

PREFACE TO THE SECOND EDITION

Mitchell Johnson, President of JMS-Southeast, joined Dr. Kerlin in preparing this second edition. He brings a wealth of knowledge about real-world applications of thermocouples.

The descriptions of thermocouple principles, the tools needed to analyze thermocouple performance, the causes of thermocouple errors, and the characteristics of the commonly-used thermocouples in the 1999 edition of this book are still as pertinent and correct as they were in 1999.

The second edition updates the book with increased coverage of topics related to thermocouple applications. It provides new solved sample problems that include illustrations of the use of the thermocouple loop analysis method. It includes new or revised sections to discuss new developments and to expand treatments of important technologies. It includes case studies of real-world problems and their solutions.

Part of the motivation for preparing this second edition is the apparent lack of widespread use of thermocouple loop analysis to characterize thermocouple performance and problems. We contend that this method is an essential tool for those who are responsible for measuring temperature with thermocouples.

One might argue that internet information now makes a book on thermocouples unnecessary. Certainly, almost everything found in this book can be found on the internet. However, the book eliminates the need to search through, evaluate, and digest a huge information resource. The book is intended as an easy-to-use reference that organizes and explains the subject in a concise fashion and is convenient to access.

1

INTRODUCTION

1.1 THE THERMOCOUPLE

The thermocouple must surely be one of the simplest measuring devices ever conceived. What could be simpler than two different wires joined at one end? With this arrangement, a voltage is produced along the wires that increases in magnitude as the temperature difference between the joined end and the open end increases. All that is needed to determine the temperature at the junction of the wires is to measure the voltage at the open end, make adjustments to compensate for differences between the open-end temperature and the open-end temperature used in calibration, and convert this compensated voltage into temperature using the calibration for the wire types.

This approach is a proven technology for temperature measurement in industry. Thermocouples account for more temperature measurements in U.S. industry than any other sensor type. Thermocouples are rugged, inexpensive, and easy to use. However, they have significant inherent inaccuracies and a tendency to degrade with use. Users should understand these phenomena so they can properly assess the accuracy of their measurements, select the proper thermocouple for a given application, and install and operate the thermocouple in the most advantageous way.

This short book focuses on the practical aspects of thermocouple thermometry: how thermocouples work; how they go bad; how to assess measurement accuracy; and how to select, install, and operate them. In this book, a thermocouple will usually be shown schematically, as in Figure 1-1. In practical applications, however, the arrangement is often as shown in Figure 1-2. In the case illustrated in Figure 1-2, the wires are contained in a metallic sheath where the junction is formed. The wires come in three categories: base metal (such as copper, nickel, and iron and are cheapest and most common), refractory metal (such as tungsten and rhenium and used for very high temperatures) and noble metals (such as platinum and rhodium and used for high accuracy and high temperature). The open end is connected to a readout that automatically measures the voltage, corrects for effects caused by the temperature at the open end, and then computes and displays the

