THERMOCOUPLE MEASURING INSTRUMENT CALIBRATION

Paul Withers
Xitron Technologies
San Diego, CA

THERMOCOUPLE THEORY

This paragraph explains the basic theory behind the operation of thermocouples, it is not intended as a full theoretical discussion of the physics involved.

The basic principle behind the operation of a thermocouple is that when a temperature gradient is imposed upon a metal conductor then a voltage gradient across the conductor is also created. The size of this voltage gradient is determined by the molecular structure of the metal, and thus differing metals exposed to the same temperature gradient will exhibit differing voltage gradients. The most obvious question arising from this is - Why don't we see the effect with just a single piece of copper wire? The answer to this is that, in order to measure the voltage drop across the piece of wire, a connection would have to be made from each end of the wire to the measuring instrument, and both terminals of the measuring instrument are at the same temperature, thus the total temperature gradient is zero, thus the total voltage gradient is also zero! If, however, dissimilar metals were used, e.g. the connection from the measuring device to the "hot" temperature were made using a copper wire, and the return connection were made using Constantan (i.e. a "T" type thermocouple), then although the overall temperature gradient is zero, the overall voltage gradient is non-zero due to the different voltage gradients in each wire. As demonstrated above, it is the temperature gradient between the "ends" of the wires which determines the voltage, and not the actual temperature at the junction (as is commonly believed), or the actual temperatures along the wires.

THERMOCOUPLE USE

Thermocouples are usually used either as a single junction, or as a pair of junctions. This paragraph describes these two methods, and their usages.

Single Junction Thermocouples

In this case, a wire of type "A" is connected to the positive terminal of the measuring instrument, and a wire of type "B" is connected to the negative side of the instrument. The junction of these two wires is at an unknown temperature T_U, and the measuring instrument terminals are at a temperature T_A.

Thus, the voltage drop across wire "A" is given by :

$$V_A = K_A * (T_U - T_A)$$

Where, K_A is the voltage drop per degree for wire "A".

And, the voltage drop across wire "B" is given by :

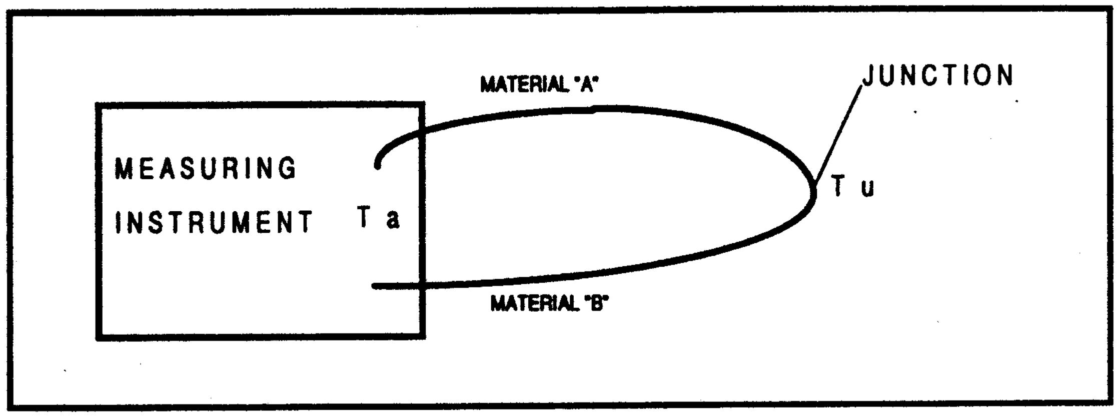
$V_B = K_B * (T_U - T_A)$

Where, K_B is the voltage drop per degree for wire "B".

