FINAL REPORT

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SIM Thermocouple Type S Supplementary Comparison

Type S Thermocouple Wire over the Range 100 °C to 1100 ° C

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Abstract
A collapsed star type S thermocouple intercomparison was performed over the International Temperature Scale of 1990 (ITS-90) temperature range from 0 °C to 1100 °C. This was an Inter-American Metrology System (SIM) regional intercomparison piloted by the National Institute of Standards and Technology (NIST). Eleven laboratories (including NIST) participated in the intercomparison. Twenty-one type S thermocouples were constructed and calibrated at NIST, of which ten served as transfer standards. The thermocouples were identified as Cut 1 through Cut 21. Each thermocouple was calibrated by the metal fixed-point method at the freezing points of Zn, Al, Ag, and Au. The 21 calibrations were ultimately used to determine the reference values (RV) for the intercomparison. Subsequently the artifacts were calibrated at a participating laboratory by comparison with a

local standard and/or by fixed-point method. Subsequently they were returned to the pilot laboratory where they were remeasured at the freezing point of silver (for purposes of determining a transfer uncertainty). Although thermocouples are not a standard interpolating instrument on the ITS-90, they are proposed as an approximation technique and are a widely used thermometer; so, it is useful to look at the measurement capabilities involved in their calibration.

Table 0. List of Participating Laboratories

Acronym	Country	Laboratory name
INTI	Argentina	Instituto Nacional de Tecnologia Industrial
INMETRO	Brazil	Instituto Nacional de Metrologia, Qualidade y Industrial, Rio de Janeiro
NRC	Canada	National Research Council of Canada
CESMEC-LCPNT	Chile	Laboratorio Custodio de los Patrones Nacionales de Temperatura (Red Nacional de Metrologia)
INM	Colombia	Instiuto Nacional de Metrologia de Colombia
LACOMET	Costa Rica	Laboratorio Costarricense de Metrologia
BSJ	Jamaica	Bureau of Standards Jamaica
CENAM	Mexico	Centro Nacional de Metrologia
SNM-INDECOPI	Peru	Instituto Nacional de Defensa de la Competencia y de la Propiedad Intelectual, Servicio Nacional de Metrologia
LATU	Uruquay	Laboratorio Tecnologia del Uruquay
NIST	USA	National Institute of Standards and Technology

1. Comparison Timeline and Artifacts

1.1 Timeline

In 2008 an invitation was sent to the SIM laboratories for participation in a type S thermocouple supplemental comparison. Of the original list of laboratories that responded that they wanted to participate, 11 laboratories completed the comparison. In 2009 NIST purchased 30.5 m of type S ITS-90 reference grade wire. In 2009 the laboratories returned the surveys that described how they typically performed their calibrations and they completed an uncertainty component table that was provided. Thermocouples began to be sent to participating laboratories in early 2011. Additional thermocouples were being calibrated at the pilot laboratory during this period as well. Upon completion of their calibrations and scans, the test thermocouples were sent to participating laboratories. By May 2013 all the participating laboratories had received their thermocouples for calibration. All of the participants' thermocouples and calibration results were received at the pilot laboratory by May of 2014. In March of 2016 the laboratories with En> |1| were given the opportunity to revise their results if they felt they had made any mistakes in the data they submitted. Draft A of the supplemental comparison went out for review in July 2017. All comments and suggestions were received by November 2017. Draft B went out for review on May 18th, 2018. Laboratories were requested to reply with any comments or editorial remarks by June 8th, 2018. Subsequently the paper was revised with only editorial changes and in September 2018 it was submitted to the NIST editorial board.

1.2 Calibration Artifacts

NIST purchased 30.5 m of ITS-90 Reference Grade type S thermocouple wire (Pt and Pt/10%Rh each 0.51 mm in diameter) from Sigmund Cohn Corp. The wire was cut into various lengths ranging from 1.0 m to 1.80 m. Each wire pair (thermocouple) was numbered consecutively from one end of the spool. All thermocouples were constructed from the same spools of thermocouple wire. The lengths of the thermocouples were based on the needs of the various participating laboratories.

Each thermocouple was a minimum of 100 cm long. Each thermocouple was assembled in a new high purity alumina insulator that had been baked at approximately 1100 °C for 3 h. Each leg had an acrylic sleeve and heat shrink tubing covering the last half centimeter of the insulator and of both wires where they exit the insulator (to minimize handling strain). Matched copper leads were soldered to each thermocouple leg for use as the ice-point reference junctions and to minimize the generation of stray thermal emf.

After welding the two legs of the thermocouple together, they underwent a multi-step procedure. First the thermocouple wires were electrically annealed in air for 45 minutes at 1450 ºC followed by 30 minutes at 750 ºC. Then they were assembled in a high-purity two bore alumina insulator, and given a furnace anneal and finally, a homogeneity scan. The furnace anneals consisted of a one hour anneal in air at 1100 °C followed by an overnight anneal at 450 °C. NIST measured the thermocouples at the freezing points of Zn, Al, Ag, and Au in their respective metal freezing point cells. A primary calibration was performed on the thermocouples in ascending temperature. Then the thermocouples were given another furnace anneal and a final homogeneity scan. Subsequently they were sent to participating laboratories. Six of the participating laboratories received one thermocouple, however, if a laboratory claimed uncertainties ≤ 0.5 μV it received two thermocouples. After participating laboratories completed their measurements, they returned the thermocouples and measurement results to NIST. Upon return of each thermocouple to NIST, the thermocouple was measured at the freezing point of Ag to determine whether a transfer uncertainty needed to be applied. The original plan included a homogeneity scan; however, this was not possible as the bath was not working properly and required major repairs. Then the thermocouple was furnace annealed.. NIST test methods are described in NIST SP250-35 (1) and NISTIR 5340 (2).

The calibration was conducted over the range of 0 ºC to 1100 ºC; however, a laboratory was not expected to calibrate the thermocouple(s) outside of its CMC (calibration measurement capabilities) claims or normal operating range. Although the pilot laboratory only performed measurements at the four metal freezing points, the test comparison calibration points included 100 °C, 200 °C, 400 °C, 500 °C, 600 °C, 800 °C, 1000 °C, and 1100 °C as well. These calibration points were interpolated values from a quadratic fit to each set of fixed-point data. The values are derived from a second-degree polynomial fitted to the data by the method of least squares. The deviation at 0 °C was constrained to zero.

If the laboratory performed calibrations by fixed-point method, the results at the fixed-point temperatures were reported. A laboratory could present their comparison data as well. The thermocouples were annealed by NIST and the participants were requested not to reanneal them. The laboratories were to calibrate the thermocouple(s) in order of increasing temperature. Any constraints or limitations that would prevent a laboratory from performing a calibration at any of these calibration points were communicated to NIST prior to the start of the test.

2. Determination of Reference Values

Fixed-point calibrations were performed on 21 consecutive cuts of wire from the same spools of type S wire. Measurements were performed at the freezing points of Zn, Al, Ag and Au. Each of the four fixed-point cells contained approximately 125 cc of high-purity metal. Measurements of thermocouple emf, E were compared with the type S reference function fixed point emf values (E_{ref}). The values of E-E_{ref} of all 21 thermocouples were within ± 1.5 µV (± 0.126 °C at 1100 °C). The emf values at the calibration points of 100 °C, 200 °C, 400 °C, 500 °C, 600 °C, 800 °C, 1000 °C, and 1100 °C are interpolated values from a least squares fit to each of the 21 sets of fixed-point data. Each set of data was comprised of an average emf value based on two freezes for each of the 4 cells. The reference value (RV) was calculated from the simple mean (emf) at each temperature of the 21 pilot laboratory calibration data sets. The median emf at each temperature was also calculated. The simple mean became the reference value. The median value was not chosen as the difference between the mean and median emf at each point was tabulated. The average difference was less than the standard deviation of the tabulated differences. A plot of the difference between the mean values and median values at each calibration point versus emf showed no significant skew.
The final associated uncertainties for the interpolated reference values included an uncertainty component for the goodness of fit (the least squares fit). Each of the 21 sets of data were first used to determine a quadratic deviation fit from the type S thermocouple reference function emf values at the four fixed-point temperatures. Then, the reference function polynomial was added to the deviation polynomial to generate a unique polynomial for each thermocouple. In doing so the analysis program provided the emf residuals at each of the 4 temperature. These residuals are used to generate an overall standard deviation of the residuals, which became the goodness of fit uncertainty component. This component consisted of one emf that was added in quadrature to the uncertainty at each interpolated value. The uncertainties for the freezing point emfs are strictly the standard deviation of the emf (of the 21 sets of data) at each of the 4 metal fixed-points and do not include a goodness of fit component. The reference values and associated uncertainties at each calibration point were calculated from only the pilot laboratory data. In Tables 11-20 the NIST data for the test thermocouples and the RV can be found. In part, we decided not to include the data from the participating laboratories in the reference value calculations because laboratories provided comparison data and/or fixed-point data; therefore, most of the laboratories did not provide data at every temperature. We did not attempt to interpolate or extrapolate the participating laboratory’s data to provide data at every temperature. However, for completeness sake, the simple mean, median, and weighted mean (based on data from participating laboratories) were determined at the fixed-point temperature of zinc, 419.527

°C. The freezing-point of zinc was the calibration point chosen to compare the statistics with, and without, the inclusion of the participating laboratories data since the pilot laboratory had made measurements at the fixed-points and the freezing point of Zn was the temperature for which the greatest number of participating laboratories provided data. In a comparison of the simple mean, median, and weighted mean statistics, the data including the participating laboratory results, resulted in smaller statistical uncertainties than the pilot laboratories data. The equation for the weighted mean, X_{weighted} and its uncertainty, u, was (3):

$$X_{weighted} = \frac{\Sigma\left(\frac{X_i}{u^2(X_i)}\right)}{\Sigma\frac{1}{u^2(X_i)}} \qquad (1)$$

$$u^2\left(X_{weighted}\right) = \frac{1}{\Sigma\frac{1}{u^2(X_i)}} \qquad (2)$$

Hence, the interpolated reference values and associated uncertainties are derived from only the pilot laboratory data.

2.1 Evaluation of Uncertainties

The measurement uncertainties for the participating laboratories were obtained from the calibration results spreadsheet provided by the laboratory. To simplify the presentation and interpretation of the results, laboratories that received two test thermocouples and provided two sets of calibration results had their emf values averaged to obtain one set of results. In the tables of bilateral differences between laboratories the NIST averaged its results for its two sets of data to attain one averaged set of results. This averaged emf set of results is used for the bilateral differences calculations

2.2 Transfer Uncertainty Evaluation

Each thermocouple was measured at the Ag freezing point upon return to pilot laboratory. If the difference between the two measured NIST Ag fixed-point emf values was within the combined NIST assigned uncertainty (k=2) for two measurements, no additional transfer uncertainty was assigned to the thermocouple artifact. Only one of the 10 transfer artifacts required an additional transfer uncertainty. This thermocouple (Cut 1) suffered damage to the insulator during calibration at the participating laboratory, which may be responsible for the shift in measured emf. The participating laboratory completed the calibration with the broken insulator. After the thermocouple was returned to NIST the thermocouple was repaired prior to testing in the Ag cell, as we did not want to insert a broken thermocouple assembly in the freezing point cell. The thermocouple was removed from the insulator and electrically annealed and then reassembled with a new cleaned and baked high-purity alumina insulator. After assembly, the thermocouple was given a furnace anneal before measuring in the silver cell.

2.3 Evaluation of Degrees of Equivalence with Reference Value

The following equation was used to determine the degree of equivalence (E_n) of each participating lab with respect to the combined uncertainty U_n. The error bars in figures 1-10 represent the expanded uncertainties (k=2) of the differences. The E_n results at each temperature are computed for the test thermocouple for each laboratory. E_n is calculated as:

$$E_n = \frac{|E(Lab's\ emf) - E(RV\ emf)|}{U_{combined}} \qquad (3)$$

where $U_{combined}$ represents a combined uncertainty including both uncertainty of the RV and that of the participating laboratory and if applicable a transfer uncertainty.

$$U_{combined} = \sqrt{U(RV)^2 + U(Lab)^2} \quad (4)$$

An $E_n < 1$ signifies an emf deviation from the reference value smaller than the combined uncertainty of the laboratory and the RV, for the participating laboratory.

Additionally, an uncertainty ratio U(RV) / U(Lab) is included such that a value greater than 1 signifies that the participant is claiming an uncertainty smaller than the RV uncertainty. The results of the comparison are given in Tables 1 through 10.

3. Results

After the data was analyzed, any lab that had an $E_n > 1$ for a calibration point was given an opportunity to reexamine their data and report appropriate revisions. The Laboratory received an email stating, "I am writing to let you know that some of the results of this comparison appear to be anomalous. We invite you to check your results and/or their associated uncertainties for numerical errors." After the revised results were returned, the laboratory data were analyzed again. All requested revisions were found reasonable by the pilot laboratory.

3.1 Laboratory Comparison Data

Tables 1 through 10 present the comparison data in tabular form for each laboratory. The second column of each table contains ΔE values which represent the difference in emf between the laboratory result and the RV at each temperature. Comparison results of $E_n < 1$ signify compliance for the participating laboratory. Figures 1 through 10 present the comparison data graphically for each laboratory relative to the comparison reference value.

Table 1. Comparison test results for LACOMET.

