CCT-K2.4: NRC/INTiBS/LNE-Cnam trilateral comparison of capsule-type standard platinum resistance thermometers from 13.8 K to 273.16 K

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Abstract. A trilateral comparison of capsule-type standard platinum resistance thermometers is reported that links the INTiBS realization of the International Temperature Scale of 1990 to the results of the Consultative Committee for Thermometry Key Comparison 2 in the temperature range 13.8033 K to 273.16 K. The report also supplies evidence to support the revision of the LNE-Cnam uncertainties in the KCDB list of CMCs at the triple points of neon and hydrogen.

1. Introduction

The Consultative Committee for Thermometry Key Comparison 2 (CCT-K2) results were published in 2002 [1]. NRC served as the pilot laboratory for CCT-K2 and remains able to perform bilateral comparisons linked to the original key comparison results.

Two capsule-type standard platinum resistance thermometers (CSPRT), Leeds and Northrup (L&N) 1866334 and Tinsley 234721, were chosen by the Institute of Low Temperature and Structure Research (INTiBS[1]) for international comparisons to determine the accuracy of the local realization of the International Temperature Scale of 1990 (ITS-90) in the temperature range from 24 K to 273.16 K. Initially, measurements of the thermometer resistances at the triple points of water and mercury were made using cells fabricated at INTiBS. Then, NPL cell 972 was used to realize the water triple point. Cell 972 belongs to a group of NPL cells showing instability, as reported in the EUROMET 549 comparison of water triple point cells [2]. The mercury triple point was realized in an INTiBS miniature cell [3]. These initial results obtained at INTiBS were confirmed by a bilateral comparison with IMGC[2] [4].

Afterward, INTiBS asked BNM-INM[3] to calibrate these thermometers within the scope of EUROMET project no 730[4]. At that time, a national standard of temperature in the range from 13.8033 K to 273.16 K was established at INTiBS at the decision of the President of the Central Office of Measures[5] (GUM) – certificate no. 14 [5]. With this authority, the Polish

[1] INTiBS abbreviation from the Institute name in Polish – Instytut Niskich Temperatur i Badań Strukturalnych
[2] IMGC – presently INRIM – Istituto Nazionale di Ricerca Metrologica
[3] presently LNE-Cnam – Laboratoire Commun de Métrologie entre le Laboratoire National de Metrologie et d'Essais (LNE) et le Conservatoire National des Arts et Métiers, named LNE-Cnam in this text
[4] EUROMET Project 730 - *A comparison of temperature scale near fixed points in the low temperature range*
[5] The Central Office of Measures (GUM) – the NMI of Poland

CSPRTs could be included in the CCT-K2 key comparisons. After reaching agreement with the NRC, the coordinator of CCT-K2, the thermometers were sent directly from LNE-Cnam to NRC. After the measurements at NRC, the thermometers were transported again to France and measured by LNE-Cnam. LNE-Cnam sent their results to NRC and the thermometers were given back to INTiBS, where they were calibrated at the fixed points of the ITS-90.

2. Experimental details

2.1 Measurements performed at INTiBS

For the hydrogen, neon, and argon triple point realizations, the following cells (produced by IMGC) were applied: H_2 – E2H2, Ne – E3Ne, Ar – E5Ar. These cells were tested during the EU 'Multicells' project, G6RD-CT-1999-00114 [6]. The triple point of oxygen was realized in the IMGC cell no 202 3-IX-76, which was included in the EUROMET project 377 [7]. The cells were placed in an adiabatic cryostat as described in [8]. To realize the mercury and water triple points, cell Hg 220 and H_2O cell B11/50/465 were used with their respective baths manufactured by ISOTECH. Both of these cells are being tested in bilateral comparisons under the EUROMET projects 895[6] and 914[7].

The thermometer resistances were measured with a Measurements International 6015T resistance bridge. Tinsley standard resistors (model 5685) placed in temperature-controlled enclosures were used as references for the resistance bridge: a 1 Ω resistor for the measurements at the hydrogen and neon triple points and a 25 Ω resistor for the oxygen, argon, mercury, and water triple points. To determine the self-heating correction (and the resistance value for zero current, $R_{I=0}$), three measuring currents were used: $I_1 = \sqrt{2}$ mA, $I_2 = 2$ mA, and $I_3 = 2\sqrt{2}$ mA.

The resistances obtained from three runs at each fixed point were averaged to obtain the comparison values. The calibration temperatures, resistance ratios, and combined standard uncertainties (u_L, for k=1) for the CSPRTs at INTiBS are listed in Table 1. The detailed uncertainty budgets for the CSPRTs measured at INTiBS are presented in Appendix A.

[6] EUROMET Project No 895 - *Bilateral comparison of water triple point cells*
[7] EUROMET Project No 916 - *Bilateral comparison of mercury triple point cells*

Table 1. Calibration data for the CSPRT thermometers at INTiBS. The values *in italics* at 273.16 K are the resistances of the thermometers (in ohms) at that temperature.

Fixed point	T / K	Tinsley 234721		L&N 1866334	
		W	u_L/ mK	W	u_L/ mK
H_2	13.8033	0.001 473 512	0.32	0.001 214 964	0.32
Ne	24.5561	0.008 774 93	0.20	0.008 513 43	0.20
O_2	54.3584	0.092 022 05	0.23	0.091 833 87	0.23
Ar	83.8058	0.216 118 01	0.20	0.215 967 07	0.20
Hg	234.3156	0.844 192 01	0.23	0.844 163 64	0.23
H_2O	273.16	*24.5819763*	0.16	*25.5373757*	0.16

The uncertainty budgets for the CSPRTs measurements carried out at INTiBS are presented in Appendix A.

2.3 Measurements performed at LNE-Cnam

At LNE-Cnam, the thermometers were measured at the six low-temperature points in fixed-point cells. The measurements took place from 2005/10/25 to 2006/03/13. Since the time that the CCT-K2 measurements took place more than 10 years ago, LNE-Cnam measurement capabilities at low temperatures have evolved, particularly in regard to realizations of the triple points of neon and hydrogen. These developments led to improved multi-compartment cells and a new adiabatic calorimeter. Comparisons were carried out between the old and the new apparatus to establish the traceability of the measurements, leading to revised uncertainty budgets for the neon and hydrogen triple points, the details of which are elaborated in Appendix B of this report. The uncertainty values given in CCT-K2 are maintained for the other triple points.

During the course of the measurements, concerns were raised with the behaviour of CSPRT 234721. The thermal equilibration time was observed to be significantly larger than observed for 1866334 (and also CSPRT 1041 - used for CCT-K2 - that we used as a check) and the self-heating was quite a bit larger (1.94 mK) than for 1866334 (0.85 mK) and 1041 (0.9 mK). This raised the concern that the exchange gas in the thermometer may have leaked.

The thermometers underwent additional checks at the water triple point. For thermometer 1866334, the self-heating of slightly less than 1 mK was confirmed, as was the larger self-heating of thermometer 234721 (roughly 1.8 mK). In checking the stability over a one-month period, thermometer 1866334 was stable within 60 μK. On the other hand, thermometer 234721 changed by 0.5 mK without thermal cycling (except between room temperature and the water triple point) with the electrical resistance increasing with time.

After completion of the comparison, concerns were raised with the calibration of CSPRTs in the mercury triple-point cell of LNE-Cnam. The temperature measured by thermometer 1866334 was in disagreement by 1.40 mK with that measured at NRC, outside of the combined measurement uncertainties. Measurements carried out with check thermometer 1041 showed a difference of -0.79 mK with the mercury triple point temperature measured in

CCT-K2. Subsequent tests carried out with CSPRTs on the mercury cell used by LNE-Cnam showed a reproducibility within ±1.5 mK. The determination of the reasons for such a large irreproducibility is not straightforward, and it is presumed to result from the concurrence of factors such as the progressive degradation of the cell, improper design of the thermometric well conceived to accommodate CSPRTs, poor thermal coupling of the thermometer to the phase transition, use of unsuitable contact fluids in the well, and moisture on the thermometer leads.

To overcome the problem, LNE-Cnam built and characterized a new type of calorimeter for the calibration of both long-stem and capsule-type SPRTs at the mercury triple point. Measurements carried out with CSPRT 1041 in the new cell [9] are in agreement with the CCT-K2 measurements. This validates the hypothesis that the CCT-K2.4 measurements at the mercury triple point reported by LNE-Cnam were unreliable.

Table 2. Resistance ratios obtained at LNE-Cnam. The values in italics are the resistances of the thermometers (in ohms) at 273.16 K. The uncertainties for the hydrogen and neon fixed points are detailed in Appendix B. The uncertainties at the other fixed points are the same as given in the CCT-K2 report [1].

Fixed point	T / K	W(234721)	W(1866334)	u_L / mK
H_2	13.80338	0.001 473 215	0.001 214 793	0.37
Ne	24.5561	0.008 774 250	0.008 512 954	0.30
O_2	54.3584	0.092 021 523	0.091 833 911	0.23
Ar	83.8058	0.216 117 861	0.215 967 357	0.20
Hg	234.3156	0.844 197 705	0.844 170 518	0.27
H_2O	273.16	*24.581 831*	*25.537 273*	0.17

2.3 Measurements performed at NRC

2.3.1 Comparison measurements

In the original CCT-K2 measurements, CSPRTs calibrated by the participating NMIs were compared at NRC in a nearly isothermal copper block. When the protocol for CCT-K2 was first envisaged, it was assumed that the reporting of the comparison results would include temperatures between the calibration fixed points. However, although such data was collected during the course of the CCT-K2 measurements, the final report focuses nearly exclusively on the results obtained near the defining fixed points of the ITS-90.

