Bilateral Interlaboratory Comparison

CSIR-NML (South Africa) and QSAE (Ethiopia)

Thermocouple and liquid-in-glass thermometry

Report: draft A

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INTRODUCTION

This report describes the results of a comparison of thermometer calibration capabilities between CSIR-NML (South Africa) and the Quality and Standards Authority of Ethiopia (QSAE). A type K thermocouple was measured from 0 °C to 500 °C and a mercury-in-glass thermometer was measured from 0 °C to 50 °C.

MEASUREMENT PROCEDURE

A mineral-insulated type K thermocouple (sheathed in 446 stainless steel) and a reference junction made of type K extension wire were circulated to the participating laboratories:

Description: MIMS type K thermocouple
Manufacturer: Thermocouple Products
Serial number: K446-6 08-04
Dimensions: 600 mm long, 6 mm diameter
Reference junction: CKY 07-97

The measurement procedure was as follows:

calibrate at 0,50,100,200,250,300,400 and 500°C, taking care not to heat the thermocouple above 520°C.

A mercury-in-glass thermometer was circulated to the participating laboratories:

Description: Solid-stem mercury-in-glass thermometer
Manufacturer: Amarell
Serial number: 21-01
Full range: -10,9°C to 50,5°C
Graduation: 0,1°C
Dimensions: 420 mm long, 6,3 mm diameter

The measurement procedure was as follows:

calibrate at the ice point, 10°C, 20°C, 30°C, 40°C and 50°C, at total immersion.

MEASUREMENT PERIODS

Contact details of the participants:

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Mr Wondwosen Fisseha / Mr Gezahegn Teferi	QSAE	P.O.Box 2310, Addis Ababa	Ethiopia	+251-1-460 542	+251-1-460 880 (81)	wondwosen@qsae.org

Laboratory	Measurement period	
	Type K thermocouple	Mercury-in-glass thermometer
CSIR-NML	22-24 September 2004	29 January 2003, 18 January 2005, 26 August 2005
QSAE	11-14 July 2005	11-14 July 2005

DATA ANALYSIS

Type K thermocouple:

The initial measurements at CSIR-NML were used as the reference values.

The differences Lab Value – Reference Value (LV - RV) were determined as follows:

$$LV - RV = \{V_{NML} - [V_{QSAE} + dV/dt \times (t_{NML} - t_{QSAE})]\} \times dt/dV$$
$$= [V_{NML} - V_{QSAE}] \times dt/dV + [t_{QSAE} - t_{NML}]$$
$$= [V_{NML} - V_{QSAE}] \times [t_{QSAE} - t_{NML}] / [V_{fit}(t_{QSAE}) - V_{fit}(t_{NML})] + [t_{QSAE} - t_{NML}]$$

The curve $V_{fit}(t)$ was determined by fitting a fourth-order polynomial to the deviations of the NML data from the type K reference function,

$$\text{deviation}(t) = V_{measured}(t) - V_{ref\ function}(t).$$

Since

$$V(t) = V_{ref\ function}(t) + \text{deviation}(t),$$

$V_{fit}(t)$ was determined from the fitted deviation polynomial as follows:

$$V_{fit}(t) = V_{ref\ function}(t) + \text{deviation}_{fit}(t).$$

The voltages measured by QSAE and NML were compared directly: only the slope of the fitted curve was used to adjust V_{QSAE} from t_{QSAE} to t_{NML}, and to convert from units of voltage to temperature. In this way, shortcomings in the type K reference function, leading to significant structure in the deviation polynomial and large curve fit residuals, have little effect on the calculated differences LV – RV.

Mercury-in-glass thermometer:
The initial measurements at CSIR-NML were used as the reference values.
The differences Lab Value – Reference Value (LV - RV) were determined as follows:

LV – RV = correction determined at QSAE – correction determined at NML

QSAE's measurements at partial immersion (at 10, 20, 30, 40 and 50 °C) were corrected to total immersion using the following formula:

reading at total immersion = reading at partial immersion + 1.6 x 10^{-4} °C^{-1} x n x (t_{bath} – t_{ELC}),

where n is the length of the emergent liquid column (expressed in number of degrees on the thermometer scale), t_{bath} is the temperature of the calibration bath and t_{ELC} is the average temperature of the emergent liquid column.
The reduced correction, i.e. the difference between the correction at temperature T and the correction at 0°C ($corr_T$ – $corr_{0°C}$), is also reported.

For both the type K thermocouple and the mercury-in-glass thermometer, En values (deviations normalised with respect to the uncertainties of the laboratories) are used to quantify the agreement between the participating laboratory and the reference values:

$En = (LV – RV) / \sqrt{(U_{LV}^2 + U_{RV}^2)}$,

where U_{LV} and U_{RV} are the expanded uncertainties of measurement (k=2).