Temperature °C	ΔE, μV	$U_{LACOMET}$, *k*=2, μV	U_{RV}, *k*=2, μV	$U_{combined}$, *k*=2, μV	En	$U_{RV}/U_{LACOMET}$
100	-0.33	5.8	0.76	5.9	0.06	0.13
200	-0.97	6.7	0.86	6.7	0.14	0.13
400	-0.78	7.6	1.0	7.6	0.10	0.13
500	-0.85	7.8	1.1	7.9	0.11	0.14
600	-1.47	10.1	1.2	10.2	0.14	0.12
800	-1.57	10.8	1.3	10.8	0.15	0.12
1000	-2.97	11.4	1.5	11.5	0.26	0.13
1100	-3.60	11.7	1.6	11.8	0.30	0.14
419.527	-0.42	4.72	0.96	4.8	0.09	0.20
660.323	-2.52	5.1	1.00	5.2	0.49	0.20

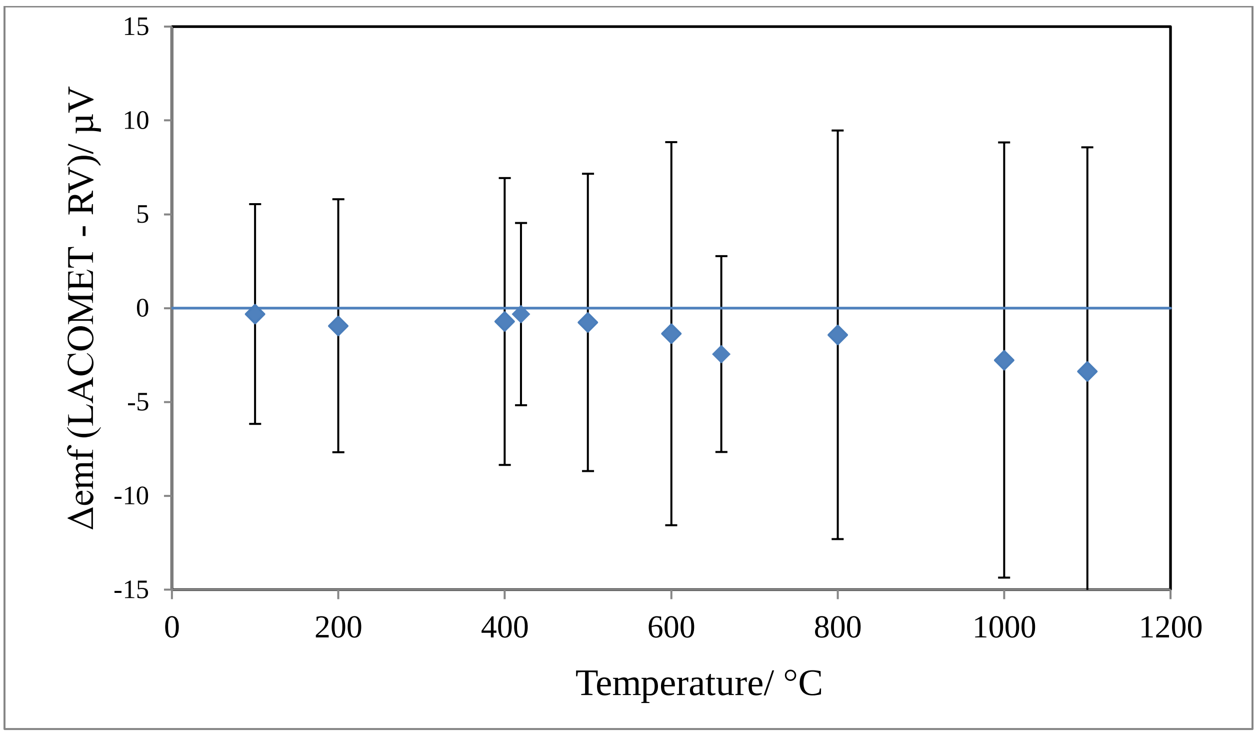

Figure 1. Type S thermocouple emf measurement differences between LACOMET and that of the RV. Uncertainty bars are the combined uncertainty (*k*=2) in μV.

Table 2. Comparison test results for BSJ. The values written in bold type represent the temperatures for which *En* >1.

Temperature, °C	ΔE, µV	U_{BSJ}, *k*=2, µV	U_{RV}, *k*=2, µV	$U_{combined}$, *k*=2, µV	En	U_{RV}/U_{BSJ}
100	-0.99	1.0	0.76	1.3	0.79	0.76
200	-1.18	1.3	0.86	1.6	0.76	0.66
400	-0.75	1.5	1.0	1.8	0.41	0.68
500	-2.68	1.5	1.1	1.9	**1.4**	0.74
419.527	-0.32	1.0	0.96	1.4	0.23	0.96

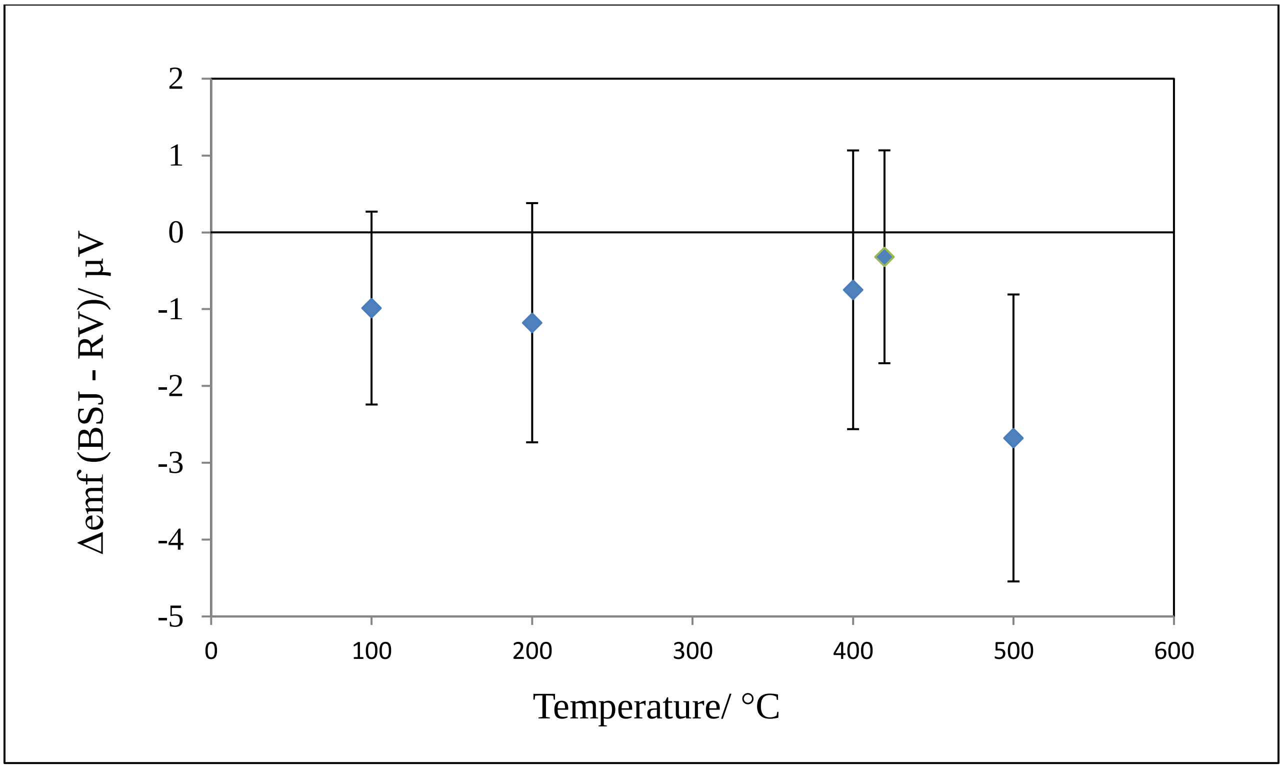

Figure 2. Type S thermocouple emf measurement differences between BSJ and that of the RV. Uncertainty bars are the combined uncertainty (*k*=2) in µV.

Table 3. Comparison test results for LATU. The values written in bold type represent the temperatures for which *En* >1.

Temperature, °C	ΔE, μV	U_{LATU}, *k*=2, μV	U_{RV}, *k*=2, μV	$U_{combined}$, *k*=2, μV	En	U_{RV}/U_{LATU}
100	-0.09	1.9	0.76	2.1	0.04	0.40
200	0.82	3.7	0.86	3.9	0.21	0.23
400	6.45	10.0	1.0	11.0	0.59	0.09
500	10.32	6.8	1.1	6.9	**1.5**	0.16
600	13.80	7.3	1.2	7.4	**1.9**	0.16
800	15.49	8.9	1.3	9.0	**1.7**	0.14
1000	1.23	13.0	1.5	13.4	0.09	0.11

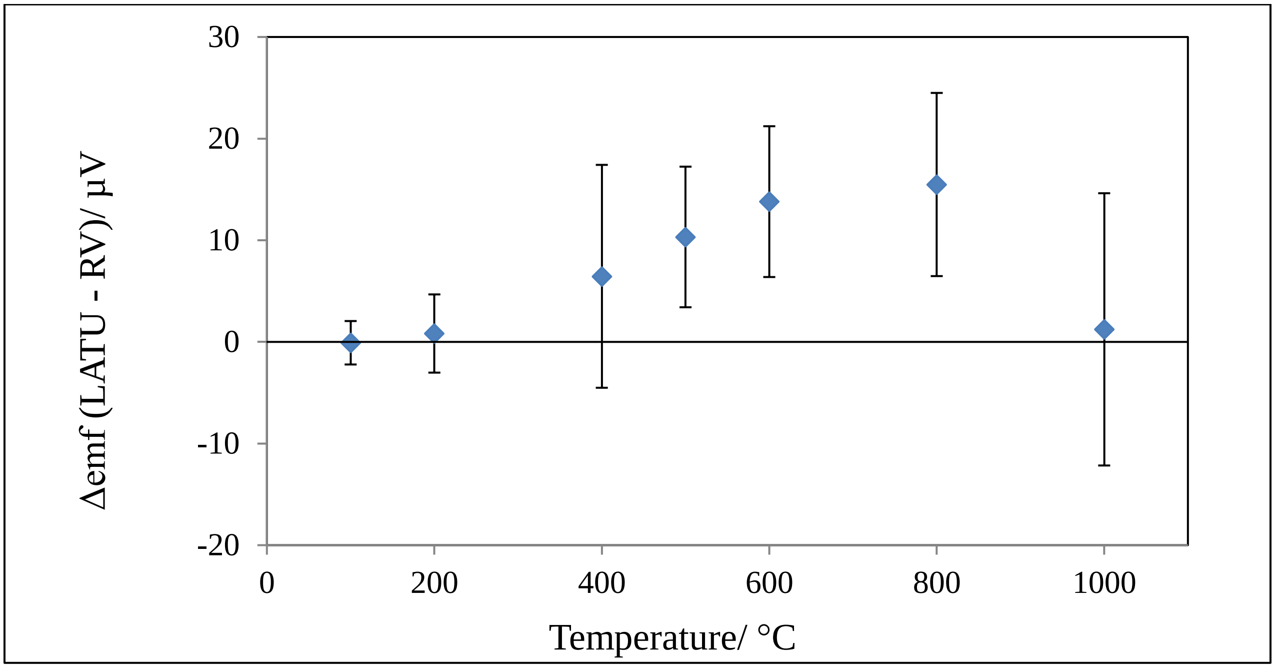

Figure 3. Type S thermocouple emf measurement differences between LATU and that of the RV. Uncertainty bars are the combined uncertainty (*k*=2) in μV.

Table 4. Comparison test results for CESMEC-LCPNT.

Temperature, °C	ΔE, μV	U_{CESMEC}, *k*=2, μV	U_{RV}, *k*=2, μV	$U_{combined}$, *k*=2, μV	En	U_{RV}/U_{CESMEC}
100	-1.68	4.4	0.76	4.5	0.38	0.17
200	-2.06	4.5	0.86	4.6	0.45	0.19
400	-2.86	5.2	1.0	5.3	0.54	0.20
500	0.50	6.1	1.1	6.2	0.08	0.18
600	0.11	8.6	1.2	8.7	0.01	0.14
800	-5.99	27.	1.3	26.93	0.22	0.05
1000	-15.95	39.	1.5	39.33	0.41	0.04

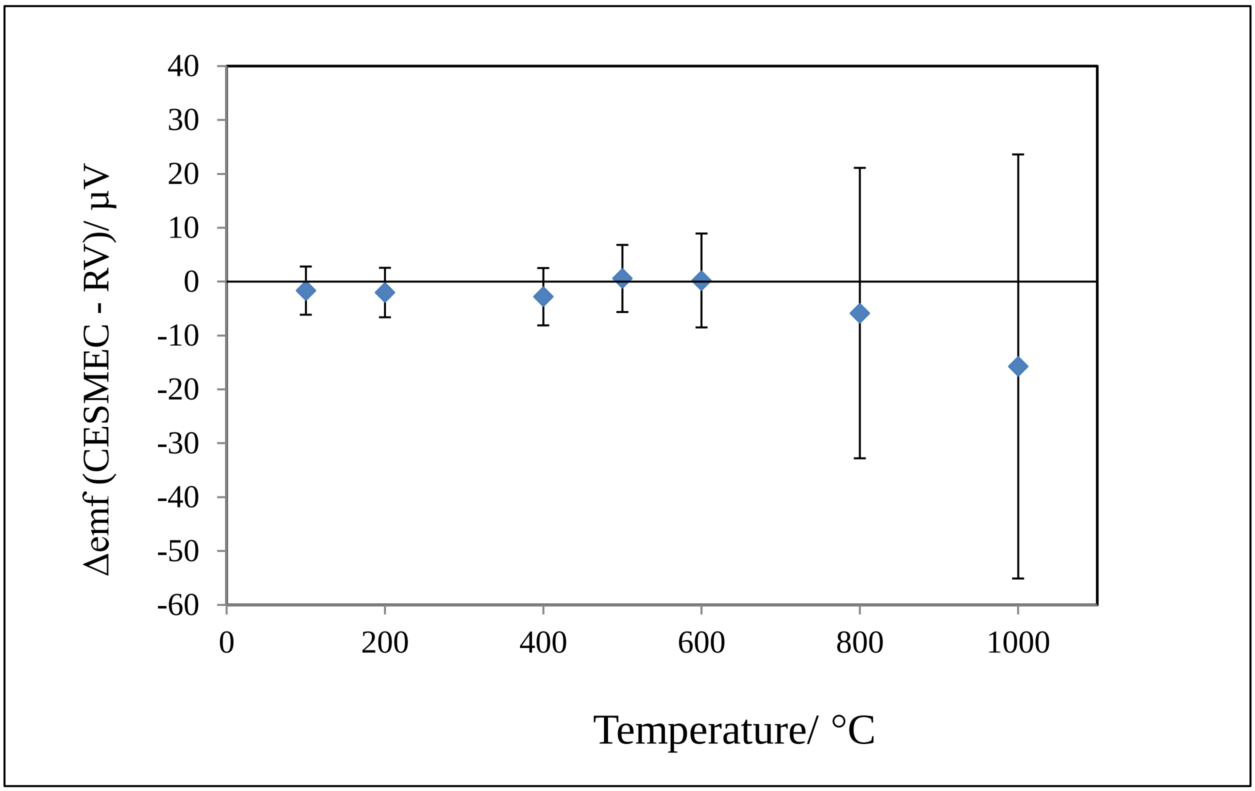

Figure 4. Type S thermocouple emf measurement differences between CESMEC and that of the RV. Uncertainty bars are the combined uncertainty (*k*=2) in μV.

