

Practical Temperature Measurements*

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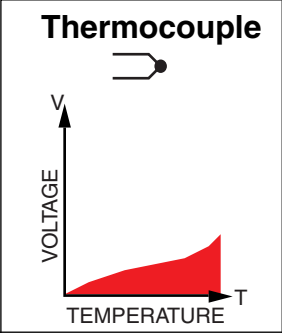
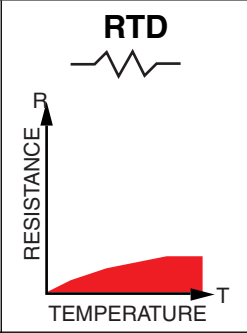
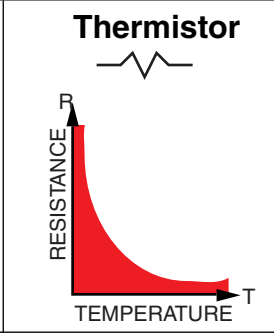
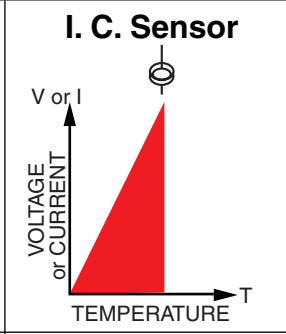
	Thermocouple 	RTD 	Thermistor 	I. C. Sensor 
Advantages	<input type="checkbox"/> Self-powered <input type="checkbox"/> Simple <input type="checkbox"/> Rugged <input type="checkbox"/> Inexpensive <input type="checkbox"/> Wide variety <input type="checkbox"/> Wide temperature range	<input type="checkbox"/> Most stable <input type="checkbox"/> Most accurate <input type="checkbox"/> More linear than thermocouple	<input type="checkbox"/> High output <input type="checkbox"/> Fast <input type="checkbox"/> Two-wire ohms measurement	<input type="checkbox"/> Most linear <input type="checkbox"/> Highest output <input type="checkbox"/> Inexpensive
Disadvantages	<input type="checkbox"/> Non-linear <input type="checkbox"/> Low voltage <input type="checkbox"/> Reference required <input type="checkbox"/> Least stable <input type="checkbox"/> Least sensitive	<input type="checkbox"/> Expensive <input type="checkbox"/> Current source required <input type="checkbox"/> Small $\varnothing R$ <input type="checkbox"/> Low absolute resistance <input type="checkbox"/> Self-heating	<input type="checkbox"/> Non-linear <input type="checkbox"/> Limited temperature range <input type="checkbox"/> Fragile <input type="checkbox"/> Current source required <input type="checkbox"/> Self-heating	<input type="checkbox"/> $T < 200^{\circ}\text{C}$ <input type="checkbox"/> Power supply required <input type="checkbox"/> Slow <input type="checkbox"/> Self-heating <input type="checkbox"/> Limited configurations

Figure 1

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*Courtesy Hewlett Packard Company

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INTRODUCTION

Synthetic fuel research, solar energy conversion and new engine development are but a few of the burgeoning disciplines responding to the state of our dwindling natural resources. As all industries place new emphasis on energy efficiency, the fundamental measurement of temperature assumes new importance. The purpose of this application note is to explore the more common temperature monitoring techniques and introduce procedures for improving their accuracy.

We will focus on the four most common temperature transducers: the thermocouple, the RTD, the thermistor and the integrated circuit sensor. Despite the widespread popularity of the thermocouple, it is frequently misused. For this reason, we will concentrate primarily on thermocouple measurement techniques.

Appendix A contains the empirical laws of thermocouples which are the basis for all derivations used herein. Readers wishing a more thorough discussion of thermocouple theory are invited to read REFERENCE 17 in the Bibliography.

For those with a specific thermocouple application, Appendix B may aid in choosing the best type of thermocouple.

Throughout this application note, we will emphasize the practical considerations of transducer placement, signal conditioning and instrumentation.

Early Measuring Devices - Galileo is credited with inventing the thermometer, circa 1592.^{1,2,3} In an open container filled with colored alcohol he suspended a long narrow-throated glass tube, at the upper end of which was a hollow sphere. When heated, the air in the sphere expanded and bubbled through the liquid. Cooling the sphere caused the liquid to move up the tube.¹ Fluctuations in the temperature of the sphere could then be observed by noting the position of the liquid inside the tube. This "upside-down" thermometer was a poor indicator since the level changed with barometric pressure and the tube had no scale. Vast improvements were made in temperature measurement accuracy with the development of the

Florentine thermometer, which incorporated sealed construction and a graduated scale.

In the ensuing decades, many thermometric scales were conceived, all based on two or more fixed points. One scale, however, wasn't universally recognized until the early 1700's, when Gabriel Fahrenheit, a Dutch instrument maker, produced accurate and repeatable mercury thermometers. For the fixed point on the low end of his temperature scale, Fahrenheit used a mixture of ice water and salt (or ammonium chloride). This was the lowest temperature he could reproduce, and he labeled it "zero degrees". For the high end of his scale, he chose human blood temperature and called it 96 degrees.

Why 96 and not 100 degrees? Earlier scales had been divided into twelve parts. Fahrenheit, in an apparent quest for more resolution divided his scale into 24, then 48 and eventually 96 parts.

The Fahrenheit scale gained popularity primarily because of the repeatability and quality of the thermometers that Fahrenheit built.

Around 1742, Anders Celsius proposed that the melting point of ice and the boiling point of water be used for the two benchmarks. Celsius selected zero degrees as the boiling point and 100 degrees as the melting point. Later, the end points were reversed and the centigrade scale was born. In 1948 the name was officially changed to the Celsius scale.