RESULTS

The type of reference thermometer, heat source and immersion depth (total or partial) used by each laboratory is given in the table below:

Type K thermocouple:

Laboratory	Ref thermometer	Heat source
CSIR-NML	Leeds & Northrup 8167-25 SPRT, Tinsley 5187SA SPRT	Ice point, stirred oil & salt baths
QSAE	Rosemount 162CE SPRT	Ice point, stirred oil & fluidised baths

Mercury-in-glass thermometer:

Laboratory	Ref thermometer	Heat source	Rising / stable temp	Immersion
CSIR-NML	Industrial PRT (4-wire)	Ice point, stirred water bath	Rising	Total
QSAE	Industrial PRT (4-wire)	Ice point, stirred alcohol & water baths	Stable	Total (0°C), partial (other temperatures)

Type K thermocouple:

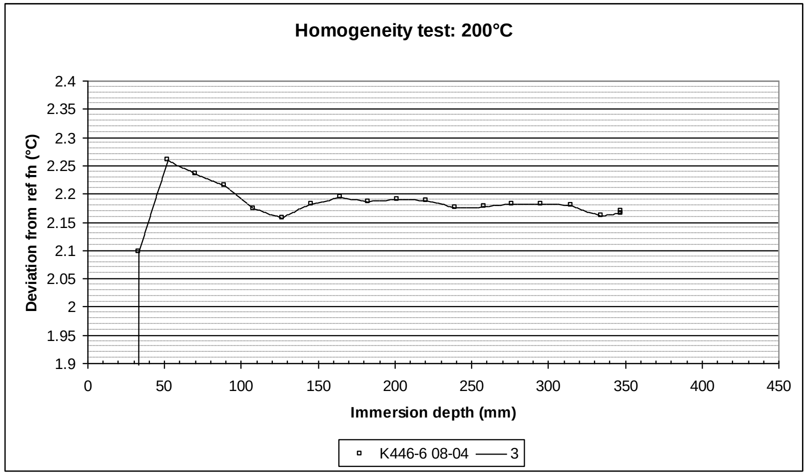
Lab name	LV (°C)	UUT (μV)	Deviation (μV)	dV/dt (μV/°C)	Deviation (°C)	U(k=2) (°C)	LV-RV (°C)	En	Immersion depth of UUT (mm)
NML	0.00	12.0	12.0	39.5	0.31	0.24			180
	50.05	2025.7	0.5	41.2	0.01	0.24			240
	100.00	4123.7	27.5	41.4	0.65	0.24			240
	199.98	8271.5	133.7	40.0	3.29	0.27			240
	251.40	10348.1	137.7	40.7	3.35	0.29			240
	299.09	12302.5	131.8	41.4	3.19	0.31			240
	399.56	16512.7	134.1	42.2	3.20	0.35			240
	499.22	20750.0	138.9	42.6	3.18	0.40			240
QSAE	0.00	15.5	15.5	39.5	0.39	0.05	**-0.09**	-0.36	134
	50.26	2039.7	5.8	41.6	0.14	0.24	**-0.13**	-0.37	135
	99.87	4124.6	33.9	42.2	0.81	0.25	**-0.15**	-0.45	150
	200.10	8280.7	138.1	40.6	3.41	0.26	**-0.10**	-0.28	160
	298.34	12283.2	143.6	41.4	3.44	0.29	**-0.28**	-0.66	340
	399.81	16528.1	138.9	41.9	3.29	0.30	**-0.12**	-0.25	340
	498.49	20737.4	157.4	43.7	3.74	0.31	**-0.44**	-0.87	340

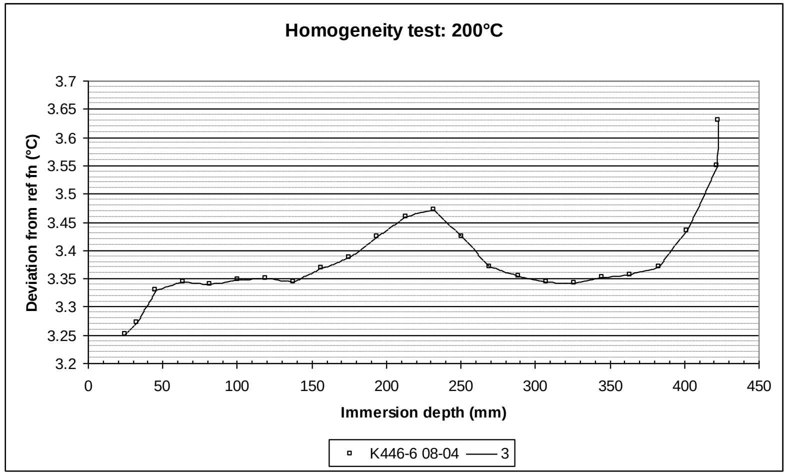
Uncertainty budgets:

