Conversion of Thermocouple Voltage to Temperature

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Abstract

This article provides a practical introduction to the conversion of thermocouple voltage to temperature. Beginning with a description of the Seebeck effect, the basic equations relating EMF and temperature are presented. A few of the more practical thermocouple circuits are analyzed, temperature measurement with a basic ice-point reference circuit is described, and computational formulas for data reduction are given. Use of a zone box with a floating reference junction temperature is also explained.

1 Overview

Thermocouples are inexpensive and versatile devices for measuring temperature. Thermocouples can be purchased in many different prefabricated configurations. For basic laboratory work, thermocouples can be easily fabricated from bulk thermocouple wire. The proper fabrication and installation of thermocouples is not discussed here. This document provides the necessary background and computational procedures for conversion of voltage measurements from thermocouples fabricated in the lab, or purchased from a vendor.

Thermocouple measurement devices range from hand-held units to multichannel data acquisition systems. Since thermocouples can only indicate temperature differences, a reference junction is required to make an absolute temperature measurement. Turnkey thermocouple systems include a method for temperature compensation for the reference junction. The correct data conversion procedure for a reference junction at an arbitrary temperature is not difficult. Unfortunately the steps in this process do not appear to be widely known.

The goal of this document is to equip the reader with the knowledge and calculation procedures for converting raw thermocouple voltage readings to temperature. Readers wishing to use turnkey systems will benefit from understanding the process of data conversion. In particular, the reader will see that one reason

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for uncertainties associated with thermocouple temperature measurement is the lack of control over the reference junction temperature in turnkey systems. It is easy to construct a zone box that maintains the reference junction(s) at a uniform temperature, and thereby achieve more accurate temperature measurement than is possible with most turnkey systems.

2 Physics of Thermocouples

The equations necessary for the practical use of thermocouples are derived from the basic definition of the Seebeck Effect. This information is extracted from Chapter 2 of *A Manual on the Use of Thermocouples in Temperature Measurement* by the American Society for Testing and Materials [1]. Anyone using thermocouples would benefit from studying the ASTM manual.

2.1 The Seebeck Effect

Electrically conductive materials exhibit three types of thermoelectric phenomena: the Seebeck effect, the Thompson effect, and the Peltier effect. The Seebeck effect is manifest as a voltage potential that occurs when there is a temperature gradient along the length of a conductor. This temperature-induced electrical potential is called an *electromotive force* and abbreviated as EMF.

The macroscopic manifestation of EMF is due to the rearrangement of the free electrons in the conductor. When the temperature and all other environmental variables that might affect the wire are uniform, the most probable distribution of the free electrons is uniform. The presence of a temperature gradient causes a redistribution of the free electrons, which results in a nonuniform distribution of the electric charge on the conductor. Above submicron length scales, the charge distribution does not depend on the geometry, e.g. cross-section shape or length, of the conductor. As a practical consequence of the charge distribution, the conductor exhibits a variation of voltage potential (the EMF) that is directly related to the temperature gradient imposed on the conductor. Because the EMF is uniquely related to the temperature *gradient*, the Seebeck effect can be used to measure temperature.

Figure 1 represents a conceptual experiment that exhibits the Seebeck effect. The two ends of a conducting wire are held at two different temperatures T_1 and T_2. For clarity, assume that $T_2 > T_1$, although with appropriate changes of sign, the development that follows is also applicable to the case where $T_2 < T_1$. If the probes of an ideal voltmeter could be connected to the two ends of the wire without disturbing the temperature or voltage potential of the wire, the voltmeter would indicate a voltage difference on the order of 10^{-5} volts per degree Celsius of temperature difference. The relationship between the EMF and the temperature difference can be represented as

$$E_{12} = \bar{\sigma}(T_2 - T_1) \tag{1}$$

where $\bar{\sigma}$ is the average *Seebeck coefficient* for the wire material over the temperature range $T_1 \leq T \leq T_2$.

The voltmeter in Figure 1 is imaginary because the copper leads of the voltmeter probe also exhibit the Seebeck effect. If the leads of the voltmeter

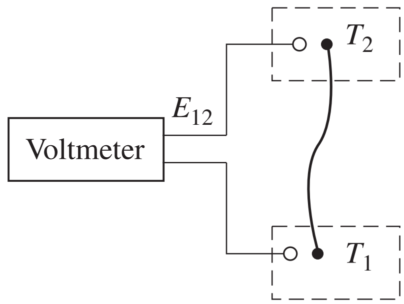


Figure 1: A conceptual experiment to exhibit the Seebeck effect in a wire with end temperatures T_1 and T_2. The dashed boxes represent local environments at uniform temperatures. The open circles are the ends of the measuring probes of the ideal voltmeter that can detect the voltage potential E_{12} without actually touching the ends of the wire. The solid circles are the ends of the wire.

were connected to the wire, the voltage indicated by the voltmeter would be the combined potential due to the Seebeck effect in the wire sample and the Seebeck effect in the probe leads. Thus, the circuit in Figure 1 is not practical for measuring temperature.

The Seebeck coefficient is a property of the wire material. The value of $\bar{\sigma}$ does not depend on the length, diameter, or any other geometrical feature of the conductor wire. On the other hand, the Seebeck coefficient of a given material *can* be effected by oxidation or reduction of the conductor material, or by plastic strain of the conductor.

In general, the Seebeck coefficient is a function of temperature. To develop a more precise and versatile relationship than Equation (1), consider an experiment where T_1 is fixed, and T_2 is varied. For practical thermocouple materials the relationship between E and T is continuous. Hence, for sufficiently small change ΔT_2 in T_2, the EMF indicated by the voltmeter will change by a corresponding small amount ΔE_{12}. Since ΔT_2 and ΔE_{12} are small, it is reasonable to linearize the EMF response as

$$E_{12} + \Delta E_{12} = \bar{\sigma}(T_2 - T_1) + \sigma(T_2)\Delta T_2 \tag{2}$$

where $\sigma(T_2)$ is the value of the Seebeck coefficient at T_2. The change in EMF only depends on the value of the Seebeck coefficient at T_2 because T_1 is held fixed. Subtract Equation (1) from Equation (2) to get

$$\Delta E_{12} = \sigma(T_2)\Delta T_2 \tag{3}$$

which can be rearranged as

$$\sigma(T_2) = \frac{\Delta E_{12}}{\Delta T_2} \tag{4}$$

If σ is an intrinsic property of the material, then the preceding equation must hold for any temperature. Replacing all references to T_2 with an arbitrary temperature T, and taking the limit as the temperature perturbation goes to zero, gives

$$\sigma(T) = \lim_{\Delta T \to 0} \frac{\Delta E}{\Delta T} \tag{5}$$

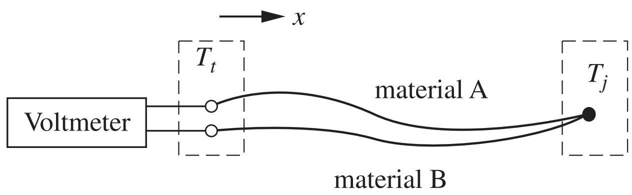


Figure 2: A simple thermocouple.

Using the Fundamental Theorem of Calculus, the limit becomes a derivative. The result is the general *definition of the Seebeck Coefficient*

$$\sigma(T) = \frac{dE}{dT} \tag{6}$$

Equation (6) contains all the theoretical information necessary to analyze thermocouple circuits.

