The Calibration and Use of Thermocouple Simulators

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Abstract

Thermocouple simulators and calibrators have greatly simplified thermometer calibration. Their use will be contrasted with historical calibration methods. The paper details the three critical calibration parameters: DC Voltage gain, cold junction calibration, and implementation of the thermocouple curves. The implementation of cold junction compensation internal to the thermometer or thermocouple simulator will be described. An uncertainty analysis will be presented for a specific calibrator based on the guidance of EA-10/11 [1]. And an explanation will be given for reporting measured values of 30,000 degC, much hotter than the surface of the sun, on calibration certificates for the example calibrator.

1. Introduction

Originally, Direct Voltage and Low Frequency (DCLF) calibrators were designed for only one or two functions. There were DC calibrators, AC calibrators, and resistance calibrators. In the 1980s multifunction calibrators were introduced. They typically provided five functions in a single precision instrument: DC voltage and current, AC voltage and current, and resistance. In the 1990s, a new term, multiproduct calibrator, was coined to describe the greatly expanded capabilities of instruments designed to match the increased functionality of the intended workload with a single calibrator. Though more versatile, these multiproduct calibrators are less costly and less accurate than the most capable multifunction calibrators.

The increased capability of the multiproduct calibrators comes, in part, from additional circuitry but also from generous re-use of existing circuitry. Synthesized capacitance and RTD thermometer probe simulation use much of the synthesized resistance circuitry. Power and phase capabilities result from activating the voltage and current simultaneously. By using direct digital synthesis, non-sinusoidal waveforms can be produced with the same hardware that produces the precision sinusoids. The addition of a connector and software allows interface of pressure modules. Adding a plug-in card and accessing signals from the other functions facilitates the calibration of oscilloscopes. And finally, a sophisticated isothermal block combined with the DC sourcing and measurement capability of the calibrator added thermocouple (TC) measurement and simulation functions.

It is this thermocouple capability we will look into in this paper; how the functionality is accomplished and how it is calibrated.

2. What is a Thermocouple?

Temperature is the most frequently measured of all physical parameters. In 1821 T.J. Seebeck discovered a current is developed in a loop formed with dissimilar metals and a voltage is developed across two conductors of dissimilar metals when they are joined at one end. Since that time, thermocouples have become the most common method of measuring temperature.

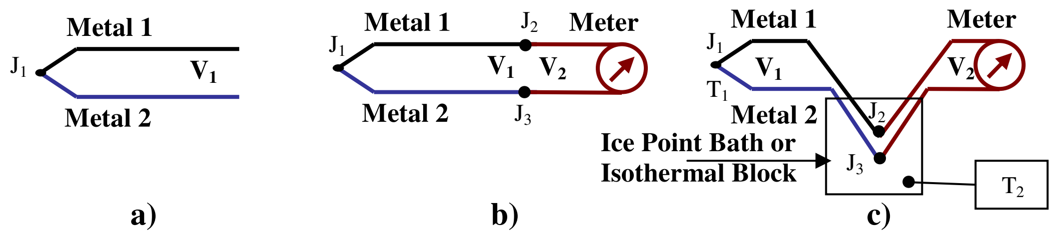

Figure 1. Configurations of the bi-metallic thermocouple.

In Figure 1a, J_1 is a junction of two dissimilar metals. A voltage V_1 is produced that is proportional to the temperature of the junction. The relationship of temperature and voltage has been cataloged for junctions of many metals. The more common metal pairs have been given letter designations.

If, as in Figure 1b, we connect a voltmeter to the thermocouple at J_2 and J_3, we may be surprised to find that we don't measure the voltage V_1 we as would expect from the tables. In fact, we may read no voltage on the meter at all. That's because, in addition to the thermocouple junction at J_1, we have thermocouples between Metal 1 and the meter and Metal 2 and the meter at J_2 and J_3. The metal used in most meters is copper. The meter reading will generally be a function of the temperatures at all three junctions. If all three junctions are at the same temperature, no voltage will be produced at the meter's terminals. Despite the fact that voltages are produced at each of the junctions, the sum of the voltages will be zero.

