WHITE PAPER

How to Prevent Temperature Measurement Errors When Installing Thermocouple Sensors and Transmitters

- **Temperature Measurement Background**
- **Building a Thermocouple**
- **Three Fundamental Principles of Thermocouples**
- **The Cold Junction & Cold Junction Compensation**
- **Connection Materials**
- **Thermocouple Sensor Wiring and Wire Routing**
- **A Review of Best Practices When Making Thermocouple Connections**
- **Important Principles to Keep in Mind**
- **Conclusion**

Temperature Measurement Background

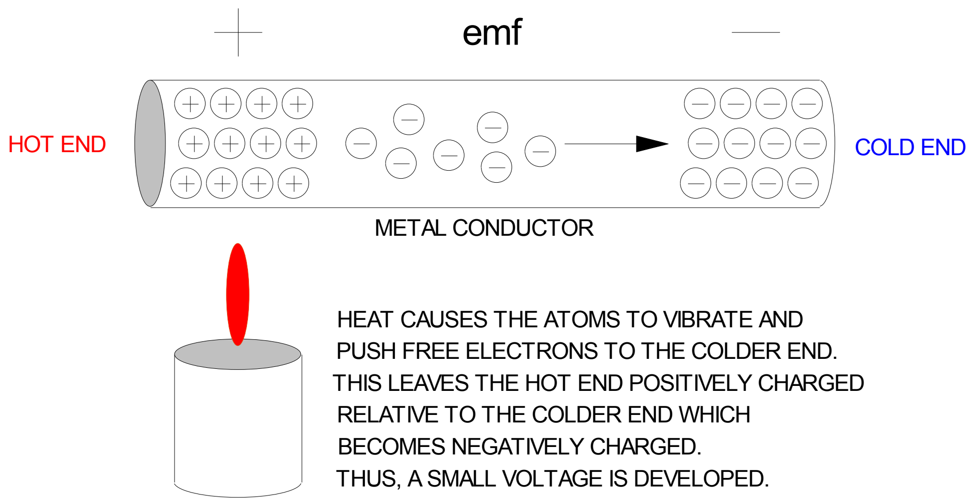
Nearly two-thirds of all temperature measurement in the US makes use of the thermocouple in some form. Likewise, most industrial applications remotely sense temperature using thermocouples, and optionally transmit the thermocouple signal some distance using industrial transmitters for the purpose of monitoring and controlling a process. An industrial transmitter is commonly used to amplify, isolate, and convert the low-level thermocouple signal to some other signal suitable for monitoring or retransmission. Unfortunately, the interface between these sensors and their mating instruments is widely misunderstood and this leads to system error. With a little understanding of thermocouples and how they work, these errors could be avoided. This paper will focus on the connectivity aspects of thermocouples and temperature transmitters, but can be extended to include any thermocouple instruments.

The thermocouple is a thermoelectric device used to measure temperature. It is typically comprised of a pair of dissimilar metal wires, joined at one end (commonly referred to as the hot junction). At the open end of this wire pair (the cold junction or reference junction), a low level voltage can be measured proportional to the difference in temperature between the hot junction and the cold junction. The thermocouple itself has the widest application temperature of available temperature sensor types and is capable of accurately measuring extreme hot or cold temperatures in very harsh environments. Since the thermocouple voltage signal is proportional to the difference in temperature between the ends, it requires a reference temperature measurement in order to determine the temperature at the opposite end (the hot junction). Unfortunately, the output voltage of a thermocouple is not linear with temperature and the conversion from voltage to temperature is normally done using a complex polynomial equation specific to the type of thermocouple, or optionally via lookup from a standard table of thermocouple voltage versus temperature for the particular thermocouple type. In the old days, thermocouple voltage was tabulated with respect to holding the reference junction in an ice bath, corresponding to 0°C (hence the term cold junction). Modern thermocouple types are still referenced to a cold junction of 0°C, and the standard table for the particular type tabulates their output voltage over temperature with respect to 0.000mV at 0°C. The use of these standard tables and a simple correction can reduce the conversion from voltage to temperature for any thermocouple to a combination of measured and tabulated voltages (more on this later).

Unfortunately, the nature of the thermocouple circuit is that it is prone to produce errors when mating it to a measurement device without a little insight into how these devices and their associated components work. This paper will review thermocouple behavior and outline some of the problems that people encounter when connecting to thermocouples to measure temperature. It contains helpful information for minimizing system error so that you can get the best possible performance from your thermocouple temperature measurement system. It is written primarily for industrial users of thermocouples and thermocouple transmitters, but much of this information can be extended to any thermocouple instrument. For more comprehensive information specific to thermocouples, please refer to whitepaper 8500-911, The Basics of Temperature Measurement Using Thermocouples, available free for download from www.acromag.com.

Building a Thermocouple

Thermocouples were developed based on a principle first demonstrated in 1822 by German physicist Thomas Seebeck. He observed that the application of temperature along a metal conductor will drive a charge separation in the conductor such that a small voltage is developed across it (see figure below). By using two dissimilar materials joined at one end in order to complete a circuit, he was able to measure this thermoelectric effect and relate the small voltage produced at the open end to the difference in temperature between the ends. This thermoelectric effect was only evident using two dissimilar metals, and he found that metals of different types produced different voltage levels for the same temperature difference. This thermoelectric effect was later coined as "The Seebeck Effect" and the Seebeck Coefficient of various materials remains as a measure of the magnitude of the thermoelectric voltage or "thermopower" that can be obtained in response to a temperature difference across that material. The Seebeck coefficient of a material has units of volts per Kelvin (V/K), or microvolts per Kelvin (uV/K), and is inversely related to a materials current carrier density. Thus, insulators will have a high Seebeck coefficient, while metals will have lower values due to their higher carrier concentration.



Specifically, by application of heat energy to one end of a conductor, the atoms that make up the metal will vibrate more. The kinetic energy produced by the rapidly vibrating atoms will spread along the wire and conduct heat from the hotter end to the colder end. These rapidly vibrating atoms at the heated end of the metal also drive free orbiting electrons to the colder end of the wire, leaving the hotter end more positively charged than the colder end. The magnitude of the resultant charge separation, or voltage, varies with different conductor materials. Further, neither the length of the conductor, or the gage of the conductor have any effect on the magnitude of the voltage generated. Because different materials exhibit different degrees of charge separation for the same temperature gradient, by tying these two conductors together at one end, we can measure a net voltage difference at the open end of this conductor loop that is directly proportional to the difference in temperature between the hot end (at the metal junction), and the cold end (the open end where we make our voltage measurement). By tabulating the voltage difference produced for various temperatures imposed on the hot end, while holding the cold end at a steady temperature, the relationship between the thermoelectric voltage and its respective temperature can be derived.

