# 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 | ⁰C |
|---|---|---|---|
| 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.



THE SEEBECK EFFECT
**Figure 2**
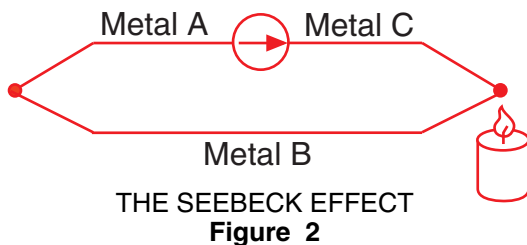
If this circuit is broken at the center, the net open circuit voltage (the Seebeck voltage) is a function of the junction temperature and the composition of the two metals.



$e_{AB}$ = SEEBECK VOLTAGE
**Figure 3**
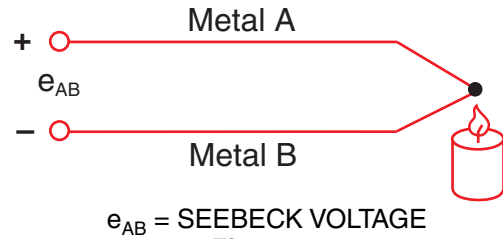
All dissimilar metals exhibit this effect. The most common combinations of two metals are listed in **Appendix B** of this application note, along with their important characteristics. For small changes in temperature the Seebeck voltage is linearly proportional to temperature:

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

Where $\alpha$, 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:
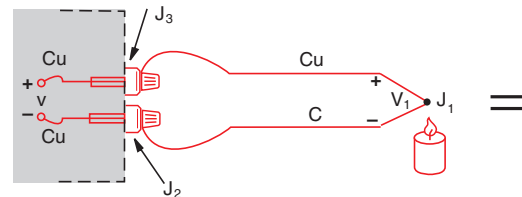


EQUIVALENT CIRCUITS
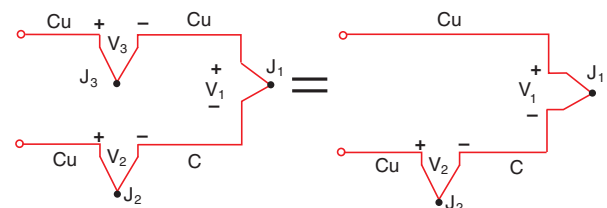


MEASURING JUNCTION VOLTAGE WITH A DVM
**Figure 4**

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 $J_2$.

# The Reference Junction
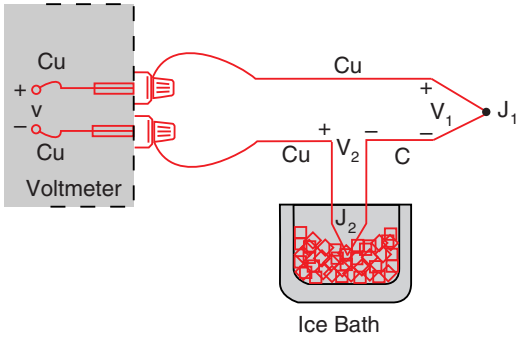


**EXTERNAL REFERENCE JUNCTION**
**Figure 5**

One way to determine the temperature of $J_2$ is to physically put the junction into an ice bath, forcing its temperature to be 0˚C and establishing $J_2$ as the *Reference Junction*. Since both voltmeter terminal junctions are now copper-copper, they create no thermal emf and the reading *V* on the voltmeter is proportional to the temperature difference between $J_1$ and $J_2$.

Now the voltmeter reading is (see Figure 5):

$V = (V_1 - V_2) \cong \alpha(t_{J_1} - t_{J_2})$

If we specify $T_{J_1}$ in degrees Celsius:

$T_{J_1} (˚C) + 273.15 = t_{J_1}$

then V becomes:

$V = V_1 - V_2 = \alpha [(T_{J_1} + 273.15) - (T_{J_2} + 273.15)]$
$\quad\quad = \alpha (T_{J_1} - T_{J_2}) = \alpha (T_{J_1} - 0)$

$V = \alpha T_{J_1}$

We use this protracted derivation to emphasize that the ice bath junction output, $V_2$, is *not* zero volts. It is a function of absolute temperature.

