FINAL REPORT

SIM Supplementary Comparison 3.9: Type K Thermocouple Wire over the Range 100 °C to 1100 °C

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Abstract

Type K thermocouples are one of the most commonly used temperature sensors in industry. The skills, personnel, and facilities necessary for calibrating type K thermocouples are also applicable to the calibration of other base metal thermocouples, and, to a lesser extent, calibration of platinum-rhodium alloy thermocouples. Under the auspices of the Inter-american Metrology System (SIM), the National Institute of Standards and Technology (NIST) initiated a regional comparison for type K thermocouples from 100 °C to 1100 °C, with 11 participating countries. The use of type K material above approximately 200 °C is considered destructive. Therefore, each participating laboratory was sent new, unused wire from a lot of material characterized by NIST. The uniformity of the lot was remarkable, especially at temperatures above 500 °C; the standard deviation of the thermocouple emf values of multiple cuts tested at NIST was 2.7 µV or less over the full temperature range. The high uniformity eliminated any need to correct for variations of the transfer standard among the laboratories, greatly simplifying the analysis. The level of agreement among the laboratories' results was quite good. Of the 380 total bilateral combinations of the data at the eight test temperatures, only 13 (i.e., 3.4 % of all combinations) are outside the k = 2 limits, and of these 13, only 3 are outside k = 3 limits. All of the outliers occur at temperatures of 800 °C and below, which suggests that drift of the type K wire due to high-temperature oxidation did not cause changes in thermocouple emf comparable to or larger than the claimed uncertainties.

Description of the Test

Type K thermocouples are one of the most commonly used temperature sensors in industry. The skills and facilities necessary for calibration of type K thermocouples are also applicable to the testing of other base metal thermocouples, and, to a lesser extent, calibration of platinum-rhodium alloy thermocouples. NIST initiated a SIM Supplementary Comparison for Type K Thermocouples from 100 °C to 1100 °C in 2004, inviting all SIM countries to participate. The same wire lot and calibration protocol was used for a simultaneous proficiency test of U.S. commercial laboratories.

A relatively large wire gauge was chosen for two reasons. First, handling of large wire sizes is relatively more difficult for the calibration laboratory, so the comparison is more stringent compared to a calibration of fine gauge wire. Second, experience at NIST with small gauge wire has shown that very large thermoelectric drifts occur at temperatures above 800 °C, and such drift would compromise the reliability of the comparison.

The testing of type K material above approximately 200 °C is considered destructive. Therefore, each participating laboratory was sent new, unheated wire from the lot of material characterized by NIST. The wires were shipped to the participants in a coil of radius similar to the coil of the originating lot to prevent significant mechanical strain.

Samples were sent to a total of 11 participants, including NIST (the pilot laboratory). The proficiency test measurements were performed by the participating laboratories from 11 May to 22 September, 2004. Measurements at NIST were performed from 1 March to 16 June, 2004. The full protocol for the comparison is given in Appendix A.

Table 1 lists the participants, along with identifying codes used in some of the figures.

Table 1. List of laboratories participating in the comparison.

Laboratory code	Laboratory Acronym	Country	Laboratory name
A	CENAM	Mexico	Centro Nacional de Metrología
B	CONACYT	El Salvador	Consejo Nacional de Ciencia y Tecnología
C	IBMETRO	Bolivia	Instituto Boliviano de Metrología
D	INMETRO	Brazil	Instituto Nacional de Metrología, Normalização e Qualidade Industrial, Rio de Janeiro
E	INTI	Argentina	Instituto Nacional de Tecnología Industrial
F	LATU	Uruguay	Laboratorio Tecnológico del Uruguay
G	LCPNT	Chile	Laboratorio Custodio de los Patrones Nacionales de Temperatura (Red Nacional de Metrología)
H	NIST	Unites States	National Institute of Standards and Technology
I	NRC	Canada	National Research Council of Canada
J	SENCAMER	Venezuela	Servicio Autónomo Nacional de Normalización, Calidad, Metrología y Reglamentos Técnicos
K	SNM - INDECOPI	Peru	Instituto Nacional de Defensa de la Competencia y de la Protección de la Propiedad Intelectual, Servicio Nacional de Metrología

Characterization of the Transfer Standard

The NIST Thermometry Group acquired 60 m of type K, uninsulated, 1.63 mm diameter (14 gauge) thermocouple wire, supplied as a matched set of KP and KN thermoelements on separate spools, which had been annealed by the manufacturer to reduce the thermal hysteresis characteristic of type K thermocouples. The wire was then cut into 1.1 m lengths. Each cut was numbered consecutively from one end of the spools To evaluate the thermoelectric inhomogeneity and the average emf versus temperature response of the wire, selected cuts from the lot were calibrated by two separate methods. For calibration temperatures of 500 °C and below, two thermocouples were tested by comparison to a NIST-calibrated Standard Platinum Resistance Thermometer (SPRT) in stirred liquid baths—an oil bath for 100 °C and 200 °C, and a salt bath for 400 °C and 500 °C. Three additional samples from the lot were calibrated in a horizontal tube furnace by comparison with a NIST-calibrated type S thermocouple, over the temperature range 100 °C to 1100 °C. Seven additional samples were calibrated by comparison in a separate high-temperature tube furnace, but this furnace had insufficient temperature uniformity to give reliable emf versus temperature data. Nonetheless, data from this furnace was highly repeatable and was retained for the evaluation of the lot homogeneity. Calibration methods are described in NIST Special Publication 250-35 [1] and NISTIR 5340 [2].

For each of the three sets of thermocouples calibrated in the three apparatuses, the standard deviation of the emf readings at each temperature was calculated, as seen in Table 2. There were no statistically significant differences between the standard deviations measured in each apparatus, so the results were pooled to obtain the second column from the right of Table 2. Values in this column give the Type A uncertainties of the NIST measurements. This component of uncertainty includes both calibration repeatability and thermoelectric inhomogeneity of the tested wire lot and may be taken as an upper limit on the standard uncertainty ($k = 1$) due to wire inhomogeneity, u_I. The uniformity of the lot was remarkable, especially at temperatures above 500 °C. No trends were observed in the emf of one end of the lot versus the other end, and no outliers were seen. Thus, the emf versus temperature response of any one cut can be assumed equal to the average response of the tested cuts. The participants were not informed of the high degree of lot uniformity prior to the comparison.

Table 2. Thermocouple inhomogeneity and repeatability. *s*: standard deviation; df: degrees of freedom.

	High-temp. furnace		Tube furnace		Stirred baths + SPRT		Pooled	
Temperature °C	*s* µV	df	*s* µV	df	*s* µV	df	*s* µV	df
100	0.96	4	1.59	2	0.21	1	1.1	7
200	1.91	4	1.75	2	1.31	1	1.8	7
400	2.81	4	2.67	2	2.44	1	2.7	7
500	3.19	4	0.43	2	2.86	1	2.7	7
600	2.89	4	0.83	2			2.4	6
800	1.84	4	1.79	2			1.8	6
1000	2.16	4	1.03	2			1.9	6
1100	2.48	4	1.17	2			2.1	6

Because the calibration using stirred baths and an SPRT as a reference thermometer has significantly lower Type B uncertainties than the calibration in the tube furnace, the average emf for the lot was obtained by averaging the emf values obtained in the stirred baths for temperatures of 500 °C and below, and averaging the emf values obtained in the tube furnace for higher temperatures. Figure 1 shows the measured deviation *D* of each thermocouple, as expressed in units of equivalent temperature, from the type K reference function.

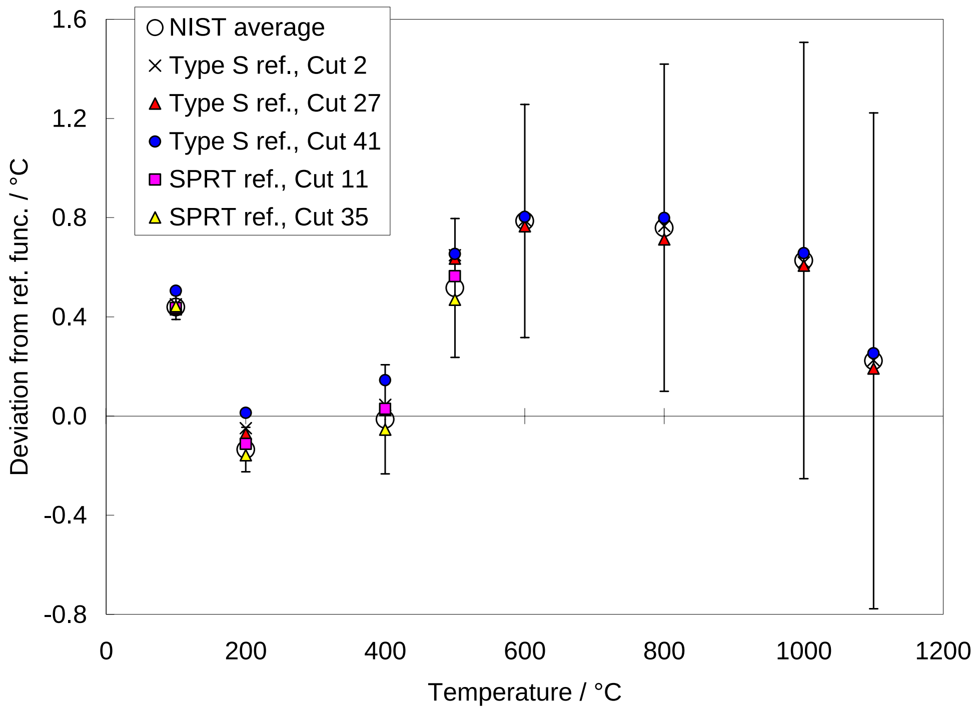

Fig. 1. Deviation of thermocouple readings from the reference function for type K thermocouples. The uncertainty bars are U_{NIST} (k=2), as described in Table 2 and the text.

Evaluation of Uncertainties

The measurement uncertainties for the participating laboratories were obtained from the survey results. In six cases, the uncertainties on the results spreadsheet (Appendix A.1, discussed in Appendix A) did not match the uncertainties entered on the survey spreadsheet (Appendix A.2, discussed in Appendix A), which was sent to the pilot laboratory prior to the start of the comparison. These laboratories were asked by the pilot laboratory to clarify which uncertainties should be used; all participants sent this information to the pilot laboratory before the Draft A Report was written.

To simplify the presentation and interpretation of the results, the emf values for the two cuts calibrated by each laboratory (three cuts from NIST for 600 °C to 1100 °C) were averaged. Upon taking the average, any run-to-run variance in the calibration results will be reduced, due to the statistical averaging of the two samples. The combined uncertainty of the two laboratories is calculated as:

$$u_{\mathrm{c}} = \left[u_{\mathrm{S,A}}^{2} + \left(u_{\mathrm{I,A}}^{2} + u_{\mathrm{R,A}}^{2} \right) / n_{\mathrm{A}} + u_{\mathrm{S,B}}^{2} + \left(u_{\mathrm{I,B}}^{2} + u_{\mathrm{R,B}}^{2} \right) / n_{\mathrm{B}} \right]^{1/2} \quad , \qquad (1)$$

where n_{A} and n_{B} are the number of calibration runs conducted by laboratories A and B; $u_{\mathrm{I,A}}$ and $u_{\mathrm{I,B}}$ account for thermocouple inhomogeneity; $u_{\mathrm{R,A}}$ and $u_{\mathrm{R,B}}$ are the standard uncertainties (k = 1) attributed by laboratories A and B to effects that are random from run to run; and $u_{\mathrm{S,A}}$ and $u_{\mathrm{S,B}}$ are the standard uncertainties attributed to systematic effects. The term $u_{\mathrm{I,A}}$ or $u_{\mathrm{I,B}}$ is set equal to

u_I if a laboratory did not include thermocouple inhomogeneity as an uncertainty component; otherwise the term is set to zero (see Appendix B for detailed uncertainty statements for each laboratory). The designation of random or systematic is not equivalent to Type A or Type B methods in the evaluation of these uncertainties. Participating laboratories were free to calculate $u_{R,x}$ and $u_{S,x}$ by either Type A or Type B methods. The initial survey of uncertainty values was flawed: the values of $u_{R,x}$ were not requested. These values were obtained after the measurement phase of the comparison, but prior to writing the Draft A Report, and the row labeled "Random components of expanded uncertainty" was added to the responses given in Appendix B.

All calculations were performed with coverage factor of two. No attempt was made to calculate uncertainties with a confidence limit of 95 %.

Results

The measured emf reported for the two or three wire cuts calibrated by laboratory *i* at a nominal test temperature were averaged to obtain the quantity $E_{a,i}$. The bilateral difference between laboratories *i* and *j* is defined as $D_{ij} \equiv (E_{a,i} - E_{a,j})/S(t)$, where $S(t)$ is the Seebeck coefficient at the nominal test temperature *t*. These differences are given in Tables 3 to 10, together with their combined expanded uncertainties ($k = 2$).

Table 3. Bilateral difference D_{ij} and the bilateral expanded uncertainty U_{ij} (k=2) at a nominal temperature of 100 °C. Values in bold font indicate $|D_{ij}| > U_{ij}$.

Laboratory *j* \ Laboratory *i*	CENAM	CONACYT	IBMETRO	INMETRO	INTI	LATU	LCPNT	NIST	NRC	SENCAMER	SNM - INDECOPI	
CENAM		–0.19	–0.02	0.09	0.37	–0.37	0.08	0.05	0.02	0.13	–0.21	D_{ij} / K
		0.22	0.31	0.94	0.81	0.47	0.21	0.21	0.28	0.83	0.41	U_{ij} / K
CONACYT	0.19		0.18	0.29	0.56	–0.18	0.27	0.24	0.22	0.32	–0.02	D_{ij} / K
	0.22		0.26	0.92	0.79	0.43	0.10	0.10	0.22	0.81	0.36	U_{ij} / K
IBMETRO	0.02	–0.18		0.11	0.38	–0.35	0.10	0.07	0.04	0.14	–0.20	D_{ij} / K
	0.31	0.26		0.95	0.82	0.49	0.24	0.24	0.31	0.84	0.43	U_{ij} / K
INMETRO	–0.09	–0.29	–0.11		0.27	–0.46	–0.01	–0.04	–0.07	0.03	–0.31	D_{ij} / K
	0.94	0.92	0.95		1.21	1.01	0.92	0.92	0.94	1.22	0.98	U_{ij} / K
INTI	–0.37	–0.56	–0.38	–0.27		–0.74	–0.29	–0.32	–0.34	–0.24	–0.58	D_{ij} / K
	0.81	0.79	0.82	1.21		0.89	0.78	0.78	0.81	1.12	0.86	U_{ij} / K
LATU	0.37	0.18	0.35	0.46	0.74		0.45	0.42	0.39	0.50	0.16	D_{ij} / K
	0.47	0.43	0.49	1.01	0.89		0.43	0.43	0.47	0.91	0.55	U_{ij} / K
LCPNT	–0.08	–0.27	–0.10	0.01	0.29	–0.45		–0.03	–0.06	0.05	–0.29	D_{ij} / K
	0.21	0.10	0.24	0.92	0.78	0.43		0.06	0.21	0.81	0.36	U_{ij} / K
NIST	–0.05	–0.24	–0.07	0.04	0.32	–0.42	0.03		–0.03	0.08	–0.26	D_{ij} / K
	0.21	0.10	0.24	0.92	0.78	0.43	0.06		0.20	0.81	0.36	U_{ij} / K
NRC	–0.02	–0.22	–0.04	0.07	0.34	–0.39	0.06	0.03		0.10	–0.24	D_{ij} / K
	0.28	0.22	0.31	0.94	0.81	0.47	0.21	0.20		0.83	0.41	U_{ij} / K
SENCAMER	–0.13	–0.32	–0.14	–0.03	0.24	–0.50	–0.05	–0.08	–0.10		–0.34	D_{ij} / K
	0.83	0.81	0.84	1.22	1.12	0.91	0.81	0.81	0.83		0.88	U_{ij} / K
SNM - INDECOPI	0.21	0.02	0.20	0.31	0.58	-0.16	0.29	0.26	0.24	0.34		D_{ij} / K
	0.41	0.36	0.43	0.98	0.86	0.55	0.36	0.36	0.41	0.88		U_{ij} / K

Table 4. Bilateral difference D_{ij} and the bilateral expanded uncertainty U_{ij} (k=2) at a nominal temperature of 200 °C. Values in bold font indicate $|D_{ij}| > U_{ij}$.