For CCT-K2.4, the NRC measurements employed the superior thermal environment of the multi-well fixed-point cells that were used very effectively to calibrate the CSPRTs for the determination of the temperature of the triple point of xenon [10]. The hydrogen cell used at NRC was filled from the same container of gas that contributed to the determination of the sensitivity coefficient for deuterium contamination [11], the implication being that the triple point temperature of cell SS-M-2 is 13.80338 K. The measurements at NRC were carried out between 2005/01/06 and 2005/05/17.

With regard to CSPRT 234721, its self-heating at the triple point of water was found to be 1.4 mK compared to 0.5 mK for 1866334. Another Tinsley CSPRT measured at the same time exhibited a self-heating of 0.8 mK, so 234721 appeared to be anomalous. In addition, repeated realizations of the triple point of water carried out from 2005/01/06 to 2005/01/14 with the two CSPRTs showed 234721 to be considered less stable than 1866334, and at this point we were concerned that 234721 may prove unsuitable for the comparison.

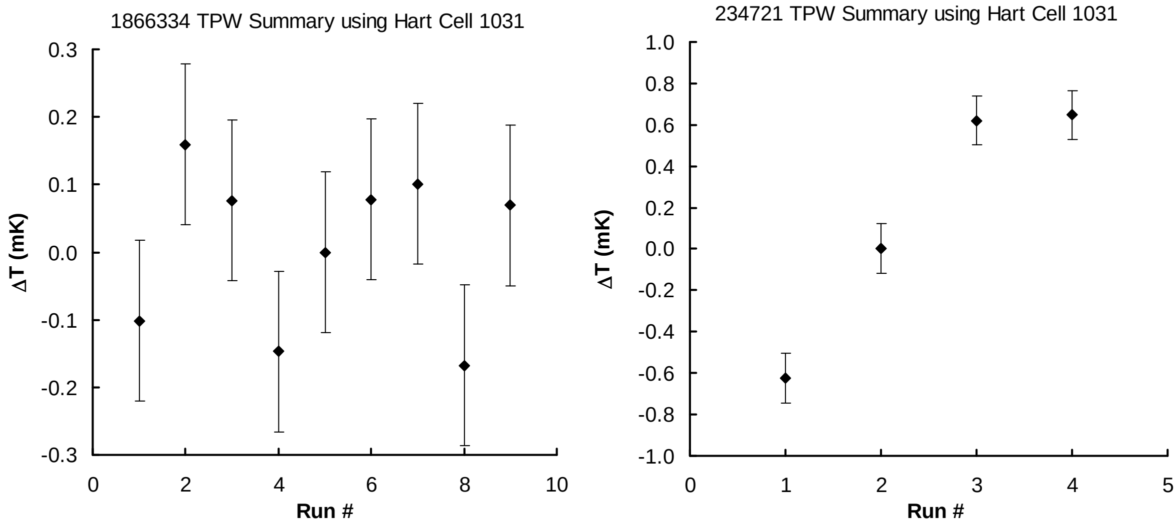

Figure 1. Stability of the CSPRTs as assessed via repeated realizations of the triple point of water at NRC.

Table 3. Resistance ratios obtained at NRC. The values in italics are the resistances of the thermometers (in ohms) at 273.16 K.

Fixed point	Cell identification	T / K	W(234721)	W(1866334)	u_L / mK
H_2	SS-M-2	13.80338	0.001 470 557	0.001 214 808	0.20
Ne	Cu-M-1	24.5561	0.008 772 186	0.008 513 452	0.20
O_2	Cu-M-3	54.3584	0.092 019 176	0.091 833 725	0.20
Ar	Cu-M-7	83.8058	0.216 113 705	0.215 965 358	0.20
Hg	SS-M-Hg	234.3156	0.844 193 364	0.844 164 875	0.20
H_2O	Cu-M-6	273.16	*24.581 730*	*25.537 277*	0.15

2.3.2 Resistance measurements

The resistance measurements were made with the same Automatic Systems Laboratories Model F18 resistance bridge used for CCT-K2. A 25 Ω Tinsley Model 5685A reference resistor was used, thermostatted at 25 °C ± 2 mK in a Guildline 9732VT oil bath. From 13.8033 K to 24.5561 K, currents of 5 mA and 5√2 mA were used. At 54.3584 K, currents of 2 mA and 2√2 mA were used. From 83.8058 K to 273.16 K, currents of 1 mA and √2 mA were used.

2.3.3 Traceability to CCT-K2

NRC contributed to CCT-K2 a single Leeds and Northrup CSPRT, S/N 1872174, that had been calibrated in specific sealed fixed-point cells produced at NRC (e-H_2 cell 22, Ne cell

F15, O_2 cell F10, Ar cell F13), as well as in a hydrogen vapour-pressure cryostat at temperatures near 17.0018 K and 20.2676 K, in a large glass cell suitable for long-stem thermometers (cell Hg-2), and in a large glass triple point of water cell.

The NRC thermometer (L&N 1872174) used in the original CCT-K2 comparison [1] was broken several years ago. In addition, establishing traceability to CCT-K2 via resistance ratios obtained more than 10 years ago for a single CSPRT would offer potentially dubious results without additional checks. The values in Table 2 reflect fixed-point realizations using the multi-well cells currently favoured at NRC. Nonetheless, we have linked the contemporary cells to the single-well sealed cells that were used to calibrate the NRC CSPRT for the CCT-K2 exercise. The resistance ratios of Leeds and Northrup CSPRT S/N 1876687 were measured in the multi-well cells at the same time that the resistance ratios were determined during a comparison of thermometers carried out in 2006. Immediately following the comparison exercise, S/N 1876687 was measured in cell 22 (e-H_2), cell F17 (Ne), cell F10 (O_2), and cell F13 (Ar). For e-H_2, O_2, and Ar, the linkage to the cells used for CCT-K2 is direct, assuming that the cells realize the same temperature as they did 10 years earlier.

For Ne, the link to the CCT-K2 cell, F15, was established via measurements carried out with CSPRT S/N 1872174. Cell F17 was measured in September 2002, and 3 months later we determined that cell F15 was 0.053 mK hotter than cell F17.

By this mechanism, we determined that:

1) Hydrogen – SS-M-2 is 0.527 mK hotter than cell 22
2) Neon – Cu-M-1 is 0.112 mK colder than F17, and F17 is 0.053 mK colder than F15
3) Oxygen – Cu-M-3 is 0.098 mK hotter than F10
4) Argon – Cu-M-7 is 0.120 mK colder than F13

3. Results

The experimental measurement uncertainty budget remains 0.12 mK at 20.3 K and below and 0.09 mK above 20.3 K, the same as in the CCT-K2 report [1]. This uncertainty component, u_{Exp}, is summed in quadrature with each of the laboratory uncertainties, u_L, to form a combined uncertainty, u_C. The pair uncertainty for the comparison, u_P, is obtained by summing in quadrature the combined uncertainties for each laboratory. The justification for treating the experimental uncertainty components as completely uncorrelated when evaluating the pair uncertainty is explained in further detail in the CCT-K2 report. The relevant uncertainty equations are as follows:

$$u_C = \sqrt{u_L^2 + u_{Exp}^2} \qquad (1)$$

$$u_p = \sqrt{u_{NRC}^2 + u_{Lab}^2 + 2u_{Exp}^2} \qquad (2)$$

The results of the comparison are summarized in Table 4 and Figure 2 with respect to the current NRC realization of the ITS-90.

Tables 1-3 include the triple point of water (TPW) resistances given by INTiBS, LNE-Cnam, and NRC for the thermometers.

Table 4. Comparison data for the INTiBS thermometers expressed with respect to the 2006 NRC realization of the ITS-90 based on the new generation of multi-well fixed points. The table includes the expanded pair uncertainties (k = 2) for these temperature differences. The values at 273.16 K express the consistency in the triple point of water realizations at the participating laboratories as carried on the thermometers.