By adding the voltage of the ice point reference junction, we have now referenced the reading V to 0˚C. This method is very accurate because the ice point temperature can be precisely controlled. The ice point is used by the National Bureau of Standards (NBS) as the fundamental reference point for their thermocouple tables, so we can now look at the NBS tables and directly convert from voltage V to Temperature $T_{J_1}$.
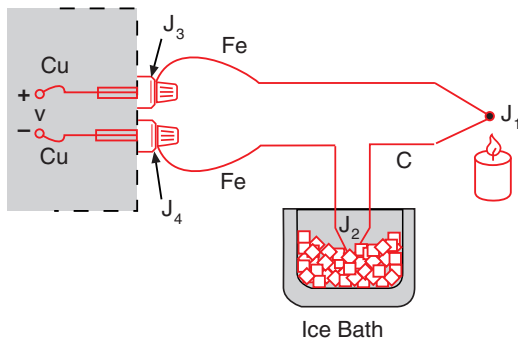


**IRON-CONSTANTAN COUPLE**
**Figure 6**
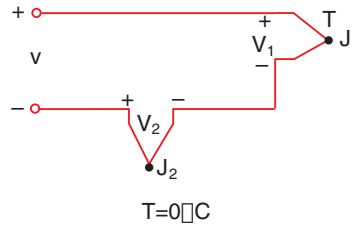
The copper-constantan thermocouple shown in Figure 5 is a unique example because the copper wire is the same metal as the voltmeter terminals. Let's use an iron-constantan (Type J) thermocouple instead of the copper-constantan. The iron wire (Figure 6) increases the number of dissimilar metal junctions in the circuit, as both voltmeter terminals become Cu-Fe thermocouple junctions.



$V_1 = V$
if $V_3 = V_4$
i.e., if
$T_{J_3} = T_{J_4}$
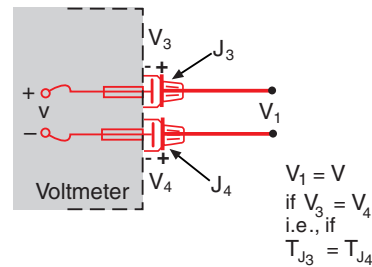
**JUNCTION VOLTAGE CANCELLATION**
**Figure 7**

If both front panel terminals are not at the same temperature, there will be an error. For a more precise measurement, the copper voltmeter leads should be extended so the copper-to-iron junctions are made on an *isothermal* (same temperature) block:
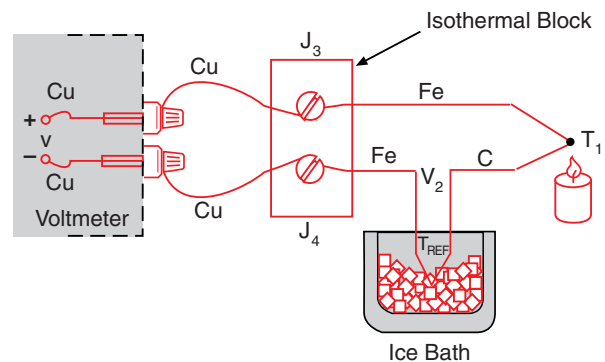


**REMOVING JUNCTIONS FROM DVM TERMINALS**
**Figure 8**

The isothermal block is an electrical insulator but a good heat conductor, and it serves to hold $J_3$ and $J_4$ at the same temperature. The absolute block temperature is unimportant because the two Cu-Fe junctions act in opposition. We still have

$$V = \alpha (T_1 - T_{REF})$$

# Reference Circuit

Let's replace the ice bath with another isothermal block
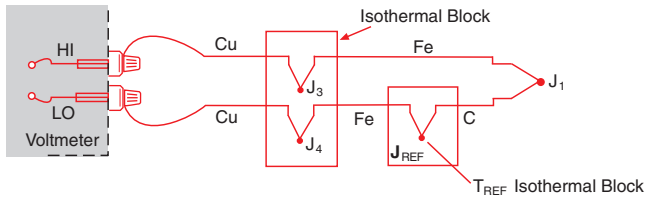


