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New Methodologies for Achieving Ultra High Accuracy in Temperature Measurements With Thermocouples

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Thermocouples consist of two wires of dissimilar metals joined electrically at one end, commonly referred to as the measuring junction. The end that is joined together is inserted into the fluid or attached to the solid that we wish to measure the temperature of.

In modern instrumentation, the other end of the pair of wires is usually connected directly to a voltage measuring device and that end of the wire pair is referred to as the reference junction. If there is a temperature difference between the measuring junction and the other end of the wires, a small voltage will be produced that is proportional to the temperature difference between the ends of the wires. It is important to note that voltage is not produced at the measuring junction of the thermocouple wires, rather it is produced along the portions of the thermocouple wires that experience temperature differences.

All thermocouple circuits must have two junctions, a measuring junction and a reference junction. And the voltage produced in the circuit is related to the difference between the temperature of the measuring junction and the temperature of the reference junction. Therefore, in order to calculate the temperature of the measuring junction from the measurement of the small voltage produced by the thermocouple circuit, we must know the temperature of the reference junction or otherwise compensate for that temperature.

In early work with thermocouples, the reference junction was placed in an ice water bath, because this arrangement could assure that the reference junction was at or very near a known temperature, the melting point of ice, 0 °C. Ice point reference junctions are still used today by some systems that require very high accuracy in temperature measurement.

The GEC Instruments thermocouple scanners use a reference junction technique that, except for high channel counts, provides a reference junction accuracy as good or better than those systems that use an ice point reference.

Tables of EMF produced by the measuring junction of a thermocouple circuit as a function measuring junction temperature are commonly based on a reference junction temperature of 0 °C.

Because of this usage, the reference junction is often referred to as the cold junction, and the measuring junction is often called the hot junction. In reality, the reference junction does not have to be at 0 °C. The only requirement is that its temperature must be known and accounted for properly or otherwise compensated for. And the reference junction does not have to be colder than the measuring junction. It can be at a higher temperature than the measuring junction. In any instance where the reference junction is warmer or hotter than the measuring junction, it would be a misnomer to refer to it as the cold junction. Therefore at GEC Instruments we do not refer to a thermocouple reference junction as the cold junction. It could be colder, hotter or the same temperature as the measuring junction. And for the same reasons, we do not refer to the measuring junction as the hot junction. We prefer to call it the measuring junction, because that is a more correct and more descriptive terminology.

The most recent thermocouple tables were published in 1993 as NIST Monograph 175 – Temperature-Electromotive Force Reference Functions and Tables for the Letter-Designated Thermocouple Types Based on the ITS-90. The EMF values in these tables are given in microvolts as a function of temperature, and are based on a thermocouple reference junction temperature of 0 °C.

Monograph 175 presents exact functions, for 8 letter designated thermocouple types B, E, J, K, N, R, S and T, used to designate the EMF output (in microvolts) of a thermocouple circuit based on temperature of the measuring junction in °C, and with the reference junction at 0 °C. The functions to convert from a temperature in °C to EMF in microvolts are represented as polynomials, with the coefficients of the polynomials differing in number depending on thermocouple type and temperature range of consideration.

Appendix A of Monograph 175 also has approximate inverse functions that can be used to convert the voltage generated by a thermocouple circuit to a temperature of the measuring junction, for the 8 letter designated thermocouple types B, E, J, K, N, R, S and T. Again these functions are based on a reference junction temperature of °C. The approximate inverse functions used to convert from EMF in microvolts to a temperature in °C are represented as polynomials, with the coefficients of the polynomials differing in number depending on thermocouple type and temperature range of consideration. These approximate inverse functions can have maximum errors (relative to the exact functions) ranging from -.06 °C to 0.06 °C.

At GEC instruments, we have generated our own inverse functions for thermocouple types B, E, J, K, N, R, S and T by fitting polynomials to data sets generated from the exact functions for those thermocouple types. These GEC inverse functions are based on narrower temperature ranges than the approximate inverse functions published by NIST. The GEC inverse functions are more accurate, with a maximum error of 0.002 °C.

ITS-90 thermocouple coefficients for exact functions, for approximate inverse functions, and thermocouple tables for thermocouple types B, E, J, K, N, R, S and T are also available at <http://srdata.nist.gov/its90/main/> but with EMF values given in millivolts rather than microvolts.

In most modern electronic thermocouple measuring systems, the reference junction occurs at the point where the end of the thermocouple opposite the measuring junction end is connected to the input of the voltage measuring circuitry. This reference junction temperature, different from 0 °C, must be determined and accounted for in the final determination of the temperature of the measuring junction.

The standard PPM software supplied with GEC Instruments thermocouple scanners uses the coefficients for the exact functions to adjust the EMF reading of the thermocouple circuit to an EMF based on a reference junction of 0 °C. Then the software uses the coefficients for the accurate GEC calculated inverse functions to convert this EMF to a temperature of the measuring junction.