Laboratory *j* \ Laboratory *i*	CENAM	CONACYT	IBMETRO	INMETRO	INTI	LATU	LCPNT	NIST	NRC	SENCAMER	SNM - INDECOPI	
CENAM		–0.02	0.00	0.17	0.23	0.23	0.12	0.06	0.11	–0.04	–0.21	D_{ij} / K
		0.24	0.40	0.91	0.81	0.48	0.23	0.23	0.37	0.79	0.43	U_{ij} / K
CONACYT	0.02		0.02	0.19	0.25	0.25	0.14	0.08	0.13	–0.02	–0.19	D_{ij} / K
	0.24		0.35	0.89	0.79	0.44	0.13	0.13	0.32	0.77	0.39	U_{ij} / K
IBMETRO	0.00	–0.02		0.17	0.23	0.23	0.12	0.06	0.11	–0.04	–0.21	D_{ij} / K
	0.40	0.35		0.95	0.85	0.54	0.34	0.34	0.45	0.83	0.50	U_{ij} / K
INMETRO	–0.17	–0.19	–0.17		0.06	0.06	–0.05	–0.11	–0.06	–0.21	–0.38	D_{ij} / K
	0.91	0.89	0.95		1.18	0.99	0.89	0.89	0.94	1.17	0.96	U_{ij} / K
INTI	–0.23	–0.25	–0.23	–0.06		0.00	–0.11	–0.17	–0.12	–0.27	–0.44	D_{ij} / K
	0.81	0.79	0.85	1.18		0.89	0.78	0.78	0.84	1.09	0.87	U_{ij} / K
LATU	–0.23	–0.25	–0.23	–0.06	0.00		–0.11	–0.17	–0.12	–0.27	–0.44	D_{ij} / K
	0.48	0.44	0.54	0.99	0.89		0.43	0.43	0.52	0.87	0.57	U_{ij} / K
LCPNT	–0.12	–0.14	–0.12	0.05	0.11	0.11		–0.06	–0.01	–0.16	–0.33	D_{ij} / K
	0.23	0.13	0.34	0.89	0.78	0.43		0.10	0.31	0.76	0.38	U_{ij} / K
NIST	–0.06	–0.08	–0.06	0.11	0.17	0.17	0.06		0.05	–0.10	–0.27	D_{ij} / K
	0.23	0.13	0.34	0.89	0.78	0.43	0.10		0.31	0.76	0.38	U_{ij} / K
NRC	–0.11	–0.13	–0.11	0.06	0.12	0.12	0.01	–0.05		–0.15	–0.32	D_{ij} / K
	0.37	0.32	0.45	0.94	0.84	0.52	0.31	0.31		0.82	0.48	U_{ij} / K
SENCAMER	0.04	0.02	0.04	0.21	0.27	0.27	0.16	0.10	0.15		–0.17	D_{ij} / K
	0.79	0.77	0.83	1.17	1.09	0.87	0.76	0.76	0.82		0.85	U_{ij} / K
SNM - INDECOPI	0.21	0.19	0.21	0.38	0.44	0.44	0.33	0.27	0.32	0.17		D_{ij} / K
	0.43	0.39	0.50	0.96	0.87	0.57	0.38	0.38	0.48	0.85		U_{ij} / K

Table 5. 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 $|D_{ij}| > U_{ij}$.

Laboratory *j* \ Laboratory *i*	CENAM	CONACYT	IBMETRO	INMETRO	INTI	LATU	LCPNT	NIST	NRC	SENCAMER	SNM - INDECOPI	
CENAM		0.25	−1.05	0.43	0.10	0.07	**0.39**	−0.02	0.11	−0.62	−0.50	D_{ij} / K
		0.74	1.32	0.92	0.84	0.72	0.28	0.33	0.57	0.81	1.14	U_{ij} / K
CONACYT	−0.25		−1.30	0.18	−0.15	−0.18	0.14	−0.27	−0.14	−0.87	−0.75	D_{ij} / K
	0.74		1.47	1.12	1.05	0.96	0.70	0.72	0.86	1.03	1.31	U_{ij} / K
IBMETRO	1.05	1.30		1.49	1.15	1.12	**1.44**	1.04	1.16	0.43	0.55	D_{ij} / K
	1.32	1.47		1.57	1.52	1.46	1.30	1.31	1.39	1.51	1.71	U_{ij} / K
INMETRO	−0.43	−0.18	−1.49		−0.33	−0.37	−0.05	−0.45	−0.32	−1.05	−0.93	D_{ij} / K
	0.92	1.12	1.57		1.19	1.12	0.89	0.91	1.02	1.18	1.42	U_{ij} / K
INTI	−0.10	0.15	−1.15	0.33		−0.04	0.28	−0.12	0.01	−0.72	−0.60	D_{ij} / K
	0.84	1.05	1.52	1.19		1.04	0.80	0.82	0.95	1.11	1.37	U_{ij} / K
LATU	−0.07	0.18	−1.12	0.37	0.04		0.32	−0.08	0.05	−0.69	−0.57	D_{ij} / K
	0.72	0.96	1.46	1.12	1.04		0.68	0.71	0.85	1.03	1.30	U_{ij} / K
LCPNT	**−0.39**	−0.14	**−1.44**	0.05	−0.28	−0.32		**−0.40**	−0.28	**−1.01**	−0.89	D_{ij} / K
	0.28	0.70	1.30	0.89	0.80	0.68		0.23	0.52	0.78	1.12	U_{ij} / K
NIST	0.02	0.27	−1.04	0.45	0.12	0.08	**0.40**		0.13	−0.60	−0.48	D_{ij} / K
	0.33	0.72	1.31	0.91	0.82	0.71	0.23		0.55	0.80	1.13	U_{ij} / K
NRC	−0.11	0.14	−1.16	0.32	−0.01	−0.05	0.28	−0.13		−0.73	−0.61	D_{ij} / K
	0.57	0.86	1.39	1.02	0.95	0.85	0.52	0.55		0.92	1.22	U_{ij} / K
SENCAMER	0.62	0.87	−0.43	1.05	0.72	0.69	**1.01**	0.60	0.73		0.12	D_{ij} / K
	0.81	1.03	1.51	1.18	1.11	1.03	0.78	0.80	0.92		1.35	U_{ij} / K
SNM – INDECOPI	0.50	0.75	−0.55	0.93	0.60	0.57	0.89	0.48	0.61	−0.12		D_{ij} / K
	1.14	1.31	1.71	1.42	1.37	1.30	1.12	1.13	1.22	1.35		U_{ij} / K

Table 6. 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 $|D_{ij}| > U_{ij}$.

Laboratory *i*

Laboratory *j*	CENAM	CONACYT	IBMETRO	INMETRO	INTI	LATU	LCPNT	NIST	NRC	SENCAMER	SNM – INDECOPI	
CENAM		0.37	–0.32	–0.25	–0.11	–0.52	0.13	–0.01	0.15	–0.65	–0.49	D_{ij} / K
		0.73	1.40	0.92	0.83	1.05	0.31	0.39	0.67	0.81	1.19	U_{ij} / K
CONACYT	–0.37		–0.69	–0.61	–0.48	–0.89	–0.24	–0.38	–0.22	–1.01	–0.85	D_{ij} / K
	0.73		1.53	1.10	1.03	1.22	0.68	0.73	0.90	1.01	1.34	U_{ij} / K
IBMETRO	0.32	0.69		0.08	0.21	–0.20	0.45	0.31	0.47	–0.32	–0.16	D_{ij} / K
	1.40	1.53		1.63	1.58	1.71	1.38	1.40	1.50	1.57	1.79	U_{ij} / K
INMETRO	0.25	0.61	–0.08		0.13	–0.28	0.37	0.24	0.39	–0.40	–0.24	D_{ij} / K
	0.92	1.10	1.63		1.17	1.34	0.88	0.91	1.06	1.15	1.44	U_{ij} / K
INTI	0.11	0.48	–0.21	–0.13		–0.41	0.24	0.10	0.26	–0.54	–0.38	D_{ij} / K
	0.83	1.03	1.58	1.17		1.28	0.79	0.83	0.99	1.09	1.39	U_{ij} / K
LATU	0.52	0.89	0.20	0.28	0.41		0.65	0.51	0.67	–0.13	0.04	D_{ij} / K
	1.05	1.22	1.71	1.34	1.28		1.02	1.05	1.18	1.26	1.54	U_{ij} / K
LCPNT	–0.13	0.24	–0.45	–0.37	–0.24	–0.65		–0.14	0.02	–0.77	–0.61	D_{ij} / K
	0.31	0.68	1.38	0.88	0.79	1.02		0.29	0.61	0.76	1.16	U_{ij} / K
NIST	0.01	0.38	–0.31	–0.24	–0.10	–0.51	0.14		0.16	–0.64	–0.48	D_{ij} / K
	0.39	0.73	1.40	0.91	0.83	1.05	0.29		0.66	0.80	1.18	U_{ij} / K
NRC	–0.15	0.22	–0.47	–0.39	–0.26	–0.67	–0.02	–0.16		–0.79	–0.63	D_{ij} / K
	0.67	0.90	1.50	1.06	0.99	1.18	0.61	0.66		0.96	1.30	U_{ij} / K
SENCAMER	0.65	1.01	0.32	0.40	0.54	0.13	0.77	0.64	0.79		0.16	D_{ij} / K
	0.81	1.01	1.57	1.15	1.09	1.26	0.76	0.80	0.96		1.38	U_{ij} / K
SNM - INDECOPI	0.49	0.85	0.16	0.24	0.38	-0.04	0.61	0.48	0.63	-0.16		D_{ij} / K
	1.19	1.34	1.79	1.44	1.39	1.54	1.16	1.18	1.30	1.38		U_{ij} / K

Table 7. 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 $|D_{ij}| > U_{ij}$.

Laboratory *i*

Laboratory *j*	CENAM	CONACYT	IBMETRO	INMETRO	INTI	LATU	LCPNT	NIST	NRC	SENCAMER	SNM - INDECOPI	
CENAM		0.34	–0.60	0.11	–0.04	–0.64	0.04	0.18	0.74	–0.60	–0.39	D_{ij} / K
		0.95	1.52	0.93	0.84	1.06	0.33	0.63	0.83	0.82	1.27	U_{ij} / K
CONACYT	–0.34		–0.94	–0.23	–0.38	–0.98	–0.30	–0.16	0.40	–0.94	–0.73	D_{ij} / K
	0.95		1.73	1.25	1.19	1.35	0.90	1.04	1.18	1.17	1.52	U_{ij} / K
IBMETRO	0.60	0.94		0.72	0.57	–0.03	0.64	0.79	1.34	0.01	0.21	D_{ij} / K
	1.52	1.73		1.72	1.68	1.80	1.49	1.58	1.67	1.67	1.93	U_{ij} / K
INMETRO	–0.11	0.23	–0.72		–0.15	–0.75	–0.07	0.07	0.62	–0.71	–0.50	D_{ij} / K
	0.93	1.25	1.72		1.17	1.34	0.87	1.02	1.16	1.15	1.50	U_{ij} / K
INTI	0.04	0.38	–0.57	0.15		–0.60	0.08	0.22	0.77	–0.56	–0.35	D_{ij} / K
	0.84	1.19	1.68	1.17		1.28	0.79	0.95	1.10	1.09	1.46	U_{ij} / K
LATU	0.64	0.98	0.03	0.75	0.60		0.68	0.82	**1.37**	0.04	0.25	D_{ij} / K
	1.06	1.35	1.80	1.34	1.28		1.02	1.15	1.27	1.26	1.59	U_{ij} / K
LCPNT	–0.04	0.30	–0.64	0.07	–0.08	–0.68		0.14	0.70	–0.64	–0.43	D_{ij} / K
	0.33	0.90	1.49	0.87	0.79	1.02		0.55	0.77	0.76	1.23	U_{ij} / K
NIST	–0.18	0.16	–0.79	–0.07	–0.22	–0.82	–0.14		0.55	–0.78	–0.57	D_{ij} / K
	0.63	1.04	1.58	1.02	0.95	1.15	0.55		0.94	0.93	1.34	U_{ij} / K
NRC	–0.74	–0.40	–1.34	–0.62	–0.77	**–1.37**	–0.70	–0.55		**–1.33**	–1.13	D_{ij} / K
	0.83	1.18	1.67	1.16	1.10	1.27	0.77	0.94		1.08	1.45	U_{ij} / K
SENCAMER	0.60	0.94	–0.01	0.71	0.56	–0.04	0.64	0.78	**1.33**		0.21	D_{ij} / K
	0.82	1.17	1.67	1.15	1.09	1.26	0.76	0.93	1.08		1.44	U_{ij} / K
SNM – INDECOPI	0.39	0.73	–0.21	0.50	0.35	–0.25	0.43	0.57	1.13	–0.21		D_{ij} / K
	1.27	1.52	1.93	1.50	1.46	1.59	1.23	1.34	1.45	1.44		U_{ij} / K

Table 8. 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 $|D_{ij}| > U_{ij}$.

