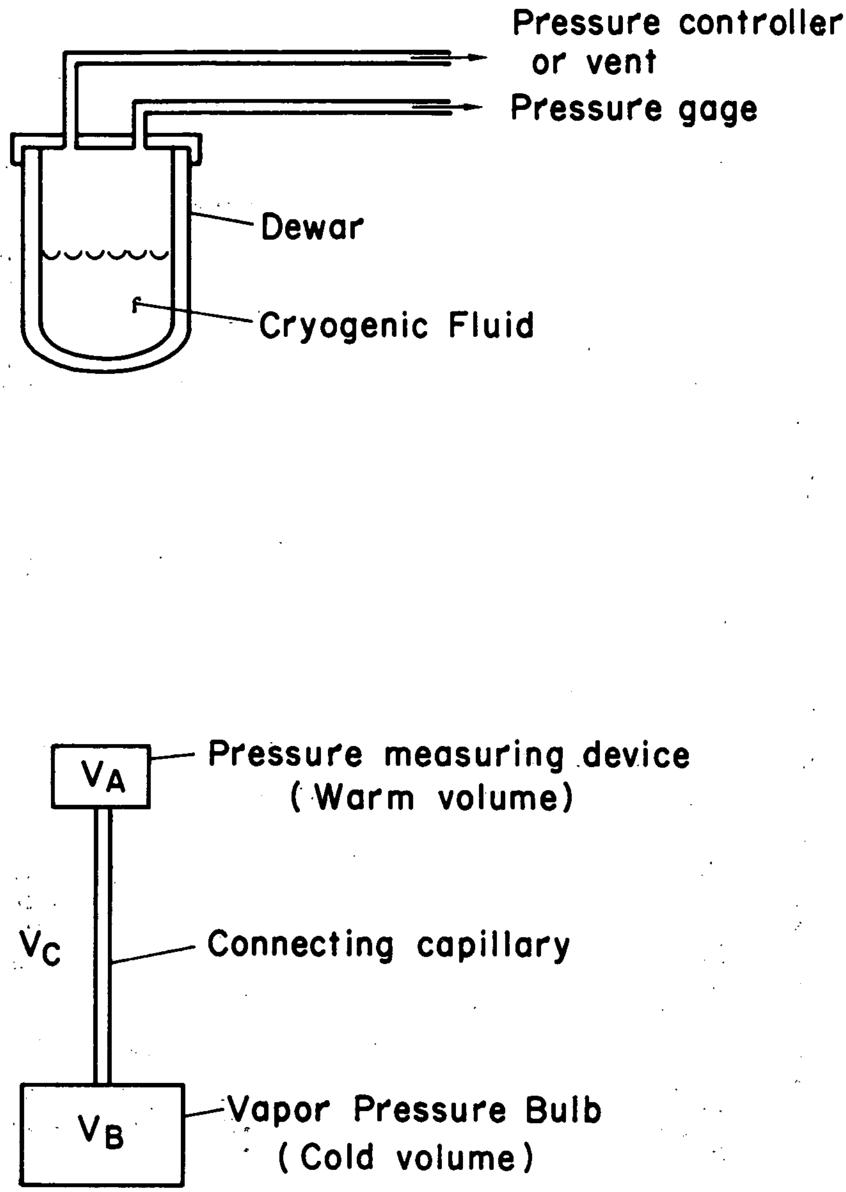
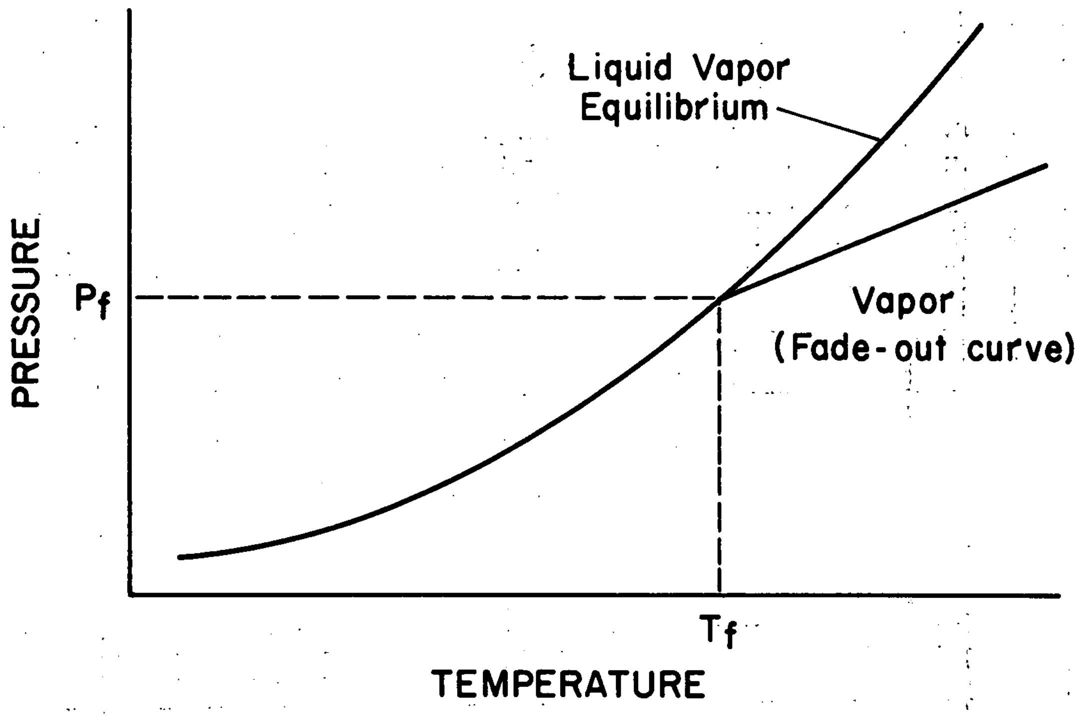


Figure 25. Schematic representation of two general vapor-pressure systems. (a) The ullage pressure in a cryogenic system is used to determine the cryogen temperature. (b) System particularly designed for vapor pressure thermometry.



Pf and Tf indicate critical fade-out conditions.

Figure 26. Illustration of "fade-out" which occurs when the vapor pressure bulb is entirely filled with the gaseous phase of the fill substance.

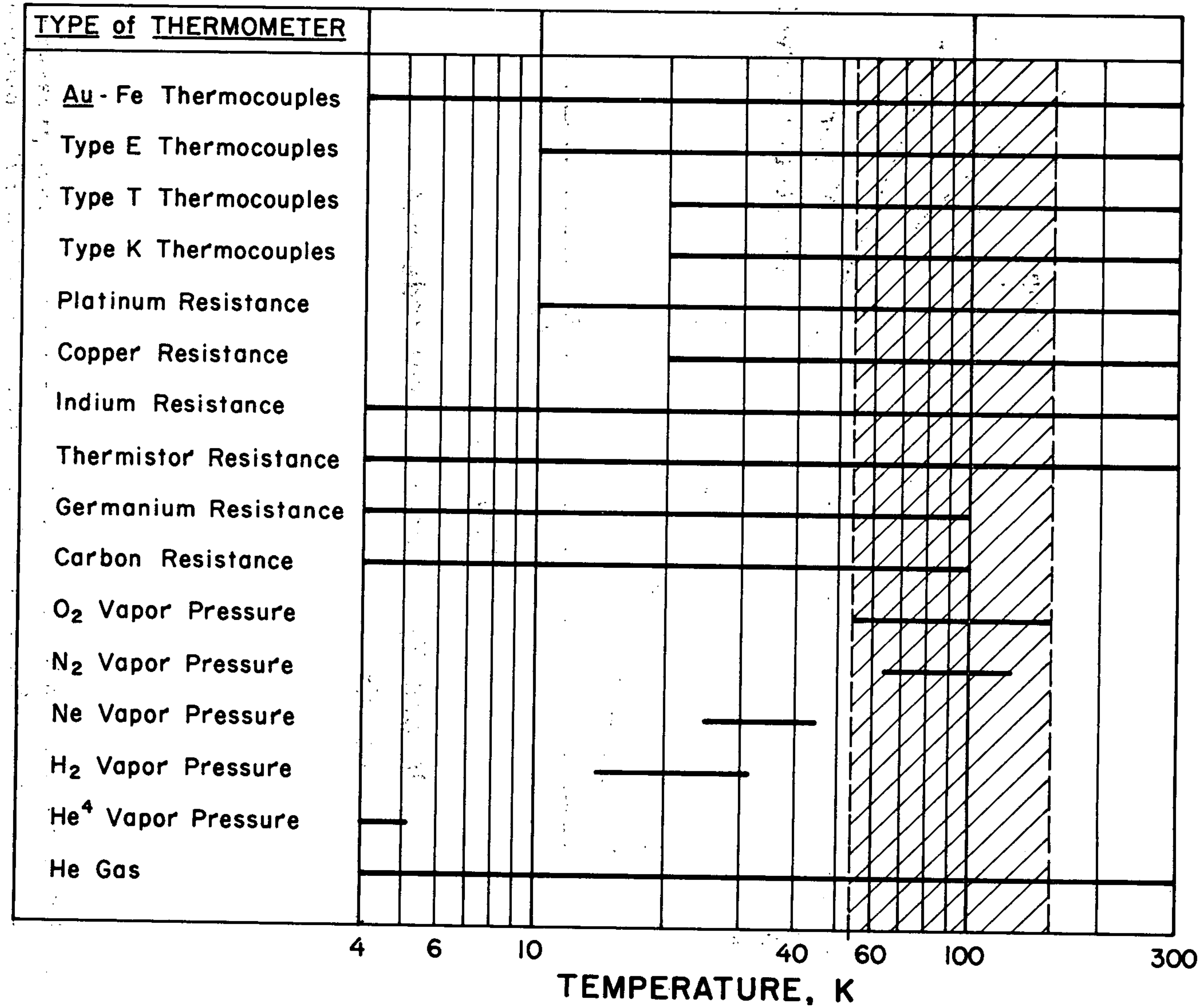


Figure 27. Graphic summary of the approximate range of use of several temperature transducers between 4 and 300 K. The shaded area represents the temperature range between the triple point and critical point of oxygen.

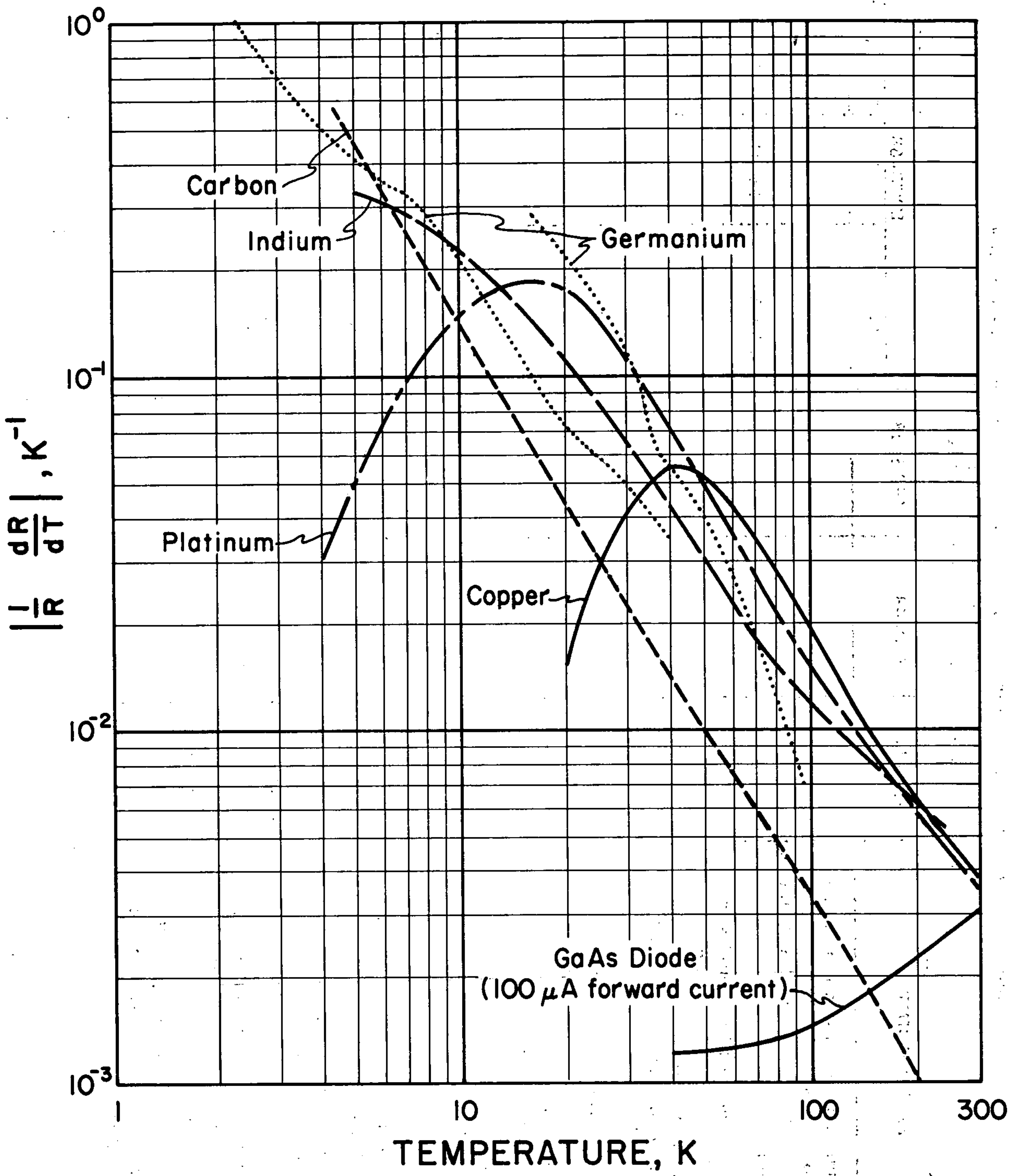


Figure 28. Comparative absolute values of the temperature coefficient of resistance (K^{-1}) versus temperature (K) for several resistance thermometers and one junction diode.

Table 1. Primary fixed points of IPTS-68 are given in degrees Celsius and kelvin. Also shown are the comparative values from previous international temperature scales.

FIXED POINT	ITS-27 °C	ITS-48 °C	IPTS-48 °C	IPTS-68		
				°C	K	Uncertainty (K)
Equilibrium between the solid, liquid and vapour phases of equilibrium hydrogen (triple point of equilibrium hydrogen)				-259.34	13.81	0.01
Equilibrium between the liquid and vapour phases of equilibrium hydrogen at a pressure of 33.330.6 N/m³ (25/76 standard atmosphere)				-256.108	17.042	0.01
Equilibrium between the liquid and vapour phases of equilibrium hydrogen (boiling point of equilibrium hydrogen)				-252.87	20.28	0.01
Equilibrium between the liquid and vapour phases of neon (boiling point of neon)				-246.048	27.102	0.01
Equilibrium between the solid, liquid and vapour phases of oxygen (triple point of oxygen)				-218.789	54.361	0.01
Equilibrium between the liquid and vapour phases of oxygen (boiling point of oxygen)	-182.97	-182.970	-182.97	-182.962	90.188	0.01
Equilibrium between the solid and liquid phases of water (freezing point of water)	0.000	0				
Equilibrium between the solid, liquid and vapour phases of water (triple point of water)			+ 0.01	+ 0.01	273.16	Exact

Table 1. Primary fixed points of IPTS-68 are given in degrees Celsius and kelvin. Also shown are the comparative values from previous international temperature scales (continued).

FIXED POINT	ITS-27 °C	ITS-48 °C	IPTS-48 °C	IPTS-68		
				°C	K	Uncertianty (K)
Equilibrium between the liquid and vapour phases of water (boiling point of water)	100.000	100	100	100	373.15	0.005
Equilibrium between the solid and liquid phases of zinc (freezing point of zinc)				419.58	692.73	0.03
Equilibrium between the liquid and vapour phases of sulfur (boiling point of sulfur)	444.60	444.600	444.6			
Equilibrium between the solid and liquid phases of silver (freezing point of silver)	960.5	960.8	960.8	961.93	1235.08	0.2
Equilibrium between the solid and liquid phases of gold (freezing point of gold)	1063	1063.0	1063	1064.43	1337.58	0.2

Table 2. Temperature differences in degrees kelvin, $\Delta T = T_{68} - T_x$, are given where T_{68} represents temperatures on the IPTS-68 temperature scale, and T_x represents NBS-55, NPL-61, PRMI-54, or PSU-54 temperature scales. Temperature range for the scales represented by T_x is 14 K to 90 K.

	ΔT (mK)					ΔT (mK)			
IPTS-68 (K)	IPTS-68 minus NBS-55	IPTS-68 minus NPL-61	IPTS-68 minus PRMI-54	IPTS-68 minus PSU-54	IPTS-68 (K)	IPTS-68 minus NBS-55	IPTS-68 minus NPL-61	IPTS-68 minus PRMI-54	IPTS-68 minus PSU-54
14	-2.3	-1.4	-47.4	9.9	53	10.4	-4.7	-3.5	20.7
15	2.0	2.8	-36.9	16.4	54	8.9	-4.1	-3.4	20.6
16	5.1	1.3	-28.0	19.3	55	7.1	-3.2	-3.4	20.3
17	7.1	0.1	-21.0	21.4	56	5.2	-2.0	-3.6	19.9
18	8.4	4.4	-16.5	22.4	57	3.4	-0.5	-4.3	19.0
19	8.8	9.9	-14.2	22.9	58	1.7	1.1	-5.3	18.3
20	9.0	9.7	-12.9	23.3	59	0.3	2.8	-6.5	18.1
21	8.9	7.3	-11.9	23.5	60	-0.8	4.3	-7.9	18.0
22	8.8	5.3	-10.8	23.7	61	-1.4	5.9	-9.3	18.0
23	8.6	4.3	-9.7	24.0	62	-1.5	7.2	-10.6	18.0
24	8.3	3.7	-9.1	24.6	63	-1.2	8.1	-12.0	18.0
25	7.8	4.1	-8.6	24.6	64	-0.7	8.8	-13.1	18.1
26	7.3	4.5	-8.2	24.1	65	-0.1	9.2	-14.0	18.8
27	7.1	5.0	-7.8	23.5	66	0.5	9.1	-14.5	18.9
28	7.1	5.4	-7.4	23.4	67	0.9	8.8	-15.0	19.6
29	7.3	5.3	-7.2	23.6	68	1.1	8.2	-15.2	20.4
30	7.6	4.9	-7.3	24.0	69	0.9	7.3	-15.2	21.7
31	8.0	4.0	-7.5	24.5	70	0.3	6.3	-15.0	22.6
32	8.4	2.9	-7.6	25.3	71	-0.6	5.2	-15.0	22.8
33	9.0	1.6	-7.6	27.0	72	-1.7	4.0	-14.8	22.5
34	9.9	0.5	-7.6	28.5	73	-3.0	3.0	-14.7	22.0
35	11.0	-0.5	-7.5	28.8	74	-4.3	2.2	-14.7	21.2
36	12.2	-1.1	-7.3	28.8	75	-5.6	1.6	-14.6	20.9
37	13.3	-1.5	-7.3	28.8	76	-6.8	1.3	-14.5	21.7
38	14.2	-1.5	-7.3	28.8	77	-7.8	1.3	-14.4	22.6
39	14.9	-1.3	-7.0	28.7	78	-8.6	1.7	-14.3	23.3
40	15.4	-0.9	-7.0	28.6	79	-9.0	2.4	-14.4	23.9
41	15.7	-0.5	-7.0	28.1	80	-9.0	3.4	-14.5	24.4
42	15.8	-0.3	-6.9	27.5	81	-8.6	4.6	-14.7	25.2
43	15.7	-0.3	-6.9	27.0	82	-7.7	5.9	-14.9	26.2
44	15.5	-0.6	-6.9	26.7	83	-6.4	7.3	-15.0	27.2
45	15.1	-1.1	-6.7	26.7	84	-4.9	8.5	-14.9	28.9

Table 2. Temperature differences in degrees kelvin, $\Delta T = T_{68} - T_x$, are given where T_{68} represents temperatures on the IPTS-68 temperature scale, and T_x represents NBS-55, NPL-61, PRMI-54, or PSU-54 temperature scales. Temperature range for the scales represented by T_x is 14 K to 90 K (continued).

	Δ T (mK)					Δ T (mK)			
IPTS-68	IPTS-68 minus NBS-55	IPTS-68 minus NPL-61	IPTS-68 minus PRMI-54	IPTS-68 minus PSU-54	IPTS-68	IPTS-68 minus NBS-55	IPTS-68 minus NPL-61	IPTS-68 minus PRMI-54	IPTS-68 minus PSU-54
46	14.8	- 1.7	- 6.6	26.4	85	- 2.9	9.5	- 14.8	30.0
47	14.5	- 2.4	- 6.1	25.7	86	- 0.5	10.2	- 14.5	31.0
48	14.2	- 3.2	- 5.8	24.7	87	2.2	10.5	- 14.0	32.1
49	13.7	- 4.0	- 5.3	23.2	88	4.9	10.5	- 13.4	33.0
50	13.1	- 4.6	- 4.8	21.4	89	7.4	10.1	- 13.0	34.2
51	12.4	- 4.9	- 4.2	20.7	90	9.6	9.3	- 12.7	35.5
52	11.6	- 4.8	- 3.8	20.6	91	11.1	7.9	- 12.7	36.3

Table 3. Temperature differences in degrees Celsius, $\Delta t = t_{68} - t_{48}$, where t_{68} represents temperatures on the IPTS-68 temperature scale and t_{48} represents temperatures on the IPTS-48 temperature scale. Differences are given for the range from -180°C to 4000°C.

IPTS-68 (°C)	0	-10	-20	-30	-40	-50	-60	-70	-80	-90	-100
-100	0.022	0.013	0.003	-0.006	-0.013	-0.013	-0.005	0.007	0.012		
- 0	0.000	0.006	0.012	0.018	0.024	0.029	0.032	0.034	0.033	0.029	0.022

IPTS-68 (°C)	0	10	20	30	40	50	60	70	80	90	100
0	0.000	-0.004	-0.007	-0.009	-0.010	-0.010	-0.010	-0.008	-0.006	-0.003	0.000
100	0.000	0.004	0.007	0.012	0.016	0.020	0.025	0.029	0.034	0.038	0.043
200	0.043	0.047	0.051	0.054	0.058	0.061	0.064	0.067	0.069	0.071	0.073
300	0.073	0.074	0.075	0.076	0.077	0.077	0.077	0.077	0.077	0.076	0.076
400	0.076	0.075	0.075	0.075	0.074	0.074	0.074	0.075	0.076	0.077	0.079
500	0.079	0.082	0.085	0.089	0.094	0.100	0.108	0.116	0.126	0.137	0.150
600	0.150	0.165	0.182	0.200	0.23	0.25	0.28	0.31	0.34	0.36	0.39
700	0.39	0.42	0.45	0.47	0.50	0.53	0.56	0.58	0.61	0.64	0.67
800	0.67	0.70	0.72	0.75	0.78	0.81	0.84	0.87	0.89	0.92	0.95
900	0.95	0.98	1.01	1.04	1.07	1.10	1.12	1.15	1.18	1.21	1.24
1000	1.24	1.27	1.30	1.33	1.36	1.39	1.42	1.44			

IPTS-68 (°C)	0	100	200	300	400	500	600	700	800	900	1000
1000		1.5	1.7	1.8	2.0	2.2	2.4	2.6	2.8	3.0	3.2
2000	3.2	3.5	3.7	4.0	4.2	4.5	4.8	5.0	5.3	5.6	5.9
3000	5.9	6.2	6.5	6.9	7.2	7.5	7.9	8.2	8.6	9.0	9.3

Table 4. Temperature differences in degrees kelvin, $\Delta T = T_{68} - T_A$, where T_{68} represents temperatures on the IPTS-68 temperature scale and T_A represents temperatures on the NBS P 2-20(65) (acoustical) temperature scale. The range where these scales overlap is from 14 K to 19 K.