Table 5. Comparison test results for INDECOPI. The values written in bold type represent the temperatures for which *En* >1.

Temperature, °C	ΔE, µV	$U_{INDECOPI}$, *k*=2, µV	U_{RV}, *k*=2, µV	$U_{combined}$, *k*=2, µV	En	$U_{RV}/U_{INDECOPI}$
100	0.91	2.2	0.76	2.3	0.39	0.34
200	1.82	4.3	0.86	4.4	0.42	0.20
400	4.25	4.9	1.0	5.0	0.85	0.21
500	4.72	5.3	1.1	5.4	0.87	0.21
600	4.90	5.7	1.2	5.8	0.84	0.21
800	5.29	5.8	1.3	5.9	0.89	0.22
1000	4.93	5.9	1.5	6.1	0.81	0.25
419.527	4.55	3.6	0.96	3.7	**1.2**	0.27
660.323	4.64	4.5	1.0	4.6	**1.0**	0.22

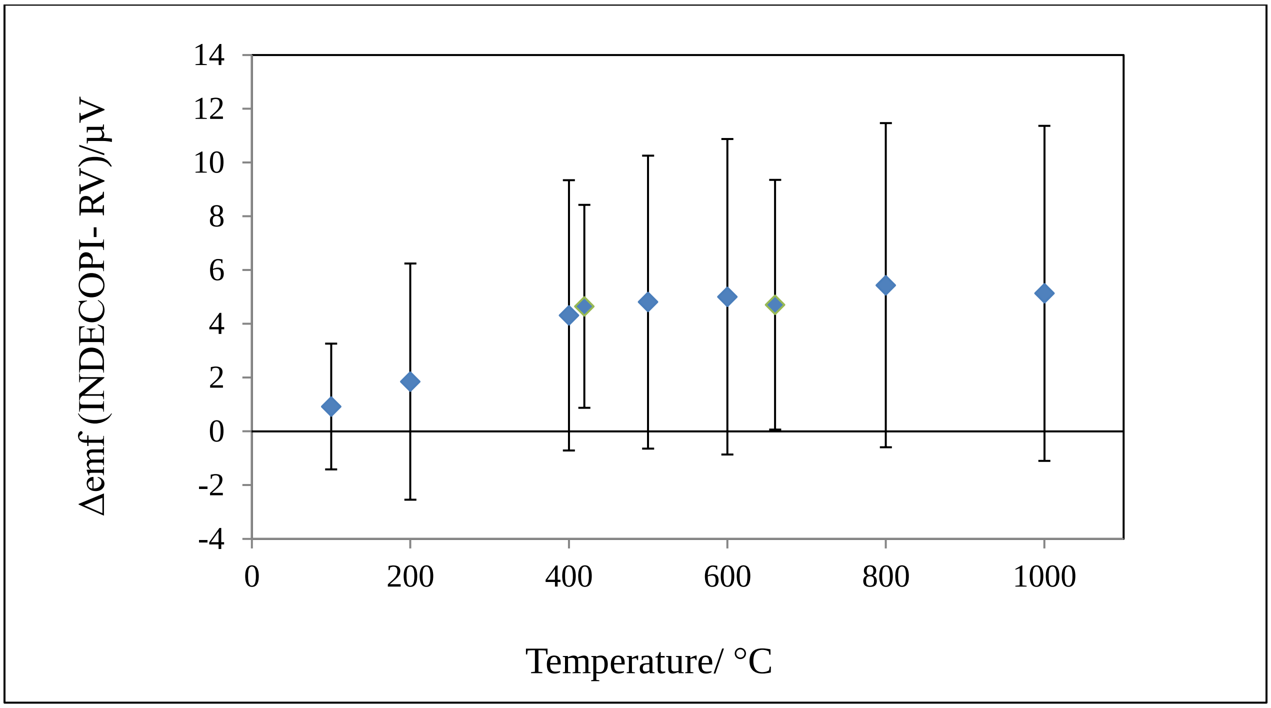

Figure 5. Type S thermocouple emf measurement differences between INDECOPI and that of the RV. Uncertainty bars are the combined uncertainty (*k*=2) in µV.

Table 6. Comparison test results for INM. The values written in bold type represent the temperatures for which *En* >1.

Temperature, °C	ΔE, µV	U_{INM}, *k*=2, µV	U_{RV}, *k*=2, µV	$U_{combined}$, *k*=2, µV	En	U_{RV}/U_{INM}
100	-0.71	0.77	0.76	1.1	0.65	0.99
200	-0.04	0.82	0.86	1.2	0.04	1.04
400	2.18	1.2	1.0	1.6	**1.4**	0.85
500	4.12	1.4	1.1	1.8	**2.3**	0.79
600	6.40	1.6	1.2	2.0	**3.2**	0.73
800	28.08	2.4	1.3	2.7	**10**	0.53
1000	15.36	2.2	1.5	2.6	**5.8**	0.66
1100	25.84	1.7	1.6	2.3	**11.0**	0.95

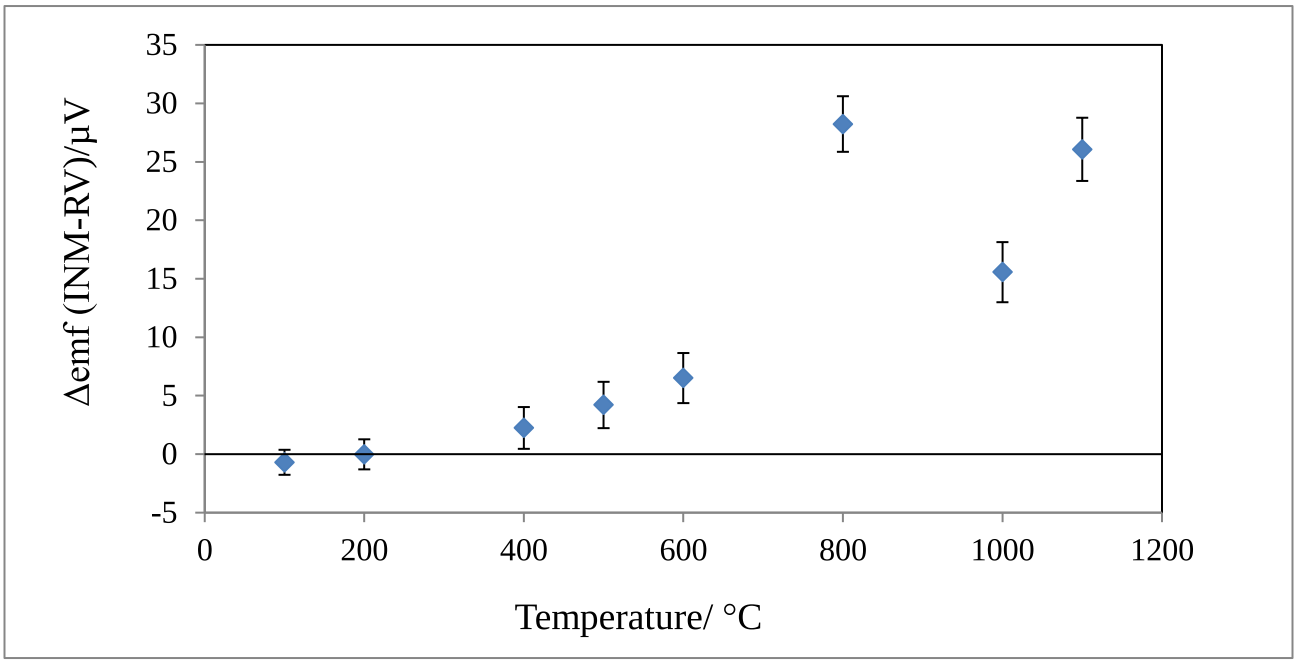

Figure 6. Type S thermocouple emf measurement differences between INM and that of the RV. Uncertainty bars are the combined uncertainty (*k*=2) in µV.

Table 7. Comparison test results for CENAM.

Temperature, °C	ΔE, μV	U_{CENAM}, *k*=2, μV	U_{RV}, *k*=2, μV	$U_{combined}$, *k*=2, μV	En	U_{RV}/U_{CENAM}
419.527	-0.16	0.58	0.96	1.1	0.14	1.66
660.323	-0.04	0.65	1.0	1.2	0.03	1.53
961.78	0.77	1.4	1.3	1.9	0.41	0.90

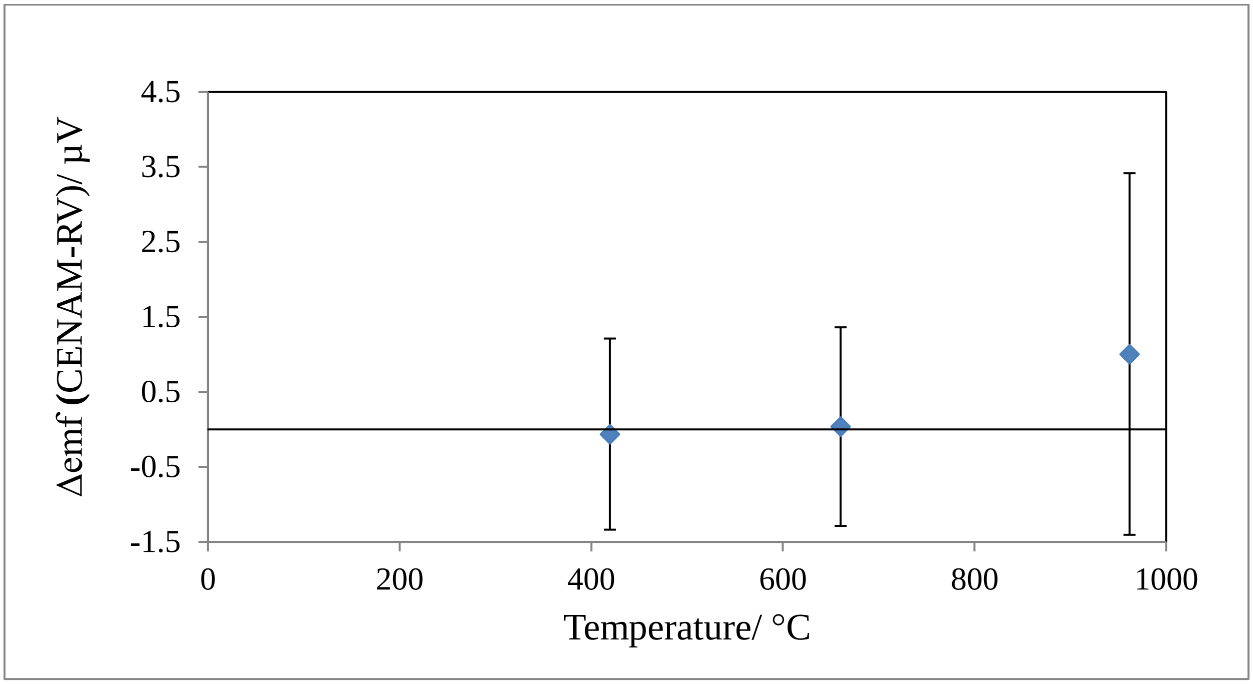

Figure 7. Type S thermocouple emf measurement differences between CENAM and that of the RV. Uncertainty bars are the combined uncertainty (*k*=2) in μV.

Table 8. Comparison test results for INMETRO. The values written in bold type represent the temperatures for which *En* >1.

Temperature, °C	ΔE, μV	$U_{INMETRO}$, *k*=2, μV	U_{RV}, *k*=2, μV	$U_{combined}$, *k*=2, μV	En	$U_{RV}/U_{INMETRO}$
100	-0.43	1.1	0.76	1.3	0.33	0.72
200	-0.49	1.4	0.86	1.7	0.29	0.60
400	-1.26	1.9	1.02	2.2	0.59	0.54
500	5.88	4.3	1.1	4.5	**1.3**	0.26
600	5.44	4.5	1.2	4.7	**1.2**	0.26
800	9.13	4.9	1.3	5.1	**1.8**	0.26
1000	13.65	9.7	1.5	9.8	**1.4**	0.15
1100	10.44	15	1.6	15	0.71	0.11
419.527	0.29	1.7	0.96	2.0	0.15	0.55
660.323	0.31	2.0	1.0	2.2	0.14	0.50
961.78	1.28	2.4	1.3	2.7	0.47	0.52

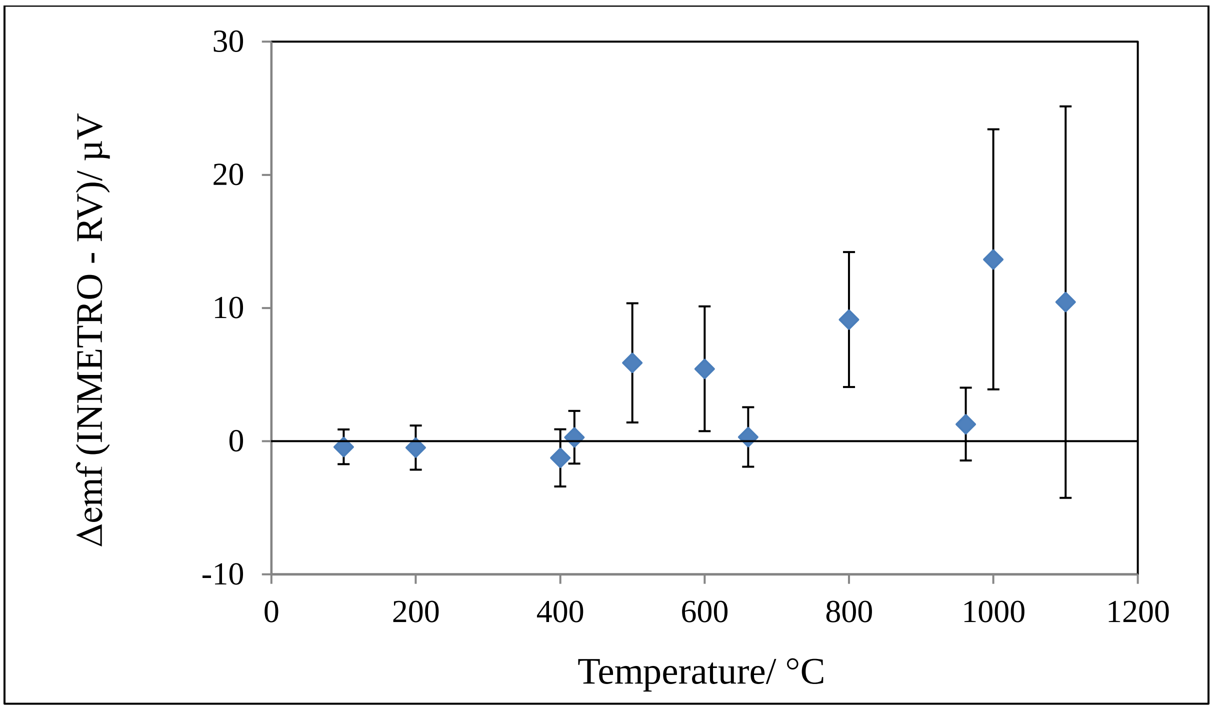

Figure 8. Type S thermocouple emf measurement differences between INMETRO and that of the RV. Uncertainty bars are the combined uncertainty (*k*=2) in μV.