It's important to make the distinction that contrary to popular definitions of a thermocouple, it is the temperature difference between one end of a conductor and the other end that produces the small electromotive force (emf) or charge imbalance that leads us to the temperature difference across the conductor, <u>not the junction of the two dissimilar metals that form the thermocouple circuit</u>.

While you can form a thermocouple simply by combining two dissimilar metal conductors, a number of standard thermocouple types are available that utilize specific metals and alloys, combined to produce larger, more stable, and predictable output voltages with respect to applied thermal gradients. These standard types are referenced to a cold-junction at 0°C, and their thermoelectric voltages at specific temperatures are tabulated in their standard thermocouple tables relative to 0.000mV at 0°C. Note that these thermocouple voltages could have been referenced to any temperature, like a room temperature of 25°C, but 0°C was chosen because it's easily reproducible to within ±0.2°C using a mixture or slurry of ice and water. Thus, if you hold the cold junction at 0°C, your measured voltage will directly correspond to the thermoelectric voltage contribution of the hot junction temperature and this temperature can be easily found via look up in the standard table for the particular thermocouple type.

Three Fundamental Principles of Thermocouples

In order to understand how to correctly apply thermocouples, it's important to understand three fundamental thermoelectric principles which govern the behavior of thermocouples and that contain important inferences relative to properly conditioning them.

The first basic observation is The Law of Homogeneous Materials (see Wikipedia.org):

A thermoelectric current cannot be sustained in a circuit composed of a single homogeneous material by the application of heat alone, and regardless of how the material may vary in cross-section.

This law tells us a few important things about thermocouples:

- No current flows in a thermocouple circuit made of a single metal material by the application of heat alone.
- Two different metals are required to form a thermocouple.
- The size or gage of the wire does not affect the voltage produced.
- The voltage signal produced is independent of the temperature variations along its path.

If we instead choose to use the same metal in a thermocouple loop rather than two dissimilar metals, then the voltage produced by a temperature difference formed along the path between the hot and cold ends of our conductor pair would be cancelled by equal and opposite voltages produced in a return path, resulting in a net output voltage of zero.

Because two different wires are required to form a thermocouple and their size has no effect on the output signal, we can surmise that any current detected in a single wire thermocouple circuit with an applied thermal gradient along its length will prove that the circuit is not homogeneous.

If the junction of two dissimilar metals is maintained at some temperature, and the other end at another temperature, then the thermoelectric voltage produced by this circuit is independent of the temperature distribution along the conductor. This allows us to pass our thermocouple wires through hot and cold areas without affecting our measurement, as long as the individual wire material is consistent along this path. This is because the small voltages created as the continuous wire enters and leaves an area of varying temperature will sum to zero and have no net effect on our final end-to-end temperature measurement. It also allows us to add junctions along the wire path and not affect the output voltage, as long as the metal used to make the transitions is the same metal as the T/C wire (T/C connection blocks & extension wires).

A second important principle that governs our thermocouple application is The Law of Intermediate Materials (see Wikipedia.org):

The algebraic sum of the thermoelectric emf's in a circuit composed of any number of dissimilar materials is zero if all of the junctions are maintained at a uniform temperature.

This important principle tells us that if a third metal (or fourth, or fifth,…), different from the T/C materials is inserted into either or both thermocouple wires while making connection, then as long as the two new junctions produced into and out of the new material are kept at the same temperature, there will be no net voltage contribution driven by the presence of the new material in our measurement system.

This has profound value to our thermocouple temperature measurement system in that it gives us a way to introduce new metals to our circuit without affecting the measurement we are trying to make. However, our ability to overlook these errant thermocouple junctions introduced by the new metals will really depend on how well we can maintain the connections through the metals at the same temperature or isothermal.

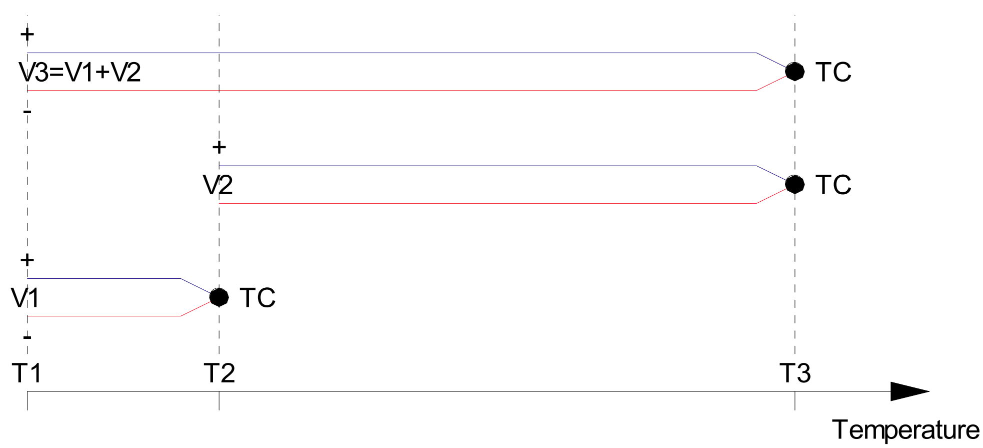
Extending this principle to a cold junction compensation circuit, we say that it is isothermal when its temperature remains constant, usually following a period of heat exchange with its surroundings where its temperature adjusts slowly over time (i.e. the warm-up period), then finally reaching thermal equilibrium. Don't forget that the cold junction circuit includes the metals that it ties to (the leads, the solder, the copper traces, etc).

A third important principle that governs the application of thermocouples helps us combine thermoelectric voltages algebraically using standard tabulated voltage values taken with respect 0°C. It is referred to as "The Law of Successive or Intermediate Temperatures" (see Wikipedia.org):

If two dissimilar homogeneous materials produce a thermoelectric voltage V1 when its junctions are at T1 and T2, and then produce thermoelectric voltage V2 when the junctions are at T2 and T3 , then the voltage produced when the junctions are at T1 and T3 will be V1 + V2, as long as T1<T2<T3.