IPTS - 68 (K)	Δ T (mK) IPTS - 68 minus NBS P 2-20 (1965)
14	-0. 3
15	+6. 2
16	+6. 1
17	+5. 1
18	+4. 3
19	+4. 3

Table 5. Lengths of copper and constantan wire which must be thermally anchored to a heat sink at temperature T_s in order to bring the temperature of the wire to within 1 mK of T_s. Three sets of conditions for the sink temperature and initial wire temperature (T_1) are given.

Material	T_s	T_1	Tempering length (ℓ) for various wire gages			
			40 AWG	35 AWG	30 AWG	24 AWG
Copper	4	20	0.09m	0.18m	0.35m	0.82m
	20	78	0.15	0.25	0.45	0.95
	78	273	0.06	0.11	0.22	0.44
Constantan	4	20	0.0	0.01	0.01	0.03
	20	78	0.01	0.02	0.04	0.07
	78	273	0.01	0.02	0.04	0.08

Table 6. Thermal conductivity (W/cm·K) at several cryogenic temperatures for a commercial varnish and contact grease.

Material	THERMAL CONDUCTIVITY, (W/cm·K)						
	10K	30K	100K	150K	200K	250K	300K
G. E. 7031 Varnish	0.0008	0.0013	0.0024		0.0035		0.0044
Apiezon N			0.0015	0.0020	0.0021	0.0024	0.0024

Table 7. Results of platinum resistance thermometer tests. Data denoted C result from two calibration points and one precision calibration of a similar thermometer. Data denoted M result from 3 calibration points and two precision calibrations from similar thermometers.

Method	T_1 (K)	T_2 (K)	T_3 (K)	Temperature Interval Examined (K)	Average Maximum Errors (mK)
C	20	90		20 to 90	5
C	30	90		30 to 90	3
M	20	90	273.15	20 to 90	3
				90 to 273.15	2
M	20	90	50	20 to 90	2
M	30	90	273.15	20 to 30	7
				30 to 90	1.3
				90 to 273.15	2
M	20	90	30	20 to 30	1.2
				30 to 90	1.2
M	20	50	30	20 to 30	0.8
				30 to 50	0.3
M	30	90	50	20 to 30	5
				30 to 50	0.2
				50 to 90	0.2
M	14	20	90	14 to 20	3
M	10	20	90	10 to 20	9
M	90	200	273.15	90 to 273.15	0.6 (one only)

Table 8. Cragoe Z functions versus temperature (K) for indium.

T (K)	Z	T (K)	Z
3.5	-0.000035	30	0.0488
4.0	-0.000012	35	0.0651
4.5	+0.000016	40	0.0813
5.0	0.000062	45	0.0980
6.0	0.000214	50	0.1157
7	0.000468	60	0.1505
8	0.000860	70	0.1855
9	0.00145	80	0.2200
10	0.00220	90	0.2555
11	0.00314	100	0.2908
12	0.00425	120	0.3620
13	0.00562	140	0.437
14	0.00715	160	0.514
15	0.00888	180	0.593
16	0.01076	200	0.675
18	0.0150	220	0.760
20	0.0198	240	0.846
22	0.0250	260	0.937
24	0.0305	280	1.032
25	0.0333	300	1.128
		(273.15)	(1.000)

Table 9. Resistance ratio $R_T/R_{273.16}$ versus temperature (K) for commercial copper wire.

Temperature (K)	$R_T/R_{273.16}$	Temperature (K)	$R_T/R_{273.16}$
4.2	0.011180	68	0.10137
19	0.011753	72	0.11626
20	0.011918	76	0.13239
21	0.012116	80	0.14854
22	0.012352	85	0.16975
23	0.012621	90	0.19145
24	0.012919	95	0.21348
25	0.013268	100	0.23582
26	0.013675	110	0.28105
27	0.014128	120	0.32649
28	0.014642	130	0.37192
29	0.015201	140	0.41723
30	0.015827	150	0.46233
31	0.01651	160	0.50705
32	0.01727	170	0.55169
33	0.01812	180	0.59603
34	0.01903	190	0.64002
35	0.02004	200	0.68387
36	0.02113	210	0.72750
38	0.02355	220	0.77098
40	0.02621	230	0.81429
42	0.02927	240	0.85750
44	0.03274	250	0.90051
46	0.03671	260	0.94358
48	0.04089	270	0.98650
50	0.04547	273.16	1.00000
52	0.05039	280	1.02930
54	0.05563	290	1.07218
56	0.06130	300	1.11504
58	0.06732	310	1.15785
60	0.07359	320	1.20061
64	0.08686		

Table 10. Cragoe Z functions versus temperature (K) for copper with $R_{273}/R_4 \cong 100$.

Temperature (K)	Z	Temperature (K)	Z
295	1.09467	65	0.08021
273.15	1.00000	60	0.06311
260	0.94295	55	0.04787
240	0.85589	50	0.03468
220	0.76839	48	0.03005
200	0.68030	46	0.02582
180	0.59146	44	0.02180
170	0.54662	42	0.01829
160	0.50148	40	0.01520
150	0.45626	38	0.01251
140	0.41064	36	0.01006
130	0.36482	34	0.00793_9
120	0.31888	32	0.00615_9
110	0.27292	30	0.004700
100	0.22718	28	0.003501
90	0.18231	26	0.002523
85	0.16036	24	0.001759
80	0.13891	22	0.001185
75	0.11850	20	0.000746
70	0.09874		

Table 11. Resistance ratio R_T/R_{296} versus temperature for a commercial 0.1 watt, 270 ohm carbon resistor.

Temperature (K)	R_T/R_{296}	Temperature (K)	R_T/R_{296}
4.00	37.65	26.0	2.527
4.50	28.11	28.0	2.396
5.00	22.10	30.0	2.285
5.50	18.05	35.0	2.071
6.00	15.18	40.0	1.915
6.50	13.06	45.0	1.797
7.00	11.45	50.0	1.703
7.50	10.19	55.0	1.627
8.00	9.185	60.0	1.565
8.50	8.363	65.0	1.512
9.00	7.683	70.0	1.467
9.50	7.111	75.0	1.428
10.0	6.625	80.0	1.393
11.0	5.845	100.0	1.290
12.0	5.249	120.0	1.220
13.0	4.780	140.0	1.170
14.0	4.401	160.0	1.131
15.0	4.090	180.0	1.100
16.0	3.831	200.0	1.076
17.0	3.610	220.0	1.055
18.0	3.421	240.0	1.038
19.0	3.257	260.0	1.023
20.0	3.114	280.0	1.010
22.0	2.987	296.0	1.000
24.0	2.683		

Table 12. Limits of error for thermocouples.

Type	Temperature Range		Limits of Error			
			Standard[1]		Special[1]	
	deg F	deg C	deg F	deg C	deg F	deg C
J	32 to 530	0 to 277	± 4 F	Note 2	± 2 F	Note 2
	530 to 1400	277 to 760	± 3/4 percent		± 3/8 percent	
K	32 to 530	0 to 277	± 4 F		± 2 F	
	530 to 2300	277 to 1260	± 3/4 percent		± 3/8 percent	
R or S	32 to 1000	0 to 538	± 2-1/2 F			
	100 to 2700		± 1/4 percent			
T	-300 to -75	-184 to -59			± 1 percent	
	-150 to -75	-101 to -59	± 2 percent		± 1 percent	
	- 75 to +200	- 59 to +93	± 1-1/2 F		± 3/4 F	
	200 to 700	+ 93 to +371	± 3/4 percent		± 3/8 percent	
E	32 to 600	0 to 316	± 3 F		± 2-1/4 F	
	600 to 1600	316 to 871	± 1/2 percent		± 3/8 percent	
B	1600 to 3100	871 to 1705	± 1/2 percent			

1 Special lots of thermocouple materials are selected from each melt -- these special lots are closer to the standard table values than are the standard materials. In general, note that the limit of error for the special materials is about 1/2 that of the standard materials.

2 Errors in degrees Celsius may be determined by multiplying errors expressed in degrees Fahrenheit by 5/9. Percentage errors given in the Fahrenheit column also apply to degrees Celsius when the temperature interval is in degrees Celsius.

Table 13. Reference data for type E thermocouple-thermoelectric voltage, E(T), thermoelectric sensitivity, S(T), and the derivative of the thermoelectric sensitivity, dS(T).

T K	E μV	S μV/K	dS/dT nV/K^2	T K	E μV	S μV/K	dS/dT nV/K^2	T K	E μV	S μV/K	dS/dT nV/K^2
0	0.00	-0.203	604.4	60	704.83	21.637	280.0	120	2445.13	35.611	199.7
1	0.09	0.384	571.8	61	726.61	21.915	277.7	121	2480.84	35.811	198.8
2	0.76	0.941	543.0	62	748.66	22.192	275.4	122	2516.75	36.009	198.0
3	1.97	1.472	517.7	63	770.99	22.466	273.1	123	2552.86	36.207	197.1
4	3.69	1.978	495.6	64	793.59	22.738	270.9	124	2589.17	36.403	196.2
5	5.92	2.464	476.2	65	816.47	23.008	268.8	125	2625.67	36.599	195.4
6	8.61	2.931	459.4	66	839.61	23.276	266.7	126	2662.36	36.794	194.5
7	11.77	3.383	444.7	67	863.02	23.541	264.6	127	2699.25	36.988	193.7
8	15.38	3.821	432.1	68	886.69	23.805	262.6	128	2736.34	37.181	192.9
9	19.41	4.248	421.1	69	910.63	24.067	260.7	129	2773.62	37.374	192.0
10	23.87	4.664	411.7	70	934.82	24.326	258.8	130	2811.09	37.565	191.2
11	28.74	5.072	403.6	71	959.28	24.584	256.9	131	2848.75	37.756	190.4
12	34.01	5.472	396.7	72	983.99	24.840	255.1	132	2886.60	37.946	189.6
13	39.68	5.865	390.8	73	1008.96	25.094	253.4	133	2924.64	38.136	188.9
14	45.74	6.254	385.8	74	1034.18	25.347	251.7	134	2962.87	38.324	188.1
15	52.18	6.637	381.5	75	1059.65	25.598	250.0	135	3001.29	38.512	187.3
16	59.01	7.017	377.8	76	1085.37	25.847	248.4	136	3039.89	38.699	186.6
17	66.22	7.393	374.6	77	1111.35	26.095	246.9	137	3078.69	38.885	185.9
18	73.80	7.766	371.9	78	1137.56	26.341	245.4	138	3117.66	39.070	185.1
19	81.75	8.137	369.5	79	1164.03	26.585	243.9	139	3156.83	39.255	184.4
20	90.07	8.505	367.4	80	1190.73	26.829	242.4	140	3196.17	39.439	183.7
21	98.76	8.872	365.6	81	1217.68	27.070	241.0	141	3235.70	39.623	183.0
22	107.81	9.237	363.9	82	1244.87	27.311	239.7	142	3275.42	39.805	182.3
23	117.23	9.600	362.3	83	1272.30	27.550	238.3	143	3315.31	39.987	181.6
24	127.01	9.961	360.8	84	1299.97	27.787	237.0	144	3355.39	40.169	180.9
25	137.15	10.321	359.3	85	1327.88	28.024	235.7	145	3395.65	40.349	180.3
26	147.65	10.680	357.9	86	1356.02	28.259	234.5	146	3436.09	40.529	179.6
27	158.51	11.037	356.4	87	1384.40	28.493	233.2	147	3476.71	40.708	179.0
28	169.73	11.393	354.9	88	1413.01	28.725	232.0	148	3517.51	40.887	178.3
29	181.30	11.747	353.4	89	1441.85	28.957	230.9	149	3558.48	41.065	177.7
30	193.22	12.099	351.8	90	1470.92	29.187	229.7	150	3599.64	41.242	177.0
31	205.50	12.450	350.1	91	1500.22	29.416	228.6	151	3640.97	41.419	176.4
32	218.12	12.800	348.4	92	1529.75	29.644	227.4	152	3682.47	41.595	175.8
33	231.09	13.147	346.5	93	1559.51	29.871	226.3	153	3724.16	41.771	175.2
34	244.41	13.493	344.6	94	1589.49	30.097	225.2	154	3766.02	41.946	174.6
35	258.08	13.836	342.7	95	1619.70	30.321	224.1	155	3808.05	42.120	173.9
36	272.09	14.178	340.6	96	1650.13	30.545	223.1	156	3850.26	42.293	173.3
37	286.43	14.517	338.4	97	1680.79	30.768	222.0	157	3892.64	42.466	172.7
38	301.12	14.855	336.2	98	1711.67	30.989	221.0	158	3935.19	42.639	172.1
39	316.14	15.190	333.9	99	1742.77	31.210	219.9	159	3977.91	42.811	171.5
40	331.50	15.523	331.5	100	1774.09	31.429	218.9	160	4020.81	42.982	170.9
41	347.19	15.853	329.1	101	1805.63	31.647	217.9	161	4063.88	43.153	170.3
42	363.20	16.181	326.6	102	1837.38	31.865	216.9	162	4107.11	43.323	169.7
43	379.55	16.506	324.1	103	1869.36	32.081	215.9	163	4150.52	43.492	169.1
44	396.21	16.829	321.5	104	1901.54	32.297	214.9	164	4194.10	43.661	168.5
45	413.20	17.149	318.9	105	1933.95	32.511	213.9	165	4237.84	43.829	167.9
46	430.51	17.467	316.3	106	1966.57	32.724	212.9	166	4281.76	43.997	167.3
47	448.14	17.782	313.6	107	1999.40	32.937	211.9	167	4325.84	44.164	166.7
48	466.07	18.094	311.0	108	2032.44	33.148	210.9	168	4370.08	44.330	166.1
49	484.32	18.404	308.3	109	2065.69	33.359	210.0	169	4414.50	44.496	165.5
50	502.88	18.711	305.6	110	2099.16	33.568	209.0	170	4459.07	44.661	164.9
51	521.74	19.015	303.0	111	2132.83	33.777	208.1	171	4503.82	44.826	164.3
52	540.91	19.317	300.3	112	2166.71	33.984	207.1	172	4548.73	44.990	163.7
53	560.38	19.616	297.7	113	2200.80	34.191	206.2	173	4593.80	45.153	163.1
54	580.14	19.912	295.1	114	2235.09	34.397	205.2	174	4639.03	45.316	162.5
55	600.20	20.206	292.5	115	2269.59	34.601	204.3	175	4684.43	45.478	161.8
56	620.55	20.497	289.9	116	2304.29	34.805	203.4	176	4729.99	45.640	161.2
57	641.19	20.786	287.4	117	2339.20	35.008	202.4	177	4775.71	45.800	160.6
58	662.12	21.072	284.9	118	2374.31	35.210	201.5	178	4821.59	45.961	160.0
59	683.33	21.355	282.5	119	2409.62	35.411	200.6	179	4867.63	46.120	159.4
60	704.83	21.637	280.0	120	2445.13	35.611	199.7	180	4913.83	46.279	158.7

Table 13. Reference data for type E thermocouple-thermoelectric voltage, E(T), thermoelectric sensitivity, S(T), and the derivative of the thermoelectric sensitivity, dS(T) (continued).

T K	E μV	S μV/K	dS/dT nV/K^2	T K	E μV	S μV/K	dS/dT nV/K^2
180	4913.83	46.279	158.7	240	7954.95	54.767	126.1
181	4960.19	46.438	158.1	241	8009.78	54.893	125.7
182	5006.70	46.596	157.5	242	8064.74	55.018	125.2
183	5053.38	46.753	156.9	243	8119.82	55.143	124.8
184	5100.21	46.909	156.2	244	8175.02	55.268	124.3
185	5147.20	47.065	155.6	245	8230.35	55.392	123.9
186	5194.34	47.221	155.0	246	8285.81	55.516	123.5
187	5241.64	47.375	154.4	247	8341.38	55.639	123.1
188	5289.09	47.529	153.7	248	8397.09	55.762	122.7
189	5336.70	47.683	153.1	249	8452.91	55.884	122.3
190	5384.46	47.835	152.5	250	8508.85	56.006	121.9
191	5432.37	47.988	151.9	251	8564.92	56.128	121.5
192	5480.43	48.139	151.2	252	8621.11	56.250	121.2
193	5528.65	48.290	150.6	253	8677.42	56.371	120.8
194	5577.01	48.440	150.0	254	8733.85	56.491	120.5
195	5625.53	48.590	149.4	255	8790.40	56.611	120.1
196	5674.19	48.739	148.8	256	8847.07	56.731	119.8
197	5723.00	48.888	148.2	257	8903.86	56.851	119.4
198	5771.97	49.036	147.6	258	8960.78	56.970	119.1
199	5821.08	49.183	147.0	259	9017.81	57.089	118.7
200	5870.33	49.330	146.4	260	9074.95	57.208	118.3
201	5919.74	49.476	145.9	261	9132.22	57.326	117.9
202	5969.28	49.622	145.3	262	9189.61	57.444	117.4
203	6018.98	49.767	144.7	263	9247.11	57.561	116.9
204	6068.82	49.911	144.1	264	9304.73	57.677	116.3
205	6118.80	50.055	143.6	265	9362.46	57.793	115.6
206	6168.93	50.198	143.0	266	9420.31	57.908	114.8
207	6219.20	50.341	142.5	267	9478.28	58.023	113.9
208	6269.61	50.483	141.9	268	9536.36	58.136	112.8
209	6320.16	50.625	141.4	269	9594.55	58.248	111.5
210	6370.86	50.766	140.9	270	9652.85	58.359	110.0
211	6421.69	50.907	140.3	271	9711.27	58.468	108.2
212	6472.67	51.047	139.8	272	9769.79	58.575	106.2
213	6523.79	51.186	139.3	273	9828.42	58.680	103.7
214	6575.04	51.325	138.8	274	9887.15	58.783	100.9
215	6626.44	51.464	138.3	275	9945.98	58.882	97.6
216	6677.97	51.602	137.8	276	10004.91	58.978	93.8
217	6729.64	51.739	137.3	277	10063.94	59.069	89.3
218	6781.45	51.876	136.8	278	10123.05	59.156	84.2
219	6833.39	52.013	136.3	279	10182.25	59.237	78.2
220	6885.47	52.149	135.8	280	10241.52	59.312	71.4
221	6937.69	52.284	135.3				
222	6990.04	52.419	134.8				
223	7042.53	52.554	134.3				
224	7095.15	52.688	133.8				
225	7147.90	52.821	133.3				
226	7200.79	52.955	132.8				
227	7253.81	53.087	132.3				
228	7306.97	53.219	131.9				
229	7360.25	53.351	131.4				
230	7413.67	53.482	130.9				
231	7467.22	53.613	130.4				
232	7520.89	53.743	129.9				
233	7574.70	53.872	129.4				
234	7628.64	54.002	129.0				
235	7682.70	54.130	128.5				
236	7736.90	54.259	128.0				
237	7791.22	54.386	127.5				
238	7845.67	54.514	127.1				
239	7900.25	54.641	126.6				
240	7954.95	54.767	126.1				

Table 14. Reference data for type K thermocouple-thermoelectric voltage, E(T), thermoelectric sensitivity, S(T), and the derivative of the thermoelectric sensitivity, dS(T).

T K	E μV	S μV/K	dS/dT nV/K^2	T K	E μV	S μV/K	dS/dT nV/K^2	T K	E μV	S μV/K	dS/dT nV/K^2
0	0.00	0.241	146.9	60	383.56	12.757	197.0	120	1473.20	23.144	153.9
1	0.32	0.391	154.3	61	396.41	12.954	196.0	121	1496.42	23.297	153.4
2	0.78	0.549	161.3	62	409.47	13.149	195.0	122	1519.80	23.451	152.8
3	1.42	0.714	167.7	63	422.71	13.344	194.0	123	1543.32	23.603	152.2
4	2.21	0.884	173.7	64	436.15	13.537	193.0	124	1567.00	23.755	151.6
5	3.19	1.061	179.2	65	449.79	13.730	192.1	125	1590.83	23.906	151.1
6	4.34	1.243	184.3	66	463.61	13.922	191.1	126	1614.81	24.057	150.5
7	5.67	1.429	189.0	67	477.63	14.112	190.2	127	1638.95	24.207	149.9
8	7.20	1.621	193.4	68	491.84	14.302	189.2	128	1663.23	24.357	149.3
9	8.92	1.816	197.3	69	506.23	14.491	188.3	129	1687.66	24.506	148.8
10	10.83	2.015	200.9	70	520.82	14.678	187.4	130	1712.24	24.654	148.2
11	12.95	2.218	204.2	71	535.59	14.865	186.5	131	1736.97	24.802	147.6
12	15.27	2.424	207.2	72	550.55	15.051	185.6	132	1761.84	24.950	147.0
13	17.80	2.632	209.9	73	565.69	15.237	184.8	133	1786.87	25.096	146.4
14	20.53	2.843	212.3	74	581.02	15.421	183.9	134	1812.04	25.243	145.9
15	23.48	3.057	214.5	75	596.53	15.604	183.1	135	1837.35	25.388	145.3
16	26.65	3.272	216.4	76	612.23	15.787	182.2	136	1862.81	25.533	144.7
17	30.03	3.489	218.1	77	628.11	15.969	181.4	137	1888.42	25.678	144.1
18	33.63	3.708	219.5	78	644.17	16.150	180.6	138	1914.17	25.821	143.5
19	37.45	3.928	220.8	79	660.41	16.330	179.8	139	1940.06	25.965	142.9
20	41.48	4.150	221.9	80	676.83	16.510	179.1	140	1966.10	26.107	142.3
21	45.75	4.372	222.8	81	693.43	16.688	178.3	141	1992.28	26.249	141.7
22	50.23	4.595	223.5	82	710.20	16.866	177.5	142	2018.60	26.391	141.1
23	54.94	4.819	224.0	83	727.16	17.043	176.8	143	2045.06	26.532	140.6
24	59.87	5.043	224.4	84	744.29	17.220	176.1	144	2071.66	26.672	140.0
25	65.02	5.268	224.7	85	761.60	17.396	175.3	145	2098.40	26.811	139.4
26	70.40	5.493	224.9	86	779.08	17.571	174.6	146	2125.28	26.950	138.8
27	76.01	5.718	224.9	87	796.74	17.745	173.9	147	2152.30	27.089	138.2
28	81.84	5.942	224.8	88	814.57	17.918	173.2	148	2179.46	27.227	137.6
29	87.89	6.167	224.6	89	832.58	18.091	172.6	149	2206.75	27.364	137.0
30	94.17	6.392	224.3	90	850.75	18.264	171.9	150	2234.19	27.501	136.4
31	100.68	6.616	224.0	91	869.10	18.435	171.2	151	2261.76	27.637	135.7
32	107.40	6.840	223.5	92	887.62	18.606	170.6	152	2289.46	27.772	135.1
33	114.36	7.063	223.0	93	906.31	18.776	169.9	153	2317.30	27.907	134.5
34	121.53	7.285	222.4	94	925.18	18.946	169.3	154	2345.27	28.041	133.9
35	128.93	7.508	221.7	95	944.21	19.115	168.6	155	2373.38	28.175	133.3
36	136.54	7.729	221.0	96	963.40	19.283	168.0	156	2401.62	28.308	132.7
37	144.38	7.950	220.3	97	982.77	19.451	167.4	157	2430.00	28.440	132.1
38	152.44	8.169	219.4	98	1002.31	19.618	166.8	158	2458.50	28.572	131.5
39	160.72	8.388	218.6	99	1022.01	19.784	166.2	159	2487.14	28.703	130.9
40	169.22	8.607	217.7	100	1041.87	19.950	165.5	160	2515.91	28.834	130.3
41	177.94	8.824	216.8	101	1061.91	20.115	164.9	161	2544.81	28.964	129.7
42	186.87	9.040	215.8	102	1082.11	20.280	164.3	162	2573.84	29.093	129.0
43	196.02	9.256	214.9	103	1102.47	20.444	163.7	163	2603.00	29.222	128.4
44	205.38	9.470	213.9	104	1122.99	20.608	163.2	164	2632.28	29.350	127.8
45	214.95	9.683	212.9	105	1143.68	20.770	162.6	165	2661.70	29.478	127.2
46	224.74	9.896	211.8	106	1164.53	20.933	162.0	166	2691.24	29.604	126.6
47	234.75	10.107	210.8	107	1185.55	21.094	161.4	167	2720.90	29.731	126.0
48	244.96	10.317	209.7	108	1206.72	21.255	160.8	168	2750.70	29.856	125.3
49	255.38	10.526	208.7	109	1228.06	21.416	160.2	169	2780.62	29.981	124.7
50	266.01	10.735	207.6	110	1249.55	21.576	159.7	170	2810.66	30.106	124.1
51	276.85	10.942	206.5	111	1271.21	21.735	159.1	171	2840.83	30.230	123.5
52	287.89	11.148	205.5	112	1293.02	21.894	158.5	172	2871.12	30.353	122.9
53	299.14	11.353	204.4	113	1315.00	22.052	157.9	173	2901.53	30.475	122.2
54	310.60	11.556	203.3	114	1337.13	22.210	157.4	174	2932.07	30.597	121.6
55	322.26	11.759	202.3	115	1359.42	22.367	156.8	175	2962.73	30.718	121.0
56	334.12	11.961	201.2	116	1381.86	22.524	156.2	176	2993.51	30.839	120.4
57	346.18	12.162	200.1	117	1404.46	22.679	155.6	177	3024.41	30.959	119.7
58	358.44	12.361	199.1	118	1427.22	22.835	155.1	178	3055.42	31.079	119.1
59	370.90	12.560	198.1	119	1450.13	22.990	154.5	179	3086.56	31.197	118.5
60	383.56	12.757	197.0	120	1473.20	23.144	153.9	180	3117.82	31.316	117.9

Table 14. Reference data for type K thermocouple-thermoelectric voltage, E(T), thermoelectric sensitivity, S(T), and the derivative of the thermoelectric sensitivity, dS(T) (continued).