CSIR-NML:

Inhomogeneity scans:

The thermoelectric homogeneity of the thermocouple was checked by lowering it into a stirred salt bath (at 200 °C) at 10 mm/minute and observing the variation in generated emf as a function of immersion depth. Scans performed before and after calibration (on 21 and 27 September 2004) are shown below:





The apparent increase in emf at the deepest immersion depths is due to the reference PRT (lowered with the thermocouple, but at 25 mm deeper immersion) being close to the cooler bottom of the bath. The uncertainty component used for inhomogeneity is

$$u(k=1) = [V_{200°C,\max} - V_{200°C,\min}]/[V_{200°C,mean} - V_{20°C}]/2/\sqrt{3} \cdot [V_T - V_{20°C}]$$

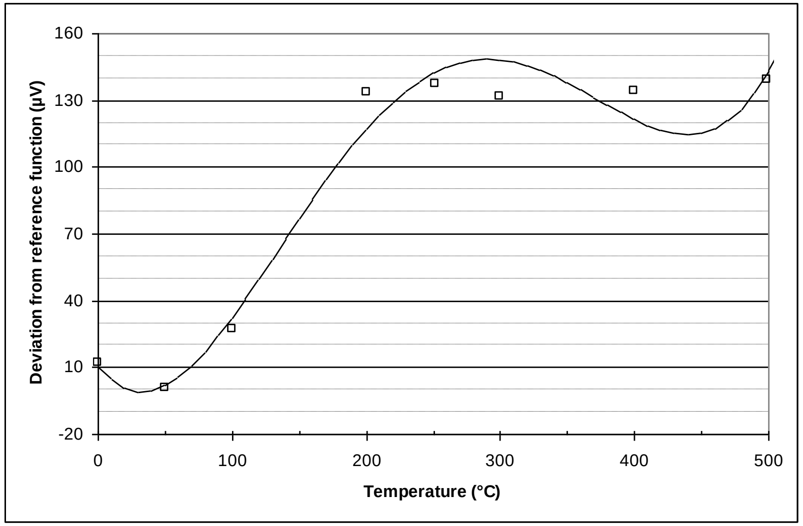
For the scans shown above, the following values were calculated for [$V_{200°C,\ max}$ – $V_{200°C,\ min}$] / [$V_{200°C,\ mean}$ – $V_{20°C}$] / 2

Before calibration: 0.032 % from 50 to 350 mm immersion

After calibration: 0.061 % from 50 to 420 mm immersion (or 0.039 % from 50 to 400 mm; the larger figure is used in the budget, to be conservative)

Curve fit:

The following fourth-order polynomial was fitted to the NML data, by the method of weighted least squares:



As can be seen from the graph, the type K reference function does not represent the behaviour of a real type K thermocouple very well (the deviations do not follow a smooth, simple curve). Even a polynomial of fourth degree produced curve fit residuals (= measured deviation – fitted deviation) up to 0.4 °C. As explained in the data analysis section, only the slope of the fitted voltage vs temperature function (= type K reference function + fitted deviation function) was used in the comparison of results. Considering that the largest difference between t_{QSAE} and t_{NML} is less than 1 °C, the uncertainty component of u(k=1) = 0.2 °C / √3 that was included in the uncertainty budget for non-ideality of the curve fit was conservative.

Extension wire reference junction:

The reference junction used with the type K thermocouple deviated from the type K reference function by 1.3 µV at 21 °C (ambient temperature in the NML lab): this deviation was corrected for in the NML measurements, but not in the QSAE measurements. (It was not specified in the measurement instructions that such a correction was to be applied, so the QSAE procedure of calibrating the thermocouple and reference junction as a system was correct.) For this reason, an uncertainty component of 1.3 µV was included in the NML budget for the deviation of the reference junction from the type K reference function. The deviation of the reference junction from the reference function varies by approximately 0.06 µV/°C around room temperature: assuming that the temperature of the connection between reference junction and thermocouple remains within ± 10 °C of room temperature (it may have been warmed if it was close to a high-temperature bath), an additional uncertainty component of 0.6 µV was included for this possible variation in the emf generated by the reference junction.