Table 9. Comparison test results for INTI.

Temperature, °C	ΔE, µV	U_{INTI}, k=2, µV	U_{RV}, k=2, µV	$U_{combined}$, k=2, µV	En	U_{RV}/U_{INTI}
419.527	0.00	2.4	0.96	2.6	0.00	0.40
660.323	0.19	2.5	1.0	2.7	0.07	0.40
961.78	2.65	3.1	1.3	3.3	0.80	0.41

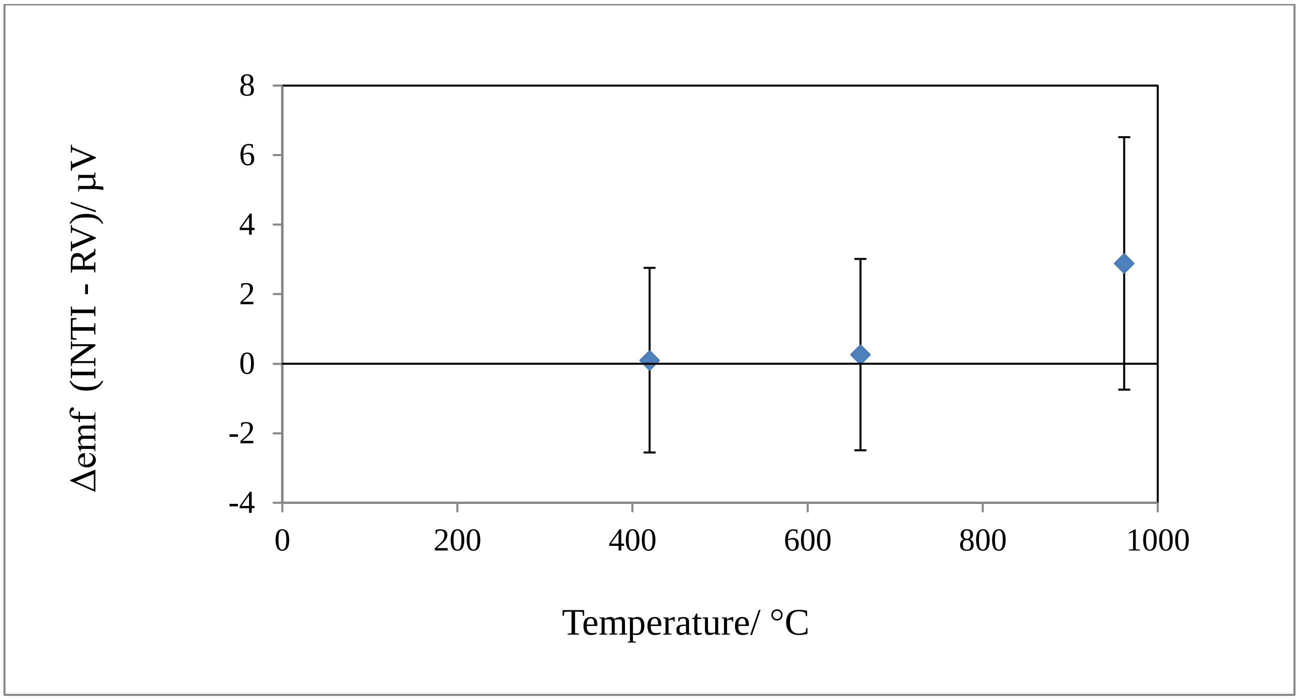

Figure 9. Type S thermocouple emf measurement differences between INTI and that of the RV. Uncertainty bars are the combined uncertainty (k=2) in µV.

Table 10. Comparison test results for NRC.

Temperature, °C	ΔE, μV	U_{NRC}, *k*=2, μV	U_{RV}, *k*=2, μV	$U_{combined}$, *k*=2, μV	En	U_{RV}/U_{NRC}
419.527	0.13	1.2	0.96	1.5	0.09	0.83
660.323	-0.06	1.7	1.0	1.9	0.03	0.60
961.78	0.24	2.5	1.3	2.8	0.09	0.51

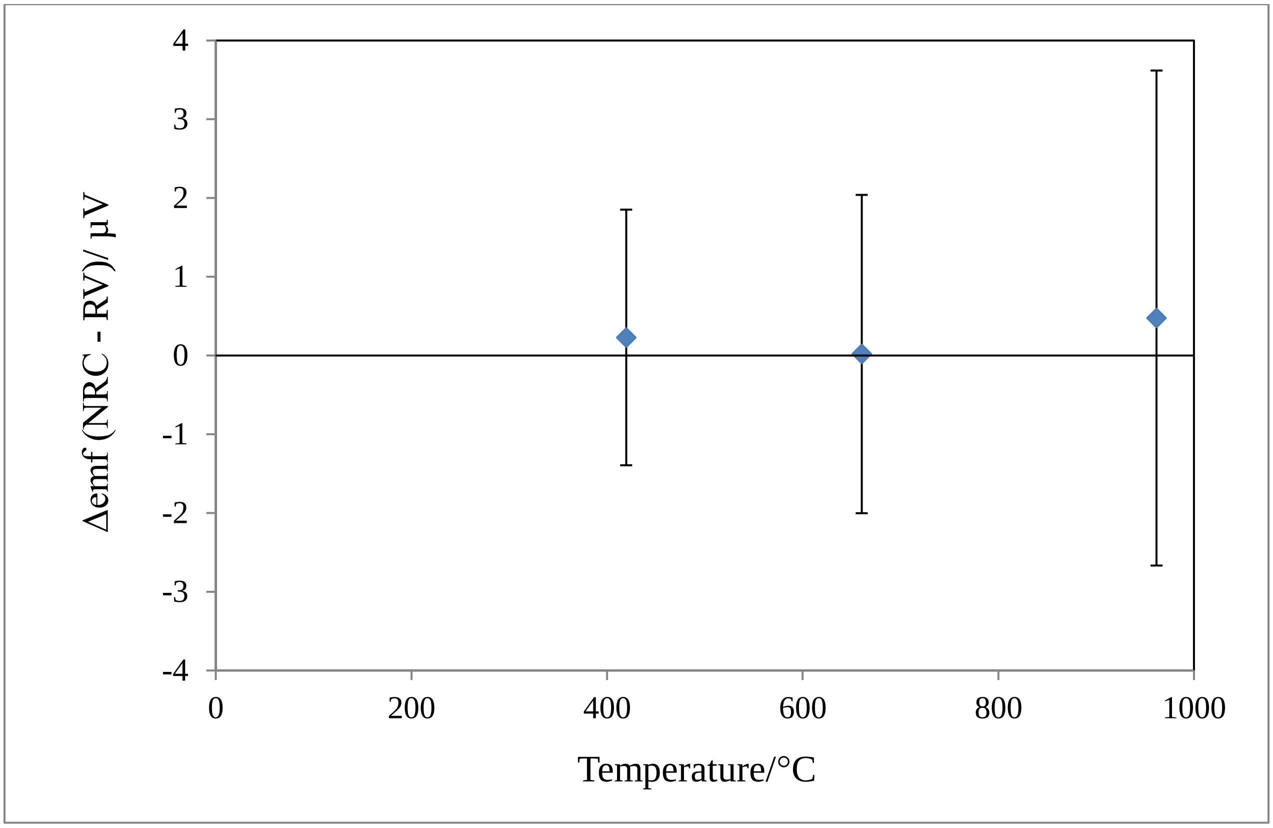

Figure 10. Type S thermocouple emf measurement differences between NRC and that of the RV. Uncertainty bars are the combined uncertainty (*k*=2) in μV.

Tables 11 through 20 give the comparison test results for the NIST calibrated transfer artefacts relative to the reference values. Tables 11 through 20 present only the NIST data for the Cuts that were sent out for calibration by participating laboratories. Figure 11 is a plot of the emf difference of the NIST data and the intercomparison RV's (for each of the 10 test artefacts), as a function of temperature.

Table 11.
Cut 1.

Temperature, °C	ΔE, μV	U_{NIST}, k=2, μV	U_{RV}, k=2, μV	Ucombined k=2, μV	En	U_{RV}/U_{NIST}
100	0.11	0.5	0.76	0.91	0.13	1.52
200	0.22	0.6	0.86	1.1	0.21	1.43
400	0.35	0.7	1.0	1.2	0.28	1.46
500	0.42	0.7	1.1	1.3	0.32	1.59
600	0.50	0.8	1.2	1.4	0.35	1.47
800	0.49	0.8	1.3	1.5	0.32	1.59
1000	0.43	0.9	1.5	1.7	0.25	1.62
1100	0.43	1	1.6	1.9	0.23	1.61
419.527	0.35	0.7	0.96	1.2	0.30	1.37
660.323	0.69	0.9	1.0	1.3	0.51	1.11
961.78	0.16	0.8	1.3	1.5	0.11	1.57

Table 12.
Cut 2.

Temperature, °C	ΔE, μV	U_{NIST}, k=2, μV	U_{RV}, k=2, μV	Ucombined k=2, μV	En	U_{RV}/U_{NIST}
100	0.11	0.5	0.76	0.94	0.12	1.52
200	0.22	0.6	0.86	1.1	0.21	1.43
400	0.35	0.7	1.0	1.3	0.27	1.46
500	0.32	0.7	1.1	1.5	0.22	1.59
600	0.40	0.8	1.2	1.6	0.25	1.47
800	0.39	0.8	1.3	1.8	0.21	1.59
1000	0.33	0.9	1.5	2.2	0.15	1.62
1100	0.23	1	1.6	2.5	0.09	1.61
419.527	0.36	0.7	0.96	1.3	0.27	1.37
660.323	0.45	0.9	1.0	1.5	0.31	1.11
961.78	0.12	0.8	1.3	2.1	0.06	1.57

Table 13.
Cut 3.

Temperature, °C	ΔE, μV	U_{NIST}, k=2, μV	U_{RV}, k=2, μV	Ucombined k=2, μV	En	U_{RV}/U_{NIST}
100	0.11	0.5	0.76	0.94	0.12	1.52
200	0.22	0.6	0.86	1.1	0.21	1.43
400	0.25	0.7	1.0	1.3	0.19	1.46
500	0.32	0.7	1.1	1.5	0.22	1.59
600	0.20	0.8	1.2	1.6	0.12	1.47
800	-0.01	0.8	1.3	1.8	0.01	1.59
1000	-0.37	0.9	1.5	2.2	0.17	1.62
1100	-0.57	1	1.6	2.5	0.23	1.61
419.527	0.08	0.70	0.96	1.3	0.06	1.37
660.323	0.57	0.90	1.0	1.5	0.39	1.11
961.78	-0.65	0.80	1.3	2.1	0.31	1.57

Table 14.
Cut 4.

Temperature, °C	ΔE, μV	U_{NIST}, k=2, μV	U_{RV}, k=2, μV	Ucombined k=2, μV	En	U_{RV}/U_{NIST}
100	0.01	0.5	0.76	0.94	0.02	1.52
200	0.02	0.6	0.86	1.1	0.02	1.43
400	0.05	0.7	1.0	1.3	0.04	1.46
500	0.22	0.7	1.1	1.5	0.15	1.59
600	0.30	0.8	1.2	1.6	0.19	1.47
800	0.59	0.8	1.3	1.8	0.32	1.59
1000	1.03	0.9	1.5	2.2	0.47	1.62
1100	1.23	1	1.6	2.5	0.50	1.61
419.527	0.43	0.7	0.96	1.3	0.32	1.37
660.323	0.05	0.9	1.0	1.5	0.03	1.11
961.78	0.94	0.8	1.3	2.1	0.44	1.57

Table 15.
Cut 5.

Temperature, °C	ΔE, μV	U_{NIST}, k=2, μV	U_{RV}, k=2, μV	Ucombined k=2, μV	En	U_{RV}/U_{NIST}
100	0.01	0.5	0.76	0.94	0.02	1.52
200	0.02	0.6	0.86	1.1	0.02	1.43
400	0.15	0.7	1.0	1.3	0.11	1.46
500	0.22	0.7	1.1	1.5	0.15	1.59
600	0.40	0.8	1.2	1.6	0.25	1.47
800	0.69	0.8	1.3	1.8	0.37	1.59
1000	1.13	0.9	1.5	2.2	0.52	1.62
1100	1.43	1	1.6	2.5	0.58	1.61
419.527	0.18	0.7	0.96	1.3	0.14	1.37
660.323	0.42	0.9	1.0	1.5	0.29	1.11
961.78	1.02	0.8	1.3	2.1	0.48	1.57

Table 16.
Cut 6.

