

Updated Uncertainty Budgets For NIST Thermocouple Calibrations

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Abstract. We have recently updated the uncertainty budgets for calibrations in the NIST Thermocouple Calibration Laboratory. The purpose for the updates has been to 1) revise the estimated values of the relevant uncertainty elements to reflect the current calibration facilities and methods, 2) provide uncertainty budgets for every standard calibration service offered, and 3) make the uncertainty budgets more understandable to customers by expressing all uncertainties in units of temperature ($^{\circ}\text{C}$) rather than emf. We have updated the uncertainty budgets for fixed-point calibrations of type S, R, and B thermocouples and comparison calibrations of type R and S thermocouples using a type S reference standard. In addition, we have constructed new uncertainty budgets for comparison calibrations of type B thermocouples using a type B reference standard as well as using both a type S and type B reference standard (for calibration over a larger range). We have updated the uncertainty budgets for comparison calibrations of base-metal thermocouples using a type S reference standard and alternately using a standard platinum resistance thermometer reference standard. Finally, we have constructed new uncertainty budgets for comparison tests of noble-metal and base-metal thermoelements using a type S reference standard. A description of these updates is presented in this paper.

Keywords: Thermocouples, Thermoelements, Calibration

INTRODUCTION

The Thermocouple Calibration Laboratory (TCL) of the National Institute of Standards and Technology (NIST) provides a complete description of its thermocouple calibration facilities and services in its NIST SP 250 document. This document includes descriptions of the existing calibration facilities, the traceability of the temperature references to the current temperature scale, and uncertainty budgets for the calibration services provided. This document is intended to be periodically updated as the facilities and the methods of the TCL evolve.

The first version of the NIST TCL's SP 250 document was SP 250-35. [1]. It was supplemented in 1994 by NISTIR 5340 [2], which provided new uncertainty budgets that were compatible with the newly-published Guide for Uncertainty in Measurement (GUM) [3]; these new uncertainty budgets superseded those provided in the older SP 250-35. Refs. [1–2] only included uncertainty estimates for the most frequently used calibration services. Also, uncertainty estimates were provided in electromotive force (emf) rather than temperature, leading to confusion for many customers.

The NIST TCL is preparing a new version of the SP 250 document, SP 250-92 [4]. This new version describes the current facilities and calibration

procedures in the TCL, reflecting the improvements made over the past 23 years. The new version gives descriptions of all standard calibration and testing services provided by the TCL. Finally, it provides updated uncertainty budgets for all standard calibration and testing services to reflect the current facilities and measurement procedures of the TCL. The uncertainties are provided in temperature for the convenience of NIST customers.

In this paper we briefly describe some of the new uncertainty budgets for the NIST TCL. A more complete description will be given in Ref. [4].

CALIBRATION AND TESTING SERVICES PROVIDED

The following thermocouple calibrations are provided by the NIST TCL:

- Fixed-point calibrations for type S, R and B thermocouples using the freezing points of Zn ($419.527\text{ }^{\circ}\text{C}$), Al ($660.323\text{ }^{\circ}\text{C}$), Ag ($961.78\text{ }^{\circ}\text{C}$), and Au ($1064.18\text{ }^{\circ}\text{C}$). The calibration results are extrapolated from $1064.18\text{ }^{\circ}\text{C}$ to $1450\text{ }^{\circ}\text{C}$.
- Fixed-point calibrations for type B thermocouples using the freezing points of Zn, Al, Ag, Au and the melting temperature of Pd in air ($1553.4\text{ }^{\circ}\text{C}$). The

calibration results are extrapolated from 1553.4 °C to 1750 °C.

- Comparison calibration of type R and type S thermocouples using a type S reference thermocouple over the range 0 °C to 1100 °C. The calibration results are extrapolated from 1100 °C to 1450 °C.
- Comparison calibration of type B thermocouples using a type B reference thermocouple over the range 800 °C to 1550 °C. The calibration results are extrapolated from 1550 °C to 1750 °C.
- Comparison calibration of type B thermocouples over the range 0 °C to 1550 °C using a type S reference thermocouple (0 °C to 1100 °C) and a type B reference thermocouple (800 °C to 1550 °C). The calibration results are extrapolated from 1550 °C to 1750 °C.
- Comparison calibration of base metal thermocouples using a type S reference thermocouple, available over the range 0 °C to 1260 °C. The calibration report provides a table of emf values at the respective calibration temperatures.