A more useful configuration, known as an isothermal junction, is shown in Figure 1c. Here junctions J_2 and J_3 are held at the same temperature, T_2. A realization of this configuration would be a differential thermometer. It would indicate the difference in temperature between J_1 (T_1) and T_2. An absolute thermometer would be possible if the temperature T_2 is known. This can be accomplished by controlling T_2 or by measuring it. Traditionally, T_2 is established at the freezing point of water, 0 degC, because of the relative ease to reproduce it in the laboratory. Most published tables of thermocouple curves do not list the thermocouple voltage, V_1, but V_2 with a reference junction temperature T_2 of 0 degC and copper connections to the metering circuitry.

To make a more portable instrument, J2 and J3 are held at the same temperature, $T_{2,}$ which is measured. This seems a bit circular as it requires a thermometer measuring T_2 to build a thermometer capable of making an absolute measurement of T_1. In practice, however, this is not as unreasonable as it first sounds. The "auxiliary" thermometer is only required to measure over a small temperature range from its initial calibration temperature. Thermistors or silicon p-n junctions are commonly used for this purpose. They do generally need to be calibrated, however.

3. What is a Thermocouple Simulator?

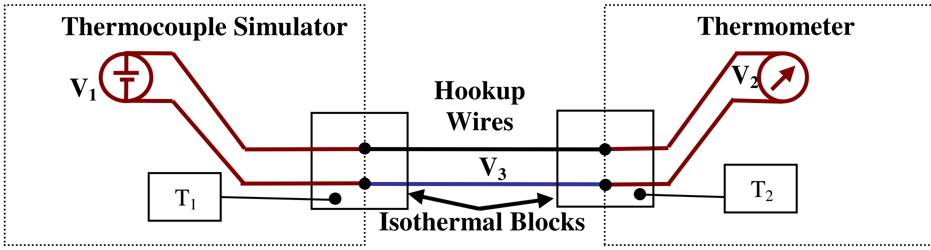

Figure 2. Thermocouple simulator connected to a thermometer.

As shown in Figure 2, the thermocouple simulator has many of the same features as the thermometer. Internally, it uses all copper conductors. It also has an isothermal block to keep its connections to the hookup wires at the same temperature. The temperature of the simulator's block, T_1, is measured with a sensor just as the thermometer's isothermal block is measured with a sensor.

To be useful, the simulator must be able to present the proper voltage at the input terminals of thermometers for many types of thermocouples. Hookup wires are often made from thermocouple extension wires. These are fabricated from the same materials as the thermocouple but are not electrically connected to each other. The simulator must provide the same voltage, V_3, as would be produced by a thermocouple over a wide range of temperatures. A thermocouple produces the "table values" only when its copper connections are in an ice point reference bath. The simulator does this by measuring the temperature of the isothermal block, calculating the thermocouple voltage across the two copper-to-hookup-wire junctions, and adjusting V_1 appropriately.

Often, however, the appropriate hookup wire is copper. First of all copper connections may be made so the calibrator (TC simulator) can apply voltages to calibrate the metering functions of the thermometer independent of thermocouple effects. Secondly, the thermometer may allow or require an external ice point bath. In that case, the thermometer reads V_3 and directly converts it to a temperature without any corrections being made for the temperature of the thermometer's isothermal block, T_2. This configuration, with both the simulator and thermometer set for external ice point compensation, allows the calibration to be performed without actually building the ice point bath. Most TC simulators also allow DC voltages to be applied directly to the thermometer to allow thermocouple types whose thermal emf tables are not stored internally. In this case, the user must make the conversion from voltage to temperature manually.