Thus, the overall voltage measured will be VA - VB

i.e. $K_A * (T_U - T_A) - K_B * (T_U - T_A)$

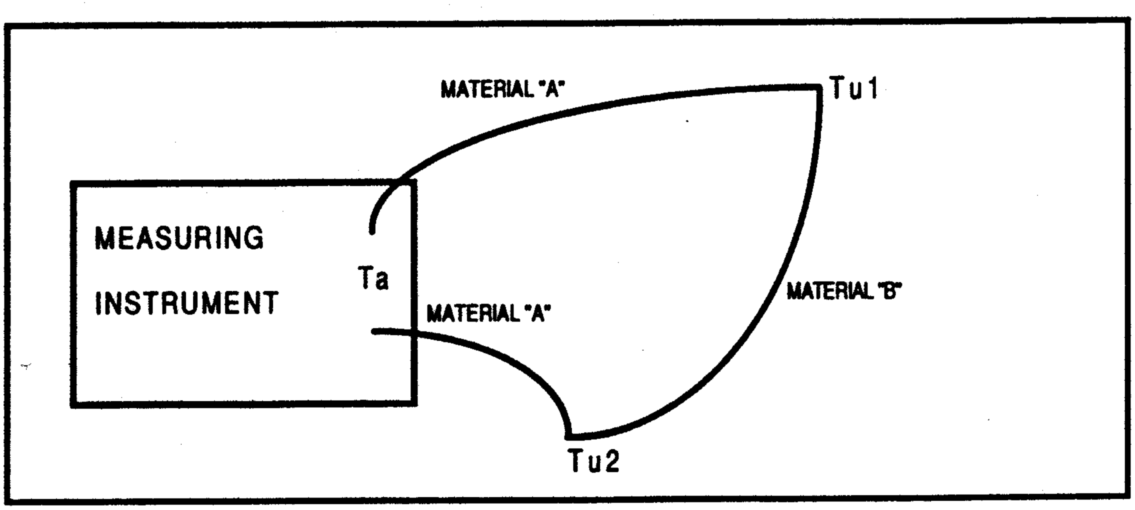
or $(T_U - T_A) * (K_A - K_B)$



Thus, the indicated voltage is dependant upon the difference between the junction temperature and the ambient temperature. This method is often used where it is desired to measure a temperature rise above ambient, as this is what is actually measured by this technique.

Two Junction Thermocouples

In this case, both connections to the measuring instrument are made using wire of type "A", and a wire of type "B" is connected between the two other ends of these wires. One junction (often called the "hot" junction) is at temperature T_{U1}, and the other junction (often called the "cold" or reference junction) is at temperature T_{U2}, and the measuring instrument terminals are at a temperature T_A.



The voltage drop across each wire "A" is given by -

$V_{A1} = K_A * (T_{U1} - T_A)$

$V_{A2} = K_A * (T_{U2} - T_A)$

Where, K_A is the voltage drop per degree for wire "A".

And, the voltage drop across wire "B" is given by :

$V_B = K_B * (T_{U1} - T_{U2})$

Where, K_B is the voltage drop per degree for wire "B".

Thus, the overall voltage measured will be $V_{A1} - V_B - V_{A2}$

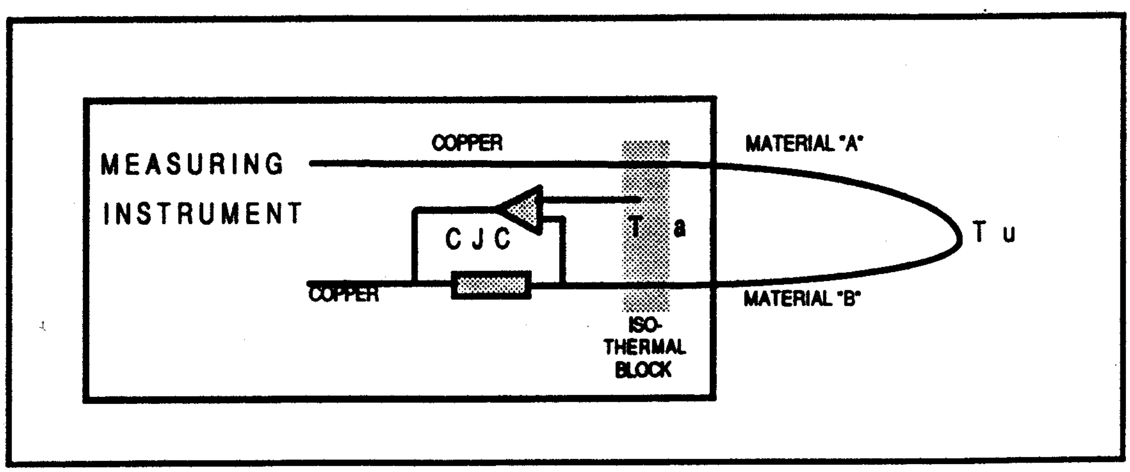
i.e. $K_A * (T_{U1} - T_A) - K_B * (T_{U1} - T_{U2}) - K_A * (T_{U2} - T_A)$