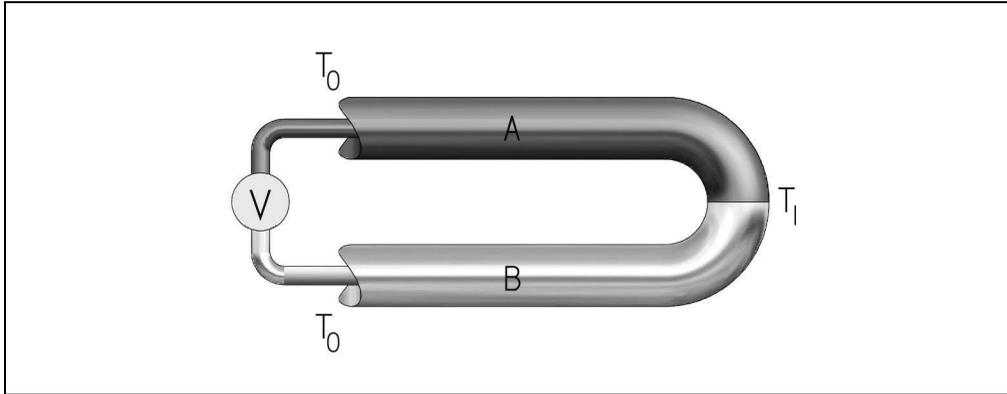


Figure 1-1. Schematic View of a Thermocouple

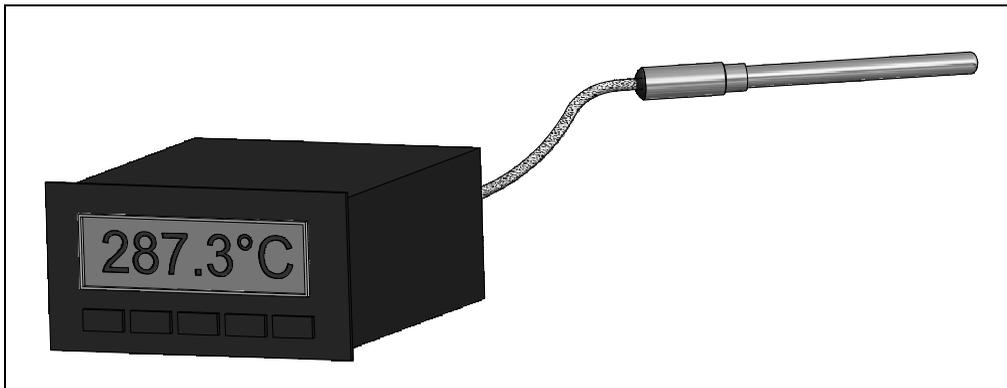


Figure 1-2. Thermocouple in Practical Applications

temperature. This simplicity of implementation is both a blessing and a curse. On the one hand, it is very easy to obtain a measurement: just turn the system on and the result appears. On the other hand, this ease of use often discourages users from expending enough time to understand what is happening, and the unfortunate result may be undetected and unnecessary measurement errors.

1.2 THE COMPETITION

Thermocouples are used routinely for temperature measurements ranging from -270°C to 2320°C . Other sensor types are available for use over portions of this range.¹⁻³ Specifically, the sensors that are alternatives to thermocouples (and their range of application) are as follows:

<u>Sensor</u>	<u>Useful Temperature Range</u>
Typical resistance temperature detectors (RTDs) ¹	-196°C to 661°C
Thermistors	-55°C to 100°C
Integrated circuit sensors	-55°C to 150°C

Resistance temperature detectors and *thermistors* (the latter for a narrow range of temperatures near ambient) are the only serious competitors for use as immersion sensors in process environments that require a sheath or protection tube to isolate the sensor from the process.

Integrated circuit sensors are used in benign environments such as for heating, ventilating, and air conditioning systems or as components of electronic instrumentation systems.

The competitors to thermocouples for process measurements have different relative advantages, mainly with respect to measures of suitability for a given application. These measures are allowable temperature range, accuracy, and measurement system affordability (the measurement system consists of the three components needed to make a measurement: the sensor, wiring and instrumentation).

For a number of years, thermocouples have been losing market share to RTDs in total temperature sensor sales. This trend is likely to continue. RTDs have evolved from fragile, expensive laboratory sensors to quite rugged and inexpensive industrial sensors—largely due to improvements in the quality of thin film RTD elements—though they are still not as rugged as thermocouples. RTDs have lower decalibration tendencies and lower costs for wiring between the sensor and its transmitter or readout. Greater achievable accuracy is an advantage for RTDs over any type of thermocouple up to around 460°C. Beyond this temperature, RTDs still have lower limits of error than base-metal thermocouples, but larger limits of error than noble-metal thermocouples.

Thermocouples remain the least expensive sensor for many applications, their accuracy and decalibration tendency are improving as the subtleties of the underlying principles of thermocouple thermometry are understood better and improvements arise in composition control and sensor fabrication procedures. They are suitable for use in unusual configurations, they are rugged, and they are able to operate at high temperatures. These advantages guarantee that thermocouples will continue to be very important sensors for industry.

