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A Critical Look at Type T Thermocouples in Low-Temperature Measurement Applications

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Abstract Type T thermocouples are commonly used in industrial measurement applications due to their accuracy relative to other thermocouple types, low cost, and the ready availability of measurement equipment. Type T thermocouples are very effective when used in differential measurements, as there is no cold junction compensation necessary for the connections to the measurement equipment. Type T's published accuracy specifications result in its frequent use in low-temperature applications. An examination of over 250 samples from a number of manufacturers has been completed for this investigation. Samples were compared to a standard platinum resistance thermometer (SPRT) at the LN2 boiling point along with four other standardized measurement points using a characterized ice point reference, low-thermal EMF scanner, and an 8.5 digit multimeter, and the data were compiled and analyzed. The test points were approximately −196 °C, −75 °C, 0 °C, +100 °C, and +200 °C. These data show an anomaly in the conformance to the reference functions where the reference functions meet at zero. Additionally, in the temperature region between −100 °C and −200 °C, a positive offset of up to 5.4 °C exists between the reference function equations published in the United States in ASTM E230-06 for the nitrogen point and the measured response of the actual wire. This paper also examines the historical and technological reasons for this anomaly in the US reference function. The study concludes that Type T thermocouples typically do not conform to the ASTM E230-06 published reference function describing their performance when used to measure temperature in the range of −100 °C to −200 °C.

Keywords Low temperature · Reference function · Thermocouples · Type T

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1 Introduction

Type T thermocouples are commonly used in industrial measurement applications due to their accuracy relative to other thermocouple types: low cost, ready availability of measurement equipment, and fairly high Seebeck coefficient.

The positive thermoelement TP is made up of low-oxygen, high-conductivity copper, and above −200 °C, the thermoelectric properties of type TP thermoelements are very uniform and exhibit very little to lot variation. This differs from the negative thermoelement TN which is a copper–nickel alloy and does exhibit thermoelectric variability. Type T thermocouples are very effective when used in differential measurements, as there is no cold junction compensation necessary for the connections to the measurement equipment.

Most uses of type T thermocouples are in the range of −70 °C to +400 °C. When used within this temperature range, type T thermocouples yield excellent results. The published accuracy specifications of type T thermocouples result in their frequent use in low-temperature applications. Many of the applications supported by Lockheed Martin Sunnyvale MSL require a calibrated measurement range of −200 °C to +200 °C. Supporting these applications has become the basis for this investigation.

There are two anomalies in the published reference function for type T thermocouples. The first is a discontinuity at zero Celsius, and the second is an approximate 5.4 °C offset at the N_2 boiling point.

2 Background

In NIST Monograph 175 [1], "*Temperature-Electromotive Force Reference Functions and Tables for the Letter-Designated Thermocouple Types Based on the ITS-90*," the authors outline the development of each thermocouple type. The chapter on type T provides insight into the origins of the anomalies that exist in the reference function. The original tabular data, which express the temperature–voltage relation, was presented by Adams in 1920 [2]. In the mid-1930s, Roeser and Dahl [3] studied the temperature–voltage relationship of a large number of manufacturers, determined that their results agreed very closely with that of Adams, and in 1938 published the first reference tables of thermoelectric values to be widely used by industry. In this document, Roeser and Dahl state that the tabular values for the thermocouple were intended primarily for use above 0 °C. Although they presented values in the range of −200 °C to 0 °C, it was indicated that the values were for convenience only and were based on only a few sample points. Two years later, Scott [4] published a more representative table in the range of −192 °C to 0 °C.

In 1951, the Roeser and Dahl high-temperature table was combined with the Scott low-temperature table, with corrections to account for the change in the temperature scale from ITS-27 to IPTS-48 and the change in electrical units from international to absolute. These tables were published as part of NBS Circular 508 [5] and again in 1955 as NBS Circular 561 [6].

In the late 1960s and early 1970s, the NBS Cryogenics Division in Boulder, Colorado, conducted extensive research into the low-temperature properties of commonly used thermocouple types. They established a type T reference function and table covering the range from +7 °C to −270 °C, which was published in 1972 as part of NBS Monograph 124 [7].

Two years later, the Monograph 124 below zero reference function and the Circular 561 above zero reference function were combined with corrections to account for the changes in the temperature scale from ITS-48 to IPTS-68. These reference functions and tables were published as part of NBS Monograph 125 [8]. This combination of separately developed reference functions has resulted in the situation we have today.