or $(K_A - K_B) * (T_{U1} - T_{U2})$

Thus, this technique measures the temperature difference between the two junctions. Normally, the second (reference) junction is maintained at 0°C in order that the actual temperature at the first (hot) junction is measured.

Cold Junction Compensation

The single junction technique offers the advantage (over the 2 junction technique) of not requiring any temperature reference, however it is often required that the actual temperature is measured and not the temperature rise above ambient. The 2 junction technique compensates for the ambient temperature, but requires an exactly known temperature environment at the second junction, as previously mentioned this is normally achieved by placing this junction in a maintained ice/water mixture (i.e. at 0°C). Several measuring instruments offer what is normally known as "Cold Junction Compensation" (CJC), this term indicates that the equipment has internal circuitry which measures the temperature of the input terminals and applies a correction voltage to the input which compensates for the ambient temperature term in the input (i.e. simulates the second junction at 0°C).



INACCURACIES & CALIBRATION TECHNIQUES

Single Junction Measurements

The most accurate measurements are made when using the single junction technique, i.e. when measuring uncompensated temperature rise above ambient. In this case, the major sources of inaccuracy are as follows -

1. Offset voltage in the measuring instrument. Several thermocouple types have outputs as low as 10uV/°C, thus an input zero offset of 2uV will yield an error of 0.2°C. The common thermocouple types have outputs of the order of 40uV/°C, thus a 2uV offset equates to an error of 0.05°C.

2. Thermocouples often have source impedances of the order of several hundred ohms, thus the measuring instrument must have a low input offset current. If the measuring instrument has an input current of 100nA, and a 30ohm thermocouple is used, then this yields a 3uV equivalent input offset voltage, thus up to 0.3°C error.

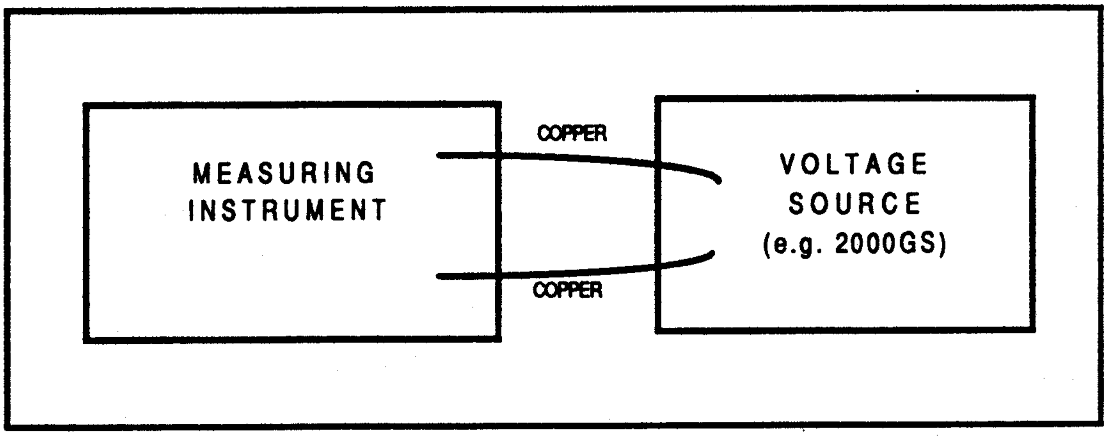
3. Any temperature difference between the input terminals will directly affect the temperature measurement, thus a 0.5°C difference will yield a 0.5°C error in the measurement. This affect is normally reduced by placing a thermal "shunt" (a low thermal resistance path) between the input terminals, and by the user reducing cold (or hot) draughts across the terminals. Most instruments have input terminals made from the actual thermocouple materials, this enables the "actual" input terminals (i.e. the point at which the material becomes copper, or at which it is measured) to be internal to the unit, and thus reduces the affects of draughts and makes the manufacture of the "thermal shunt" significantly easier, however it reduces the instrument to only being usable with that particular thermocouple type.