Sample uncertainty budgets (type B uncertainties are assigned a large number of degrees of freedom):

t (°C):	**0**					
	Value	Unit	Divisor	Sensitivity coeff	ui(k=1) (°C)	D.o.f.
REFERENCE STANDARD:						
Fixed point:						
Chemical impurity	0.002	°C	1.732	1	**0.001**	500
PRT:						
Calibration of standard thermometer						
Drift of standard thermometer						
Self-heating						
Stability of Rtp						
Uncertainty of reference temperature (WTP or ice point)						
Calibration of measuring instrument						
Specification of measuring instrument						
Reference resistor: calibration						
Reference resistor: temperature coefficient						
Stem conduction						
HEAT SOURCE:						
Temperature difference between std & UUT: horizontal temp gradients						
Control cycle of heat source: Zero if averaged over several cycles						
UNIT UNDER TEST:						
TC:						
Thermoelectric inhomogeneity	6.10E-04	V/V	1.732	-22.28	**-0.008**	500
Uncertainty of reference temperature (ice point or Cold Junction Compensation)	0.01	°C	1.732	1	**0.006**	500
Calibration of measuring instrument	0.03	µV	2.000	0.0253	**0.000**	500
Specification of measuring instrument	0.04	µV	1.732	0.0253	**0.001**	500
Spurious thermal emfs	0.4	µV	1.732	0.0253	**0.006**	500
Curve fit residuals	0.2	°C	1.732	1	**0.115**	500
Compensating wire cold junction	1.4	µV	1.732	0.0253	**0.021**	500
Stem conduction						
Repeatability	0.010	°C	1.000	1	**0.010**	7
Reproducibility		°C	1.000	1	**0.000**	500
uc(k=1) (°C):					0.118	
Effective degrees of freedom					547.6	
Student's t (effective d.o.f.):					2	
U(k=2) (°C):					**0.237**	
U(k=2) (µV):					9.33	

t (°C):	**500**					
	Value	Unit	Divisor	Sensitivity coeff	ui(k=1) (°C)	D.o.f.
REFERENCE STANDARD:						
Fixed point:						
Chemical impurity						
PRT:						
Calibration of standard thermometer	0.0021	°C	2.000	1	**0.001**	500
Drift of standard thermometer	0.0028	°C	1.732	1	**0.002**	500
Self-heating						
Stability of Rtp	0.00053	°C	1.732	2.846	**0.001**	500
Uncertainty of reference temperature (WTP or ice point)	0.0003	°C	2.000	2.846	**0.000**	500
Calibration of measuring instrument						
Specification of measuring instrument	2.00E-07	Ω/Ω	2.000	1185.2	**0.000**	41
Reference resistor: calibration						
Reference resistor: temperature coefficient	0.2	°C	1.732	-5.9E-04	**0.000**	500
Stem conduction		°C	1.732	1	**0.000**	500
HEAT SOURCE:						
Temperature difference between std & UUT: horizontal temp gradients	0.00585	°C	1.732	1	**0.003**	500
Control cycle of heat source: Zero if averaged over several cycles						
UNIT UNDER TEST:						
TC:						
Thermoelectric inhomogeneity	6.10E-04	V/V	1.732	463.67	**0.163**	500
Uncertainty of reference temperature (ice point or Cold Junction Compensation)	0.01	°C	1.732	0.9254	**0.005**	500
Calibration of measuring instrument	0.44	µV	2.000	0.0235	**0.005**	500
Specification of measuring instrument	1.43	µV	1.732	0.0235	**0.019**	500
Spurious thermal emfs	0.4	µV	1.732	0.0235	**0.005**	500
Curve fit residuals	0.2	°C	1.732	1	**0.115**	500
Compensating wire cold junction	1.4	µV	1.732	0.0235	**0.019**	500
Stem conduction		°C	1.732	1	**0.000**	500
Repeatability	0.008	°C	1.000	1	**0.008**	2
Reproducibility		°C	1.000	1	**0.000**	500
uc(k=1) (°C):					0.202	
Effective degrees of freedom					939.8	
Student's t (effective d.o.f.):					2	
U(k=2) (°C):					**0.404**	
U(k=2) (µV):					17.24	

QSAE:

Sample uncertainty budgets:

t (°C):	**0**					
	Value	Unit	Divisor	Sensitivity coeff	ui(k=1) (°C)	D.o.f.
REFERENCE STANDARD:						
Fixed point:						
Chemical impurity						
PRT:						
Calibration of standard thermometer	0.016	°C	2.000	1	**0.008**	500
Drift of standard thermometer	0.0004	°C	1.732	1	**0.000**	500
Self-heating						
Stability of Rtp		°C	1.732	1.000	**0.000**	500
Uncertainty of reference temperature (WTP or ice point)		°C	2.000	1.000	**0.000**	500
Calibration of measuring instrument						
Specification of measuring instrument		ratio W	2.000	250.7	**0.000**	500
Reference resistor: calibration		ratio W	1.732	250.7	**0.000**	500
Reference resistor: temperature coefficient		°C	1.732	9.8E-04	**0.000**	500
Stem conduction		°C	1.732	1	**0.000**	500
HEAT SOURCE:						
Temperature difference between std & UUT: horizontal temp gradients		°C	1.732	1	**0.000**	500
Control cycle of heat source: Zero if averaged over several cycles						
UNIT UNDER TEST:						
TC:						
Thermoelectric inhomogeneity	3.95E-02	°C	1.732	1.00	**0.023**	500
Uncertainty of reference temperature (ice point or Cold Junction Compensation)	0.002	°C	1.732	1	**0.001**	500
Calibration of measuring instrument	0.10	µV	2.000	0.0253	**0.001**	500
Specification of measuring instrument		µV	1.732	0.0253	**0.000**	500
Spurious thermal emfs	0.2	µV	1.732	0.0253	**0.003**	500
Curve fit residuals	0.12	µV	1.732	0.0253	**0.002**	500
Compensating wire cold junction		µV	1.732	0.0253	**0.000**	500
Stem conduction						
Repeatability	0.000	µV	1.000	0.0253	**0.000**	5
Reproducibility		°C	1.000	1	**0.000**	500
uc(k=1) (°C):					0.024	
Effective degrees of freedom					652.7	
Student's t (effective d.o.f.):					2	
U(k=2) (°C):					**0.049**	
U(k=2) (µV):					1.93	

t (°C):	**500**					
	Value	Unit	Divisor	Sensitivity coeff	ui(k=1) (°C)	D.o.f.
REFERENCE STANDARD:						
Fixed point:						
Chemical impurity						
PRT:						
Calibration of standard thermometer	0.016	°C	2.000	1	**0.008**	500
Drift of standard thermometer	0.0025	°C	1.732	1	**0.001**	500
Self-heating						
Stability of Rtp	0	°C	1.732	2.846	**0.000**	500
Uncertainty of reference temperature (WTP or ice point)	0	°C	2.000	2.846	**0.000**	500
Calibration of measuring instrument						
Specification of measuring instrument	2.90E-04	ratio W	2.000	294.1	**0.043**	500
Reference resistor: calibration	0.0008	ratio W	1.732	294.1	**0.136**	500
Reference resistor: temperature coefficient	0	°C	1.732	1.2E-03	**0.000**	500
Stem conduction		°C	1.732	1	**0.000**	500
HEAT SOURCE:						
Temperature difference between std & UUT: horizontal temp gradients	0.1	°C	1.732	1	**0.058**	500
Control cycle of heat source: Zero if averaged over several cycles						
UNIT UNDER TEST:						
TC:						
Thermoelectric inhomogeneity	4.26E-02	°C	1.732	1.00	**0.025**	500
Uncertainty of reference temperature (ice point or Cold Junction Compensation)	0.03	°C	2.000	0.9254	**0.014**	500
Calibration of measuring instrument	0.10	µV	2.000	0.0235	**0.001**	500
Specification of measuring instrument	0.00	µV	1.732	0.0235	**0.000**	500
Spurious thermal emfs	0.2	µV	1.732	0.0235	**0.003**	500
Curve fit residuals	0.84	µV	1.732	0.0253484	**0.012**	500
Compensating wire cold junction	0.0	µV	1.732	0.0235	**0.000**	500
Stem conduction		°C	1.732	1	**0.000**	500
Repeatability	0.001	°C	1.000	1	**0.001**	5
Reproducibility		°C	1.000	1	**0.000**	500
uc(k=1) (°C):					0.157	
Effective degrees of freedom					853.7	
Student’s t (effective d.o.f.):					2	
U(k=2) (°C):					**0.314**	
U(k=2) (µV):					13.38	

Notes:

(i) The QSAE uncertainty budget at 0 °C includes both a component for a reference PRT (0.016 °C) and a component for an ice point (0.002 °C). Budgets for the other temperatures include a component for the uncertainty of the reference junction temperature with a different value (0.03 °C). It is recommended that these components be checked for consistency: a component for uncertainty of the reference junction temperature should be included at all temperatures (even 0 °C), and the uncertainty of the measuring junction temperature can be determined from the uncertainty of the ice point realisation if measured in an ice point, <u>or</u> from the uncertainty of calibration of the reference PRT if the calibration point is performed by comparison.

(ii) From the sensitivity coefficient (dT/dW ~ 250 °C), it appears that the uncertainty of the reference resistor is 0.000 8 in units of PRT resistance ratio, i.e. approximately 20 mΩ when multiplied by Rtp of the standard PRT used (25.5 Ω). This seems quite large for a 100 Ω standard resistor (200 ppm). Is the sensitivity coefficient correct, or is the component actually 0.000 8 mΩ?

(iii) The uncertainty of the voltage measuring instrument (U(k=2) = 0.1 µV up to 20.6 mV) seems quite small: the one year drift specification of the 7.5 digit nanovoltmeter used by NML is ± 1.4 µV at 20.6 mV, and its calibration uncertainty is ± 0.4 µV at this voltage.