Laboratory *i*

Laboratory *j*	CENAM	CONACYT	IBMETRO	INMETRO	INTI	LATU	LCPNT	NIST	NRC	SENCAMER	SNM – INDECOPI	
CENAM			–0.52	0.10	0.11	–0.61	–0.46	0.11	0.73	–0.59	–0.60	D_{ij} / K
			2.14	0.94	0.87	1.24	1.26	0.81	1.03	0.86	1.36	U_{ij} / K
CONACYT												D_{ij} / K
												U_{ij} / K
IBMETRO	0.52			0.62	0.63	–0.09	0.06	0.63	1.24	–0.08	–0.08	D_{ij} / K
	2.14			2.27	2.25	2.42	2.43	2.23	2.31	2.25	2.48	U_{ij} / K
INMETRO	–0.10		–0.62		0.01	–0.71	–0.56	0.01	0.63	–0.69	–0.70	D_{ij} / K
	0.94		2.27		1.16	1.46	1.48	1.12	1.28	1.16	1.56	U_{ij} / K
INTI	–0.11		–0.63	–0.01		–0.72	–0.57	0.00	0.62	–0.70	–0.71	D_{ij} / K
	0.87		2.25	1.16		1.42	1.43	1.06	1.24	1.10	1.52	U_{ij} / K
LATU	0.61		0.09	0.71	0.72		0.15	0.72	1.34	0.02	0.01	D_{ij} / K
	1.24		2.42	1.46	1.42		1.69	1.38	1.52	1.42	1.76	U_{ij} / K
LCPNT	0.46		–0.06	0.56	0.57	–0.15		0.57	1.18	–0.14	–0.14	D_{ij} / K
	1.26		2.43	1.48	1.43	1.69		1.40	1.54	1.43	1.77	U_{ij} / K
NIST	–0.11		–0.63	–0.01	0.00	–0.72	–0.57		0.62	–0.70	–0.71	D_{ij} / K
	0.81		2.23	1.12	1.06	1.38	1.40		1.20	1.06	1.49	U_{ij} / K
NRC	–0.73		–1.24	–0.63	–0.62	–1.34	–1.18	–0.62		–1.32	–1.32	D_{ij} / K
	1.03		2.31	1.28	1.24	1.52	1.54	1.20		1.23	1.62	U_{ij} / K
SENCAMER	0.59		0.08	0.69	0.70	–0.02	0.14	0.70	1.32		0.00	D_{ij} / K
	0.86		2.25	1.16	1.10	1.42	1.43	1.06	1.23		1.52	U_{ij} / K
SNM - INDECOPI	0.60		0.08	0.70	0.71	–0.01	0.14	0.71	1.32	0.00		D_{ij} / K
	1.36		2.48	1.56	1.52	1.76	1.77	1.49	1.62	1.52		U_{ij} / K

Table 9. 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 $|D_{ij}| > U_{ij}$.

		Laboratory *i*											
	Laboratory	CENAM	CONACYT	IBMETRO	INMETRO	INTI	LATU	LCPNT	NIST	NRC	SENCAMER	SNM – INDECOPI	
Laboratory *j*	CENAM			–0.22	0.21	0.66	–0.20	0.50	0.37	0.91	–0.23	–0.12	D_{ij} / K
				2.39	0.98	0.92	1.30	1.82	1.04	1.25	0.92	1.51	U_{ij} / K
	CONACYT												D_{ij} / K
													U_{ij} / K
	IBMETRO	0.22			0.43	0.89	0.03	0.73	0.59	1.13	–0.01	0.10	D_{ij} / K
		2.39			2.49	2.46	2.63	2.92	2.51	2.60	2.46	2.74	U_{ij} / K
	INMETRO	–0.21		–0.43		0.45	–0.41	0.29	0.16	0.70	–0.44	–0.33	D_{ij} / K
		0.98		2.49		1.15	1.47	1.95	1.25	1.43	1.15	1.66	U_{ij} / K
	INTI	–0.66		–0.89	–0.45		–0.86	–0.16	–0.29	0.25	–0.89	–0.78	D_{ij} / K
		0.92		2.46	1.15		1.43	1.92	1.20	1.39	1.10	1.63	U_{ij} / K
	LATU	0.20		–0.03	0.41	0.86		0.70	0.57	1.11	–0.03	0.08	D_{ij} / K
		1.30		2.63	1.47	1.43		2.13	1.51	1.66	1.43	1.87	U_{ij} / K
	LCPNT	–0.50		–0.73	–0.29	0.16	–0.70		–0.13	0.41	–0.73	–0.62	D_{ij} / K
		1.82		2.92	1.95	1.92	2.13		1.98	2.10	1.92	2.26	U_{ij} / K
	NIST	–0.37		–0.59	–0.16	0.29	–0.57	0.13		0.54	–0.60	–0.49	D_{ij} / K
		1.04		2.51	1.25	1.20	1.51	1.98		1.47	1.20	1.69	U_{ij} / K
	NRC	–0.91		–1.13	–0.70	–0.25	–1.11	–0.41	–0.54		–1.14	–1.03	D_{ij} / K
		1.25		2.60	1.43	1.39	1.66	2.10	1.47		1.38	1.83	U_{ij} / K
	SENCAMER	0.23		0.01	0.44	0.89	0.03	0.73	0.60	1.14		0.11	D_{ij} / K
		0.92		2.46	1.15	1.10	1.43	1.92	1.20	1.38		1.62	U_{ij} / K
	SNM - INDECOPI	0.12		–0.10	0.33	0.78	–0.08	0.62	0.49	1.03	–0.11		D_{ij} / K
		1.51		2.74	1.66	1.63	1.87	2.26	1.69	1.83	1.62		U_{ij} / K

Table 10. 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 $|D_{ij}| > U_{ij}$.

Laboratory *j* \ Laboratory *i*	CENAM	CONACYT	IBMETRO	INMETRO	INTI	LATU	LCPNT	NIST	NRC	SENCAMER	SNM – INDECOPI	
CENAM												D_{ij} / K
												U_{ij} / K
CONACYT												D_{ij} / K
												U_{ij} / K
IBMETRO					0.76		–0.44	0.34	0.86	–0.45		D_{ij} / K
					2.90		3.30	2.97	3.06	2.96		U_{ij} / K
INMETRO												D_{ij} / K
												U_{ij} / K
INTI			–0.76				–1.20	–0.42	0.10	–1.21		D_{ij} / K
			2.90				1.92	1.29	1.47	1.27		U_{ij} / K
LATU												D_{ij} / K
												U_{ij} / K
LCPNT			0.44		1.20			0.78	1.30	–0.01		D_{ij} / K
			3.30		1.92			2.04	2.16	2.02		U_{ij} / K
NIST			–0.34		0.42		–0.78		0.52	–0.79		D_{ij} / K
			2.97		1.29		2.04		1.62	1.43		U_{ij} / K
NRC			–0.86		–0.10		–1.30	–0.52		–1.31		D_{ij} / K
			3.06		1.47		2.16	1.62		1.60		U_{ij} / K
SENCAMER			0.45		1.21		0.01	0.79	1.31			D_{ij} / K
			2.96		1.27		2.02	1.43	1.60			U_{ij} / K
SNM – INDECOPI												D_{ij} / K
												U_{ij} / K

Choice of Reference Value

From the reported data, three candidate reference values were calculated: the weighted mean, the median, and the mean. The protocol suggested that the NIST lot mean would be used for the reference value. This suggestion was discarded for two compelling reasons:

a. The thermocouple wire was found to be so thermoelectrically uniform that it was not necessary to correct each laboratory's results for deviations of the particular tested wire cuts from the lot mean. Thus, each laboratory's measurements can be taken as representative of the whole lot.
b. Although a large number of tests at NIST validated the lot homogeneity, most of these tests at NIST were performed in a different furnace than the one used for the final NIST calibration results. Consequently, the number of degrees of freedom for the NIST results is not appreciably higher than for other participants.

Figure 2 shows the candidate reference values as a function of temperature. At temperatures of 400 °C and 500 °C and below, the results of LCPNT are heavily weighted in the calculation of the weighted mean, yet these results also are possible outliers, as seen in Tables 5 and 6. If these results are omitted from the calculation of the weighted mean, the revised weighted mean shifts from the original calculation by an amount well in excess of the k=2 statistical uncertainty. To a lesser extent, the same difficulty arises with the results of CONACYT at 100 °C and 200 °C. Because of this difficulty, the weighted mean is deemed to be a flawed reference value. Of the two other candidates, the median is chosen as the reference value because it is insensitive to outliers. Strictly speaking, we use the term median in this paper to denote the median of an assumed probability distribution, which was calculated by assuming that each reported result at a given temperature can be represented by a normal distribution, centered on the mean emf value of the two calibrated lot samples with a scale parameter equal to the standard uncertainty reported by the laboratory. The probability distributions of all laboratories were summed numerically, and the 50 % point of the combined distribution was taken as the median. The uncertainty of the median, as seen in Fig. 2, was calculated using the approximate formula:

$$u(E_{\mathrm{med}}) = 1.253 s_{\mathrm{m}} \quad , \tag{2}$$

where the two or three emf values from each laboratory at a given temperature are first averaged, and then the standard deviation of the mean, s_{m}, is determined from that population.

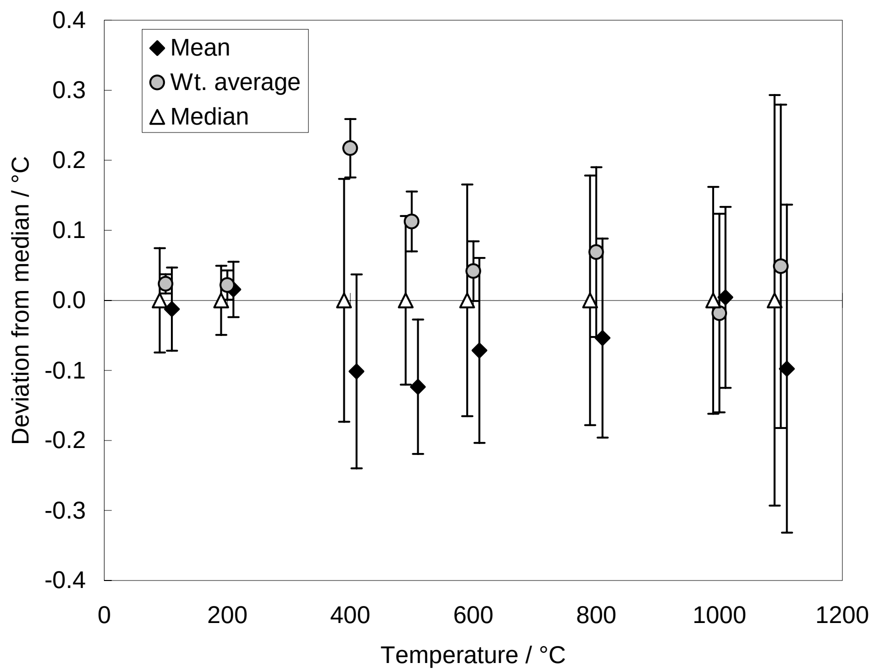

Fig. 2. Several candidate reference values, plotted as a function of temperature (offset for visualization). The bars indicate k=1 standard uncertainties.

Two additional checks were made to examine the internal consistency of the data. First, the internal consistency of the calibrations within a laboratory were assessed using the method of Youden plots, as discussed below. Second, a third-order polynomial was used to fit the emf deviation from the reference function for each of the laboratories. The residuals of each laboratory's data were compared to the residual plots for other laboratories, to look for possible anomalous patterns. These procedures identified several possible outliers; removal of these possible outliers from the calculation of the median (but not from the average emf value for each laboratory) had a negligible effect on the results presented in the figures. For all of the figures, all data is included in the calculation of the median.

Figures 3 to 13 present the comparison data for each laboratory graphically, using the median simply as a baseline. In the figures, the uncertainty for laboratory *i* is calculated from the terms of Eq. 1 applicable to laboratory *i*:

$$u_{\mathrm{c}} = \left[u_{\mathrm{S},i}{}^2 + \left(u_{\mathrm{I,i}}{}^2 + u_{\mathrm{R},i}{}^2 \right) \Big/ n_i \right]^{1/2} \quad , \tag{3}$$

For laboratories that did not explicitly include wire inhomogeneity as a component in their uncertainty budget, an uncertainty $u_{\mathrm{I},i}$ is included to account for the uncertainty of the emf average E_i resulting from the inhomogeneity of the tested wires. For the laboratories that explicitly included wire inhomogeneity in their random uncertainties, the $u_{\mathrm{I},i}$ term was set to zero. The uncertainty of the median, which is correlated to the uncertainty of the individual measurements in a relatively complex way [3], is not included in the uncertainty bars. Note that the bilateral tables, unlike the figures, are independent of the choice of reference value and the uncertainty of that reference value.

In Figures 14 to 21, Youden plots of are presented for the measured emf of the two cuts of wires calibrated by each laboratory. Three cuts were calibrated by the pilot laboratory above 600 °C; for the Youden plots, the two most discrepant cuts were used in this case. At each temperature, the pair of emf values measured by a laboratory is plotted as abscissa and ordinate. The uncertainty bars represent the calibration uncertainty of each laboratory combined with the uncertainty due to wire inhomogeneity, all at the k=1 level. (Using k=1 instead of k=2 bars greatly enhances the readability of the plots.) No additional inhomogeneity uncertainty was included for CENAM, IBMETRO, INTI, NIST, NRC, and SNM-INDECC, which include wire inhomogeneity as part of their calibration uncertainty. The dashed line in each plot indicates equal emf values for the two cuts. Since the lot of thermocouple wire is known to be quite homogeneous, the data are expected to cluster near this line. Examination of the plots indicates that the observed differences between laboratories are due predominantly to systematic biases (e.g., furnace effects) between the laboratories, rather than irrepeatability of the results.

Figures 22 and 23 are Youden plots for the same data, in equivalent degrees Celsius deviation from the median, and without uncertainty bars for the individual laboratories. The dashed ellipses indicate deviations equivalent to one, two, and three standard deviations, where the standard deviation is taken for all measured emf values of the individual cuts of wire at that nominal test temperature.

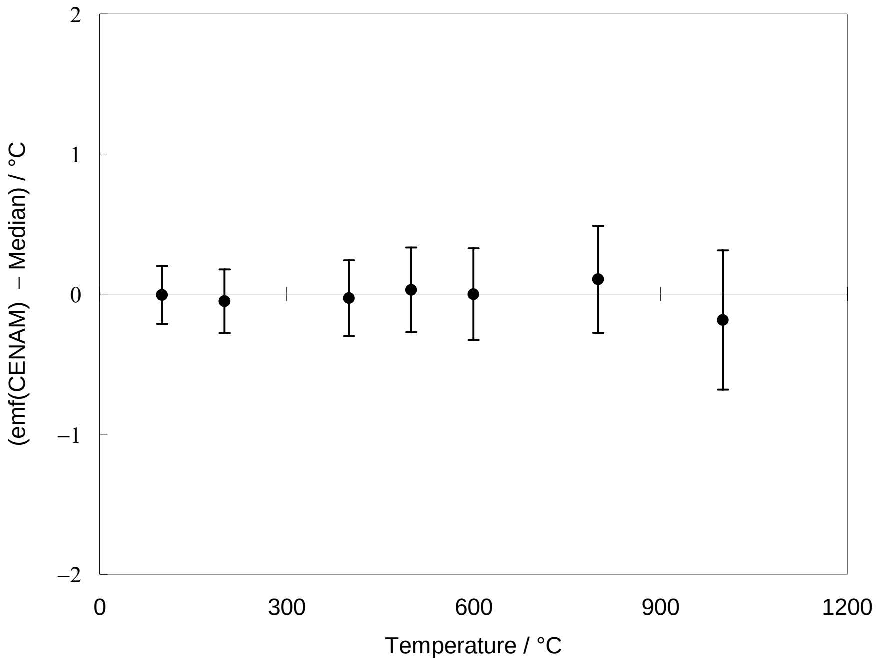

Fig. 3. Results of CENAM as a function of temperature. The bars are k=2 expanded uncertainties including only the CENAM uncertainties, which include thermocouple inhomogeneity.