2.2 EMF Relationships for Thermocouples

The wire depicted in Figure 1 is not directly useful for measuring temperature. For the situation in Figure 1, the voltmeter probes also experience a temperature gradient. The probes are made of Copper wire, and Copper has a Seebeck coefficient comparable with other metals used to make thermocouples. Thus, unless both ends of each probe wire are at the same temperature, the probes themselves will contribute an additional EMF to the circuit. In other words, although one might imagine the measurement of the EMF for a single wire, it is not feasible to do so in practice.

Practical exploitation of the Seebeck effect to measure temperature requires a combination of two wires with dissimilar Seebeck coefficients. The name thermo*couple* reflects the reality that wires with two different compositions are combined to form a thermocouple circuit. Figure 2 represents such a basic thermocouple. The two wires of the thermocouple are joined at one end called the *junction*, which is represented by the solid dot on the right side of Figure 2. The junction is in thermal equilibrium with a local environment at temperature T_j. The other ends of the thermocouple wires are attached to the terminals of a voltmeter. The voltmeter terminals are both in thermal equilibrium with a local environment at temperature T_t.

Equation (6) is applied to the thermocouple circuit in Figure 2 by writing

$$dE = \sigma(T)\, dT \tag{7}$$

Thus, the EMF generated in material A between the junction at T_t and the junction at T_j is

$$E_{A,tj} = \int_{T_t}^{T_j} \sigma_A(T) dT \tag{8}$$

Applying Equation (8) to consecutive segments of the circuit gives

$$E_{AB} = \int_{T_t}^{T_j} \sigma_A\, dT + \int_{T_j}^{T_t} \sigma_B\, dT \tag{9}$$

where σ_A is the absolute Seebeck coefficient of material A, and σ_B is the absolute Seebeck coefficient of material B. The order of integration is specified by moving continuously around the loop: from the terminal to the junction, and back to the terminal.

The position of the junction around the thermocouple circuit is identified by the x coordinate in Figure 2. For the purpose of analyzing thermocouple circuits, the physical length of wire is immaterial. Accordingly, x should be thought of an indicator of position only, not a measure of distance.

Notice that the value of E_{AB} in Equation (9) is due to integrals along the length of the thermocouple elements. This leads to the following essential and often misunderstood fact of thermocouple thermometry:

> **The EMF generated by the Seebeck effect is due to the temperature gradient along the wire. The EMF is not generated at the junction between two dissimilar wires.**

The thermocouple junction performs two essential roles.

- The junction provides electrical continuity between the two legs of the thermocouple.
- The junction provides a heat conduction path that helps to maintain the ends of the two dissimilar wires at the same temperature (T_j).

The EMF of the thermocouple exists because there is a temperature difference between the junction at T_j and the open circuit measuring terminals at T_t.

Switching the order of the limits for the second integral in Equation (9) allows the following manipulation

$$E_{AB} = \int_{T_t}^{T_j} \sigma_A \, dT - \int_{T_t}^{T_j} \sigma_B \, dT = \int_{T_t}^{T_j} (\sigma_A - \sigma_B) \, dT \tag{10}$$

Now *define* the Seebeck coefficient for the material pair AB as

$$\sigma_{AB} = \sigma_A - \sigma_B \tag{11}$$

If the two materials have the same absolute Seebeck coefficients, i.e. if $\sigma_A = \sigma_B$, then the thermocouple generates no EMF, regardless of the temperature difference $T_j - T_t$. There are standard combinations of materials that provide large values of σ_{AB} that are slowly varying with T.

Substituting the definition of σ_{AB} into Equation (10) gives

$$E_{AB} = \int_{T_t}^{T_j} \sigma_{AB} \, dT \tag{12}$$

Equation (12) is the fundamental equation for the analysis of thermocouple circuits. It is not yet in the form of a computational formula for data reduction. Indeed, conversion of thermocouple EMF to temperature does *not* require the evaluation of integrals. Before a data reduction formula can be developed, however, the role of the reference junction needs to be clarified.

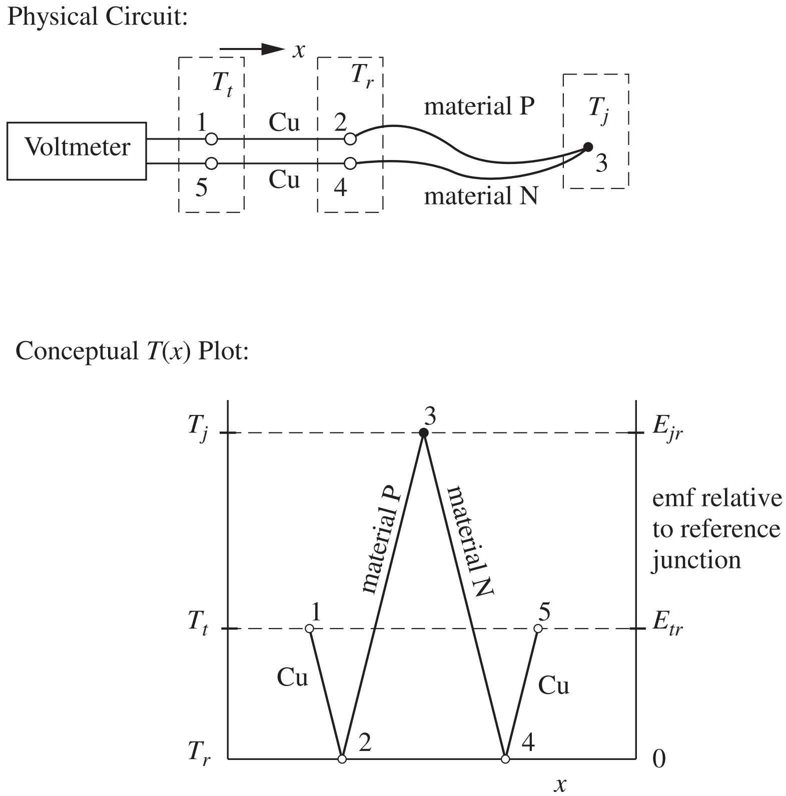


Figure 3: A thermocouple with a reference junction. The upper portion of the diagram represents the physical arrangement of the wires in the circuit. The lower portion of the diagram is a conceptual representation of the relationship between temperature and EMF along the wires.

2.3 Reference Junction

Equation (12) shows how the EMF generated by a thermocouple depends on the temperature difference between the T_j and T_t. All thermocouple circuits measure one temperature relative to another. The only way to obtain the absolute[1] temperature of a junction is to arrange the thermocouple circuit so that it measures T_j relative to an independently known temperature. The known temperature is referred to as the reference temperature T_r. A second thermocouple junction, called the *reference junction*, is located in an environment at T_r.

Figure 3 shows a thermocouple circuit with a reference junction at temperature T_r. The case of $T_r < T_t$ is depicted, but the analysis of the circuit EMF also works with $T_r \geq T_t$. At the reference junction, copper extension wires connect the voltmeter to the legs of the thermocouple. The thermocouple wires are labelled P for positive and N for negative. Beginning with the terminal block at temperature T_t, there are five junctions around the circuit. Using x as a position

[1]Here "absolute" means not being relative to another temperature in the circuit, not necessarily a thermodynamic absolute temperature.

indicator, the five labelled junctions are numbered in order of increasing x.

The lower half of Figure 3 is a schematic representation of the thermocouple circuit. The horizontal axis is the position x. The left vertical axis is the temperature. The right vertical axis is the EMF relative to the reference junction. The scale of the EMF axis applies only to the P and N legs of the thermocouple, not the copper extension wires.