The following thermoelement test measurements are provided by the NIST TCL:

- Noble-metal thermoelement (BN, BP, RP, and SP) emf as a function of temperature by comparison with the Pt reference thermoelement Pt-67[5].
- Base-metal thermoelement (EP, EN, JP, JN, KP, KN, NP, NN, TP, and TN) emf as a function of temperature by comparison with the Pt reference thermoelement Pt-67 [5].
- Platinum thermoelement emf as a function of temperature by comparison with the Pt reference thermoelement Pt-67 [5].

For all thermoelement tests, the calibration report provides a table of emf values at the respective calibration temperatures.

Descriptions of all the calibration procedures are described in Ref. [4].

DESCRIPTION OF UNCERTAINTY COMPONENTS

The uncertainty analysis for thermocouple calibrations is based on the ISO and NIST guidelines for the expression of uncertainty in measurement [3,6]. The total uncertainty is obtained by first determining the values of the individual uncertainty components. Uncertainty components are categorized as type A, which can be evaluated using statistical analysis, or type B, which must be evaluated using other methods.

For independent (uncorrelated) uncertainty components u_i , the expanded total uncertainty U is related to these n uncertainty components u_i (expressed as standard uncertainties) by

$$U^2 = k \sum_{i=1}^n u_i^2 \quad 1)$$

where k is the coverage factor. In this assessment, we use $k = 2$. The uncertainty due to inhomogeneity of the test thermocouple is not included in this assessment.

Fixed-Point Calibration of Type S, Type R and Type B Thermocouples

Uncertainty Components at the Fixed Points

Fixed-point calibrations for type S, type R, and type B thermocouples are performed at the freezing points of zinc, aluminum, silver, and gold. For type B thermocouples, the melting point of palladium in air (obtained using the wire bridge method) may also be used as a fixed point. For the range between the fixed points, the thermocouple is calibrated by using a quadratic function to model the deviation of the measured emf from the thermocouple's reference function. For type S and type R thermocouples, this function is extended down to 0 °C. Descriptions of the uncertainty components for the Zn, Al, Ag and Au fixed-point calibrations of thermocouples (including the use of the quadratic deviation function) are listed in Table 1. The uncertainty components for the Pd melting point are the same as those listed in Table 1, except that the fixed-point drift component is replaced by a component due to temperature variations on the melting plateau, $u_{fp-plat}$.

Table 1. Descriptions of the uncertainty components for fixed-point calibrations of thermocouples.

	Uncertainty Component	u
Type A	Calibration Repeatability	u_{repeat}
	Uncertainty of Quadratic Function	u_{quad}
Type B	Emf Measuring System	u_{emf}
	Fixed-Point Temperature	$u_{fp-temp}$
	Fixed-Point Drift	$u_{fp-drift}$
	Heat leak at Measuring Junction	$u_{heat-mj}$
	Heat leak at Reference Junction	$u_{heat-tj}$

The uncertainty due to calibration repeatability, u_{repeat} , has been determined statistically by analysis of type-S check-standard data obtained over many years of calibrations. The analysis is described in Appendix

A1.1 of Ref. [4]. While no such data currently exists for type R and type B thermocouples, we assume here that the results of this analysis pertain to type R and type B thermocouples as well. The uncertainty of the quadratic function, u_{quad} , results from the assumption that the deviation of the measured emf from the reference function can be represented by a quadratic function. The basis for the estimate of this uncertainty is provided in Appendix A1.2 of SP 250-92 [4].

The uncertainty for the emf measuring system, u_{emf} , is based on the combination of the uncertainty of the DVM measurements and the uncertainty of the corrections made for the thermal emfs existing in the system. The uncertainty of the fixed-point temperature for a TCL fixed-point cell, $u_{\text{fp-temp}}$, is obtained from the Certificate of Analysis for the fixed point. The uncertainty for the drift of the fixed-point temperature of a TCL fixed-point cell, $u_{\text{fp-drift}}$, reflects the possibility that it may change from the time of certification due to slow contamination, and is based on measurements of the slope of the freezing-point plateau and on monotonic drifts of measurements made by the Au/Pt and Pt/Pd check standards at the fixed points. The uncertainty due to a heat leak at the measuring junction, $u_{\text{heat-mj}}$, reflects the possibility that the measuring junction of the thermocouple is at a slightly different temperature than that of the fixed-point cell; this uncertainty is based on measurements of the emf as a function of measuring-junction immersion depth into the cell. Finally, the uncertainty of a heat leak at the reference junction, $u_{\text{heat-rj}}$, reflects the possibility that the reference junction temperature differs slightly from 0 °C; this uncertainty is based on measurements of the emf as a function of reference-junction immersion depth into the ice bath.