Table 1-1 summarizes the relative advantages and disadvantages of thermocouples and RTDs.

Table 1-1. Comparison of Thermocouples and RTDs

	Thermocouple	RTD
Accuracy	Limits of error wider than for RTDs (except for noble metal thermocouples above roughly 460°C)	Limits of error smaller than base-metal thermocouples at all temperatures and noble metal thermocouples below roughly 460°C
Ruggedness	Excellent	Relatively sensitive to temperature-induced strain, thermal or mechanical shock and pressure
Range	-270°C to 2320°C	-196°C to 661°C (typical) (somewhat lower and higher limits in special designs)
Size	Can be as small as .01" and may be tip sensitive	Limited to 1/16", temperature sensitive for length of bulb
Drift	Should be checked periodically for drift	Less drift than thermocouples (typically 0.01 to 0.1°C / year)
Resolution	Must resolve fractions of millivolts per degree, lower signal-to-noise ratio	Must resolve fractions of ohms per degree, higher signal-to-noise ratio
Cold Junction	Required	Not Required
Lead Wire	Must match lead wire calibration to thermocouple calibration	Can use copper wire for extension wire
Response	Can be made small enough for millisecond response time	Thermal mass restricts time to seconds in most cases
Cost	Low	Higher than thermocouples

Noncontact temperature sensors are also available. They provide measurement capability that includes situations where measurements with thermocouples are not possible. Infrared temperature sensors and optical pyrometers can measure temperatures that far exceed those possible by means of any contact temperature sensors. These sensors work by measuring the electromagnetic radiation emitted from an object. They are useful for monitoring surface temperatures. Disadvantages of non-contact sensors include high cost, error caused by emissivity uncertainties, the inability to take an internal temperature and the fragility of the measuring device itself.

1.3 STANDARDS

Standards serve to define the acceptable performance levels of products such as thermocouples. In the United States, consensus standards are prepared by professional societies and are then approved and promulgated by the American National Standards Institute (ANSI). The American Society for Testing and Materials (ASTM) maintains Committee E.20 to address the needs of thermometry standards in the United States. The Instrument Society of America (now renamed the International Society of Automation) previously developed and maintained a thermocouple standard (labeled MC 96.1), but this standard was abandoned in 1982 in favor of the ASTM standard. The ASTM standard has not received ANSI approval, but it is the pertinent and universally used standard for thermocouples in the U.S.

International commerce involves the movement of products across national boundaries, and its growth has created a need for international standards to ensure compatibility and consistency of thermocouple performance. The International Electrotechnical Commission (IEC) serves this function by coordinating standards activities, publishing international standards, and maintaining its Committee WG65B to deal with thermometry. However, different standards still exist in different industrialized countries. These differences, especially differences in color coding, often cause confusion in selecting appropriate thermocouples for use in systems built in countries where standards differ from local standards. Chapter 5 provides information about U.S. and international standards.

Thermocouple standards define the nominal performance and tolerances for the thermocouples used in most industrial applications. The tolerances are chosen by defining products that are adequate in most applications but do not require unrealistically costly manufacturing processes. In their purchase specifications, purchasers of thermocouples often cite standards as minimum performance requirements.

Standards serve a crucial role in industrial temperature measurement. They greatly facilitate sensor replacement and interchangeability and the assessment of thermocouple performance.

1.4 KEY REFERENCES

Many useful books are available that provide information on thermocouples, their principle of operation, their construction, their degradation in use, and their selection.⁴⁻²⁵