To find the EMF produced by the thermocouple circuit in Figure 3, apply Equation (8) to each segment of wire in the circuit

$$E_{15} = \int_{T_t}^{T_r} \sigma_C dT + \int_{T_r}^{T_j} \sigma_P dT + \int_{T_j}^{T_r} \sigma_N dT + \int_{T_r}^{T_t} \sigma_C dT \tag{13}$$

where σ_C is the absolute Seebeck coefficient of copper, σ_P is the absolute Seebeck coefficient of the material in the positive leg, and σ_N is the absolute Seebeck coefficient of the material in the negative leg. Reversing the limits of integration for the first term in Equation (13) gives

$$\int_{T_t}^{T_r} \sigma_C dT = -\int_{T_r}^{T_t} \sigma_C dT \tag{14}$$

Therefore, the first and last terms in Equation (13) cancel. Furthermore, reversing the limits of integration in the third term in Equation (13) and simplifying yields

$$E_{15} = \int_{T_r}^{T_j} \sigma_{PN} dT \tag{15}$$

where $\sigma_{PN} = \sigma_P - \sigma_N$.

The result in Equation (15) can be interpreted graphically with the lower half of Figure 3. The EMF across the copper segments 1-2 and 4-5 cancel because the EMF on these segments is of equal magnitude and opposite sign. Think of going down in potential from 1 to 2, and up in potential from 4 to 5. The EMF across segments 2-3 and 3-4 does not cancel, however, because the absolute Seebeck coefficients for these two segments are not equal. Indeed, a thermocouple is only possible when two dissimilar wires are joined so that $\sigma_{PN} = \sigma_P - \sigma_N \neq 0$.

The circuit in Figure 3 provides a practical means for measuring temperature T_j relative to temperature T_r. To use this circuit an independent method of measuring T_r is required, along with the value of σ_{PN}.

2.4 Standard Calibration Curves

The ASTM identifies eight standard types of thermocouples. The nominal compositions of the positive (P) and negative (N) elements for these standard thermocouples are listed in Table 1 in Appendix A. For each of the standard thermocouple types, references [1] and [2] provide calibration tables and polynomial curve fit coefficients for those tables. The calibration tables and equations use Equation (15) with a reference temperature of 0 °C, which is easily obtainable with a mixture of ice and water.

The integral in Equation (15) is a formal statement of the relationship between EMF on temperature. To develop a calibration for a particular thermocouple type, the EMF is measured as T_j is varied and T_r is held fixed at 0 °C.

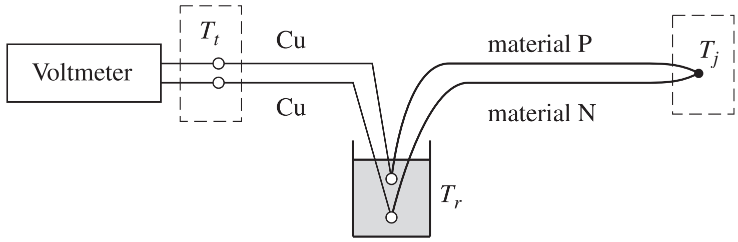


Figure 4: A thermocouple with an ice-point reference junction for both the P and N leads. The two reference junctions are placed in the same ice bath and are electrically isolated from each other.

The result of the calibration is a table of EMF versus T values. *The integral is never directly evaluated.* Instead a polynomial curve fit to the calibration data gives

$$E_{0j} = F(T_j) = b_0 + b_1 T_j + b_2 T_j^2 + \ldots + b_n T_j^n \tag{16}$$

In terms of the formalism of the preceding sections, $E_{0j} = \int_0^{T_j} \sigma_{PN} dT$. From the same calibration data a curve fit of the form

$$T_j = G(E_{0j}) = c_0 + c_1 E_{0j} + c_2 E_{0j}^2 + \ldots + c_m E_{0j}^m \tag{17}$$

is also obtained. The $F(T_j)$ and $G(E_{0j})$ symbols provide convenient shorthand notation for the two calibration polynomials. Equation (17) is directly useful for temperature measurements with thermocouples. For the circuit in Figure 3, with $T_r = 0$, Equation (17) allows a measured EMF to be converted to a temperature.

The coefficients of the calibration equations for type J thermocouples are given in Table 2 through Table 5 in Appendix A. Similar calibration data for other standard thermocouples are provided in [1, 2].

3 Practical Thermocouple Circuits

The equations in the preceding sections are now applied to develop thermocouple circuits that can be used in a laboratory. The following topics are covered.

- Compensation with a reference junction in an ice bath;
- Compensation with a reference junction at an arbitrary temperature;
- Use of zone boxes for large numbers of thermocouples.

3.1 Ice-Bath Reference Junctions

Figure 3 depicts a useful thermocouple circuit. The most straightforward implementation of this circuit is to place the reference junctions (block labelled T_r) in an ice bath. The resulting circuit is sketched in Figure 4. The two junctions can share the same ice bath if they are electrically insulated from each other[2].

[2]Refer to [1] for the recommended construction of an ice bath.

For the thermocouple circuit in Figure 4, the standard calibration equations are used directly.

An alternative circuit with an ice bath reference is shown in Figure 5. The isothermal zone labelled T_b is a connector block where the lead wires are connected to the P and N legs of the thermocouple. A single junction is located in the ice bath. The connector block has two junctions between the copper extension wires and two separate P elements, one for each leg of the thermocouple.

Applying Equation (8) to each segment of wire in the circuit gives

$$E_{16} = \int_{T_t}^{T_b} \sigma_C dT + \int_{T_b}^{T_j} \sigma_P dT + + \int_{T_j}^{T_r} \sigma_N dT + \int_{T_r}^{T_b} \sigma_P dT + \int_{T_b}^{T_t} \sigma_C dT$$

The first and last integrals cancel, (Cf. Equation (14).) Rearranging the remaining terms gives

$$\begin{aligned} E_{16} &= \int_{T_r}^{T_b} \sigma_P dT + \int_{T_b}^{T_j} \sigma_P dT + \int_{T_j}^{T_r} \sigma_N dT \\ &= \int_{T_r}^{T_j} \sigma_P dT - \int_{T_r}^{T_j} \sigma_N dT \\ &= \int_{T_r}^{T_j} \sigma_{PN} dT \end{aligned}$$

Since $T_r = 0$ (the standard reference temperature), Equations (16) and (17) may be used directly for the thermocouple circuit in Figure 5.

Example 1: Conversion of Thermocouple EMF to Temperature

A type J thermocouple is used to create the circuit in Figure 5. If the measured output is 4.10 mV, what is the temperature of the thermocouple junction?