Uncertainty Within The Calibration Range

For the temperature range within the fixed points, the uncertainty of the quadratic deviation function mentioned above has been obtained using a Monte Carlo simulation [7] of data sets at the fixed points. These data sets have standard deviations equal to the combined standard uncertainty at these points.

Extrapolation Of Calibration Results To Higher Temperatures

At NIST, the calibration results for type S and type R thermocouples determined at the fixed points of Zn, Al, Ag and Au are extrapolated from 1064 °C to 1450 °C. To accomplish this, the deviation function described above is extrapolated linearly from 1064 °C to 1450 °C. The extrapolation is linear for historical reasons.

The standard extrapolation uncertainty and its components at the temperature 1450 °C are listed in Table 2. The extrapolation uncertainty may be assumed to increase linearly from 0 °C at 1064 °C to 0.36 °C (the value estimated in the table) at 1450 °C.

The estimates for the reproducibility uncertainty and linearity uncertainty of the extrapolations are discussed in Appendix A1.3 of Ref. [4]. The uncertainties due to slope bias and emf bias at 1064 °C have been evaluated by comparing the results of independent calibrations of thermocouples by both fixed-point and comparison methods. This evaluation results in a very conservative estimate for the bias uncertainty for fixed-point calibrations, since these calibrations are significantly more accurate than comparison calibrations.

Table 2. Uncertainty u for the extrapolation of the thermocouple calibration at 1450 °C.

	Uncertainty Component	u, °C
Type A	Reproducibility of extrapolation	0.23
Type B	Linearity of emf deviation	0.20
	Bias of slope at 1064.18 °C	0.14
	Bias of emf at 1064 °C	0.12
Combined Expanded ($k=2$) Extrapolation Uncertainty		0.72

For type B thermocouples calibrated at the fixed points of Zn, Al, Ag and Au, the deviation function determined over the calibration range is continued from 1064.18 to 1450 °C. Similarly, if the Pd point is included as a calibration fixed point, the quadratic deviation function is continued from 1553.5 °C to 1750 °C. The uncertainty of this deviation function has been obtained using a Monte Carlo simulation of data sets at the fixed points with standard deviations equal to the combined standard uncertainty at these points.

Calibration of Type S, Type R and Type B Thermocouples by Comparison to a Reference Thermocouple

The NIST TCL performs calibrations of Type S and type R thermocouples by comparison with a type S reference thermocouple over the range 0 °C to 1100 °C. The reference thermocouple has been calibrated at the fixed points of Zn, Al, Ag and Au, as described in the previous section. The comparison calibrations are performed in a nickel-chromium furnace. As with the fixed-point calibrations, the calibration results are used to determine a quadratic

function to represent the deviation of the measured emf values from the reference function.

The TCL calibrates Type B thermocouples by comparison with a type B thermocouple over the range 800 °C to 1550 °C in a silicon carbide furnace. In addition, type B thermocouples may be calibrated by comparison with a type S reference thermocouple over the range 0 °C to 1100 °C in the nickel-chromium furnace. If the latter comparison is performed, it is used in conjunction with the former comparison to provide a type B calibration over the range 0 °C to 1550 °C.

Uncertainty Over The Calibration Range

The uncertainty components for calibration of type R and type S thermocouples by comparison with a type S reference thermocouple over the temperature range 0 °C to 1100 °C are itemized in Table 3. The uncertainty due to calibration repeatability, u_{repeat} , is obtained from multiple measurements of the difference between a fixed-point calibration and a comparison calibration for a type S test thermocouple, as discussed in Appendix A2.1 of Ref. [4]. While these results pertain only to type S test thermocouples, we assume that results obtained using type R test thermocouples would yield similar values for u_{repeat} . The uncertainty u_{emf} includes the emf measurement for both the test and reference thermocouple. Finally, the estimate for the standard uncertainty for reference thermocouple inhomogeneity, $u_{\text{rt-inhom}}$, is discussed in Appendix A2.2 of Ref. [4].

Table 3. Standard uncertainty components for calibrations of type B, type S, and type R test thermocouples by comparison with a type S reference thermocouple.

	Uncertainty Component	u
Type A	Calibration Repeatability	u_{repeat}
Type B	Emf Measurement (test and reference)	u_{emf}
	Furnace Temperature Non-uniformity	u_{furn}
	Heat Leak at Reference Junction	$u_{\text{heat-rj}}$
	Reference Thermocouple Calibration	$u_{\text{rt-cal}}$
	Reference Thermocouple Inhomogeneity	$u_{\text{rt-inhom}}$

Extrapolation Of Calibration Results To Higher Temperatures

The calibration results for type S and type R thermocouples determined by comparison with a type S reference thermocouple are extrapolated from 1064 °C to 1450 °C. To accomplish this, the quadratic deviation function described above is extrapolated linearly from 1064 °C to 1450 °C.