REFERENCES

1. Ball, K. E., "Thermocouples and RTD's: The Controversy Continues," *InTech*, Vol. 33, August 1986, pp. 43-45.
2. Smith, J., "Matching Temperature Sensors with Process Tasks," *Instrumentation and Control Systems*, Vol. 67, April 1994, pp. 77-82.
3. Waterbury, R. C., "Hot Issue: RTDs vs. Thermocouples," *InTech*, Vol. 41, March 1994, pp. 44-47.
4. *The Theory and Properties of Thermocouple Elements*, American Society for Testing and Materials publication STP 492.
5. *The Use of Thermocouples in Temperature Measurement*, American Society for Testing and Materials, ASTM 470B Fourth Edition, 1993.
6. Benedict, R. P., *Fundamentals of Temperature, Pressure, and Flow Measurements*, John Wiley & Sons, New York, 1969.
7. Burns, G. W. and Scroger, M. G., *The Calibration of Thermocouples and Thermocouple Materials*, NIST Special Publication 250-35, April 1989.
8. Burns, G. W., *Temperature-Electromotive Force Reference Functions and Tables for the Letter-Designated Thermocouple Types Based on the ITS-90*, National Institute of Standards and Technology publication NIST Monograph 175, Superintendent of Documents, U. S. Government Printing Office, Washington, DC, 1993.
9. Ripple, D.C. and Burns, G.W., *Standard Reference Material 1749: Au/Pt Thermocouple Thermometer*, NIST Special Publication 260-134, March 2002.
10. Garrity, K., Ripple, D. C. et al., *A Regional Comparison of Calibration Results for Type K Wire from 100 C to 1100 C*, TEMPMEKO, Vol. 29, Issue 5, pp.1828-1837, 5 June 2008.
11. Kinzie, P. A., *Thermocouple Temperature Measurement*, John Wiley & Sons, New York, 1973.
12. Kerlin, T. W., and Shepard, R. L., *Industrial Temperature Measurement*, ISA, Research Triangle Park, NC, 1982.

13. Magison, E. C., *Temperature Measurement in Industry*, ISA, Research Triangle Park, NC, 1990.
14. McGee, T. D., *Principles and Methods of Temperature Measurement*, John Wiley & Sons, New York, 1988.
15. Michalski, L., Eckersdorf, K., and McGhee, J., *Temperature Measurement*, John Wiley & Sons, New York, 1991.
16. Nicholas, J. V., and White, D. R., *Traceable Temperatures*, John Wiley & Sons, New York, 1994.
17. Nicholas, J. V., and White, D. R., *Traceable Temperatures*, New Zealand Department of Scientific and Industrial Research, DS.R Bulletin 234, 1982.
18. Pollock, D. D., *Thermoelectricity: Theory, Thermometry, Tool*, American Society for Testing and Materials Special Technical Publication 852, 1985.
19. Pollock, D. D., *Thermocouples: Theory and Properties*, CRC Press, Boca Raton, FL, 1991.
20. Quinn, T. J., *Temperature*, Academic Press, New York, 1983.
21. Schooley, James F., *Thermometry*, CRC Press, Boca Raton, FL, 1986.
22. Bentley, R. E., *Handbook of Temperature Measurement*, Vol. 3 Springer, 1998.
23. Liptak, B. G., *Temperature Measurement*, CRC Press, 1993.
24. McMillan, G. K. *Advanced Temperature Measurement & Control*, ISA, 2nd Ed., 2010.
25. Kerlin, T. W., and Johnson, M. P., "Thermocouples: What One Needs To Know," *InTech*, Vol. 58, Sept/Oct. 2011, pp. 52–53.

2

FUNDAMENTALS

THE MAIN POINTS

- Voltage is not produced at the junction of the thermocouple wires.
- Voltage is produced along the portions of the thermocouple wires that experience temperature differences.
- Voltage for an ideal thermocouple is related to the temperature difference between the junction end and the open end.
- Thermocouple loop analysis is simple and can explain all the important phenomena in thermocouples related to temperature measurement. Even casual users of thermocouples will benefit by understanding and using this simple analysis method.
- For temperature measurement, the quantity of interest is the open-circuit voltage (OCV), that is, the voltage that occurs when there is no current flowing.
- It does not matter how thermocouple wires are joined (twisted, welded, soldered, bolted, clamped, etc.) insofar as the thermocouple's temperature measuring capability is concerned.