T K	E μV	S μV/K	dS/dT nV/K²	T K	E μV	S μV/K	dS/dT nV/K²
180	3117.82	31.316	117.9	240	5185.83	37.228	79.0
181	3149.19	31.433	117.2	241	5223.10	37.307	78.4
182	3180.68	31.550	116.6	242	5260.44	37.385	77.7
183	3212.29	31.666	116.0	243	5297.87	37.462	77.1
184	3244.02	31.782	115.3	244	5335.37	37.539	76.4
185	3275.86	31.897	114.7	245	5372.94	37.615	75.8
186	3307.81	32.011	114.1	246	5410.60	37.691	75.1
187	3339.88	32.125	113.4	247	5448.32	37.765	74.5
188	3372.06	32.238	112.8	248	5486.13	37.840	73.8
189	3404.36	32.351	112.2	249	5524.00	37.913	73.2
190	3436.76	32.463	111.5	250	5561.95	37.986	72.5
191	3469.28	32.574	110.9	251	5599.98	38.058	71.9
192	3501.91	32.684	110.3	252	5638.07	38.130	71.2
193	3534.65	32.794	109.6	253	5676.23	38.201	70.6
194	3567.50	32.904	109.0	254	5714.47	38.271	69.9
195	3600.46	33.012	108.3	255	5752.78	38.340	69.2
196	3633.52	33.120	107.7	256	5791.15	38.409	68.5
197	3666.70	33.228	107.1	257	5829.59	38.477	67.9
198	3699.98	33.334	106.4	258	5868.10	38.545	67.2
199	3733.36	33.440	105.8	259	5906.68	38.612	66.5
200	3766.86	33.546	105.1	260	5945.33	38.678	65.8
201	3800.46	33.651	104.5	261	5984.04	38.743	65.1
202	3834.16	33.755	103.8	262	6022.81	38.808	64.3
203	3867.96	33.858	103.2	263	6061.65	38.872	63.6
204	3901.87	33.961	102.5	264	6100.56	38.935	62.8
205	3935.89	34.063	101.9	265	6139.52	38.998	62.1
206	3970.00	34.165	101.2	266	6178.55	39.059	61.3
207	4004.22	34.266	100.6	267	6217.64	39.120	60.5
208	4038.53	34.366	99.9	268	6256.79	39.180	59.6
209	4072.95	34.466	99.3	269	6296.00	39.239	58.8
210	4107.46	34.565	98.6	270	6335.27	39.298	57.9
211	4142.08	34.663	98.0	271	6374.60	39.355	57.0
212	4176.79	34.761	97.3	272	6413.98	39.412	56.1
213	4211.60	34.857	96.7	273	6453.42	39.467	55.1
214	4246.50	34.954	96.0	274	6492.91	39.522	54.1
215	4281.51	35.049	95.3	275	6532.46	39.575	53.0
216	4316.60	35.144	94.7	276	6572.06	39.628	51.9
217	4351.79	35.239	94.0	277	6611.72	39.679	50.8
218	4387.08	35.333	93.4	278	6651.42	39.729	49.6
219	4422.46	35.426	92.7	279	6691.18	39.778	48.4
220	4457.93	35.518	92.1	280	6730.98	39.826	47.1
221	4493.49	35.610	91.4				
222	4529.15	35.701	90.7				
223	4564.90	35.791	90.1				
224	4600.73	35.881	89.4				
225	4636.66	35.970	88.8				
226	4672.67	36.059	88.1				
227	4708.77	36.146	87.5				
228	4744.96	36.233	86.8				
229	4781.24	36.320	86.2				
230	4817.60	36.406	85.5				
231	4854.05	36.491	84.8				
232	4890.59	36.575	84.2				
233	4927.20	36.659	83.5				
234	4963.90	36.743	82.9				
235	5000.69	36.825	82.2				
236	5037.55	36.907	81.6				
237	5074.50	36.988	80.9				
238	5111.53	37.069	80.3				
239	5148.64	37.149	79.6				
240	5185.83	37.228	79.0				

Table 15. Reference data for type T thermocouple-thermoelectric voltage, E(T), thermoelectric sensitivity, S(T), and the derivative of the thermoelectric sensitivity, dS(T).

T K	E μV	S μV/K	dS/dT nV/K²	T K	E μV	S μV/K	dS/dT nV/K²	T K	E μV	S μV/K	dS/dT nV/K²
0	0.00	-0.400	526.6	60	461.11	13.826	154.6	120	1540.74	21.931	126.0
1	-0.15	0.099	473.2	61	475.01	13.980	152.9	121	1562.73	22.057	125.8
2	0.18	0.549	428.0	62	489.07	14.132	151.3	122	1584.85	22.182	125.6
3	0.94	0.958	390.1	63	503.28	14.283	149.8	123	1607.10	22.308	125.4
4	2.09	1.332	358.4	64	517.64	14.432	148.4	124	1629.47	22.433	125.3
5	3.59	1.677	332.3	65	532.14	14.580	147.1	125	1651.96	22.558	125.1
6	5.43	1.998	310.9	66	546.79	14.726	146.0	126	1674.58	22.683	125.0
7	7.58	2.300	293.5	67	561.59	14.872	144.9	127	1697.33	22.808	124.8
8	10.03	2.586	279.7	68	576.54	15.016	143.9	128	1720.20	22.933	124.7
9	12.75	2.860	268.8	69	591.62	15.159	142.9	129	1743.20	23.058	124.5
10	15.74	3.124	260.3	70	606.86	15.302	142.1	130	1766.31	23.182	124.4
11	19.00	3.381	254.0	71	622.23	15.444	141.3	131	1789.56	23.306	124.3
12	22.50	3.633	249.3	72	637.74	15.584	140.6	132	1812.93	23.431	124.2
13	26.26	3.880	246.0	73	653.40	15.725	139.9	133	1836.42	23.555	124.0
14	30.26	4.125	243.8	74	669.19	15.864	139.3	134	1860.04	23.679	123.9
15	34.51	4.368	242.5	75	685.13	16.003	138.8	135	1883.78	23.803	123.8
16	39.00	4.610	241.8	76	701.20	16.142	138.3	136	1907.64	23.926	123.7
17	43.73	4.852	241.5	77	717.41	16.280	137.8	137	1931.63	24.050	123.5
18	48.70	5.094	241.6	78	733.76	16.417	137.4	138	1955.74	24.173	123.4
19	53.92	5.335	241.8	79	750.24	16.555	137.0	139	1979.98	24.297	123.3
20	59.37	5.577	242.2	80	766.87	16.691	136.6	140	2004.33	24.420	123.2
21	65.07	5.820	242.5	81	783.63	16.828	136.2	141	2028.82	24.543	123.0
22	71.01	6.062	242.7	82	800.52	16.964	135.9	142	2053.42	24.666	122.9
23	77.20	6.305	242.7	83	817.55	17.100	135.6	143	2078.15	24.789	122.7
24	83.62	6.548	242.6	84	834.72	17.235	135.3	144	2103.00	24.911	122.6
25	90.29	6.790	242.2	85	852.02	17.370	135.0	145	2127.97	25.034	122.4
26	97.20	7.032	241.6	86	869.46	17.505	134.7	146	2153.07	25.156	122.3
27	104.36	7.273	240.8	87	887.03	17.640	134.5	147	2178.28	25.279	122.1
28	111.75	7.513	239.7	88	904.74	17.774	134.2	148	2203.62	25.401	121.9
29	119.38	7.752	238.3	89	922.58	17.908	133.9	149	2229.08	25.522	121.8
30	127.25	7.990	236.7	90	940.56	18.042	133.7	150	2254.67	25.644	121.6
31	135.36	8.226	234.8	91	958.66	18.175	133.4	151	2280.37	25.766	121.4
32	143.70	8.459	232.7	92	976.91	18.309	133.1	152	2306.20	25.887	121.2
33	152.28	8.691	230.4	93	995.28	18.442	132.9	153	2332.15	26.008	121.0
34	161.08	8.920	227.9	94	1013.79	18.574	132.6	154	2358.21	26.129	120.7
35	170.12	9.147	225.2	95	1032.43	18.707	132.3	155	2384.40	26.249	120.5
36	179.38	9.371	222.4	96	1051.20	18.839	132.1	156	2410.71	26.370	120.3
37	188.86	9.592	219.4	97	1070.11	18.971	131.8	157	2437.14	26.490	120.1
38	198.56	9.809	216.4	98	1089.14	19.102	131.5	158	2463.69	26.610	119.8
39	208.48	10.024	213.2	99	1108.31	19.234	131.2	159	2490.36	26.730	119.6
40	218.61	10.236	210.0	100	1127.61	19.365	131.0	160	2517.15	26.849	119.3
41	228.95	10.444	206.7	101	1147.04	19.496	130.7	161	2544.06	26.968	119.0
42	239.49	10.649	203.4	102	1166.60	19.626	130.4	162	2571.09	27.087	118.8
43	250.24	10.851	200.1	103	1186.29	19.757	130.1	163	2598.24	27.206	118.5
44	261.19	11.049	196.8	104	1206.12	19.886	129.8	164	2625.50	27.324	118.2
45	272.34	11.245	193.5	105	1226.07	20.016	129.6	165	2652.88	27.442	118.0
46	283.68	11.437	190.3	106	1246.15	20.146	129.3	166	2680.39	27.560	117.7
47	295.21	11.625	187.1	107	1266.36	20.275	129.0	167	2708.00	27.678	117.4
48	306.93	11.811	184.0	108	1286.70	20.404	128.7	168	2735.74	27.795	117.1
49	318.83	11.993	181.0	109	1307.17	20.532	128.5	169	2763.59	27.912	116.8
50	330.92	12.173	178.0	110	1327.76	20.661	128.2	170	2791.56	28.029	116.6
51	343.18	12.349	175.2	111	1348.49	20.789	128.0	171	2819.65	28.145	116.3
52	355.62	12.523	172.5	112	1369.34	20.916	127.7	172	2847.85	28.261	116.0
53	368.23	12.694	169.8	113	1390.32	21.044	127.5	173	2876.17	28.377	115.7
54	381.00	12.863	167.3	114	1411.43	21.171	127.2	174	2904.61	28.493	115.5
55	393.95	13.029	164.9	115	1432.66	21.298	127.0	175	2933.16	28.608	115.2
56	407.06	13.193	162.6	116	1454.02	21.425	126.8	176	2961.82	28.723	114.9
57	420.33	13.354	160.4	117	1475.51	21.552	126.6	177	2990.60	28.838	114.7
58	433.77	13.514	158.4	118	1497.13	21.678	126.3	178	3019.50	28.952	114.4
59	447.36	13.671	156.4	119	1518.87	21.805	126.1	179	3048.51	29.067	114.2
60	461.11	13.826	154.6	120	1540.74	21.931	126.0	180	3077.63	29.181	113.9

Table 15. Reference data for type T thermocouple-thermoelectric voltage, E(T), thermoelectric sensitivity, S(T), and the derivative of the thermoelectric sensitivity, dS(T) (continued).

T K	E μV	S μV/K	dS/dT nV/K^2
180	3077.63	29.181	113.9
181	3106.87	29.294	113.7
182	3136.22	29.408	113.4
183	3165.68	29.521	113.2
184	3195.26	29.634	113.0
185	3224.95	29.747	112.8
186	3254.76	29.860	112.5
187	3284.67	29.972	112.3
188	3314.70	30.085	112.1
189	3344.84	30.197	111.9
190	3375.09	30.308	111.7
191	3405.46	30.420	111.5
192	3435.93	30.531	111.3
193	3466.52	30.643	111.1
194	3497.22	30.754	111.0
195	3528.03	30.865	110.8
196	3558.95	30.975	110.6
197	3589.98	31.086	110.4
198	3621.12	31.196	110.2
199	3652.37	31.306	110.0
200	3683.73	31.416	109.8
201	3715.20	31.526	109.6
202	3746.78	31.635	109.4
203	3778.47	31.744	109.2
204	3810.27	31.853	108.9
205	3842.18	31.962	108.7
206	3874.20	32.071	108.5
207	3906.32	32.179	108.2
208	3938.55	32.287	108.0
209	3970.90	32.395	107.7
210	4003.34	32.503	107.4
211	4035.90	32.610	107.2
212	4068.56	32.717	106.9
213	4101.34	32.824	106.6
214	4134.21	32.930	106.3
215	4167.20	33.036	106.0
216	4200.29	33.142	105.7
217	4233.48	33.248	105.4
218	4266.78	33.353	105.0
219	4300.19	33.458	104.7
220	4333.70	33.562	104.4
221	4367.31	33.667	104.0
222	4401.03	33.770	103.7
223	4434.85	33.874	103.4
224	4468.78	33.977	103.1
225	4502.81	34.080	102.7
226	4536.94	34.183	102.4
227	4571.17	34.285	102.1
228	4605.51	34.387	101.8
229	4639.94	34.488	101.5
230	4674.46	34.590	101.2
231	4709.12	34.691	101.0
232	4743.87	34.792	100.7
233	4778.71	34.892	100.5
234	4813.65	34.993	100.2
235	4848.69	35.093	100.0
236	4883.84	35.193	99.9
237	4919.08	35.293	99.7
238	4954.42	35.392	99.5
239	4989.86	35.492	99.4
240	5025.40	35.591	99.3

T K	E μV	S μV/K	dS/dT nV/K^2
240	5025.40	35.591	99.3
241	5061.04	35.690	99.2
242	5096.78	35.789	99.1
243	5132.62	35.888	99.0
244	5168.56	35.987	98.9
245	5204.60	36.086	98.8
246	5240.73	36.185	98.8
247	5276.97	36.284	98.7
248	5313.30	36.382	98.6
249	5349.73	36.481	98.5
250	5386.26	36.579	98.4
251	5422.89	36.678	98.3
252	5459.62	36.776	98.1
253	5496.44	36.874	97.9
254	5533.37	36.972	97.6
255	5570.39	37.069	97.3
256	5607.50	37.166	97.0
257	5644.72	37.263	96.6
258	5682.03	37.359	96.1
259	5719.44	37.455	95.6
260	5756.94	37.551	95.0
261	5794.54	37.645	94.3
262	5832.23	37.739	93.6
263	5870.02	37.833	92.9
264	5907.90	37.925	92.1
265	5945.87	38.017	91.3
266	5983.93	38.108	90.5
267	6022.08	38.198	89.8
268	6060.32	38.287	89.0
269	6098.66	38.376	88.4
270	6137.08	38.464	88.0
271	6175.58	38.552	87.7
272	6214.18	38.640	87.8
273	6252.86	38.728	88.2
274	6291.64	38.816	89.0
275	6330.50	38.906	90.5
276	6369.45	38.997	92.6
277	6408.49	39.091	95.6
278	6447.63	39.189	99.7
279	6486.87	39.291	105.0
280	6526.22	39.399	111.8

Table 16. Reference data for the thermocouple combination KP versus Au-0.07 at % Fe - thermoelectric voltage, E(T), thermoelectric sensitivity, S(T), and the derivative of the thermoelectric sensitivity, dS(T).

T K	E μV	S μV/K	dS/dT nV/K²	T K	E μV	S μV/K	dS/dT nV/K²	T K	E μV	S μV/K	dS/dT nV/K²
0	0.00	0.000	0.0	60	962.74	17.139	43.4	120	2065.91	19.513	31.8
1	7.85	8.673	1565.8	61	979.90	17.183	43.6	121	2085.44	19.545	31.5
2	17.27	10.127	1346.7	62	997.11	17.226	43.7	122	2105.00	19.576	31.2
3	28.04	11.375	1152.4	63	1014.36	17.270	43.7	123	2124.59	19.607	30.9
4	39.96	12.439	980.4	64	1031.65	17.314	43.7	124	2144.21	19.638	30.6
5	52.86	13.342	828.8	65	1048.99	17.358	43.7	125	2163.87	19.668	30.3
6	66.59	14.103	695.4	66	1066.36	17.401	43.7	126	2183.55	19.698	30.0
7	81.03	14.739	578.6	67	1083.79	17.445	43.6	127	2203.26	19.728	29.7
8	96.04	15.265	476.7	68	1101.25	17.489	43.5	128	2223.00	19.758	29.4
9	111.52	15.697	388.1	69	1118.76	17.532	43.4	129	2242.78	19.787	29.2
10	127.40	16.045	311.5	70	1136.32	17.575	43.3	130	2262.58	19.816	28.9
11	143.59	16.323	245.6	71	1153.92	17.619	43.2	131	2282.41	19.845	28.7
12	160.03	16.540	189.2	72	1171.56	17.662	43.1	132	2302.27	19.873	28.4
13	176.65	16.704	141.4	73	1189.24	17.705	42.9	133	2322.16	19.902	28.2
14	193.42	16.825	101.0	74	1206.96	17.748	42.8	134	2342.07	19.930	28.0
15	210.29	16.909	67.3	75	1224.73	17.790	42.7	135	2362.02	19.958	27.7
16	227.23	16.962	39.5	76	1242.55	17.833	42.6	136	2381.99	19.985	27.5
17	244.21	16.989	16.8	77	1260.40	17.875	42.4	137	2401.99	20.013	27.3
18	261.20	16.997	-1.4	78	1278.30	17.918	42.3	138	2422.01	20.040	27.1
19	278.19	16.988	-15.7	79	1296.24	17.960	42.2	139	2442.07	20.067	26.9
20	295.17	16.966	-26.6	80	1314.22	18.002	42.0	140	2462.15	20.094	26.7
21	312.12	16.935	-34.6	81	1332.24	18.044	41.9	141	2482.25	20.120	26.5
22	329.04	16.898	-40.1	82	1350.30	18.086	41.8	142	2502.39	20.147	26.3
23	345.92	16.856	-43.5	83	1368.41	18.128	41.6	143	2522.55	20.173	26.1
24	362.75	16.811	-45.1	84	1386.56	18.169	41.5	144	2542.73	20.199	26.0
25	379.54	16.766	-45.3	85	1404.75	18.211	41.3	145	2562.94	20.225	25.8
26	396.28	16.721	-44.2	86	1422.98	18.252	41.2	146	2583.18	20.250	25.6
27	412.98	16.678	-42.1	87	1441.25	18.293	41.0	147	2603.45	20.276	25.4
28	429.64	16.637	-39.2	88	1459.57	18.334	40.9	148	2623.73	20.301	25.3
29	446.26	16.600	-35.7	89	1477.92	18.375	40.7	149	2644.05	20.327	25.1
30	462.84	16.566	-31.8	90	1496.32	18.415	40.5	150	2664.39	20.352	24.9
31	479.39	16.536	-27.5	91	1514.75	18.456	40.3	151	2684.75	20.376	24.7
32	495.92	16.511	-23.0	92	1533.23	18.496	40.2	152	2705.14	20.401	24.6
33	512.42	16.490	-18.4	93	1551.74	18.536	40.0	153	2725.55	20.426	24.4
34	528.90	16.474	-13.8	94	1570.30	18.576	39.7	154	2745.99	20.450	24.2
35	545.37	16.463	-9.2	95	1588.89	18.615	39.5	155	2766.45	20.474	24.1
36	561.83	16.456	-4.7	96	1607.53	18.655	39.3	156	2786.94	20.498	23.9
37	578.28	16.453	-0.4	97	1626.20	18.694	39.1	157	2807.45	20.522	23.7
38	594.73	16.455	3.8	98	1644.92	18.733	38.8	158	2827.98	20.545	23.5
39	611.19	16.461	7.8	99	1663.67	18.772	38.5	159	2848.54	20.569	23.4
40	627.66	16.471	11.6	100	1682.46	18.810	38.3	160	2869.12	20.592	23.2
41	644.13	16.484	15.2	101	1701.29	18.848	38.0	161	2889.72	20.615	23.0
42	660.63	16.501	18.5	102	1720.16	18.886	37.7	162	2910.35	20.638	22.8
43	677.14	16.521	21.5	103	1739.06	18.924	37.4	163	2931.00	20.661	22.6
44	693.67	16.544	24.3	104	1758.00	18.961	37.1	164	2951.67	20.683	22.5
45	710.22	16.569	26.9	105	1776.98	18.998	36.8	165	2972.37	20.706	22.3
46	726.81	16.597	29.3	106	1796.00	19.035	36.5	166	2993.08	20.728	22.1
47	743.42	16.628	31.4	107	1815.05	19.071	36.2	167	3013.82	20.750	21.9
48	760.06	16.660	33.3	108	1834.14	19.107	35.8	168	3034.58	20.772	21.7
49	776.74	16.694	35.0	109	1853.27	19.143	35.5	169	3055.37	20.793	21.5
50	793.45	16.730	36.5	110	1872.43	19.178	35.2	170	3076.17	20.815	21.3
51	810.20	16.767	37.8	111	1891.62	19.213	34.8	171	3096.99	20.836	21.1
52	826.99	16.806	38.9	112	1910.85	19.248	34.5	172	3117.84	20.857	21.0
53	843.81	16.845	39.9	113	1930.12	19.282	34.2	173	3138.71	20.878	20.8
54	860.68	16.885	40.7	114	1949.42	19.316	33.8	174	3159.60	20.899	20.6
55	877.58	16.926	41.4	115	1968.75	19.350	33.5	175	3180.51	20.919	20.4
56	894.53	16.968	42.0	116	1988.12	19.383	33.2	176	3201.44	20.939	20.2
57	911.52	17.010	42.5	117	2007.52	19.416	32.8	177	3222.38	20.960	20.1
58	928.55	17.053	42.9	118	2026.95	19.449	32.5	178	3243.35	20.980	19.9
59	945.63	17.096	43.2	119	2046.41	19.481	32.2	179	3264.34	20.999	19.7
60	962.74	17.139	43.4	120	2065.91	19.513	31.8	180	3285.35	21.019	19.6

Table 16. Reference data for the thermocouple combination KP versus Au-0.07 at % Fe - thermoelectric voltage, E(T), thermoelectric sensitivity, S(T), and the derivative of the thermoelectric sensitivity, dS(T) (continued).