The temperature is obtained by evaluating Equation (17) with the c_i coefficients from Table 3.

$$\begin{aligned} T = G(E_{0j}) &= 1.978425 \times 10^1 (4.1) - 2.001204 \times 10^{-1} (4.1)^2 \\ &\quad + 1.036969 \times 10^{-2} (4.1)^3 - 2.549687 \times 10^{-4} (4.1)^4 \\ &\quad + 3.585153 \times 10^{-6} (4.1)^5 - 5.344285 \times 10^{-8} (4.1)^6 \\ &\quad + 5.099890 \times 10^{-10} (4.1)^7 \\ &= 78.4^\circ\mathrm{C} \end{aligned}$$

□

3.2 Reference Junction at Arbitrary Temperature

Although the standard calibration equations are for a reference junction at 0 °C, thermocouple circuits with reference junctions at arbitrary temperatures provide considerable convenience and flexibility. The reference junction still needs to be measured independently, for example, with a thermistor. In this type of thermocouple circuit, the reference junction is usually placed in a protected

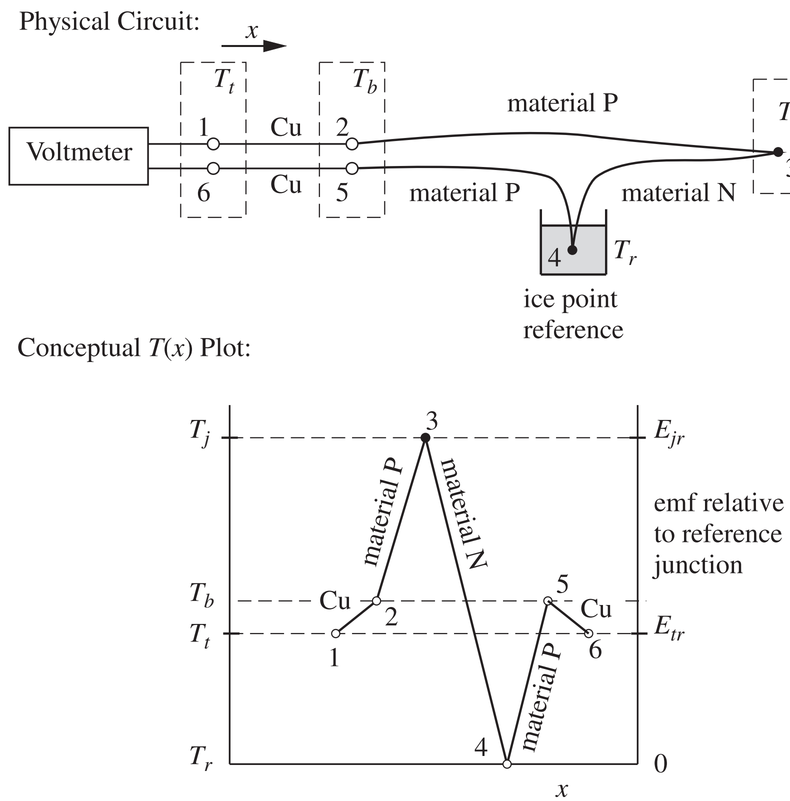


Figure 5: A thermocouple with an ice-point reference junction for just the N lead.

environment so that its temperature varies only slowly. The temperature of the measurement junction is then obtained by accounting for the difference between the actual reference junction temperature and the reference junction temperature for which the thermocouple was calibrated.

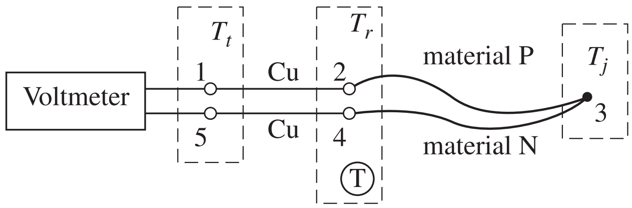
Reconsider the thermocouple circuit in Figure 3. Suppose that there is some independent method for determining T_r and that $T_r \neq 0$. This situation is depicted in Figure 6. The Ⓣ symbol indicates a temperature sensor that is used to measure T_r. Equation (15) still applies, but since $T_r \neq 0$, the standard thermocouple calibration data cannot be applied directly.

Let E_{rj} be the EMF due to the temperature difference between T_r and T_j.

$$E_{rj} = E_{15} = \int_{T_r}^{T_j} \sigma_{PN} dT$$

In other words, E_{rj} is the EMF generated by the thermocouple circuit with its reference junction at $T_r \neq 0$. Add and subtract $\int_0^{T_r} \sigma_{PN} dT$ from the right hand

Physical Circuit:



Conceptual $T(x)$ Plot:

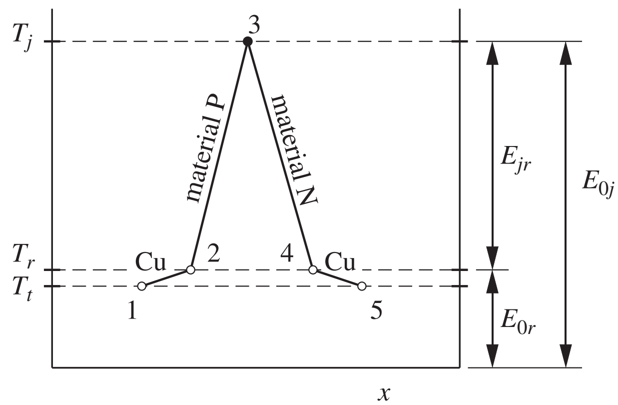


Figure 6: Thermocouple circuit with and arbitrary, but known, reference junction.

side of the preceding expression to get

$$E_{rj} = \int_{T_r}^{T_j} \sigma_{PN} dT + \int_0^{T_r} \sigma_{PN} dT - \int_0^{T_r} \sigma_{PN} dT$$

$$= \int_0^{T_j} \sigma_{PN} dT - \int_0^{T_r} \sigma_{PN} dT \tag{18}$$

For convenience, define

$$E_{0j} = \int_0^{T_j} \sigma_{PN} dT, \qquad \text{and} \qquad E_{0r} = \int_0^{T_r} \sigma_{PN} dT. \tag{19}$$

E_{0j} is the EMF of a thermocouple with its reference junction at 0 °C and its measuring junction at T_j. E_{0r} is the EMF of a thermocouple with its reference junction at 0 °C and its measuring junction at T_r. These EMF values are depicted in the right half of the $T(x)$ plot in Figure 6. With these definitions, Equation (18) is equivalent to

$$E_{rj} = E_{0j} - E_{0r} \qquad \text{or} \qquad E_{0j} = E_{rj} + E_{0r} \tag{20}$$

E_{rj} is the output of the thermocouple circuit in Figure 6. E_{rj} is known because it is measured. E_{0r} is not measured, but it can be computed from Equation (16) if T_r is known. Given the measured value of E_{rj} and the computed value of E_{0r}, the value of E_{0j} is calculated from Equation (20). Finally, the temperature of the junction is computed with Equation (17).

Summary: The following steps are used to compute the temperature of a thermocouple with a reference junction at an arbitrary temperature T_r:

1. Measure E_{rj}, the EMF of a thermocouple with its reference junction at T_r and its measuring junction at T_j.
2. Measure T_r with some device such as an ice-point compensated thermocouple, a thermistor, or a solid state temperature sensor.
3. Compute $E_{0r} = F(T_r)$, the EMF of an ice-point compensated thermocouple at temperature T_r.
4. Compute $E_{0j} = E_{rj} + E_{0r}$, the EMF of an ice-point compensated thermocouple at T_j.
5. Compute $T_j = G(E_{0j})$ from the ice-point calibration data for the thermocouple.

Example 2: Thermocouple with a Floating Reference Junction

A type J thermocouple is used to create the circuit in Figure 6. The reference temperature is $T_r = 21.23°\mathrm{C}$ and the thermocouple EMF (relative to the reference temperature) is $E_{rj} = 1.672\,\mathrm{mV}$. What is the temperature of the thermocouple junction?