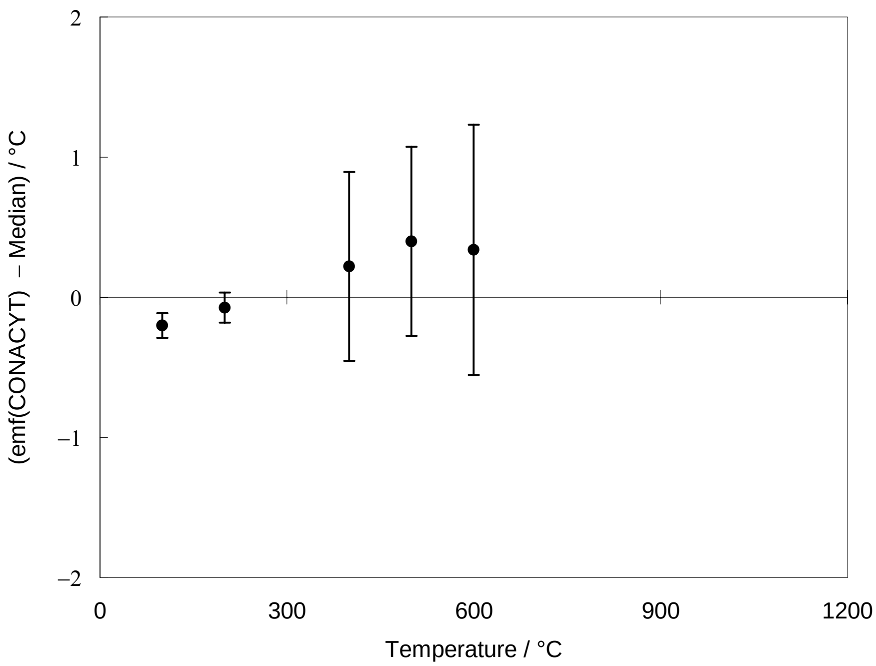

Fig. 4. Results of CONACYT as a function of temperature. The bars are k=2 expanded uncertainties including only the CONACYT uncertainties and the thermocouple inhomogeneity.

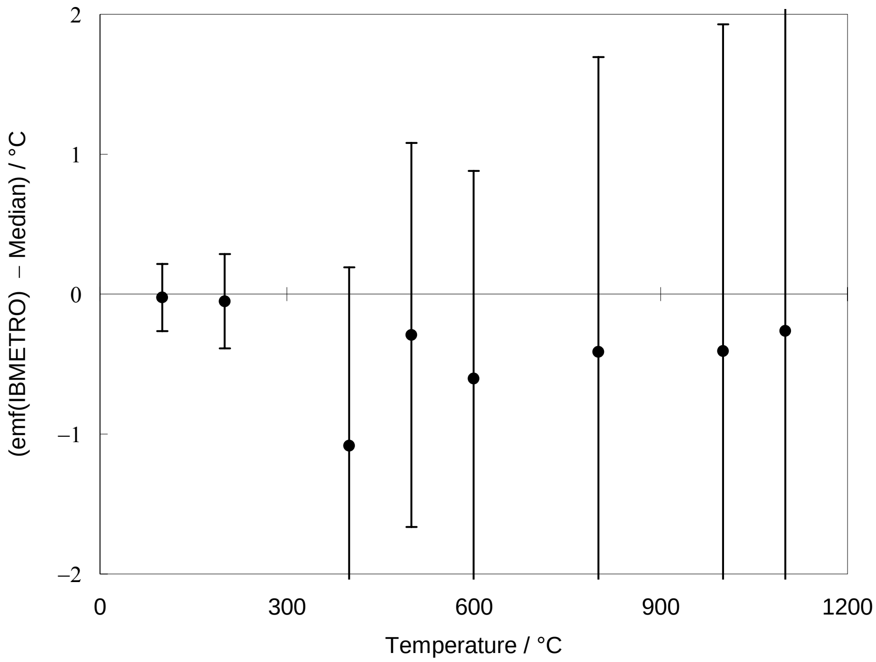

Fig. 5. Results of IBMETRO as a function of temperature. The bars are k=2 expanded uncertainties including only the IBMETRO uncertainties, which include thermocouple inhomogeneity.

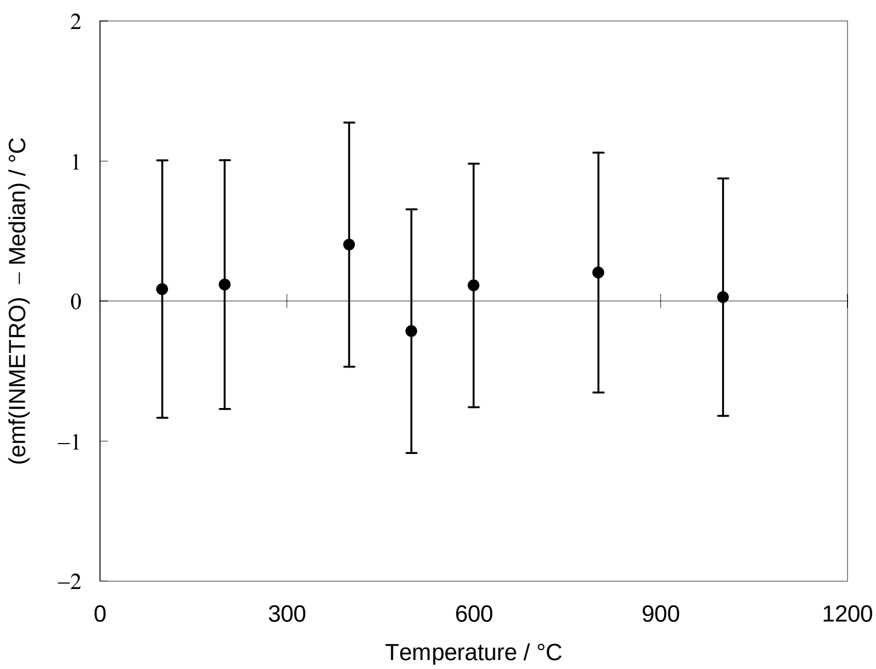

Fig. 6. Results of INMETRO as a function of temperature. The bars are k=2 expanded uncertainties including only the INMETRO uncertainties and the thermocouple inhomogeneity.

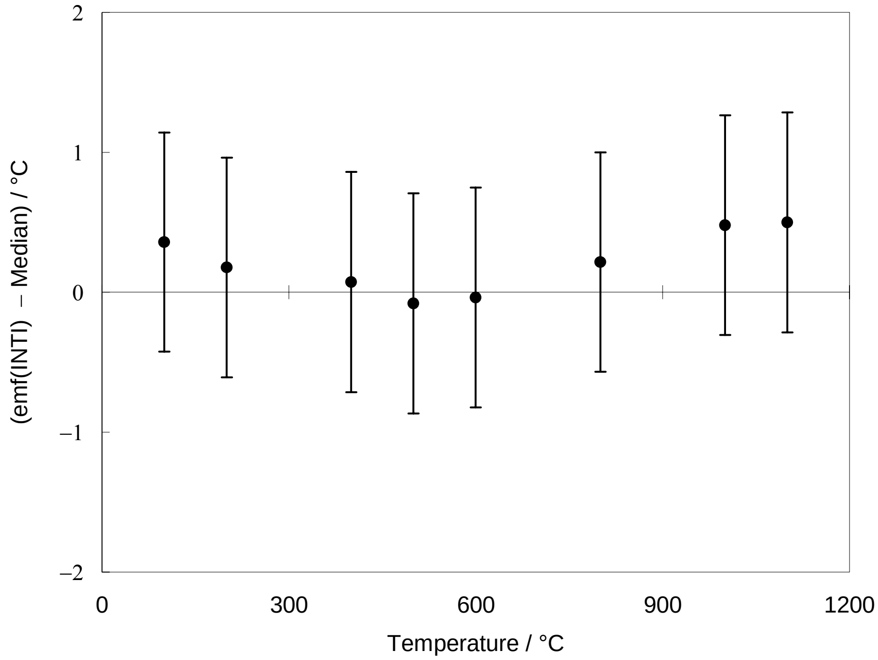

Fig. 7. Results of INTI as a function of temperature. The bars are k=2 expanded uncertainties including only the INTI uncertainties, which include thermocouple inhomogeneity.

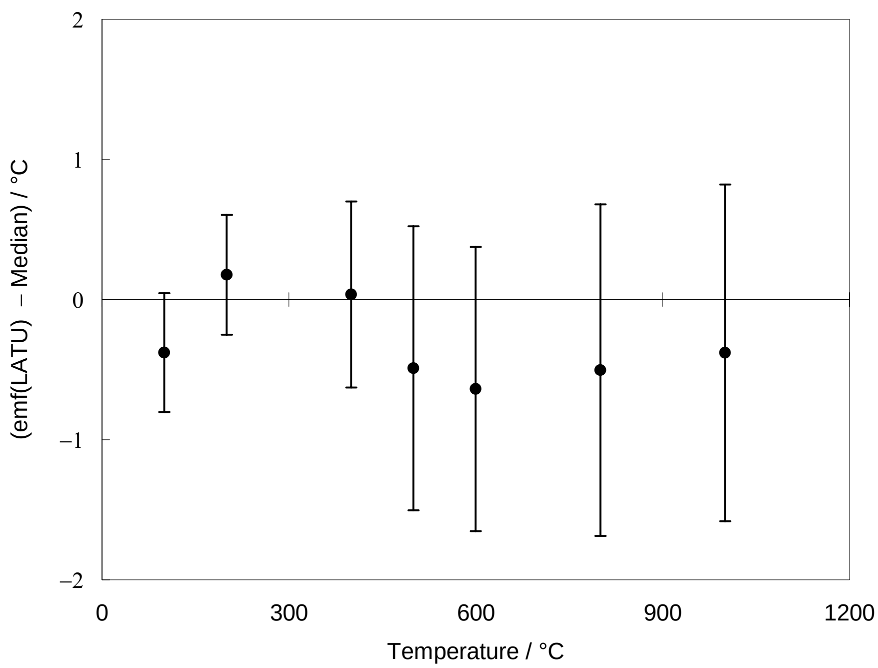

Fig. 8. Results of LATU as a function of temperature. The bars are k=2 expanded uncertainties including only the LATU uncertainties and the thermocouple inhomogeneity.

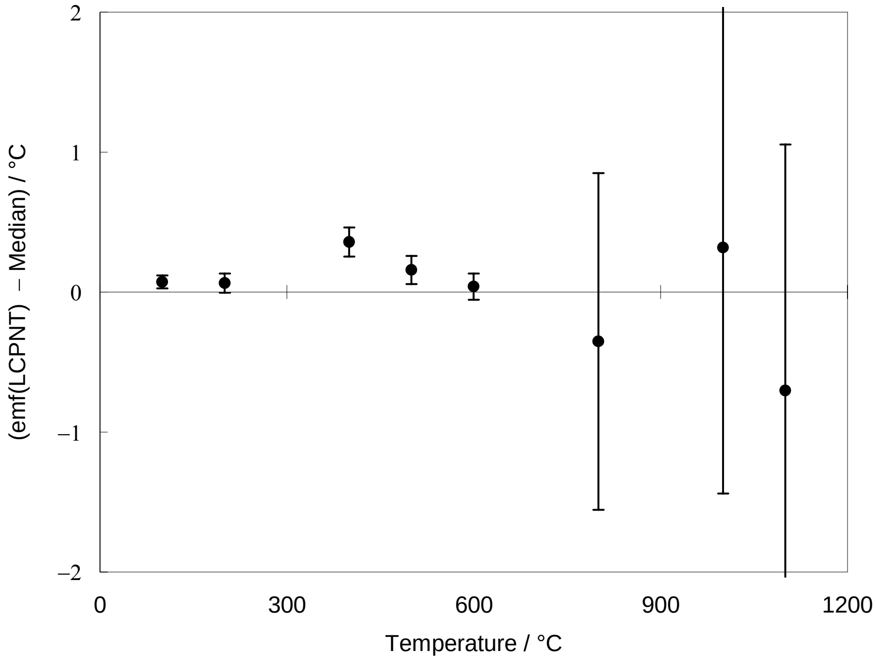

Fig. 9. Results of LCPNT as a function of temperature. The bars are k=2 expanded uncertainties including only the LCPNT uncertainties and the thermocouple inhomogeneity.

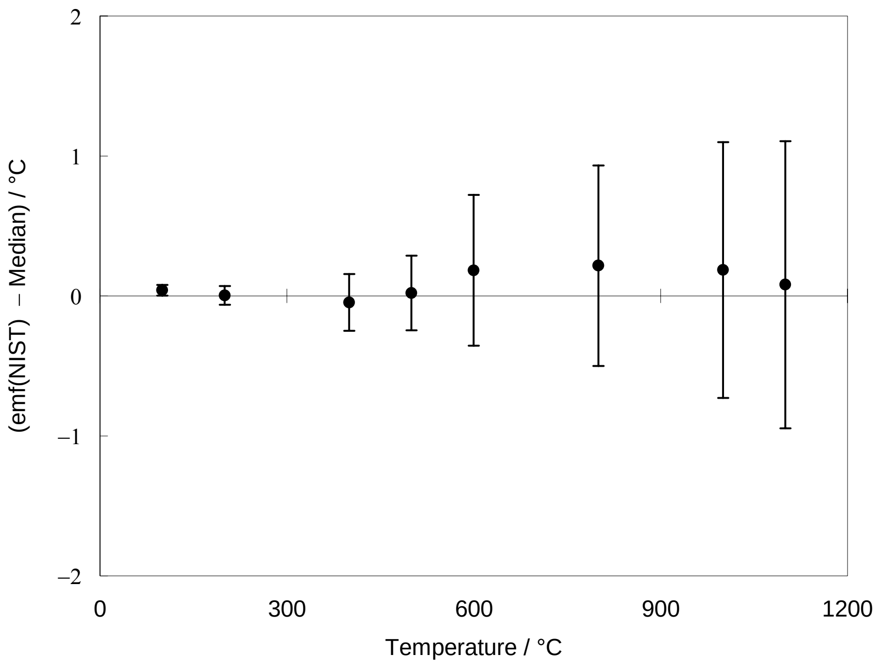

Fig. 10. Results of NIST as a function of temperature. The bars are k=2 expanded uncertainties including only the NIST uncertainties, which include thermocouple inhomogeneity.

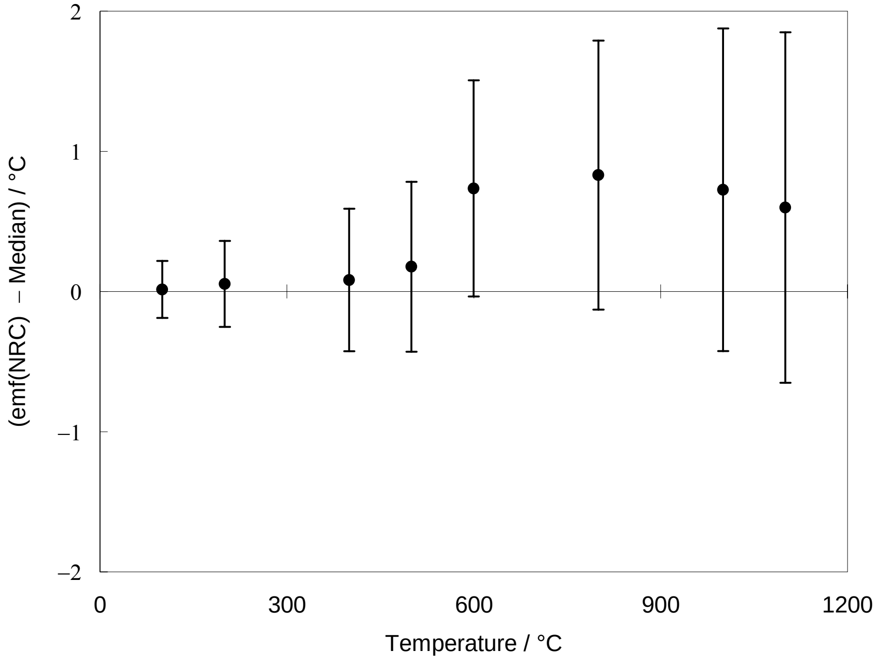

Fig. 11. Results of NRC as a function of temperature. The bars are k=2 expanded uncertainties including only the NRC uncertainties, which include thermocouple inhomogeneity.