T K	E μV	S μV/K	dS/dT nV/K²	T K	E μV	S μV/K	dS/dT nV/K²
180	3285.35	21.019	19.6	240	4576.81	21.930	9.5
181	3306.38	21.038	19.4	241	4598.74	21.940	9.4
182	3327.43	21.058	19.2	242	4620.69	21.949	9.3
183	3348.50	21.077	19.1	243	4642.64	21.958	9.3
184	3369.58	21.096	18.9	244	4664.61	21.968	9.2
185	3390.69	21.115	18.8	245	4686.58	21.977	9.2
186	3411.81	21.133	18.6	246	4708.56	21.986	9.3
187	3432.96	21.152	18.5	247	4730.55	21.995	9.3
188	3454.12	21.171	18.4	248	4752.55	22.005	9.4
189	3475.30	21.189	18.3	249	4774.56	22.014	9.5
190	3496.49	21.207	18.1	250	4796.58	22.024	9.6
191	3517.71	21.225	18.0	251	4818.61	22.034	9.8
192	3538.94	21.243	17.9	252	4840.64	22.043	10.0
193	3560.20	21.261	17.8	253	4862.69	22.053	10.2
194	3581.47	21.279	17.7	254	4884.75	22.064	10.3
195	3602.75	21.296	17.6	255	4906.82	22.074	10.6
196	3624.06	21.314	17.5	256	4928.90	22.085	10.8
197	3645.38	21.331	17.4	257	4950.99	22.096	11.0
198	3666.72	21.348	17.3	258	4973.09	22.107	11.1
199	3688.08	21.366	17.2	259	4995.20	22.118	11.3
200	3709.45	21.383	17.1	260	5017.33	22.129	11.5
201	3730.84	21.400	17.0	261	5039.46	22.141	11.6
202	3752.25	21.417	16.9	262	5061.61	22.152	11.6
203	3773.68	21.434	16.8	263	5083.77	22.164	11.7
204	3795.12	21.450	16.7	264	5105.94	22.176	11.6
205	3816.58	21.467	16.5	265	5128.12	22.187	11.5
206	3838.05	21.483	16.4	266	5150.31	22.199	11.3
207	3859.54	21.500	16.3	267	5172.52	22.210	11.1
208	3881.05	21.516	16.2	268	5194.73	22.221	10.7
209	3902.58	21.532	16.0	269	5216.96	22.231	10.3
210	3924.12	21.548	15.9	270	5239.19	22.241	9.7
211	3945.67	21.564	15.8	271	5261.44	22.251	9.0
212	3967.24	21.580	15.6	272	5283.70	22.259	8.2
213	3988.83	21.595	15.4	273	5305.96	22.267	7.3
214	4010.43	21.610	15.3	274	5328.23	22.274	6.3
215	4032.05	21.626	15.1	275	5350.51	22.280	5.2
216	4053.69	21.641	14.9	276	5372.79	22.284	4.0
217	4075.33	21.655	14.7	277	5395.08	22.288	2.7
218	4097.00	21.670	14.5	278	5417.36	22.290	1.3
219	4118.67	21.684	14.3	279	5439.65	22.290	-0.1
220	4140.36	21.698	14.0	280	5461.94	22.289	-1.4
221	4162.07	21.712	13.8				
222	4183.79	21.726	13.6				
223	4205.52	21.739	13.3				
224	4227.27	21.753	13.1				
225	4249.03	21.766	12.8				
226	4270.80	21.778	12.5				
227	4292.58	21.791	12.3				
228	4314.38	21.803	12.0				
229	4336.19	21.815	11.8				
230	4358.01	21.826	11.5				
231	4379.84	21.838	11.3				
232	4401.68	21.849	11.0				
233	4423.54	21.860	10.8				
234	4445.40	21.870	10.5				
235	4467.28	21.881	10.3				
236	4489.17	21.891	10.1				
237	4511.06	21.901	9.9				
238	4532.97	21.911	9.8				
239	4554.88	21.921	9.6				
240	4576.81	21.930	9.5				

Table 17. Reference data for the thermocouple combination KP versus Au-0.02 at % Fe - thermoelectric voltage, E(T), thermoelectric sensitivity, S(T), and the derivative of the thermoelectric sensitivity, dS(T).

T K	E μV	S μV/K	dS/dT nV/K²	T K	E μV	S μV/K	dS/dT nV/K²	T K	E μV	S μV/K	dS/dT nV/K²
0	0.00	0.000	0.0	60	808.49	13.053	55.5	120	1694.43	16.360	45.9
1	8.28	9.226	1787.8	61	821.57	13.109	56.1	121	1710.81	16.406	45.6
2	18.34	10.856	1479.4	62	834.71	13.166	56.6	122	1727.24	16.452	45.2
3	29.89	12.198	1209.2	63	847.90	13.222	57.1	123	1743.72	16.497	44.9
4	42.65	13.286	973.4	64	861.15	13.280	57.5	124	1760.24	16.541	44.6
5	56.39	14.155	768.6	65	874.46	13.337	57.8	125	1776.80	16.586	44.2
6	70.90	14.833	591.6	66	887.83	13.395	58.0	126	1793.41	16.630	43.9
7	86.00	15.346	439.4	67	901.25	13.453	58.2	127	1810.06	16.674	43.6
8	101.55	15.719	309.3	68	914.73	13.512	58.4	128	1826.75	16.717	43.4
9	117.40	15.972	199.1	69	928.27	13.570	58.5	129	1843.49	16.760	43.1
10	133.46	16.123	106.3	70	941.87	13.629	58.6	130	1860.27	16.803	42.8
11	149.62	16.189	29.1	71	955.53	13.687	58.6	131	1877.10	16.846	42.6
12	165.81	16.186	-34.4	72	969.25	13.746	58.7	132	1893.97	16.888	42.4
13	181.97	16.125	-85.9	73	983.02	13.805	58.7	133	1910.88	16.931	42.1
14	198.04	16.017	-126.9	74	996.86	13.863	58.8	134	1927.83	16.973	41.9
15	213.99	15.874	-158.7	75	1010.75	13.922	58.8	135	1944.82	17.015	41.7
16	229.78	15.703	-182.5	76	1024.70	13.981	58.8	136	1961.86	17.056	41.5
17	245.39	15.511	-199.5	77	1038.71	14.040	58.7	137	1978.93	17.098	41.3
18	260.80	15.306	-210.6	78	1052.78	14.098	58.7	138	1996.05	17.139	41.1
19	276.00	15.091	-216.7	79	1066.91	14.157	58.7	139	2013.21	17.180	40.9
20	290.98	14.874	-218.6	80	1081.09	14.216	58.6	140	2030.41	17.221	40.8
21	305.75	14.656	-216.9	81	1095.34	14.274	58.6	141	2047.65	17.261	40.6
22	320.29	14.441	-212.4	82	1109.64	14.333	58.5	142	2064.93	17.302	40.4
23	334.63	14.231	-205.5	83	1124.00	14.391	58.4	143	2082.26	17.342	40.2
24	348.76	14.030	-196.7	84	1138.42	14.450	58.3	144	2099.62	17.382	40.0
25	362.69	13.839	-186.5	85	1152.90	14.508	58.2	145	2117.02	17.422	39.9
26	376.44	13.658	-175.2	86	1167.44	14.566	58.1	146	2134.46	17.462	39.7
27	390.01	13.488	-163.1	87	1182.04	14.624	57.9	147	2151.94	17.502	39.5
28	403.42	13.332	-150.5	88	1196.69	14.682	57.8	148	2169.47	17.541	39.3
29	416.68	13.188	-137.6	89	1211.40	14.740	57.6	149	2187.03	17.580	39.1
30	429.80	13.057	-124.6	90	1226.17	14.797	57.4	150	2204.63	17.619	38.9
31	442.80	12.938	-111.7	91	1240.99	14.854	57.2	151	2222.26	17.658	38.7
32	455.68	12.833	-99.0	92	1255.88	14.911	56.9	152	2239.94	17.696	38.5
33	468.47	12.740	-86.7	93	1270.82	14.968	56.7	153	2257.66	17.735	38.2
34	481.17	12.659	-74.8	94	1285.81	15.025	56.4	154	2275.41	17.773	38.0
35	493.79	12.590	-63.4	95	1300.87	15.081	56.1	155	2293.20	17.811	37.8
36	506.35	12.533	-52.5	96	1315.97	15.137	55.8	156	2311.03	17.848	37.5
37	518.86	12.485	-42.2	97	1331.14	15.193	55.5	157	2328.90	17.886	37.3
38	531.33	12.448	-32.5	98	1346.36	15.248	55.1	158	2346.80	17.923	37.0
39	543.76	12.420	-23.4	99	1361.63	15.303	54.8	159	2364.75	17.960	36.7
40	556.17	12.401	-15.0	100	1376.97	15.357	54.4	160	2382.72	17.996	36.5
41	568.56	12.390	-7.1	101	1392.35	15.412	54.0	161	2400.74	18.033	36.2
42	580.95	12.386	0.1	102	1407.79	15.465	53.6	162	2418.79	18.069	35.9
43	593.34	12.390	6.7	103	1423.28	15.519	53.2	163	2436.88	18.105	35.6
44	605.73	12.400	12.8	104	1438.83	15.572	52.8	164	2455.00	18.140	35.3
45	618.14	12.415	18.3	105	1454.42	15.624	52.3	165	2473.16	18.175	35.0
46	630.56	12.436	23.4	106	1470.07	15.676	51.9	166	2491.35	18.210	34.7
47	643.01	12.462	27.9	107	1485.78	15.728	51.5	167	2509.58	18.245	34.4
48	655.49	12.492	31.9	108	1501.53	15.779	51.0	168	2527.84	18.279	34.1
49	668.00	12.526	35.6	109	1517.34	15.830	50.6	169	2546.13	18.313	33.8
50	680.54	12.563	38.8	110	1533.19	15.881	50.1	170	2564.46	18.346	33.5
51	693.12	12.603	41.7	111	1549.10	15.930	49.7	171	2582.83	18.380	33.2
52	705.75	12.646	44.2	112	1565.05	15.980	49.2	172	2601.22	18.413	32.9
53	718.42	12.691	46.4	113	1581.06	16.029	48.8	173	2619.65	18.445	32.6
54	731.13	12.739	48.3	114	1597.11	16.078	48.4	174	2638.11	18.478	32.3
55	743.90	12.788	50.0	115	1613.21	16.126	47.9	175	2656.61	18.510	32.0
56	756.71	12.839	51.5	116	1629.36	16.173	47.5	176	2675.13	18.542	31.7
57	769.57	12.891	52.7	117	1645.56	16.221	47.1	177	2693.69	18.573	31.4
58	782.49	12.944	53.8	118	1661.80	16.268	46.7	178	2712.28	18.605	31.1
59	795.46	12.998	54.7	119	1678.09	16.314	46.3	179	2730.90	18.636	30.8
60	808.49	13.053	55.5	120	1694.43	16.360	45.9	180	2749.55	18.666	30.6

Table 17. Reference data for the thermocouple combination KP versus Au-0.02 at % Fe - thermoelectric voltage, E(T), thermoelectric sensitivity, S(T), and the derivative of the thermoelectric sensitivity, dS(T) (continued).

T K	E µV	S µV/K	dS/dT nV/K²	T K	E µV	S µV/K	dS/dT nV/K²
180	2749.55	18.666	30.6	240	3918.02	20.167	19.1
181	2768.23	18.697	30.3	241	3938.19	20.186	19.0
182	2786.94	18.727	30.1	242	3958.39	20.205	19.0
183	2805.69	18.757	29.9	243	3978.60	20.224	19.0
184	2824.46	18.787	29.6	244	3998.84	20.243	19.0
185	2843.26	18.816	29.4	245	4019.09	20.262	18.9
186	2862.09	18.845	29.2	246	4039.36	20.281	19.0
187	2880.95	18.875	29.0	247	4059.65	20.299	19.0
188	2899.84	18.903	28.8	248	4079.96	20.318	19.0
189	2918.76	18.932	28.6	249	4100.29	20.337	18.9
190	2937.70	18.961	28.5	250	4120.63	20.356	18.9
191	2956.68	18.989	28.3	251	4141.00	20.375	18.9
192	2975.68	19.017	28.2	252	4161.38	20.394	18.8
193	2994.71	19.046	28.0	253	4181.79	20.413	18.7
194	3013.77	19.073	27.9	254	4202.21	20.431	18.5
195	3032.86	19.101	27.7	255	4222.65	20.450	18.3
196	3051.98	19.129	27.6	256	4243.11	20.468	18.1
197	3071.12	19.156	27.5	257	4263.59	20.486	17.7
198	3090.29	19.184	27.4	258	4284.08	20.503	17.4
199	3109.49	19.211	27.2	259	4304.59	20.521	16.9
200	3128.71	19.238	27.1	260	4325.12	20.537	16.4
201	3147.96	19.265	27.0	261	4345.67	20.553	15.9
202	3167.24	19.292	26.9	262	4366.23	20.569	15.2
203	3186.55	19.319	26.7	263	4386.80	20.584	14.6
204	3205.88	19.346	26.6	264	4407.40	20.598	13.9
205	3225.24	19.372	26.5	265	4428.00	20.612	13.2
206	3244.62	19.399	26.3	266	4448.62	20.625	12.6
207	3264.04	19.425	26.2	267	4469.25	20.637	12.0
208	3283.47	19.451	26.0	268	4489.89	20.649	11.5
209	3302.94	19.477	25.9	269	4510.55	20.660	11.2
210	3322.43	19.503	25.7	270	4531.21	20.671	11.1
211	3341.94	19.529	25.5	271	4551.89	20.682	11.4
212	3361.49	19.554	25.3	272	4572.58	20.694	12.0
213	3381.05	19.579	25.1	273	4593.28	20.706	13.2
214	3400.64	19.604	24.9	274	4613.99	20.721	15.1
215	3420.26	19.629	24.7	275	4634.72	20.737	17.8
216	3439.90	19.653	24.4	276	4655.47	20.757	21.5
217	3459.57	19.678	24.2	277	4676.23	20.780	26.5
218	3479.26	19.702	23.9	278	4697.03	20.810	33.0
219	3498.97	19.726	23.7	279	4717.86	20.847	41.2
220	3518.71	19.749	23.4	280	4738.72	20.893	51.5
221	3538.47	19.772	23.1				
222	3558.25	19.795	22.9				
223	3578.06	19.818	22.6				
224	3597.89	19.841	22.3				
225	3617.74	19.863	22.0				
226	3637.62	19.885	21.7				
227	3657.51	19.906	21.5				
228	3677.43	19.928	21.2				
229	3697.37	19.949	20.9				
230	3717.32	19.969	20.7				
231	3737.30	19.990	20.4				
232	3757.30	20.010	20.2				
233	3777.32	20.030	20.0				
234	3797.37	20.050	19.8				
235	3817.43	20.070	19.6				
236	3837.51	20.090	19.5				
237	3857.60	20.109	19.4				
238	3877.72	20.128	19.2				
239	3897.86	20.148	19.2				
240	3918.02	20.167	19.1				

Table 18. Reference data for the thermocouple combination copper versus Au-0.07 at % Fe - thermoelectric voltage, E(T), thermoelectric sensitivity, S(T), and the derivative of the thermoelectric sensitivity, dS(T).

T K	E μV	S μV/K	dS/dT nV/K^2	T K	E μV	S μV/K	dS/dT nV/K^2	T K	E μV	S μV/K	dS/dT nV/K^2
0	0.00	0.000	0.0	60	719.52	9.331	-81.7	120	1162.03	5.835	-41.8
1	7.78	8.531	1423.5	61	728.81	9.250	-80.9	121	1167.85	5.793	-41.4
2	16.98	9.839	1197.0	62	738.02	9.169	-80.1	122	1173.62	5.752	-41.1
3	27.38	10.934	997.5	63	747.15	9.089	-79.3	123	1179.35	5.711	-40.7
4	38.79	11.842	822.3	64	756.20	9.010	-78.5	124	1185.04	5.671	-40.3
5	51.01	12.586	669.0	65	765.17	8.932	-77.7	125	1190.69	5.630	-40.0
6	63.91	13.187	535.4	66	774.07	8.855	-76.9	126	1196.30	5.591	-39.6
7	77.35	13.663	419.3	67	782.88	8.778	-76.1	127	1201.87	5.551	-39.2
8	91.20	14.030	318.9	68	791.62	8.703	-75.2	128	1207.41	5.512	-38.8
9	105.38	14.305	232.5	69	800.29	8.628	-74.4	129	1212.90	5.474	-38.5
10	119.78	14.500	158.5	70	808.88	8.554	-73.5	130	1218.35	5.435	-38.1
11	134.35	14.626	95.5	71	817.40	8.481	-72.6	131	1223.77	5.397	-37.7
12	149.02	14.694	42.3	72	825.84	8.409	-71.7	132	1229.15	5.360	-37.3
13	163.72	14.713	-2.4	73	834.22	8.338	-70.7	133	1234.49	5.323	-36.9
14	178.43	14.692	-39.5	74	842.52	8.267	-69.8	134	1239.79	5.286	-36.5
15	193.10	14.636	-70.0	75	850.75	8.198	-68.9	135	1245.06	5.250	-36.1
16	207.69	14.553	-94.8	76	858.92	8.130	-67.9	136	1250.29	5.214	-35.7
17	222.20	14.448	-114.7	77	867.01	8.062	-67.0	137	1255.49	5.178	-35.3
18	236.58	14.326	-130.2	78	875.04	7.996	-66.0	138	1260.65	5.143	-34.9
19	250.84	14.189	-142.1	79	883.00	7.930	-65.1	139	1265.78	5.109	-34.6
20	264.96	14.042	-150.8	80	890.90	7.866	-64.2	140	1270.87	5.074	-34.2
21	278.92	13.888	-156.9	81	898.73	7.802	-63.3	141	1275.92	5.040	-33.8
22	292.73	13.729	-160.8	82	906.51	7.739	-62.3	142	1280.95	5.007	-33.4
23	306.38	13.567	-162.8	83	914.21	7.677	-61.4	143	1285.94	4.973	-33.1
24	319.87	13.404	-163.2	84	921.86	7.616	-60.6	144	1290.89	4.940	-32.7
25	333.19	13.241	-162.4	85	929.45	7.556	-59.7	145	1295.82	4.908	-32.4
26	346.35	13.080	-160.7	86	936.97	7.497	-58.9	146	1300.71	4.876	-32.0
27	359.35	12.920	-158.1	87	944.44	7.438	-58.0	147	1305.57	4.844	-31.7
28	372.19	12.764	-155.0	88	951.85	7.381	-57.2	148	1310.40	4.812	-31.4
29	384.88	12.610	-151.5	89	959.20	7.324	-56.5	149	1315.20	4.781	-31.1
30	397.41	12.461	-147.6	90	966.50	7.268	-55.7	150	1319.96	4.750	-30.8
31	409.80	12.315	-143.6	91	973.74	7.212	-55.0	151	1324.70	4.720	-30.5
32	422.04	12.173	-139.5	92	980.92	7.158	-54.3	152	1329.40	4.689	-30.2
33	434.15	12.036	-135.4	93	988.05	7.104	-53.6	153	1334.07	4.659	-29.9
34	446.12	11.903	-131.4	94	995.13	7.051	-52.9	154	1338.72	4.629	-29.7
35	457.96	11.773	-127.4	95	1002.15	6.998	-52.3	155	1343.33	4.600	-29.4
36	469.67	11.648	-123.6	96	1009.13	6.946	-51.7	156	1347.92	4.571	-29.2
37	481.25	11.526	-120.0	97	1016.05	6.894	-51.1	157	1352.47	4.542	-28.9
38	492.72	11.408	-116.6	98	1022.92	6.844	-50.6	158	1357.00	4.513	-28.7
39	504.07	11.293	-113.4	99	1029.73	6.793	-50.0	159	1361.50	4.484	-28.5
40	515.31	11.181	-110.3	100	1036.50	6.744	-49.5	160	1365.97	4.456	-28.3
41	526.43	11.072	-107.6	101	1043.22	6.694	-49.0	161	1370.41	4.427	-28.1
42	537.45	10.966	-105.0	102	1049.89	6.645	-48.6	162	1374.82	4.399	-27.9
43	548.36	10.862	-102.6	103	1056.51	6.597	-48.1	163	1379.21	4.372	-27.8
44	559.17	10.760	-100.4	104	1063.09	6.549	-47.7	164	1383.57	4.344	-27.6
45	569.89	10.661	-98.4	105	1069.61	6.502	-47.3	165	1387.90	4.316	-27.4
46	580.50	10.564	-96.6	106	1076.09	6.455	-46.8	166	1392.20	4.289	-27.2
47	591.01	10.468	-94.9	107	1082.52	6.408	-46.5	167	1396.48	4.262	-27.1
48	601.43	10.374	-93.4	108	1088.90	6.362	-46.1	168	1400.72	4.235	-26.9
49	611.76	10.281	-92.0	109	1095.24	6.316	-45.7	169	1404.95	4.208	-26.8
50	622.00	10.190	-90.8	110	1101.54	6.270	-45.3	170	1409.14	4.181	-26.6
51	632.14	10.099	-89.6	111	1107.78	6.225	-45.0	171	1413.31	4.155	-26.5
52	642.20	10.010	-88.5	112	1113.99	6.180	-44.6	172	1417.45	4.128	-26.3
53	652.16	9.922	-87.5	113	1120.15	6.136	-44.2	173	1421.57	4.102	-26.2
54	662.04	9.835	-86.6	114	1126.26	6.092	-43.9	174	1425.66	4.076	-26.0
55	671.83	9.749	-85.7	115	1132.33	6.048	-43.5	175	1429.72	4.050	-25.8
56	681.54	9.664	-84.8	116	1138.36	6.005	-43.2	176	1433.76	4.025	-25.7
57	691.16	9.579	-84.0	117	1144.34	5.962	-42.9	177	1437.77	3.999	-25.5
58	700.70	9.496	-83.2	118	1150.28	5.919	-42.5	178	1441.75	3.974	-25.3
59	710.15	9.413	-82.5	119	1156.18	5.877	-42.2	179	1445.71	3.948	-25.1
60	719.52	9.331	-81.7	120	1162.03	5.835	-41.8	180	1449.65	3.923	-24.9

Table 18. Reference data for the thermocouple combination copper versus Au-0.07 at % Fe - thermoelectric voltage, E(T), thermoelectric sensitivity, S(T), and the derivative of the thermoelectric sensitivity, dS(T) (continued).

T K	E μV	S μV/K	dS/dT nV/K²
180	1449.65	3.923	-24.9
181	1453.56	3.898	-24.7
182	1457.45	3.874	-24.5
183	1461.31	3.849	-24.3
184	1465.15	3.825	-24.1
185	1468.96	3.801	-23.9
186	1472.75	3.777	-23.6
187	1476.51	3.754	-23.4
188	1480.26	3.731	-23.2
189	1483.98	3.708	-22.9
190	1487.67	3.685	-22.7
191	1491.35	3.662	-22.4
192	1495.00	3.640	-22.1
193	1498.63	3.618	-21.9
194	1502.23	3.596	-21.6
195	1505.82	3.575	-21.3
196	1509.38	3.554	-21.1
197	1512.93	3.533	-20.8
198	1516.45	3.512	-20.5
199	1519.95	3.492	-20.3
200	1523.43	3.472	-20.0
201	1526.89	3.452	-19.7
202	1530.33	3.432	-19.5
203	1533.76	3.413	-19.3
204	1537.16	3.394	-19.0
205	1540.54	3.375	-18.8
206	1543.91	3.356	-18.6
207	1547.26	3.337	-18.4
208	1550.58	3.319	-18.3
209	1553.89	3.301	-18.1
210	1557.19	3.283	-18.0
211	1560.46	3.265	-17.8
212	1563.72	3.247	-17.7
213	1566.95	3.229	-17.6
214	1570.17	3.212	-17.6
215	1573.38	3.194	-17.5
216	1576.56	3.177	-17.5
217	1579.73	3.159	-17.4
218	1582.88	3.142	-17.4
219	1586.01	3.125	-17.4
220	1589.13	3.107	-17.5
221	1592.23	3.090	-17.5
222	1595.31	3.072	-17.5
223	1598.37	3.055	-17.6
224	1601.42	3.037	-17.6
225	1604.45	3.019	-17.7
226	1607.46	3.002	-17.7
227	1610.45	2.984	-17.8
228	1613.42	2.966	-17.9
229	1616.38	2.948	-17.9
230	1619.32	2.930	-18.0
231	1622.24	2.912	-18.0
232	1625.15	2.894	-18.0
233	1628.03	2.876	-18.0
234	1630.90	2.858	-18.0
235	1633.75	2.840	-17.9
236	1636.58	2.822	-17.9
237	1639.39	2.805	-17.8
238	1642.19	2.787	-17.7
239	1644.97	2.769	-17.5
240	1647.73	2.752	-17.3
240	1647.73	2.752	-17.3
241	1650.47	2.735	-17.1
242	1653.20	2.718	-16.9
243	1655.90	2.701	-16.6
244	1658.60	2.684	-16.3
245	1661.27	2.668	-16.0
246	1663.93	2.653	-15.6
247	1666.58	2.637	-15.2
248	1669.21	2.622	-14.8
249	1671.82	2.607	-14.4
250	1674.42	2.593	-14.0
251	1677.01	2.579	-13.6
252	1679.58	2.566	-13.1
253	1682.14	2.553	-12.7
254	1684.69	2.541	-12.3
255	1687.22	2.528	-12.0
256	1689.75	2.517	-11.6
257	1692.26	2.505	-11.3
258	1694.76	2.494	-11.0
259	1697.25	2.483	-10.8
260	1699.72	2.472	-10.7
261	1702.19	2.462	-10.6
262	1704.65	2.451	-10.5
263	1707.09	2.441	-10.5
264	1709.53	2.430	-10.6
265	1711.95	2.419	-10.8
266	1714.37	2.409	-10.9
267	1716.77	2.398	-11.1
268	1719.16	2.386	-11.3
269	1721.54	2.375	-11.5
270	1723.91	2.363	-11.6
271	1726.27	2.352	-11.6
272	1728.62	2.340	-11.5
273	1730.95	2.329	-11.1
274	1733.27	2.318	-10.4
275	1735.59	2.308	-9.3
276	1737.89	2.300	-7.6
277	1740.19	2.293	-5.2
278	1742.48	2.290	-2.1
279	1744.77	2.289	2.1
280	1747.06	2.294	7.6

Table 19. Reference data for the thermocouple combination copper versus Au-0.02 at % Fe - thermoelectric voltage, E(T), thermoelectric sensitivity, S(T), and the derivative of the thermoelectric sensitivity, dS(T).