An inspection of Figure 2 shows that many elements of a thermocouple simulator and a thermometer are the same, most notably the isothermal block and its temperature monitor. Careful attention needs to be given to both. Figure 3 shows some of the construction details for the thermocouple simulator portion of a multiproduct calibrator. The assembly looks simple but the design represents considerable engineering to provide good thermal conductivity between the copper buttons and the thermocouple connector, between the copper buttons themselves, and between the buttons and the temperature sensor. When the thermocouple connector is inserted, springs hold the conductors against the copper buttons and provide some wiping action during insertion to ensure a good electrical connection. Another part of the thermal design protects the isothermal block from much of the internal heat rise inside the instrument. Use of amplifiers and attenuators within the block, close to the terminals, reduces errors due to thermal emfs and noise.

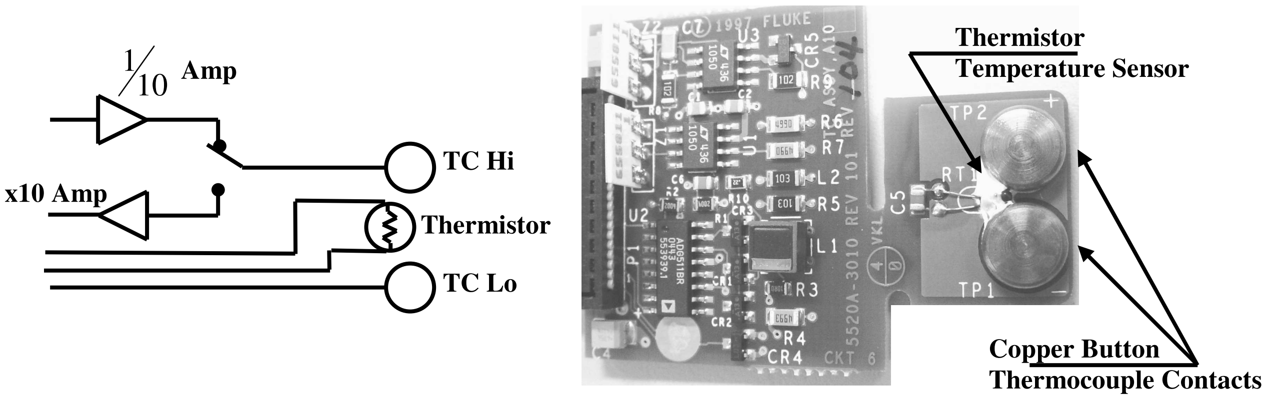

Figure 3. Fluke 5520A multiproduct calibrator isothermal block

4. Calibration and Verification

Most modern thermocouple simulators and thermometers are calibrated by considering the three main functional blocks independently.

4.1 Electrical Sourcing and Measuring

A thermocouple simulator can be calibrated with an accurate DMM. The metering functions of most electronic thermometers can be calibrated with a precision source or calibrator. Even though it is purely an electronic calibration, the measurand for some instruments is still temperature because of user interface issues. The Fluke 5520A uses entries in degrees Celsius or Fahrenheit to direct the output to the TC terminals. If the instrument is asked to output a voltage, the output will be directed to the Normal terminals. Since the only way to get voltages to the TC terminals is to enter a temperature, a thermocouple type, 10 µV/degC, was created. This conversion factor was chosen because it is the same order of magnitude of the change in voltage vs. temperature for a number of the more popular thermocouples. So, calibrating the full range of the thermocouple terminals from zero volts to full scale of ±300 mV in the 10 µV/degC mode, results in displayed temperatures from -30,000 degC and plus 30,000 degC. On calibration certificates, reported values of temperatures exceeding those of the surface of the sun and those far below absolute zero have sometimes raised eyebrows, but all can be made in a calibration lab in one's shirtsleeves. Just recognize it is a DC Voltage calibration of simulated temperature with a sensitivity coefficient of 10 µV/degC. It was a designer's quirk to make entry simple and consistent, though not always intuitive.