Temperature, °C	ΔE, μV	U_{NIST}, k=2, μV	U_{RV}, k=2, μV	Ucombined k=2, μV	En	U_{RV}/U_{NIST}
100	0.01	0.5	0.76	0.91	0.02	1.52
200	0.12	0.6	0.86	1.1	0.12	1.43
400	0.25	0.7	1.0	1.2	0.20	1.46
500	0.32	0.7	1.1	1.3	0.25	1.59
600	0.40	0.8	1.2	1.4	0.28	1.47
800	0.59	0.8	1.3	1.5	0.39	1.59
1000	0.73	0.9	1.5	1.7	0.43	1.62
1100	0.83	1	1.6	1.9	0.44	1.61
419.527	0.66	0.7	0.96	1.2	0.56	1.37
660.323	0.02	0.9	1.0	1.3	0.01	1.11
961.78	0.73	0.8	1.3	1.5	0.49	1.57

Table 17.
Cut 8

Temperature, °C	ΔE, μV	U_{NIST}, k=2, μV	U_{RV}, k=2, μV	Ucombined k=2, μV	En	U_{RV}/U_{NIST}
100	0.11	0.5	0.76	0.94	0.12	1.52
200	0.12	0.6	0.86	1.1	0.11	1.43
400	0.25	0.7	1.0	1.3	0.19	1.46
500	0.32	0.7	1.1	1.5	0.22	1.59
600	0.30	0.8	1.2	1.6	0.19	1.47
800	0.29	0.8	1.3	1.8	0.16	1.59
1000	0.23	0.9	1.5	2.2	0.11	1.62
1100	0.23	1	1.6	2.5	0.09	1.61
419.527	0.29	0.7	0.96	1.3	0.22	1.37
660.323	0.14	0.9	1.0	1.5	0.09	1.11
961.78	0.61	0.8	1.3	2.1	0.29	1.57

Table 18.
Cut 9.

Temperature, °C	ΔE, μV	U_{NIST}, k=2, μV	U_{RV}, k=2, μV	Ucombined k=2, μV	En	U_{RV}/U_{NIST}
100	0.01	0.5	0.76	0.91	0.02	1.52
200	-0.08	0.6	0.86	1.1	0.07	1.43
400	-0.15	0.7	1.0	1.2	0.12	1.46
500	-0.28	0.7	1.1	1.3	0.21	1.59
600	-0.30	0.8	1.2	1.4	0.21	1.47
800	-0.51	0.8	1.3	1.5	0.34	1.59
1000	-0.77	0.9	1.5	1.7	0.45	1.62
1100	-0.97	1	1.6	1.9	0.51	1.61
419.527	-0.24	0.7	0.96	1.2	0.20	1.37
660.323	-0.25	0.9	1.0	1.3	0.19	1.11
961.78	-0.98	0.8	1.3	1.5	0.66	1.57

Table 19.
Cut 11.

Temperature, °C	ΔE, μV	U_{NIST}, k=2, μV	U_{RV}, k=2, μV	Ucombined k=2, μV	En	U_{RV}/U_{NIST}
100	0.11	0.5	0.76	0.94	0.12	1.52
200	0.22	0.6	0.86	1.1	0.21	1.43
400	0.35	0.7	1.0	1.3	0.27	1.46
500	0.42	0.7	1.1	1.5	0.29	1.59
600	0.50	0.8	1.2	1.6	0.31	1.47
800	0.49	0.8	1.3	1.8	0.27	1.59
1000	0.53	0.9	1.5	2.2	0.24	1.62
1100	0.43	1	1.6	2.5	0.18	1.61
419.527	0.41	0.7	0.96	1.3	0.31	1.37
660.323	0.45	0.9	1.0	1.5	0.31	1.11
961.78	0.47	0.8	1.3	2.1	0.22	1.57

Table 20.
Cut 13.

Temperature, °C	ΔE, μV	U_{NIST}, k=2, μV	U_{RV}, k=2, μV	Ucombined k=2, μV	En	U_{RV}/U_{NIST}
100	0.11	0.5	0.76	0.94	0.12	1.52
200	0.22	0.6	0.86	1.1	0.21	1.43
400	0.35	0.7	1.0	1.3	0.27	1.46
500	0.42	0.7	1.1	1.5	0.29	1.59
600	0.50	0.8	1.2	1.6	0.31	1.47
800	0.59	0.8	1.3	1.8	0.32	1.59
1000	0.63	0.9	1.5	2.2	0.29	1.62
1100	0.73	1	1.6	2.5	0.30	1.61
419.527	0.35	0.7	0.96	1.3	0.26	1.37
660.323	0.59	0.9	1.0	1.5	0.40	1.11
961.78	0.58	0.8	1.3	2.1	0.27	1.57

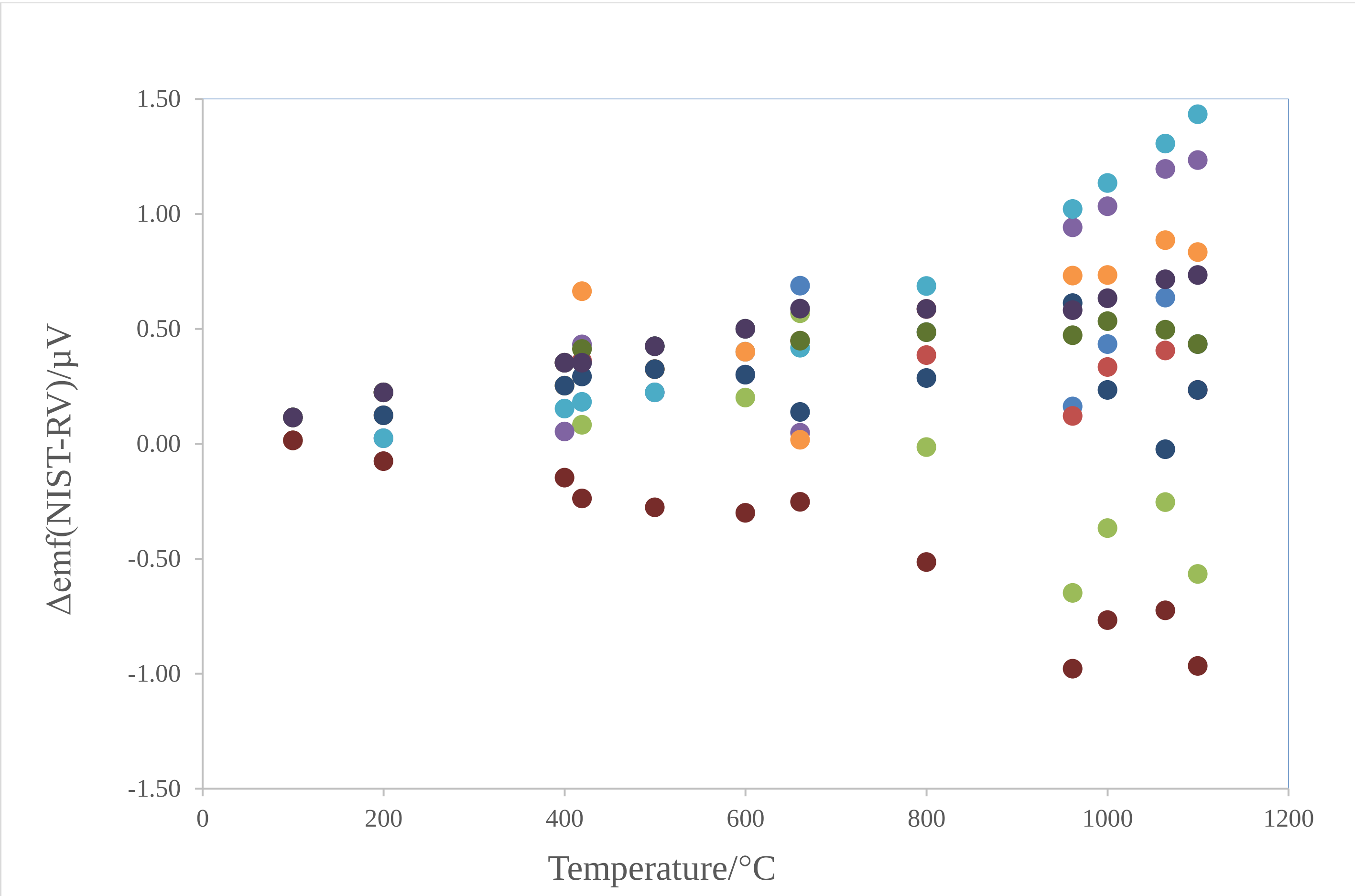

Figure 11**.** Type S thermocouple emf measurement differences between NIST and that of the RV as a function of temperature for the 10 cuts of wire that were sent to the participating laboratories. The colored symbols represent the emf difference for the gold, silver, aluminum, and zinc fixed-point data and the interpolated reference values data.

3.2 Bilateral Differences Between Participating Laboratories

For each of the test temperatures, Tables 21 to 30 give the bilateral differences between the participating laboratories, together with their combined expanded uncertainties. The bilateral difference between laboratories *i* and *j* is defined as $D_{ij} = (D_i - D_j)/\mu V$, at the nominal test temperature (5). The combined expanded uncertainty included the reported laboratory uncertainties (for laboratory *i* and *j*) at each temperature added in quadrature. The structure of this comparison allowed a direct calculation of the bilateral difference between NIST and each participating laboratory, since in each case a cut or set of cuts was directly measured by NIST and that laboratory. Thus, the tables include multiple lines for NIST, representing the individual cuts. The bilateral difference is then calculated using data from the cuts sent to that specific laboratory.

Table 21. Bilateral difference D_{ij} and the bilateral expanded uncertainty U_{ij} (k=2) at a nominal temperature of 100 °C. The data presented for the NIST Cuts represent the cuts calibrated by the other participants at 100 °C.

100 °C	LACOMET	JSB	LATU	CESMEC	INDECOPI	INM	INMETRO	
LACOMET		0.7 5.9	-0.2 6.2	1.4 7.3	-1.2 6.2	0.4 5.9	0.1 5.9	Dij/μV Uij/μV
JSB	-0.7 5.9		-0.9 2.4	0.7 4.6	-1.9 2.5	-0.3 1.5	-0.6 1.6	Dij/μV Uij/μV
LATU	0.2 6.2	0.9 2.4		1.6 4.9	-1.0 3.1	0.6 2.3	0.3 2.4	Dij/μV Uij/μV
CESMEC	-1.4 7.3	-0.7 4.6	-1.6 4.9		-2.6 5.0	-1.0 4.5	-1.3 4.6	Dij/μV Uij/μV
INDECOPI	1.2 6.2	1.9 2.5	1.0 3.1	2.6 5.0		1.6 2.5	1.3 2.6	Dij/μV Uij/μV
INM	-0.4 5.9	0.3 1.5	-0.6 2.3	1.0 4.5	-1.6 2.5		-0.3 1.5	Dij/μV Uij/μV
INMETRO	-0.1 5.9	0.6 1.6	-0.3 2.4	1.3 4.6	-1.3 2.6	0.3 1.5		Dij/μV Uij/μV
NIST9	0.3 5.9	1.0 1.4						Dij/μV Uij/μV
NIST1			0.2 2.1					Dij/μV Uij/μV
NIST3				1.8 4.5				Dij/μV Uij/μV
NIST6					-0.9 2.4	0.7 1.2		Dij/μV Uij/μV
NIST5&8							0.5 1.4	Dij/μV Uij/μV

Table 22. Bilateral difference D_{ij} and the bilateral expanded uncertainty U_{ij} (k=2) at a nominal temperature of 200 °C. The data presented for the NIST Cuts represent the cuts calibrated by the other participants at 200 °C.

200°C	LACOMET	JSB	LATU	CESMEC	INDECOPI	INM	INMETRO	
LACOMET		0.2 6.9	-1.8 7.7	1.1 8.1	-2.8 8.0	-0.9 6.8	-0.5 6.9	*Dij*/μV *Uij*/μV
JSB	-0.2 6.9		-2.0 4.1	0.9 4.8	-3.0 4.6	-1.1 1.8	-0.7 2.1	*Dij*/μV *Uij*/μV
LATU	1.8 7.7	2.0 4.1		2.9 5.9	-1.0 5.8	0.9 3.9	1.3 4.1	*Dij*/μV *Uij*/μV
CESMEC	-1.1 8.1	-0.9 4.8	-2.9 5.9		-3.9 6.3	-2.0 4.7	-1.6 4.8	*Dij*/μV *Uij*/μV
INDECOPI	2.8 8.0	3.0 4.6	1.0 5.8	3.9 6.3		1.9 4.5	2.3 4.6	*Dij*/μV *Uij*/μV
INM	0.9 6.8	1.1 1.8	-0.9 3.9	2.0 4.7	-1.9 4.5		0.4 1.9	*Dij*/μV *Uij*/μV
INMETRO	0.5 6.9	0.7 2.1	-1.3 4.1	1.6 4.8	-2.3 4.6	-0.4 1.9		*Dij*/μV *Uij*/μV
NIST 9	0.9 6.8	1.1 1.7						Dij/μV Uij/μV
NIST1			-0.6 3.8					Dij/μV Uij/μV
NIST3				2.3 4.6				Dij/μV Uij/μV
NIST 6					-1.7 4.4	0.2 1.3		Dij/μV Uij/μV
NIST5&8							0.6 1.8	Dij/μV Uij/μV

Table 23. Bilateral difference D_{ij} and the bilateral expanded uncertainty U_{ij} (k=2) at a nominal temperature of 400 °C. Values in bold font indicate $|D_{ij}| > U_{ij}$. The data presented for the NIST Cuts represent the cuts calibrated by the other participants at 400 °C.