T K	E μV	S μV/K	dS/dT nV/K^2	T K	E μV	S μV/K	dS/dT nV/K^2	T K	E μV	S μV/K	dS/dT nV/K^2
0	0.00	0.000	0.0	60	565.27	5.245	-69.6	120	790.55	2.682	-27.7
1	8.20	9.084	1645.5	61	570.48	5.176	-68.4	121	793.22	2.655	-27.4
2	18.06	10.568	1329.6	62	575.62	5.108	-67.1	122	795.86	2.628	-27.0
3	29.24	11.757	1054.3	63	580.70	5.042	-66.0	123	798.48	2.601	-26.7
4	41.48	12.689	815.3	64	585.70	4.976	-64.8	124	801.07	2.574	-26.4
5	54.55	13.399	608.9	65	590.65	4.912	-63.7	125	803.63	2.548	-26.0
6	68.22	13.916	431.5	66	595.53	4.849	-62.6	126	806.16	2.522	-25.7
7	82.32	14.270	280.0	67	600.35	4.787	-61.5	127	808.67	2.497	-25.3
8	96.71	14.484	151.5	68	605.10	4.726	-60.4	128	811.15	2.471	-24.9
9	111.25	14.580	43.4	69	609.80	4.666	-59.3	129	813.61	2.447	-24.5
10	125.84	14.577	-46.7	70	614.43	4.607	-58.2	130	816.05	2.422	-24.1
11	140.38	14.492	-121.0	71	619.01	4.550	-57.1	131	818.46	2.398	-23.7
12	154.80	14.340	-181.4	72	623.53	4.493	-56.0	132	820.85	2.375	-23.3
13	169.04	14.133	-229.7	73	628.00	4.438	-54.9	133	823.21	2.352	-22.9
14	183.05	13.884	-267.4	74	632.41	4.383	-53.9	134	825.55	2.329	-22.5
15	196.80	13.601	-296.0	75	636.77	4.330	-52.8	135	827.87	2.307	-22.1
16	210.25	13.294	-316.8	76	641.07	4.278	-51.7	136	830.16	2.285	-21.7
17	223.38	12.970	-331.0	77	645.32	4.226	-50.7	137	832.44	2.263	-21.3
18	236.18	12.634	-339.4	78	649.52	4.176	-49.6	138	834.69	2.242	-20.9
19	248.65	12.293	-343.1	79	653.67	4.127	-48.6	139	836.92	2.222	-20.5
20	260.77	11.950	-342.8	80	657.78	4.079	-47.6	140	839.13	2.201	-20.1
21	272.55	11.608	-339.2	81	661.83	4.032	-46.6	141	841.32	2.181	-19.7
22	283.99	11.272	-333.0	82	665.84	3.986	-45.6	142	843.50	2.162	-19.3
23	295.09	10.943	-324.7	83	669.81	3.941	-44.6	143	845.65	2.143	-19.0
24	305.88	10.623	-314.8	84	673.72	3.897	-43.7	144	847.78	2.124	-18.6
25	316.34	10.314	-303.7	85	677.60	3.853	-42.8	145	849.90	2.105	-18.3
26	326.51	10.016	-291.7	86	681.43	3.811	-42.0	146	851.99	2.087	-18.0
27	336.38	9.731	-279.1	87	685.22	3.769	-41.1	147	854.07	2.069	-17.6
28	345.97	9.458	-266.3	88	688.97	3.729	-40.3	148	856.13	2.052	-17.3
29	355.30	9.198	-253.3	89	692.68	3.689	-39.6	149	858.17	2.035	-17.1
30	364.37	8.951	-240.4	90	696.35	3.650	-38.9	150	860.20	2.018	-16.8
31	373.21	8.717	-227.8	91	699.98	3.611	-38.2	151	862.21	2.001	-16.5
32	381.81	8.495	-215.5	92	703.57	3.573	-37.5	152	864.20	1.985	-16.3
33	390.20	8.286	-203.7	93	707.13	3.536	-36.9	153	866.18	1.969	-16.1
34	398.39	8.088	-192.3	94	710.64	3.499	-36.3	154	868.14	1.953	-15.9
35	406.38	7.901	-181.6	95	714.12	3.463	-35.7	155	870.08	1.937	-15.7
36	414.19	7.725	-171.4	96	717.57	3.428	-35.2	156	872.01	1.921	-15.5
37	421.83	7.558	-161.8	97	720.98	3.393	-34.7	157	873.93	1.906	-15.4
38	429.31	7.401	-152.9	98	724.36	3.359	-34.3	158	875.82	1.890	-15.3
39	436.64	7.252	-144.6	99	727.70	3.324	-33.8	159	877.71	1.875	-15.1
40	443.82	7.111	-136.9	100	731.01	3.291	-33.4	160	879.57	1.860	-15.0
41	450.86	6.978	-129.8	101	734.28	3.258	-33.0	161	881.43	1.845	-14.9
42	457.78	6.851	-123.3	102	737.52	3.225	-32.7	162	883.26	1.830	-14.9
43	464.57	6.731	-117.4	103	740.73	3.192	-32.4	163	885.09	1.815	-14.8
44	471.24	6.616	-111.9	104	743.91	3.160	-32.0	164	886.90	1.801	-14.7
45	477.80	6.507	-107.0	105	747.05	3.128	-31.7	165	888.69	1.786	-14.7
46	484.25	6.402	-102.5	106	750.16	3.097	-31.4	166	890.47	1.771	-14.6
47	490.61	6.302	-98.4	107	753.24	3.065	-31.2	167	892.23	1.757	-14.6
48	496.86	6.205	-94.8	108	756.29	3.034	-30.9	168	893.98	1.742	-14.5
49	503.02	6.112	-91.4	109	759.31	3.003	-30.6	169	895.71	1.728	-14.5
50	509.09	6.022	-88.4	110	762.30	2.973	-30.4	170	897.44	1.713	-14.5
51	515.06	5.935	-85.7	111	765.26	2.943	-30.1	171	899.14	1.699	-14.4
52	520.96	5.851	-83.2	112	768.19	2.913	-29.9	172	900.83	1.684	-14.4
53	526.77	5.769	-81.0	113	771.08	2.883	-29.6	173	902.51	1.670	-14.4
54	532.49	5.689	-79.0	114	773.95	2.854	-29.4	174	904.17	1.655	-14.3
55	538.14	5.611	-77.1	115	776.79	2.824	-29.1	175	905.82	1.641	-14.3
56	543.72	5.534	-75.4	116	779.60	2.795	-28.8	176	907.45	1.627	-14.2
57	549.21	5.460	-73.8	117	782.38	2.767	-28.6	177	909.07	1.613	-14.2
58	554.64	5.387	-72.3	118	785.13	2.738	-28.3	178	910.68	1.599	-14.1
59	559.99	5.315	-70.9	119	787.86	2.710	-28.0	179	912.27	1.585	-14.0
60	565.27	5.245	-69.6	120	790.55	2.682	-27.7	180	913.85	1.571	-13.9

Table 19. Reference data for the thermocouple combination copper versus Au-0.02 at % Fe - thermoelectric voltage, E(T), thermoelectric sensitivity, S(T), and the derivative of the thermoelectric sensitivity, dS(T) (continued).

T K	E μV	S μV/K	dS/dT nV/K²	T K	E μV	S μV/K	dS/dT nV/K²
180	913.85	1.571	-13.9	240	988.94	0.988	-7.7
181	915.41	1.557	-13.8	241	989.92	0.981	-7.5
182	916.96	1.543	-13.7	242	990.90	0.973	-7.2
183	918.50	1.529	-13.5	243	991.87	0.966	-6.9
184	920.02	1.516	-13.4	244	992.83	0.960	-6.6
185	921.53	1.503	-13.3	245	993.79	0.953	-6.3
186	923.03	1.489	-13.1	246	994.74	0.947	-5.9
187	924.51	1.476	-12.9	247	995.68	0.941	-5.6
188	925.98	1.464	-12.7	248	996.62	0.936	-5.3
189	927.44	1.451	-12.5	249	997.55	0.931	-5.0
190	928.88	1.439	-12.3	250	998.48	0.926	-4.7
191	930.31	1.426	-12.1	251	999.40	0.921	-4.5
192	931.73	1.414	-11.9	252	1000.32	0.917	-4.3
193	933.14	1.403	-11.6	253	1001.24	0.912	-4.2
194	934.54	1.391	-11.4	254	1002.15	0.908	-4.2
195	935.92	1.380	-11.2	255	1003.05	0.904	-4.2
196	937.30	1.369	-10.9	256	1003.95	0.900	-4.3
197	938.66	1.358	-10.7	257	1004.85	0.895	-4.5
198	940.01	1.347	-10.4	258	1005.75	0.891	-4.8
199	941.36	1.337	-10.2	259	1006.63	0.886	-5.2
200	942.69	1.327	-9.9	260	1007.52	0.880	-5.7
201	944.01	1.317	-9.7	261	1008.39	0.874	-6.3
202	945.32	1.308	-9.5	262	1009.27	0.868	-6.9
203	946.63	1.298	-9.3	263	1010.13	0.860	-7.6
204	947.92	1.289	-9.1	264	1010.99	0.852	-8.3
205	949.20	1.280	-8.9	265	1011.83	0.844	-9.0
206	950.48	1.271	-8.7	266	1012.67	0.834	-9.7
207	951.75	1.263	-8.5	267	1013.50	0.824	-10.2
208	953.01	1.254	-8.4	268	1014.32	0.814	-10.5
209	954.26	1.246	-8.3	269	1015.13	0.803	-10.6
210	955.50	1.238	-8.2	270	1015.93	0.793	-10.2
211	956.73	1.230	-8.1	271	1016.72	0.783	-9.3
212	957.96	1.222	-8.0	272	1017.50	0.775	-7.7
213	959.17	1.214	-8.0	273	1018.27	0.768	-5.2
214	960.38	1.206	-7.9	274	1019.03	0.765	-1.6
215	961.59	1.198	-7.9	275	1019.80	0.765	3.4
216	962.78	1.190	-7.9	276	1020.57	0.772	10.0
217	963.96	1.182	-7.9	277	1021.34	0.786	18.6
218	965.14	1.174	-8.0	278	1022.14	0.810	29.6
219	966.31	1.166	-8.0	279	1022.97	0.846	43.4
220	967.47	1.158	-8.1	280	1023.84	0.898	60.5
221	968.63	1.150	-8.1				
222	969.77	1.142	-8.2				
223	970.91	1.133	-8.3				
224	972.04	1.125	-8.4				
225	973.16	1.116	-8.5				
226	974.27	1.108	-8.6				
227	975.38	1.099	-8.6				
228	976.47	1.091	-8.7				
229	977.56	1.082	-8.7				
230	978.64	1.073	-8.8				
231	979.70	1.064	-8.8				
232	980.76	1.056	-8.8				
233	981.82	1.047	-8.8				
234	982.86	1.038	-8.7				
235	983.89	1.029	-8.6				
236	984.92	1.021	-8.5				
237	985.93	1.013	-8.4				
238	986.94	1.004	-8.2				
239	987.94	0.996	-8.0				
240	988.94	0.988	-7.7				

Table 20. Reference data for the thermocouple combination normal silver versus Au-0.07 at % Fe - thermoelectric voltage, E(T), thermoelectric sensitivity, S(T), and the derivative of the thermoelectric sensitivity, dS(T).

T K	E μV	S μV/K	dS/dT nV/K²	T K	E μV	S μV/K	dS/dT nV/K²	T K	E μV	S μV/K	dS/dT nV/K²
0	0.00	0.000	0.0	60	700.37	8.447	-81.3	120	1099.00	5.267	-37.0
1	7.74	8.478	1402.0	61	708.77	8.367	-79.7	121	1104.25	5.230	-36.8
2	16.88	9.774	1193.0	62	717.10	8.288	-78.2	122	1109.46	5.194	-36.5
3	27.22	10.872	1006.5	63	725.35	8.210	-76.7	123	1114.63	5.157	-36.2
4	38.57	11.794	840.7	64	733.52	8.134	-75.3	124	1119.77	5.121	-36.0
5	50.76	12.560	693.6	65	741.62	8.060	-74.0	125	1124.88	5.085	-35.7
6	63.64	13.187	563.5	66	749.64	7.986	-72.7	126	1129.94	5.050	-35.5
7	77.09	13.692	448.8	67	757.59	7.914	-71.4	127	1134.98	5.014	-35.3
8	90.99	14.089	348.0	68	765.47	7.843	-70.2	128	1139.97	4.979	-35.0
9	105.24	14.392	259.7	69	773.28	7.774	-69.1	129	1144.93	4.944	-34.8
10	119.75	14.612	182.8	70	781.02	7.705	-67.9	130	1149.86	4.910	-34.5
11	134.44	14.761	116.0	71	788.69	7.638	-66.8	131	1154.75	4.875	-34.3
12	149.25	14.847	58.4	72	796.29	7.572	-65.8	132	1159.61	4.841	-34.0
13	164.11	14.880	8.9	73	803.83	7.506	-64.7	133	1164.44	4.807	-33.8
14	178.99	14.868	-33.3	74	811.31	7.442	-63.7	134	1169.23	4.774	-33.5
15	193.84	14.816	-68.9	75	818.72	7.379	-62.7	135	1173.98	4.740	-33.3
16	208.61	14.732	-98.8	76	826.06	7.317	-61.7	136	1178.71	4.707	-33.0
17	223.29	14.620	-123.6	77	833.35	7.255	-60.8	137	1183.40	4.674	-32.8
18	237.85	14.486	-143.9	78	840.57	7.195	-59.8	138	1188.06	4.642	-32.5
19	252.26	14.333	-160.3	79	847.74	7.136	-58.9	139	1192.68	4.609	-32.3
20	266.51	14.166	-173.1	80	854.85	7.077	-58.0	140	1197.28	4.577	-32.0
21	280.59	13.988	-183.0	81	861.90	7.020	-57.1	141	1201.84	4.545	-31.7
22	294.48	13.801	-190.2	82	868.89	6.963	-56.3	142	1206.37	4.514	-31.5
23	308.19	13.608	-195.2	83	875.82	6.907	-55.4	143	1210.86	4.482	-31.2
24	321.70	13.412	-198.2	84	882.70	6.852	-54.6	144	1215.33	4.451	-31.0
25	335.01	13.213	-199.5	85	889.53	6.798	-53.8	145	1219.77	4.420	-30.7
26	348.12	13.013	-199.5	86	896.30	6.745	-53.0	146	1224.17	4.390	-30.5
27	361.03	12.814	-198.3	87	903.02	6.692	-52.2	147	1228.55	4.359	-30.3
28	373.75	12.617	-196.1	88	909.68	6.640	-51.5	148	1232.89	4.329	-30.0
29	386.27	12.422	-193.2	89	916.30	6.589	-50.7	149	1237.20	4.299	-29.8
30	398.60	12.231	-189.6	90	922.86	6.539	-50.0	150	1241.49	4.270	-29.5
31	410.73	12.043	-185.5	91	929.37	6.489	-49.3	151	1245.74	4.240	-29.3
32	422.68	11.860	-181.0	92	935.84	6.440	-48.7	152	1249.97	4.211	-29.1
33	434.45	11.681	-176.3	93	942.25	6.392	-48.0	153	1254.17	4.182	-28.8
34	446.05	11.507	-171.4	94	948.62	6.344	-47.4	154	1258.33	4.153	-28.6
35	457.47	11.338	-166.4	95	954.94	6.297	-46.8	155	1262.47	4.125	-28.4
36	468.72	11.174	-161.3	96	961.22	6.250	-46.2	156	1266.58	4.097	-28.2
37	479.82	11.016	-156.3	97	967.44	6.205	-45.6	157	1270.67	4.068	-28.0
38	490.76	10.862	-151.3	98	973.63	6.159	-45.1	158	1274.72	4.041	-27.8
39	501.54	10.713	-146.4	99	979.76	6.114	-44.6	159	1278.75	4.013	-27.6
40	512.19	10.569	-141.6	100	985.85	6.070	-44.1	160	1282.75	3.985	-27.4
41	522.68	10.430	-136.9	101	991.90	6.026	-43.6	161	1286.72	3.958	-27.2
42	533.05	10.295	-132.5	102	997.91	5.983	-43.1	162	1290.66	3.931	-27.0
43	543.28	10.165	-128.2	103	1003.87	5.940	-42.6	163	1294.58	3.904	-26.8
44	553.38	10.039	-124.1	104	1009.79	5.898	-42.2	164	1298.47	3.877	-26.6
45	563.36	9.917	-120.1	105	1015.66	5.856	-41.8	165	1302.34	3.851	-26.4
46	573.21	9.798	-116.4	106	1021.50	5.814	-41.4	166	1306.17	3.825	-26.3
47	582.95	9.684	-112.9	107	1027.29	5.773	-41.0	167	1309.98	3.798	-26.1
48	592.58	9.573	-109.5	108	1033.04	5.732	-40.6	168	1313.77	3.772	-25.9
49	602.10	9.465	-106.3	109	1038.76	5.692	-40.3	169	1317.53	3.747	-25.8
50	611.51	9.360	-103.3	110	1044.43	5.651	-39.9	170	1321.26	3.721	-25.6
51	620.82	9.258	-100.5	111	1050.06	5.612	-39.6	171	1324.97	3.695	-25.5
52	630.03	9.159	-97.9	112	1055.65	5.572	-39.3	172	1328.65	3.670	-25.3
53	639.14	9.062	-95.3	113	1061.20	5.533	-39.0	173	1332.31	3.645	-25.1
54	648.15	8.968	-93.0	114	1066.72	5.494	-38.7	174	1335.94	3.620	-25.0
55	657.08	8.876	-90.7	115	1072.19	5.456	-38.4	175	1339.55	3.595	-24.8
56	665.91	8.787	-88.6	116	1077.63	5.418	-38.1	176	1343.13	3.570	-24.7
57	674.65	8.699	-86.7	117	1083.03	5.380	-37.8	177	1346.69	3.545	-24.5
58	683.31	8.613	-84.8	118	1088.39	5.342	-37.5	178	1350.22	3.521	-24.4
59	691.88	8.529	-83.0	119	1093.71	5.304	-37.3	179	1353.73	3.497	-24.2
60	700.37	8.447	-81.3	120	1099.00	5.267	-37.0	180	1357.22	3.472	-24.1

Table 20. Reference data for the thermocouple combination normal silver versus Au-0.07 at % Fe - thermoelectric voltage, E(T), thermoelectric sensitivity, S(T), and the derivative of the thermoelectric sensitivity, dS(T) (continued).

T K	E µV	S µV/K	dS/dT nV/K²	T K	E µV	S µV/K	dS/dT nV/K²
180	1357.22	3.472	-24.1	240	1528.08	2.288	-18.2
181	1360.68	3.448	-23.9	241	1530.36	2.270	-18.1
182	1364.11	3.425	-23.8	242	1532.62	2.252	-18.0
183	1367.53	3.401	-23.6	243	1534.86	2.234	-17.9
184	1370.92	3.377	-23.4	244	1537.09	2.216	-17.7
185	1374.28	3.354	-23.3	245	1539.29	2.198	-17.6
186	1377.62	3.331	-23.1	246	1541.48	2.181	-17.3
187	1380.94	3.308	-22.9	247	1543.65	2.163	-17.1
188	1384.24	3.285	-22.8	248	1545.81	2.146	-16.8
189	1387.51	3.262	-22.6	249	1547.95	2.130	-16.5
190	1390.76	3.240	-22.4	250	1550.07	2.113	-16.1
191	1393.99	3.217	-22.2	251	1552.17	2.098	-15.7
192	1397.20	3.195	-22.0	252	1554.26	2.082	-15.3
193	1400.38	3.173	-21.9	253	1556.34	2.067	-14.8
194	1403.54	3.152	-21.7	254	1558.40	2.053	-14.3
195	1406.69	3.130	-21.5	255	1560.44	2.038	-13.8
196	1409.80	3.109	-21.3	256	1562.48	2.025	-13.2
197	1412.90	3.087	-21.1	257	1564.49	2.012	-12.6
198	1415.98	3.067	-20.9	258	1566.50	2.000	-12.1
199	1419.04	3.046	-20.7	259	1568.49	1.988	-11.5
200	1422.07	3.025	-20.5	260	1570.48	1.977	-10.9
201	1425.09	3.005	-20.3	261	1572.45	1.966	-10.4
202	1428.08	2.985	-20.1	262	1574.41	1.956	-9.9
203	1431.06	2.965	-19.9	263	1576.36	1.946	-9.4
204	1434.01	2.945	-19.7	264	1578.30	1.937	-9.1
205	1436.94	2.925	-19.6	265	1580.23	1.928	-8.8
206	1439.86	2.906	-19.4	266	1582.16	1.920	-8.6
207	1442.76	2.886	-19.2	267	1584.07	1.911	-8.6
208	1445.63	2.867	-19.0	268	1585.98	1.902	-8.7
209	1448.49	2.848	-18.9	269	1587.88	1.893	-9.1
210	1451.33	2.829	-18.7	270	1589.77	1.884	-9.7
211	1454.15	2.811	-18.6	271	1591.65	1.874	-10.5
212	1456.95	2.792	-18.5	272	1593.51	1.863	-11.7
213	1459.73	2.774	-18.3	273	1595.37	1.851	-13.2
214	1462.50	2.755	-18.2	274	1597.21	1.836	-15.1
215	1465.24	2.737	-18.1	275	1599.04	1.820	-17.4
216	1467.97	2.719	-18.0	276	1600.85	1.801	-20.2
217	1470.68	2.701	-18.0	277	1602.64	1.780	-23.6
218	1473.38	2.683	-17.9	278	1604.41	1.754	-27.6
219	1476.05	2.665	-17.9	279	1606.15	1.724	-32.3
220	1478.71	2.648	-17.8	280	1607.86	1.689	-37.7
221	1481.34	2.630	-17.8				
222	1483.97	2.612	-17.8				
223	1486.57	2.594	-17.8				
224	1489.15	2.576	-17.8				
225	1491.72	2.559	-17.8				
226	1494.27	2.541	-17.8				
227	1496.80	2.523	-17.8				
228	1499.32	2.505	-17.9				
229	1501.81	2.487	-17.9				
230	1504.29	2.469	-18.0				
231	1506.75	2.451	-18.0				
232	1509.19	2.433	-18.1				
233	1511.62	2.415	-18.1				
234	1514.03	2.397	-18.2				
235	1516.41	2.379	-18.2				
236	1518.78	2.361	-18.2				
237	1521.13	2.342	-18.2				
238	1523.47	2.324	-18.2				
239	1525.78	2.306	-18.2				
240	1528.08	2.288	-18.2				

Table 21. Reference data for the thermocouple combination normal silver versus Au-0.02 at % Fe - thermoelectric voltage, E(T), thermoelectric sensitivity, S(T), and the derivative of the thermoelectric sensitivity, dS(T).