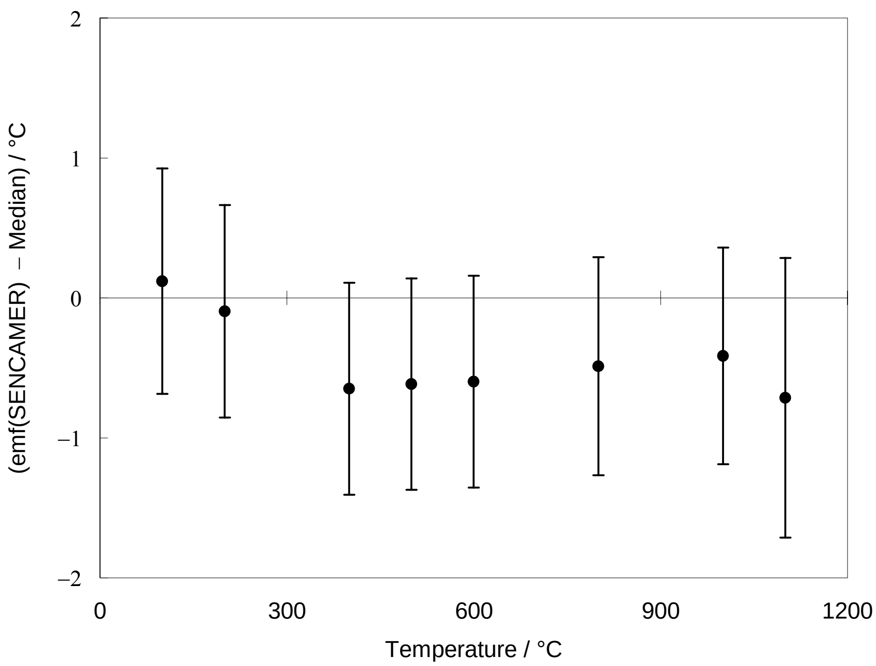

Fig. 12. Results of SENCAMER as a function of temperature. The bars are k=2 expanded uncertainties including only the SENCAMER uncertainties and the thermocouple inhomogeneity.

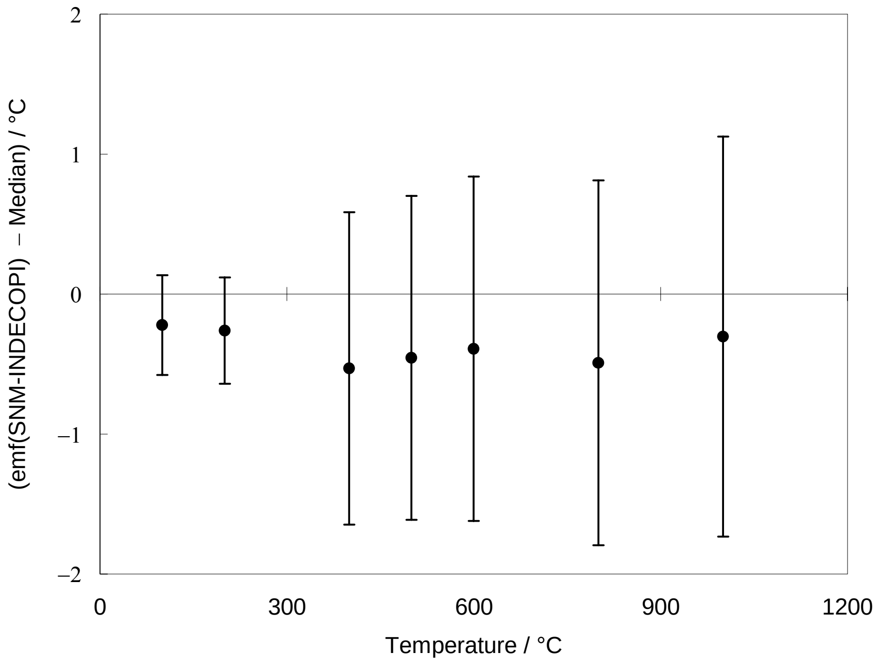

Fig. 13. Results of SNM-INDECOPI as a function of temperature. The bars are k=2 expanded uncertainties including only the SNM-INDECOPI uncertainties, which include thermocouple inhomogeneity.

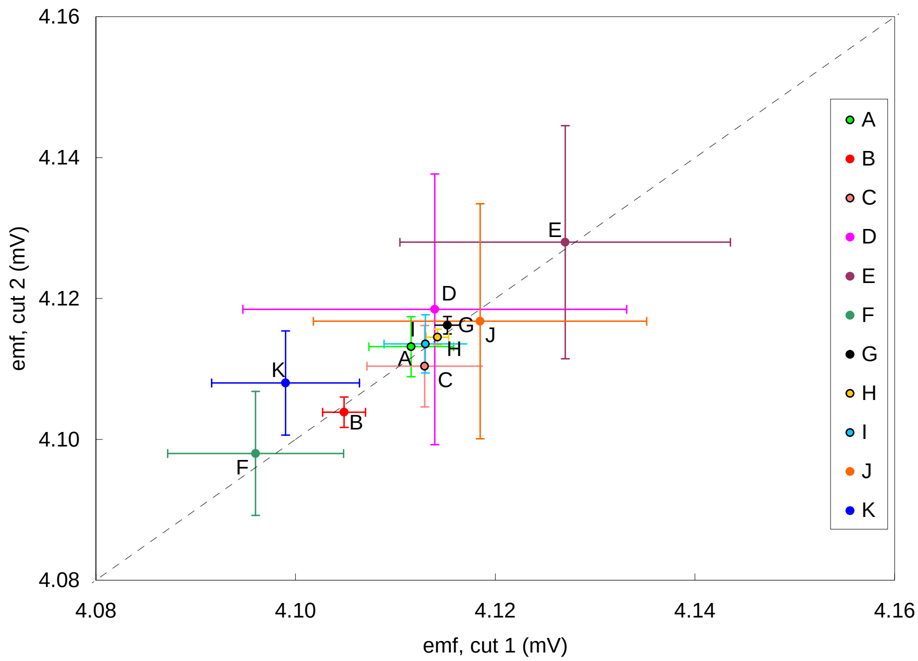

Fig. 14. Youden plot for a nominal test temperature of 100 °C. The bars are k=1 standard uncertainties including only the calibration uncertainty of each laboratory for one cut of wire and the thermocouple inhomogeneity.

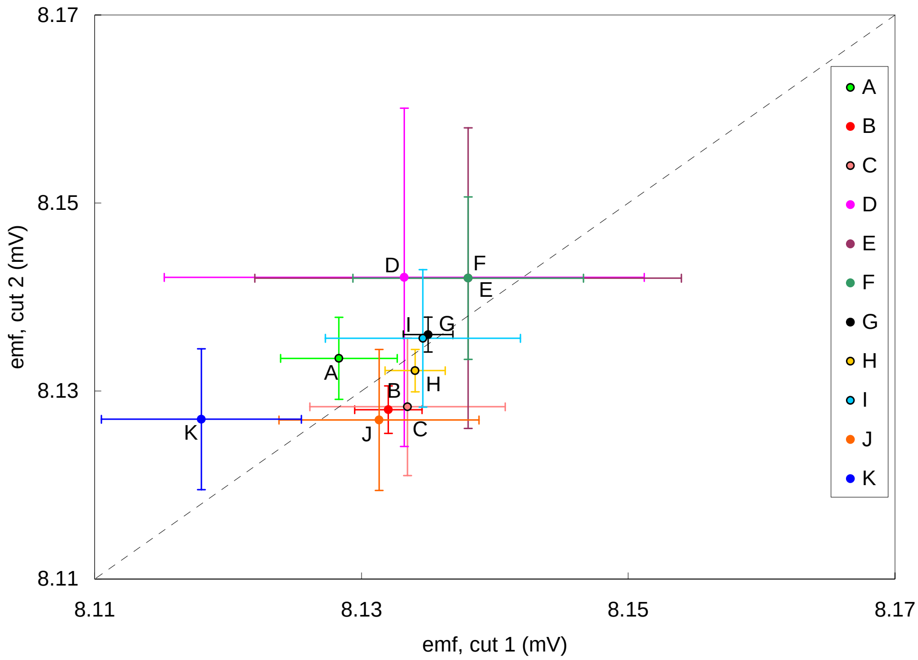

Fig. 15. Youden plot for a nominal test temperature of 200 °C. The bars are k=1 standard uncertainties including only the calibration uncertainty of each laboratory for one cut of wire and the thermocouple inhomogeneity.

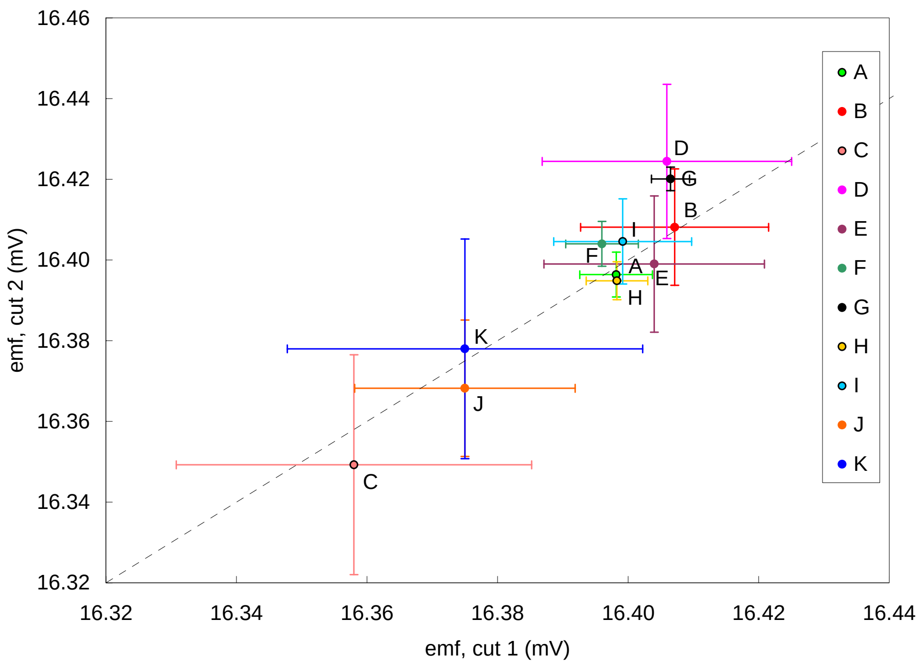

Fig. 16. Youden plot for a nominal test temperature of 400 °C. The bars are k=1 standard uncertainties including only the calibration uncertainty of each laboratory for one cut of wire and the thermocouple inhomogeneity.

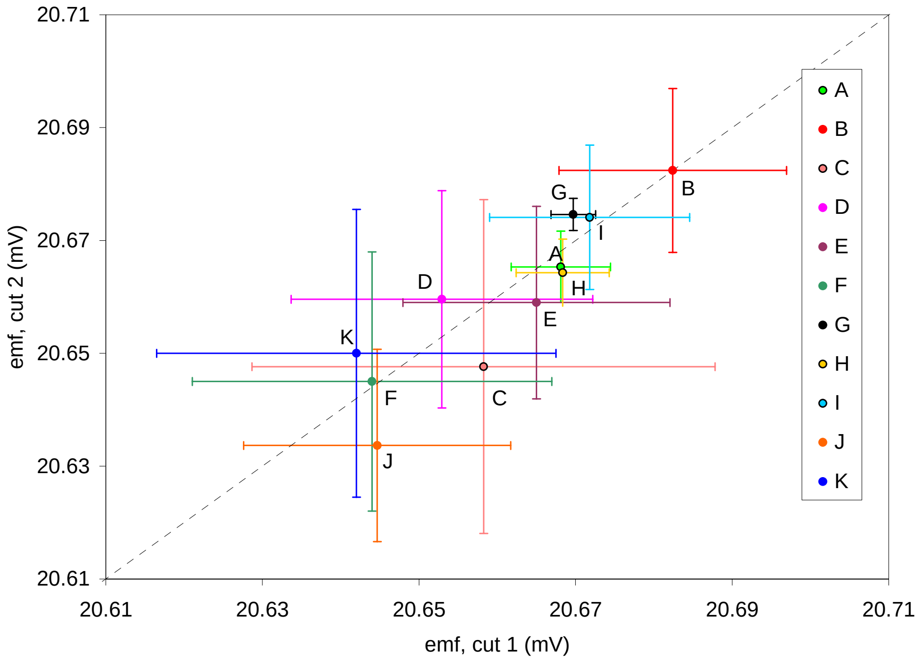

Fig. 17. Youden plot for a nominal test temperature of 500 °C. The bars are *k*=1 standard uncertainties including only the calibration uncertainty of each laboratory for one cut of wire and the thermocouple inhomogeneity.

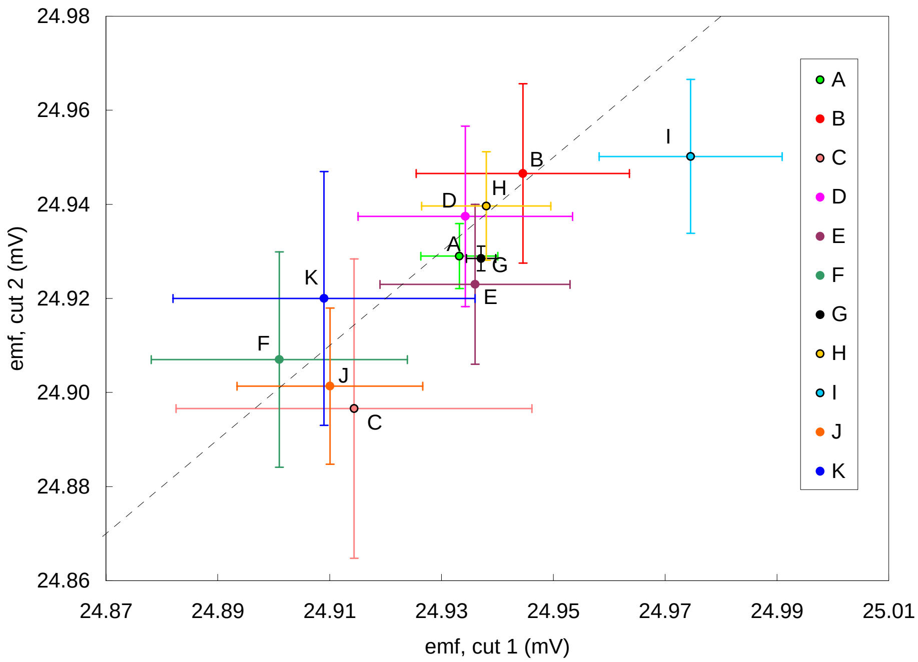

Fig. 18. Youden plot for a nominal test temperature of 600 °C. The bars are *k*=1 standard uncertainties including only the calibration uncertainty of each laboratory for one cut of wire and the thermocouple inhomogeneity.