400°C	LACOMET	JSB	LATU	CESMEC	INDECOPI	INM	INMETRO	
LACOMET		0.0	-7.2	2.1	-5.0	-3.0	0.5	Dij/μV
		7.8	13	9.2	9.1	7.7	7.9	Uij/μV
JSB	0.0		-7.2	2.1	-5.0	**-2.9**	0.5	Dij/μV
	7.8		11	5.5	5.2	**2.2**	2.6	Uij/μV
LATU	7.2	7.2		9.3	2.2	4.3	7.7	Dij/μV
	13	11		12	12	11	11	Uij/μV
CESMEC	-2.1	-2.1	-9.3		-7.1	-5.0	-1.6	Dij/μV
	9.2	5.5	12		7.2	5.4	5.6	Uij/μV
INDECOPI	5.0	5.0	-2.2	7.1		2.1	**5.5**	Dij/μV
	9.1	5.2	12	7.2		5.1	**5.4**	Uij/μV
INM	3.0	**2.9**	-4.3	5.0	-2.1		**3.4**	Dij/μV
	7.7	**2.2**	11	5.4	5.1		**2.5**	Uij/μV
INMETRO	-0.5	-0.5	-7.7	1.6	**-5.5**	**-3.4**		Dij/μV
	7.9	2.6	11	5.6	**5.4**	**2.5**		Uij/μV
NIST9	0.6	0.6						Dij/μV
	7.7	1.9						Uij/μV
NIST1			-6.1					Uij/μV
			11					Uij/μV
NIST3				3.1				Uij/μV
				5.3				Uij/μV
NIST6					-4.0	**-1.9**		Uij/μV
					5.1	**1.7**		Uij/μV
NIST5&8							1.5	Uij/μV
							2.3	Uij/μV

Table 24. Bilateral difference D_{ij} and the bilateral expanded uncertainty U_{ij} (k=2) at a nominal temperature of 500 °C. Values in bold font indicate $|D_{ij}| > U_{ij}$. The data presented for the NIST Cuts represent the cuts calibrated by the other participants at 500 °C.

500°C	LACOMET	JSB	LATU	CESMEC	INDECOPI	INM	INMETRO	
LACOMET		1.8 8.0	**-11** **10**	-1.3 10	-5.6 9.5	-5.0 8.0	-6.7 9.0	Dij/μV Uij/μV
JSB	-1.8 8.0		**-13** **7.1**	-3.2 6.4	**-7.4** **5.6**	**-6.8** **2.3**	**-8.6** **4.7**	Dij/μV Uij/μV
LATU	**11** **8.0**	**13** **7.1**		**9.8** **9.2**	5.6 8.7	6.2 7.1	4.4 8.2	Dij/μV Uij/μV
CESMEC	1.3 10	3.2 6.4	**-9.8** **9.2**		-4.2 8.2	-3.6 6.4	-5.4 7.6	Dij/μV Uij/μV
INDECOPI	5.6 9.5	**7.4** **5.6**	-5.6 8.7	4.2 8.2		0.6 5.6	-1.2 6.9	Dij/μV Uij/μV
INM	5.0 8.0	**6.8** **2.3**	-6.2 7.1	3.6 6.4	-0.6 5.6		-1.8 4.7	Dij/μV Uij/μV
INMETRO	6.7 9.0	**8.6** **4.7**	-4.4 8.2	5.4 7.6	1.2 6.9	1.8 4.7		Dij/μV Uij/μV
NIST9	0.6 7.9	2.4 2.0						Dij/μV Uij/μV
NIST1			**-9.9** **6.9**					Dij/μV Uij/μV
NIST3				-0.2 6.2				Dij/μV Uij/μV
NIST6					-4.4 5.5	**-3.8** **1.9**		Dij/μV Uij/μV
NIST5&8							**-5.6** **4.5**	Dij/μV Uij/μV

Table 25. Bilateral difference D_{ij} and the bilateral expanded uncertainty U_{ij} (k=2) at a nominal temperature of 600 °C. Values in bold font indicate $|D_{ij}| > U_{ij}$. The data presented for the NIST Cuts represent the cuts calibrated by the other participants at 600 °C.

600°C	LACOMET	LATU	CESMEC	INDECOPI	INM	INMETRO	
LACOMET		**-15**	-1.6	-6.4	-7.9	-6.9	Dij/µV
		13	13	12	10	11	Uij/µV
LATU	**15**		**14**	8.9	7.4	8.4	Dij/µV
	13		**11**	9.4	7.6	8.7	Uij/µV
CESMEC	1.6	**-14**		-4.8	-6.3	-5.3	Dij/µV
	13	**11**		10	8.8	9.8	Uij/µV
INDECOPI	6.4	-8.9	4.8		-1.5	-0.5	Dij/µV
	12	9.4	10		6.0	7.4	Uij/µV
INM	7.9	-7.4	6.3	1.5		1.0	Dij/µV
	10	7.6	8.8	6.0		5.0	Uij/µV
INMETRO	6.9	-8.4	5.3	0.5	-1.0		Dij/µV
	11	8.7	9.8	7.4	5.0		Uij/µV
NIST9	1.2						Dij/µV
	10						Uij/µV
NIST1		**-13**					Dij/µV
		7.4					Uij/µV
NIST3			0.1				Dij/µV
			8.7				Uij/µV
NIST6				-4.5	**-6.0**		Dij/µV
				5.9	**2.1**		Uij/µV
NIST5&8						**-5.1**	Dij/µV
						4.8	Uij/µV

Table 26. Bilateral difference D_{ij} and the bilateral expanded uncertainty U_{ij} (k=2) at a nominal temperature of 800 °C. Values in bold font indicate $|Dij| > Uij$. The data presented for the NIST Cuts represent the cuts calibrated by the other participants at 800 °C.

800°C	LACOMET	LATU	CESMEC	INDECOPI	INM	INMETRO	
LACOMET		**-17** **14**	4.4 29	-6.9 12	**-30** **11**	-11 12	Dij/μV Uij/μV
LATU	**17** **14**		21 28	10 11	**-13** **9.3**	6.4 10	Dij/μV Uij/μV
CESMEC	-4.4 29	-21 28		-11 28	**-34** **27**	-15 27	Dij/μV Uij/μV
INDECOPI	6.9 12	-10 11	11 28		**-23** **6.4**	-3.8 7.7	Dij/μV Uij/μV
INM	**30** **11**	**13** **9.3**	**34** **27**	**23** **6.4**		**19** **5.6**	Dij/μV Uij/μV
INMETRO	11 12	-6.4 10	15 27	3.8 7.7	**-19** **5.6**		Dij/μV Uij/μV
NIST9	1.1 11						Dij/μV Uij/μV
NIST1		-15 9.0					Dij/μV Uij/μV
NIST3			6.0 27				Dij/μV Uij/μV
NIST6				-4.7 6.0	**-27** **6.0**		Dij/μV Uij/μV
NIST5&8						**-8.6** **5.1**	Dij/μV Uij/μV

Table 27. Bilateral difference D_{ij} and the bilateral expanded uncertainty U_{ij} (k=2) at a nominal temperature of 1000 °C. Values in bold font indicate $|D_{ij}| > U_{ij}$.. The data presented for the NIST Cuts represent the cuts calibrated by the other participants at 1000 °C.

1000°C	LACOMET	LATU	CESMEC	INDECOPI	INM	INMETRO	
LACOMET		-4.2 18	13.0 41	-7.9 13	**-18** **12**	**-17** **15**	Dij/µV Uij/µV
LATU	4.2 18		17 42	-4 15	**-14** **14**	-12 17	Dij/µV Uij/µV
CESMEC	-13 41	-17 42		-21 40	-31 39	-30 40	Dij/µV Uij/µV
INDECOPI	7.9 13	3.7 15	21 40		**-10** **6.5**	-8.7 11	Dij/µV Uij/µV
INM	**18** **12**	**14** **14**	31 39	**10** **6.5**		1.7 10	Dij/µV Uij/µV
INMETRO	**17** **15**	12 17	30 40	8.7 11	-1.7 10		Dij/µV Uij/µV
NIST9	2.2 12						Dij/µV Uij/µV
NIST1		-0.8 13					Dij/µV Uij/µV
NIST3			16 39				Dij/µV Uij/µV
NIST6				-4.2 6.1	**-15** **2.8**		Dij/µV Uij/µV
NIST5&8						**-13** **9.8**	Dij/µV Uij/µV

Table 28. Bilateral difference D_{ij} and the bilateral expanded uncertainty U_{ij} (k=2) at a nominal temperature of 1100 °C. Values in bold font indicate $|D_{ij}| > U_{ij}$. The data presented for the NIST Cuts represent the cuts calibrated by the other participants at 1100 °C.

1100°C	LACOMET	INM	INMETRO	
LACOMET		**-29**	-14	Dij/µV
		12	19	Uij/µV
INM	**29**		**15**	Dij/µV
	12		**15**	Uij/µV
INMETRO	14	**-15**		Dij/µV
	19	**15**		Uij/µV
NIST9	2.6			Dij/µV
	12			Uij/µV
NIST6		**-25**		Dij/µV
		2.5		Uij/µV
NIST5&8			-9.6	Dij/µV
			15	Uij/µV

Table 29. Bilateral difference D_{ij} and the bilateral expanded uncertainty U_{ij} (k=2) at a nominal temperature of 419.527 °C. Values in bold font indicate $|D_{ij}| > U_{ij}$.. The data presented for the NIST Cuts represent the cuts calibrated by the other participants at 419.527 °C.

419.527 °C	LACOMET	JSB	INDECOPI	CENAM	INMETRO	INTI	NRC	
LACOMET		0.5	-5.0	-0.3	-0.7	-0.4	-0.5	*Dij*/µV
		4.9	6.0	4.9	5.1	5.4	5.0	*Uij*/µV
JSB	-0.5		**-5.5**	-0.8	-1.2	-1.0	-1.1	*Dij*/µV
	4.9		**3.9**	1.5	2.2	2.8	1.8	*Uij*/µV
INDECOPI	5.0	**5.5**		**4.7**	**4.3**	**4.6**	**4.4**	*Dij*/µV
	6.0	**3.9**		**3.8**	**4.1**	**4.4**	**3.9**	*Uij*/µV
CENAM	0.3	0.8	**-4.7**		-0.5	-0.2	-0.3	*Dij*/µV
	4.9	1.5	**3.8**		2.1	2.6	1.6	*Uij*/µV
INMETRO	0.7	1.2	**-4.3**	0.5		0.3	0.2	*Dij*/µV
	5.1	2.2	**4.1**	2.1		3.1	2.3	*Uij*/µV
INTI	0.4	1.0	**-4.6**	0.2	-0.3		-0.1	Dij/µV
	5.4	2.8	**4.4**	2.6	3.1		2.8	Uij/µV
NRC	0.5	1.1	**-4.4**	0.3	-0.2	0.1		Dij/µV
	5.0	1.8	**3.9**	1.6	2.3	2.8		Uij/µV
NIST 9	0.2	0.7						Dij/µV
	4.9	1.6						Uij/µV
NIST 6			**-3.9**					Dij/µV
			3.8					Uij/µV
NIST 2&4				0.6				Dij/µV
				1.3				Uij/µV
NIST 5&8					-0.1	0.2		Dij/µV
					2.1	2.7		Uij/µV
NIST11&13							0.3	Dij/µV
							1.7	Uij/µV

Table 30. Bilateral difference D_{ij} and the bilateral expanded uncertainty U_{ij} (k=2) at a nominal temperature of 660.323 °C. Values in bold font indicate $|D_{ij}| > U_{ij}$ The data presented for the NIST Cuts represent the cuts calibrated by the other participants at 660.323 °C.

660.323 °C	LACOMET	INDECOPI	CENAM	INMETRO	INTI	NRC	
LACOMET		**-7.2**	-2.5	-2.8	-2.7	-2.5	Dij/μV
		6.9	5.2	5.6	5.8	5.4	Uij/μV
INDECOPI	**7.2**		**4.7**	4.3	4.5	4.7	Dij/μV
	6.9		**4.7**	5.0	5.2	4.9	Uij/μV
CENAM	2.5	**-4.7**		-0.3	-0.2	0.0	Dij/μV
	5.2	**4.7**		2.3	2.8	2.0	Uij/μV
INMETRO	2.8	-4.3	0.3		0.1	0.4	Dij/μV
	5.6	5.0	2.3		3.4	2.8	Uij/μV
INTI	2.7	-4.5	0.2	-0.1		0.2	Dij/μV
	5.8	5.2	2.8	3.4		3.2	Uij/μV
NRC	2.5	-4.7	0.0	-0.4	-0.2		Dij/μV
	5.4	4.9	2.0	2.8	3.2		Uij/μV
NIST 9	2.3						Dij/μV
	5.3						Uij/μV
NIST 6		-4.6					Dij/μV
		4.7					Uij/μV
NIST 2&4			0.3				Dij/μV
			1.5				Uij/μV
NIST 5&8				0.0	0.1		Dij/μV
				2.4	2.8		Uij/μV
NIST11&13						0.6	Dij/μV
						2.1	Uij/μV

Table 31. Bilateral difference D_{ij} and the bilateral expanded uncertainty U_{ij} (k=2) at a nominal temperature of 961.323 °C. Values in bold font indicate $|D_{ij}| > U_{ij}$. The data presented for the NIST Cuts represent the cuts calibrated by the other participants at 961.78 °C.

961.78 °C	CENAM	INMETRO	INTI	NRC	
CENAM		-0.5	-1.9	0.5	*Dij*/µV
		3.1	3.6	3.1	*Uij*/µV
INMETRO	0.5		-1.4	1.0	*Dij*/µV
	3.1		4.1	3.7	*Uij*/µV
INTI	1.9	1.4		2.4	*Dij*/µV
	3.6	4.1		4.1	*Uij*/µV
NRC	-0.5	-1.0	-2.4		*Dij*/µV
	3.1	3.7	4.1		*Uij*/µV
NIST2&4	-0.2				*Dij*/µV
	2.0				*Uij*/µV
NIST5&8		-0.5	-1.8		*Dij*/µV
		2.8	3.4		*Uij*/µV
NIST11&13				0.3	*Dij*/µV
				2.9	*Uij*/µV

Conclusions

Thermocouples are a critical component of temperature measurement and control in industrial and scientific environments. They are also used as an approximation technique for the ITS-90. Their proper use supports a wide array of industries such as aerospace, plastics, process control and measurement, among others. Although they have a relatively simple operating principle, it belies the intricacy of their proper use. It is easy to make temperature measurements with a thermocouple, but it is more challenging to make accurate and reproducible ones. Intercomparisons are used to substantiate a laboratory's calibration measurement capabilities (CMC) claims for thermocouples. The CMCs support the CIPM MRA (International Committee for Weights and Measure Mutual Recognition Arrangement).