The EMF of an ice-point compensated thermocouple at T_r would be (using the polynomial coefficients from Table 2).

$$E_{0r} = F(21.23°\mathrm{C}) = 1.0825\,\mathrm{mV}$$

If the measuring junction was referenced to an ice-bath, its EMF would be

$$E_{0j} = 1.6721 + 1.0825 = 2.7546\,\mathrm{mV}$$

Now, using the ice-point calibration data, compute T_j

$$T_j = G(2.7546\,\mathrm{mV}) = 53.18°\mathrm{C}.$$

□

3.3 Use of a Zone Box for Multiple Thermocouples

The basic ice-point reference circuit in Figure 5 can in principle be replicated when two or more temperatures need to be measured. Fabricating and maintaining multiple ice-point junctions is tedious, however. For multiple temperature measurements, a *zone box* provides a more convenient and reliable device for controlling the reference junction temperature. A zone box is an insulated container that maintains one or more thermocouple junctions at a uniform temperature. The zone box does not (usually) have an active temperature control.

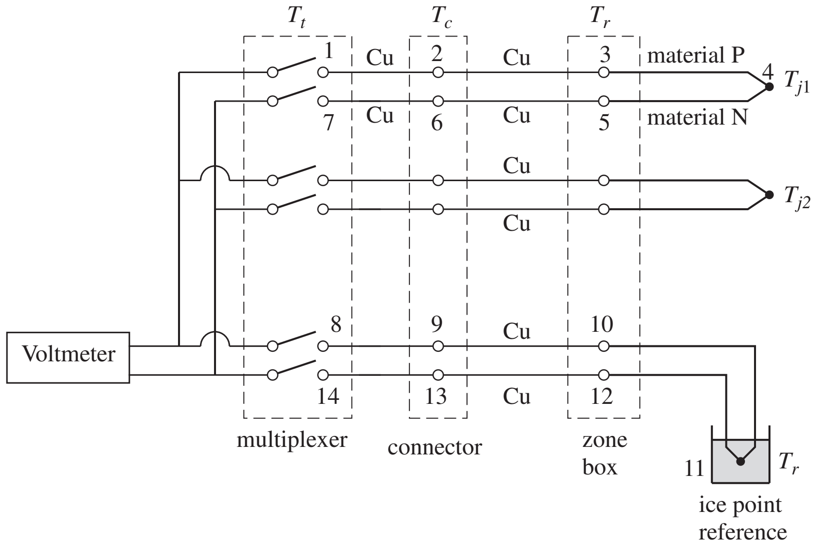


Figure 7: A zone box with an ice-point reference junction.

It just a isolated environment with a stable and measurable temperature. A simple type of zone box construction is described in § 4.

Figure 7 shows one possible zone box circuit. A single ice-point reference is provided for several measurement junctions T_{j1}, T_{j2}, etc. The measurement junctions are placed wherever temperature measurements need to be made. The ice-point junction is placed in a convenient location near the zone box.

The multiplexer and connector are not part of the zone box. A connector, if present in the circuit, allows the data collection instruments (the multiplexer and voltmeter) to be disconnected from the thermocouple circuit when the experimental apparatus is not being used. The multiplexer is a series of switches that connect one thermocouple junction at a time to the voltmeter. Often, the multiplexer and voltmeter are combined into a single instrument.

The ice-bath thermocouple for the circuit in Figure 7 provides the reference junction EMF for all measurement junctions attached to the multiplexer through the zone box. To see how the data reduction procedure works, consider the conversion of the EMF from the first measuring junction. The EMF at the multiplexer for the first thermocouple is

$$\begin{aligned} E_{rj,1} = E_{17} = & \int_{T_t}^{T_c} \sigma_C dT + \int_{T_c}^{T_r} \sigma_C dT \\ & + \int_{T_r}^{T_j} \sigma_{PN} dT \\ & \quad + \int_{T_r}^{T_c} \sigma_C dT + \int_{T_c}^{T_t} \sigma_C dT \end{aligned}$$

In the right hand side of this equation, the EMF contributions on the first and third lines cancel, so

$$E_{rj,1} = \int_{T_r}^{T_j} \sigma_{PN} dT. \tag{21}$$

Similarly, the EMF at the multiplexer for the thermocouple in the ice bath is

$$E_{r0} = E_{8-14} = \int_{T_r}^{0} \sigma_{PN} dT \tag{22}$$

where the equal and opposite EMFs from the extension wires has already been cancelled.

Now, suppose that instead of the circuit in Figure 7, the temperature at $T_{j,1}$ was measured with a thermocouple having an ice-bath reference junction. The EMF output of that thermocouple would be

$$E_{0j,1} = \int_{0}^{T_{j1}} \sigma_{PN} dT.$$

Writing the preceding integral as the sum of two integrals gives

$$E_{0j,1} = \int_{0}^{T_r} \sigma_{PN} dT + \int_{T_r}^{T_{j1}} \sigma_{PN} dT. \tag{23}$$

Substituting Equations (21) and (22) into Equation (23) gives

$$E_{0j,1} = -E_{r0} + E_{rj,1}. \tag{24}$$

Therefore, by combining the two electrical measurements of E_{r0} and $E_{rj,1}$, the effective EMF of a thermocouple with a reference junction at 0 °C is obtained.

The connector is idealized as a single point where two wires are joined. In practice a standard electrical connector, e.g. a DB-25 or DB-50 computer communication connector, is used. One must be aware that standard electrical connectors might involve dissimilar metals along the signal path. As long as the temperature of the connector is uniform, however, the dissimilar metals will not introduce a measurement error.

Summary: The following steps are used to compute the temperatures of the measuring junctions in Figure 7:

1. Measure E_{r0}, $E_{rj,1}$, $E_{rj,2}$, ...
2. For each measuring junction, compute

   $$E_{0j,i} = E_{rj,i} - E_{r0} \qquad i = 1, \ldots, n$$

   where n is the total number of measuring junctions.
3. Use the thermocouple tables, or Equation (17) to compute the temperature of each junction T_{ji} from $E_{0j,i}$.

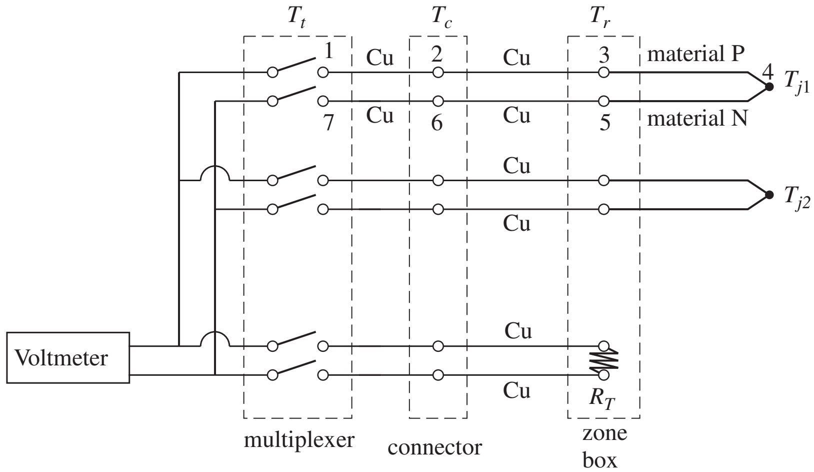


Figure 8: A zone box with a thermistor to measure T_r. Note that the thermistor reading requires a multimeter that can measure resistance.

3.4 Measuring Zone Box Temperature with a Thermistor

The zone box circuit in Figure 7 requires maintenance of an ice bath reference for determining the reference junction temperature. The ice bath can be eliminated if T_r is measured with another sensor. Figure 8 shows a zone box with T_r measured by a thermistor.

To compute the temperature of the thermocouple junctions in Figure 8 the thermistor output must be converted to the EMF of a thermocouple at T_r. The procedure for using an independently measured T_r to calculate the effective ice-point compensation EMF is described in § 3.2.