T_{NRC} / K	$T_{INTiBS} - T_{NRC}$ / mK			$T_{LNE\text{-}Cnam} - T_{NRC}$ / mK		
	234721	1866334	$2u_p$	234721	1866334	$2u_p$
13.8033	11.93	0.64	0.83	10.73	-0.06	0.91
24.5561	2.23	-0.02	0.62	1.68	-0.40	0.76
54.3584	0.74	0.04	0.66	0.60	0.05	0.66
83.8058	0.99	0.39	0.62	0.96	0.46	0.62
234.3156	-0.34	-0.31	0.66	1.08	1.40	0.72
273.1600	2.51	0.97	0.51	1.03	-0.03	0.52

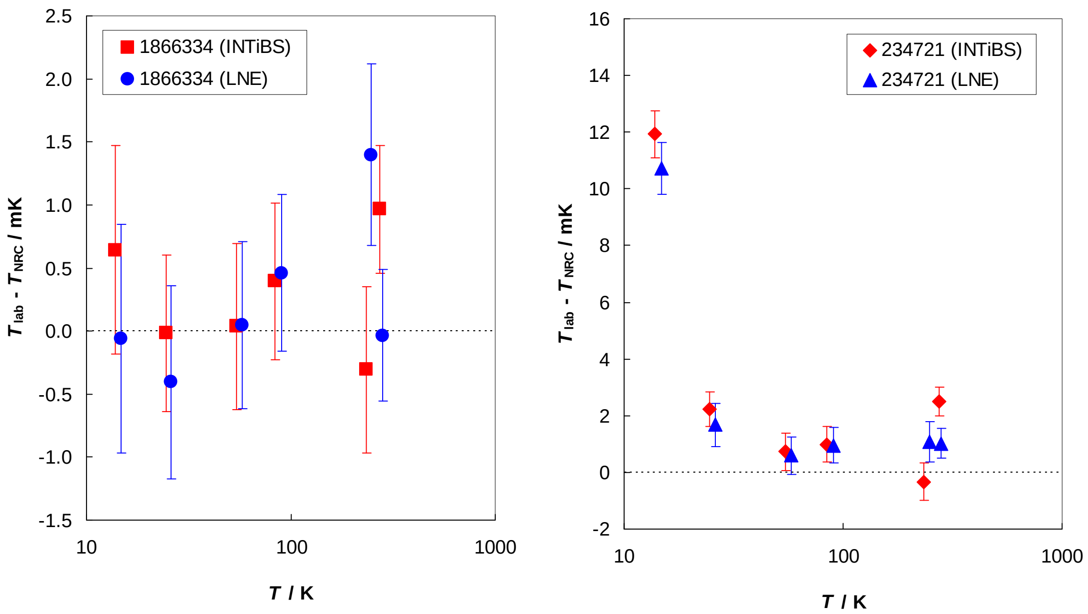

Figure 2. The comparison data for the INTiBS CSPRTs plotted with respect to the 2006 NRC realization of the ITS-90 based on the new generation of multi-well fixed points. The error bars represent the expanded uncertainties of the temperature differences, $2u_p$. It is readily evident that the data for 1866334 is compatible amongst the participating laboratories while that for 234721 is less so.

The INTiBS data may be related to the CCT-K2 results by combining the results from Table 4 with the differences reported for the NRC thermometer with respect to the KCRV as determined by the CCT-K2 exercise. Since the NRC thermometer was used in both Groups A and B of CCT-K2, the degrees of equivalence for INTiBS with respect to the CCT-K2 KCRV were calculated for both determinations of ($T_{NRC\text{-}1996} - T_{KCRV}$) according to Equation 3. These values, together with their average, are compiled in Table 5.

$$D_{INTiBS} = \left(T_{INTiBS} - T_{NRC-2006}\right) + \left(T_{NRC-2006} - T_{NRC-1996}\right) + \left(T_{NRC-1996} - T_{KCRV}\right)_{CCT-K2} \tag{3}$$

The expanded uncertainty, U, of the INTiBS degree of equivalence (also listed in Table 5), is obtained by appropriately combining the uncertainties of the bracketed terms in Equation 3. The uncertainty of ($T_{INTiBS} - T_{NRC}$) is readily identified as u_p from Equation 2, and reported in Table 4. Since the CCT-K2 KCRV has zero uncertainty by definition, the uncertainty of the second term in Equation 3, ($T_{NRC\text{-}1996} - T_{KCRV}$), is determined solely by the uncertainty in $T_{NRC\text{-}1996}$. This is simply the combined standard uncertainty of the NRC calibration in 1996, $u_{NRC\text{-}1996}$, and the experimental comparison uncertainty of CCT-K2, which is equal to u_{Exp}, calculated according to Equation 1. The NRC laboratory uncertainties for CCT-K2 are identical to those in Table 3.

In combining the bracketed terms of Equation 3, we must consider the extent to which the two uncertainties for T_{NRC} and $T_{NRC\text{-}1996}$ are correlated. The 1996 and 2006 calibrations utilized (except for Ne) the same fixed-point cells, resistance bridge, and experimental apparatus. Under the assumption that the temperatures realized by the NRC sealed cells are stable in time, the Type B components of the uncertainty budgets for CCT-K2 and this bilateral key comparison can be considered to be completely correlated, and so only the Type A repeatability component from the full laboratory uncertainty budget should be counted twice – once as the component of u_{NRC} for this measurement comparison, and once to accommodate the uncorrelated component of $u_{NRC\text{-}1996}$ reported in CCT-K2. This component is u_{TypeA} = 0.07 mK for all five triple point temperatures. Equation 4 summarizes the calculation of the expanded uncertainties of Tables 5 and 6 for the INTiBS degree of equivalence to the Key Comparison Reference Value of CCT-K2.

$$U = 2\sqrt{\left(u_{NRC}^2 + u_{INTiBS}^2 + 2u_{Exp}^2\right) + u_{TypeA}^2 + u_{Exp}^2} \tag{4}$$

Table 5 and Figure 3 show that the INTiBS measurements for thermometer 1866334 agree with the CCT-K2 KCRV within the expanded combined uncertainties, U, at all temperatures.

Table 5. The degrees of equivalence, D, for INTiBS thermometer 1866334 expressed with respect to the KCRV for Groups A and B from the CCT-K2 report and their average, mediated by the NRC realization of ITS-90. The table includes the expanded uncertainties of the degrees of equivalence, U (k = 2).

T / K	D_A / mK	D_B / mK	D_{Avg} / mK	U / mK
13.8033	0.83	0.82	0.83	0.84
24.5561	-0.24	-0.30	-0.27	0.64
54.3584	0.32	0.38	0.35	0.68
83.8058	0.45	0.51	0.48	0.64
234.3156	-0.45	-0.45	-0.45	0.64

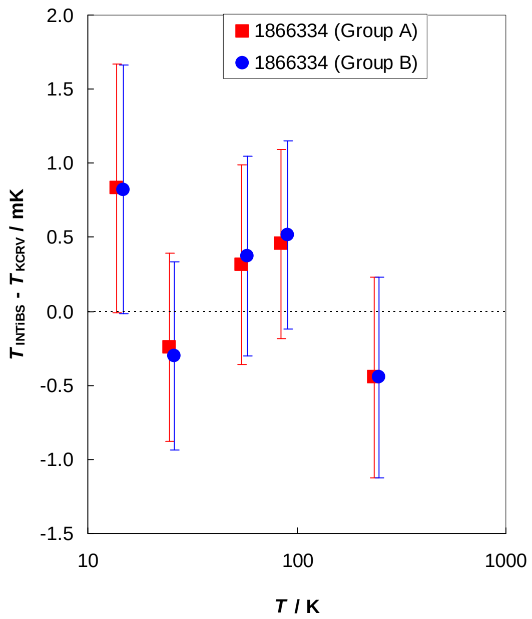

Figure 3. The comparison data for the INTiBS CSPRT S/N 1866334 plotted with respect to the KCRV determined from the two Groups of measurements from the CCT-K2 report, mediated by the NRC realization of the ITS-90. The error bars represent the expanded uncertainties, *U*.

A similar analysis can be carried out for the LNE-Cnam measurements with the INTiBS CSPRT S/N 1866334. Table 6 and Figure 4 summarize the LNE-Cnam data with respect to the CCT-K2 KCRV. The neon and hydrogen triple point measurements are consistent with the KCRV within the combined uncertainties, validating the new LNE-Cnam uncertainty budgets detailed in Appendix B and supporting revised Calibration Measurement Capabilities at the neon and hydrogen triple points. The oxygen and argon triple point measurements remain consistent with the CCT-K2 KCRV.

Table 6. The degrees of equivalence, *D*, for the measurements carried out at LNE-Cnam (using the INTiBS thermometer 1866334) expressed with respect to the KCRV for Groups A and B from the CCT-K2 report and their average, mediated by the NRC realization of ITS-90. The table includes the expanded uncertainties of the degrees of equivalence, *U* (k = 2).

T / K	D_A / mK	D_B / mK	D_{Avg} / mK	U / mK
13.8033	0.12	0.11	0.12	0.92
24.5561	-0.63	-0.69	-0.66	0.78
54.3584	0.33	0.39	0.36	0.68
83.8058	0.52	0.58	0.55	0.64
234.3156	1.26	1.26	1.26	0.73

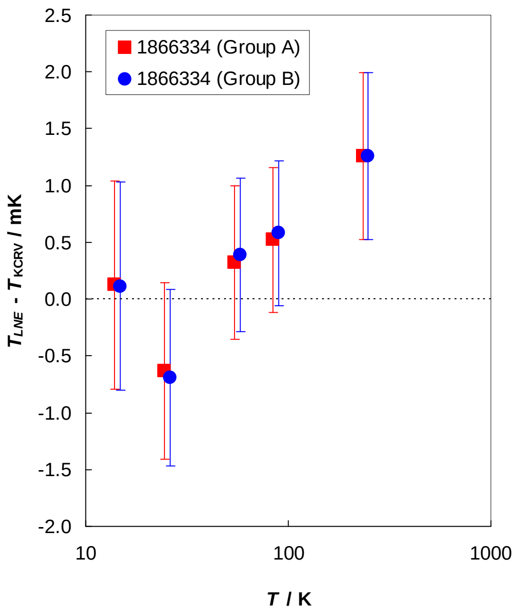

Figure 4. The comparison data for the measurements carried out at LNE-Cnam (using the INTiBS CSPRT S/N 1866334) plotted with respect to the KCRV determined from the two Groups of measurements from the CCT-K2 report, mediated by the NRC realization of the ITS-90. The error bars represent the expanded uncertainties, *U*.

