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Thermodynamic temperature measurements of the melting temperatures of Co-C, Pt-C, and Re-C fixed points at NRC

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Abstract. This article outlines measurements made at the National Research Council Canada (NRC) of the thermodynamic melting temperatures of Co-C, Pt-C and Re-C fixed points that have been part of the high-temperature fixed point research plan of Working Group 5 of the Consultative Committee for Thermometry (CCT-WG5) to assign melting temperatures to those fixed points. This document will outline the equipment used; describe the scheme used to calibrate a pyrometer with traceability to a cryogenic electrical substitution radiometer and; detail the method of measuring the fixed points. It will then report the uncertainties in the measurements and the results. A brief description of the improvements that we plan to implement to the scheme to reduce the uncertainties for future measurements will be given. The thermodynamic temperatures determined for the three fixed points are: 1597.776 K with an expanded uncertainty of 0.36 K; 2011.390 K with an expanded uncertainty of 0.55 K; and 2748.056 K with an expanded uncertainty of 0.95 K, for the Co-C, Pt-C and Re-C fixed points, respectively (all expanded uncertainties assume a 95 % confidence interval and a Gaussian distribution).

1. Introduction

Low-uncertainty determination of the thermodynamic melting temperatures of the high-temperature eutectic fixed-points (HTFPs) of Co-C, Pt-C and Re-C is essential to the upcoming implementation of the *Mise en pratique for the definition of the kelvin* (MeP-K) [1]. The discovery of metal-carbon (M-C) eutectic fixed points by Yamada *et al.* in 1999 [2] brought about the development of reproducible temperature reference points above the freezing point of copper. Since then a number of studies have been published that have assessed the repeatability and stability of various M-C and metal carbide-carbon (MC-C) eutectic fixed points (see review by Woolliams *et al.* [3]).

The high-temperature fixed point research plan of Working Group 5 of the Consultative Committee for Thermometry (CCT-WG5) has been working to develop high temperature fixed-points to be used as low-uncertainty temperature reference points for thermometry. This research plan includes investigating long-term stability of the fixed points, construction methods, uncertainties, a preliminary assessment of how well the temperatures of the fixed points can be determined, and a final determination of the transition temperature of a set of fixed points.

As part of this research plan, national metrology institutes (NMIs) from around the world need to measure the thermodynamic melting temperatures of these fixed points with independent traceability to an electrical substitution cryogenic radiometer. Schemes to measure the thermodynamic melting temperature of HTFPs vary from NMI to NMI but generally involve a filter radiometer (FR) that has had its absolute spectral response calibrated with respect to a transfer detector which has been calibrated with respect to a cryogenic radiometer. A number of these methods are described in [1] and [4]. Anhalt *et al.* described a method to measure the thermodynamic melting temperature of fixed points of Co-C, Pd-C, Pt-C and Ru-C using a pyrometer [5]. Prior to measuring the fixed point melting transition, the pyrometer measured the output of a reference blackbody source which was stabilized near the transition temperature. The thermodynamic temperature of blackbody source was determined by a filter radiometer calibrated with traceability to a cryogenic radiometer.

A Work Package (WP4) of the CCT-WG5 high-temperature fixed point research plan was envisaged to assess the ability of NMIs to realize thermodynamic temperature and measure the absolute melting temperature of high-temperature fixed points [6]. This work package used two loops, each loop measuring one each of Co-C, Pt-C and Re-C. Physikalisch-Technische Bundesanstalt (PTB) piloted the measurements and measured all the fixed points at the start (2009) and end (2011) of the measurements. Loop 1 contained PTB, the National Physical Laboratory (NPL) and the National Measurement Institute of Australia (NMIA). Loop 2 contained PTB, Laboratoire Commun de Métrologie (LNE-Cnam), the All-Russian Research Institute for Optical and Physical Measurements (VNIIOFI) and NRC. The full description and results of this work package were presented in [7]. Here, we describe the measurement method, uncertainties, and results obtained by NRC that contributed to this work package and the plans to improve the method used. Work Package 4 is one step in the preparation to definitively measure and assign the absolute melting temperatures to these fixed points.

2. Experiment and Method

2.1. Furnace used

The furnace used for the measurements of the three fixed points was a BB3500M furnace (HTBB) [8]. The arrangement of the pyrolytic graphite rings that form the heater tube had not been optimized. The position of the fixed point within the furnace was chosen for each fixed-point type based on measurements of the fixed-point melting and freezing plateaus in different locations within the furnace. The location that provided the best melting curve (smallest melting plateau slope, sharpest transition on to and off of the melting plateau) was used for the subsequent fixed-point measurements. This furnace, used in blackbody mode, was also used to transfer a calibration from a filter radiometer to the NRC pyrometer which was used to measure the fixed-point melting and freezing curves.