Example 3: Multiple Thermocouples with Floating T_r

The zone box circuit in Figure 8 is used in an experiment involving three type J thermocouples. The thermistor temperature is 19.7 °C, and the EMFs of the three thermocouples are $E_{rj,1} = -0.760\,\text{mV}$, $E_{rj,2} = 0.514\,\text{mV}$, and $E_{rj,3} = 1.985\,\text{mV}$. Compute the temperatures of the thermocouple junctions.

Converting the measured EMFs to temperature involves applying the steps listed at the end of § 3.2. The EMF of an ice-point compensated thermocouple at the same temperature of the zone box is found by evaluating Equation (16) at $T = 19.7\,°\text{C}$. The b_i are taken from Table 2.

$$\begin{aligned}
E_{0r} &= 5.0381187815 \times 10^{-2}(19.7) + 3.0475836930 \times 10^{-5}(19.7)^2 \\
&\quad - 8.5681065720 \times 10^{-8}(19.7)^3 + 1.3228195295 \times 10^{-10}(19.7)^4 \\
&\quad - 7.7052958337 \times 10^{-13}(19.7)^5 + 2.0948090697 \times 10^{-16}(19.7)^6 \\
&\quad - 1.2538395336 \times 10^{-19}(19.7)^7 + 1.5631725697 \times 10^{-23}(19.7)^8 \\
&= 1.0037\,\text{mV}
\end{aligned}$$

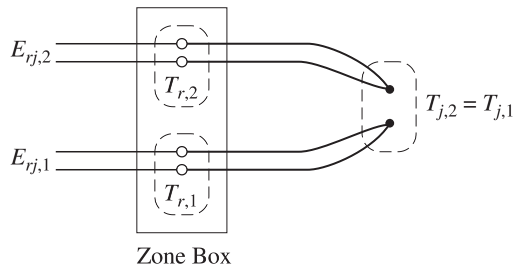


Figure 9: A zone box with unequal temperatures of reference junctions. To analyze the effect of non-uniform zone box temperature, the measurement junctions are assumed to be at the same temperature.

The output of the thermocouples if each was referenced to and ice-bath would be

$$E_{0j,1} = 1.0037 - 0.760 = 0.2437\,\mathrm{mV}$$

$$E_{0j,2} = 1.0037 + 0.514 = 1.5177\,\mathrm{mV}$$

$$E_{0j,3} = 1.0037 - 1.985 = 2.9887\,\mathrm{mV}$$

Using Equation (17) and the c_i from Table 3 gives $T_1 = 4.8\,°\mathrm{C}$, $T_2 = 29.6\,°\mathrm{C}$, and $T_3 = 57.6\,°\mathrm{C}$.

□

3.5 Effect of Non-uniform Zone Box Temperature

A zone box is designed to hold the temperature of all reference junctions at a uniform and easily measured value. For convenience only a limited number of sensors (typically one) are used to measure the temperature of the reference junctions. In this section, a model is developed to assess the measurement error introduced by non-uniformities in zone box temperature.

Figure 9 depicts a zone box containing the reference junctions for two thermocouples. Suppose that the reference junctions are at two different temperatures $T_{r,1}$ and $T_{r,2}$. Suppose further that the two measuring junctions are at the *same* temperature, i.e., $T_{j,1} = T_{j,2}$. The difference in reference junction temperatures causes the measured EMF of the two thermocouples to be different. How large is the error in *indicated* junction temperature due to the difference in reference junction temperature? Note that the error is not because the junction temperatures are not at the ice point. Rather, the temperatures indicated by the thermocouples are different due to the difference in reference junction temperatures.

For convenience, assume that $T_{r,1}$ is the temperature of the reference junctions as measured by a sensor in the zone box (e.g. a thermistor). The *correct* ice-point compensated EMF for the first thermocouple is

$$E_{0j,1} = E_{rj,1} + F(T_{r,1})$$

where $F(T)$ is the calibration function yielding the EMF of an ice-point compensated thermocouple at temperature T. The *incorrect* ice-point compensated

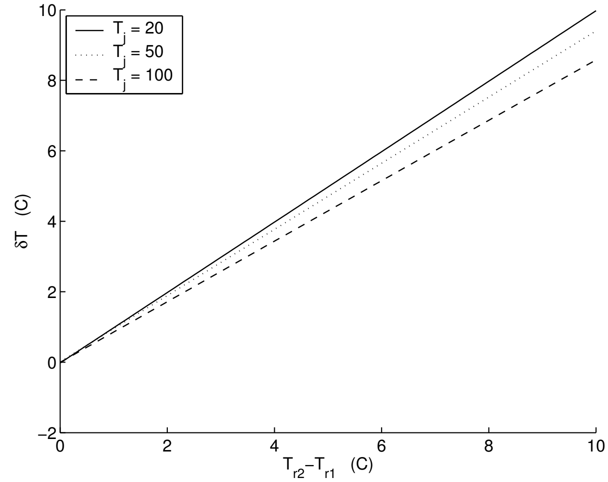


Figure 10: Error in indicated junction temperature due to unequal temperatures of reference junctions. $T_{r,1} = 20°\text{C}$.

EMF for the second thermocouple is

$$\tilde{E}_{0j,2} = E_{rj,2} + F(T_{r,2})$$

where the tilde indicates an incorrect value. The value of $\tilde{E}_{0j,2}$ is incorrect because $T_{r,2} \neq T_{r,1}$ and the reference sensor in the zone box only measures $T_{r,1}$. Define the error in the indicated temperature for $T_{j,2}$ as

$$\begin{aligned}\delta T = T_{j,2} - \tilde{T}_{j,2} &= G(E_{0j,2}) - G(\tilde{E}_{0j,2}) \\ &= G(E_{0j,1}) - G(\tilde{E}_{0j,2}) \\ &= G(E_{0j,1}) - G(E_{rj,2} + F(\tilde{T}_{r,2})).\end{aligned}$$

Remember that the right hand side of the preceding expression will not be zero because $T_{r,2} \neq T_{r,1}$.

Figure 10 shows the error (δT) in the indicated value of $T_{j,2}$ as a function of $T_{r,2} \neq T_{r,1}$ for type T thermocouples. To a very good approximation, the error in the indicated temperature is proportional to the difference in junction temperatures within the zone box.

4 Zone Box Construction

The purpose of a zone box is to provide a uniform temperature environment for a group of reference junctions. Although the (ideally) uniform temperature inside the zone box can vary in time, it should do so slowly. Any time variation in the temperature of the zone box implies thermal gradients at the edges of the zone box, which is a violation of the goal that the temperature inside the box is uniform.

Figure 11 is a photograph of a simple zone box. The thermocouple wires are attached to the copper lead wires at a screw terminal barrier strip. The barrier strip is mounted on a slab of aluminum. The thermocouple wires are electrically insulated from, but in good thermal contact with, the metal slab. This entire assembly is surrounded by insulation to isolate the slab and the junctions from any heat loads and temperature fluctuations in the environment.

Apart from the barrier strip, the zone box in Figure 11 can be constructed from scrap metal and insulation. Electrical barrier strips are inexpensive and but are not necessary. For example, the thermocouples could be soldered directly to the lead wires. If desired, the insulation can be enclosed in a protective box. Any structural enhancement to the box does not affect the thermal performance so long it does not compromise the effectiveness of the insulation.