ELIMINATING THE ICE BATH
**Figure 9a**

The new block is at Reference Temperature $T_{REF}$, and because $J_3$ and $J_4$ are still at the same temperature, we can again show that

$$V = \alpha \ (T_1 - T_{REF})$$

This is still a rather inconvenient circuit because we have to connect two thermocouples. Let's eliminate the extra Fe wire in the negative (LO) lead by combining the Cu-Fe junction ($J_4$) and the Fe-C junction ($J_{REF}$).

We can do this by first joining the two isothermal blocks (Figure 9b).
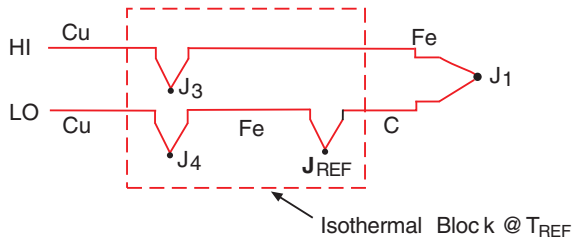


JOINING THE ISOTHERMAL BLOCKS
**Figure 9b**

We haven't changed the output voltage V. It is still

$$V = \alpha \ (T_{J_1} - T_{J_{REF}})$$

Now we call upon the law of intermediate metals (see Appendix A) to eliminate the extra junction. This empirical "law" states that a third metal (in this case, iron) inserted between the two dissimilar metals of a thermocouple junction will have no effect upon the output voltage as long as the two junctions formed by the additional metal are at the same temperature:



Isothermal Connection
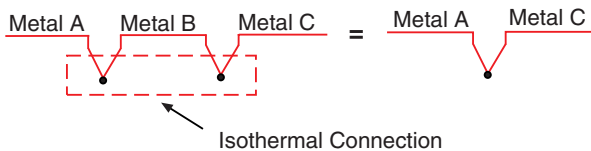
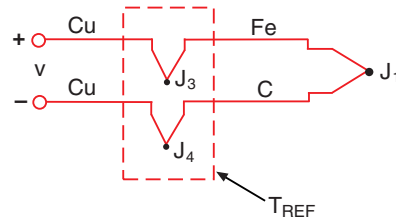Thus the low lead in Fig. 9b:     Becomes:
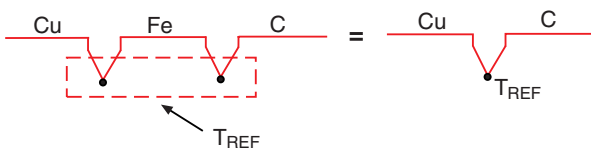


LAW OF INTERMEDIATE METALS
**Figure 10**

This is a useful conclusion, as it completely eliminates the need for the iron (Fe) wire in the LO lead:



EQUIVALENT CIRCUIT
**Figure 11**

Again, $V = \alpha \ (T_{J_1} - T_{REF})$, where $\alpha$ is the Seebeck coefficient for an Fe-C thermocouple.

Junctions $J_3$ and $J_4$, take the place of the ice bath. These two junctions now become the *Reference Junction.*

Now we can proceed to the next logical step: Directly measure the temperature of the isothermal block (the *Reference Junction*) and use that information to compute the unknown temperature, $T_{J_1}$.
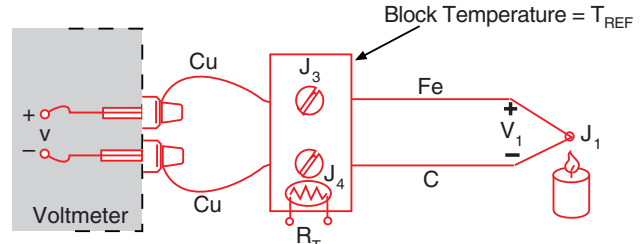