The standard extrapolation uncertainty and its components at the temperature 1450 °C are listed in Table 2. The extrapolation uncertainty is assumed to increase linearly from 0 °C at 1064 °C to 0.36 °C (the value estimated in the table) at 1450 °C.

For type B thermocouples calibrated by comparison with a reference thermocouple, the quadratic deviation function determined over the calibration range is continued from 1550 °C to 1750 °C. The uncertainty of this deviation function has been obtained using a Monte Carlo simulation of data sets at the calibration points with standard deviations equal to the standard total uncertainty at these calibration points.

Calibration of Base-Metal Thermocouples

Comparison with a Reference Thermocouple

The TCL can calibrate base-metal thermocouples by comparison with a type S reference thermocouple. The calibration is performed in the nickel-chromium furnace within the range 0 °C to 1100 °C.

Most uncertainty components for this calibration are shown in Table 3. For base-metal thermocouples there is an additional uncertainty component for emf drift of the test thermocouple, $u_{\text{tt-drift}}$, during the period of the calibration. This drift results from the rapid oxidation of the base-metal thermocouples at higher temperatures.

Test Measurements of Thermoelements

A thermocouple is composed of two dissimilar thermoelements, and periodically NIST is asked to perform tests to determine the emf as a function of temperature for individual thermoelements. For temperatures between 0 °C and 1100 °C, the TCL tests letter-designated thermoelements by determining their emf relative to that of the NIST standard platinum thermoelement Pt-67. This determination is made by comparing the emf of the thermoelement to that of the platinum thermoelement of a type S reference thermocouple, where the latter emf is known relative to Pt-67. The temperature of the emf comparison measurement is provided by the reference thermocouple. The uncertainty of a determined thermoelement emf at a given temperature is the combined expanded calibration uncertainty U for its corresponding thermocouple divided by the Seebeck coefficient of the thermoelement at that temperature. This Seebeck coefficient may be found in NIST Monograph 175 [8].

UNCERTAINTIES OF CALIBRATIONS AND TESTS

The numerical values of the uncertainties for all NIST thermocouple calibrations and thermoelement tests are given in Ref. [4]. Some examples of these values are shown below. We provide the uncertainties for calibrations of type S, type R, and type B thermocouples at the Zn, Al, Ag, and Au fixed points in Table 4. We also provide the uncertainties for calibrations of type B thermocouples at the Pd fixed point in Table 5. The propagated combined expanded uncertainty U of the deviation curve and its extrapolation above 1064 °C for type S and type R thermocouples as a function of temperature (resulting from the calibration uncertainties at the fixed points) is shown in Table 6. Here, the two columns on the right include the uncertainty for the extrapolation of the deviation curve. Table 7 shows the propagated expanded total uncertainty U of the deviation curve and its extrapolation above 1064 °C for type B thermocouples as a function of temperature (resulting

from the calibration uncertainties at the fixed points). Here the two columns on the left pertain to calibrations made at the Zn, Al, Ag, and Au fixed points and the two columns on the right refer to calibrations made at the Zn, Al, Ag, Au, and Pd fixed points. Finally, Table 8 shows the combined expanded uncertainty U and its components for calibrations of type R and type S thermocouples by comparison with a type S reference thermocouple.

SUMMARY

We have presented here brief descriptions and some current numerical values of uncertainties and their components for thermocouple calibrations and thermoelement tests performed at the NIST TCL. Complete descriptions of these uncertainties and the sources of their estimates will be found in the new NIST SP 250-92 [4]. A listing of the numerical values of these uncertainties and their components for all thermocouple calibrations and thermoelement tests may also be found in this document.

Table 4. Values of standard uncertainty components u and the total uncertainty U for calibrations of thermocouples at the gold, silver, aluminum, and zinc fixed points. These components are described in Table 1. The combined expanded uncertainty U at these fixed points is given at the right of the table. Uncertainties are expressed in °C. The total uncertainty does not consider the inhomogeneity of the test thermocouple.