4. Scaling errors in the measuring instrument. At significant temperature indications, scaling errors in the measuring instrument can become a dominant affect, at 1000°C temperature rise a "K" type thermocouple will output 41.269mV, if the measuring instrument has 0.1% scaling accuracy then this translates to a 41.269uV error (i.e. approximately 1.1°C).

This type of measuring device is also the most accurate to calibrate, since no compensation needs to be made for the ambient temperature, either at the measuring or calibration instrument. In this case, the user simply connects the measuring instruments' input terminals to a voltage source using normal copper wires and sets the voltage level to that which will cause any particular indication on the measuring instrument. The main sources of error during calibration are as follows -

1. Voltage offsets in the calibrator output. As previously shown a 2uV offset will yield a temperature offset of up to 0.2°C. The ***Xitron Technologies 2000GS*** offers 0.2uV offset accuracy, thus this error become insignificant (this is included in the published 2000GS specifications for thermocouple simulation).

2. Thermal E.M.F. induced at the measuring instrument terminals. As previously mentioned, several measuring instruments offer input terminals made from the actual thermocouple material, thus voltages can be introduced when copper wires are used. If the actual thermocouple wires are used, then while this error source is apparently eliminated, it is merely "shifted" to the calibrator "end" of the wires (the junctions now being at the output terminals of the calibrator). The only method of reducing this error is to reduce draughts across the terminals, if the calibrator had terminals made from the specific materials then it would only be usable with that particular thermocouple type.



4. Scaling error in the calibrator output. This is effectively the same effect as scaling error in the measuring instrument. Thus if the calibrator has a 0.1% scaling accuracy, then this yields a 0.9°C error at 1000°C with a "S" type thermocouple. The *Xitron Technologies 2000GS* has a scaling specification of 0.002% (20ppm) at this level, this only yields a 0.02°C error (this is included in the published thermocouple simulation specifications).

Dual Junction Measurements

In this case, the major sources of measurement inaccuracy are as for the single junction case, with the following addition -

1. The "reference" junction must be maintained at a constant and known temperature. Even with a water/ice mixture, this can vary by as much as 0.25°C (or more) unless extreme care is taken. Alternatively, an electronic "ice-point" (or CJC) can be used in place of the second junction to compensate for the ambient temperature, see the discussion below for the error sources associated with this technique.

This type of measuring device is identical in calibration to the single junction type, since no compensation needs to be made for the ambient temperature, either at the measuring or calibration instrument. In this case, the user simply connects the measuring instruments' input terminals to a voltage source using normal copper wires and sets the voltage level to that which will cause any particular indication on the measuring instrument. With the *Xitron Technologies 2000GS* the user simply selects the desired thermocouple type, a 0°C reference temperature, and then selects any desired simulation temperature.

Cold Junction Compensated Measurements

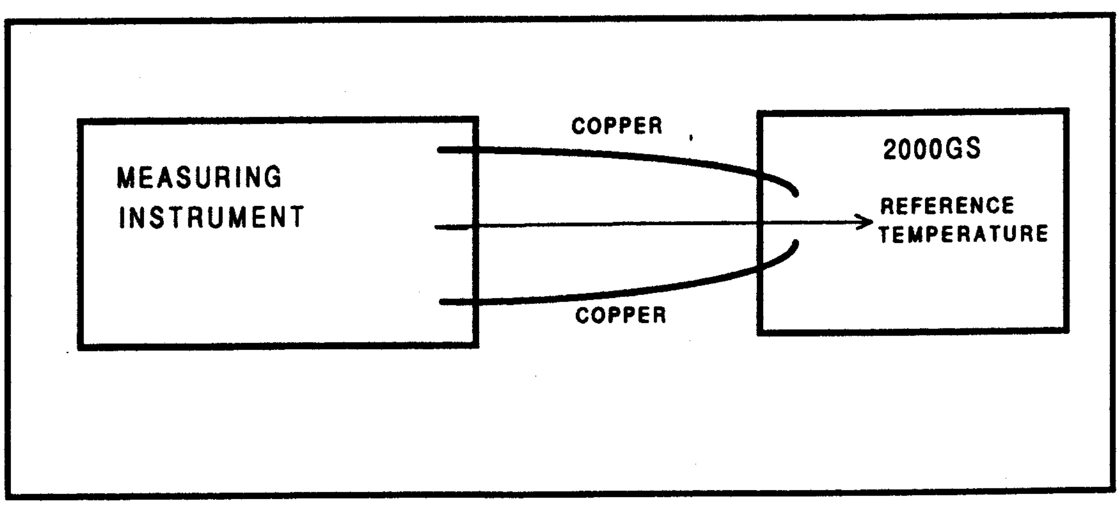
In this case, the major sources of measurement inaccuracy are as for the single junction case, with the following addition -