It is convenient to use a screw terminal barrier strip in a zone box. However, if high accuracy of thermocouple measurements is the goal, it is better to solder the thermocouple junctions to the copper extension wires. Soldered connections allow the reference junctions to be located physically close together and in good contact with the sensor measuring the reference junction temperature. In § 3.5 it was shown that any non-uniformity in reference junction temperature causes a proportional error in the indicated temperature of measurement junction temperature.

Users of the zone box should be aware of the thermal transient that occurs just after the zone box is constructed, or after any maintenance on the junctions inside the box. The insulation that isolates the inside of the box from the laboratory environment also slows the decay of any transients driven by bulk temperature differences between the inside and outside of the box. In general, it is good practice to record the zone box temperature at least at the beginning and end of an experiment. Any appreciable change in zone box temperature indicates that the reference junctions are not at a stable temperature. Additional confidence can be gained by measuring the temperature at more than one location inside the zone box. Monitoring the zone box temperature enables detection of anomalous transients due to zone box construction, maintenance, or other environmental factors.

It is natural to bundle the wires that carry the electrical signals into and out of the zone box. Because these wires provide thermal paths in addition to electrical paths, temperature gradients down the lead wires will cause temperature changes inside the zone box. Figure 12 depicts a temperature measurment scenario involving a zone box where an undetected heat input is present on the thermocouple wires. The heat load could be caused, for example, when the thermocouple wires are routed near the cooling fins of a DC power supply. The undetected heat input causes a heat flow Q_r along the leads toward the zone box. This heat load would cause the zone box temperature to increase during the experiment. Of course the heat load Q_j could also cause errors in the temperatures of the measuring junction.

In general the experimentalist must be observant of the apparatus and skeptical of all data collected. The heat load depicted in Figure 12 would be detected as a change in zone box temperature in time. As long as the zone box temperature changes slowly, and as long as the zone box temperature is recorded during the experiment, the effect of varying reference temperature can be accounted for and minimized.

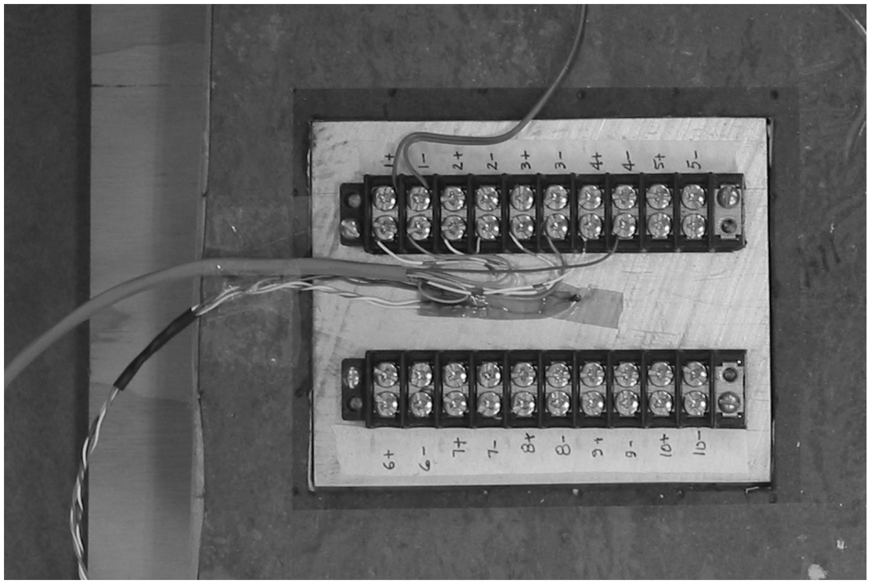


Figure 11: A simple zone box with a thermistor to measure T_r. The pairs of screws are wiring strips, which are optional. (The thermocouple junctions could be soldered to the lead wires, for example). The wiring strips are mounted on a slab of Aluminum 1.3 cm thick. The assembly is embedded in a block of rigid polystyrene insulation. A matching block of polystyrene forms a cover, which is held in place by duct tape.

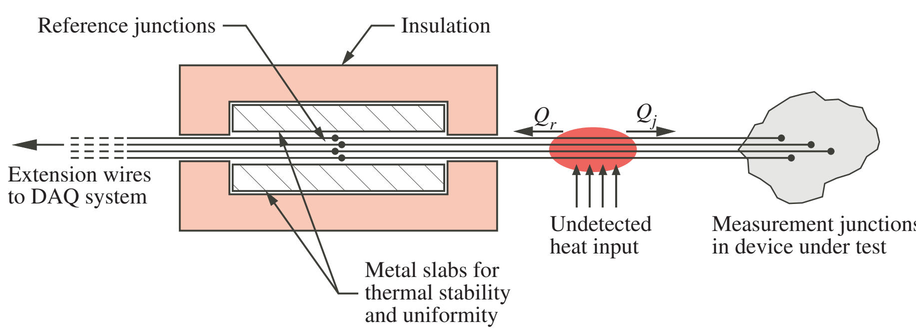


Figure 12: Heat load on a zone box can be caused by heat conduction along the thermocouple or lead wires.

5 Summary

Thermocouples are inexpensive and versatile temperature sensors. With proper installation and reference junction compensation, thermocouples can be used for routine and accurate temperature measurement. These advantages are substantial when large numbers of temperatures need to be measured.

Data acquisition vendors sell systems for temperature compensation of thermocouple junctions. These devices are essentially zone boxes with an independent sensor for measuring reference junction temperature. A knowledgable experimentalist can build her own zone box and use a digital multimeter, with suitable amplification, to measure temperature with thermocouples. As long as the reference junction is accurately measured, a home-made zone box is likely to be more accurate than a commercial electronic thermocouple compensation device. Commercial devices for reference junction compensation are usually poorly insulated and they are often attached to electronic equipment with internal heat sources. As shown in § 3.5, any uncertainty or error in reference junction temperature results in a proportionate uncertainty or error in the indicated temperature of the measuring junction.

This document provides detailed descriptions of procedures for converting thermocouple EMF measurements to temperature. Step-by-step instructions for converting ice-point and floating reference junction compensation are given. Use of a zone box for the reference junctions of multiple thermocouples is described.

5.1 Conversion Recipes

For thermocouple circuits with the reference junction at $T_r = 0°\mathrm{C}$, the temperature of the measuring junction is

$$T_j = G(E_{0j})$$

where E_{0j} is the measured EMF, and $G(E)$ is the appropriate calibration equation (or tabular data) for the thermocouple. For type J and type T thermocouples, $G(E)$ is of the form of Equation (17) where the polynomial coefficients are given in Table 3 (type J) or Table 5 (type T).

For thermocouple circuits with the reference junction at $T_r \neq 0°\mathrm{C}$, the temperature of the measuring junction is computed in a two-step process. First compute

$$E_{0r} = F(T_r)$$

where $F(T)$ is of the form of Equation (16) with polynomial coefficients are given in Table 2 (type J) or Table 4 (type T). Then compute the temperature of the junction with

$$T_j = G(E_{0r} + E_{rj})$$

where E_{rj} is the measured EMF, and $G(E)$ is of the form of Equation (17) where the polynomial coefficients are given in Table 3 (type J) or Table 5 (type T).

References

[1] American Society for Testing and Materials. *A Manual on the Use of Thermocouples in Temperature Measurement*. ASTM, Philadelphia, New York, fourth edition, 1993.

[2] G.W. Burns, M.G Scroger, and G.F. Strouse. Temperature-electromotive force reference functions and tables for the letter-designated thermocouple types based on the its-90. NIST Monograph 175, National Institute for Standards and Technology, Washington, DC, 1993.