(iv) The component due to thermoelectric inhomogeneity does not scale in the expected way, i.e. according to [V(T) – V(20 °C)]. The component is very small at temperatures far from ambient: inhomogeneity equivalent to 0.043 °C at 500 °C, expressed as a percentage, is

[V(500.043 °C) – V(500 °C)] / [V(500 °C) – V(20 °C)] = 1.83 µV / 19846.17 µV = 0.01 %

According to "Bentley R.E., *Handbook of Temperature Measurement: Volume 3 – Theory and Practice of Thermoelectric Thermometry*, Springer-Verlag, 1998", the as-new level of inhomogeneity in base-metal thermocouples used above 200 °C is approximately ± 0.1 %. (The as-new level in noble-metal thermocouples, and in base-metal thermocouples limited to use below 200 °C, is about ± 0.02 %.) If thermocouples are not scanned for inhomogeneity during calibration, it is recommended that, as a minimum, these as-new levels of inhomogeneity be included in the uncertainty budgets. For example, the component for a type K thermocouple at 500 °C would be u(k=2) = ± 0.1 % x [V_K(500 °C) – V_K(20 °C)] = ± 19.8 µV, equivalent to 0.47 °C.

Mercury-in-glass thermometer:

Date	Lab name	Immersion	Actual temp (°C)	Indicated temp (°C)	ELC corr (°C)	Correction (°C)	Uncert (k=2) (°C)	LV-RV (°C)	En	Reduced corr (°C)	LV-RV (red) (°C)	En (red)
29-Jan-03	CSIRa	Total	-0.012	0.000	0.000	-0.012	0.025	0.000	0.000	0.000	0.000	0.000
		Total	9.999	10.000	0.000	-0.001	0.025	0.000	0.000	0.011	0.000	0.000
		Total	19.942	20.000	0.000	-0.058	0.025	0.000	0.000	-0.046	0.000	0.000
		Total	29.949	30.000	0.000	-0.051	0.025	0.000	0.000	-0.039	0.000	0.000
		Total	39.923	40.000	0.000	-0.077	0.025	0.000	0.000	-0.065	0.000	0.000
		Total	49.906	50.000	0.000	-0.094	0.026	0.000	0.000	-0.082	0.000	0.000
18-Jan-05	CSIRe	Total	0.000	0.000	0.000	0.000	0.030	0.012	0.307	0.005	0.005	0.091
		Total	9.988	10.000	0.000	-0.012	0.020	-0.011	-0.344	-0.007	-0.018	-0.356
		Total	19.931	20.000	0.000	-0.069	0.020	-0.011	-0.344	-0.064	-0.018	-0.356
		Total	30.026	30.100	0.000	-0.074	0.020	-0.023	-0.718	-0.069	-0.030	-0.594
		Total	40.015	40.100	0.000	-0.085	0.020	-0.008	-0.250	-0.080	-0.015	-0.297
		Total	50.010	50.100	0.000	-0.090	0.020	0.004	0.122	-0.085	-0.003	-0.059
14-Jul-05	QSAE	Total	0.000	0.010	0.000	-0.010	0.062	0.002	0.030	0.000	0.000	0.000
		1°C	9.909	9.890	-0.019	0.038	0.062	0.039	0.576	0.048	0.037	0.386
		7°C	20.261	20.240	0.001	0.020	0.062	0.078	1.169	0.030	0.076	0.806
		17°C	30.077	30.100	0.012	-0.035	0.062	0.016	0.246	-0.025	0.014	0.153
		27°C	40.043	40.100	0.027	-0.084	0.062	-0.007	-0.097	-0.074	-0.009	-0.090
		27°C	50.017	50.110	0.067	-0.160	0.062	-0.066	-0.984	-0.150	-0.068	-0.719
26-Aug-05	CSIRf	Total	1.095	1.100	0.000	-0.005	0.020	0.007	0.219	0.000	0.000	0.000
		Total	19.945	20.000	0.000	-0.055	0.020	0.003	0.078	-0.050	-0.004	-0.099

Notes:
(i) The Emergent Liquid Column (ELC) corrections applied by QSAE used (average temperature of ELC – immersion depth) as the length of the ELC. This is incorrect: in the above table, the length of the ELC is correctly calculated as (indicated temperature – immersion depth).