4. Conclusion

The NRC/INTiBS bilateral comparison of capsule-style platinum resistance thermometers over the range 13.8 K to 273.16 K has revealed calibrations at INTiBS to be in agreement with the KCRV of CCT-K2 within the expanded uncertainty for all temperatures of the comparison based on the data for CSPRT 1866334. After the CSPRTs returned to INTiBS, the resistance of 1866334 at the triple point of water was greater than its value prior to shipment to NRC by the equivalent of 0.17 mK and its resistance at the triple point of mercury was less than its value prior to shipment to NRC by the equivalent of 0.20 mK. Both values are within the uncertainty of measurement and indicate that the CSPRT remained stable throughout the comparison.

CSPRT 234721 is considered anomalous due to its apparent instability and anomalous self-heating, and though the data has been included herein for completeness, it does not bear consideration when evaluating the capabilities of INTiBS.

The linkage to the CCT-K2 data supports the inclusion of the INTiBS CMCs in Appendix C of the KCDB.

The LNE-Cnam data at the hydrogen and neon triple points is consistent with the KCRV of CCT-K2 within the expanded uncertainty of the comparison. This supports revision of the uncertainties for the LNE-Cnam CMCs at these two fixed points of the ITS-90.

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Appendix A

The detailed uncertainty budget for the CSPRT measurements at INTiBS.

Fixed point Nominal substance purity	H_2 5N	Ne 5N	O_2 4N8	Ar 5N7	Hg 7N	H_2O
Uncertainty components (mK)						
Bridge measurement and self-heating error	0.10	0.05	0.02	0.02	0.02	0.04
Uncertainty propagation from TPW	0.01	0.02	0.10	0.10	0.13	-
Standard resistor	0.01	0.01	0.02	0.02	0.02	0.08
Choice of fixed point value	0.24	0.10	0.05	0.05	0.10	0.05
Chemical impurities and isotopes	0.17	0.16	0.19	0.15	0.10	0.05
Hydrostatic head correction	0.01	0.01	0.01	0.02	0.04	0.01
Heat flux error	0.11	0.02	0.02	0.03	0.04	0.02
Repeatability of measurements	0.05	0.03	0.03	0.03	0.05	0.05
Reproducibility of CSPRT	0.05	0.05	0.05	0.05	0.10	0.10
Standard combined uncertainty (mK)	0.32	0.20	0.23	0.20	0.23	0.16
Expanded uncertainty (k = 2)	0.64	0.40	0.46	0.40	0.46	0.32

Appendix B

Evaluation of the LNE-Cnam Uncertainty Budget at the Triple Points of Hydrogen and Neon for the CCT-K2.4 Comparison

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B.1 Overview: CCT-K2 and CCT-K2.4 comparisons

The measurements performed for the CCT-K2.4 comparison at the triple points of equilibrium hydrogen, neon, oxygen and argon were carried out in a temperature-controlled adiabatic calorimeter with a multi-compartment "Improved M-Cell" of the latest generation, developed by the LNE-Cnam[8] in the framework of the *Multicells* project [B.8]. The characteristics of the Improved M-Cells were studied and reported by LNE-Cnam and NMi-VSL [B.1]. The article compares the Improved M-Cells with the M-cells of the previous generations. The behavior and the stability of the new cells are now well characterized, and they are suitable for temperature realization at the primary level. While at the time of the CCT-K2 comparison [B.2] the LNE-Cnam realized the preliminary calibration of the thermometers with the old generation cells, the CCT-K2.4 was carried out with the new Improved M-Cells.

CCT-K2.4 and subsequent measurements were carried out with the Improved M-Cells using two different adiabatic calorimeters. One, cooled with liquid helium, is the same as used at the time of CCT-K2 for the preliminary calibration of the thermometers participating in the comparison. The second one is a cryocooler-based adiabatic calorimeter built in 2006. It provides better adiabaticity and temperature uniformity, as it is equipped with three thermal shields and two separate vacuum chambers [B.3, B.9].

All the measurements on the Improved M-cells were carried out with a batch of thermometers that included CSPRT 1041 – the LNE-Cnam Group B thermometer of CCT-K2 – to link CCT-K2 to the measurements performed with the new cell. The stability of the thermometer was checked after each thermal cycle by measuring its reduced resistance W at the triple points of oxygen and argon, and its resistance at the triple point of water. Neither resistance drift nor thermometer instability was observed during the measurements, and the data were consistent with those of CCT-K2.

In this document, we use data obtained with the Improved M-Cells to calculate revised uncertainty budgets for the triple points of equilibrium hydrogen and neon.

B.2. Triple point of equilibrium hydrogen

Since the CCT-K2.4 measurements were carried out, the LNE-Cnam has used the new generation hydrogen cell number $H_2$02/1. This cell is well characterized and took part in an international research project among eight metrological institutes to determine the dependence of the triple-point temperature of equilibrium hydrogen on the deuterium content [B.4].

CCT-K2.4 measurements were carried out at the beginning of 2006 in the liquid-cooled adiabatic calorimeter, with an ASL model F18 resistance bridge and a Tinsley standard resistor of nominal value 1 Ω, compatible with AC and DC resistance bridges.

[8] Formerly BNM-INM

New measurements were performed at the end of 2006 with the same apparatus, after having moved to the new laboratory, and two other runs were performed in 2007 in the cryocooler-based adiabatic calorimeter. Thermometer 1041 was used to link the new measurements to the CCT-K2.

B.2.1 Correction of CCT-K2 Key Comparison Reference Value (KCRV) for H_2

In order to correctly compare CCT-K2 measurements with the new ones, it must be remembered that the CCT-K2 measurements were performed *near* the hydrogen triple point, so the reduced resistance W_{K2} given in CCT-K2 needs to be corrected to calculate the reduced resistance *at* the triple point value, $W_{H2,K2}$. This is necessary to compare the CCT-K2 results with the subsequent ones, which were carried out *at* the temperature of the triple point of hydrogen.

The value of W_{K2} in CCT-K2 is $W_{K2} = 0.001\,251\,264$ (see Table 11 in [B.2]) while the calibration value supplied in CCT-K2 by the LNE-Cnam at the hydrogen triple point is $W_{H2,LNE\text{-}Cnam} = 0.001\,251\,856$ (see Table 1 in [B.2]). Using the ITS-90, we can estimate the sensitivity of the thermometer at $W_{H2,LNE\text{-}Cnam}$ obtaining $S_{H2} = 2.536 \cdot 10^{-4}\ K^{-1}$. S_{H2} allows conversions from reduced resistances to temperatures.

Table 11 in [B.2] gives the difference between T_{K2} – the temperature associated with W_{K2} – and the Key Comparison Reference Value (KCRV) near the hydrogen point for thermometer 1041: $T_{K2} - \mathrm{KCRV} = -2.60$ mK. It is possible to correct W_{K2} to obtain the reduced resistance of thermometer 1041 *at* the KCRV[9] value:

$W_{KCRV} = W_{K2} - (T_{K2} - \mathrm{KCRV}) \cdot S_{H2} = 0.001\,251\,923$

W_{KCRV} is the resistance *at* the KCRV, while $W_{H2,LNE\text{-}Cnam}$ is the resistance *at* the triple point. It is then possible to determine the difference between the KCRV and the triple point temperature:

$\Delta T_{KCRV,H2} = \mathrm{KCRV} - T_{H2,LNE\text{-}Cnam} = (W_{KCRV} - W_{H2,LNE\text{-}Cnam})/S_{H2} = 0.27$ mK

$\Delta T_{KCRV,H2}$ is the correction to be applied to the thermometers of Group B of Table 11 in [B.2] to obtain the reduced resistance value W *at* the triple point temperature. By applying the correction $\Delta T_{KCRV,H2}$ to the reduced resistance W_{K2} of thermometer 1041, we obtain the CCT-K2 value *at* the triple point value:

$\boldsymbol{W_{H2,K2}} = W_{K2} - \Delta T_{KCRV,H2} \cdot S_{H2} = \mathbf{0.001\,251\,197}$

B.2.2 Data at the triple point of hydrogen

The value $W_{H2,K2}$ is reported in Table B.1, together with the recent measurements of reduced resistances W for thermometer 1041. A graphical representation is given in Figure B.1.

The standard deviation calculated from the values in Table B.1 is $\sigma_W = 6.14 \cdot 10^{-8}$, and its temperature equivalent is $\sigma_{T,W} = 0.24$ mK.

[9] The KCRV is not the triple point temperature. See [2] for more information regarding the KCRV.

Table B.1. Reduced resistances of thermometer 1041 at the hydrogen triple point.