The NBS Monograph 125 reference functions and values were used when NIST implemented the change in the temperature scale to the ITS-90 in Monograph 175 [1]. This is the temperature scale in use today worldwide.

Looking at this sequence of events, we see that the seminal work on the type T reference function for the range above zero was performed in the 1920s and 1930s. The below zero work took place 40 years later; performed with different materials and done by different researchers. This resulted in two serious anomalies in the description of type T thermocouple performance throughout its complete range. The first is a discontinuity at the zero point. This can be clearly seen in Fig. 1. The input data to Monograph 175 had a discontinuity in the first derivative as well; when the 1990 tables were generated, continuity of the first derivative at 0 °C was forced. There is a substantial discontinuity at zero where the two reference functions fail to meet where they should—at zero. The second anomaly is a typical positive offset in the measurement results in the region between −150 °C and −200 °C as demonstrated in Fig. 2.

The reason for this is that the materials used to generate the reference function for type T thermocouples in the cryogenic realm were significantly different than the materials used in the original work done to produce the reference function above zero. Historically, there was typically enough variance in the manufacturing process that material could be selected which provided a good fit across the range of interest. With

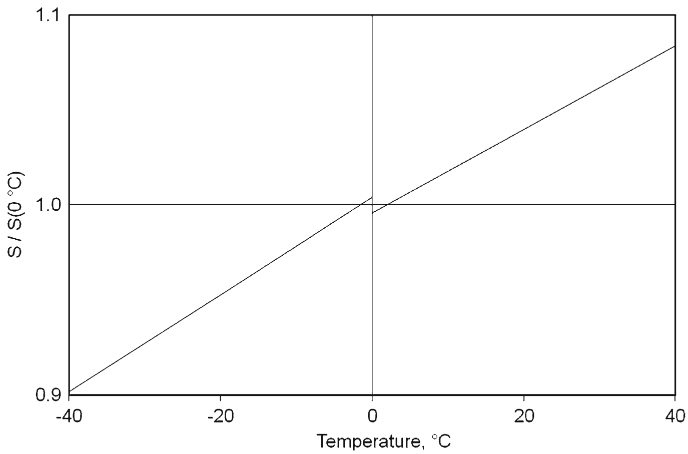

Fig. 1 Type T scaled Seebeck coefficient near 0 °C

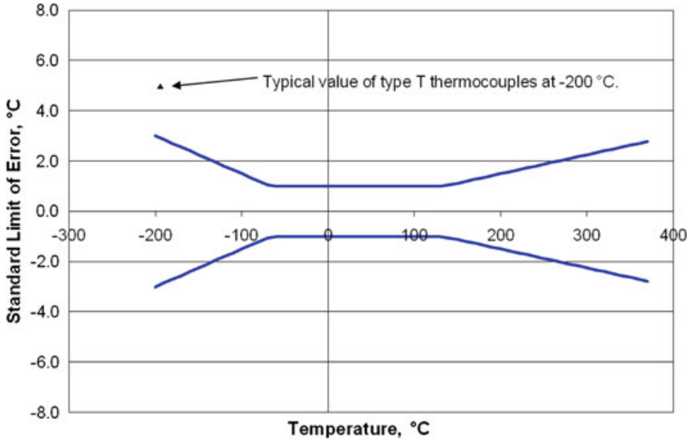

Fig. 2 Type T thermocouple standard limit of error specification

modern manufacturing process control, type T thermocouple materials have less variability and are more difficult to select for conformance to the reference function below zero.

3 Measurements

This investigation compiled incoming calibration results on spools of new type T wire, purchased from three different manufacturers. Each purchase order specified that the type T material conform to the ASTM E230-03 [9] accuracy requirements in the range of $-200\,^{\circ}$C to $+200\,^{\circ}$C. Samples were removed from the front and rear of the spools and tested at the N_2 boiling point, $-75\,^{\circ}$C, $0\,^{\circ}$C, $+100\,^{\circ}$C, and $+200\,^{\circ}$C. The samples were calibrated using comparison technique to a standard platinum resistance thermometer (SPRT). The wire sample and the reference thermometer were inserted in a copper isothermal block and allowed to soak at temperature until equilibrium was reached. The resistance ratio of the reference thermometer was measured with an ASL F18 AC resistance bridge and Tinsley standard resistor. The EMF output of the type T sample was read through an ice point reference, a low EMF scanner, and an 8.5 digit multimeter. The expanded uncertainty of the measurement system is $\pm 0.037\,^{\circ}$C.