Since relatively small DC voltages are being calibrated, voltages of both polarities are often applied to cancel the effects of undesirable thermal emfs in the copper only measurement system. One would not expect to measure Seebeck voltages in the all copper system since it does not involve dissimilar metals. However, most copper conductors are not pure. They have alloys, contaminants, grain structure and corrosion which make them differ slightly; enough that significant emf voltages may be present. The electrical portion of a thermometer is calibrated with a TC simulator with copper hookup wire as shown in Figure 2. Cold junction compensation would be disabled for both instruments.

4.2 Isothermal Block Temperature Calibration

A p-n silicon junction or a thermistor is used to sense the isothermal block temperature in most modern thermocouple thermometers or calibrators. They are quite stable and accurate over the very limited temperature range of the environment the metering unit will experience. However, they are generally not inherently accurate enough to be used without making a calibration of the isothermal block at least one temperature. This can be accomplished by connecting a thermocouple to the thermometer and comparing the reading with that of an accurate PRT or SPRT thermometer. This comparison takes place at room temperature in a lag bath of water or mineral oil. Such a bath may be constructed from a dewar made for that purpose or an ordinary wide-mouth thermos bottle with holes drilled in the lid for the thermocouple and PRT thermometer. If a thermos is used, the sensing portions of the PRT and TC must be mounted so their sensing elements are near each other. And extreme care must be taken to locate it where thermal gradients or significant air drafts will cause internal thermal gradients. This means of calibrating the isothermal block near room temperature is used for most thermocouple simulators. Alternatively, the isothermal junction may be calibrated by connecting a thermocouple to the thermometer and placing its junction in an ice point bath. However, in this method, the errors due to the thermocouple are much larger than if the temperatures are nearly equal. Differences in individual thermocouple performance are quite small over the range of just a few degrees that the isothermal block temperature may vary from the lag bath. However, different thermocouples can produce significantly different voltages (compared to the uncertainty we would like to calibrate the isothermal block) over the 20-25 degC between the ice point and the isothermal block temperature.

If one has a calibrated thermocouple simulator, calibration of the thermometer's isothermal block is even easier. Connections are made as shown in Figure 2 but this time the hookup wires are thermocouple extension wire and the TC simulator and thermometer each have their internal ice point compensation selected. Calibration is performed by selecting a TC simulator temperature near 0 degC and adjusting the thermometer's internal isothermal block temperature sensor until the reading matches that of the TC simulator (0 degC). Choosing 0 degC minimizes the contribution of gain error of the TC simulators to this measurement as the output voltages will be small.

Calibration of the isothermal block temperature sensor by either method is performed after the electrical calibrations listed in the section above have been made. Once calibrated, an electronic thermocouple thermometer will read the temperature of its isothermal block when its input terminals are connected with a copper short.

4.3 Thermocouple tables

Finally, the tables and interpolation algorithms used to compute temperatures from voltage can be verified. Since these are coded in the instrument's software, this needs to be done only once. It can be done by the user or a decision may be made to accept the manufacturer's validation of the tables. A thermometer can be driven with accurate DC voltage to verify the tables. External ice point compensation is selected and the DC voltage is applied with copper hookup wire. Some multiproduct calibrators display both the measured voltage and the calculated temperature simplifying this process.

5. Uncertainty Calculations

The uncertainties for the measurement or simulation of thermocouples may be considered for the same three categories. EA-10/08 [2] lists many of the sources of error. Some of the sources of error to consider are:

5.1 Electrical Sourcing and Measuring

Accuracy of the calibration standard (STD)
Stability of the unit under test (UUT)
Resolution of the measuring unit
Electromagnetic Interference
Repeatability of the measurements

5.2 Isothermal Block Calibration

Accuracy of the calibration standard PRT or SPRT
Temperature uniformity of the lag bath
Temperature differences between the thermocouple connections
Temperature differences between the thermocouple connections and the block's temperature sensor
Stability of the p-n or thermistor sensor
Accuracy of the p-n or thermistor relative to the cal temperature over the specified ambient temperature range of the measuring or sourcing instrument.
Parasitic emfs and contamination effects
Thermocouple errors over the temperature difference between the reference temperature and the isothermal junction as covered in Section 4.2

5.3 Thermocouple tables

There is an uncertainty associated with the tables themselves and the interpolation between the temperature points of the table.