2.1 TEMPERATURE SCALES

It will be assumed that the reader knows what temperature is and why he or she wants to measure it. Precise definitions of temperature may be based on thermodynamics or on quantum physics.¹⁻⁵ These have tremendous practical importance to people working on defining the temperature scale or performing high-accuracy sensor calibration, but they are usually not of much importance in industrial temperature measurements. The user wants his or

her measurements to conform to a temperature scale that is universally consistent.

The most common scale for scientific use is the Celsius scale, and for industrial use both the Celsius and Fahrenheit scales are commonly used. The Celsius and Fahrenheit scales are related to the Kelvin and Rankine absolute scales, respectively.

The relationships between the scales are as follows:

$$^{\circ}\text{F} = 1.8 \times ^{\circ}\text{C} + 32$$

$$^{\circ}\text{C} = (^{\circ}\text{F} - 32)/1.8$$

$$\text{K} = ^{\circ}\text{C} + 273.15$$

$$^{\circ}\text{R} = ^{\circ}\text{F} + 459.67$$

It is customary to refer to the temperatures as “degrees C,” “degrees F,” “degrees R,” and “kelvins.” This special treatment of the terminology for the Kelvin scale honors Lord Kelvin’s contributions to thermometry.

The temperature scales are revised periodically because scientists are continually striving to improve the numbers used for the temperatures that define reference thermal states. Here, a reference thermal state is defined as a reproducible thermal condition such as a melting point for a pure material. Scientists also strive to develop interpolations that define temperatures at thermal states other than those that can be reproduced readily. This suggests that there are “correct temperatures,” not just values that are arbitrarily assigned (as in the creation of the Celsius and Fahrenheit scales). This conclusion is certainly true. Temperature appears as a variable in many laws of physics, and these variables cannot have arbitrary values. These values, which are the object of the scientific efforts to define “correct temperatures,” might be called “physical temperatures” but are commonly called “thermodynamic temperatures.” One feature of a thermodynamic temperature scale is that it has a zero value at some lowest possible temperature. The Kelvin and Rankine scales have this feature.

Scientific experts meet regularly to evaluate new results in their effort to establish “correct temperatures” and to prescribe procedures for conforming to these values in industrial practice. During the twentieth century, this has led to revised specifications about every twenty years. Through 1968, these specifications were called the International Practical Temperature Scale and were designated by the abbreviation *IPTS* followed by the last two digits of the year of adoption. This led to *IPTS-28*, *IPTS-48*, and *IPTS-68*. The terminology changed in 1990 when a new scale, called the International Temperature Scale and designated *ITS-90*, was adopted.⁵ The difference

between IPTS-68 and ITS-90 temperature scales is small (less than 0.4°C for temperatures below 1000°C and about 0.05 percent of the Celsius temperature above 1000°C).

The obvious question is, "How do these changes affect the industrial practitioner?" The answer is "Very little." Thermocouples still provide the same output when they experience the same thermal state. The small differences in defining the scale result in small differences in the tables, graphs, and equations used to provide thermocouple calibration information. These differences are smaller than the uncertainties on industrial measurements using thermocouples but are still a possible source of confusion. In this book, the values used in all tables, graphs, and equations will be based on ITS-90.

2.2 WHAT CAUSES THE THERMOCOUPLE VOLTAGE?

It is not necessary to undertake a detailed analysis of the physics behind the thermoelectric voltage produced by a conductor in a temperature gradient. It is, however, useful to have a qualitative feel for the underlying physics so the behavior of thermocouples becomes understandable.⁶⁻⁷

Consider first a single conductor in a temperature gradient. The conductor experiences an electrical potential that can be viewed as being caused by variations in the density of free electrons in the conductor. The electrons in the high-temperature region have a higher kinetic energy than those in the low-temperature region. This electron diffusion causes production of a potential difference along a wire that experiences a temperature gradient. The magnitude of the effect depends on the composition of the conductor, its metallurgical state, and the absolute temperature of the conductor.