T K	E μV	S μV/K	dS/dT nV/K^2	T K	E μV	S μV/K	dS/dT nV/K^2	T K	E μV	S μV/K	dS/dT nV/K^2
0	0.00	0.000	0.0	60	546.11	4.361	-69.2	120	727.52	2.115	-22.9
1	8.17	9.032	1624.0	61	550.44	4.293	-67.2	121	729.62	2.092	-22.7
2	17.96	10.503	1325.6	62	554.70	4.227	-65.2	122	731.70	2.069	-22.5
3	29.08	11.695	1063.4	63	558.89	4.163	-63.3	123	733.76	2.047	-22.3
4	41.27	12.641	833.7	64	563.02	4.100	-61.6	124	735.80	2.025	-22.0
5	54.29	13.372	633.5	65	567.09	4.039	-59.9	125	737.81	2.003	-21.8
6	67.95	13.917	459.6	66	571.10	3.980	-58.4	126	739.80	1.981	-21.6
7	82.07	14.299	309.5	67	575.05	3.923	-56.9	127	741.77	1.960	-21.3
8	96.50	14.543	180.6	68	578.95	3.867	-55.4	128	743.72	1.939	-21.1
9	111.11	14.667	70.7	69	582.79	3.812	-54.0	129	745.65	1.918	-20.8
10	125.80	14.690	-22.4	70	586.57	3.758	-52.7	130	747.56	1.897	-20.6
11	140.46	14.627	-100.5	71	590.30	3.706	-51.4	131	749.44	1.876	-20.3
12	155.03	14.493	-165.3	72	593.98	3.656	-50.1	132	751.31	1.856	-20.1
13	169.43	14.300	-218.4	73	597.61	3.606	-48.9	133	753.16	1.836	-19.8
14	183.61	14.060	-261.2	74	601.20	3.558	-47.8	134	754.98	1.817	-19.5
15	197.54	13.781	-294.9	75	604.73	3.511	-46.6	135	756.79	1.797	-19.3
16	211.17	13.473	-320.8	76	608.22	3.465	-45.5	136	758.58	1.778	-19.0
17	224.48	13.142	-339.9	77	611.66	3.420	-44.4	137	760.35	1.759	-18.7
18	237.45	12.795	-353.1	78	615.06	3.376	-43.4	138	762.10	1.741	-18.5
19	250.06	12.437	-361.2	79	618.41	3.333	-42.4	139	763.83	1.722	-18.2
20	262.32	12.074	-365.1	80	621.72	3.291	-41.4	140	765.54	1.704	-17.9
21	274.21	11.708	-365.3	81	624.99	3.250	-40.4	141	767.24	1.686	-17.7
22	285.73	11.344	-362.5	82	628.22	3.210	-39.5	142	768.91	1.669	-17.4
23	296.90	10.984	-357.1	83	631.41	3.171	-38.6	143	770.57	1.652	-17.2
24	307.70	10.630	-349.8	84	634.57	3.133	-37.7	144	772.22	1.635	-16.9
25	318.16	10.285	-340.8	85	637.68	3.095	-36.9	145	773.84	1.618	-16.7
26	328.28	9.949	-330.5	86	640.76	3.059	-36.1	146	775.45	1.601	-16.4
27	338.06	9.624	-319.3	87	643.80	3.023	-35.3	147	777.05	1.585	-16.2
28	347.53	9.311	-307.4	88	646.80	2.988	-34.6	148	778.62	1.569	-16.0
29	356.69	9.010	-295.0	89	649.77	2.954	-33.9	149	780.18	1.553	-15.8
30	365.55	8.721	-282.4	90	652.71	2.921	-33.2	150	781.73	1.537	-15.6
31	374.14	8.445	-269.7	91	655.62	2.888	-32.5	151	783.26	1.522	-15.4
32	382.45	8.182	-257.0	92	658.49	2.856	-31.9	152	784.77	1.507	-15.2
33	390.50	7.931	-244.6	93	661.33	2.824	-31.3	153	786.27	1.491	-15.0
34	398.31	7.692	-232.4	94	664.14	2.793	-30.7	154	787.75	1.476	-14.9
35	405.89	7.466	-220.5	95	666.91	2.762	-30.2	155	789.22	1.462	-14.7
36	413.25	7.251	-209.1	96	669.66	2.733	-29.7	156	790.68	1.447	-14.6
37	420.40	7.048	-198.1	97	672.38	2.703	-29.2	157	792.12	1.433	-14.4
38	427.35	6.855	-187.6	98	675.07	2.674	-28.8	158	793.54	1.418	-14.3
39	434.11	6.672	-177.6	99	677.73	2.646	-28.3	159	794.95	1.404	-14.2
40	440.70	6.499	-168.2	100	680.36	2.617	-27.9	160	796.35	1.390	-14.1
41	447.11	6.336	-159.2	101	682.96	2.590	-27.6	161	797.73	1.376	-14.0
42	453.37	6.181	-150.8	102	685.54	2.562	-27.2	162	799.10	1.362	-13.9
43	459.48	6.034	-143.0	103	688.09	2.535	-26.9	163	800.46	1.348	-13.8
44	465.44	5.895	-135.6	104	690.61	2.508	-26.6	164	801.80	1.334	-13.8
45	471.27	5.763	-128.7	105	693.10	2.482	-26.3	165	803.13	1.320	-13.7
46	476.97	5.637	-122.3	106	695.57	2.456	-26.0	166	804.44	1.307	-13.7
47	482.55	5.518	-116.4	107	698.02	2.430	-25.7	167	805.74	1.293	-13.6
48	488.01	5.404	-110.9	108	700.43	2.404	-25.5	168	807.03	1.279	-13.6
49	493.36	5.296	-105.7	109	702.82	2.379	-25.2	169	808.30	1.266	-13.5
50	498.60	5.193	-101.0	110	705.19	2.354	-25.0	170	809.56	1.252	-13.5
51	503.74	5.094	-96.6	111	707.53	2.329	-24.8	171	810.80	1.239	-13.4
52	508.79	4.999	-92.6	112	709.85	2.305	-24.5	172	812.04	1.226	-13.4
53	513.74	4.909	-88.8	113	712.14	2.280	-24.3	173	813.25	1.212	-13.4
54	518.61	4.822	-85.4	114	714.41	2.256	-24.1	174	814.46	1.199	-13.3
55	523.39	4.738	-82.2	115	716.65	2.232	-23.9	175	815.65	1.186	-13.3
56	528.09	4.657	-79.2	116	718.87	2.208	-23.7	176	816.83	1.172	-13.2
57	532.70	4.579	-76.4	117	721.07	2.184	-23.5	177	818.00	1.159	-13.2
58	537.25	4.504	-73.9	118	723.24	2.161	-23.3	178	819.15	1.146	-13.2
59	541.71	4.432	-71.5	119	725.39	2.138	-23.1	179	820.29	1.133	-13.1
60	546.11	4.361	-69.2	120	727.52	2.115	-22.9	180	821.41	1.120	-13.0

Table 21. Reference data for the thermocouple combination normal silver versus Au-0.02 at % Fe - thermoelectric voltage, E(T), thermoelectric sensitivity, S(T), and the derivative of the thermoelectric sensitivity, dS(T) (continued).

T K	E μV	S μV/K	dS/dT nV/K^2	T K	E μV	S μV/K	dS/dT nV/K^2
180	821.41	1.120	-13.0	240	869.29	0.524	-8.6
181	822.53	1.107	-13.0	241	869.81	0.516	-8.5
182	823.63	1.094	-12.9	242	870.32	0.507	-8.4
183	824.71	1.081	-12.8	243	870.82	0.499	-8.2
184	825.79	1.068	-12.7	244	871.32	0.491	-8.0
185	826.85	1.055	-12.6	245	871.80	0.483	-7.9
186	827.90	1.043	-12.5	246	872.28	0.475	-7.7
187	828.94	1.030	-12.4	247	872.75	0.468	-7.5
188	829.96	1.018	-12.3	248	873.22	0.460	-7.3
189	830.97	1.006	-12.2	249	873.68	0.453	-7.1
190	831.97	0.994	-12.1	250	874.12	0.446	-6.8
191	832.96	0.982	-11.9	251	874.57	0.439	-6.6
192	833.94	0.970	-11.8	252	875.00	0.433	-6.5
193	834.90	0.958	-11.6	253	875.43	0.426	-6.3
194	835.85	0.946	-11.5	254	875.86	0.420	-6.1
195	836.79	0.935	-11.3	255	876.27	0.414	-6.0
196	837.72	0.924	-11.1	256	876.68	0.408	-5.9
197	838.64	0.913	-11.0	257	877.09	0.402	-5.9
198	839.55	0.902	-10.8	258	877.49	0.396	-5.8
199	840.44	0.891	-10.6	259	877.88	0.391	-5.9
200	841.33	0.881	-10.4	260	878.27	0.385	-6.0
201	842.20	0.870	-10.3	261	878.65	0.379	-6.1
202	843.07	0.860	-10.1	262	879.03	0.372	-6.3
203	843.93	0.850	-9.9	263	879.40	0.366	-6.5
204	844.77	0.840	-9.8	264	879.76	0.359	-6.8
205	845.61	0.831	-9.6	265	880.12	0.353	-7.1
206	846.43	0.821	-9.5	266	880.46	0.345	-7.4
207	847.25	0.812	-9.3	267	880.81	0.338	-7.7
208	848.05	0.802	-9.2	268	881.14	0.330	-7.9
209	848.85	0.793	-9.1	269	881.47	0.322	-8.1
210	849.64	0.784	-8.9	270	881.78	0.314	-8.2
211	850.42	0.775	-8.8	271	882.09	0.305	-8.2
212	851.19	0.767	-8.7	272	882.39	0.297	-7.9
213	851.95	0.758	-8.7	273	882.69	0.290	-7.3
214	852.71	0.749	-8.6	274	882.97	0.283	-6.3
215	853.45	0.741	-8.5	275	883.25	0.277	-4.8
216	854.19	0.732	-8.5	276	883.53	0.274	-2.7
217	854.92	0.724	-8.5	277	883.80	0.272	0.2
218	855.64	0.715	-8.4	278	884.08	0.274	4.0
219	856.35	0.707	-8.4	279	884.35	0.281	9.0
220	857.05	0.698	-8.4	280	884.64	0.293	15.3
221	857.74	0.690	-8.5				
222	858.43	0.681	-8.5				
223	859.11	0.673	-8.5				
224	859.78	0.664	-8.5				
225	860.44	0.656	-8.6				
226	861.09	0.647	-8.6				
227	861.73	0.639	-8.7				
228	862.36	0.630	-8.7				
229	862.99	0.621	-8.8				
230	863.61	0.612	-8.8				
231	864.22	0.604	-8.8				
232	864.81	0.595	-8.9				
233	865.40	0.586	-8.9				
234	865.99	0.577	-8.9				
235	866.56	0.568	-8.9				
236	867.12	0.559	-8.9				
237	867.68	0.550	-8.8				
238	868.22	0.542	-8.8				
239	868.76	0.533	-8.7				
240	869.29	0.524	-8.6				

Table 22. Power series coefficients for representation of thermoelectric voltage in the range 0 K to 280 K with a 0 K reference temperature. Thermocouple types E, K, T, and KP, copper, and normal silver versus Au-0.02, 0.07 at % Fe are included; E(T).

Power Series Coefficients	T	E	K
B(1)	$-3.9974007864 \times 10^{-1}$	$-2.0344697205 \times 10^{-1}$	$2.4061140104 \times 10^{-1}$
B(2)	$2.6329515981 \times 10^{-1}$	$3.0220985715 \times 10^{-1}$	$7.3438313272 \times 10^{-2}$
B(3)	$-9.6491216443 \times 10^{-3}$	$-5.7844373965 \times 10^{-3}$	$1.2873437647 \times 10^{-3}$
B(4)	$3.8973308068 \times 10^{-4}$	$1.7879650162 \times 10^{-4}$	$-2.2622572598 \times 10^{-5}$
B(5)	$-9.8186150331 \times 10^{-6}$	$-3.6597667313 \times 10^{-6}$	$2.1765238991 \times 10^{-7}$
B(6)	$1.6059280063 \times 10^{-7}$	$4.9073685405 \times 10^{-8}$	$-1.3304091711 \times 10^{-9}$
B(7)	$-1.7932074012 \times 10^{-9}$	$-4.4751468891 \times 10^{-10}$	$5.2493539029 \times 10^{-12}$
B(8)	$1.4080710479 \times 10^{-11}$	$2.8331235582 \times 10^{-12}$	$-1.2997123230 \times 10^{-14}$
B(9)	$-7.8671373053 \times 10^{-14}$	$-1.2476596612 \times 10^{-14}$	$1.8403309812 \times 10^{-17}$
B(10)	$3.1144995156 \times 10^{-16}$	$3.7536769066 \times 10^{-17}$	$-1.1382797374 \times 10^{-20}$
B(11)	$-8.5433550766 \times 10^{-19}$	$-7.3627479508 \times 10^{-20}$	
B(12)	$1.5448411036 \times 10^{-21}$	$8.4898427718 \times 10^{-23}$	
B(13)	$-1.6565456476 \times 10^{-24}$	$-4.3671808488 \times 10^{-26}$	
B(14)	$7.9795893156 \times 10^{-28}$		

Table 22. Power series coefficients for representation of thermoelectric voltage in the range 0 K to 280 K with a 0 K reference temperature. Thermocouple types E, K, T, and KP, copper, and normal silver versus Au-0.02, 0.07 at % Fe are included; E(T) (continued).

Power Series Coefficients	KP vs Au 7 Fe	KP vs Au 2 Fe	Cu vs Au 7 Fe
B(1)	6.9864426367	7.2668579396	6.9819441789
B(2)	$9.0607276605 \times 10^{-1}$	1.0692244345	$8.4001378651 \times 10^{-1}$
B(3)	$-4.3469694773 \times 10^{-2}$	$-6.2220191022 \times 10^{-2}$	$-4.5417070202 \times 10^{-2}$
B(4)	$1.2468246660 \times 10^{-3}$	$1.9487031660 \times 10^{-3}$	$1.3796048892 \times 10^{-3}$
B(5)	$-2.3500537590 \times 10^{-5}$	$-3.8863862277 \times 10^{-5}$	$-2.7648679333 \times 10^{-5}$
B(6)	$3.0837610415 \times 10^{-7}$	$5.3284892976 \times 10^{-7}$	$3.8534874955 \times 10^{-7}$
B(7)	$-2.9032251684 \times 10^{-9}$	$-5.2094815173 \times 10^{-9}$	$-3.8382718939 \times 10^{-9}$
B(8)	$1.9881512159 \times 10^{-11}$	$3.6920742674 \times 10^{-11}$	$2.7684122233 \times 10^{-11}$
B(9)	$-9.9174829612 \times 10^{-14}$	$-1.9020522841 \times 10^{-13}$	$-1.4483161512 \times 10^{-13}$
B(10)	$3.5645229362 \times 10^{-16}$	$7.0508285353 \times 10^{-16}$	$5.4390389051 \times 10^{-16}$
B(11)	$-8.9864698504 \times 10^{-19}$	$-1.8317974022 \times 10^{-18}$	$-1.4282076268 \times 10^{-18}$
B(12)	$1.5071673023 \times 10^{-21}$	$3.1644035401 \times 10^{-21}$	$2.4882871621 \times 10^{-21}$
B(13)	$-1.5093916059 \times 10^{-24}$	$-3.2636069898 \times 10^{-24}$	$-2.5831198571 \times 10^{-24}$
B(14)	$6.8264293980 \times 10^{-28}$	$1.5201593461 \times 10^{-27}$	$1.2089129004 \times 10^{-27}$

Table 22. Power series coefficients for representation of thermoelectric voltage in the range 0 K to 280 K with a 0 K reference temperature. Thermocouple types E, K, T, and KP, copper, and normal silver versus Au-0.02, 0.07 at % Fe are included; E(T) (continued).

Power Series Coefficients	Cu vs Au 2 Fe	n.Ag vs Au 7 Fe	n.Ag vs Au 2 Fe
B(1)	7.2623594676	6.9616414011	7.2420566898
B(2)	1.0031654569	$8.1796982011 \times 10^{-1}$	$9.8112149062 \times 10^{-1}$
B(3)	$-6.4167566583 \times 10^{-2}$	$-4.1183301479 \times 10^{-2}$	$-5.9933797876 \times 10^{-2}$
B(4)	$2.0814833941 \times 10^{-3}$	$1.1332864853 \times 10^{-3}$	$1.8351649913 \times 10^{-3}$
B(5)	$-4.3012004132 \times 10^{-5}$	$-2.0564116972 \times 10^{-5}$	$-3.5927441812 \times 10^{-5}$
B(6)	$6.0982157678 \times 10^{-7}$	$2.6125849627 \times 10^{-7}$	$4.8573132442 \times 10^{-7}$
B(7)	$-6.1445282582 \times 10^{-9}$	$-2.3898974345 \times 10^{-9}$	$-4.6961538119 \times 10^{-9}$
B(8)	$4.4723352843 \times 10^{-11}$	$1.5931957622 \times 10^{-11}$	$3.2971188358 \times 10^{-11}$
B(9)	$-2.3586201427 \times 10^{-13}$	$-7.7417132540 \times 10^{-14}$	$-1.6844753253 \times 10^{-13}$
B(10)	$8.9253445111 \times 10^{-16}$	$2.7100280116 \times 10^{-16}$	$6.1963336555 \times 10^{-16}$
B(11)	$-2.3613580435 \times 10^{-18}$	$-6.6485927163 \times 10^{-19}$	$-1.5980097000 \times 10^{-18}$
B(12)	$4.1455233949 \times 10^{-21}$	$1.0835762248 \times 10^{-21}$	$2.7408124807 \times 10^{-21}$
B(13)	$-4.3373352305 \times 10^{-24}$	$-1.0525122333 \times 10^{-24}$	$-2.8067276336 \times 10^{-24}$
B(14)	$2.0464292991 \times 10^{-27}$	$4.6057748723 \times 10^{-28}$	$1.2980938998 \times 10^{-27}$

Table 23. Power series coefficients for type E thermocouple in degrees Celsius and with a 0°C reference temperature; E(T).

Temperature Range	Degree	Coefficients	Term
0 to 273 K	13	$5.8695857799 \times 10^{+1}$	T
		$5.1667517705 \times 10^{-2}$	T^2
		$-4.4652683347 \times 10^{-4}$	T^3
		$-1.7346270905 \times 10^{-5}$	T^4
		$-4.8719368427 \times 10^{-7}$	T^5
		$-8.8896550447 \times 10^{-9}$	T^6
		$-1.0930767375 \times 10^{-10}$	T^7
		$-9.1784535039 \times 10^{-13}$	T^8
		$-5.2575158521 \times 10^{-15}$	T^9
		$-2.0169601996 \times 10^{-17}$	T^{10}
		$-4.9502138782 \times 10^{-20}$	T^{11}
		$-7.0177980633 \times 10^{-23}$	T^{12}
		$-4.3671808488 \times 10^{-26}$	T^{13}
0 to 1000°C	9	$5.8695857799 \times 10^{+1}$	T
		$4.3110945462 \times 10^{-2}$	T^2
		$5.7220358202 \times 10^{-5}$	T^3
		$-5.4020668085 \times 10^{-7}$	T^4
		$1.5425922111 \times 10^{-9}$	T^5
		$-2.4850089136 \times 10^{-12}$	T^6
		$2.3389721459 \times 10^{-15}$	T^7
		$-1.1946296815 \times 10^{-18}$	T^8
		$2.5561127497 \times 10^{-22}$	T^9

Table 24. Power series coefficients for type K thermocouple in degrees Celsius and with a 0°C reference temperature; E(T).

Temperature Range	Degree	Coefficients	Term
0 to 273 K	10	$3.9475433139 \times 10^{+1}$	T
		$2.7465251138 \times 10^{-2}$	T^2
		$-1.6565406716 \times 10^{-4}$	T^3
		$-1.5190912392 \times 10^{-6}$	T^4
		$-2.4581670924 \times 10^{-8}$	T^5
		$-2.4757917816 \times 10^{-10}$	T^6
		$-1.5585276173 \times 10^{-12}$	T^7
		$-5.9729921255 \times 10^{-15}$	T^8
		$-1.2688801216 \times 10^{-17}$	T^9
		$-1.1382797374 \times 10^{-20}$	T^{10}
0 to 1372°C	8 + exp.	$-1.8533063273 \times 10^{+1}$	---
		$3.8918344612 \times 10^{+1}$	T
		$1.6645154356 \times 10^{-2}$	T^2
		$-7.8702374448 \times 10^{-5}$	T^3
		$2.2835785557 \times 10^{-7}$	T^4
		$-3.5700231258 \times 10^{-10}$	T^5
		$2.9932909136 \times 10^{-13}$	T^6
		$-1.2849848798 \times 10^{-16}$	T^7
		$2.2239974336 \times 10^{-20}$	T^8

$$+ 125 \exp\left[-\frac{1}{2}\left(\frac{T-127}{65}\right)^2\right]$$

Table 25. Power series coefficients for type T thermocouple in degrees Celsius and with a 0°C reference temperature; E(T).

Temperature Range	Degree	Coefficients	Term
0 to 273 K	14	$3.8740773840 \times 10^{+1}$	T
		$4.4123932482 \times 10^{-2}$	T^2
		$1.1405238498 \times 10^{-4}$	T^3
		$1.9974406568 \times 10^{-5}$	T^4
		$9.0445401187 \times 10^{-7}$	T^5
		$2.2766018504 \times 10^{-8}$	T^6
		$3.6247409380 \times 10^{-10}$	T^7
		$3.8648924201 \times 10^{-12}$	T^8
		$2.8298678519 \times 10^{-14}$	T^9
		$1.4281383349 \times 10^{-16}$	T^{10}
		$4.8833254364 \times 10^{-19}$	T^{11}
		$1.0803474683 \times 10^{-21}$	T^{12}
		$1.3949291026 \times 10^{-24}$	T^{13}
		$7.9795893156 \times 10^{-28}$	T^{14}
0 to 400°C	8	$3.8740773840 \times 10^{+1}$	T
		$3.3190198092 \times 10^{-2}$	T^2
		$2.0714183645 \times 10^{-4}$	T^3
		$-2.1945834823 \times 10^{-6}$	T^4
		$1.1031900550 \times 10^{-8}$	T^5
		$-3.0927581898 \times 10^{-11}$	T^6
		$4.5653337165 \times 10^{-14}$	T^7
		$-2.7616878040 \times 10^{-17}$	T^8

Table 26. **Power series coefficients for type J thermocouple in degrees Celsius and with a 0°C reference temperature; E(T).**

Temperature Range	Degree	Coefficients	Term
-210 to 760 °C	7	$5.0372753027 \times 10^{+1}$	T
		$3.0425491284 \times 10^{-2}$	T^2
		$-8.5669750464 \times 10^{-5}$	T^3
		$1.3348825735 \times 10^{-7}$	T^4
		$-1.7022405966 \times 10^{-10}$	T^5
		$1.9416091001 \times 10^{-13}$	T^6
		$-9.6391844859 \times 10^{-17}$	T^7
760 to 1200	5	$2.9721751778 \times 10^{+5}$	---
		$-1.5059632873 \times 10^{+3}$	T
		$3.2051064215 \times 10^{+0}$	T^2
		$-3.2210174230 \times 10^{-3}$	T^3
		$1.5949968788 \times 10^{-6}$	T^4
		$-3.1239801752 \times 10^{-10}$	T^5

Table 27. Reference data for the thermocouple combination KP versus Au-2.1 at % Co - thermoelectric voltage, EMF(T), thermoelectric voltage difference, DELEMF(T), and thermoelectric sensitivity, DE/DT(T).