5.4 Thermocouples

Thermocouples may be used with or without verification. Thermocouple manufacturers specify the variation that can be expected in their devices. This depends on their ability to control the purity of the materials, fabrication methods, annealing and sheathing. The conditions of use can also affect thermocouple errors. Subjecting a thermocouple to high temperatures or mechanical stress can alter the shape of its voltage-vs-temperature performance curve. Thermocouples can also be calibrated at specific temperatures and the curves for their type of thermocouple used to interpolate other temperatures between those characterized. Some of the thermocouple errors include:

Immersion depth and/or thermal resistance from the thermistor to the object being measured
Electromagnetic interference
Mechanical stresses and changes to the grain structure of the thermocouple elements
Oxidation and corrosion
Diffusion of contaminants into the thermocouple elements
Purity of the materials and control of alloy proportions

Table 1. 5520A Uncertainty analysis for calibration of the isothermal block.

THERMOCOUPLE TEMPERATURE (Type J)

Temperature	8520A/PRT		Bath Temp	Bath Temp	Type J Cal	Type J TC	UUT	UUT			
23 °C	90 Day Spec Deg C	90 Day Deg Freed	Diff Unc Deg C	Diff Deg Freed	Unc (k = 2) Deg C	Cal Deg Freed	Rand Unc Deg C	Rand Deg Freed	Comb Uncert Deg C	Effect Deg Freed	Expand Unc Deg C
	0.017	200	0.01	10	0.03	200	0.000	4	0.019	108	0.038
Type	B		A		B		A				
Distribution	Normal		Normal		Normal		Normal				
C.L or C.F.	99%		1		2		1				
Notes	2		3		4						

Notes:
1. A Type J Thermocouple is connected to the UUT TC Input and the probe end immersed in a room temperature bath. The temperature of the bath is measured using a Fluke 8520A/PRT, its probe is also in the bath.
2. Uncertainty for the Fluke 8520A.PRT Thermometer comes from the manufacturer's Specifications and is known to have a 99% confidence level.
3. The difference in the temperature between the Type J Probe and the 8520A/PRT probe was determined by measurements
4. Uncertainty of the Type J Thermocouple comes from the Calibration Certificate.

Table 1 shows the uncertainty analysis for the calibration of the Isothermal Block of the 5520A. It is the uncertainty at time of test so does not include many of the uncertainty components listed above. Some of the other uncertainty components were considered and judged to be negligible. Other error contributors, regarded possibly to be significant, are included in the repeated runs; random, Type A uncertainty. The data show little variation in this case, however. Of note, is the very small uncertainty for the Type J thermocouple when used in a lag bath to calibrate the isothermal block. This uncertainty is only possible because the temperature differential is very small. These few lines are part of an uncertainty spreadsheet for the 5520A of nearly 1000 lines.

6. Conclusion

Thermocouple simulators, whether they are standalone or a part of a more complex calibrator, greatly simplify the calibration of thermocouple based thermometers. They allow most of the calibration to be performed in an all copper system supplemented by a single calibration of the thermometer's isothermal block temperature sensor using thermocouple extension wire between the STD and UUT. Elimination of the need for an ice point bath significantly reduces the errors due to the thermo couple extension wire.

Calibration of a thermocouple simulator can be accomplished by independently calibrating the metering/sourcing function and the isothermal block's temperature sensor.

References

1. EA-10/11, Guidelines on the Calibration of Temperature Indicators and Simulators by Electrical Simulation and Measurement, European co-operation for Accreditation, Rev. 00, February, 2000.

2. EA-10/08 (also known as EAL-G31), Calibration of Thermocouples, European co-operation for Accreditation, Rev. 01, October, 1997.