This law permits a thermocouple calibrated at a given reference temperature to be used at any other reference temperature by making a simple mathematic correction. The importance of this law is that it helps us to accomplish cold junction compensation for the thermocouple by allowing us to simply subtract the equivalent cold junction thermoelectric voltage from the corresponding thermoelectric voltage produced at the hot junction temperature and get the actual voltage measured for a thermocouple between the cold junction and hot junction of a thermocouple circuit. This is illustrated graphically in the following figure:

LAW OF SUCCESSIVE OR INTERMEDIATE TEMPERATURES



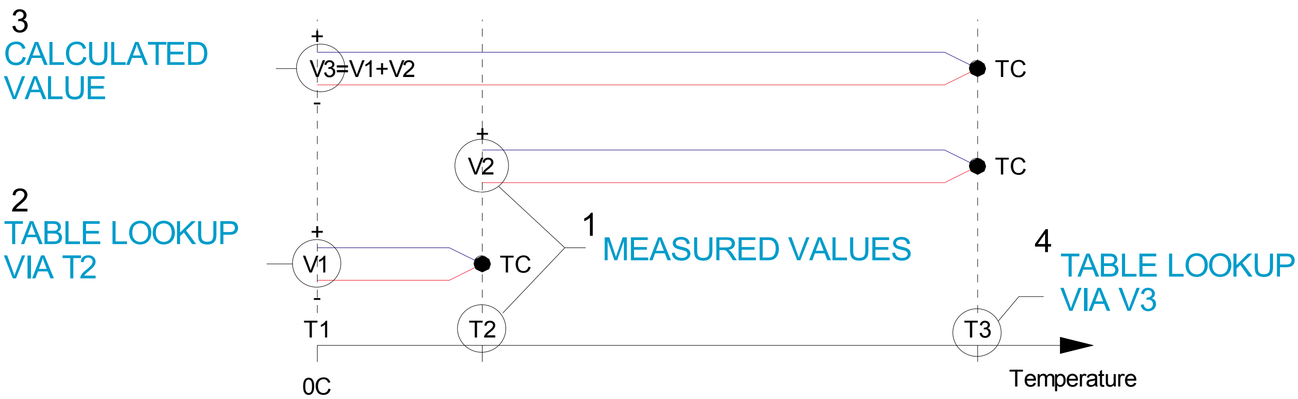
IF T1 < T2 < T3, THEN V3 = V1 + V2, AND V2 = V3 - V1

Because a thermocouple gives us a thermoelectric voltage related to the temperature difference between the hot and cold ends, we need the temperature at one end to determine the temperature of the opposite end. By this law, if we tabulate the voltage produced for a thermocouple type relative to some reference temperature (like 0°C), we can easily calculate the voltage of the same thermocouple relative to another temperature.

For example, with a J-Type thermocouple, you can refer to its thermoelectric voltage versus temperature table which gives you its output voltage at various temperatures relative to a cold junction at 0°C (V1 & V3 of Figure). If I want to relate the voltage produced (V2) by the same thermocouple at another temperature (T3), but relative to another cold junction temperature (T2), then I can compute it by simply subtracting V1 from V3 (V2 = V3 – V1, assuming T1 < T2 < T3).

Of course in most applications, temperature T3 is unknown and the cold junction temperature is not 0°C. In this instance, you can measure the voltage V2 of this thermocouple, and additionally measure the temperature of the cold junction T2. The voltage produced by the thermocouple relative to 0°C for the cold junction temperature can be looked up in the voltage versus temperature table for the thermocouple to get its equivalent thermoelectric voltage V1. Then you can add V1 to your measured voltage V2 to get V3, which can then be matched to its corresponding temperature T3 by again referring to the standard thermoelectric voltage versus temperature table for the thermocouple type. This is illustrated below:

LAW OF SUCCESSIVE OR INTERMEDIATE TEMPERATURES



IF T1 < T2 < T3, THEN V3 = V1 + V2, AND V2 = V3 - V1

The behavior of a given thermocouple type is normally characterized by a 5^{th} or higher order polynomial. The polynomial is used to calculate the voltages tabulated in the standard table for the particular type. The Law of Successive or Intermediate Temperatures allows us to more easily relate a measured voltage to temperature using these standard tables for the particular thermocouple type. It also gives us a convenient way of cold-junction compensating our thermocouple voltage measurement.

The Cold Junction and Cold Junction Compensation

You may be wondering why this paper is about to discuss cold junction compensation when it's supposed to be about making thermocouple connections. The reason is because your connections between the thermocouple and your instrument will play a major role in how well the instrument's cold junction compensation circuit operates on your signal. Unfortunately, the presence of cold junction compensation in your instrument will impose limits on your measurement circuit that must be respected. While you can't change the method an instrument uses to cold junction compensate your thermocouple signal, you need to be aware of the conditions that can exacerbate cold junction compensation error.

Our thermocouple measurement of the open-end voltage across a thermocouple only relates the thermoelectric voltage to the difference in temperature between both ends. That is, we need to know the temperature of the cold junction at one end in order to extract the sensed temperature from the other end (hot junction). Ideally, if both connections made at the measuring end were at 0°C, their thermoelectric equivalent voltage contribution to our measurement would be 0mV, allowing us to easily determine the sensed temperature by a simple lookup of our measured voltage in the standard voltage versus temperature table for our thermocouple type. Since keeping one end at 0°C cannot be easily assured in practice, the actual temperature of the cold junction connection points are usually measured separately. Then the measured T/C signal can be compensated for the non-zero thermoelectric contribution of the connection point or "cold junction", and we can extract the actual temperature at the remote end of our thermocouple circuit via a simple mathematical combination based on the measured voltage and measured temperature at our reference junction. This is what we mean by Cold Junction Compensation of our temperature measurement—it is the method by which we extract the actual sensed temperature at the hot junction of our thermocouple when our cold junction reference temperature is not 0°C.