4 Results

The results were grouped by wire lot and averaged. A total of 208 spools of type T wire from 24 wire lots were tested for a total of 416 data points at each temperature measurement point. The wire lot averages were binned to produce Fig. 3, which shows the frequency distribution of the nitrogen boiling-point measurement. This graph shows clearly the offset at approximately $-200\,^{\circ}$C, resulting from the reference function equation describing the curve in this temperature region. Out of the 416 samples measured, 44 samples, or 10.6 %, met the accuracy requirements of ASTM E230-03.

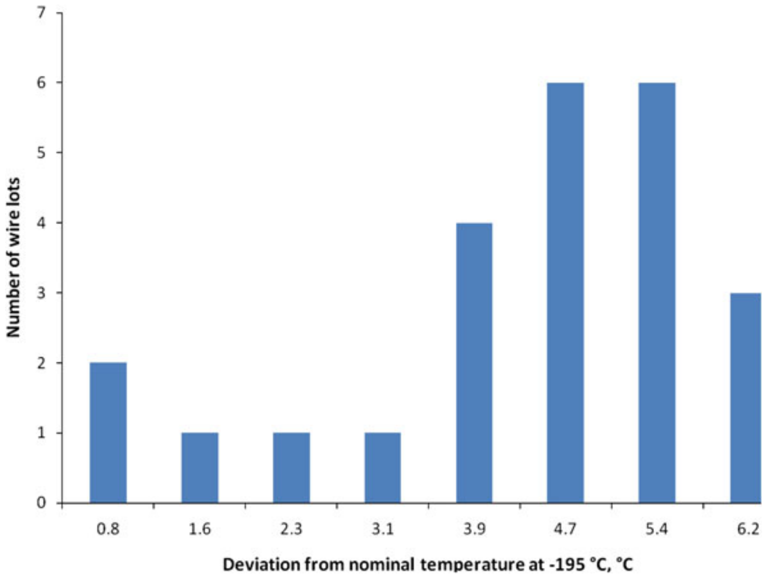

Fig. 3 Type T thermocouple performance at the N_2 boiling point

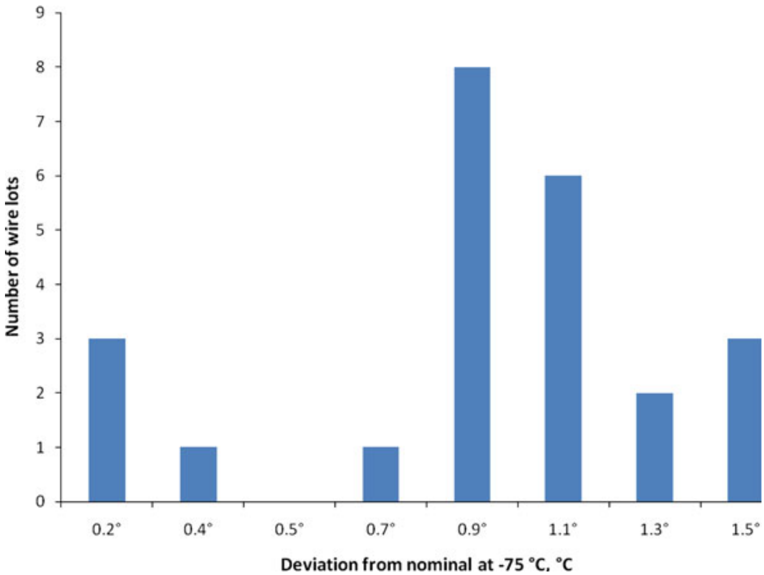

Fig. 4 Type T thermocouple performance at −75°C

The results show that the median deviation of type T thermocouples at approximately −196 °C is 4.5 °C, well above the specified accuracy of ±2.94 °C. Figure 4 shows the distribution at −75 °C, where the median of 0.893 °C is within the specified accuracy of ±1.125 °C.

5 Conclusions

For our internal customers who have a critical requirement for accuracy in this temperature range, Lockheed Martin reports coefficients based on actual measurements from each spool. Certain instruments allow the input of coefficients for use in the conversion of emf to temperature values. Using these coefficients rather than the nominal values brings the accuracy of these materials into the range of accuracy stated in ASTM E230-03 [9]. However, many users do not own equipment required to make these conversions and may not be achieving the accuracy they need.

This investigation demonstrates the need for an improved reference function for type T thermocouples in the −150 °C to −200 °C temperature range that reflects currently produced materials in use today.

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