One might be tempted to conclude that the existence of a potential difference in a conductor that experiences a temperature gradient would permit the temperature to be measured by measuring the voltage on a single wire. Not so! The measurement of potential must be made by an instrument to which the wire is connected. Therefore, the potential increases along one leg of the loop and decreases by an equal amount in the other, giving a net potential of zero at the measuring instrument.

If one wire will not work, then how about two? Consider a situation involving two different conductors, as shown in Figure 2-1. Because of the different tendencies of the two conductors to generate variations in free electron densities (and therefore different tendencies to generate electrical potentials),

the two wires produce different electrical potentials. The net result is a potential difference at the open end (where the measuring instrument is connected). This is the basis for thermocouple thermometry. The open end is also called the reference end of the thermocouple.

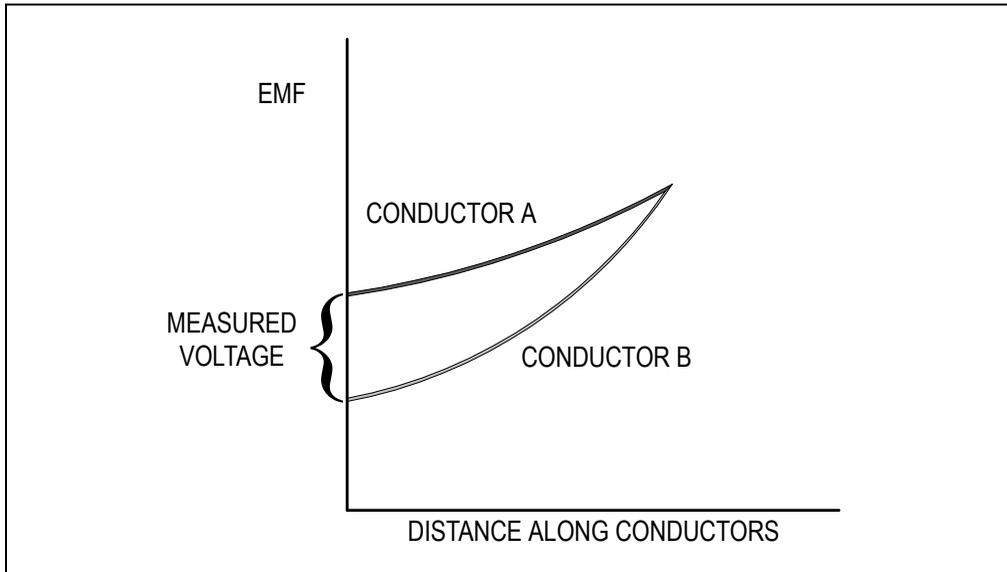


Figure 2-1. Voltage Produced by Two Dissimilar Conductors

It should be noted that the voltage at the open end is the *open-circuit voltage (OCV)*. That is, it is the voltage produced in the absence of electrical current in the thermocouple loop. If a current existed, it would reduce the differences in free electron density that are responsible for the thermoelectric *electromotive force (emf)*. Consequently, the measurement of the thermoelectric emf must be done in a way that ensures insignificantly small current flows. In a practical sense, this means that the input impedance of the voltage-measuring instrument must be large.

2.3 THE SEEBECK COEFFICIENT AND THERMOCOUPLE LOOP ANALYSIS

A homogeneous section of a conductor that experiences a temperature T_0 at one end and a temperature T_1 at the other end experiences a voltage difference, V , between the two ends. The voltage is given by the following equation:⁷⁻⁹

$$V = S (T_1 - T_0) \quad (2-1)$$

where

$$S = \text{the Seebeck coefficient } (\mu\text{V}/^\circ\text{C})$$

The Seebeck coefficient (also called the “thermoelectric power”) is the fundamental thermoelectric property related to thermocouple thermometry. It is a physical property of a material, like its density, thermal conductivity, or electrical resistivity. It is independent of the size and shape of the conductor but does vary with temperature. Because of this temperature dependence, the relation shown in Equation 2-1 is an approximation. This approximation is adequate for the qualitative analysis of thermocouple circuits but is inadequate for predicting the voltage that would be observed for a specific thermocouple in a specific temperature gradient. However, for the uses to which it is put in this book—understanding how various thermocouple configurations work—it is quite satisfactory.