As noted earlier, by the Law of Intermediate Materials, the sum of the thermoelectric voltages in a thermocouple circuit created by any number of dissimilar metals will be zero, if all of the mating junctions through the other metal are maintained at the same temperature. This gives us a way to connect a meter or transmitter to a thermocouple without affecting the measurement. All the additional thermocouple junctions that exist between the leads of the thermocouple, the leads of the meter, plus the copper and solder on the circuit board inside the meter does not affect the measurement, but only as long as we can keep the junctions into and out of all the intermediate metals at the same temperature. This is easier said then done, as it can be very difficult to maintain these elements at the same temperature, particularly when they extend some distance, or are individually subject to other influences that may unevenly affect their temperature. In most cases, the inadvertent thermocouples cannot be completely avoided in making thermocouple connections, as keeping them isothermal is difficult. Rather we work to keep their contribution small by simply limiting influences that vary temperature in their presence. Manufacturers of thermocouple instruments have two major challenges:

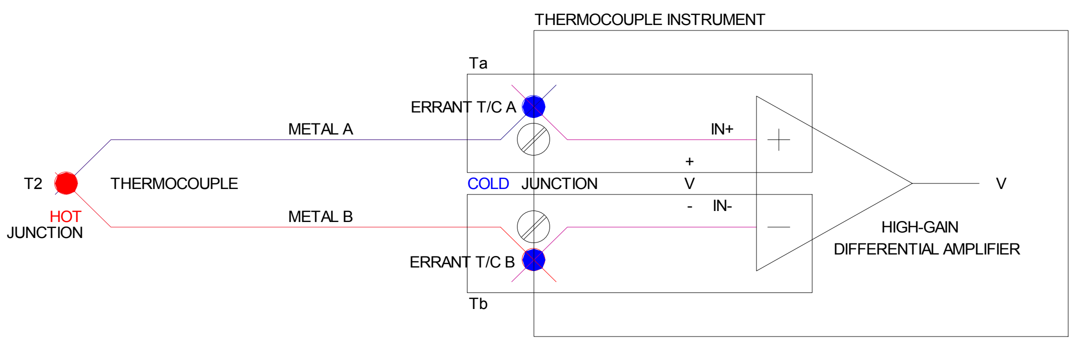
- Make the cold junction circuit isothermal as quickly as possible. The connection points to the thermocouple wires must be kept at the same temperature, or “isothermal”. Any temperature gradient from one point to the other will be a source of error (Recall the Law of Intermediate Materials explored earlier).
- The actual temperature of the connection points must be measured accurately, or at least as accurate as the thermocouple itself. The response time of the CJC sensor can also be a factor in maintaining accuracy, in particular for systems that require a fast response time, but may be subject to unstable cold-junction ambient conditions

Unfortunately in practice, it’s not easy to overcome these challenges. The performance of a particular thermocouple transmitter will generally reflect how well the manufacturer was able to meet these challenges and some compromise will always be required. For example, the transmitter may exhibit a very long warm-up time, making it vulnerable to temporary error driven by quickly changing temperatures or power conditions near the cold junction. Likewise, it may not measure its cold junction temperature as accurately as the thermocouple, or with an equivalent resolution, increasing the combined measurement uncertainty. In the field, users of these instruments may be following installation practices that exacerbate system or cold junction errors. The end result is that the errors contributed by cold junction compensation remain as one of the greatest sources of temperature measurement error in thermocouple measurement systems.

The Law of Intermediate Materials allows us to connect to our thermocouple to make a measurement using other connection metals without actually affecting the measured voltage. However, this is only true if the “other metals” used to make the T/C connections are at the same temperature. This means that our cold junction connections must be isothermal to keep them from negatively affecting our measured voltage. Likewise, to accurately associate our T/C voltage measurement with the hot junction temperature, the instrument must accurately measure the temperature of its “isothermal” cold junction circuit. Effectively, the accuracy of our temperature measurement system can only be as good as the accuracy of the measurement of the cold junction temperature.

A simplified thermocouple circuit including the cold junction is illustrated in the Figure below:

SIMPLIFIED THERMOCOUPLE MEASUREMENT CIRCUIT



CONNECTING OUR INSTRUMENT TO A THERMOCOUPLE GENERATES ADDITIONAL THERMOCOUPLES. BY THE LAW OF INTERMEDIATE METALS, WE CAN IGNORE THE NEGATIVE EFFECT OF THESE ERRANT THERMOCOUPLES IF WE CAN ENSURE THAT THIS MATERIAL IS ISOTHERMAL (Ta = Tb).

In an ideal world, instruments designed to interface with thermocouples would have a short warm up time (indicative of a fast cold junction compensation method), and also closely couple their cold junction temperature sensor to the cold junction terminals (or use terminals made of a compatible TC material). In most cases, the cold junction temperature sensor resides on the circuit board, while the actual cold junction connections are made outside the enclosure. Some manufacturers will try to embed the sensor in the bulk of the terminals (usually in the plastic), but most will simply locate the sensor as close as possible to the terminal connections on the circuit board. Both approaches are limited in their ability to precisely measure the real temperature of the cold junction connections and this will be reflected in their specifications, which usually indicate increased error with cold junction compensation enabled. Some manufacturers of thermocouple instruments will use cold junction terminals made of the same material as the thermocouple type. This pushes the cold junction down to the circuit board and in closer contact with an on-board temperature sensor. Unfortunately, it makes the instrument T/C type specific and the junction is still vulnerable to heat sources variations driven by components on the circuit board itself. Realistically, a temperature measurement instrument can only be as accurate its method of cold junction compensation. The reality is that thermocouple instruments come in many shapes, styles, and sizes, and their construction often involves tradeoffs that affect cold junction compensation relative to cost and performance. Be aware of the potential problem areas to help minimize error that can be attributed to cold junction compensation.

The best way to make the cold junction connections isothermal is to minimize the distance between them, balance their thermal masses, and reduce the thermal resistance between the connections (we want their heat to be evenly distributed across them). This means that anything that can drive a difference in temperature in the circuit between and including the cold junction connections, will build error into our thermocouple measurement system.