1. Any inaccuracy in the internal CJC will directly affect the measurement, thus if the measuring instruments' CJC is 1°C different from the actual terminal junction temperature, then a 1°C error will be present in the measurement indication. This is of particular importance when the CJC is external to the measuring instrument, since ambient temperatures may be different in these differing locations.

This type of measuring device is difficult to calibrate because the voltage source must include compensation for the ambient temperature in the same manner as the measuring device includes internally. There are several methods to achieve this -

1. Measure the actual ambient temperature at the terminals of the measuring instrument and adjust the calibrator output voltage accordingly. In general this involves the usage of an air thermometer, accuracies of down to 0.1°C are achievable using this technique, however the user must ensure that the temperature measurement is given sufficient time to settle and that the correction is correctly applied (with full allowance for non-linearity in the thermocouple characteristic). The ***Xitron Technologies 2000GS*** incorporates full compensation for the entered "reference" junction temperature thus any error sources associated with incorrectly applying this correction are eliminated. In this technique the user must use copper wires from the voltage source to the thermocouple measuring device, otherwise the ambient temperature difference between the voltage source and the measuring instrument will directly cause an error (alternatively, the user may use the desired thermocouple wire and measure the ambient temperature at the voltage source to achieve the same results).

2. Connect an "ice-point" reference in series with the voltage source and use the correct thermocouple wire throughout. This technique uses the "second" junction (at 0°C) to perform ambient temperature compensation, and the voltage source to simulate the "hot" junction. In this case the errors are purely



those of the voltage source (previously discussed) and those associated with the "ice-point" reference (also previously discussed). Again the *Xitron Technologies 2000GS* performs well in this situation, offering full simulation of a wide range of thermocouple types.

3. Use a voltage source which incorporates an internal CJC. In this case the user connects the output of the voltage source to the input of the measuring instrument using the actual thermocouple wire, the voltage source then continuously adjusts its' output voltage level for the measured ambient level, according to the correction for the particular thermocouple type. This method achieves good results after the system has stabilized in temperature (usually of the order of a few minutes) and provides the simplicity of operation as for the single thermocouple system described earlier. However, the inaccuracies associated with making (effectively) two temperature measurements (one in the measuring instrument, the other in the voltage source) indicate that accuracies of the order of 0.2°C are achieved, it being doubtful that temperature stabilization to better than 0.1°C is achievable in each position. The *Xitron Technologies 2000CJC* offers the user with the flexibility to select any of these methods when calibrating this type of measuring instrument, with the full range of thermocouple types being available from this instrument.

SUMMARY

In circumstances where the measuring device has no internal CJC, the *Xitron Technologies 2000GS* is readily capable of being used as a calibration source, with accuracies in the range of 0.02°C to 0.07°C being attainable (dependant on thermocouple type). When the measuring instrument has an internal CJC then the *Xitron Technologies 2000GS* may also be used in conjunction with either an "ice-point" reference junction or by monitoring the ambient temperature. Alternatively the *Xitron Technologies 2000CJC* may be used with either measuring instrument type, using either numerically entered "reference" junction temperatures (with the accuracy levels shown for the 2000GS), or using the CJC within the calibrator. When the internal CJC is used then accuracies in the range of 0.1°C to 0.2°C are readily attainable.

For reprints of this document, or additional information, please contact Stephen Merrill at (619) 458-9852.