Thermocouple Wire Error

The NIST reference functions and tables of thermocouple electromotive force (emf) versus temperature in NIST Monograph 175 have been adopted as standards by the American Society for Testing and Materials (ASTM standard E230) and the International Electrotechnical Commission (IEC 60 584-1). All letter-designated thermocouple types are manufactured to match these standards to within specified tolerances. The ASTM tolerances give designated limits of error for standard thermocouple wire, and tighter limits of error for thermocouple wire designated "special limits of error" (SLE).

For Type T thermocouples, the errors allowed over the range -65 to 130 °C are 1.0 °C for standard wire and 0.5 °C for SLE wire.

For Type J thermocouples, the errors allowed over the range 0 to 285 °C are 2.2 °C for standard wire and 1.1 °C for SLE wire.

For Type K thermocouples, the errors allowed over the range -110 to 285 °C are 2.2 °C for standard wire and over the range 0 to 285 °C the allowed error is 1.1 °C for SLE wire.

So we see that the standards allow thermocouple wire errors to be as much as 2.2 °C. Even special SLE wire can have an error as much as 0.5 °C for type T and higher error for other wire types. And the allowable errors are even greater at higher temperatures.

GEC Instruments Improves Measurement Accuracy with Thermocouple Calibration

When a customer purchases a thermocouple scanner and thermocouples from GEC Instruments, we usually do a 2 point calibration of the instrument and connected thermocouples to enable higher accuracy in thermocouple measurements. A set of slopes and offsets for each thermocouple channel that is calibrated is embedded in the configuration file for that instrument. This procedure enables extremely high measurement accuracy at the calibration points, with less accuracy at intermediate points depending on how well the wire fits the NIST reference functions over the range of interest. Data following calibration of numerous instruments, showing accuracies of 0.05 °C or better, are available at:

http://www.gecinstruments.com/ultra_accurate_tc_measurements.pdf

Users of GEC Instruments thermocouple scanners can also do a one or two point comparison calibration of their connected thermocouples, against another thermocouple connected to the instrument, or against their own reference thermometer, by using the Calibration Wizard in the PinPoint Monitor software accompanying their instrument.

Beginning in 2009, in an attempt to attain even higher accuracies in temperature measurements with thermocouples, GEC Instruments developed in house procedures for accurately measuring EMF vs. temperature data for individual thermocouple wire. These data are then used to develop polynomial coefficients for reference functions (temperature to microvolts) and other polynomial coefficients for inverse functions (microvolts to temperature) representing this particular wire. These coefficients are then embedded in the configuration file for the instrument.

Our PinPoint Monitor software was modified to use these individual coefficients, when they are available, rather than the standard NIST reference functions. With this procedure, measurement accuracies better than 0.02 °C have been attained with type T and with type E thermocouple wire at all points over temperature ranges of -10 to 60 °C. Similar accuracies should be available over very wide temperature ranges with any thermocouple wire type, provided accurate EMF vs. temperature data can be obtained on individual wires over the range of interest, and provided the wire is homogeneous.

Welcome to TCConfig

Now GEC instruments is making these new techniques available to customers that want to make temperature measurements with our instrumentation, but wish to develop and use accurate polynomial coefficients for their own particular thermocouple wire.

TCConfig is a software application from GEC Instruments designed to enable the user of a GEC Instruments thermocouple scanner to insert coefficients for their particular thermocouple wire into a configuration file (*.ppc) for their instrument that details the device setup for the PinPoint Monitor software.

The coefficients must be based on a reference junction temperature of 0 °C, with temperature in units of °C and EMF in units of microvolts.

There will be two sets of coefficients, one set for a forward polynomial used to convert temperature to microvolts and another set of coefficients for an inverse polynomial used to convert microvolts to temperature.

The range of the forward polynomial needs to cover only the range that the reference junction internal to the instrument will be subjected to. The temperature of the reference junction is normally slightly warmer than the ambient temperature surrounding the instrument.

The coefficients will usually have several significant figures for best accuracy. And the coefficients may use exponential notation, i.e. 2.74257334833e-005

Before using TCConfig to insert the thermocouple coefficients for your thermocouple wire into a PPC file, you must first put those coefficients into a text file.

- 1) Please refer to the example file provided (default path: C:\Program Files\GEC\TCConfig\Sample Coefficients.txt).
- 2) Lines beginning with a semicolon; are comment lines and are not read by TCConfig.
- 3) The first (non-comment) line must be the number of polynomial pairs. This should be 1 for now (Multiple polynomials are not currently supported).
- 4) The next (non-comment) line will give details for the “forward” polynomial. This is used to convert the reference junction temperature to microvolts.