As an installer of this type of equipment, you need to protect the cold junction terminals from being affected by anything that could drive a temperature difference between the terminals, or force an uneven distribution of heat across them. You want to reduce thermal gradients driven by unstable ambient conditions in and around the cold junction connections and across its circuit. You should look at sources of varying temperature and your goal should be too make the thermal conditions acting on or near your cold junction circuit relatively stable. Examine adjacent sources of heat (power supplies, other modules, etc.), cooling fans, etc. Focus on items that operate intermittently or with variable power dissipation. It may not be possible to eliminate these items, but you can take measures that minimize their influence on the cold junction connections. For example, you might locate the measuring instrument (or at least its cold junction terminals) outside of the air stream of a cooling fan. You might consider adding space between the instrument and adjacent sources of heat. Consider the position of the instrument relative to its venting—is it positioned in such a way that it can more easily release hot air trapped inside? You should also be careful in routing the sensor leads to the instrument and make sure that at the point you break out the T/C leads to make your connection, that one lead is not subject to a source of heat that might cause its lead to conduct that heat to the cold junction connection and upset the thermal balance across the cold junction. You should also be careful to make sure that you do not introduce other inadvertent thermocouples to your loop that might upset the measurement. For example, have you selected external terminal blocks that match the material in the thermocouple? Or have you substituted less expensive isotherm blocks that require you to maintain the same temperature from ingress to egress (these blocks introduce one more path for inadvertent thermocouple connections to occur that will negatively affect your measurement if you cannot keep them isothermal)? Have you shared a termination with one T/C lead such that the adjacent wire is possibly heat sinking the T/C lead and upsetting the balance of temperature across the cold junction circuit? Small thermal gradients across the cold junction circuit may also occur as a result of the self-heating of components across the circuit board. So you might also consider changes to the operating state of your instrument that might drive changes in the internal power dissipation as it acts on the cold junction temperature sensor sharing that space.

Another source of “temporary” measurement error is often overlooked in thermocouple instrument connections and arises from the fact that changes in cold junction temperatures are tracked very slowly. That is, while thermocouples have a very fast response time, and a change in temperature at the hot junction is reflected very quickly in the voltage signal, changes that occur in and around the cold junction connections are tracked more slowly. This is usually a result of the larger thermal mass of the connectors and poor thermal coupling to the sensor used to measure its temperature. A slower responding cold junction does act to filter out some of the rapid changes in temperature that may occur at the cold junction, but it does not prevent the slow progression of an instrument to an accurate measurement after a notable shift in ambient conditions in and around the cold junction circuit. The cold junction connections and its embedded temperature sensor need more time to reach thermal equilibrium, causing periods of increased measurement error immediately following changes in cold junction ambient conditions.

This is evident by the long warm-up times specified for thermocouple instruments that include cold junction compensation. The measurement accuracy will generally improve as the change in ambient temperature is absorbed by the cold junction materials and its heat is evenly distributed across and between these connections and to the cold junction temperature sensor. For example, if someone suddenly opens a cabinet door and the hot air within rushes out causing the ambient around the cold junctions to shift—this will temporarily throw off the measurement until a new thermal equilibrium can be reached. Or perhaps, a fan is operated intermittently inside the cabinet causing the ambient to shift. For thermocouple transmitter connections, or connections to any electronic equipment that includes cold junction compensation, it might take from 30-60 minutes to reach a new thermal equilibrium. When assessing a temperature measurement system for the presence of these conditions, you also have to keep in mind that a shift in operating environment can be sourced by the circuit itself. That is, you must consider if the operating state of the circuit has changed abruptly such that internal power dissipation inside the circuit has changed appreciably. For a loop-powered two-wire transmitter, this would be true if the external load being driven has been reduced, or if the power supply voltage has changed or is excessive relative to that required to drive the load.

Some instruments will allow you to optionally disable cold junction compensation, and doing so can be a good indicator to determine how much error might be contributed by “thermal gradients” acting on the cold junction compensation circuit. To resolve these errors, take care to review module placement, adjacent influences, your wiring, etc.

In addition to conditions that magnify cold junction compensation error, other real sources of temperature measurement error will involve poor choices of connection materials (wire, cable, terminals, etc.) and thermocouple sensor to transmitter routing errors. These are outlined in the following paragraphs.

<u>Connection Materials</u>

The connection materials used to connect to a thermocouple will also impact the performance of your system. These materials include thermocouple terminal blocks, thermocouple wire and cable, and extension cable. Particulars of each of these elements are covered in the following paragraphs.

Terminal Blocks

Thermocouple wires are very fine by design, as this helps to prevent the mass of the wire from affecting the sensed temperature at the point of contact (the hot junction). But this has a disadvantage in that it makes the wires delicate and they may break easily. Manufacturers of thermocouple instruments like to include recommended wiring diagrams that show field thermocouples wired directly to cold junction input terminals on their instrument. But the reality is that most of the time, and for most industrial users, this is not the case. Rather, many applications will employ thermocouple terminal blocks separate from the instrument to land the thermocouple leads. Then, either thermocouple wire or thermocouple extension cable is used to connect between these external terminal blocks and the terminals of the transmitter. This extra set of terminals acts as a strain relief for the delicate T/C wire and facilitates change-out of a failed or faulty instrument (or field sensor), without upsetting the mating connections or equipment. Unfortunately, it’s also a potential source of system error, but mostly related to the choice of terminal block. Some users not familiar with the Law of Homogeneous Materials, or The Law of Intermediate Metals, will incorrectly chose standard panel wiring terminal blocks that subject the T/C leads to errant thermocouple voltages related to thermal gradient that may develop across this junction. It is highly recommended that you instead use terminal blocks designed specifically for thermocouple connection, or your system error will be negatively affected. There are three main types of thermocouple terminal blocks that can be utilized, and they come in many physical forms. Most will integrate a DIN rail connector and some may include a special socket for connecting the plug of a hand-held meter designed to monitor thermocouple voltage.

The best type of thermocouple connector will use a connection material that is the <u>same</u> as the thermocouple itself, or of a compatible alloy. In this instance, and by the Law of Homogeneous Materials, the introduction of this connector into your wired path will not affect the voltage measured by your transmitter, simply because it matches or closely matches the material in your thermocouple leads. Further, by the Law of Homogeneous Materials, temperature variations in this material will not affect your measured thermocouple voltage as it operates essentially transparent to the thermocouple wire. Of course, these connectors are generally more expensive and they are specific to the thermocouple type.

Errors that result from using matching thermocouple terminals will be a result of mismatching them to the thermocouple, or wiring them incorrectly. That is, they must match the T/C type exactly, and they are polarized according to the T/C material. In the US, the body color of thermocouple connectors is generally the same color, or a similar color, as the outer sheath of the matching thermocouple.