TEMP DEG K	EMF MIC V	DELEMF MIC V	DE/DT MIC V/DGK	TEMP DEG K	EMF MIC V	DELEMF MIC V	DE/DT MIC V/DGK
1	0.6	0.6	1.210	41	758.3	31.7	31.930
2	2.4	1.8	2.390	42	790.5	32.2	32.410
3	5.4	3.0	3.550	43	823.2	32.7	32.880
4	9.5	4.1	4.680	44	856.4	33.2	33.340
5	14.7	5.2	5.780	45	890.0	33.6	33.790
6	21.0	6.3	6.860	46	924.0	34.0	34.240
7	28.4	7.4	7.910	47	958.4	34.4	34.680
8	36.8	8.4	8.940	48	993.2	34.8	35.110
9	46.2	9.4	9.940	49	1028.5	35.3	35.530
10	56.6	10.4	10.910	50	1064.2	35.7	35.940
11	68.0	11.4	11.860	51	1100.3	36.1	36.350
12	80.4	12.4	12.780	52	1136.8	36.5	36.750
13	93.7	13.3	13.670	53	1173.7	36.9	37.150
14	107.9	14.2	14.540	54	1211.0	37.3	37.540
15	123.0	15.1	15.390	55	1248.7	37.7	37.930
16	138.9	15.9	16.210	56	1286.8	38.1	38.310
17	155.6	16.7	17.010	57	1325.3	38.5	38.680
18	173.1	17.5	17.790	58	1364.2	38.9	39.040
19	191.4	18.3	18.560	59	1403.5	39.3	39.400
20	210.4	19.0	19.320	60	1443.1	39.6	39.750
21	230.1	19.7	20.060	61	1483.1	40.0	40.090
22	250.5	20.4	20.780	62	1523.4	40.3	40.430
23	271.6	21.1	21.490	63	1564.0	40.6	40.760
24	293.4	21.8	22.180	64	1604.9	40.9	41.090
25	315.9	22.5	22.850	65	1646.1	41.2	41.410
26	339.1	23.2	23.510	66	1687.6	41.5	41.720
27	363.0	23.9	24.150	67	1729.4	41.8	42.020
28	387.6	24.6	24.780	68	1771.5	42.1	42.320
29	412.8	25.2	25.390	69	1813.9	42.4	42.610
30	438.6	25.8	25.990	70	1856.6	42.7	42.890
31	464.9	26.3	26.580	71	1899.6	43.0	43.170
32	491.8	26.9	27.160	72	1942.9	43.3	43.440
33	519.3	27.5	27.730	73	1986.5	43.6	43.710
34	547.3	28.0	28.290	74	2030.4	43.9	43.980
35	575.9	28.6	28.840	75	2074.6	44.2	44.240
36	605.0	29.1	29.380	76	2119.0	44.4	44.500
37	634.6	29.6	29.910	77	2163.7	44.7	44.760
38	664.7	30.1	30.430	78	2208.6	44.9	45.020
39	695.4	30.7	30.940	79	2253.8	45.2	45.270
40	726.6	31.2	31.440	80	2299.2	45.4	45.520

Table 27. Reference data for the thermocouple combination KP versus Au-2.1 at % Co - thermoelectric voltage, EMF(T), thermoelectric voltage difference, DELEMF(T), and thermoelectric sensitivity, DE/DT(T) (continued).

TEMP DEG K	EMF MIC V	DELEMF MIC V	DE/DT MIC V/DGK	TEMP DEG K	EMF MIC V	DELEMF MIC V	DE/DT MIC V/DGK
81	2344.9	45.7	45.770	121	4343.2	53.3	53.370
82	2390.8	45.9	46.020	122	4396.6	53.4	53.510
83	2436.9	46.1	46.270	123	4450.2	53.6	53.650
84	2483.3	46.4	46.510	124	4503.9	53.7	53.780
85	2529.9	46.6	46.750	125	4557.8	53.9	53.910
86	2576.8	46.9	46.990	126	4611.8	54.0	54.040
87	2623.9	47.1	47.230	127	4665.9	54.1	54.170
88	2671.2	47.3	47.460	128	4720.2	54.3	54.300
89	2718.8	47.6	47.690	129	4774.6	54.4	54.420
90	2766.6	47.8	47.920	130	4829.1	54.5	54.540
91	2814.6	48.0	48.140	131	4883.7	54.6	54.660
92	2862.9	48.3	48.360	132	4938.4	54.7	54.780
93	2911.4	48.5	48.580	133	4993.3	54.9	54.900
94	2960.1	48.7	48.790	134	5048.3	55.0	55.020
95	3009.0	48.9	48.990	135	5103.4	55.1	55.140
96	3058.1	49.1	49.190	136	5158.6	55.2	55.260
97	3107.4	49.3	49.390	137	5213.9	55.3	55.370
98	3156.9	49.5	49.590	138	5269.3	55.4	55.480
99	3206.6	49.7	49.780	139	5324.8	55.5	55.590
100	3256.5	49.9	49.970	140	5380.4	55.6	55.700
101	3306.5	50.0	50.160	141	5436.2	55.8	55.810
102	3356.7	50.2	50.340	142	5492.1	55.9	55.920
103	3407.1	50.4	50.520	143	5548.1	56.0	56.020
104	3457.7	50.6	50.700	144	5604.2	56.1	56.120
105	3508.5	50.8	50.870	145	5660.4	56.2	56.220
106	3559.5	51.0	51.040	146	5716.7	56.3	56.320
107	3610.6	51.1	51.210	147	5773.1	56.4	56.420
108	3661.9	51.3	51.380	148	5829.6	56.5	56.520
109	3713.4	51.5	51.550	149	5886.2	56.6	56.620
110	3765.0	51.6	51.710	150	5942.8	56.6	56.710
111	3816.8	51.8	51.870	151	5999.5	56.7	56.800
112	3868.8	52.0	52.030	152	6056.3	56.8	56.890
113	3920.9	52.1	52.190	153	6113.2	56.9	56.980
114	3973.2	52.3	52.350	154	6170.2	57.0	57.070
115	4025.6	52.4	52.500	155	6227.3	57.1	57.160
116	4078.2	52.6	52.650	156	6284.5	57.2	57.250
117	4130.9	52.7	52.800	157	6341.8	57.3	57.340
118	4183.8	52.9	52.950	158	6399.2	57.4	57.430
119	4236.8	53.0	53.090	159	6456.7	57.5	57.510
120	4289.9	53.1	53.230	160	6514.2	57.5	57.590

Table 27. Reference data for the thermocouple combination KP versus Au-2.1 at % Co - thermoelectric voltage, EMF(T), thermoelectric voltage difference, DELEMF(T), and thermoelectric sensitivity, DE/DT(T) (continued).

TEMP DEG K	EMF MIC V	DELEMF MIC V	DE/DT MIC V/DGK	TEMP DEG K	EMF MIC V	DELEMF MIC V	DE/DT MIC V/DGK
161	6571.8	57.6	57.670	201	8935.4	60.3	60.330
162	6629.5	57.7	57.750	202	8995.8	60.4	60.380
163	6687.3	57.8	57.830	203	9056.2	60.4	60.430
164	6745.2	57.9	57.910	204	9116.7	60.5	60.480
165	6803.1	57.9	57.990	205	9177.2	60.5	60.530
166	6861.1	58.0	58.070	206	9237.7	60.5	60.580
167	6919.2	58.1	58.150	207	9298.3	60.6	60.630
168	6977.4	58.2	58.220	208	9358.9	60.6	60.680
169	7035.7	58.3	58.290	209	9419.6	60.7	60.730
170	7094.0	58.3	58.360	210	9480.3	60.7	60.780
171	7152.4	58.4	58.430	211	9541.1	60.8	60.820
172	7210.9	58.5	58.500	212	9601.9	60.8	60.860
173	7269.4	58.5	58.570	213	9662.8	60.9	60.900
174	7328.0	58.6	58.640	214	9723.7	60.9	60.950
175	7386.7	58.7	58.710	215	9784.7	61.0	60.990
176	7445.4	58.7	58.780	216	9845.7	61.0	61.030
177	7504.2	58.8	58.850	217	9906.8	61.1	61.070
178	7563.1	58.9	58.920	218	9967.9	61.1	61.110
179	7622.0	58.9	58.990	219	10029.0	61.1	61.150
180	7681.0	59.0	59.060	220	10090.2	61.2	61.190
181	7740.1	59.1	59.130	221	10151.4	61.2	61.230
182	7799.3	59.2	59.200	222	10212.7	61.3	61.270
183	7858.5	59.2	59.270	223	10274.0	61.3	61.310
184	7917.8	59.3	59.340	224	10335.4	61.4	61.350
185	7977.2	59.4	59.410	225	10396.8	61.4	61.390
186	8036.6	59.4	59.470	226	10458.2	61.4	61.430
187	8096.1	59.5	59.530	227	10519.7	61.5	61.470
188	8155.7	59.6	59.590	228	10581.2	61.5	61.510
189	8215.3	59.6	59.650	229	10642.7	61.5	61.540
190	8275.0	59.7	59.710	230	10704.3	61.6	61.570
191	8334.7	59.7	59.770	231	10765.9	61.6	61.600
192	8394.5	59.8	59.830	232	10827.5	61.6	61.630
193	8454.4	59.9	59.890	233	10889.1	61.6	61.670
194	8514.3	59.9	59.950	234	10950.8	61.7	61.700
195	8574.3	60.0	60.010	235	11012.5	61.7	61.730
196	8634.3	60.0	60.070	236	11074.2	61.7	61.760
197	8694.4	60.1	60.130	237	11136.0	61.8	61.790
198	8754.6	60.2	60.180	238	11197.8	61.8	61.820
199	8814.8	60.2	60.230	239	11259.6	61.8	61.850
200	8875.1	60.3	60.280	240	11321.5	61.9	61.880

Table 27. Reference data for the thermocouple combination KP versus Au-2.1 at % Co - thermoelectric voltage, EMF(T), thermoelectric voltage difference, DELEMF(T), and thermoelectric sensitivity, DE/DT(T) (continued).

TEMP DEG K	EMF MIC V	DELEMF MIC V	DE/DT MIC V/DGK	TEMP DEG K	EMF MIC V	DELEMF MIC V	DE/DT MIC V/DGK
241	11383.4	61.9	61.910				
242	11445.3	61.9	61.940				
243	11507.2	61.9	61.970				
244	11569.2	62.0	62.000				
245	11631.2	62.0	62.030				
246	11693.2	62.0	62.060				
247	11755.3	62.1	62.080				
248	11817.4	62.1	62.100				
249	11879.5	62.1	62.120				
250	11941.6	62.1	62.140				
251	12003.8	62.2	62.160				
252	12066.0	62.2	62.180				
253	12128.2	62.2	62.200				
254	12190.4	62.2	62.220				
255	12252.6	62.2	62.240				
256	12314.9	62.3	62.260				
257	12377.2	62.3	62.280				
258	12439.5	62.3	62.300				
259	12501.8	62.3	62.320				
260	12564.1	62.3	62.330				
261	12626.4	62.3	62.340				
262	12688.7	62.3	62.350				
263	12751.0	62.3	62.360				
264	12813.4	62.4	62.370				
265	12875.8	62.4	62.380				
266	12938.2	62.4	62.390				
267	13000.6	62.4	62.400				
268	13063.0	62.4	62.410				
269	13125.4	62.4	62.420				
270	13187.8	62.4	62.430				
271	13250.2	62.4	62.440				
272	13312.6	62.4	62.450				
273	13375.0	62.4	62.450				
274	13437.4	62.4	62.450				
275	13499.8	62.4	62.450				
276	13562.2	62.4	62.450				
277	13624.6	62.4	62.450				
278	13687.0	62.4	62.450				
279	13749.4	62.4	62.450				
280	13811.9	62.5	62.460				

Table 28. Reference data for the thermocouple combination copper versus Au-2.1 at % Co - thermoelectric voltage, EMF(T), thermoelectric voltage difference, DELEMF(T), and thermoelectric sensitivity, DE/DT(T).

TEMP DEG K	EMF MIC V	DELEMF MIC V	DE/DT MIC V/DGK	TEMP DEG K	EMF MIC V	DELEMF MIC V	DE/DT MIC V/DGK
1	0.53	0.53	1.047	41	640.6	26.4	26.600
2	2.09	1.56	2.070	42	667.4	26.8	26.963
3	4.66	2.57	3.069	43	694.6	27.2	27.317
4	8.22	3.56	4.044	44	722.1	27.5	27.662
5	12.74	4.52	4.994	45	749.9	27.8	27.998
6	18.20	5.46	5.920	46	778.1	28.2	28.326
7	24.57	6.37	6.822	47	806.6	28.5	28.646
8	31.83	7.26	7.700	48	835.4	28.8	28.958
9	39.96	8.13	8.554	49	864.5	29.1	29.262
10	48.93	8.97	9.383	50	893.9	29.4	29.558
11	58.72	9.79	10.188	51	923.6	29.7	29.846
12	69.30	10.58	10.969	52	953.6	30.0	30.127
13	80.65	11.35	11.726	53	983.9	30.3	30.402
14	92.75	12.10	12.458	54	1014.4	30.5	30.669
15	105.6	12.8	13.165	55	1045.2	30.8	30.929
16	119.1	13.5	13.848	56	1076.2	31.0	31.183
17	133.2	14.1	14.513	57	1107.5	31.3	31.430
18	148.0	14.8	15.165	58	1139.1	31.6	31.671
19	163.5	15.5	15.803	59	1170.9	31.8	31.906
20	179.6	16.1	16.427	60	1202.9	32.0	32.134
21	196.4	16.8	17.038	61	1235.1	32.2	32.356
22	213.7	17.3	17.635	62	1267.5	32.4	32.573
23	231.6	17.9	18.219	63	1300.2	32.7	32.784
24	250.1	18.5	18.791	64	1333.1	32.9	32.989
25	269.2	19.1	19.349	65	1366.2	33.1	33.189
26	288.8	19.6	19.893	66	1399.5	33.3	33.384
27	308.9	20.1	20.424	67	1433.0	33.5	33.574
28	329.6	20.7	20.941	68	1466.7	33.7	33.759
29	350.8	21.2	21.446	69	1500.5	33.8	33.938
30	372.5	21.7	21.938	70	1534.5	34.0	34.112
31	394.7	22.2	22.417	71	1568.7	34.2	34.280
32	417.3	22.6	22.884	72	1603.1	34.4	34.442
33	440.4	23.1	23.340	73	1637.6	34.5	34.599
34	464.0	23.6	23.785	74	1672.3	34.7	34.753
35	488.0	24.0	24.218	75	1707.1	34.8	34.905
36	512.4	24.4	24.640	76	1742.1	35.0	35.056
37	537.3	24.9	25.052	77	1777.2	35.1	35.205
38	562.6	25.3	25.454	78	1812.5	35.3	35.352
39	588.2	25.6	25.846	79	1847.9	35.4	35.497
40	614.2	26.0	26.228	80	1883.5	35.6	35.641

Table 28. Reference data for the thermocouple combination copper versus Au-2.1 at % Co - thermoelectric voltage, EMF(T), thermoelectric voltage difference, DELEMF(T), and thermoelectric sensitivity, DE/DT(T) (continued).

TEMP DEG K	EMF MIC V	DELEMF MIC V	DE/DT MIC V/DGK	TEMP DEG K	EMF MIC V	DELEMF MIC V	DE/DT MIC V/DGK
81	1919.2	35.7	35.785	121	3442.6	39.8	39.873
82	1955.0	35.8	35.929	122	3482.5	39.9	39.941
83	1991.0	36.0	36.071	123	3522.5	40.0	40.008
84	2027.2	36.2	36.211	124	3562.5	40.0	40.073
85	2063.5	36.3	36.348	125	3602.6	40.1	40.137
86	2099.9	36.4	36.483	126	3642.8	40.2	40.200
87	2136.4	36.5	36.615	127	3683.0	40.2	40.262
88	2173.1	36.7	36.744	128	3723.3	40.3	40.322
89	2209.9	36.8	36.871	129	3763.7	40.4	40.381
90	2246.8	36.9	36.995	130	3804.1	40.4	40.440
91	2283.9	37.1	37.117	131	3844.6	40.5	40.498
92	2321.1	37.2	37.236	132	3885.1	40.5	40.554
93	2358.4	37.3	37.353	133	3925.7	40.6	40.609
94	2395.8	37.4	37.468	134	3966.3	40.6	40.664
95	2433.3	37.5	37.581	135	4007.0	40.7	40.718
96	2470.9	37.6	37.692	136	4047.7	40.7	40.770
97	2508.6	37.7	37.801	137	4088.5	40.8	40.821
98	2546.5	37.9	37.907	138	4129.4	40.9	40.871
99	2584.5	38.0	38.011	139	4170.3	40.9	40.920
100	2622.6	38.1	38.113	140	4211.2	40.9	40.969
101	2660.7	38.1	38.213	141	4252.2	41.0	41.017
102	2698.9	38.2	38.312	142	4293.2	41.0	41.064
103	2737.3	38.4	38.409	143	4334.3	41.1	41.110
104	2775.8	38.5	38.504	144	4375.5	41.2	41.155
105	2814.4	38.6	38.597	145	4416.7	41.2	41.199
106	2853.0	38.6	38.688	146	4457.9	41.2	41.242
107	2891.7	38.7	38.778	147	4499.1	41.2	41.285
108	2930.6	38.9	38.866	148	4540.4	41.3	41.327
109	2969.5	38.9	38.953	149	4581.8	41.4	41.368
110	3008.5	39.0	39.038	150	4623.2	41.4	41.408
111	3047.6	39.1	39.121	151	4664.6	41.4	41.448
112	3086.8	39.2	39.202	152	4706.1	41.5	41.487
113	3126.0	39.2	39.282	153	4747.6	41.5	41.525
114	3165.3	39.3	39.361	154	4789.1	41.5	41.562
115	3204.7	39.4	39.439	155	4830.7	41.6	41.599
116	3244.2	39.5	39.515	156	4872.3	41.6	41.635
117	3283.7	39.5	39.589	157	4914.0	41.7	41.670
118	3323.3	39.6	39.662	158	4955.7	41.7	41.705
119	3363.0	39.7	39.734	159	4997.4	41.7	41.739
120	3402.8	39.8	39.804	160	5039.1	41.7	41.772

Table 28. Reference data for the thermocouple combination copper versus Au-2.1 at % Co - thermoelectric voltage, EMF(T), thermoelectric voltage difference, DELEMF(T), and thermoelectric sensitivity, DE/DT(T) (continued).

TEMP DEG K	EMF MIC V	DELEMF MIC V	DE/DT MIC V/DGK	TEMP DEG K	EMF MIC V	DELEMF MIC V	DE/DT MIC V/DGK
161	5080.9	41.8	41.805	201	6773.3	42.7	42.688
162	5122.7	41.8	41.837	202	6816.0	42.7	42.701
163	5164.6	41.9	41.868	203	6858.7	42.7	42.714
164	5206.5	41.9	41.899	204	6901.4	42.7	42.727
165	5248.4	41.9	41.929	205	6944.1	42.7	42.740
166	5290.3	41.9	41.959	206	6986.8	42.7	42.752
167	5332.3	42.0	41.988	207	7029.6	42.8	42.764
168	5374.3	42.0	42.016	208	7072.4	42.8	42.775
169	5416.3	42.0	42.044	209	7115.2	42.8	42.786
170	5458.4	42.1	42.072	210	7158.0	42.8	42.797
171	5500.5	42.1	42.099	211	7200.8	42.8	42.808
172	5542.6	42.1	42.125	212	7243.6	42.8	42.818
173	5584.7	42.1	42.151	213	7286.4	42.8	42.828
174	5626.9	42.2	42.176	214	7329.2	42.8	42.838
175	5669.1	42.2	42.201	215	7372.0	42.8	42.848
176	5711.3	42.2	42.225	216	7414.9	42.9	42.857
177	5753.5	42.2	42.249	217	7457.8	42.9	42.866
178	5795.8	42.3	42.272	218	7500.7	42.9	42.875
179	5838.1	42.3	42.295	219	7543.5	42.8	42.883
180	5880.4	42.3	42.317	220	7586.4	42.9	42.891
181	5922.7	42.3	42.339	221	7629.3	42.9	42.899
182	5965.0	42.3	42.360	222	7672.2	42.9	42.906
183	6007.4	42.4	42.381	223	7715.1	42.9	42.913
184	6049.8	42.4	42.402	224	7758.0	42.9	42.920
185	6092.2	42.4	42.422	225	7801.0	43.0	42.927
186	6134.6	42.4	42.441	226	7843.9	42.9	42.934
187	6177.1	42.5	42.460	227	7886.8	42.9	42.940
188	6219.6	42.5	42.479	228	7929.7	42.9	42.946
189	6262.1	42.5	42.497	229	7972.6	42.9	42.952
190	6304.6	42.5	42.515	230	8015.6	43.0	42.958
191	6347.1	42.5	42.533	231	8058.6	43.0	42.963
192	6389.6	42.5	42.550	232	8101.6	43.0	42.968
193	6432.2	42.6	42.567	233	8144.6	43.0	42.973
194	6474.8	42.6	42.583	234	8187.6	43.0	42.978
195	6517.4	42.6	42.599	235	8230.5	42.9	42.983
196	6560.0	42.6	42.615	236	8273.5	43.0	42.987
197	6602.6	42.6	42.630	237	8316.5	43.0	42.991
198	6645.2	42.6	42.645	238	8359.5	43.0	42.995
199	6687.9	42.7	42.660	239	8402.5	43.0	42.999
200	6730.6	42.7	42.674	240	8445.5	43.0	43.002

Table 28. Reference data for the thermocouple combination copper versus Au-2.1 at % Co - thermoelectric voltage, EMF(T), thermoelectric voltage difference, DELEMF(T), and thermoelectric sensitivity, DE/DT(T) (continued).

TEMP DEG K	EMF MIC V	DELEMF MIC V	DE/DT MIC V/DGK	TEMP DEG K	EMF MIC V	DELEMF MIC V	DE/DT MIC V/DGK
241	8488.5	43.0	43.005	281	10209.3	43.0	42.995
242	8531.5	43.0	43.008	282	10252.3	43.0	42.992
243	8574.5	43.0	43.011	283	10295.3	43.0	42.989
244	8617.5	43.0	43.014	284	10338.3	43.0	42.986
245	8660.5	43.0	43.016	285	10381.3	43.0	42.982
246	8703.6	43.1	43.018	286	10424.3	43.0	42.978
247	8746.6	43.0	43.020	287	10467.2	42.9	42.974
248	8789.6	43.0	43.022	288	10510.2	43.0	42.970
249	8832.6	43.0	43.024	289	10553.2	43.0	42.966
250	8875.6	43.0	43.026	290	10596.1	42.9	42.962
251	8918.7	43.1	43.027	291	10639.1	43.0	42.958
252	8961.7	43.0	43.028	292	10682.1	43.0	42.953
253	9004.7	43.0	43.029	293	10725.1	43.0	42.949
254	9047.8	43.1	43.030	294	10768.0	42.9	42.945
255	9090.8	43.0	43.031	295	10810.9	42.9	42.940
256	9133.8	43.0	43.031	296	10853.8	42.9	42.935
257	9176.9	43.1	43.031	297	10896.8	43.0	42.930
258	9219.9	43.0	43.031	298	10939.7	42.9	42.925
259	9262.9	43.0	43.031	299	10982.6	42.9	42.920
260	9305.9	43.0	43.031	300	11025.5	42.9	42.915
261	9349.0	43.1	43.031				
262	9392.0	43.0	43.031				
263	9435.0	43.0	43.030				
264	9478.1	43.1	43.029				
265	9521.1	43.0	43.028				
266	9564.1	43.0	43.027				
267	9607.2	43.1	43.026				
268	9650.2	43.0	43.025				
269	9693.2	43.0	43.024				
270	9736.2	43.0	43.022				
271	9779.2	43.0	43.020				
272	9822.3	43.1	43.018				
273	9865.3	43.0	43.016				
274	9908.3	43.0	43.014				
275	9951.3	43.0	43.012				
276	9994.3	43.0	43.010				
277	10037.3	43.0	43.007				
278	10080.3	43.0	43.004				
279	10123.3	43.0	43.001				
280	10166.3	43.0	42.998				

Table 29. Reference data for the thermocouple combination normal silver versus Au-2.1 at % Co - thermoelectric voltage, EMF(T), thermoelectric voltage difference, DELEMF(T), and thermoelectric sensitivity, DE/DT(T).