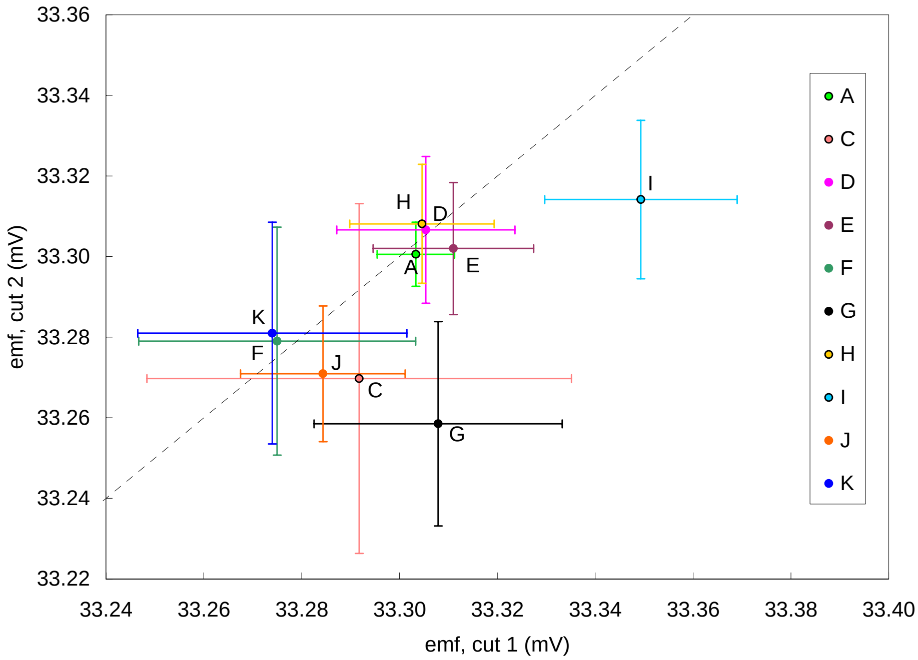

Fig. 19. Youden plot for a nominal test temperature of 800 °C. The bars are k=1 standard uncertainties including only the calibration uncertainty of each laboratory for one cut of wire and the thermocouple inhomogeneity.

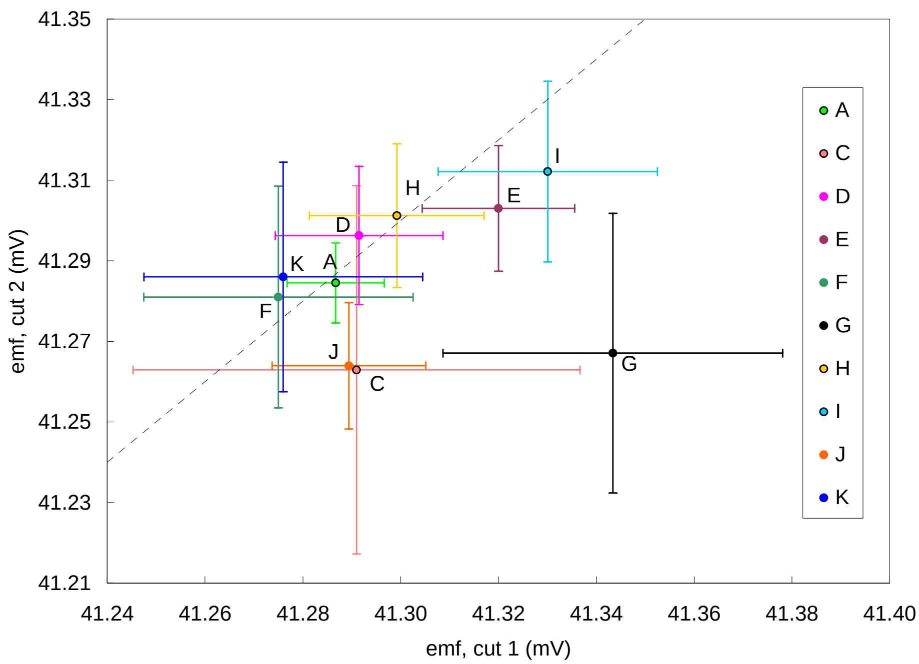

Fig. 20. Youden plot for a nominal test temperature of 1000 °C. The bars are k=1 standard uncertainties including only the calibration uncertainty of each laboratory for one cut of wire and the thermocouple inhomogeneity.

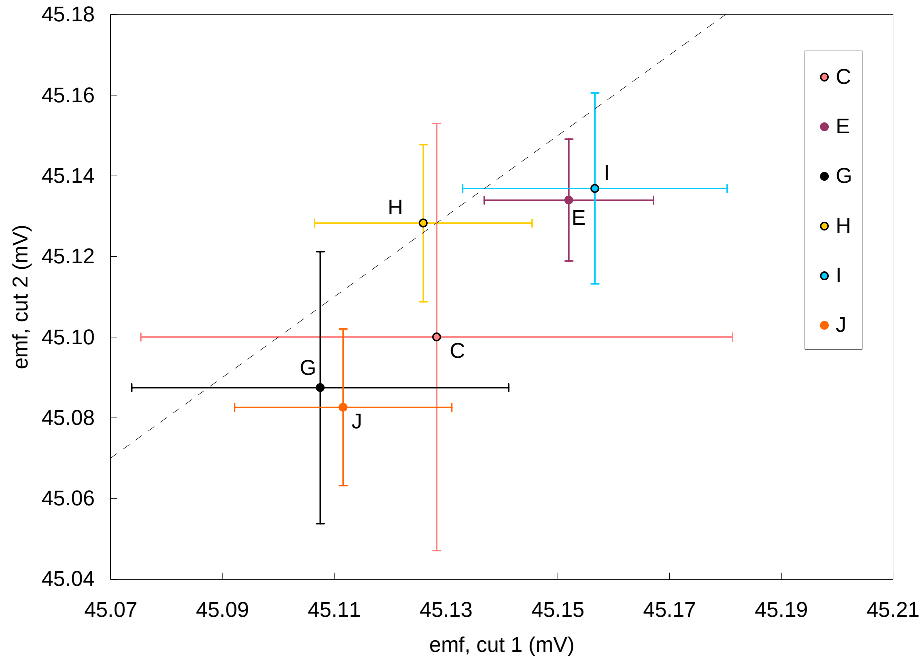

Fig. 21. Youden plot for a nominal test temperature of 1100 °C. The bars are k=1 standard uncertainties including only the calibration uncertainty of each laboratory for one cut of wire and the thermocouple inhomogeneity.

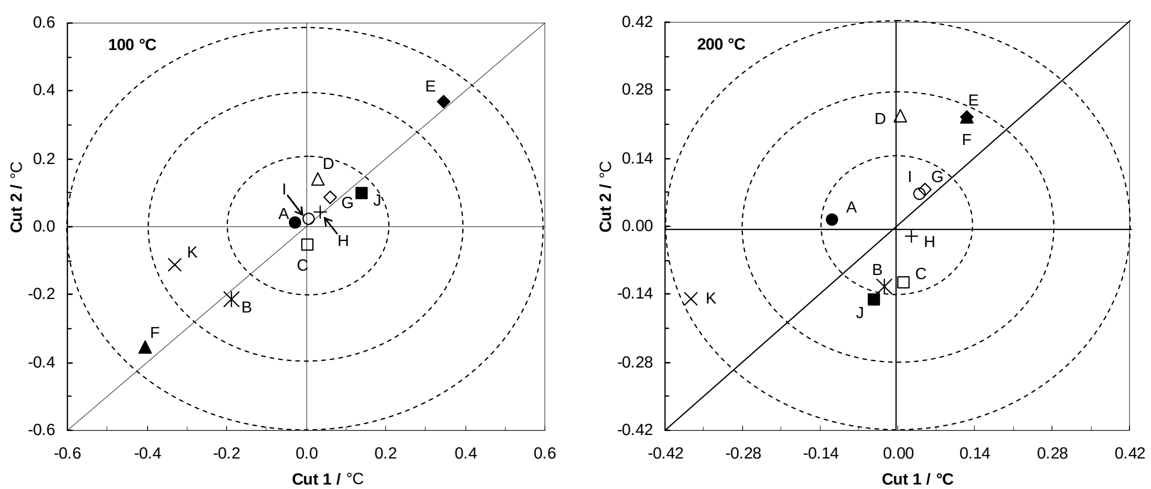

Fig. 22. Concise Youden plots for test temperatures of 100 °C and 200 °C, indicating deviation of the data from the median. The dashed ellipses indicate deviations equivalent to one, two, and three standard deviations of the calibration data.

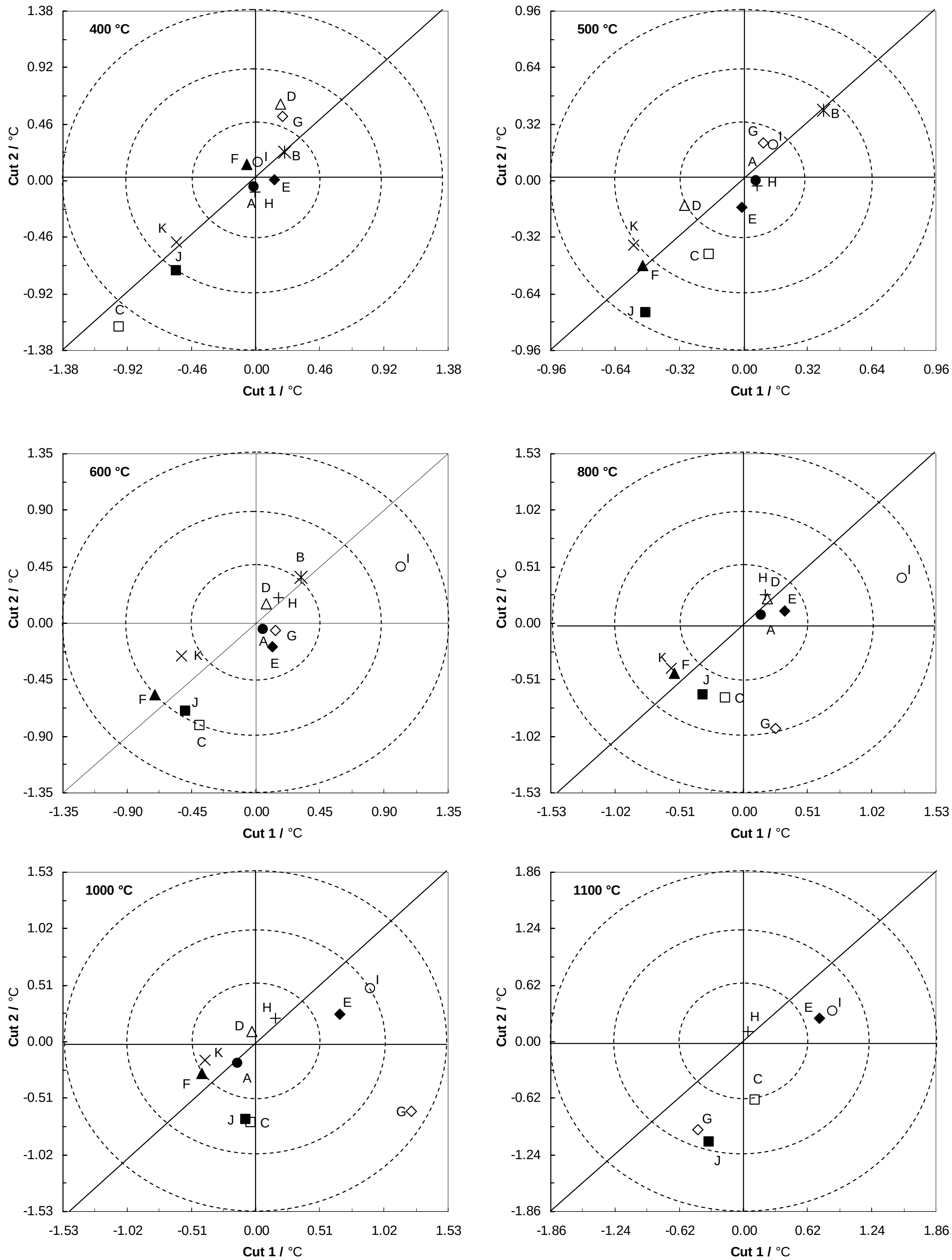

Fig. 23. Concise Youden plots for test temperatures of 400 °C through 1100 °C, indicating deviation of the data from the median. The dashed ellipses indicate deviations equivalent to one, two, and three standard deviations of the calibration data.

Discussion of Results

The level of agreement in this comparison is quite good. Of the 380 possible bilateral combinations of the data, only 13 (i.e., 3.4 % of all combinations) are outside the $k = 2$ limits, and of these 13, only 3 are outside $k = 3$ limits. All of the outliers occur at temperatures of 800 °C and below, which suggests that drift of the type K wire due to high-temperature oxidation did not cause changes in thermocouple emf comparable to or larger than the claimed uncertainties.

References

1. G.W. Burns and M.G. Scroger, "The Calibration of Thermocouples and Thermocouple Materials," NIST Special Publication 250-35, U.S. Govt. Printing Office, Washington, D.C., 1989, 200 pp.
2. 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.
3. M.G. Cox, *Metrologia* **39**, 589-595 (2002).

Appendix A. Protocol

[Two appendices of the Protocol, giving blank templates for reporting of results and for survey responses have been deleted, since this information is duplicated elsewhere in this report.]

Protocol for the SIM Supplemental Comparison for
Type K Thermocouples from 0 °C to 1100 °C

The SIM Supplementary Comparison will be coordinated by NIST. Participant information is as follows:

NIST	Contact: Karen Garrity
100 Bureau Dr.	Phone: 301 975 4818
MS 8363	Fax: 301 548 0206
Gaithersburg, MD 20899-8363	E-mail: kgarrity@nist.gov

Participating Laboratories:

Argentina: M. Jimenez R., Instituto Nacional de Tecnologia Industrial CEFIS, chclo@inti.gov.ar

Bolivia: Ing. Juan Carlos Castillo Villaroel, Instituto Boliviano de Metrologia, IBMETRO, ibmetro_bo@yahoo.com

Brazil: Sr. Slavolhub Garcia Petkovic, Laboratorio Nacional de Metrologia, LNM/ INMETRO, sgpetkovic@inmetro.gov.br

Canada: Dr. Ken Hill, National Research Council Canada, ken.hill@nrc.ca

Chile: Eng. Raul Nunes Brantes, Instituto Nacional de Normalizacion (INN), raul.nunez@inn.ci

El Salvador: Myrna Evelyn de Vanegas, CONACYT, evanegas@conacyt.gob.sv

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

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

Uruguay: Ing. Quim. Luis Mussio, Laboratorio Tecnologico del Uruguay (LATU), lmussio@latu.org.uy

USA: Karen Garrity, National Institute of Standards and Technology (NIST), kgarrity@nist.gov

The instructions and procedures given below must be followed by the participants for the comparison of calibrations of type K thermocouples. By the declared acceptance of this protocol, 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.