Each fixed point was held in the furnace using a graphite holder tube installed between the rings that make up the furnace tube. A different holder tube was used for each fixed-point type and the fixed point was installed within the tube using the graphite felt provided with each fixed point. The furnace heater tube and fixed-point holders were baked in the furnace before each fixed point was measured. The Co-C fixed point holder was baked at 1500 °C in vacuum for 30 minutes and then for another 30 minutes in flowing Ar. The holder for the Pt-C fixed point was baked in vacuum for 90 minutes above 1900 °C and then for a further 30 minutes at the same temperature under a slowly-flowing (4.5 L/min) Ar atmosphere. The Re-C fixed-point holder was baked in vacuum for 90 minutes above 1900 °C and then for a further 60 minutes under a slowly-flowing (4.5 L/min) Ar atmosphere at a temperature above 2500 °C.

2.2. Fixed point measurement configuration

The fixed points were measured using the NRC LP3 pyrometer which had been focused (with the furnace at room temperature) on the fixed point aperture plane. The alignment of the LP3 to fixed point aperture was checked once the HTBB was near the transition temperature and adjusted as necessary. A constant distance of 72 cm from the front of the LP3's lens to the fixed point aperture was maintained for all the fixed point measurements. During the LP3-filter radiometer transfer calibration, a distance of 72 cm was also maintained from the LP3's lens to the blackbody aperture.

2.3. LP3 calibration

An LP3 radiation thermometer (IKE, Stuttgart) [9] was used to measure the melting and freezing temperatures of the high temperature fixed points. NRC's LP3 uses an interference filter with a centre wavelength of nominally 650 nm and a bandwidth of approximately 10 nm. To link the LP3 output signal to thermodynamic temperature, a chain of traceability was established to NRC's electrical substitution cryogenic radiometer [10] via a high-temperature blackbody, a FR and Si transfer standard detectors. This method is similar to that suggested

by Anhalt *et al.* [5] however, NRC's cryogenic radiometer facility is monochromator-based (as opposed to laser-based) and uses wide-band filter radiometers based on glass filters (as opposed to interference filters). Figure 1 shows a schematic of the calibration chain.

The first step in the chain was to calibrate Si transfer-standard detectors using NRC's monochromator-based cryogenic radiometer. Three vacuum-compatible detectors were calibrated in the range of 400 to 1000 nm in steps of 50 nm. The wide-band filter radiometer used in this work was constructed using a coloured-glass filter to give a nominal centre wavelength of 650 nm and a bandwidth of approximately 100 nm. The filter radiometer-unit contained a thermoelectric cooler to maintain it at a temperature of 30.0 °C during calibration and use. A 6.348 mm ($u = 0.0005$ mm) diameter aperture was integrated into the front of the FR housing. A tungsten-halogen source coupled into a double monochromator was used in conjunction with the Si transfer standards to measure the responsivity of the FR. The details of this calibration and the construction of the FR can be found in [11].

To transfer the calibration to the LP3, the HTBB was set to operate close to the melting temperature of one of the fixed-point types. To ensure a well-stabilized blackbody, the HTBB heating current was increased at a rate of 4 A/min (≈ 18 K/min) to a value slightly above what was expected to be required to realize the desired temperature. When the furnace was close to the desired temperature, the current was manually adjusted until the required temperature was achieved. Once stable, the HTBB's feedback control system was enabled. With the HTBB stabilized and under feedback control, the LP3 was moved into position in front of the HTBB for five minutes and the signal was recorded. Then, a five minute measurement using the FR determined the temperature of the HTBB. The LP3 was then moved back into place in front of the HTBB to verify that its temperature had not changed. This was repeated several times over the course of the day. The LP3 was focused on the HTBB aperture and was placed 72 cm from the HTBB aperture. The LP3's spot-size on the furnace septum was slightly larger than the calculated spot-size of the FR. Horizontal and vertical scans of the HTBB aperture showed no detectable change in temperature. This obviated the need to correct for differences in the field-of-view of the LP3 and the FR. To enable temperature measurement with the FR, a 8.560 mm ($u = 0.0007$ mm) diameter aperture was placed in front of the HTBB and the distance between this aperture and the aperture of the FR was set using a gauge bar 0.913063 m in length. The blackbody aperture was water cooled and held at constant temperature of 19.5 °C. This sequence of calibration was repeated near each fixed-point transition temperature both before and after the actual fixed point melting measurements. Figure 2 shows the difference between the blackbody temperature determined by the filter radiometer and the temperature indicated by the LP3. The $\bigcirc$ indicate the difference between the LP3 and FR temperatures determined before the fixed points were measured and the $+$ indicated those determined after the fixed points were measured.

2.4. Inflection point determination

Inflection point determination was achieved by applying 10-point and 20-point smoothing to each plateau. Then, a cubic function was fit to each of the smoothed plateaux and the

un-smoothed plateau. The minimum of the derivative of the cubic functions determined the inflection point. The average of the inflection-point temperatures determined from both smoothed and un-smoothed plateaux was taken to be the inflection point. The standard deviation in the inflection point determined with the different smoothing routines was used to estimate the uncertainty in finding the inflection point of the plateaux.