EXTERNAL REFERENCE JUNCTION-NO ICE BATH
**Figure 12**

A thermistor, whose resistance $R_T$ is a function of temperature, provides us with a way to measure the absolute temperature of the reference junction. Junctions $J_3$ and $J_4$ and the thermistor are all assumed to be at the same temperature, due to the design of the isothermal block. Using a digital multimeter under computer control, we simply:

1) Measure $R_T$ to find $T_{REF}$ and convert $T_{REF}$ to its equivalent reference junction voltage, $V_{REF}$, then
2) Measure V and add $V_{REF}$ to find $V_1$, and convert $V_1$ to temperature $T_{J_1}$.

This procedure is known as *Software Compensation* because it relies upon the software of a computer to compensate for the effect of the reference junction. The isothermal terminal block temperature sensor can be any device which has a characteristic proportional to absolute temperature: an RTD, a thermistor, or an integrated circuit sensor.

It seems logical to ask: If we already have a device that will measure absolute temperature (like an RTD or thermistor), why do we even bother with a thermocouple that requires reference junction compensation? The

single most important answer to this question is that the thermistor, the RTD, and the integrated circuit transducer are only useful over a certain temperature range. Thermocouples, on the other hand, can be used over a range of temperatures, and optimized for various atmospheres. They are much more rugged than thermistors, as evidenced by the fact that thermocouples are often welded to a metal part or clamped under a screw. They can be manufactured on the spot, either by soldering or welding. In short, thermocouples are the most versatile temperature transducers available and, since the measurement system performs the entire task of reference compensation and software voltage to-temperature conversion, using a thermocouple becomes as easy as connecting a pair of wires.

Thermocouple measurement becomes especially convenient when we are required to monitor a large number of data points. This is accomplished by using the isothermal reference junction for more than one thermocouple element (see Figure 13).

A reed relay scanner connects the voltmeter to the various thermocouples in sequence. All of the voltmeter and scanner wires are copper, independent of the type of thermocouple chosen. In fact, as long as we know what each thermocouple is, we can mix thermocouple types on the same isothermal junction block (often called a *zone box*) and make the appropriate modifications in software. The junction block temperature sensor $R_T$ is located at the center of the block to minimize errors due to thermal gradients.

Software compensation is the most versatile technique we have for measuring thermocouples. Many thermocouples are connected on the same block, copper leads are used throughout the scanner, and the technique is independent of the types of thermocouples chosen. In addition, when using a data acquisition system with a built-in zone box, we simply connect the thermocouple as we would a pair of test leads. All of the conversions are performed by the computer. The one disadvantage is that the computer requires a small amount of additional time to calculate the reference junction temperature. For maximum speed we can use hardware compensation.
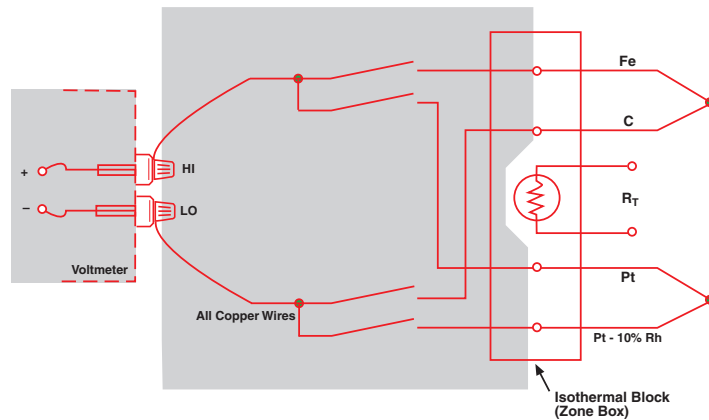


ZONE BOX SWITCHING
**Figure 13**

# Hardware Compensation

Rather than measuring the temperature of the reference junction and computing its equivalent voltage as we did with software compensation, we could insert a battery to cancel the offset voltage of the reference junction. The combination of this *hardware compensation* voltage and the reference junction voltage is equal to that of a 0°C junction.