The range of temperature covered in this comparison is from 0 °C to 1100 °C. NIST will perform a lot calibration of a 60 m segment of type K thermocouple wire, consisting of a KP and KN thermoelement. Each laboratory will receive two samples of this lot, cut from different sections of the 60 m length. Return of the thermoelements to NIST will only be requested in the event of anomalous results.

Transfer artifacts

The type K thermocouples will be shipped to the participating laboratories in May, 2004. Each laboratory will have a period of 8 weeks to complete calibrations of the thermocouples and to send the results in the form of a calibration certificate to NIST.

Technical Instructions

1. 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 in shipping, new wires should be requested.

2. The two thermoelements of each thermocouple will be sent to each laboratory unjoined, as the welding capability will be part of the test. If a laboratory indicates on the survey that they do not have welding capability, the NIST Thermometry Group will join the wires prior to shipment.

3. The proficiency test will be conducted over the range of 0 to 1100 ºC; however, laboratories will not be expected to calibrate the thermocouples outside of their 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. 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. If a participating laboratory feels that any of their results are problematic for any reason or the thermocouple(s) was somehow damaged please let NIST know as soon as possible and a new cut of wire will be shipped to that laboratory. Please do not wait until the 8 week test period has been completed.

4. It is anticipated that participants will calibrate the thermocouples by comparison methods. If fixed-point cells are routinely used in your laboratory for the calibration of type K thermocouples, discuss your procedures with the NIST contact prior to beginning the test. A revised spreadsheet for the uncertainty budget will be used in this case.

5. The thermocouples are to be calibrated at the series of temperatures with increasing temperature. The test is considered destructive, and only the emf values at the time of first heating will be used in analysis of the comparison results. If it is standard practice for a laboratory to make additional measurements (as the thermocouple is brought back to room temperature, for example) that data may be included in the calibration report.

6. The thermocouples should be retained until completion of the comparison.

Reporting of Data

The participating laboratories must submit the following:

1. The Excel data file listed in Appendix A.1 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 A.2 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 measured temperatures. 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 A.1 (accompanying Excel file) gives a list of each uncertainty component to be considered.

Prior to the start of the comparison, the thermocouple wire will be extensively tested by NIST for lot homogeneity and drift during calibration.

The uncertainty of the comparison for each temperature value will be derived from:

1. the calibration uncertainties estimated by NIST,
2. the calibration uncertainties estimated by each of the other participating laboratories,
3. the effect of combining the measurement results of the type K transfer artifacts to determine one bilateral difference between two non-NIST laboratories at each test temperature,
4. and the uncertainty of the type K transfer artifacts (method of calculation to be agreed on by the participants after completion of the measurements)

Determination and Reporting of Results

The wire lot will be extensively tested by NIST prior to shipment, including tests on lot homogeneity and drift during calibration. Up to 500 °C, several samples will be calibrated both by comparison with a type S thermocouple and by comparison with an SPRT in stirred-liquid baths. Because of this high degree of redundancy, we anticipate using the NIST data as the reference value for the comparison. It is anticipated that lot homogeneity and drift will be significant components in the overall uncertainty budget.

The measurement results and associated uncertainties for the two type K thermocouples tested by each laboratory will be combined for each participating laboratory to generate only one average emf and associated uncertainty for each test temperature. Corrections may be made at NIST for variations of the emf versus temperature response of the thermocouples as a function of cut number, if such a variation is clearly observed in the initial lot calibration and is a sufficiently smooth function of cut number. One method of examining the data will be with Youden Diagrams.

After the data is analyzed, significant discrepancies between the two tested thermocouples 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."

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 NIST reference value.

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

The results of this comparison will be published in two forms. First, the results will be published giving 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.1 Results Form

Please place your responses in the green boxes.

Name of laboratory	
Date spreadsheet was filled out	
Name of technical contact filling out survey	

Thermocouple emf at the time of first heating

	Cut number			
temperature / °C	Emf / mV	U(k=2) / mV	Emf / mV	U(k=2) / mV
100				
200				
400				
500				
600				
800				
1000				
1100				

Appendix A.2 Survey Form

Please place your responses in the green boxes.

Name of laboratory	
Date survey was filled out	
Name of technical contact filling out survey	
Phone number of technical contact	
Fax number of technical contact	
E-mail of technical contact	

1. Basic Methods

Do you perform calibrations by a comparison method? ______ (y/n)

If yes, please fill in the following information

1a. Type of reference thermometer (e.g., type S TC) ______

1b. Type of furnace or bath, and temperature range of each

type	temperature range	thermocouple immersion in furnace/bath

1c. Is an isothermal block used? ______ (y/n)

1d. Are the test thermocouples thermally anchored to the reference thermometer? ______ (y/n)

Do you perform calibrations at fixed points? ______ (y/n)

Reference Junctions

1f. Type of reference junction bath (ice/water in Dewar, electronic compensation, refrigerator) ______

1g. Thermocouple immersion into bath (cm) ______

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 service. Enter component uncertainties in units of equivalent temperature, at a confidence level of *k* =1.

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
Reference thermometer calibration								
Reference thermometer drift								
Reference thermometer repeatability								
Reference thermometer readout								
Test thermocouple repeatability								
Test thermocouple readout								
Test thermocouple inhomogeneity								
Test thermocouple stability								
Reference junction temperature uncertainty								
Bath or furnace temperature stability								
Bath or furnace temperature non-uniformity								
Extraneous emf of wiring, scanners, etc.								

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

3. Thermal history

3a. Please describe, approximately, the duration and temperature for each exposure of the test thermocouple to temperatures above 100 °C

(An alternative description in words is acceptable.)

temperature of exposure / °C	duration / minutes

4. Immersion history

4a. Please describe, in words, whether the test thermocouple is kept at a single, fixed immersion through the test, or whether the immersion of the thermocouple varies throughout the test.

Appendix B. Survey Responses

A summary of the responses of the laboratories to the survey on test methods is given on the following pages.

Name of laboratory **CENAM**

Comparison apparatus

Furnace or bath type	Reference thermometer	Lower temp. (°C)	Upper temp. (°C)	TC immersion (cm)	Isothermal block	Test and reference thermally anchored?
Three-zone furnace	type S thermocouple	100	700	45	yes	no
Heat-pipe furnace	type S thermocouple	700	1000	45	yes	no

Reference junctions

Type of reference junction bath	Thermocouple immersion (cm)
Ice/water in Dewar	10

Thermal history

Temperature of exposure (°C)	Duration (min)	Immersion (cm)
100		45
200	150	45
300	165	45
400	200	45
500	1040	45
600	205	45
700	155	45
800	125	45
900	160	45
1000	180	45

Name of laboratory **CENAM**

Uncertainty components (k=1), (°C)				**Test temperature**			
	100 °C	**200 °C**	**400 °C**	**500 °C**	**600 °C**	**800 °C**	**1000 °C**
Reference thermometer calibration	0.058	0.058	0.058	0.058	0.058	0.058	0.058
Reference thermometer drift	0.055	0.055	0.031	0.031	0.027	0.027	0.082
Reference thermometer repeatability	0.005	0.005	0.021	0.021	0.005	0.005	0.084
Reference thermometer readout	0.013	0.025	0.034	0.048	0.060	0.038	0.075
Test thermocouple repeatability	0.008	0.003	0.024	0.024	0.028	0.030	0.003
Test thermocouple readout	0.011	0.012	0.022	0.027	0.033	0.045	0.059
Test thermocouple inhomogeneity	0.025	0.045	0.075	0.095	0.115	0.150	0.185
Test thermocouple stability	0.004	0.008	0.007	0.009	0.009	0.010	0.010
Reference junction temperature uncertainty	0.005	0.005	0.005	0.005	0.005	0.005	0.005
Bath or furnace temperature stability	0.021	0.015	0.032	0.042	0.040	0.056	0.036
Bath or furnace temperature non-uniformity	0.010	0.010	0.020	0.030	0.030	0.040	0.050
Extraneous emf of wiring, scanners, etc.	0.047	0.049	0.057	0.045	0.030	0.039	0.021
Total expanded uncertainty (k=2), (°C)	**0.205**	**0.218**	**0.263**	**0.298**	**0.324**	**0.387**	**0.510**
Random components of expanded uncertainty (k=2), (°C)	**0.046**	**0.032**	**0.090**	**0.104**	**0.098**	**0.128**	**0.184**

Name of laboratory **CONACYT**

Comparison apparatus

Furnace or bath type	Reference thermometer	Lower temp. (°C)	Upper temp. (°C)	TC immersion (cm)	Isothermal block	Test and reference thermally anchored?
Oil bath	100 ohm PRT	100	200	25	no	no
Furnace	Type S TC	400	650	25	yes	no

Reference junctions

Type of reference junction bath	Thermocouple immersion (cm)
Ice/water in Dewar	23

Thermal history for 200 °C and above

Temperature of exposure (°C)	Duration (min)	Immersion (cm)
200	40	41
400	100	41
500	100	41
650	100	41

Name of laboratory **CONACYT**

Uncertainty components (k=1), (°C)				**Test temperature**	
	100 °C	**200 °C**	**400 °C**	**500 °C**	**650 °C**
Reference thermometer calibration	0.003	0.003	0.110	0.110	0.310
Reference thermometer drift	0.003	0.003			
Reference thermometer repeatability	0.001	0.001	0.040	0.040	0.040
Reference thermometer readout	0.001	0.001	0.030	0.030	0.030
Test thermocouple repeatability					
Test thermocouple readout					
Test thermocouple inhomogeneity					
Test thermocouple stability					
Reference junction temperature uncertainty	0.013	0.013	0.013	0.013	0.013
Bath or furnace temperature stability	0.030	0.030	0.200	0.200	0.200
Bath or furnace temperature non-uniformity	0.030	0.030	0.240	0.240	0.240
Extraneous emf of wiring, scanners, etc.					
Interpolation			0.005	0.005	0.005
Total expanded uncertainty (k=2), (°C)	**0.089**	**0.089**	**0.670**	**0.670**	**0.890**
Random components of expanded uncertainty (k=2), (°C)	**0.060**	**0.027**	**0.065**	**0.065**	**0.065**

Name of laboratory **IBMETRO**

Comparison apparatus

Furnace or bath type	Reference thermometer	Lower temp. (°C)	Upper temp. (°C)	TC immersion (cm)	Isothermal block	Test and reference thermally anchored?
Oil bath	SPRT	100	200	30	yes	no
furnace	Type S TC	400	1100	40	yes	no

Reference junctions

Type of reference junction bath	Thermocouple immersion (cm)
Ice/water in Dewar	20

Thermal history for 200 °C and above

Temperature of exposure (°C)	Duration (min)	Immersion (cm)
200	180	30
300	110	30
400	190	40
600	200	40
800	270	40
1000	250	40
1100	250	40

Name of laboratory **IBMETRO**

Uncertainty components (k=1), (°C)	**Test temperature**							
	100 °C	**200 °C**	**400 °C**	**500 °C**	**600 °C**	**800 °C**	**1000 °C**	**1100 °C**
Reference thermometer calibration	0.005	0.005	0.492	0.492	0.492	0.776	0.776	1.020
Reference thermometer drift	0.006	0.006	0.144	0.144	0.144	0.144	0.144	0.144
Reference thermometer repeatability	0.006	0.006	0.100	0.100	0.100	0.100	0.100	0.100
Reference thermometer readout	0.039	0.044	0.240	0.289	0.336	0.428	0.515	0.560
Test thermocouple repeatability	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100
Test thermocouple readout	0.027	0.029	0.032	0.033	0.038	0.046	0.054	0.060
Test thermocouple inhomogeneity	0.067	0.133	0.265	0.332	0.398	0.532	0.667	0.734
Test thermocouple stability	0.007	0.014	0.029	0.036	0.043	0.058	0.072	0.079
Reference junction temperature uncertainty	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004
Bath or furnace temperature stability	0.016	0.016	0.026	0.026	0.026	0.026	0.026	0.026
Bath or furnace temperature non-uniformity	0.006	0.006	0.032	0.032	0.032	0.062	0.107	0.107
Extraneous emf of wiring, scanners, etc.	0.049	0.051	0.021	0.020	0.020	0.019	0.017	0.017
Total expanded uncertainty (k=2), (°C)	**0.279**	**0.366**	**1.289**	**1.387**	**1.497**	**2.117**	**2.345**	**2.797**
Random components of expanded uncertainty (k=2), (°C)	**0.203**	**0.203**	**0.288**	**0.288**	**0.288**	**0.288**	**0.288**	**0.288**

Name of laboratory **INMETRO**

Comparison apparatus

Furnace or bath type	Reference thermometer	Lower temp. (°C)	Upper temp. (°C)	TC immersion (cm)	Isothermal block	Test and reference thermally anchored?
Tube furnace	Type S TC	100	1000	35	no	no

Reference junctions

Type of reference junction bath	Thermocouple immersion (cm)
Ice/water in Dewar	25

Thermal history for 200 °C and above

Temperature of exposure (°C)	Duration (min)	Immersion (cm)
200	30 to 60	35
400	30 to 60	35
500	30 to 60	35
600	30 to 60	35
800	30 to 60	35
1000	30 to 60	35

Name of laboratory	**INMETRO**						
Uncertainty components (k=1), (°C)				**Test temperature**			
	100 °C	**200 °C**	**400 °C**	**500 °C**	**600 °C**	**800 °C**	**1000 °C**
Reference thermometer calibration	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Reference thermometer drift							
Reference thermometer repeatability							
Reference thermometer readout	0.011	0.009	0.008	0.008	0.007	0.007	0.008
Test thermocouple repeatability	0.075	0.075	0.15	0.15	0.15	0.15	0.15
Test thermocouple readout	0.002	0.002	0.002	0.002	0.002	0.002	0.003
Test thermocouple inhomogeneity							
Test thermocouple stability							
Reference junction temperature uncertainty	0.003	0.003	0.003	0.003	0.003	0.003	0.003
Bath or furnace temperature stability	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Bath or furnace temperature non-uniformity	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Extraneous emf of wiring, scanners, for reference	0.248	0.217	0.173	0.173	0.173	0.158	0.145
Extraneous emf of wiring, scanners for test	0.041	0.043	0.041	0.040	0.040	0.042	0.044
Reference junction temp. uncert. for refer. Therm.	0.002	0.002	0.002	0.002	0.002	0.002	0.001
Total expanded uncertainty (k=2), (°C)	**0.93**	**0.90**	**0.90**	**0.90**	**0.90**	**0.88**	**0.88**
Random components of expanded uncertainty (k=2), (°C)	**0.19**	**0.19**	**0.32**	**0.32**	**0.32**	**0.32**	**0.32**

Name of laboratory **INTI**

Comparison apparatus

Furnace or bath type	Reference thermometer	Lower temp. (°C)	Upper temp. (°C)	TC immersion (cm)	Isothermal block	Test and reference thermally anchored?
Furnace	Type S TC	100	1100	41	yes	no

Reference junctions

Type of reference junction bath	Thermocouple immersion (cm)
Ice/water in Dewar	14

Thermal history for 200 °C and above

Temperature of exposure (°C)	Duration (min)	Immersion (cm)
200	105	41
300	105	41
400	105	41
600	105	41
800	105	41
1000	105	41
1100	105	41

Name of laboratory **INTI**

Uncertainty components (k=1), (°C)