This intercomparison allowed the participants to demonstrate their ability to calibrate a noble metal thermocouple. E_n values were calculated for 66 measurements. About 25% of these E_n values exceeded the absolute value of 1. Measurements at 100 °C and 200 °C were notably more consistent, with no $E_\mathrm{n} > |1|$. While this intercomparison shows general agreement between labs at moderate temperatures, future studies should focus on higher temperature measurements.

The inclusion of fixed-point measurements in the study complicated data analysis. Many labs did not have access to some (or all) fixed point cells, making these points less valuable for comparison. To simplify future studies, it will be easier to only include comparison calculations.

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[3] D. Ripple, G.W. Burns, and M.G. Scroger, "Assessment of Uncertainties of Thermocouple Calibrations at NIST," NISTIR 5340, National Institute of Standards and Technology, Gaithersburg, MD, 1994, 34 pp.

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Appendix A. Protocol

Protocol for the RMO Supplemental Comparison between XXX and NIST for Type S Thermocouples from 0 °C to 1100 °C

The RMO Key Comparison will be coordinated by NIST (of the United States of America). Participant information is as follows:

NIST
100 Bureau Dr.
MS 8363
Gaithersburg, MD 20899-8363

Contact: Karen Garrity
Phone: 301 975 4818
Fax: 301 548 0206
E-mail: kgarrity@nist.gov

Participating Laboratories:
Argentina: Patricia Giorgio, Instituto Nacional de Tecnologia Industrial CEFIS, patg@inti.gov.ar

Brazil: Hamilton Davidson Vieira, Laboratorio Nacional de Metrologia, LNM/ INMETRO, hdvieira@inmetro.gov.br

Canada: Gee, Douglas, National Research Council Canada, Douglas.Gee@nrc-cnrc.gc.ca

Chile: Mauricio Araya, Instituto Nacional de Normalizacion (INN), raul.nunez@inn.ci

Costa Rica: Adrian Solano Mene, Oficina Nacional de Normas y Unidades de Medida, asolano@lacomet.go.cr

Ecuador: Diego Almeida, Instituto Ecuatoriano de Normalizacion (INEN), dalmeida@inen.gov.ec

Jamaica: Keith Bookall, Bureau of Standards, KBookall@bsj.org.jm

Mexico: Dr. Edgar Mendez Lango, Centro Nacoinal de Metrologia (CENAM), emendez@cenam.mx

Panama: Ruben Ortega, Centro Nacional de Metrologia de Panama, rortega@cenamep.org.pa

Peru: Edgar Guillen Metas, Instituto Naciounal de Defensa de la Competencia y de la Proteccion de la Propiedad Intelectual, eguillen@indecopi.gob.pe

Uruguay: Ofelia Robatto, Laboratorio Tecnologico del Uruguay (LATU), orobatto@latu.org.uy

The instructions and procedures given below must be followed by the participants in the comparison of type S thermocouple calibrations. By the declared acceptance of this invitation to participate, the laboratories agree to follow the general instructions and technical protocol written in this document, the MRA Appendix F document “Guidelines for CIPM Key Comparisons”, and the JCRB document “A Note on Supplementary Comparison” by T.J. Quinn.

The MRA Appendix F and JCRB documents are found at:

1) www.bipm.fr/pdf/guidelines.pdf,
2) and, http://www.bipm.org/utils/common/documents/jcrb/supplementary_comparisons.pdf, respectively.

Introduction

NIST is conducting this SIM supplementary comparison of type S thermocouple (Pt10%Rh vs Pt) calibrations from 0 to 1100 °C. Twelve National Metrology Institutes will participate in this comparison. The objective of the comparison is to determine the degree of equivalence of the calibration results obtained. The measurements are to be performed by the participating laboratories employing the methods they currently use to perform a calibration.

This will be a star comparison. NIST (the pilot laboratory), will assemble ten thermocouples for sending out to participating laboratories. Because the number of thermocouples is smaller than the number of comparisons to be performed, the thermocouples will be sent out to a first group of laboratories, returned to NIST, and then sent out to the next group of laboratories.
NIST will assemble the thermocouples in high purity alumina tubing. It will electrically anneal the thermocouples prior to assembly and furnace anneal them after assembly. The thermocouples will then be calibrated and subsequently reannealed. Finally, NIST will check the homogeneity of each thermocouple before sending it to a participating laboratory. Those laboratories whose calibration uncertainties are more than 0.5 °C will receive one thermocouple and those whose uncertainties are less than 0.5 °C will receive two thermocouples.
Each laboratory will calibrate the received thermocouple(s) by its own method and subsequently send the thermocouples and their calibration results to NIST. The laboratories that received two thermocouples will send both sets of results. When NIST receives back thermocouples from four of the laboratories, it will verify the integrity of the thermocouples. For each thermocouple, it will measure the emf at the silver point, reanneal, and test for homogeneity. The thermocouples will then be sent to the next designated laboratories in the queue.

Instructions to Participants

Each laboratory will be allowed a period of 8 weeks to complete calibrations and send the thermocouples and results back to NIST. The results should be in the form of a calibration spreadsheet. Prior to NIST sending a thermocouple to a participating laboratory, the laboratory will be contacted to determine if they are able to calibrate the thermocouple within the allotted 8 weeks. If the laboratory is unable to calibrate the thermocouple at that time, NIST will try to reschedule the participant's calibration period.

Upon receipt of the thermocouples, the laboratory must inspect the devices for damage. The thermocouples are not susceptible to shock, but if the wires are kinked or the insulator broken in shipping, NIST should be contacted.

The calibration will be conducted over the range of 0 to 1100 ºC; however, a laboratory will not be expected to calibrate the thermocouple(s) outside of its CMC claims or normal operating range. The calibration points will be 100 °C, 200 °C, 400 °C, 500 °C, 600 °C, 800 °C, 1000 °C, and 1100 °C. If fixed points are used, the results at the fixed point temperatures should be reported. If a laboratory claims uncertainties less than ±0.5 °C and uses extension wire, then an ice point or a block or a bath at 0 °C must be used for the reference junction. The thermocouples have been annealed by NIST and should not be reannealed. The laboratories should calibrate the thermocouple(s) in order of increasing temperature. This minimizes the changing of the oxidation state of the Pt 10%Rh leg. Any constraints or limitations that prevent a laboratory from performing a calibration at any of these calibration points should be communicated to the NIST contact prior to the start of the test.

Upon completion of the calibration, the thermocouple(s) should be returned to NIST in the original packaging. The thermocouple (s) will be sent in a cardboard box. The thermocouples will be tied to a strip of wood with cotton twine and the assembly wrapped in bubble wrap. Any excess space in the cardboard box will be filled with "styrofoam peanuts". This method of packing minimizes the likelihood of the insulator breaking during shipping.

The participating laboratories must submit the following:

1. The Excel data file listed in Appendix A should be used to record the emf and temperature values for each thermocouple. The results should be normalized to the nominal test temperatures.

2. The accompanying questionnaire given as an Excel data file listed in Appendix B should be used to record pertinent background information concerning the measurement equipment and methods.

Reporting of Uncertainties

The individual uncertainty components should be listed along with the total combined uncertainty assigned to each of the fixed-point cells (if used). All expanded uncertainties should be expressed as k=2. In an effort to harmonize the uncertainty budgets used by the participants, the questionnaire in Appendix B (accompanying Excel file) gives a list of each uncertainty component to be considered.

Determination and Reporting of Results

The test thermocouples will be calibrated and tested for inhomogeneity prior to shipment.
The measurement results and associated uncertainties for laboratories receiving two type S thermocouples will be combined for each participating laboratory to generate only one average emf and associated uncertainty for each test temperature.
After the data is analyzed, significant discrepancies between the tested thermocouple (or thermocouples if applicable) for each laboratory and between the laboratory and the other participants will be identified. Any discrepancies larger than a k=3 confidence limit will be reported to the participating laboratory, in accordance with the procedures in the "Guidelines for Key Comparisons." For laboratories testing two thermocouples, Youden plots will be generated and inspected.

The two outcome results to be reported are:

1. bilateral differences with associated uncertainties at each measured temperature between all participating laboratories,
2. the differences and associated uncertainties at each measured temperature between each participating laboratory and the reference value.

The calculations performed at NIST to determine the outcome results will be validated by Edgar Mendez (from CENAM) before a final report is issued.

The results of this comparison will be published in two forms. First, the results will be published listing all participating SIM laboratories by name and including authors from each laboratory. Second, with the approval of each laboratory, the data obtained in this comparison may be included by NIST in a paper describing comparison results from a larger group of participants, using the same thermocouple lot. For this second paper, all data will be presented anonymously, precluding the inclusion of all participants as authors.

Appendix A: Measurement results

Appendix B: Background information questionnaire

APPENDIX B: Participant Laboratory's Uncertainty Budgets

Laboratory: SNM-INDECOPI (Peru)

2a. Uncertainty components: comparison methods, in units of °C								Sn Freezing pt.	Zn Freezing pt.	Al freezing pt.
	t=100 °C	200 °C	400 °C	500 °C	600 °C	800 °C	1000 °C	231.9278	419.527	660.323 °C
Reference thermometer calibration **	0.083	0.081	0.080	0.080	0.079	0.078	0.079	0.0003	0.0042	0.0008
Reference thermometer drift	0.065	0.056	0.049	0.047	0.046	0.043	0.040			
Reference thermometer repeatability	0.001	0.001	0.002	0.002	0.002	0.002	0.002			
Reference thermometer readout	0.000	0.000	0.000	0.000	0.000	0.000	0.000			
Test thermocouple repeatability	0.001	0.001	0.001	0.001	0.002	0.001	0.001	0.0007	0.0011	0.0095
Test thermocouple readout	0.0004	0.0003	0.0003	0.0002	0.0003	0.0002	0.0003	0.0003	0.0003	0.0003
Test thermocouple inhomogeneity	0.040	0.070	0.090	0.100	0.120	0.125	0.147	0.0720	0.1100	0.1200
Test thermocouple stability	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.0046	0.0042	0.0577
Reference junction temperature uncertainty	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.0058	0.0058	0.0058
Bath or furnace temperature stability	0.014	0.104	0.104	0.104	0.104	0.104	0.104			
Bath or furnace temperature non-uniformity	0.008	0.139	0.139	0.139	0.139	0.139	0.139			
Extraneous emf of wiring, scanners, etc.	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.00133	0.00120	0.00056
2b. Additional components not in above list, if any										
(description of extra component)										
Other not controlled quantities	0.100	0.140	0.139	0.156	0.162	0.132	0.077	0.1501	0.1510	0.1682
Calibration´s Multimeter used with the Test TC	0.027	0.024	0.021	0.020	0.020	0.018	0.017	0.0230	0.0208	0.0192
ITS-90 realization								0.0017	0.0023	0.0026
2c. Total expanded uncertainty (k=2), comparison methods, in units of °C	0.31	0.51	0.52	0.54	0.56	0.53	0.51	0.34	0.38	0.43

The standars employed to calibration by comparison

TC type S certificate in fixed points (Zn; Al and Ag) by INMETRO

TC Au/Pt certificate in fixed points (Zn; Al and Ag) by NPL

The standars employed to calibration by fixed points

Cell Sn Calibrated by comparison with standard open cell in NIST

Cell Zn Calibrated by comparison with standard open cell in NIST

Cell Al Calibrated by comparison with standard open cell in NIST

Laboratory: NRC (Canada)

2a. Uncertainty components: comparison methods, in units of °C	250 °C	350 °C	450 °C	550 °C	650 °C	750 °C	850 °C	950 °C	1050 °C	Sn Freezing pt. 231.928 °C	Zn Freezing pt. 419.527 °C	Al freezing pt. 660.323 °C
Reference thermometer calibration	0.150	0.150	0.150	0.150	0.150	0.150	0.150	0.150	0.150			
Reference thermometer drift												
Reference thermometer repeatability												
Reference thermometer readout	0.018	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017			
Test thermocouple repeatability												
Test thermocouple readout	0.018	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.018	0.017	0.017
Test thermocouple inhomogeneity	0.025	0.035	0.045	0.055	0.065	0.075	0.085	0.095	0.105	0.023	0.042	0.066
Test thermocouple stability												
Reference junction temperature uncertainty	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Bath or furnace temperature stability												
Bath or furnace temperature non-uniformity												
Extraneous emf of wiring, scanners, etc.	0.05	0.050	0.048	0.047	0.045	0.044	0.043	0.041	0.040	0.038	0.035	0.032

2b. Additional components not in above list, if any

(description of extra component)

Copper Wire inhomogeneity	0.016	0.015	0.015	0.014	0.014	0.013	0.013	0.012	0.012	0.011	0.010	0.010
Error of Fit (calculated for each calibration)	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD

2c. Total expanded uncertainty (k=2), comparison methods, in units of °C	**0.33**	**0.33**	**0.33**	**0.34**	**0.34**	**0.35**	**0.36**	**0.37**	**0.38**	**0.10**	**0.12**	**0.15**

Standards calibrated in house.