The next best type of thermocouple connector is the "universal" type. In this type, the material used to make connection to the thermocouple does not match the material in the leads of the thermocouple. Thus, it is less expensive than the best type mentioned above. Its design is such that it closely couples the ingress and egress wires with little or no intermediate material contact, forming a near isothermal union between the T/C wires, to closely mimic a homogeneous connection. The input T/C wire enters one end, and the output T/C wire enters the opposite end. The two wires overlap for some length within the connector and make good thermal and electrical contact, usually without passing through an intermediate metal. Two clamping screws and a common pressure plate are used to secure the wires. As a result, the negative effect of using a non-homogeneous material to facilitate contact is minimized.

A less expensive universal type is also available that also does not match the T/C material, but is of a special design that seeks to equalize the temperature across the union. These are sometimes referred to as "isotherm blocks". This type of connector exploits the Law of Intermediate Materials which allows any number of dissimilar metals to be introduced into the thermocouple circuit without affecting the measurement, but only as long as the path through the material can be maintained as isothermal or at the same temperature. The screws used to secure the wires are recessed to help protect them from air drafts. The plastic is designed such that ingress and egress paths are closely spaced. But because these blocks do make connection to the thermocouple using an intermediate conductor, they are less favorable because the temperature through the third metal must be maintained at the same temperature to null their effect on the measurement voltage. They can be confused with the other universal counterparts mentioned above, which are of similar design, but differ by the fact that they limit contact with an intermediate metal. While universal connection blocks have the advantage of being less costly, and of being applied universally to any T/C type, they do not form perfect isothermal unions and small voltage effects can develop, in particular where the diameters of the two wires differ, which is often the case.

Because either universal connector type may involve some intermediary contact, precautions should be taken with both to help ensure that a difference in temperature is not introduced between the ingress and egress paths of the connection block. Of course, some error can be introduced using any connection terminals, simply because they force a breakout of the individual T/C wires from their sheath and from each other, which might expose one wire to a different temperature than the other which could conduct heat to the connection block and upset its isothermal balance across the non-homogeneous connector path. Likewise, the presence of any thermocouple terminal block in the circuit path forces a breakout of the individual wires to make the connections and this breakout leaves a portion of this wire unshielded and more vulnerable to noise pickup. The better connection blocks will include screw connections for a cable shield, which is helpful to propagate the shield right to the instrument, and this should be your goal.

But your biggest concern in using any external terminal block to land your thermocouple field sensor wires is to make sure that standard, non-thermocouple types are never used for this purpose, or have been inadvertently substituted, as these provide an easy path for errant thermocouple voltages to develop that will negatively affect the accuracy of your thermocouple measurement. Don't try to justify use of standard terminal blocks using the Law of Intermediate Metals. These blocks use steel or a nickel-plated copper alloy for their contacts, and this will be prone to form errant thermocouples in your measurement system. They could only work if you could assure that the temperature on both sides of the connection block will always stay the same, or change at the same rate. This is highly unlikely in a packed control cabinet full of warm equipment, cooling fans, or other equipment that acts to heat or cool the interior in an uneven way.

T/C Extension Wire & Cable

For thermocouples that must pass over a long distance, thermocouple extension cable is often used to make thermocouple connections. These cables can cost half as much as thermocouple wire and are also used with thermocouple terminal blocks to extend T/C cable and will effectively lower the total cost of the sensor. Since these cables also come in sizes up to 14AWG, they are additionally used to reduce loop resistance over long distances. The extension cable will use similar materials to the thermocouple itself, or materials better suited for the intervening environment. The important thing to remember about the use of extension cable is that its thermoelectric behavior sometimes only approximates that of the thermocouple, and usually over a smaller temperature range. Their use will also usually limit the applicable range of the thermocouple by virtue of its insulation. Be cognizant of the extension wire used in an application and its limitations, as it can be an increasing source of error if applied improperly with respect to temperature and environment. Note that for base metal thermocouples (J, K, N, E, and T), the extension wire conductor is the same composition as the corresponding thermocouple and will exhibit the same thermoelectric properties as the thermocouple itself. However, for noble metal thermocouples (R, S, and B), the wire is usually a different alloy which will only approximate the noble metal thermoelectric properties, but over a more limited range. The conductor material is different because the noble metals contain Platinum, which would be very expensive to use as extension wire. Use of a different material is often not a problem, as these T/C types are generally used at higher temperatures and have a lower resolution, such that the small error contribution from using a different but similar extension wire is less significant. In all cases, the maximum application temperature will be limited by the type of insulation used by the extension wire and this is an important factor in selecting the proper extension wire for a given application.

To distinguish extension cable from thermocouple wire, the outer sheath of extension cable is color-coded differently than the outer sheath of thermocouple wires, but the individual wire insulation inside the sheath matches that of the thermocouple wire for the same type. The marking convention for both extension wires and thermocouple cables will use the T/C type designation with a “P” to indicate the positive lead, and “N” to indicate the negative lead. Extension cable wires will include a suffix of “X”. For example, a “JP” marking would refer to the positive lead of a J-type thermocouple, while “JPX” would designate the positive lead of a J type extension cable.

Often the term “extension cable” is used loosely to refer to two distinct types. A second type of thermocouple extension cable is referred to as compensation cable. With the exception of the noble metal T/C types (R, S, & B), true T/C extension cables match the composition of the thermocouple alloy, making them electrically indistinguishable from T/C wire. But compensation cables have a different composition than their mating T/C wire. They are formulated to approximate the behavior of the T/C wire, usually over a shorter temperature range. This is fine for temperature variations near the cold junction of a thermocouple circuit, such as the short distance between a thermocouple connection block and the instrument itself. The advantage of compensation cable is that it offers an even cheaper alternative than T/C wire and extension wire, albeit over a limited temperature range.

Potential measurement errors encountered with extension cables are often a result of poor connections which can drive unintended thermoelectric voltage contributions to the measurement system. Other sources of error using extension cables results from mismatching extension cable to T/C type, or reversing the polarity. If you need to increase the length of thermocouple wires or extend their distance, you must use the correct type of T/C extension cable for the thermocouple and you need to observe the proper polarity when making connections. Substitution of any other type will add errant thermocouple junctions to your measurement system increasing your error. If connection blocks are used to join the wires, then you should additionally select connectors made up of the same material type. Additional connection problems using extension cable arise when an incompatible material type is used for a given environment, or where extension wire has been mismatched to the sensor or its environment. For example, thermocouples that use iron as a material will be subject to corrosion that may impede continuity, particularly in wet environments. Extension cable that does not match the thermocouple type exactly, will have a lower operating temperature range and may not be suitable for use close to the hot junction.