Uncertainty budgets:

CSIR-NML:

t (°C):	**0**					
	Value	Unit	Divisor	Sensitivity coeff	ui(k=1) (°C)	D.o.f.
REFERENCE STANDARD:						
PRT:						
Calibration of standard thermometer	0.01	°C	2.000	1	**0.005,0**	500
Drift of standard thermometer	0.0045	°C	1.732	1	**0.002,6**	500
Self-heating						
Stability of Rtp	0.0015	°C	1.732	0.999960	**0.000,9**	500
Uncertainty of reference temperature (WTP or ice point)	0.0003	°C	2.000	0.999960	**0.000,1**	500
Calibration of measuring instrument						
Specification of measuring instrument		°C	1.732	1.000	**0.000,0**	500
Reference resistor: calibration						
Reference resistor: temperature coefficient		°C	1.732	0.000752	**0.000,0**	500
Stem conduction						
HEAT SOURCE:						
Temperature difference between std & UUT: horizontal temp gradients	0.0016	°C	1.000	1	**0.001,6**	500
Control cycle of heat source: Zero if averaged over several cycles						
UNIT UNDER TEST:						
LIG:						
Resolution	0.0125	°C	1.732	1	**0.007,2**	500
Pressure dependence	14	kPa	1.732	0.001	**0.008,1**	500
ELC(cal) - ELC(use)	-0.700	°C	1.732	-0.00160	**0.000,6**	500
Uncertainty of ELC temperature	-2.83	°C	1.732	0.00011	**-0.000,2**	500
Stem conduction		°C	1.732	1	**0.000,0**	500
Repeatability		°C	1.000	1	**0.000,0**	2
Reproducibility		°C	1.732	1	**0.000,0**	500
uc(k=1) (°C):					0.012,4	
Effective degrees of freedom					1527.2	
Student's t (effective d.o.f.):					2	
U(k=2) (°C):					**0.024,7**	

t (°C):	**50**					
	Value	Unit	Divisor	Sensitivity coeff	ui(k=1) (°C)	D.o.f.
REFERENCE STANDARD:						
PRT:						
Calibration of standard thermometer	0.01	°C	2.000	1	**0.005,0**	500
Drift of standard thermometer	0.0045	°C	1.732	1	**0.002,6**	500
Self-heating						
Stability of Rtp	0.0015	°C	1.732	1.197871	**0.001,0**	500
Uncertainty of reference temperature (WTP or ice point)	0.0003	°C	2.000	1.197871	**0.000,2**	500
Calibration of measuring instrument						
Specification of measuring instrument	0	°C	1.732	1.000	**0.000,0**	500
Reference resistor: calibration						
Reference resistor: temperature coefficient	0	°C	1.732	0.000764	**0.000,0**	500
Stem conduction						
HEAT SOURCE:						
Temperature difference between std & UUT: horizontal temp gradients	0.0016	°C	1.000	1	**0.001,6**	500
Control cycle of heat source: Zero if averaged over several cycles						
UNIT UNDER TEST:						
LIG:						
Resolution	0.0125	°C	1.732	1	**0.007,2**	500
Pressure dependence	14	kPa	1.732	0.001	**0.008,1**	500
ELC(cal) - ELC(use)	-1.4	°C	1.732	0.00224	**-0.001,8**	500
Uncertainty of ELC temperature	3.60	°C	1.732	0.00022	**0.000,5**	500
Stem conduction		°C	1.732	1	**0.000,0**	500
Repeatability		°C	1.000	1	**0.000,0**	2
Reproducibility		°C	1.732	1	**0.000,0**	500
uc(k=1) (°C):					0.012,5	
Effective degrees of freedom					1593.1	
Student's t (effective d.o.f.):					2	
U(k=2) (°C):					**0.025,0**	

QSAE:

t (°C):	**0**					
	Value	Unit	Divisor	Sensitivity coeff	ui(k=1) (°C)	D.o.f.
REFERENCE STANDARD:						
Fixed point:						
Chemical impurity	0.002	°C	2.000	1	**0.001,0**	500
PRT:						
Calibration of standard thermometer	0.017	°C	2.000	1	**0.008,5**	500
Drift of standard thermometer		°C	1.732	1	**0.000,0**	500
Self-heating		Ω	1.732	2.507	**0.000,0**	500
Stability of Rtp		°C	1.732	0.999960	**0.000,0**	500
Uncertainty of reference temperature (WTP or ice point)		°C	2.000	0.999960	**0.000,0**	500
Calibration of measuring instrument						
Specification of measuring instrument	0.005	Ω	2.000	2.559	**0.006,4**	500
Reference resistor: calibration						
Reference resistor: temperature coefficient		°C	1.732	0.000752	**0.000,0**	500
Stem conduction						
HEAT SOURCE:						
Temperature difference between std & UUT: horizontal temp gradients		°C	1.732	1	**0.000,0**	500
Control cycle of heat source: Zero if averaged over several cycles						
UUT:						
LIG:						
Resolution	0.05	°C	1.732	1	**0.028,9**	500
Pressure dependence		kPa	1.732	0.001	**0.000,0**	500
ELC(cal) - ELC(use)		°C	1.732	0.00000	**0.000,0**	500
Uncertainty of ELC temperature		°C	1.732	0.00000	**0.000,0**	500
Stem conduction		°C	1.732	1	**0.000,0**	500
Repeatability	0.002	°C	1.000	1	**0.002,0**	4
Reproducibility		°C	1.732	1	**0.000,0**	500
uc(k=1) (°C):					0.030,8	
Effective degrees of freedom					643.6	
Student’s t (effective d.o.f.):					2	
U(k=2) (°C):					**0.061,7**	