Date	Cryostat	W *(symbol)*	W *(value)*
1997 – 1999 $W_{H2,K2}$ *(CCT-K2)*	NRC cryostat	$W_{H2,K2}$	0.001 251 197
January 2006 *CCT-K2.4*	Liquid-cooled adiabatic calorimeter	$W_{H2,K2.4}$	0.001 251 287
January 2007	Liquid-cooled adiabatic calorimeter (*moved to new laboratory)*	$W_{H2,jan\text{-}2007}$	0.001 251 321
February 2007	Cryocooler-based adiabatic calorimeter	$W_{H2,feb\text{-}2007}$	0.001 251 355
December 2007	Cryocooler-based adiabatic calorimeter	$W_{H2,dec\text{-}2007}$	0.001 251 329

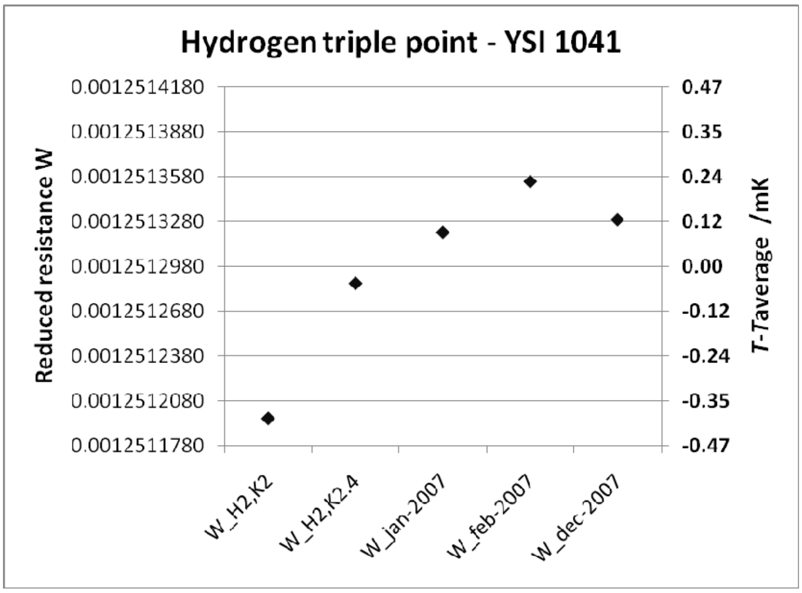

Figure B.1. Reduced resistances of thermometer 1041 at the hydrogen triple point.

B.2.3 Uncertainty budget for the calibration of platinum thermometers at the triple point of hydrogen

Data from the measurements shown in Table B.1 were used to evaluate the uncertainties associated with the calibration of a SPRT at the hydrogen triple point. The different contributions are listed and explained hereunder and the detailed budget is given in Table B.2.

B.2.3.1 Triple point value

The uncertainty contribution on triple point value is given by the standard deviation $\sigma_{T,W}$ calculated from the values of Table B.1, as previously illustrated.

B.2.3.2Electrical measurements
The LNE-Cnam has several ASL F18, ASL F900, and MI 6010T resistance bridges, but measurements of repeatability, nonlinearity, frequency dependence, and ratio error are still not available and the associated uncertainty contributions are evaluated on the basis of the measurements performed in [B.5].

Measurements at the triple point of hydrogen are carried out with 1 Ω AC/DC-compatible standard resistors. Their resistance is determined by comparison with a calibrated 25 Ω standard resistor.

The uncertainty of the electrical measurements takes into account the contributions coming from the bridge, from the comparison with the calibrated standard resistor, and from ageing and thermal instability of the standard resistors.

B.2.3.3 Self-heating
The resistance of the thermometer is extrapolated to 0 mA from measurements performed at two different currents with a ratio of $\sqrt{2}$. The uncertainty from self-heating is calculated by combining noise uncertainties at the two measuring currents [B.6].

B.2.3.4 Spurious heat flux
The measurements reported in Table B.1 are performed with the same multi-compartment cell, installed in two different adiabatic calorimeters. The uncertainty associated with the spurious heat flux is evaluated from the difference between the average value of the measurements performed in the liquid-cooled adiabatic calorimeter and the average value of the measurements performed in the cryocooler-based adiabatic calorimeter.

B.2.3.5 Isotopic composition
Although the cell $H_2$02/1 participated in the comparison described in [B.4], no measurements of its isotopic composition are available. The value recommended in [B.4] is used for the uncertainty associated with the isotopic composition.

B.2.3.6 Interpretation of the plateau
Measurements are performed at 50 % of solid melted. The realization of the plateau is fully automated and a minimum of ten heat pulses is applied to melt the substance. Considering the hypothesis of being able to locate the 50 % point of the plateau within the 38 % to 62 % melted fraction, and considering that the full melting range of the cell $H_2$02/1 is 0.17 mK [B.4], the uncertainty from interpretation of the plateau is 24%·0.17 mK ≈ 0.04 mK.

Table B.2. Detailed uncertainty budget for the calibration of a standard platinum thermometer at the equilibrium hydrogen triple point

Fixed point	H_2
Substance purity	6N
Uncertainty components, Type B estimate (mK)	
Triple point value	0.24
Electrical measurements	0.10
Self heating	0.05
Spurious heat flux	0.15
Hydrostatic pressure effect	0.00
Isotopic composition	0.20
Interpretation of the plateau	0.04
Type B combined uncertainty (mK)	0.37
Uncertainty components, Type A estimate (mK)	
Repeatability of the measurements	0.05
Type A combined uncertainty (mK)	0.05
Standard combined uncertainty (*k*=1) (mK)	**0.37**
Expanded uncertainty (*k*=2) (mK)	**0.74**

B.3. Triple point of neon

Since the CCT-K2.4 comparison measurements were carried out, the LNE-Cnam has used the new generation neon cell number Ne02/1. The characteristics of the cell were investigated by LNE-Cnam and NMi-VSL [B.1]. The CCT-K2.4 measurements were carried out at the end of 2005 in the liquid-cooled adiabatic calorimeter, with an ASL model F18 resistance bridge and a Tinsley standard resistor of nominal value 1 Ω, compatible with AC and DC resistance bridges. New measurements were performed at the end of 2006 with the same apparatus, after having moved to the new laboratory, and two other runs were performed in 2007 in the cryocooler-based adiabatic calorimeter. Thermometer 1041 was used to link the new measurements to the CCT-K2.

B.3.1 Correction to CCT-K2 Key Comparison Reference Value (KCRV) for Ne

In order to correctly compare the CCT-K2 measurements with the new ones, it must be remembered that the CCT-K2 measurements were performed *near* the neon triple point, so the reduced resistance W_{K2} given in CCT-K2 needs to be corrected to calculate the reduced resistance *at* the triple point value, $W_{Ne,K2}$. This is necessary to compare the CCT-K2 results with the subsequent ones carried out *at* the temperature of the triple point of neon.
The value of W_{K2} in CCT-K2 is W_{K2} = 0.008 524 861 (see Table 14 in [B.2]) while the calibration value supplied in CCT-K2 by the LNE-Cnam at the neon triple point is $W_{Ne,LNE\text{-}Cnam}$ = 0.008 530 388 (see Table 1 in [B.2]). Using the ITS-90, we can estimate the sensitivity of the thermometer at $W_{Ne,LNE\text{-}Cnam}$ obtaining $S_{Ne} = 1.2344\cdot10^{-3}\ K^{-1}$. S_{Ne} allows conversions from reduced resistances to temperatures. Table 14 in [B.2] gives the difference between T_{K2} – the temperature associated with W_{K2} – and the KCRV near the neon point for thermometer 1041:
T_{K2} – KCRV = -1.88 mK

It is possible to correct W_{K2} to obtain the reduced resistance of CSPRT 1041 *at* the KCRV value:

$W_{KCRV} = W_{K2} - (T_{K2} - KCRV) \cdot S_{Ne} = 0.008\ 527\ 182$

W_{KCRV} is the resistance *at* the KCRV, while $W_{Ne,LNE\text{-}Cnam}$ is the resistance *at* the triple point. It is possible to determine the difference between the KCRV and the triple point temperature:

$\Delta T_{KCRV,Ne} = KCRV - T_{Ne,LNE\text{-}Cnam} = (W_{KCRV} - W_{Ne,LNE\text{-}Cnam})/S_{Ne} = -2.60$ mK

$\Delta T_{KCRV,Ne}$ is the correction to be applied to the thermometers of Group B Table 14 in [B.2] to obtain the reduced resistance value W *at* the triple point temperature. By applying the correction $\Delta T_{KCRV,Ne}$ to the reduced resistance W_{K2} of thermometer 1041, we obtain the CCT-K2 value *at* the triple point value:

$\mathbf{W_{Ne,K2}} = W_{K2} - \Delta T_{KCRV,Ne} \cdot S_{Ne} = \mathbf{0.008\ 528\ 067}$

B.3.2 Data at the triple point of neon

The value of $W_{Ne,K2}$ is reported in Table B.3 together with subsequent measurements of the reduced resistances W for thermometer 1041. A graphical representation is given in Figure B.2. The standard deviation calculated from the values in Table B.3 is $\sigma_W = 1.25 \cdot 10^{-7}$, and its temperature equivalent is $\sigma_{T,W} = 0.10$ mK.