Laboratory: INM (Colombia)

2. Uncertainty Budget

Below are possible uncertainty components. Please fill in the relevant values for your calibration service, either at the temperatures listed or at temperatures relevant to your

2a. Uncertainty components: comparison methods, in units of °C

temperature (°C)	100.185	200.266	400.833	501.246	599.927	798.247	999.843	1100.118
Reference thermometer calibration	0.700	0.700	0.700	0.700	0.700	0.700	0.700	0.900
Reference thermometer drift	0.24	0.24	0.24	0.27	0.27	0.43	0.43	0.21
Reference thermometer repeatability	0.001	0.006	0.004	0.005	0.005	0.005	0.004	0.017
Reference thermometer readout	0.064	0.056	0.050	0.048	0.047	0.044	0.042	0.047
Test thermocouple repeatability	0.003	0.006	0.010	0.005	0.005	0.014	0.004	0.018
Test thermocouple readout	0.067	0.059	0.048	0.048	0.048	0.044	0.040	0.051
Test thermocouple inhomogeneity and drift	0.044	0.073	0.100	0.114	0.124	0.120	0.102	0.101
Test thermocouple stability	0.003	0.006	0.010	0.005	0.005	0.014	0.004	0.018
Reference junction temperature uncertainty	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
Bath or furnace temperature stability	0.001	0.006	0.004	0.005	0.005	0.005	0.004	0.017
Bath or furnace temperature non-uniformity	0.039	0.247	0.789	1.008	1.199	1.908	1.737	1.191
Extraneous emf of wiring, scanners, etc.	0.046	0.040	0.052	0.051	0.049	0.046	0.043	0.042

2b. Additional components not in above list, if any

(description of extra component)

2c. Total expanded uncertainty (k=2), comparison methods, in units of °C	0.77	0.82	1.2	1.4	1.6	2.4	2.2	1.7
							1.925508793	1.513607214

standards used were calibrated at another lab: PTB.

Laboratory: INTI (Argentina)

2a. Uncertainty components: comparison methods, in units of °C	t=100 °C	200 °C	400 °C	500 °C	600 °C	800 °C	1000 °C	1100 °C	Sn Freezing pt. 231.928 °C	Zn Freezing pt. 419.527 °C	Al freezing pt. 660.323 °C	Ag freezing pt. 961.78 °C	Au freezing pt. 1064.18 °C
Test thermocouple repeatability									0.010	0.004	0.012	0.035	
Test thermocouple readout	t=100 °C	200 °C	400 °C						0.130	0.117	0.109	0.099	
Test thermocouple inhomogeneity									0.012	0.033	0.035	0.050	
Test thermocouple stability													
Reference junction temperature uncertainty									0.010	0.010	0.010	0.010	
Extraneous emf of wiring, scanners, etc.	t=100 °C	200 °C	400 °C						0.021	0.024	0.021	0.022	
2b. Additional components not in above list, if any													
(description of extra component)													
Fixed Point Uncertainty									0.002	0.002	0.004	0.064	
2c. Total expanded uncertainty (k=2), comparison methods, in units of °C									0.27	0.25	0.23	0.27	

Standards calibrated in house.

Laboratory: BSJ (Jamaica)

2a. Uncertainty components: comparison methods, in units of °C

	t=100 °C	200 °C	400 °C	500 °C	600 °C	800 °C	1000 °C	1100 °C	Sn Freezing pt. 231.928	Zn Freezing pt. 419.527
Reference thermometer calibration	0.003	0.004	0.006	0.008					0.0035	0.006
Reference thermometer drift	0.0006	0.0006	6E-04	6E-04					0.0006	0.0006
Reference thermometer repeatability	0.0005	0.0009	0.001	0.005					0	0
Reference thermometer readout	0.0002	0.0002	2E-04	2E-04					0.0002	0.0002
Test thermocouple repeatability	0	0	0	0					0	0
Test thermocouple readout	0.003	0.003	0.003	0.003					0.003	0.003
Test thermocouple inhomogeneity	0	0	0	0					0	0
Test thermocouple stability										
Reference junction temperature uncertainty	0.001	0.001	0.001	0.001					0.001	0.001
Bath or furnace temperature stability	0.0577	0.0577	0.058	0.058					0	0
Bath or furnace temperature non-uniformity	0.0058	0.0058	0.006	0.006					0	0
Extraneous emf of wiring, scanners, etc.	0.012	0.012	0.012	0.012					0.012	0.012

2b. Additional components not in above list, if any

(description of extra component)

(description of extra component)	t=100 °C	200 °C	400 °C	500 °C	600 °C	800 °C	1000 °C	1100 °C	Sn Freezing pt. 231.928	Zn Freezing pt. 419.527

	t=100 °C	200 °C	400 °C	500 °C	600 °C	800 °C	1000 °C	1100 °C	Sn Freezing pt. 231.928	Zn Freezing pt. 419.527
2c. Total expanded uncertainty (k=2), comparison methods, in units of °C	0.119	0.119	0.119	0.120					0.026	0.028

my standards (Platinum resistance thermometers) were calibrated by CENAM. I also calibrated the thermocouple with a Zinc cell which is here in the lab.

Laboratory: LACOMET (Costa Rica)

2. Uncertainty Budget

Below are possible uncertainty components. Please fill in the relevant values for your calibration service, either at the temperatures listed or at temperatures relevant

2a. Uncertainty components: comparison methods, in units of °C									Fixed	Point	
									Sn Freezing pt.	Zn Freezing pt.	Al freezing pt.
	t=100 °C	200 °C	400 °C	500 °C	600 °C	800 °C	1000 °C	1100 °C		419.527	660.323 °C
Reference thermometer calibration	0.01	0.01	0.02	0.02	0.03	0.5	0.5	0.6	0.005	0.005	0.005
Reference thermometer drift	0.005	0.05	0.01	0.01	0.01	0.1	0.1	0.1			
Reference thermometer repeatability	0.005	0.005	0.005	0.005	0.005	0.1	0.1	0.1			
Reference thermometer readout	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Test thermocouple repeatability	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Test thermocouple readout	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Test thermocouple inhomogeneity	0.1	0.1	0.1	0.1	0.2	0.3	0.3	0.3	0.1	0.1	0.1
Test thermocouple stability	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Reference junction temperature uncertainty	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Bath or furnace temperature stability	0.05	0.05	0.05	0.1	0.1	0.2	0.2	0.2	0.02	0.02	0.02
Bath or furnace temperature non-uniformity	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.3	0.02	0.02	0.02
Extraneous emf of wiring, scanners, etc.	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
2b. Additional components not in above list, if any											
(description of extra component)											
2c. Total expanded uncertainty (k=2), comparison methods, in units of °C	0.5	0.5	0.5	0.5	0.6	1.6	1.6	1.8	0.4	0.4	0.4

(100; 200; 400; 500; 600; 800) °C, the standards were calibrated in our laboratory.

For temperatures of 1000 °C and 1100 °C, the standard was calibrated by another laboratory.

For fixed points Zn and Al we use our fixed point cells.

Laboratory: CESMEC-LCPNT (Chile)

Below are possible uncertainty components. Please fill in the relevant values for your calibration service, either at the temperatures listed or at

										Fixed	Point	Values	if used
2a. Uncertainty components: comparison methods, in units of °C	t=100 °C	200 °C	400 °C	500 °C	600 °C	800 °C	1000 °C	1100 °C	Sn Freezing pt.	Zn Freezing pt. 419.527	Al freezing pt. 660.323 °C	Ag freezing pt. 961.78 °C	Au freezing pt. 1064.18 °C
Reference thermometer calibration	0.065	0.065	0.065	0.065	0.065	0.065	0.450						
Reference thermometer drift	0.086	0.086	0.086	0.086	0.086	0.086	0.086						
Reference thermometer repeatability	0.008	0.008	0.008	0.012	0.012	0.012	0.012						
Reference thermometer readout	0.193	0.166	0.150	0.146	0.144	0.136	0.131						
Test thermocouple repeatability	0.010	0.010	0.010	0.015	0.015	0.015	0.015						
Test thermocouple readout	0.193	0.167	0.150	0.146	0.145	0.136	0.131						
Test thermocouple inhomogeneity (1)	0.008	0.039	0.119	0.194	0.349	1.208	1.625						
Test thermocouple stability	0.034	0.034	0.034	0.034	0.034	0.034	0.034						
Reference junction temperature uncertainty	0.004	0.004	0.004	0.004	0.004	0.004	0.004						
Bath or furnace temperature stability	0.015	0.015	0.025	0.025	0.025	0.050	0.050						
Bath or furnace temperature non-uniformity	0.010	0.010	0.010	0.010	0.010	0.125	0.125						
Extraneous emf of wiring, scanners, etc.	0.039	0.023	0.037	0.024	0.023	0.034	0.039						
Note 1	This test considers the joint effect of uniformity of the wires and the furnace axial gradient												
2b. Additional components not in above list, if any													
(description of extra component)													
2c. Total expanded uncertainty (k=2), comparison methods, in units of °C	0.60	0.53	0.54	0.62	0.84	2.47	3.41						

Laboratory: INMETRO (Brazil)

2a. Uncertainty components: comparison methods, in units of °C										Sn Freezing pt.	Zn Freezing pt.	Al freezing pt.	Ag freezing pt.	Au freezing pt.
		t=100 °C	200 °C	400 °C	500 °C	600 °C	800 °C	1000 °C	1100 °C	231,928°C	419,527°C	660.323 °C	961.78 °C	1064.18 °C
Reference thermometer calibration		0.0017	0.0022	0.0017	0.02	0.02	0.02	0.02	0.15					
Reference thermometer drift														
Reference thermometer repeatability		0.0002	0.0001	0.0003	0.004	0.007	0.013	0.009	0.006					
Reference thermometer readout		0.0007	0.0009	0.00135	0.007	0.006	0.005	0.005	0.009					
Test thermocouple repeatability		0.005	0.006	0.006	0.007	0.011	0.01	0.008	0.012	0.0004	0.0004	0.0002	0.000	
Test thermocouple readout		0.018	0.014	0.012	0.012	0.012	0.011	0.01	0.009	0.0184	0.0166	0.0154	0.014	
Test thermocouple inhomogeneity		0.039	0.034	0.030	0.029	0.028	0.027	0.025	0.024	0.0332	0.0301	0.0278	0.0253	
Test thermocouple stability		0.0180	0.0156	0.0138	0.0134	0.0129	0.0122	0.0115	0.0112	0.0046	0.0042	0.0039	0.0035	
Reference junction temperature uncertainty		0.0041	0.0047	0.0053	0.0055	0.0057	0.0060	0.0064	0.0066	0.0048	0.0054	0.0058	0.0063	
Bath or furnace temperature stability		0.0021	0.0023	0.0044	0.029	0.028	0.027	0.100	0.146					
Bath or furnace temperature non-uniformity		0.0017	0.0017	0.0047	0.08	0.09	0.11	0.13	0.52					
Extraneous emf of wiring, scanners, etc.														
Reference junction temperature uncertainty for reference thermocouple					0.009	0.010	0.011	0.013	0.007					
2b. Additional components not in above list, if any														
(description of extra component)														
Test thermocouple reproducibility		0.09	0.09	0.11	0.11	0.11	0.08	0.08	0.08	0.09	0.11	0.11	0.08	
Cell uncertainty										0.003	0.004	0.002	0.007	
2c. Total expanded uncertainty (k=2),		0.20	0.20	0.23	0.29	0.30	0.29	0.38	1.13	0.20	0.23	0.23	0.17	
stds. calibrated in house														

Laboratory: CENAM (Mexico)

2a. Uncertainty components: comparison methods, in units of °C									Sn Freezing pt.	Zn Freezing pt.	Al freezing pt.	Ag freezing pt.	Cu freezing pt.
	t=100 °C	200 °C	400 °C	500 °C	600 °C	800 °C	1000 °C	1100 °C		419.527	660.323 °C	961.78 °C	1084.62 °C
Reference thermometer calibration													
Reference thermometer drift													
Reference thermometer repeatability													
Reference thermometer readout													
Test thermocouple repeatability									0.024	0.0155	0.0095	0.021	0.034
Test thermocouple readout									0.0020	0.0021	0.0017	0.0016	0.0009
Test thermocouple inhomogeneity									0.015	0.025	0.029	0.056	0.043
Test thermocouple stability									0.0002	0.0002	0.0002	0.0004	0.0004
Reference junction temperature uncertainty									0.005	0.005	0.005	0.005	0.005
Bath or furnace temperature stability													
Bath or furnace temperature non-uniformity													
Extraneous emf of wiring, scanners, etc.									0.0002	0.0002	0.0002	0.0002	0.0002
2b. Additional components not in above list, if any													
(description of extra component)													
Fixed Point									0.00044	0.00066	0.0021	0.008	0.06
2c. Total expanded uncertainty (k=2), comparison methods, in units of °C									0.058	0.060	0.062	0.12	0.16
stds. calibrated in house.													

Laboratory: LATU (Uruquay)

2. Uncertainty Budget							
2a. Uncertainty components: comparison methods, in units of °C							
	100°C	200 °C	400 °C	500 °C	600 °C	800 °C	1000 °C
Reference thermometer calibration	0.005	0.005	0.015	0.3	0.3	0.3	0.3
Reference thermometer drift	0.002	0.0019	0.002309401	0.015	0.037	0.012	0.0033
Reference thermometer repeatability	0.002	0.0037	0.0021	0.00022869	0.0022984	0.00068957	0.002292715
Reference thermometer readout	0.000	0.000029	0.000029	0.00029	0.00028	0.00027	0.000250166
Test thermocouple repeatability	0.003	0.0017	0.002572868	0.00111197	0.00608965	0.00156155	0.007401628
Test thermocouple readout	0.000	0.00035508	0.000301697	0.00029157	0.00028808	0.00026558	0.000250166
Test thermocouple inhomogeneity	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Test thermocouple stability	0.013277369	0.0018	0.001592333	0.05771156	0.06924089	0.00371603	0.47452058
Reference junction temperature uncertainty	0.05	0.050	0.05	0.05	0.05	0.05	0.05
Bath or furnace temperature stability	0.00908172	0.022	0.015155445	0.00375278	0.03608439	0.00571577	0.014433757
Bath or furnace temperature non-uniformity	0.004426256	0.026	0.51	0.01996703	0.0085174	0.10259888	0.037527767
Extraneous emf of wiring, scanners, etc.	0.098348422	0.049	0.075424159	0.07289199	0.07289199	0.07289199	0.072891988
2b. Additional components not in above list, if any							
(description of extra component)							
U HP Digital Multimeter 3458 A	0.002621871	0.00253489	0.013316846	0.01286977	0.01591098	0.02231944	0.029119352
Reference Equation for SMEAS	0.057761504	0.20771737	0.227794746	0.13269638	0.16527579	0.23533562	0.06181726
2c. Total expanded uncertainty (k=2), comparison methods, in units of °C	0.25	0.44	1.13	0.69	0.73	0.81	1.15
SPRTs were calibrated in house w/traceability to PTB							
S T/C was calibrated by PTB							