The simple relation between voltage and temperature difference along the conductor may be used to predict thermocouple performance, analyze thermocouple configurations, and troubleshoot problems with thermocouple thermometry. This procedure is called *thermocouple loop analysis*.⁷⁻⁹ The procedure may be illustrated for the basic thermocouple shown in Figure 2-2. The approach is simply to sum up the voltage contributions for each homogeneous portion of the conductor. For example, if we choose to start the summing process at the open end of conductor A, the voltage is as follows:

$$V = S_A(T_1 - T_0) + S_B(T_0 - T_1) \quad (2-2)$$

$$\begin{array}{cc} \textit{contribution} & \textit{contribution} \\ \textit{from} & \textit{from} \\ \textit{conductor A} & \textit{conductor B} \end{array}$$

This is algebraically the same as

$$V = S_A(T_1 - T_0) - S_B(T_1 - T_0) \quad (2-3)$$

or

$$V = (S_A - S_B)(T_1 - T_0) \quad (2-4)$$

Note that the difference in the Seebeck coefficients for the two conductors appears in Equation 2-4. This always happens in thermocouple loop analysis, and it is the property that is of practical interest in thermocouple thermometry. It is called the relative Seebeck coefficient (between material A and material B) and is written “ S_{AB} .” That is,

$$S_{AB} = S_A - S_B \quad (2-5)$$

Consequently, Equation 2-4 may be written as follows:

$$V = S_{AB}(T_1 - T_0) \quad (2-6)$$

This is the fundamental relation in thermocouple thermometry.

Thermocouple loop analysis provides the ability to characterize all thermocouple configurations and the consequences of damage to any part of a thermocouple circuit, which often accompanies typical applications.

Appendix A contains hypothetical problems and their solutions that illustrate the use of thermocouple loop analysis for characterizing both normal and abnormal thermocouple configurations. These examples illustrate the power of loop analysis for understanding how thermocouples work, both as-installed and after degradation experienced in use. Readers are encouraged to study these examples in order to become proficient in using the loop analysis method.

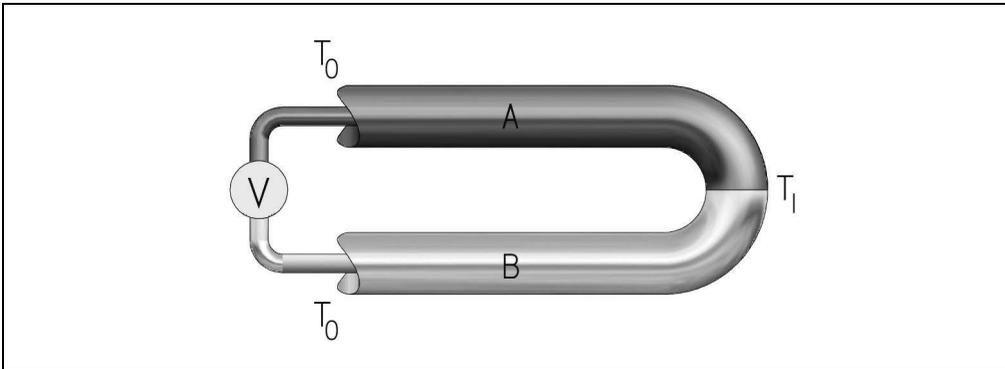


Figure 2-2. The Basic Thermocouple

An important use of thermocouple loop analysis is prediction of the voltage contribution of segments along a thermocouple circuit. Consider again the thermocouple circuit shown in Figure 2-2. The thermocouple consists of two homogeneous wires operating with a temperature difference of $T_1 - T_0$. At some point along the wires, there is a location where wires experience some other temperature, T_2 . Thermocouple loop analysis gives

$$V = S_A(T_2 - T_0) + S_A(T_1 - T_2) + S_B(T_2 - T_1) + S_B(T_0 - T_2) \quad (2-7)$$