Table B.3. Reduced resistances for thermometer 1041 at the neon triple point

Date	**Cryostat**	**W** ***(symbol)***	**W** ***(value)***
1997 – 1999 $W_{Ne,K2}$ *(CCT-K2)*	NRC cryostat	$W_{Ne,K2}$	0.008 528 067
November 2005 *CCT-K2.4*	Liquid-cooled adiabatic calorimeter	$W_{Ne,K2.4}$	0.008 527 721
January 2007	Liquid-cooled adiabatic calorimeter (*moved to new laboratory)*	$W_{Ne,jan\text{-}2007}$	0.008 527 940
June 2007	Cryocooler-based adiabatic calorimeter	$W_{Ne,jun\text{-}2007}$	0.008 527 915
November 2007	Cryocooler-based adiabatic calorimeter	$W_{Ne,nov\text{-}2007}$	0.008 527 943

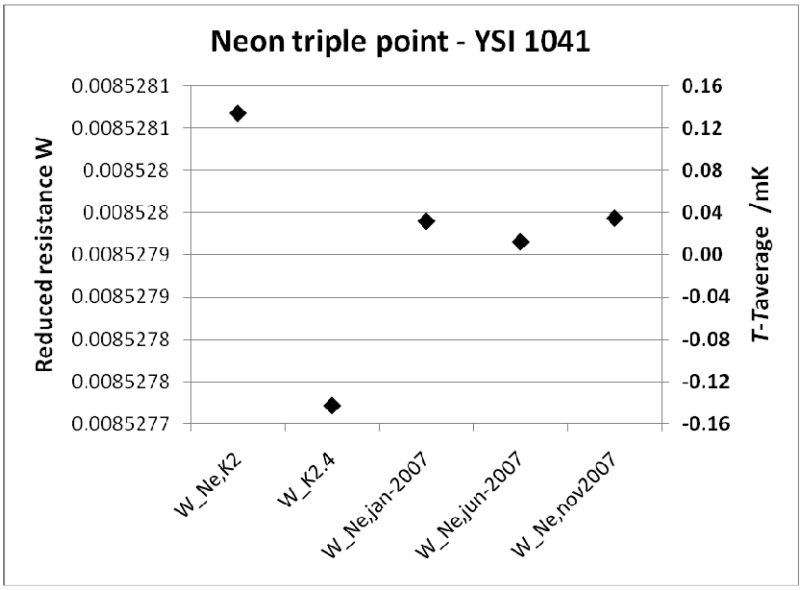

Figure B.2. Reduced resistances for thermometer 1041 at the neon triple point

B.3.3 Uncertainty budget for the calibration of platinum thermometers at the triple point of neon

Data from the measurements shown in Table B.3 are used to evaluate the uncertainties associated with the calibration of a SPRT at the neon triple point. The different contributions are listed and explained hereunder and the detailed budget is given in Table B.4.

B.3.3.1 Triple point value
The uncertainty contribution at the triple point value is given by the standard deviation $\sigma_{T,W}$ calculated from the values of Table B.3, as previously illustrated.

B.3.3.2 Electrical measurements
Same evaluation as made for the hydrogen triple point.

B.3.3.3 Self-heating
The resistance of the thermometer is extrapolated at 0 mA from measurements performed at two different currents in the ratio √2. The uncertainty of the self-heating is calculated by combining the noise uncertainties at the two measuring currents [B.6].

B.3.3.4 Spurious heat flux
The uncertainty contribution associated with the spurious heat flux is calculated in the same way as shown for the hydrogen triple point.

B.3.3.5 Isotopic composition
Several studies on the effects of the variability of the isotopic composition of neon on the triple point temperature are in progress. The problem of the variability in samples of commercial origin became known in 2003. At the present time, a preliminary international study [B.7], carried out on the samples commonly used for the filling of triple point cells, shows that the spread of triple point values – related to isotopic composition variations in the samples – is ~0.24 mK. Failing any other exhaustive study, this value is used for the uncertainty contribution due to isotopic composition.

B.3.3.6 Interpretation of the plateau

Measurements are performed at 50% of solid melted. The realization of the plateau is fully automated and a minimum of ten heat pulses is applied to melt the substance. Considering the hypothesis of being able to locate the 50% point of the plateau within the 38% to 62% melted fraction, and considering that the full melting range of the cell Ne02/1 is 0.13 mK[10], the uncertainty from interpretation of the plateau is 24%·0.13 mK ≈ 0.03 mK.

Table B.4. Detailed uncertainty budget for the calibration of a standard platinum thermometer at the neon triple point

Fixed point	Ne
Substance purity	6N
Uncertainty components, Type B estimate (mK)	
Triple point value	0.10
Electrical measurements	0.10
Self heating	0.05
Spurious heat flux	0.08
Hydrostatic pressure effect	0.00
Isotopic composition	0.24
Interpretation of the plateau	0.03
Type B combined uncertainty (mK)	0.30
Uncertainty components, Type A estimate (mK)	
Repeatability of the measurements	0.04
Type A combined uncertainty (mK)	0.04
Standard combined uncertainty (*k*=1) (mK)	**0.30**
Expanded uncertainty (*k*=2) (mK)	**0.60**

References

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[10] This value was measured by LNE-Cnam and NMi-VSL during the measurements performed for the characterization of the new generation “Improved M-cells” [B.1]. Nevertheless, though the measurements on the plateau width performed by the two laboratories were in agreement, they were not published in this paper.

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Appendix C

Tables of bilateral equivalence, including links to the original CCT-K2 data. The elements above the diagonal are the pair differences (in mK) and their expanded (*k*=2) uncertainty. The $QDE_{0.95}$ confidence intervals for pairwise agreement are given below the diagonal. Further information is found in the CCT-K2 report. The linked results for INTiBS are shown in green. The hydrogen and neon results for LNE-Cnam are shown in dark blue.

Table C.1: Linked bilateral equivalence matrix for comparison measurements near the hydrogen triple point.

H_2 Group A	BNM	IMGC	NIST	NPL	NRC	KCRV	VNIIFTRI	INTiBS	LNE-INM
BNM	-	-2.39 ± 4.17	-3.13 ± 4.17	-2.78 ± 4.18	-2.45 ± 4.19	-2.71 ± 4.16	-1.29 ± 4.39	-3.54 ± 4.24	-2.83 ± 4.26
IMGC	*5.83*	-	-0.74 ± 0.47	-0.39 ± 0.53	-0.06 ± 0.56	-0.32 ± 0.32	1.10 ± 1.44	-1.15 ± 0.90	-0.44 ± 0.97
NIST	*6.56*	*1.12*	-	0.35 ± 0.54	0.68 ± 0.57	0.42 ± 0.34	1.84 ± 1.44	-0.41 ± 0.91	0.30 ± 0.98
NPL	*6.22*	*0.82*	*0.79*	-	0.33 ± 0.62	0.07 ± 0.42	1.49 ± 1.46	-0.76 ± 0.94	-0.05 ± 1.01
NRC	*5.90*	*0.56*	*1.15*	*0.84*	-	-0.26 ± 0.46	1.16 ± 1.47	-1.09 ± 0.96	-0.38 ± 1.03
KCRV	*6.14*	*0.58*	*0.70*	*0.43*	*0.64*	-	1.42 ± 1.40	-0.83 ± 0.84	-0.12 ± 0.92
VNIIFTRI	*4.97*	*2.28*	*3.02*	*2.69*	*2.37*	*2.57*	-	-2.25 ± 1.63	-1.54 ± 1.68
INTiBS	*7.03*	*1.89*	*1.16*	*1.53*	*1.88*	*1.52*	*3.59*	-	0.71 ± 1.25
LNE-INM	*6.34*	*1.25*	*1.12*	*0.99*	*1.23*	*0.93*	*2.92*	*1.74*	-

H_2 Group B	BNM	IMGC	NIST	NPL	NRC	PTB	KCRV	VNIIFTRI	INTiBS	LNE-INM
BNM	-	-2.43 ± 4.17	-3.02 ± 4.17	-2.55 ± 4.18	-2.33 ± 4.19	-2.58 ± 4.18	-2.60 ± 4.16	-1.17 ± 4.39	-3.42 ± 4.24	-2.71 ± 4.26
IMGC	*5.87*	-	-0.59 ± 0.47	-0.12 ± 0.48	0.10 ± 0.56	-0.15 ± 0.54	-0.17 ± 0.32	1.26 ± 1.44	-0.99 ± 0.90	-0.28 ± 0.97
NIST	*6.45*	*0.97*	-	0.47 ± 0.50	0.69 ± 0.57	0.44 ± 0.56	0.42 ± 0.34	1.85 ± 1.44	-0.40 ± 0.91	0.31 ± 0.98
NPL	*5.99*	*0.53*	*0.88*	-	0.22 ± 0.58	-0.03 ± 0.57	-0.05 ± 0.36	1.38 ± 1.45	-0.87 ± 0.91	-0.16 ± 0.99
NRC	*5.78*	*0.58*	*1.16*	*0.70*	-	-0.25 ± 0.64	-0.27 ± 0.46	1.16 ± 1.47	-1.09 ± 0.96	-0.38 ± 1.03
PTB	*6.03*	*0.61*	*0.90*	*0.56*	*0.78*	-	-0.02 ± 0.44	1.41 ± 1.47	-0.84 ± 0.95	-0.13 ± 1.02
KCRV	*6.03*	*0.43*	*0.70*	*0.37*	*0.65*	*0.43*	-	1.43 ± 1.40	-0.82 ± 0.84	-0.11 ± 0.92
VNIIFTRI	*4.86*	*2.44*	*3.03*	*2.57*	*2.37*	*2.62*	*2.58*	-	-2.25 ± 1.63	-1.54 ± 1.68
INTiBS	*6.91*	*1.73*	*1.15*	*1.62*	*1.88*	*1.62*	*1.51*	*3.59*	-	0.71 ± 1.25
LNE-INM	*6.22*	*1.10*	*1.13*	*1.02*	*1.23*	*1.03*	*0.92*	*2.92*	*1.74*	-

Table C.2: Linked bilateral equivalence matrix for comparison measurements near the neon triple point.