Type S and type R thermocouples								
Fixed point	u_{repeat}	u_{quad}	u_{emf}	$u_{\text{fp-temp}}$	$u_{\text{fp-drift}}$	$u_{\text{heat-mj}}$	$u_{\text{heat-rj}}$	$U(k=2)$
Zn	0.027	0.021	0.002	0.001	0.006	0.006	0.002	0.071
Al	0.030	0.019	0.003	0.001	0.006	0.006	0.002	0.075
Ag	0.031	0.018	0.004	0.002	0.008	0.006	0.002	0.075
Au	0.035	0.017	0.004	0.003	0.009	0.006	0.002	0.081

Type B Thermocouples								
Fixed point	u_{repeat}	u_{quad}	u_{emf}	$u_{\text{fp-temp}}$	$u_{\text{fp-drift}}$	$u_{\text{heat-mj}}$	$u_{\text{heat-rj}}$	$U(k=2)$
Zn	0.063	0.047	0.005	0.001	0.006	0.006	0.002	0.16
Al	0.059	0.031	0.005	0.001	0.006	0.006	0.002	0.12
Ag	0.040	0.023	0.005	0.002	0.008	0.006	0.002	0.09
Au	0.044	0.021	0.005	0.003	0.009	0.006	0.002	0.10

Table 5. Values of the standard uncertainty components u and total uncertainty U of calibrations of type B thermocouples at the palladium fixed point. These components are described in Table 1. Uncertainties are expressed in °C. The total uncertainty does not consider the inhomogeneity of the test thermocouple.

Fixed point	u_{repeat}	u_{quad}	u_{emf}	$u_{\text{fp-temp}}$	$u_{\text{fp-plat}}$	u_{furn}	$u_{\text{heat-rj}}$	$U(k=2)$
Pd	0.043	0.017	0.008	0.4	0.2	0.006	0.002	0.90

Table 6. Propagated expanded total uncertainty U at temperature t for fixed-point calibrations of type S and type R thermocouples, in units of °C. The two columns on the right include the uncertainty for the extrapolation of the calibration. The total uncertainty does not consider the inhomogeneity of the test thermocouple.

$t, ^\circ\text{C}$	$U(k=2)$	$t, ^\circ\text{C}$	$U(k=2)$
100	0.06	1100	0.07
200	0.06	1150	0.13
300	0.07	1200	0.22
400	0.06	1250	0.32
500	0.06	1300	0.42
600	0.06	1350	0.52
700	0.06	1400	0.63
800	0.06	1450	0.72
900	0.05		
1000	0.06		
1100	0.07		

Table 7. Propagated expanded total uncertainty U at temperature t for fixed-point calibrations of type B thermocouples, in units of °C. The total uncertainty does not consider the inhomogeneity of the test thermocouple.

No Pd Point		Pd Point Used	
$t, ^\circ\text{C}$	$U(k=2)$	$t, ^\circ\text{C}$	$U(k=2)$
400	0.17	400	0.17
500	0.11	500	0.10
600	0.09	600	0.11
700	0.12	700	0.10
800	0.11	800	0.11
900	0.08	900	0.09
1000	0.06	1000	0.06
1100	0.12	1100	0.14
1200	0.22	1200	0.23
1300	0.40	1300	0.32
1400	0.56	1400	0.54
1450	0.60	1450	0.61
		1500	0.68
		1600	0.9
		1700	1.2
		1750	1.4

Table 8. Total expanded uncertainty U and its components u , in units of °C, for calibrations of type R and type S thermocouples by comparison with a type S reference thermocouple, as a function of temperature t . These components are described in Table 3. The total uncertainty does not consider the inhomogeneity of the test thermocouple.

$t, ^\circ\text{C}$	u_{repeat}	u_{emf}	u_{furn}	$u_{\text{heat-rj}}$	$u_{\text{rt-cal}}$	$u_{\text{rt-inhom}}$	$U(k=2)$
100	0.048	0.002	0.001	0.003	0.031	0.03	0.13
200	0.046	0.002	0.002	0.003	0.030	0.04	0.14
300	0.047	0.004	0.003	0.003	0.033	0.05	0.15
400	0.050	0.005	0.004	0.003	0.031	0.06	0.16
500	0.053	0.006	0.005	0.003	0.030	0.06	0.18
600	0.055	0.007	0.006	0.003	0.029	0.07	0.19
700	0.057	0.008	0.007	0.003	0.028	0.08	0.20
800	0.060	0.010	0.008	0.003	0.028	0.09	0.22
900	0.062	0.011	0.009	0.003	0.027	0.09	0.23
1000	0.063	0.012	0.010	0.003	0.030	0.10	0.25
1100	0.066	0.013	0.011	0.003	0.034	0.11	0.27

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