Individual values are separated by at least one space.

```
Type LowerBound UpperBound # of Coefficients a0 a1 a2  
2201 10 30 3 -0.069607455 38.5088920356 0.0451650121382
```

The first number in the line is a 4 digit code for the thermocouple type. Available codes are:

```
2201 Type T thermocouple  
2207 Type J thermocouple  
2208 Type K thermocouple  
2209 Type R thermocouple  
2210 Type S thermocouple  
2211 Type B thermocouple  
2212 Type E thermocouple  
2213 Type N thermocouple  
2514 Type T differential thermocouple  
2515 Type J differential thermocouple  
2516 Type K differential thermocouple
```

2517 Type R differential thermocouple
2518 Type S differential thermocouple
2519 Type B differential thermocouple
2520 Type E differential thermocouple
2521 Type N differential thermocouple

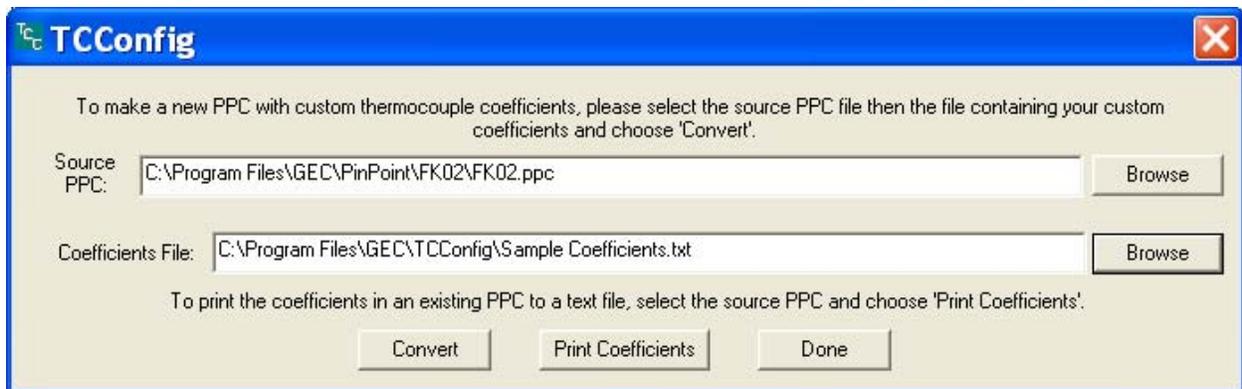
Next is the lower bound for temperature followed by the upper bound for temperature. Then the number of coefficients, followed by the coefficients.

Note: The lower bound and upper bound are temperatures in °C.

4) The last line will give details for the “inverse” polynomial (used to convert the microvolt reading to temperature) and should follow the same format as the line for the forward polynomial. The thermocouple type must be the same as the previous line. But the lower bound, upper bound and number of coefficients may be different. An example is below.

2201 -12 65 4 1.364118e-05 0.02596563 -7.726479e-07 4.2882127e-011

Once you have the details for the forward polynomial and the inverse polynomial in a text file in the proper format, you will use TCCConfig to insert those details into a PPC file for your instrument.



The above figure shows a screenshot of the TCCConfig application on startup.

To make a custom PPC

- 1) Click “Browse” button for the Source PPC. Select the PPC you wish to customize.
- 2) Click “Browse” button for the Coefficients File. Select the text file containing the details for your polynomials.

Note: The application will fail if the polynomial text file is not formatted properly.

3) Click “Convert” to make a new PPC file containing the custom coefficients. You will be prompted to supply a new and unique filename for that new PPC file.

To view the coefficients in a given PPC

1) With a PPC selected (using the top browse button), click “Print Coefficients”.

2) This will prompt you for a filename and then will print the coefficients (correctly formatted) into a text file.

Troubleshooting

- *If you see:* "Error: could not read the coefficient file. Please refer to the example provided."

Try: Re-check your coefficients text file to ensure that it is properly formatted.

This could be a problem relating to comment lines (those prefaced with a ‘;’).

- *If you see:* “Error: could not find coefficients file.”

Try: Make sure the file exists and is named properly.

- *If you see:* "Error: could not read coefficient list."

Try: Re-check your coefficients text file. This problem usually occurs when the number of coefficients (*# of coefficients*) provided does not match the actual number of coefficients in the list.

Using the new PPC

Before starting the PinPoint Monitor program to read temperatures from thermocouples with your new custom PPC file, you must use the PPSettings program to select that PPC as the Configuration File. Also you must be certain that Load Last Workspace is not selected, because the last workspace will refer to a different PPC file.

After you save the new settings, you can start PinPoint Monitor. At program startup you will need to create a new Workspace filename using the leftmost icon on the Toolbar at the upper left of the application. PinPoint Monitor will then prompt you to enter a filename for a new Input Monitor and will then begin taking readings.

If the temperature of the reference junction internal to the GEC Instruments thermocouple scanner is outside the upper or lower bounds of the forward polynomial, the PinPoint Monitor program will still use the coefficients in your custom PPC, but the reference junction readings will be preceded by an asterisk (“*”) in the Real-time Report.

If the calculated temperature of the measuring junction is outside the upper or lower bounds of the inverse polynomial for any reading on any thermocouple channel, the

PinPoint Monitor program will calculate the temperature for that channel based on the standard ITS-90 reference functions and inverse functions for that thermocouple type. If this occurs, those readings will be preceded by an asterisk (*) in the Real-time Report.