The compensation voltage, *e*, is a function of the temperature sensing resistor, $R_T$. The voltage V is now referenced to 0°C, and may be read directly and converted to temperature by using the NBS tables.

Another name for this circuit is the *electronic ice point reference.*[6] These circuits are commercially available for use with any voltmeter and with a wide variety of thermocouples. The major drawback is that a unique ice point reference circuit is usually needed for each individual thermocouple type.

Figure 15 shows a practical ice point reference circuit that can be used in conjunction with a reed relay scanner to compensate an entire block of thermocouple inputs. All the thermocouples in the block must be of the same type, but each block of inputs can accommodate a different thermocouple type by simply changing gain resistors.
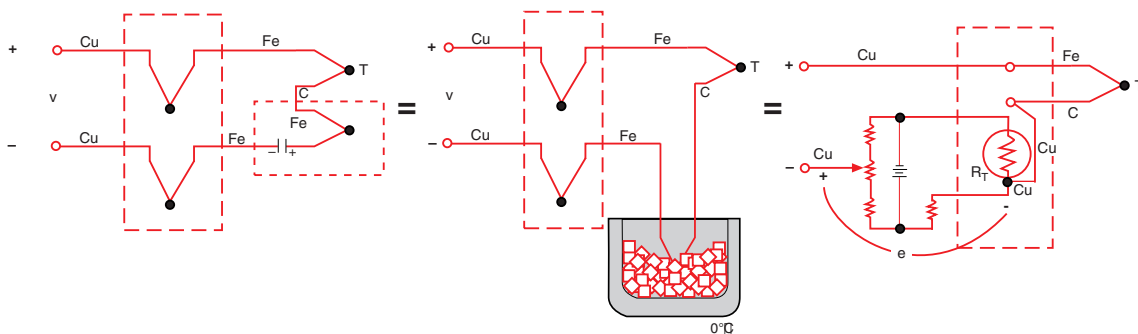
HARDWARE COMPENSATION CIRCUIT
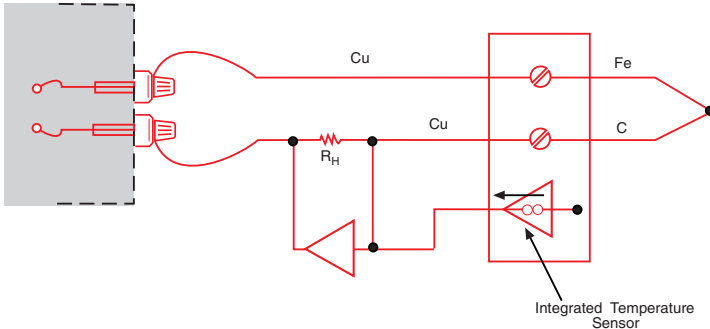**Figure 14**

[6] *Refer to Bibliography 6.*

**OMEGA** TAC-Electronic ice point™ and Thermocouple Preamplifier/Linearizer Plugs into Standard Connector



**OMEGA** Electronic ice point™ Built into Thermocouple Connector -"MCJ"



**OMEGA** ice point™ Reference Chamber. Electronic Refrigeration Eliminates Ice Bath



PRACTICAL HARDWARE COMPENSATION
**Figure 15**

The advantage of the hardware compensation circuit or *electronic ice point reference* is that we eliminate the need to compute the reference temperature. This saves us two computation steps and makes a hardware compensation temperature measurement somewhat faster than a software compensation measurement.

| HARDWARE COMPENSATION | SOFTWARE COMPENSATION |
|---|---|
| Fast<br>Restricted to one thermocouple type per card | Requires more computer manipulation time<br>Versatile - accepts any thermocouple |

**TABLE 2**

# Voltage-To-Temperature Conversion

We have used hardware and software compensation to synthesize an ice-point reference. Now all we have to do is to read the digital voltmeter and convert the voltage reading to a temperature. Unfortunately, the temperature-versus-voltage relationship of a thermocouple is not linear. Output voltages for the more common thermocouples are plotted as a function of temperature in Figure 16. If the slope of the curve (the Seebeck coefficient) is plotted vs. temperature, as in Figure 17, it becomes quite obvious that the thermocouple is a non-linear device.