In the early 1800's William Thomson (Lord Kelvin), developed a universal thermodynamic scale based upon the coefficient of expansion of an ideal gas. Kelvin established the concept of absolute zero and his scale remains the standard for modern thermometry.

The conversion equations for the four modern temperature scales are:

$$^{\circ}\text{C} = 5/9 (^{\circ}\text{F} - 32) \quad ^{\circ}\text{F} = 9/5 ^{\circ}\text{C} + 32$$

$$\text{K} = ^{\circ}\text{C} + 273.15 \quad ^{\circ}\text{R} = ^{\circ}\text{F} + 459.67$$

The Rankine Scale ($^{\circ}\text{R}$) is simply the Fahrenheit equivalent of the Kelvin scale, and was named after an early pioneer in the field of thermodynamics, W.J.M. Rankine.

^{1,2,3} Refer to Bibliography 1,2,3.

Reference Temperatures

We cannot build a temperature divider as we can a voltage divider, nor can we add temperatures as we would add lengths to measure distance. We must rely upon temperatures established by physical phenomena which are easily observed and consistent in nature. The International Practical Temperature Scale (IPTS) is based on such phenomena. Revised in 1968, it establishes eleven reference temperatures.

Since we have only these fixed temperatures to use as a reference, we must use instruments to interpolate between them. But accurately interpolating between these temperatures can require some fairly exotic transducers, many of which are too complicated or expensive to use in a practical situation. We shall limit our discussion to the four most common temperature transducers: thermocouples, resistance-temperature detector's (RTD's), thermistors, and integrated circuit sensors.

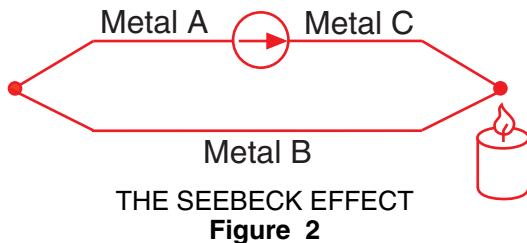
IPTS-68 REFERENCE TEMPERATURES

EQUILIBRIUM POINT	K	°C
Triple Point of Hydrogen	13.81	-259.34
Liquid/Vapor Phase of Hydrogen at 25/76 Std. Atmosphere	17.042	-256.108
Boiling Point of Hydrogen	20.28	-252.87
Boiling Point of Neon	27.102	-246.048
Triple Point of Oxygen	54.361	-218.789
Boiling Point of Oxygen	90.188	-182.962
Triple Point of Water	273.16	0.01
Boiling Point of Water	373.15	100
Freezing Point of Zinc	692.73	419.58
Freezing Point of Silver	1235.08	961.93
Freezing Point of Gold	1337.58	1064.43

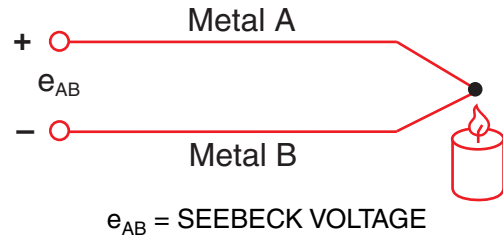
Table 1

THE THERMOCOUPLE

When two wires composed of dissimilar metals are joined at both ends and one of the ends is heated, there is a continuous current which flows in the *thermoelectric* circuit. Thomas Seebeck made this discovery in 1821.



If this circuit is broken at the center, the net open circuit voltage (the Seebeck voltage) is a function of the junction temperature and the composition of the two metals.



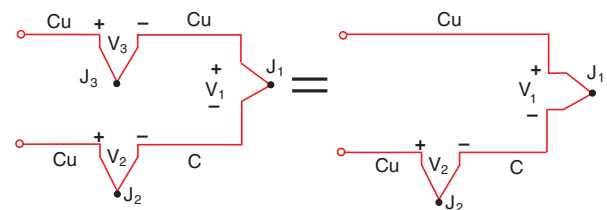
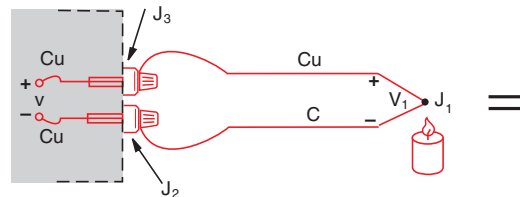
All dissimilar metals exhibit this effect. The most common combinations of two metals are listed in **Appendix B** of this application note, along with their important characteristics. For small changes in temperature the Seebeck voltage is linearly proportional to temperature:

$$\Delta e_{AB} = \alpha \Delta T$$

Where α , the Seebeck coefficient, is the constant of proportionality.

Measuring Thermocouple Voltage - We can't measure the Seebeck voltage directly because we must first connect a voltmeter to the thermocouple, and the voltmeter leads themselves create a new thermoelectric circuit.

Let's connect a voltmeter across a copper-constantan (Type T) thermocouple and look at the voltage output:



We would like the voltmeter to read only V_1 , but by connecting the voltmeter in an attempt to measure the output of Junction J_1 , we have created two more metallic junctions: J_2 and J_3 . Since J_3 is a copper-to-copper junction, it creates no thermal EMF ($V_3 = 0$), but J_2 is a copper-to-constantan junction which will add an EMF (V_2) in opposition to V_1 . The resultant voltmeter reading V will be proportional to the temperature difference between J_1 and J_2 . This says that we can't find the temperature at J_1 unless we first find the temperature of J_2 .