TEMP DEG K	EMF MIC V	DELEMF MIC V	DE/DT MIC V/DGK	TEMP DEG K	EMF MIC V	DELEMF MIC V	DE/DT MIC V/DGK
1	0.5	0.5	1.050	41	632.9	25.7	25.900
2	2.1	1.6	2.070	42	658.9	26.0	26.230
3	4.7	2.6	3.070	43	685.3	26.4	26.560
4	8.2	3.5	4.040	44	712.0	26.7	26.880
5	12.7	4.5	4.990	45	739.0	27.0	27.200
6	18.2	5.5	5.920	46	766.3	27.3	27.510
7	24.6	6.4	6.820	47	793.9	27.6	27.820
8	31.8	7.2	7.700	48	821.8	27.9	28.120
9	39.9	8.1	8.550	49	850.1	28.3	28.410
10	48.9	9.0	9.380	50	878.7	28.6	28.700
11	58.7	9.8	10.180	51	907.6	28.9	28.980
12	69.3	10.6	10.960	52	936.7	29.1	29.250
13	80.6	11.3	11.710	53	966.1	29.4	29.520
14	92.7	12.1	12.440	54	995.8	29.7	29.790
15	105.5	12.8	13.140	55	1025.7	29.9	30.050
16	119.0	13.5	13.820	56	1055.8	30.1	30.300
17	133.1	14.1	14.480	57	1086.2	30.4	30.550
18	147.9	14.8	15.120	58	1116.9	30.7	30.790
19	163.3	15.4	15.750	59	1147.8	30.9	31.020
20	179.4	16.1	16.370	60	1178.9	31.1	31.250
21	196.1	16.7	16.970	61	1210.3	31.4	31.470
22	213.4	17.3	17.550	62	1241.9	31.6	31.690
23	231.2	17.8	18.110	63	1273.7	31.8	31.900
24	249.6	18.4	18.660	64	1305.7	32.0	32.110
25	268.5	18.9	19.190	65	1337.9	32.2	32.310
26	287.9	19.4	19.700	66	1370.3	32.4	32.500
27	307.9	20.0	20.190	67	1402.9	32.6	32.690
28	328.4	20.5	20.670	68	1435.7	32.8	32.870
29	349.4	21.0	21.140	69	1468.7	33.0	33.050
30	370.8	21.4	21.600	70	1501.8	33.1	33.220
31	392.6	21.8	22.050	71	1535.1	33.3	33.390
32	414.8	22.2	22.480	72	1568.6	33.5	33.550
33	437.4	22.6	22.900	73	1602.2	33.6	33.710
34	460.4	23.0	23.310	74	1636.0	33.8	33.870
35	483.8	23.4	23.710	75	1669.9	33.9	34.030
36	507.7	23.9	24.100	76	1704.0	34.1	34.180
37	532.0	24.3	24.480	77	1738.2	34.2	34.330
38	556.7	24.7	24.850	78	1772.6	34.4	34.480
39	581.8	25.1	25.210	79	1807.2	34.6	34.630
40	607.2	25.4	25.560	80	1841.9	34.7	34.780

Table 29. Reference data for the thermocouple combination normal silver versus Au-2.1 at % Co - thermoelectric voltage, EMF(T), thermoelectric voltage difference, DELEMF(T), and thermoelectric sensitivity, DE/DT(T) (continued).

TEMP DEG K	EMF MIC V	DELEMF MIC V	DE/DT MIC V/DGK	TEMP DEG K	EMF MIC V	DELEMF MIC V	DE/DT MIC V/DGK
81	1876.7	34.8	34.930	121	3370.8	39.2	39.200
82	1911.7	35.0	35.080	122	3410.0	39.2	39.270
83	1946.9	35.2	35.230	123	3449.3	39.3	39.340
84	1982.2	35.3	35.380	124	3488.7	39.4	39.410
85	2017.6	35.4	35.530	125	3528.2	39.5	39.480
86	2053.2	35.6	35.680	126	3567.7	39.5	39.550
87	2089.0	35.8	35.820	127	3607.3	39.6	39.620
88	2124.9	35.9	35.960	128	3646.9	39.6	39.690
89	2160.9	36.0	36.100	129	3686.6	39.7	39.760
90	2197.0	36.1	36.240	130	3726.4	39.8	39.830
91	2233.3	36.3	36.380	131	3766.2	39.8	39.890
92	2269.7	36.4	36.520	132	3806.1	39.9	39.940
93	2306.3	36.6	36.660	133	3846.0	39.9	39.990
94	2343.0	36.7	36.800	134	3886.0	40.0	40.040
95	2379.8	36.8	36.930	135	3926.0	40.0	40.090
96	2416.7	36.9	37.050	136	3966.1	40.1	40.140
97	2453.7	37.0	37.160	137	4006.3	40.2	40.190
98	2490.8	37.1	37.260	138	4046.5	40.2	40.240
99	2528.1	37.3	37.350	139	4086.8	40.3	40.290
100	2565.5	37.4	37.440	140	4127.1	40.3	40.340
101	2603.0	37.5	37.530	141	4167.5	40.4	40.390
102	2640.6	37.6	37.620	142	4207.9	40.4	40.440
103	2678.2	37.6	37.710	143	4248.4	40.5	40.490
104	2715.9	37.7	37.800	144	4288.9	40.5	40.540
105	2753.7	37.8	37.890	145	4329.5	40.6	40.580
106	2791.6	37.9	37.980	146	4370.1	40.6	40.620
107	2829.6	38.0	38.070	147	4410.7	40.6	40.660
108	2867.7	38.1	38.160	148	4451.4	40.7	40.700
109	2905.9	38.2	38.250	149	4492.1	40.7	40.740
110	2944.2	38.3	38.340	150	4532.9	40.8	40.780
111	2982.6	38.4	38.430	151	4573.7	40.8	40.820
112	3021.1	38.5	38.510	152	4614.5	40.8	40.860
113	3059.6	38.5	38.590	153	4655.4	40.9	40.900
114	3098.2	38.6	38.670	154	4696.3	40.9	40.940
115	3136.9	38.7	38.750	155	4737.3	41.0	40.980
116	3175.7	38.8	38.830	156	4778.3	41.0	41.020
117	3214.6	38.9	38.910	157	4819.3	41.0	41.060
118	3253.5	38.9	38.990	158	4860.4	41.1	41.090
119	3292.5	39.0	39.060	159	4901.5	41.1	41.120
120	3331.6	39.1	39.130	160	4942.6	41.1	41.150

Table 29. Reference data for the thermocouple combination normal silver versus Au-2.1 at % Co - thermoelectric voltage, EMF(T), thermoelectric voltage difference, DELEMF(T), and thermoelectric sensitivity, DE/DT(T) (continued).

TEMP DEG K	EMF MIC V	DELEMF MIC V	DE/DT MIC V/DGK	TEMP DEG K	EMF MIC V	DELEMF MIC V	DE/DT MIC V/DGK
161	4983.8	41.2	41.180	201	6650.8	42.1	42.060
162	5025.0	41.2	41.210	202	6692.9	42.1	42.070
163	5066.2	41.2	41.240	203	6735.0	42.1	42.080
164	5107.5	41.3	41.270	204	6777.1	42.1	42.090
165	5148.8	41.3	41.300	205	6819.2	42.1	42.100
166	5190.1	41.3	41.330	206	6861.3	42.1	42.110
167	5231.5	41.4	41.360	207	6903.4	42.1	42.120
168	5272.9	41.4	41.390	208	6945.5	42.1	42.130
169	5314.3	41.4	41.420	209	6987.6	42.1	42.140
170	5355.7	41.4	41.450	210	7029.7	42.1	42.150
171	5397.1	41.4	41.480	211	7071.9	42.2	42.160
172	5438.6	41.5	41.510	212	7114.1	42.2	42.170
173	5480.1	41.5	41.540	213	7156.3	42.2	42.180
174	5521.6	41.5	41.560	214	7198.5	42.2	42.190
175	5563.1	41.5	41.580	215	7240.7	42.2	42.200
176	5604.7	41.6	41.600	216	7282.9	42.2	42.210
177	5646.3	41.6	41.620	217	7325.1	42.2	42.220
178	5687.9	41.6	41.640	218	7367.3	42.2	42.230
179	5729.5	41.6	41.660	219	7409.5	42.2	42.240
180	5771.2	41.7	41.680	220	7451.7	42.2	42.250
181	5812.9	41.7	41.700	221	7493.9	42.2	42.260
182	5854.6	41.7	41.720	222	7536.2	42.3	42.270
183	5896.3	41.7	41.740	223	7578.5	42.3	42.280
184	5938.0	41.7	41.760	224	7620.8	42.3	42.290
185	5979.8	41.8	41.780	225	7663.1	42.3	42.300
186	6021.6	41.8	41.800	226	7705.4	42.3	42.310
187	6063.4	41.8	41.820	227	7747.7	42.3	42.310
188	6105.2	41.8	41.840	228	7790.0	42.3	42.310
189	6147.1	41.9	41.860	229	7832.3	42.3	42.310
190	6189.0	41.9	41.880	230	7874.6	42.3	42.310
191	6230.9	41.9	41.900	231	7916.9	42.3	42.310
192	6272.8	41.9	41.920	232	7959.2	42.3	42.310
193	6314.7	41.9	41.940	233	8001.5	42.3	42.310
194	6356.7	42.0	41.960	234	8043.8	42.3	42.310
195	6398.7	42.0	41.980	235	8086.1	42.3	42.310
196	6440.7	42.0	42.000	236	8128.4	42.3	42.310
197	6482.7	42.0	42.020	237	8170.7	42.3	42.310
198	6524.7	42.0	42.030	238	8213.0	42.3	42.310
199	6566.7	42.0	42.040	239	8255.3	42.3	42.310
200	6608.7	42.0	42.050	240	8297.6	42.3	42.310

Table 29. Reference data for the thermocouple combination normal silver versus Au-2.1 at % Co - thermoelectric voltage, EMF(T), thermoelectric voltage difference, DELEMF(T), and thermoelectric sensitivity, DE/DT(T) (continued).

TEMP DEG K	EMF MIC V	DELEMF MIC V	DE/DT MIC V/DGK	TEMP DEG K	EMF MIC V	DELEMF MIC V	DE/DT MIC V/DGK
241	8339.9	42.3	42.310	281	10031.7	42.3	42.310
242	8382.2	42.3	42.310	282	10074.0	42.3	42.310
243	8424.5	42.3	42.310	283	10116.3	42.3	42.310
244	8466.8	42.3	42.310	284	10158.5	42.2	42.300
245	8509.1	42.3	42.310	285	10200.7	42.2	42.290
246	8551.4	42.3	42.310	286	10242.9	42.2	42.280
247	8593.7	42.3	42.310	287	10285.1	42.2	42.270
248	8636.0	42.3	42.310	288	10327.3	42.2	42.260
249	8678.3	42.3	42.310	289	10369.5	42.2	42.250
250	8720.6	42.3	42.310	290	10411.7	42.2	42.240
251	8762.9	42.3	42.310	291	10453.9	42.2	42.230
252	8805.2	42.3	42.310	292	10496.1	42.2	42.220
253	8847.5	42.3	42.310	293	10538.3	42.2	42.210
254	8889.8	42.3	42.310	294	10580.5	42.2	42.200
255	8932.1	42.3	42.310	295	10622.7	42.2	42.190
256	8974.4	42.3	42.310	296	10664.8	42.1	42.180
257	9016.7	42.3	42.310	297	10706.9	42.1	42.170
258	9059.0	42.3	42.310	298	10749.0	42.1	42.160
259	9101.3	42.3	42.310	299	10791.1	42.1	42.150
260	9143.6	42.3	42.310	300	10833.2	42.1	42.140
261	9185.9	42.3	42.310				
262	9228.2	42.3	42.310				
263	9270.5	42.3	42.310				
264	9312.8	42.3	42.310				
265	9355.1	42.3	42.310				
266	9397.4	42.3	42.310				
267	9439.7	42.3	42.310				
268	9482.0	42.3	42.310				
269	9524.3	42.3	42.310				
270	9566.6	42.3	42.310				
271	9608.9	42.3	42.310				
272	9651.2	42.3	42.310				
273	9693.5	42.3	42.310				
274	9735.7	42.2	42.310				
275	9777.9	42.2	42.310				
276	9820.2	42.3	42.310				
277	9862.5	42.3	42.310				
278	9904.8	42.3	42.310				
279	9947.1	42.3	42.310				
280	9989.4	42.3	42.310				

Table 30. Average equilibrium values for thermocouple inhomogeneity voltages.

MATERIAL	SHORT-RANGE		MEDIUM-RANGE		DIFFERENT SPOOLS	
	Liq N_2	Liq He	Liq N_2	Liq He	Liq N_2	Liq He
EP or KP	1.4μV	1.6μV	2.6μV	2.6μV	23.5μV	26.2μV
JP (iron)	4.8	5.2	10.8	10.8	35.0	36.2
TP (copper)	0.3	0.9	1.2	4.2	2.3	19.2
KN	1.5	1.7	2.9	3.2	16.1	17.6
EN or TN (constantan)	2.1	2.3	5.1	5.6	22.9	26.2

Table 31. The temperature (K) and sensitivity (mm/K) are given at the triple point, the normal boiling point, and the critical point of helium-4, equilibrium hydrogen, neon, nitrogen, and oxygen.

Substance	Triple Point		Boiling Point		Critical Point	
	Temp (K)	dP/dT(mm/K)	Temp (K)	dP/dT(mm/K)	Temp(K)	dP/dT(mm/K)
He^4	2.177 (lambda)	79.6	4.224	698.2	5.201	861
H_2 (99.79% para)	13.803	34.5	20.268	243.1	32.976	1001
Ne	24.54	120.2	27.09	229.6	44.4	2505
N_2	63.148	20.1	77.347	86.4	126.2	1058
O_2	54.351	0.4	90.18	77.6	154.576	1370

Table 32. Vapor pressure (atm) versus temperature (K) for helium-4.

Temperature (K)	Pressure (atm)	Temperature (K)	Pressure (atm)
2.177	0.04969	3.70	0.5849
2.20	0.05256	3.75	0.6182
2.25	0.05916	3.80	0.6528
2.30	0.06629	3.85	0.6886
2.35	0.07399	3.90	0.7257
2.40	0.08228	3.95	0.7642
2.45	0.09120	4.00	0.8040
2.50	0.1008	4.05	0.8452
2.55	0.1110	4.10	0.8878
2.60	0.1219	4.15	0.9318
2.65	0.1336	4.20	0.9772
2.70	0.1460	4.224	1.000
2.75	0.1591	4.25	1.024
2.80	0.1730	4.30	1.073
2.85	0.1878	4.35	1.123
2.90	0.2033	4.40	1.174
2.95	0.2198	4.45	1.227
3.00	0.2371	4.50	1.282
3.05	0.2553	4.55	1.339
3.10	0.2744	4.60	1.397
3.15	0.2945	4.65	1.457
3.20	0.3156	4.70	1.519
3.25	0.3376	4.75	1.582
3.30	0.3607	4.80	1.648
3.35	0.3848	4.85	1.715
3.40	0.4100	4.90	1.784
3.45	0.4363	4.95	1.856
3.50	0.4637	5.00	1.929
3.55	0.4923	5.05	2.004
3.60	0.5220	5.10	2.082
3.65	0.5528	5.201	2.245

Table 33. Coefficients for the analytical representation of the vapor-pressure-temperature relationship for helium-4, equilibrium hydrogen, neon, nitrogen, and oxygen.

	Vapor Pressure Substances				
Coefficient	Oxygen	Nitrogen	Neon	Hydrogen 99.79% Para	Helium
A_1	-62.5967185	$0.8394409444 \times 10^{4}$	7.46116	1.772454	-3.9394635287
A_2	2.47450429	$-0.1890045259 \times 10^{4}$	-106.090	-4.436888×10	$1.4127497598 \times 10^{2}$
A_3	$-4.68973315 \times 10^{-2}$	$-0.7282229165 \times 10^{1}$	-3.56616×10^{-2}	2.055468×10^{-2}	$-1.6407741565 \times 10^{3}$
A_4	$5.48202337 \times 10^{-4}$	$0.1022850966 \times 10^{-1}$	4.11092×10^{-4}	2.000620	$1.1974557102 \times 10^{4}$
A_5	$-4.09349868 \times 10^{-6}$	$0.5556063825 \times 10^{-3}$		-5.009708×10	$-5.5283309818 \times 10^{4}$
A_6	$1.91471914 \times 10^{-8}$	$-0.5944544662 \times 10^{-5}$		1.0044	$1.6621956504 \times 10^{5}$
A_7	$-5.13113688 \times 10^{-11}$	$0.2715433932 \times 10^{-7}$		1.748495×10^{-2}	$-3.2521282840 \times 10^{5}$
A_8	$6.02656934 \times 10^{-14}$	$-0.4879535904 \times 10^{-10}$		1.317×10^{-3}	$3.9884322750 \times 10^{5}$
A_9		$0.5095360824 \times 10^{3}$		-5.926×10^{-5}	$-2.7771806992 \times 10^{5}$
A_{10}				3.913×10^{-6}	$8.3395204183 \times 10^{4}$

Table 34. Vapor pressure (atm) versus temperature (K) for equilibrium hydrogen.

Temperature (K)	Pressure (atm)
13.803	0.069_5
14	0.077_8
15	0.133
16	0.213
17	0.325
18	0.476
19	0.673
20	0.923
20.268	1.000
21	1.233
22	1.613
23	2.069
24	2.611
25	3.245
26	3.982
27	4.829
28	5.794
29	6.887
30	8.118
31	9.501
32	11.051
32.976	12.759

Table 35. Vapor pressure (atm) versus temperature (K) for neon.

Temperature (K)	Pressure (atm)
25	0.50366
26	0.70902
27	0.97255
28	1.3037
29	1.7124
30	2.2088
31	2.8031
32	3.5061
33	4.3286
34	5.2818
35	6.3773
36	7.6271
37	9.0439
38	10.641
39	12.432
40	14.434
41	16.661
42	19.133
43	21.867
44	24.887
44.4	26.19

Table 36. Vapor pressure (atm) versus temperature (K) for nitrogen.

Temperature (K)	Pressure (atm)	Temperature (K)	Pressure (atm)
63.148	0.1237	98	6.6748
64	0.1443	100	7.6885
66	0.2037	102	8.8083
68	0.2813	104	10.041
70	0.3807	106	11.392
72	0.5059	108	12.870
74	0.6610	110	14.481
76	0.8506	112	16.233
77.347	1.0000	114	18.133
78	1.0793	116	20.190
80	1.3520	118	22.411
82	1.6739	120	24.806
84	2.0503	122	27.386
86	2.4865	124	30.174
88	2.9882	126	33.227
90	3.5607	126.200	33.555
92	4.2099		
94	4.9415		

Table 37. Vapor pressure (atm) versus temperature (K) for oxygen.

Temperature (K)	Pressure (atm)	Temperature (K)	Pressure (atm)
54.351	0.001	112	6.139
56	0.002	114	6.995
58	0.004	116	7.934
60	0.007	118	8.961
62	0.012	120	10.082
64	0.018	122	11.300
66	0.028	124	12.621
68	0.042	126	14.049
70	0.061	128	15.591
72	0.087	130	17.249
74	0.122	132	19.031
76	0.167	134	20.942
78	0.224	136	22.986
80	0.297	138	25.170
82	0.387	140	27.501
84	0.497	142	29.986
86	0.631	144	32.631
88	0.791	146	35.448
90	0.981	148	38.446
90.180	1.000	150	41.638
92	1.205	152	45.041
94	1.466	154	48.675
96	1.768	154.576	49.767
98	2.114		
100	2.509		
102	2.957		
104	3.462		
106	4.029		
108	4.661		
110	5.363		

Appendix A. Standard designations for thermocouples

ANSI, ASTM, and ISA (American National Standards Institute, American Society for Testing and Materials, and Instrument Society of America, respectively) have adopted the following letter designations for thermocouples described in this review:

THERMOCOUPLE COMBINATIONS:

	The positive thermoelectric material is conventionally written first.
Type E	Nickel-chromium alloy versus copper-nickel alloy.
Type J	Iron versus copper-nickel alloy.
Type K	Nickel-chromium alloy versus nickel-aluminum alloy.
Type T	Copper versus copper-nickel alloy.

SINGLE-LEG WIRES:

N	The negative wire in a combination.
P	The positive wire in a combination.
EN or TN	A copper-nickel alloy, often referred to as Adams' constantan; Advance[1], Cupron[4] nominally 55 wt% Cu, 45% Ni.
EP or KP	A nickel-chromium alloy, often referred to as Chromel[2]; T-1[1], ThermoKanthal KP[3], Tophel[4], nominally 90% Ni, 10% Cr.
JN	A copper-nickel alloy similar to but not generally interchangeable with EN and TN; SAMA specification.
JP	Iron: ThermoKanthal JP[3]; nominally 99.5% Fe.
KN	A nickel-aluminum alloy, often referred to as Alumel[2]; T-2[1], ThermoKanthal KN[3], Nial[4]; nominally 95% Ni, 2% Al, 2 % Mn, 1% Si.
TP	Copper, usually Electrolytic Tough Pitch.

Registered Trademarks:

1 Trademark -- Driver-Harris Co. 3 Trademark -- Kanthal Corp.

2 Trademark -- Hoskins Manufacturing Co. 4 Trademark -- Wilbur B. Driver Co.

The use of trade names does not constitute an endorsement of any manufacturer's products. All materials manufactured in compliance with the established thermoelectric voltage standards are equally acceptable.

Appendix B. Variables, units, unit conversions and selected physical constants

Primary Variable	Variables having the same units as the primary variable	Variables having units reciprocal to those of the primary variable	To convert from	To	Multiply by
Pressure		Adiabatic compressibility Isothermal compressibility	atm bar mm Hg, or torr. Pa or N/m^2	psia psia psia psia	14.695949 14.503774 0.01933678 14.503774×10^{-5}
Volume	Virial Coefficients		cm^3/mol cm^3/g dm^3/kg	ft^3/lb ft^3/lb ft^3/lb	0.0005005957 0.016018462 0.016018462
Density			mol/cm^3 g/cm^3 kg/dm^3	lb/ft^3 lb/ft^3 lb/ft^3	1997.62 62.42797 62.42797
Temperature		Volume expansivity	K °C	°R °R	1.8 1.8 and add 491.67
Enthalpy	Internal energy Latent heat Free energy Heat of transition Specific heat input		J/mol kJ/kg	BTU/lb BTU/lb	0.0134446 0.430211
Entropy	Specific heat		J/mol-K kJ/kg-°C	BTU/lb-°R BTU/lb-°R	0.0074692 0.239006
Joule-Thomson Coefficient			K/atm	°R/psi	0.12248273
Surface Tension			dyn/cm	lb_f/in	5.710147×10^{-6}
Thermal Conductivity			mW/cm-K kW/m-°C	BTU/ft-hr-°R BTU/ft-hr-°R	0.0578176 578.176
Thermal Diffusivity			cm^2/s	ft^2/hr	3.87500775
Velocity of Sound			m/s	ft/s	3.280839895
Viscosity			g/cm-s, or poise $N\text{-}s/m^2$	lb/ft-s lb/ft-s	0.067196897 0.67196897

1 dyne = 10^{-5} N

Icepoint, T_0, 273.15 K = 0°C = 491.67°R

The Gas Constant, R, 8.31434 J/mol-K = 8.31434×10^6 $N\text{-}cm^3/m^2\text{-}mol\text{-}K$ = 82.0562 $atm\text{-}cm^3/mol\text{-}K$ = 10.7314 $psi\text{-}ft^3/mol\text{-}°R$,

SUBJECT INDEX

SUBJECT INDEX (continued)

SUBJECT INDEX (continued)

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