A horizontal line in Figure 17 would indicate a constant $\alpha$, in other words, a linear device. We notice that the slope of the type K thermocouple approaches a constant over a temperature range from 0°C to 1000°C. Consequently, the type K can be used with a multiplying voltmeter and an external ice point reference to obtain a moderately accurate direct readout of temperature. That is, the temperature display involves only a scale factor. This procedure works with voltmeters.

By examining the variations in Seebeck coefficient,

*⁴ Refer to Bibliography 4.*

we can easily see that using one constant scale factor would limit the temperature range of the system and restrict the system accuracy. Better conversion accuracy can be obtained by reading the voltmeter and consulting the National Bureau of Standards Thermocouple Tables[4] on page Z-203 in this Handbook - see Table 3.

$T = a_0 + a_1 x + a_2 x^2 + a_3 x^3 \ldots + a_n x^n$
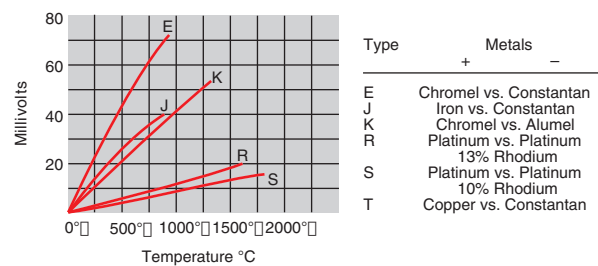
where

T = Temperature
x = Thermocouple EMF in Volts
a = Polynomial coefficients unique to each thermocouple
n = Maximum order of the polynomial

As n increases, the accuracy of the polynomial improves. A representative number is n = 9 for ± 1°C accuracy. Lower order polynomials may be used over a narrow temperature range to obtain higher system speed.

Table 4 is an example of the polynomials used to convert voltage to temperature. Data may be utilized in packages for a data acquisition system. Rather than directly calculating the exponentials, the computer is programmed to use the *nested polynomial* form to save execution time. The polynomial *fit* rapidly degrades outside the temperature range shown in Table 4 and should not be extrapolated outside those limits.



| Type | Metals |
| | + − |
|---|---|
| E | Chromel vs. Constantan |
| J | Iron vs. Constantan |
| K | Chromel vs. Alumel |
| R | Platinum vs. Platinum 13% Rhodium |
| S | Platinum vs. Platinum 10% Rhodium |
| T | Copper vs. Constantan |

THERMOCOUPLE TEMPERATURE
vs.
VOLTAGE GRAPH
**Figure 16**
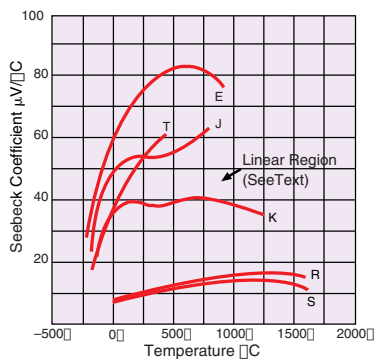
SEEBECK COEFFICIENT vs. TEMPERATURE
**Figure 17**