	Test temperature							
	100 °C	**200 °C**	**400 °C**	**500 °C**	**600 °C**	**800 °C**	**1000 °C**	**1100 °C**
Reference thermometer calibration	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Reference thermometer drift	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Reference thermometer repeatability	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Reference thermometer readout	0.06	0.06	0.06	0.06	0.06	0.06	0.08	0.08
Test thermocouple repeatability	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Test thermocouple readout	0.02	0.02	0.03	0.03	0.03	0.04	0.05	0.06
Test thermocouple inhomogeneity	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Test thermocouple stability	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23
Reference junction temperature uncertainty	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Bath or furnace temperature stability	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Bath or furnace temperature non-uniformity	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Extraneous emf of wiring, scanners, etc.								
Heat flux through cold junction of test thermometer	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Total expanded uncertainty (k=2), (°C)	**0.82**	**0.82**	**0.82**	**0.82**	**0.82**	**0.83**	**0.83**	**0.84**
Random components of expanded uncertainty (k=2), (°C)	**0.24**	**0.24**	**0.24**	**0.24**	**0.24**	**0.24**	**0.24**	**0.24**

Name of laboratory **LATU**

Comparison apparatus

Furnace or bath type	Reference thermometer	Lower temp. (°C)	Upper temp. (°C)	TC immersion (cm)	Isothermal block	Test and reference thermally anchored?
Oil bath	SPRT	100	200	40	no	no
Dry-well block	SPRT	400	400	15	yes	no
Tube furnace	Type S TC	500	1000	60	yes	no

Reference junctions

Type of reference junction bath	Thermocouple immersion (cm)
Ice/water in Dewar	10

Thermal history for 200 °C and above

Temperature of exposure (°C)	Duration (min)	Immersion (cm)
200	30	40
400	30	15
500	480	60
600	480	60
800	480	60
1000	480	60

Name of laboratory **LATU**

Uncertainty components (k=1), (°C)				**Test temperature**			
	100 °C	**200 °C**	**400 °C**	**500 °C**	**600 °C**	**800 °C**	**1000 °C**
Reference thermometer calibration	0.003	0.003	0.002	0.200	0.200	0.200	0.200
Reference thermometer drift	0.001	0.001	0.003	0.300	0.300	0.300	0.300
Reference thermometer repeatability	0.000	0.000	0.002	0.005	0.001	0.011	0.005
Reference thermometer readout	0.000	0.000	0.000	0.005	0.005	0.005	0.005
Test thermocouple repeatability	0.006	0.016	0.040	0.012	0.025	0.026	0.150
Test thermocouple readout	0.016	0.016	0.016	0.016	0.016	0.016	0.016
Test thermocouple inhomogeneity	not tested	not tested	not tested	not tested	not tested	not tested	not tested
Test thermocouple stability	not tested	not tested	not tested	not tested	not tested	not tested	not tested
Reference junction temperature uncertainty	0.200	0.200	0.200	0.200	0.200	0.200	0.200
Bath or furnace temperature stability	0.010	0.010	0.010	0.250	0.250	0.500	0.500
Bath or furnace temperature non-uniformity	0.050	0.050	0.255	0.015	0.015	0.015	0.015
Extraneous emf of wiring, scanners, etc.	0.024	0.024	0.024	0.100	0.100	0.100	0.100
Multimeter was used to measure both test TCs	0.001	0.003	0.003	0.003	0.004	0.006	0.007
Uncertainty due to regression analysis	0.036	0.036	0.036	0.208	0.208	0.208	0.208
Total expanded uncertainty (k=2), (°C)	**0.422**	**0.423**	**0.659**	**1.070**	**1.071**	**1.378**	**1.409**
Random components of expanded uncertainty (k=2), (°C)	**0.023**	**0.038**	**0.083**	**0.501**	**0.502**	**1.002**	**1.044**

Name of laboratory **LCPNT**

Comparison apparatus

Furnace or bath type	Reference thermometer	Lower temp. (°C)	Upper temp. (°C)	TC immersion (cm)	Isothermal block	Test and reference thermally anchored?
Oil bath	SPRT	100	200	35	no	no
Vertical furnace	SPRT	400	600	40	yes	no
Tube furnace	Type S TC	800	1100	30	yes	no

Reference junctions

Type of reference junction bath	Thermocouple immersion (cm)
Ice/water in Dewar	16

Thermal history for 200 °C and above

Temperature of exposure (°C)	Duration (min)	Immersion (cm)
200	140	35
400	140	40
500	160	40
600	160	40
800	160	60
1000	160	60
1100	160	60

Name of laboratory **LCPNT**

Uncertainty components (k=1), (°C)				**Test temperature**				
	100 °C	**200 °C**	**400 °C**	**500 °C**	**600 °C**	**800 °C**	**1000 °C**	**1100 °C**
Reference thermometer calibration	0.002	0.002	0.002	0.003	0.003	0.300	0.500	0.500
Reference thermometer drift	0.002	0.002	0.002	0.003	0.003	0.300	0.500	0.500
Reference thermometer repeatability	0.000	0.000	0.000	0.000	0.000	0.010	0.010	0.010
Reference thermometer readout	0.000	0.000	0.000	0.000	0.000	0.007	0.007	0.007
Test thermocouple repeatability	0.001	0.001	0.001	0.001	0.001	0.003	0.003	0.003
Test thermocouple readout	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007
Test thermocouple inhomogeneity	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Test thermocouple stability	0.010	0.010	0.015	0.015	0.015	0.025	0.025	0.025
Reference junction temperature uncertainty	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
Bath or furnace temperature stability	0.002	0.002	0.006	0.006	0.006	0.200	0.200	0.200
Bath or furnace temperature non-uniformity	0.003	0.003	0.016	0.016	0.016	0.400	0.500	0.500
Extraneous emf of wiring, scanners, etc.	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.001
Total expanded uncertainty (k=2), (°C)	**0.026**	**0.026**	**0.048**	**0.049**	**0.049**	**1.234**	**1.779**	**1.779**
Random components of expanded uncertainty (k=2), (°C)	**0.004**	**0.004**	**0.012**	**0.012**	**0.012**	**0.401**	**0.401**	**0.401**

Name of laboratory **NIST**

Comparison apparatus

Furnace or bath type	Reference thermometer	Lower temp. (°C)	Upper temp. (°C)	TC immersion (cm)	Isothermal block	Test and reference thermally anchored?
Oil bath	SPRT	100	200	30	no	no
Salt bath	SPRT	400	500	30	no	no
Tube furnace	Type S TC	200	1000	30	no	yes

Reference junctions

Type of reference junction bath	Thermocouple immersion (cm)
Ice/water in Dewar	20

Thermal history for 200 °C and above

Temperature of exposure (°C)	Duration (min)	Immersion (cm)
200	30	30
400	30	30
500	30	30
600	45	30
800	45	30
1000	45	30
1100	45	30

Name of laboratory **NIST**

Uncertainty components (k=1), (°C)	**Test temperature**							
	100 °C	**200 °C**	**400 °C**	**500 °C**	**600 °C**	**800 °C**	**1000 °C**	**1100 °C**
Reference thermometer calibration	0.001	0.001	0.001	0.001	0.067	0.067	0.067	0.076
Reference thermometer drift	0.000	0.000	0.000	0.000	0.121	0.121	0.106	0.094
Reference thermometer repeatability	Note 1							
Reference thermometer readout	0.000	0.000	0.000	0.000	0.017	0.019	0.021	0.022
Test thermocouple repeatability	Note 1							
Test thermocouple readout	0.001	0.002	0.004	0.005	0.006	0.008	0.011	0.012
Test thermocouple inhomogeneity	0.027	0.045	0.066	0.057	0.044	0.048	0.048	0.056
Test thermocouple stability	0.000	0.011	0.09	0.127	0.166	0.252	0.350	0.404
Reference junction temperature uncertainty	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Bath or furnace temperature stability	Note 1							
Bath or furnace temperature non-uniformity	0.001	0.001	0.003	0.003	0.157	0.210	0.262	0.288
Extraneous emf of wiring, scanners, for reference	0.003	0.003	0.003	0.003	0.010	0.010	0.010	0.010

Note 1: All repeatability and bath/furnace stability components combined in "Test thermocouple inhomogeneity"

Total expanded uncertainty (k=2), (°C)	**0.05**	**0.09**	**0.22**	**0.28**	**0.54**	**0.72**	**0.92**	**1.03**
Random components of expanded uncertainty (k=2), (°C)	**0.05**	**0.09**	**0.13**	**0.11**	**0.09**	**0.10**	**0.10**	**0.11**

Name of laboratory **NRC**

Comparison apparatus

Furnace or bath type	Reference thermometer	Lower temp. (°C)	Upper temp. (°C)	TC immersion (cm)	Isothermal block	Test and reference thermally anchored?
Oil Bath	SPRT	100	200	25	no	no
Salt Bath	SPRT	400	500	25	no	no
3-zone furnace	type S TC	600	1100	25	yes	no

Reference junctions

Type of reference junction bath	Thermocouple immersion (cm)
Ice/water in Dewar	>20

Thermal history for 200 °C and above

Temperature of exposure (°C)	Duration (min)	Immersion (cm)
200	60	25
400	60	25
500	60	25
600	90	25
800	90	25
1000	90	25
1100	90	25

Name of laboratory **NRC**

Uncertainty components (k=1), (°C)	**Test temperature**							
	100 °C	**200 °C**	**400 °C**	**500 °C**	**600 °C**	**800 °C**	**1000 °C**	**1100 °C**
Reference thermometer calibration	0.0006	0.0006	0.0006	0.0006	0.15	0.15	0.15	0.150
Reference thermometer drift	included above	included above	included above	included above	included above	included above	included above	included above
Reference thermometer repeatability	included above	included above	included above	included above	included above	included above	included above	included above
Reference thermometer readout	included above	included above	included above	included above	0.020	0.020	0.020	0.020
Test thermocouple repeatability								
Test thermocouple readout	0.004	0.005	0.005	0.006	0.006	0.007	0.009	0.009
Test thermocouple inhomogeneity	0.1	0.15	0.25	0.3	0.35	0.45	0.55	0.600
Test thermocouple stability								
Reference junction temperature uncertainty	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
Bath or furnace temperature stability	0.00	0.00	0.01	0.01	0.05	0.05	0.05	0.048
Bath or furnace temperature non-uniformity	0.001	0.002	0.006	0.007	0.048	0.048	0.048	0.048
Extraneous emf of wiring, scanners, for reference	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020
Total expanded uncertainty (k=2), (°C)	**0.20**	**0.30**	**0.50**	**0.60**	**0.77**	**0.96**	**1.15**	**1.25**
Random components of expanded uncertainty (k=2), (°C)	**0.00**	**0.00**	**0.01**	**0.01**	**0.10**	**0.10**	**0.10**	**0.10**

Name of laboratory **SENCAMER**

Comparison apparatus

Furnace or bath type	Reference thermometer	Lower temp. (°C)	Upper temp. (°C)	TC immersion (cm)	Isothermal block	Test and reference thermally anchored?
Oil Bath	type S TC	100	200	15	yes	no
Tubular Furnace	type S TC	400	1100	37	yes	no

Reference junctions

Type of reference junction bath	Thermocouple immersion (cm)
Ice/water in Dewar	15

Thermal history for 200 °C and above

Temperature of exposure (°C)	Duration (min)	Immersion (cm)
200	60	15
400	120	37
500	120	37
600	120	37
800	120	37
1000	120	37
1100	120	37

Name of laboratory **SENCAMER**

Uncertainty components (k=1), (°C)				**Test temperature**				
	100 °C	**200 °C**	**400 °C**	**500 °C**	**600 °C**	**800 °C**	**1000 °C**	**1100 °C**
Reference thermometer calibration	0.250	0.250	0.250	0.250	0.250	0.250	0.250	0.400
Reference thermometer drift	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050
Reference thermometer repeatability	0.011	0.005	0.003	0.032	0.028	0.066	0.035	0.031
Reference thermometer readout	0.302	0.267	0.247	0.244	0.242	0.238	0.235	0.235
Test thermocouple repeatability	0.005	0.006	0.006	0.027	0.047	0.122	0.091	0.094
Test thermocouple readout	0.066	0.075	0.084	0.085	0.091	0.106	0.123	0.132
Test thermocouple inhomogeneity								
Test thermocouple stability								
Reference junction temperature uncertainty	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029
Bath or furnace temperature stability	0.010	0.010	0.115	0.115	0.115	0.115	0.115	0.115
Bath or furnace temperature non-uniformity	0.010	0.010	0.020	0.020	0.020	0.020	0.020	0.020
Extraneous emf of wiring, scanners, for reference	0.014	0.014	0.014	0.014	0.014	0.014	0.015	0.015
Total expanded uncertainty (k=2), (°C)	**0.80**	**0.76**	**0.77**	**0.77**	**0.77**	**0.82**	**0.80**	**1.02**
Random components of expanded uncertainty (k=2), (°C)	**0.03**	**0.03**	**0.23**	**0.24**	**0.25**	**0.36**	**0.30**	**0.30**

Name of laboratory **SNM-INDECOPI**

Comparison apparatus

Furnace or bath type	Reference thermometer	Lower temp. (°C)	Upper temp. (°C)	TC immersion (cm)	Isothermal block	Test and reference thermally anchored?
Oil Bath	SPRT	100	200	25	yes	no
Tubular Furnace	type S TC	400	1000	25	yes	no

Reference junctions

Type of reference junction bath	Thermocouple immersion (cm)
Ice/water in Dewar	20

Thermal history for 200 °C and above

Temperature of exposure (°C)	Duration (min)	Immersion (cm)
200	60	25
400	60	25
500	60	25
600	60	25
800	60	25
1000	60	25

Name of laboratory **SNM-INDECOPI**

Uncertainty components (k=1), (°C)	**Test temperature**							
	100 °C	**200 °C**	**400 °C**	**500 °C**	**600 °C**	**800 °C**	**1000 °C**	**1100 °C**
Reference thermometer calibration	0.005	0.005	0.135	0.135	0.139	0.144	0.144	
Reference thermometer drift	0.005	0.005	0.150	0.150	0.180	0.200	0.250	
Reference thermometer repeatability	0.003	0.003	0.100	0.100	0.100	0.100	0.100	
Reference thermometer readout	0.000	0.000	0.029	0.029	0.029	0.029	0.029	
Test thermocouple repeatability	0.033	0.012	0.048	0.025	0.058	0.038	0.024	
Test thermocouple readout	0.007	0.007	0.007	0.007	0.007	0.007	0.007	
Test thermocouple inhomogeneity	0.134	0.143	0.048	0.122	0.172	0.106	0.161	
Test thermocouple stability								
Reference junction temperature uncertainty	0.003	0.003	0.003	0.003	0.003	0.003	0.003	
Bath or furnace temperature stability	0.010	0.010	0.200	0.200	0.200	0.200	0.200	
Bath or furnace temperature non-uniformity	0.015	0.015	0.461	0.483	0.501	0.557	0.597	
Extraneous emf of wiring, scanners, for reference	0.100	0.100	0.100	0.100	0.100	0.100	0.100	
Total expanded uncertainty (k=2), (°C)	**0.36**	**0.37**	**1.13**	**1.19**	**1.26**	**1.34**	**1.46**	
Random components of expanded uncertainty (k=2), (°C)	**0.07**	**0.03**	**0.46**	**0.45**	**0.46**	**0.45**	**0.45**	