A Thermocouple Data

Table 1: Nominal compositions of standard thermocouple wires. Data from Table 3.3 in reference [1].

Type	Positive element	Negative element
B	Platinum (70.4%), Rhodium (29.6%)	Platinum (94%), Rhodium (6%)
E	Nickel (90%), Chromium (10%)	Constantan: Nickel (55 %), Copper (45 %)
J	Iron (99.5%)	Constantan: Nickel (55 %), Copper (45 %)
K	Nickel (90%), Chromium (10%)	Nickel (95%), Aluminum (2%) Manganese (2%), Silicon (1%)
N	Nickel (84.4%), Chromium (14.2%) Silicon (1.4%)	Nickel (95.5%), Silicon (4.4%), Manganese (0.15%)
R	Platinum (87%) Rhodium (13%)	Platinum (100%)
S	Platinum (90%) Rhodium (10%)	Platinum (100%)
T	Copper (100%)	Constantan: Nickel (55 %), Copper (45 %)

Table 2: Coefficients of the calibration equation for EMF as a function of temperature for type J thermocouples, $E_{0j} = b_0 + b_1 T_j + b_2 T_j^2 + \ldots + b_n T_j^n$. T_j in °C, E_{0j} in mV. Data from Table 10.6, p. 196 in reference [1].

		$-210\,°C \leq T \leq 760\,°C$	$760\,°C \leq T \leq 1200\,°C$
b_0	=	0	$2.964\,562\,568\,1 \times 10^{2}$
b_1	=	$5.038\,118\,781\,5 \times 10^{-2}$	$-1.497\,612\,778\,6$
b_2	=	$3.047\,583\,693\,0 \times 10^{-5}$	$3.178\,710\,392\,4 \times 10^{-3}$
b_3	=	$-8.568\,106\,572\,0 \times 10^{-8}$	$-3.184\,768\,670\,1 \times 10^{-6}$
b_4	=	$1.322\,819\,529\,5 \times 10^{-10}$	$1.572\,081\,900\,4 \times 10^{-9}$
b_5	=	$-1.705\,295\,833\,7 \times 10^{-13}$	$-3.069\,136\,905\,6 \times 10^{-13}$
b_6	=	$2.094\,809\,069\,7 \times 10^{-16}$	0
b_7	=	$-1.253\,839\,533\,6 \times 10^{-19}$	0
b_8	=	$1.563\,172\,569\,7 \times 10^{-23}$	0

Table 3: Coefficients of the calibration equation for temperature as a function of EMF for type J thermocouples, $T_j = c_0 + c_1 E_{0j} + c_2 E_{0j}^2 + \ldots + c_m E_{0j}^m$. E_{0j} in mV, T_j in °C. Data from Table 10.20, p. 209 in reference [1].

		$-8.095\,\mathrm{mV} \leq E_{0j} \leq 0\,\mathrm{mV}$ ($-210\,°C \leq T \leq 0\,°C$)	$0\,\mathrm{mV} \leq E_{0j} \leq 42.919\,\mathrm{mV}$ ($0\,°C \leq T \leq 760\,°C$)
c_0	=	0	0
c_1	=	$1.952\,826\,8 \times 10^{1}$	$1.978\,425 \times 10^{1}$
c_2	=	$-1.228\,618\,5$	$-2.001\,204 \times 10^{-1}$
c_3	=	$-1.075\,217\,8$	$1.036\,969 \times 10^{-2}$
c_4	=	$-5.908\,693\,3 \times 10^{-1}$	$-2.549\,687 \times 10^{-4}$
c_5	=	$-1.725\,671\,3 \times 10^{-1}$	$3.585\,153 \times 10^{-6}$
c_6	=	$-2.813\,151\,3 \times 10^{-2}$	$-5.344\,285 \times 10^{-8}$
c_7	=	$-2.396\,337\,0 \times 10^{-3}$	$5.099\,890 \times 10^{-10}$
c_8	=	$-8.382\,332\,1 \times 10^{-5}$	0

Table 4: Coefficients of the calibration equation for EMF as a function of temperature for type T thermocouples, $E_{0j} = b_0 + b_1 T_j + b_2 T_j^2 + \ldots + b_n T_j^n$. T_j in °C, E_{0j} in mV. Data from Table 10.16, p. 206 in reference [1].

		$-270\,°\mathrm{C} \leq T \leq 0\,°\mathrm{C}$	$0\,°\mathrm{C} \leq T \leq 400\,°\mathrm{C}$
b_0	=	0	0
b_1	=	$3.874\ 810\ 636\ 4 \times 10^{-2}$	$3.874\ 810\ 636\ 4 \times 10^{-2}$
b_2	=	$4.419\ 443\ 434\ 7 \times 10^{-5}$	$3.329\ 222\ 788\ 0 \times 10^{-5}$
b_3	=	$1.184\ 432\ 310\ 5 \times 10^{-7}$	$2.061\ 824\ 340\ 4 \times 10^{-7}$
b_4	=	$2.003\ 297\ 355\ 4 \times 10^{-8}$	$-2.188\ 225\ 684\ 6 \times 10^{-9}$
b_5	=	$9.013\ 801\ 955\ 9 \times 10^{-10}$	$1.099\ 688\ 092\ 8 \times 10^{-11}$
b_6	=	$2.265\ 115\ 659\ 3 \times 10^{-11}$	$-3.081\ 575\ 877\ 2 \times 10^{-14}$
b_7	=	$3.607\ 115\ 420\ 5 \times 10^{-13}$	$4.547\ 913\ 529\ 0 \times 10^{-17}$
b_8	=	$3.849\ 393\ 988\ 3 \times 10^{-15}$	$-2.751\ 290\ 167\ 3 \times 10^{-20}$
b_9	=	$2.821\ 352\ 192\ 5 \times 10^{-17}$	
b_{10}	=	$1.425\ 159\ 477\ 9 \times 10^{-19}$	
b_{11}	=	$4.876\ 866\ 228\ 6 \times 10^{-22}$	
b_{12}	=	$1.079\ 553\ 927\ 0 \times 10^{-24}$	
b_{13}	=	$1.394\ 502\ 706\ 2 \times 10^{-27}$	
b_{14}	=	$7.979\ 515\ 392\ 7 \times 10^{-31}$	

Table 5: Coefficients of the calibration equation for temperature as a function of EMF for type T thermocouples, $T_j = c_0 + c_1 E_{0j} + c_2 E_{0j}^2 + \ldots + c_m E_{0j}^m$. E_{0j} in mV, T_j in °C. Data from Table 10.25, p. 211 in reference [1].

		$-5.603\,\mathrm{mV} \leq E_{0j} \leq 0\,\mathrm{mV}$ ($-200\,°\mathrm{C} \leq T \leq 0\,°\mathrm{C}$)	$0\,\mathrm{mV} \leq E_{0j} \leq 20.872\,\mathrm{mV}$ ($0\,°\mathrm{C} \leq T \leq 400\,°\mathrm{C}$)
c_0	=	0	0
c_1	=	2.5949192×10^{1}	2.592800×10^{1}
c_2	=	$-2.1316967 \times 10^{-1}$	-7.602961×10^{-1}
c_3	=	7.9018692×10^{-1}	4.637791×10^{-2}
c_4	=	4.2527777×10^{-1}	-2.165394×10^{-3}
c_5	=	1.3304473×10^{-1}	6.048144×10^{-5}
c_6	=	2.0241446×10^{-2}	-7.293422×10^{-7}
c_7	=	1.2668171×10^{-3}	0