You should be aware that when using thermocouples outside the US, you may need to verify the applicable color coding. Europe, Japan, and Germany all use different conventions than the standards that have originated in the US. There is little chance of a harmonized standard in this regard, as the varying conventions have been in place for more than 60 years.

Thermocouple Sensor Wiring and Wire Routing

The path that you take in routing your sensor to your instrument will also impact your ability to achieve accurate results. You must consider that the fine leads of the thermocouple are made from other materials than copper and have a higher resistance than copper, making them more sensitive to noise pickup, in particular AC-coupled noise. Additionally, because thermocouples output a low thermoelectric voltage (a low signal to noise ratio), have high conductor impedances, and drive high impedance inputs with large gain in the measuring equipment, this makes long thermocouple routes an easy pickup for errant signals from nearby equipment and power lines. You need to take measures in routing your thermocouple leads and extension cables that respect their inherent sensitivity to noise pickup. Here are some guidelines to observe:

- Route T/C wires defensively, keeping them from combining with power wires. Operation in noisy environments or nearby electric motors may benefit from the use of screened extension cable.
- Avoid combining the T/C leads over long parallel paths with output or signal wires, which can inductively couple noise into the T/C wires.
- Minimize the length or loop area where the thermocouple cables or wires part to make a connection to the instrument or to thermocouple terminal blocks.
- Individual wires can be twisted together to make sure that both leads pickup the same signal (i.e. they reject common mode noise, see below).

Note also that while the thermocouple signals are small, much larger voltages may exist at the instrument itself due to the presence of common-mode voltages driven by inductive pickup along the sensor wire, or via multiple earth ground connections in the system. For example, inductive pickup is a common problem when using a thermocouple to sense the temperature of a motor winding or power transformer. In some applications, multiple earth grounds may be inadvertent, perhaps when using a non-insulated or grounded thermocouple to measure the temperature of a hot water pipe. In this instance, any poor connections to earth ground may drive a few volts of difference between the pipe and measuring instrument. In general, the instrument makes use of high-quality, high-gain, differential instrument amplifiers which will reject this noise as it is common to both input leads, but only as long as the voltages remain within the common-mode input range of the instrument amplifier, which is usually limited to only ±3V or ±5V by the internal DC voltage rail of the instrument. This ability to reject common-mode noise is strong for signals near DC, but weaker as the frequency of the noise increases. As noted above with errant noise, it usually helps to twist the wires together to make sure that both leads pickup the same signal (i.e. common mode noise is rejected by the amplifier). Always keep the lead length short or the loop area small where the cable conductors part to make a connection to the instrument.

For long cable runs, you should consider using screened cable with earth ground applied at the instrument end to minimize noise pickup by the instrument. There are different types of screened cable which include copper or mylar/aluminum tape, or even screened twisted pair if required. You have many options to combat noise pickup along the thermocouple circuit and you should consult with your cable vendor. The following link is a good resource for learning about other options in this regard:

{HYPERLINK "http://www.thermocables.com/faq.htm"**}**

Additionally consider that the junction of a thermocouple sensor is commonly grounded, and often in direct contact with surrounding case metal which gives it a faster response time, but can be troublesome for noise pickup and potential ground loop error. Ground loop errors will significantly increase your measurement error, often many times greater than the error contributed by the other influences we've discussed. Ungrounded junction T/C sensors are available where sensor isolation is required, but usually with an increase in response time. You may alternatively select an isolated transmitter for use with a grounded thermocouple sensor to combat ground loop error.

A Review of Best Practices When Making Thermocouple Connections

Considering the thermocouple connection carefully, and the potential problems with associated with cold junction compensation, plus the cables and connectors used to make the connection, here are some things that you should consider or watch out for in your thermocouple transmitter applications if you want to increase the accuracy of your temperature measurement system:

Have you mounted the transmitter inside of an enclosure to help shield its cold junction circuitry from quickly varying air currents caused by the movement of personnel, equipment, heating and AC system fans, and outdoor air currents?

- Are the cold junction connections left exposed to open air drafts that may unevenly distribute heat across the connections? Are the input terminals of the transmitter vulnerable to drafts driven by heating or cooling-fans?
- Is the thermocouple transmitter adjacent to a power supply or other “warm” device that may be causing one terminal to be warmed above the opposite terminal, upsetting its isothermal balance? Are the leads of the thermocouple fanned out of their sheath such that one lead may be subject to a different temperature than the other lead and conducting heat to its cold junction?
- Have you observed proper polarity in connecting your sensor, any extension cables, and any matching thermocouple terminal blocks? Note that all T/C types are color-coded and the RED wire is always the Negative Lead for American or ANSI thermocouple types. This is often confused as it is opposite the convention used for DC power where a red wire typically denotes positive.
- Have you allowed the module up to 60 minutes of warm-up time after applying power to reach thermal equilibrium across the cold junction circuitry necessary for accurate cold junction compensation?
- Is the transmitter mounted in a position that retards the flow of air across, or through the unit, such that its internal ambient might run to a higher temperature? Are its vents blocked by adjacent circuits, cables, or other obstructions? Note that the larger internal ambient that would result in this situation will increase the potential for error driven by a longer thermal warm-up of the circuit and wider variation in temperature as it acts on the cold junction temperature sensor inside the unit.
- Have you positioned modules while allowing air space between them to minimize the negative effect that adjacent sources of heat can have on the cold junction connections by upsetting their isothermal balance? Are modules spaced farther apart from significant sources of heat, such as power supplies, cooling fans, etc?
- Have you spread the thermocouples wires apart such that there is a larger than required separation gap between them before they connect to your cold junction terminals? If the cold junction terminals do not match the thermocouple material, this breakout could drive a difference in temperature between the wires prior to connecting to the terminals, in particular if the individual leads are routed differently or subject to different temperature influences. This difference in temperature can act on the non-homogeneous cold-junction circuit to upset the thermal balance required across the cold junctions. Breaking the wires out of their shield also makes them more prone to noise pickup. Sometimes the thermocouple sheath is pulled back to individually tag the T/C wires, and while this looks nice, it opens the door for another potential source of error.
- Are you using crimp-on pins or terminals on the ends of the T/C wires to protect the wire when inserted into the instrument? Note that while this is done with good intention, the crimp-on material is generally not the same as the thermocouple. Thus, it effectively extends the cold junction circuit. In many cases, the thermocouple is actually displaced from its terminal by this small thermal mass making its junction more vulnerable to developing a temperature difference through it. Further, with some pin-style crimp-on connectors, the clamp of the cold junction terminals on the instrument now makes contact with the thermocouple over a smaller area (increasing the thermal resistance of the connection). In general, you will get better performance by simply connecting the T/C wire or cable directly to the cold junction terminals of the unit. Most terminals will be a cage-clamp style that already does a good job of protecting the wire and the use of these additional crimp terminals is not necessary.
- Is one lead of the thermocouple sharing a connection with another wire at the same terminal block? The presence of this other lead can heat-sink the T/C lead, driving a temperature difference across the cold junction that will contribute error. This negative effect will be magnified if the adjacent lead is of a gage greater than that of the T/C wire itself. Not only does this amplify the heat sink capability of the wire, it increases the thermal resistance between the adjacent T/C lead wire and the cold junction contact. For example, some transmitter models may require that a T/C break jumper be installed and it will share a terminal with one of the T/C lead wires—keep this jumper wire short and of a gage no greater than the T/C wire itself to avoid increasing measurement error.
- Has a fault or other condition at the transmitter caused its circuit to increase or change its nominal power dissipation and affecting the heat distribution across the cold junction connections? For example, a two-wire temperature transmitter will dissipate more heat internally if its load resistance is reduced or shorted, or if its power supply is excessive relative to the level needed to drive the load.
- Be sure that any terminal blocks used in your thermocouple circuit are not the standard type which will drive errant thermocouple voltages in your thermocouple measurement circuit. These connections should only use thermocouple terminal blocks, or isotherm (universal) terminal blocks designed specifically for thermocouple connection.