t (°C):	**50**					
	Value	Unit	Divisor	Sensitivity coeff	ui(k=1) (°C)	D.o.f.
REFERENCE STANDARD:						
PRT:						
Calibration of standard thermometer	0.017	°C	2.000	1	**0.008,5**	500
Drift of standard thermometer	0.0003	°C	1.732	1	**0.000,2**	500
Self-heating	0	Ω	1.732	2.546	**0.000,0**	500
Stability of Rtp	0	°C	1.732	1.197871	**0.000,0**	500
Uncertainty of reference temperature (WTP or ice point)	0	°C	2.000	1.197871	**0.000,0**	500
Calibration of measuring instrument						
Specification of measuring instrument	0.006	Ω	2.000	2.597	**0.007,8**	500
Reference resistor: calibration						
Reference resistor: temperature coefficient	0	°C	1.732	0.000764	**0.000,0**	500
Stem conduction						
HEAT SOURCE:						
Temperature difference between std & UUT: horizontal temp gradients	0.001	°C	1.732	1	**0.000,6**	500
Control cycle of heat source: Zero if averaged over several cycles						
UNIT UNDER TEST:						
LIG:						
Resolution	0.05	°C	1.732	1	**0.028,9**	500
Pressure dependence	0	kPa	1.732	0.001	**0.000,0**	500
ELC(cal) - ELC(use)		°C	1.732	0.00289	**0.000,0**	500
Uncertainty of ELC temperature	0.30	°C	1.732	0.00368	**0.000,6**	500
Stem conduction		°C	1.732	1	**0.000,0**	500
Repeatability	0.002	°C	1.000	1	**0.002,4**	4
Reproducibility		°C	1.732	1	**0.000,0**	500
uc(k=1) (°C):					0.031,2	
Effective degrees of freedom					668.1	
Student's t (effective d.o.f.):					2	
U(k=2) (°C):					**0.062,4**	

Notes:
(i) The uncertainty in the ELC temperature estimated by QSAE is constant at 0.3 °C. It is more likely that this uncertainty component will scale according to the difference between the bath temperature and room temperature (or according to the difference between the bath temperature and average ELC temperature). According to "Nicholas J.V., White D.R., *Traceable Temperatures: An Introduction to Temperature Measurement and Calibration*, John Wiley & Sons, 1994", the k=1 uncertainty in (t_{bath} – t_{ELC}) is usually 5 % or more. CSIR-NML uses a k=1 uncertainty of 7.5 % x (t_{bath} – $t_{ambient}$) in its budget. The sensitivity coefficient is (1.6 x 10^{-4} x length of ELC). According to NML's method, QSAE's k=1 component at 50 °C would be 0.075 x (50.02 - 22) x 1.6 x 10^{-4} x (50.11 – 27) = 0.007 8 °C.

CONCLUSIONS

The results of this bilateral comparison were, in general, satisfactory.

The results of CSIR-NML and QSAE for the type K thermocouple agree to better than 0.5 °C from 0 to 500 °C, within the square root of the sum of the squares of the expanded uncertainties of the labs. Some suggestions for the refinement of QSAE's uncertainty budgets are made in the discussion of results above. In particular, it is suggested that the components for the voltage measuring instrument and thermoelectric inhomogeneity of the thermocouple under test be checked.

The results of the two laboratories for the mercury-in-glass thermometer agree to within 0.08 °C from 0 to 50 °C. The labs agree within the square root of the sum of the squares of their expanded uncertainties, at all temperatures except 20 °C. As 20 °C is close to room temperature, the temperature of the Emergent Liquid Column (ELC) is unlikely to cause such a large discrepancy (since $t_{bath} – t_{ELC}$ is small): the reason for the difference is not clear. The ELC correction calculated by QSAE used an incorrect value for the length of the ELC; this is rectified in the results tabulated above. If liquid-in-glass thermometers to be used at total immersion must be calibrated at partial immersion, it is suggested that they be calibrated as close to total immersion as possible: the shorter the Emergent Liquid Column (ELC), the smaller the ELC correction and the smaller the uncertainty contribution from this source.