| mV | .00 | .01 | .02 | .03 | .04 | .05 | .06 | .07 | .08 | .09 | .10 | mV |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | TEMPERATURES IN DEGREES C (IPTS 1968) | | | | | | | | |
| 0.00 | 0.00 | 0.17 | 0.34 | 0.51 | 0.68 | 0.85 | 1.02 | 1.19 | 1.36 | 1.53 | 1.70 | 0.00 |
| 0.10 | 1.70 | 1.87 | 2.04 | 2.21 | 2.38 | 2.55 | 2.72 | 2.89 | 3.06 | 3.23 | 3.40 | 0.10 |
| 0.20 | 3.40 | 3.57 | 3.74 | 3.91 | 4.08 | 4.25 | 4.42 | 4.58 | 4.75 | 4.92 | 5.09 | 0.20 |
| 0.30 | 5.09 | 5.26 | 5.43 | 5.60 | 5.77 | 5.94 | 6.11 | 6.27 | 6.44 | 6.61 | 6.78 | 0.30 |
| 0.40 | 6.78 | 6.95 | 7.12 | 7.29 | 7.46 | 7.62 | 7.79 | 7.96 | 8.13 | 8.30 | 8.47 | 0.40 |
| 0.50 | 8.47 | 8.63 | 8.80 | 8.97 | 9.14 | 9.31 | 9.47 | 9.64 | 9.81 | 9.98 | 10.15 | 0.50 |
| 0.60 | 10.15 | 10.31 | 10.48 | 10.65 | 10.82 | 10.98 | 11.15 | 11.32 | 11.49 | 11.65 | 11.82 | 0.60 |
| 0.70 | 11.82 | 11.99 | 12.16 | 12.32 | 12.49 | 12.66 | 12.83 | 12.99 | 13.16 | 13.33 | 13.49 | 0.70 |
| 0.80 | 13.49 | 13.66 | 13.83 | 13.99 | 14.16 | 14.33 | 14.49 | 14.66 | 14.83 | 14.99 | 15.16 | 0.80 |
| 0.90 | 15.16 | 15.33 | 15.49 | 15.66 | 15.83 | 15.99 | 16.16 | 16.33 | 16.49 | 16.66 | 16.83 | 0.90 |
| 1.00 | 16.83 | 16.99 | 17.16 | 17.32 | 17.49 | 17.66 | 17.82 | 17.99 | 18.15 | 18.32 | 18.48 | 1.00 |
| 1.10 | 18.48 | 18.65 | 18.82 | 18.98 | 19.15 | 19.31 | 19.48 | 19.64 | 19.81 | 19.97 | 20.14 | 1.10 |
| 1.20 | 20.14 | 20.31 | 20.47 | 20.64 | 20.80 | 20.97 | 21.13 | 21.30 | 21.46 | 21.63 | 21.79 | 1.20 |
| 1.30 | 21.79 | 21.96 | 22.12 | 22.29 | 22.45 | 22.62 | 22.78 | 22.94 | 23.11 | 23.27 | 23.44 | 1.30 |
| 1.40 | 23.44 | 23.60 | 23.77 | 23.93 | 24.10 | 24.26 | 24.42 | 24.59 | 24.75 | 24.92 | 25.08 | 1.40 |