Ne Group A	BNM	IMGC	KRISS	NIST	NPL	NRC	KCRV	VNIIFTRI	INTiBS	LNE-INM
BNM	-	-0.13 ± 1.12	-0.03 ± 1.15	0.11 ± 1.13	0.08 ± 1.17	0.04 ± 1.17	-0.02 ± 1.08	-0.30 ± 1.28	0.22 ± 1.26	0.61 ± 1.33
IMGC	*1.12*	-	0.10 ± 0.49	0.24 ± 0.43	0.21 ± 0.52	0.17 ± 0.52	0.11 ± 0.28	-0.17 ± 0.74	0.35 ± 0.70	0.74 ± 0.83
KRISS	*1.13*	*0.52*	-	0.14 ± 0.51	0.11 ± 0.59	0.07 ± 0.59	0.01 ± 0.40	-0.27 ± 0.79	0.25 ± 0.75	0.64 ± 0.88
NIST	*1.12*	*0.59*	*0.57*	-	-0.03 ± 0.54	-0.07 ± 0.54	-0.13 ± 0.32	-0.41 ± 0.75	0.11 ± 0.72	0.50 ± 0.84
NPL	*1.15*	*0.64*	*0.62*	*0.53*	-	-0.04 ± 0.62	-0.10 ± 0.44	-0.38 ± 0.81	0.14 ± 0.78	0.53 ± 0.90
NRC	*1.14*	*0.61*	*0.60*	*0.55*	*0.61*	-	-0.06 ± 0.44	-0.34 ± 0.81	0.18 ± 0.78	0.57 ± 0.90
KCRV	*1.06*	*0.34*	*0.39*	*0.40*	*0.47*	*0.45*	-	-0.28 ± 0.68	0.24 ± 0.64	0.63 ± 0.78
VNIIFTRI	*1.38*	*0.79*	*0.93*	*1.03*	*1.05*	*1.01*	*0.84*	-	0.52 ± 0.93	0.91 ± 1.03
INTiBS	*1.30*	*0.93*	*0.88*	*0.73*	*0.81*	*0.84*	*0.77*	*1.29*	-	0.39 ± 1.01
LNE-INM	*1.71*	*1.42*	*1.36*	*1.19*	*1.27*	*1.31*	*1.27*	*1.76*	*1.23*	-

Ne Group B	BNM	IMGC	KRISS	NIST	NPL	NRC	PTB	KCRV	VNIIFTRI	INTiBS	LNE-INM
BNM	-	-1.99 ± 2.81	-1.73 ± 2.83	-1.92 ± 2.82	-1.69 ± 2.83	-1.76 ± 2.83	-2.14 ± 2.83	-1.88 ± 2.80	-2.10 ± 2.88	-1.58 ± 2.87	-1.19 ± 2.91
IMGC	*4.31*	-	0.26 ± 0.49	0.07 ± 0.43	0.30 ± 0.47	0.23 ± 0.52	-0.15 ± 0.49	0.11 ± 0.28	-0.11 ± 0.74	0.41 ± 0.70	0.80 ± 0.83
KRISS	*4.06*	*0.66*	-	-0.19 ± 0.51	0.04 ± 0.55	-0.03 ± 0.59	-0.41 ± 0.57	-0.15 ± 0.40	-0.37 ± 0.79	0.15 ± 0.75	0.54 ± 0.88
NIST	*4.24*	*0.44*	*0.62*	-	0.23 ± 0.50	0.16 ± 0.54	-0.22 ± 0.51	0.04 ± 0.32	-0.18 ± 0.75	0.34 ± 0.72	0.73 ± 0.84
NPL	*4.02*	*0.69*	*0.54*	*0.64*	-	-0.07 ± 0.58	-0.45 ± 0.55	-0.19 ± 0.38	-0.41 ± 0.78	0.11 ± 0.74	0.50 ± 0.87
NRC	*4.09*	*0.66*	*0.58*	*0.62*	*0.58*	-	-0.38 ± 0.59	-0.12 ± 0.44	-0.34 ± 0.81	0.18 ± 0.78	0.57 ± 0.90
PTB	*4.47*	*0.56*	*0.88*	*0.64*	*0.90*	*0.87*	-	0.26 ± 0.40	0.04 ± 0.79	0.56 ± 0.75	0.95 ± 0.88
KCRV	*4.19*	*0.34*	*0.48*	*0.32*	*0.50*	*0.49*	*0.59*	-	-0.22 ± 0.68	0.30 ± 0.64	0.69 ± 0.78
VNIIFTRI	*4.47*	*0.75*	*1.02*	*0.82*	*1.05*	*1.01*	*0.78*	*0.79*	-	0.52 ± 0.93	0.91 ± 1.03
INTiBS	*3.95*	*0.99*	*0.80*	*0.93*	*0.76*	*0.84*	*1.18*	*0.83*	*1.29*	-	0.39 ± 1.01
LNE-INM	*3.60*	*1.48*	*1.26*	*1.42*	*1.21*	*1.31*	*1.67*	*1.33*	*1.76*	*1.23*	-

Table C.3: Linked bilateral equivalence matrix for comparison measurements near the oxygen triple point.

O_2 Group A	BNM	IMGC	KRISS	NIST	NPL	NRC	KCRV	VNIIFTRI	INTiBS
BNM	-	0.13 ± 0.57	-0.16 ± 0.62	-0.14 ± 0.56	-0.09 ± 0.63	-0.25 ± 0.68	-0.07 ± 0.52	0.09 ± 0.86	-0.39 ± 0.86
IMGC	*0.62*	-	-0.29 ± 0.42	-0.27 ± 0.31	-0.22 ± 0.43	-0.38 ± 0.50	-0.20 ± 0.24	-0.04 ± 0.72	-0.52 ± 0.72
KRISS	*0.68*	*0.63*	-	0.02 ± 0.39	0.07 ± 0.50	-0.09 ± 0.56	0.09 ± 0.34	0.25 ± 0.76	-0.23 ± 0.76
NIST	*0.61*	*0.53*	*0.39*	-	0.05 ± 0.41	-0.11 ± 0.48	0.07 ± 0.20	0.23 ± 0.71	-0.25 ± 0.71
NPL	*0.64*	*0.58*	*0.50*	*0.41*	-	-0.16 ± 0.57	0.02 ± 0.36	0.18 ± 0.77	-0.30 ± 0.77
NRC	*0.82*	*0.79*	*0.57*	*0.52*	*0.64*	-	0.18 ± 0.44	0.34 ± 0.81	-0.14 ± 0.81
KCRV	*0.53*	*0.40*	*0.38*	*0.24*	*0.35*	*0.54*	-	0.16 ± 0.68	-0.32 ± 0.68
VNIIFTRI	*0.85*	*0.71*	*0.88*	*0.82*	*0.83*	*1.01*	*0.74*	-	-0.48 ± 0.96
INTiBS	*1.10*	*1.11*	*0.87*	*0.84*	*0.94*	*0.84*	*0.88*	*1.27*	-

O_2 Group B	BNM	IMGC	KRISS	NIST	NPL	NRC	PTB	KCRV	VNIIFTRI	INTiBS
BNM	-	0.17 ± 0.55	-0.09 ± 0.60	0.06 ± 0.55	-0.05 ± 0.58	-0.23 ± 0.67	-0.17 ± 0.68	0.01 ± 0.50	0.11 ± 0.84	-0.37 ± 0.84
IMGC	*0.63*	-	-0.26 ± 0.42	-0.11 ± 0.34	-0.22 ± 0.38	-0.40 ± 0.50	-0.34 ± 0.52	-0.16 ± 0.24	-0.06 ± 0.72	-0.54 ± 0.72
KRISS	*0.62*	*0.60*	-	0.15 ± 0.42	0.04 ± 0.45	-0.14 ± 0.56	-0.08 ± 0.57	0.10 ± 0.34	0.20 ± 0.76	-0.28 ± 0.76
NIST	*0.55*	*0.39*	*0.50*	-	-0.11 ± 0.38	-0.29 ± 0.50	-0.23 ± 0.52	-0.05 ± 0.24	0.05 ± 0.72	-0.43 ± 0.72
NPL	*0.58*	*0.54*	*0.45*	*0.43*	-	-0.18 ± 0.53	-0.12 ± 0.55	0.06 ± 0.30	0.16 ± 0.74	-0.32 ± 0.74
NRC	*0.78*	*0.81*	*0.61*	*0.70*	*0.62*	-	0.06 ± 0.64	0.24 ± 0.44	0.34 ± 0.81	-0.14 ± 0.81
PTB	*0.74*	*0.77*	*0.58*	*0.66*	*0.59*	*0.63*	-	0.18 ± 0.46	0.28 ± 0.82	-0.20 ± 0.82
KCRV	*0.49*	*0.36*	*0.38*	*0.25*	*0.32*	*0.60*	*0.56*	-	0.10 ± 0.68	-0.38 ± 0.68
VNIIFTRI	*0.85*	*0.71*	*0.84*	*0.71*	*0.79*	*1.01*	*0.96*	*0.69*	-	-0.48 ± 0.96
INTiBS	*1.07*	*1.13*	*0.91*	*1.02*	*0.94*	*0.84*	*0.89*	*0.94*	*1.27*	-

Table C.4: Linked bilateral equivalence matrix for comparison measurements near the argon triple point.