For multiple instruments mounted adjacent to one another, but arranged from bottom to top (i.e. perhaps on a vertical DIN rail), consider the chimney effect of rising heat that will cause the units on top to be naturally heated by the units on the bottom, possibly affecting their accuracy, as this heat will be unevenly distributed across the cold junction connection circuitry? Thermocouple transmitters are typically designed with their input terminals positioned at the bottom and power terminals at the top when mounted on a horizontal DIN rail to reduce errors via the chimney effect. It's best to respect this arrangement when field-mounting the units.

- Have you taken care to reduce the strain imposed on the thermocouple wires? Watch out for wires that are damaged or broken by pulling and routing, rough handling, vibration, or other stress. Note that thermocouple wires are very fine by design, as this helps to prevent the mass of the wire from affecting the sensed temperature at the point of contact (the hot junction). But this has a disadvantage in that the wires can be delicate and may break easily.
- Make sure that your thermocouple circuit only uses thermocouple wire or thermocouple extension wire of the same type. In some instances, an uninformed service technician may inadvertently substitute standard cable or cable of a different T/C type, which will drive error voltage into your system.
- Keep the sensitive thermocouple wires away from other current-carrying conductors, electric motors, switching solenoids, and sources of RF noise to avoid pick up. For long runs in noisy environments, you are probably better off converting the T/C signal to 4-20mA locally, for transmission of the signal over the longer distance.
- Watch the loop resistance of your thermocouple circuit and try to keep it below 100Ω. This is important because most thermocouple instruments will include T/C break detection, which involves running a small current through the sensor to detect a lead break. This small current passing through the high resistance T/C wire will generate voltage error if resistance is excessive. The increased sensor resistance also makes the sensor more susceptible to errant voltage drops as a result of coupled noise currents. When calculating this resistance, remember that your total wire length doubles by virtue of the return path. Note that by the law of homogeneous materials, you can safely extend the T/C wire with extension cable of a larger gage, which will have a lower resistance than that of the finer T/C wire.

Important Principles to Keep in Mind

By the Law of Homogeneous Materials, the thermal voltage generated by a thermocouple is NOT affected by temperature changes elsewhere along the circuit path as long as the two metals are homogeneous (or nearly homogeneous as is the case with some extension wire). Also by the Law of Homogeneous Materials, you can insert junctions of the same wire material without affecting the measured voltage (i.e. splices and extensions that use connectors that match the TC lead metal).

By the Law of Intermediate Materials, if another dissimilar metal is inserted into either or both leads, it will not affect the output voltage of the thermocouple if the junctions into and out of the third metal are kept at the same temperature. This allows us to connect our instrument to our thermocouple without affecting our measurement as long as we can ensure a constant temperature through the chain of extra metals added to the circuit.

By the Law of Successive or Intermediate Temperatures, the non-linear T/C sensor requires a complicated polynomial to resolve its voltage versus temperature relationship, but this can alternately be reduced to a simple mathematical combination of our measured thermocouple voltage with voltages found in a standard voltage versus temperature table for the thermocouple type. This allows us to cold junction compensate a measured voltage by simple addition or subtraction of voltage values using our measured voltage, the standard table, and a measured reference temperature. Likewise, we can compute an unknown temperature by adding voltage that corresponds to our reference junction temperature to our measured voltage and looking up the corresponding temperature that corresponds to this voltage in our standard table for our thermocouple. Simply stated, this law allows a thermocouple calibrated at one reference temperature to be used at any other reference temperature via a simple algebraic correction.

Conclusion

A keen understanding of the three basic laws of thermocouples: Homogeneous materials, Intermediate Metals, and Successive or Intermediate Temperatures, can be very helpful in weeding out potential sources of error in our thermocouple measurement system. It's also valuable in properly selecting and applying the components commonly used to connect thermocouples to instruments. This coupled with an awareness of how cold junction compensation works and the limitations it imposes on our measurement and wiring practice, will go a long way towards weeding out thermocouple measurement system error.

About Acromag

Acromag is a leading manufacturer of temperature transmitters and signal conditioners for use with thermocouple and RTD sensors. These instruments convert the sensor input to a proportional 4-20mA DC current, DC voltage, Modbus, Profibus, or Ethernet signal to interface with a PC, PLC, DCS, or other control equipment.

Acromag has designed and manufactured measurement and control products for more than 50 years. They are an AS9100 and ISO 9001-certified international corporation with a world headquarters near Detroit, Michigan and a global network of sales representatives and distributors. Acromag offers a complete line of industrial I/O products including a variety of process instruments, signal conditioners, and distributed fieldbus I/O modules that are available with a 7-year warranty. Industries served include chemical processing, manufacturing, defense, energy, and water services.

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