TYPE E THERMOCOUPLE
**Table 3**

| | TYPE E | TYPE J | TYPE K | TYPE R | TYPE S | TYPE T |
|---|---|---|---|---|---|---|
| | Nickel-10% Chromium(+) Versus Constantan(-) | Iron(+) Versus Constantan(-) | Nickel-10% Chromium(+) Versus Nickel-5%(-) (Aluminum Silicon) | Platinum-13% Rhodium(+) Versus Platinum(-) | Platinum-10% Rhodium(+) Versus Platinum(-) | Copper(+) Versus Constantan(-) |
| | -100°C to 1000°C ± 0.5°C | 0°C to 760°C ± 0.1°C | 0°C to 1370°C ± 0.7°C | 0°C to 1000°C ± 0.5°C | 0°C to 1750°C ± 1°C | -160°C to 400°C ±0.5°C |
| | 9th order | 5th order | 8th order | 8th order | 9th order | 7th order |
| $a_0$ | 0.104967248 | -0.048868252 | 0.226584602 | 0.263632917 | 0.927763167 | 0.100860910 |
| $a_1$ | 17189.45282 | 19873.14503 | 24152.10900 | 179075.491 | 169526.5150 | 25727.94369 |
| $a_2$ | -282639. 0850 | -218614.5353 | 67233.4248 | -48840341.37 | -31568363.94 | -767345.8295 |
| $a_3$ | 12695339.5 | 11569199.78 | 2210340.682 | 1.90002E + 10 | 8990730663 | 78025595.81 |
| $a_4$ | -448703084.6 | -264917531.4 | -860963914.9 | -4.82704E + 12 | -1.63565E + 12 | -9247486589 |
| $a_5$ | 1.10866E + 10 | 2018441314 | 4.83506E + 10 | 7.62091E + 14 | 1.88027E + 14 | 6.97688E + 11 |
| $a_6$ | -1. 76807E + 11 | | -1. 18452E + 12 | -7.20026E + 16 | -1.37241E + 16 | -2.66192E + 13 |
| $a_7$ | 1.71842E + 12 | | 1.38690E + 13 | 3.71496E + 18 | 6.17501E + 17 | 3.94078E + 14 |
| $a_8$ | -9.19278E + 12 | | -6.33708E + 13 | -8.03104E + 19 | -1.56105E + 19 | |
| $a_9$ | 2.06132E + 13 | | | | 1.69535E + 20 | |

TEMPERATURE CONVERSION EQUATION:  $T = a_0 + a_1 x + a_2 x^2 + \ldots + a_n x^n$

NESTED POLYNOMIAL FORM: $T = a_0 + x(a_1 + x(a_2 + x(a_3 + x(a_4 + a_5 x))))$ (5th order)

where x is in Volts, T is in °C

NBS POLYNOMIAL COEFFICIENTS
**Table 4**

The calculation of high-order polynomials is a time-consuming task for a computer. As we mentioned before, we can save time by using a lower order polynomial for a smaller temperature range. In the software for one data acquisition system, the thermocouple characteristic curve is divided into eight sectors, and each sector is approximated by a third-order polynomial.*



$$T_a = bx + cx^2 + dx^3$$
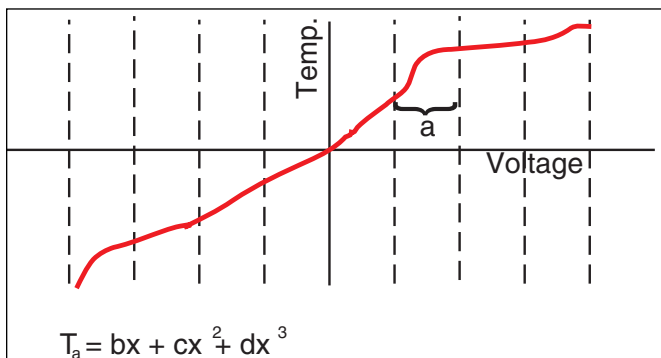
CURVE DIVIDED INTO SECTORS
**Figure 18**

*\* HEWLETT PACKARD 3054A.*

All the foregoing procedures assume the thermocouple voltage can be measured accurately and easily; however, a quick glance at Table 3 shows us that thermocouple output voltages are very small indeed. Examine the requirements of the system voltmeter:

| THERMOCOUPLE TYPE | SEEBECK COEFFICIENT (µV/°C) @ 20°C | DVM SENSITIVITY FOR 0.1°C (µV) |
|---|---|---|
| E | 62 | 6.2 |
| J | 51 | 5.1 |
| K | 40 | 4.0 |
| R | 7 | 0.7 |
| S | 7 | 0.7 |
| T | 40 | 4.0 |

REQUIRED DVM SENSITIVITY

**Table  5**

Even for the common type K thermocouple, the voltmeter must be able to resolve 4 µV to detect a 0. 1°C change. The magnitude of this signal is an open invitation for noise to creep into any system. For this reason, instrument designers utilize several fundamental noise rejection techniques, including tree switching, normal mode filtering, integration and guarding.