Ar Group A	BNM	IMGC	KRISS	NIST	NPL	NRC	KCRV	VNIIFTRI	INTiBS
BNM	-	0.27 ± 0.45	-0.48 ± 0.52	0.07 ± 0.45	0.10 ± 0.52	-0.11 ± 0.59	0.07 ± 0.40	-0.20 ± 0.75	-0.38 ± 0.75
IMGC	*0.64*	-	-0.75 ± 0.39	-0.20 ± 0.28	-0.17 ± 0.39	-0.38 ± 0.48	-0.20 ± 0.20	-0.47 ± 0.67	-0.65 ± 0.67
KRISS	*0.91*	*1.07*	-	0.55 ± 0.39	0.58 ± 0.48	0.37 ± 0.56	0.55 ± 0.34	0.28 ± 0.72	0.10 ± 0.72
NIST	*0.46*	*0.43*	*0.87*	-	0.03 ± 0.39	-0.18 ± 0.48	0.00 ± 0.20	-0.27 ± 0.67	-0.45 ± 0.67
NPL	*0.55*	*0.50*	*0.98*	*0.39*	-	-0.21 ± 0.56	-0.03 ± 0.34	-0.30 ± 0.72	-0.48 ± 0.72
NRC	*0.62*	*0.78*	*0.83*	*0.58*	*0.67*	-	0.18 ± 0.44	-0.09 ± 0.78	-0.27 ± 0.78
KCRV	*0.41*	*0.36*	*0.83*	*0.20*	*0.34*	*0.54*	-	-0.27 ± 0.64	-0.45 ± 0.64
VNIIFTRI	*0.84*	*1.02*	*0.88*	*0.83*	*0.90*	*0.78*	*0.80*	-	-0.18 ± 0.91
INTiBS	*1.00*	*1.20*	*0.74*	*1.00*	*1.08*	*0.92*	*0.98*	*0.95*	-

Ar Group B	BNM	IMGC	KRISS	NIST	NPL	NRC	PTB	KCRV	VNIIFTRI	INTiBS
BNM	-	0.20 ± 0.48	0.10 ± 0.56	0.07 ± 0.49	0.15 ± 0.51	-0.13 ± 0.62	-0.11 ± 0.61	0.11 ± 0.44	-0.22 ± 0.78	-0.40 ± 0.78
IMGC	*0.60*	-	-0.10 ± 0.39	-0.13 ± 0.30	-0.05 ± 0.33	-0.33 ± 0.48	-0.31 ± 0.47	-0.09 ± 0.20	-0.42 ± 0.67	-0.60 ± 0.67
KRISS	*0.58*	*0.43*	-	-0.03 ± 0.40	0.05 ± 0.43	-0.23 ± 0.56	-0.21 ± 0.54	0.01 ± 0.34	-0.32 ± 0.72	-0.50 ± 0.72
NIST	*0.50*	*0.38*	*0.40*	-	0.08 ± 0.34	-0.20 ± 0.49	-0.18 ± 0.47	0.04 ± 0.22	-0.29 ± 0.68	-0.47 ± 0.68
NPL	*0.58*	*0.34*	*0.43*	*0.37*	-	-0.28 ± 0.51	-0.26 ± 0.49	-0.04 ± 0.26	-0.37 ± 0.69	-0.55 ± 0.69
NRC	*0.66*	*0.73*	*0.69*	*0.61*	*0.70*	-	0.02 ± 0.61	0.24 ± 0.44	-0.09 ± 0.78	-0.27 ± 0.78
PTB	*0.63*	*0.69*	*0.66*	*0.57*	*0.67*	*0.60*	-	0.22 ± 0.42	-0.11 ± 0.77	-0.29 ± 0.77
KCRV	*0.48*	*0.26*	*0.33*	*0.23*	*0.27*	*0.60*	*0.57*	-	-0.33 ± 0.64	-0.51 ± 0.64
VNIIFTRI	*0.87*	*0.97*	*0.92*	*0.85*	*0.94*	*0.78*	*0.78*	*0.86*	-	-0.18 ± 0.91
INTiBS	*1.04*	*1.15*	*1.10*	*1.03*	*1.12*	*0.92*	*0.93*	*1.04*	*0.95*	-

Table C.5: Linked bilateral equivalence matrix for comparison measurements near the mercury triple point.

Hg Group A	BNM	IMGC	KRISS	NIST	NPL	NRC	KCRV	VNIIFTRI	INTiBS
BNM	-	-0.17 ± 0.59	-0.11 ± 0.76	-0.35 ± 0.63	-0.34 ± 0.68	-0.09 ± 0.71	-0.23 ± 0.56	0.03 ± 1.04	0.22 ± 0.88
IMGC	*0.67*	-	0.06 ± 0.56	-0.18 ± 0.34	-0.17 ± 0.43	0.08 ± 0.48	-0.06 ± 0.20	0.20 ± 0.90	0.39 ± 0.71
KRISS	*0.78*	*0.56*	-	-0.24 ± 0.59	-0.23 ± 0.64	0.02 ± 0.68	-0.12 ± 0.52	0.14 ± 1.02	0.33 ± 0.86
NIST	*0.87*	*0.46*	*0.73*	-	0.01 ± 0.47	0.26 ± 0.52	0.12 ± 0.28	0.38 ± 0.92	0.57 ± 0.74
NPL	*0.90*	*0.53*	*0.77*	*0.46*	-	0.25 ± 0.58	0.11 ± 0.38	0.37 ± 0.96	0.56 ± 0.78
NRC	*0.72*	*0.50*	*0.67*	*0.69*	*0.73*	-	-0.14 ± 0.44	0.12 ± 0.98	0.31 ± 0.81
KCRV	*0.69*	*0.23*	*0.56*	*0.35*	*0.43*	*0.51*	-	0.26 ± 0.88	0.45 ± 0.68
VNIIFTRI	*1.02*	*0.97*	*1.04*	*1.14*	*1.17*	*0.99*	*1.00*	-	0.19 ± 1.11
INTiBS	*0.96*	*0.97*	*1.04*	*1.18*	*1.20*	*0.98*	*1.01*	*1.15*	-

Hg Group B	BNM	IMGC	KRISS	NIST	NPL	NRC	PTB	KCRV	VNIIFTRI	INTiBS
BNM	-	-0.80 ± 0.59	-1.10 ± 0.76	-0.96 ± 0.61	-0.85 ± 0.66	-0.73 ± 0.71	-0.93 ± 0.68	-0.87 ± 0.56	-0.61 ± 1.04	-0.42 ± 0.88
IMGC	*1.29*	-	-0.30 ± 0.56	-0.16 ± 0.31	-0.05 ± 0.39	0.07 ± 0.48	-0.13 ± 0.43	-0.07 ± 0.20	0.19 ± 0.90	0.38 ± 0.71
KRISS	*1.73*	*0.76*	-	0.14 ± 0.57	0.25 ± 0.62	0.37 ± 0.68	0.17 ± 0.64	0.23 ± 0.52	0.49 ± 1.02	0.68 ± 0.86
NIST	*1.46*	*0.42*	*0.62*	-	0.11 ± 0.42	0.23 ± 0.50	0.03 ± 0.45	0.09 ± 0.24	0.35 ± 0.91	0.54 ± 0.72
NPL	*1.39*	*0.40*	*0.76*	*0.46*	-	0.12 ± 0.56	-0.08 ± 0.51	-0.02 ± 0.34	0.24 ± 0.94	0.43 ± 0.76
NRC	*1.32*	*0.49*	*0.93*	*0.64*	*0.59*	-	-0.20 ± 0.58	-0.14 ± 0.44	0.12 ± 0.98	0.31 ± 0.81
PTB	*1.49*	*0.49*	*0.71*	*0.44*	*0.52*	*0.68*	-	0.06 ± 0.38	0.32 ± 0.96	0.51 ± 0.78
KCRV	*1.33*	*0.24*	*0.66*	*0.29*	*0.33*	*0.51*	*0.39*	-	0.26 ± 0.88	0.45 ± 0.68
VNIIFTRI	*1.47*	*0.96*	*1.33*	*1.11*	*1.04*	*0.99*	*1.12*	*1.00*	-	0.19 ± 1.11
INTiBS	*1.15*	*0.96*	*1.38*	*1.13*	*1.06*	*0.98*	*1.15*	*1.01*	*1.15*	-