3. Measurements

3.1. Co-C

Twenty melting plateaux were measured utilizing temperature offsets of nominally 10 and 20 K above the melting point. The melting plateaux were measured on five days and the fixed point was removed and reinstalled twice (between measurements 7 and 8 and 15 and 16). A representative melting plateau is shown in Figure 3.

The inflection point was determined for each of the melting plateaux and the correction to the LP3 temperature (determined during the LP3-FR transfer calibration) was applied. The corrected melting temperatures are shown in Figure 4 for the Co-C fixed point.

3.2. Pt-C

This was the first time that a Pt-C fixed point had been measured at NRC. The Pt-C fixed point melting and freezing curves were measured 30 times (2 plateaux were not included due to poor fits to the data). A melting curve representative of the 28 melting curves used to determine the fixed point melting temperature is shown in Figure 5. Mixed furnace offsets of nominally 10 and 20 K above the melting temperature were used to induce melting. It appears as though the furnace offset may have an effect on the melting temperature. When the 10 K offset was used (points 4, 19, 27 and 27 in Figure 6), the inflection-point temperature was found to be between 50 and 100 mK below the average melting temperature. The fixed point was removed and reinstalled in the holder between measurements 8 and 9 and between measurements 14 and 15. The corrected melting-curve inflection-point temperatures determined from the melting curves are shown in Figure 6.

3.3. Re-C

Twenty-nine melting plateaux were measured using the Re-C fixed point using nominal furnace offsets of 20 and 30 K (and one 15 K) above the melting temperature. The fixed point was removed and reinstalled between measurements 12 and 13. Figure 7 shows a typical melting curve. Initially, the fixed point did not appear to be stable although there was nothing in the measurement procedure, or in the shape of the melting curves, that would suggest that something was wrong with these measurements. The inflection points did appear to stabilize after measurement 12. We have chosen to include only measurements after the fixed point had stabilized (measurements 13 through 29, inclusive) in the calculation of the average melting temperature. It should be noted that the “before” and “after” measurements performed at PTB

(and reported in [7]) showed a drift in the temperature of the Re-C fixed point in Loop 2. The inflection point temperatures determined for the Re-C fixed point are shown in Figure 8.

4. Uncertainties in the T measurements

4.1. Uncertainties in the filter radiometer calibration

A detailed break-down of the uncertainty budget for the calibration of the filter radiometer has been given elsewhere [11] and so will only be briefly described here. The three Si transfer standards were calibrated against the cryogenic radiometer approximately six months before and again, one month after the measurements of the fixed points. The difference between the before and after measurements was used to estimate the uncertainty due to ageing of the transfer standard and the repeatability of its calibration. The filter radiometer was temperature controlled to within ± 0.5 °C which lead to an uncertainty in its response of 0.05 %. The wavelength uncertainty originates from the calibration of the monochromator used in the calibration. Table 1 shows the relative uncertainties associated with the filter radiometer calibration and Table 2 shows the resulting uncertainties in terms of temperature.

4.2. Uncertainties in the calibration of the LP3

Transfer of the calibration from the FR to the LP3 near the melting temperatures of the fixed points was performed before and after the LP3 was used to measure the melting curves of the fixed points. Table 3 gives the sources and magnitudes of the uncertainties associated with the transfer of the calibration from the FR to the LP3 for each temperature. The dominant sources of uncertainty are the FR calibration, the optical alignment of the filter radiometer, and the HTBB aperture to FR aperture distance. The optical alignment uncertainty was estimated to be 0.06 %, which translates into the temperature uncertainties (near the fixed point melting temperatures) that are shown in Table 3. The HTBB aperture to FR aperture distance uncertainty was estimated at 0.25 mm which leads to the temperature uncertainties given in line 3 of Table 3. This value is an estimate of how well the bar could be aligned to the apertures and is not limited by the uncertainty in the length of the bar. The standard deviation of all the measurements (before and after) of the transfer calibrations was calculated to be 0.030 K, 0.105 K, and 0.270 K for 1597 K, 2011 K, and 2747 K, respectively. These repeatability values fall within the uncertainties estimated for the calibration transfers.

4.3. Fixed-point measurement uncertainties

The dominant source of uncertainty for the measurements of the inflection point temperature of the melting curves is the calibration of the LP3. Table 4 gives the uncertainties estimated for the measurement of the fixed point melting temperatures. We have included the standard deviation of the inflection points for each fixed point which includes effects due to the inhomogeneity of the furnace and any effect due to re-installation of the fixed point in the furnace.

The emissivity was also a large contributor to the uncertainty in determining the temperature of the fixed point transitions. The LP3 calibration and the fixed point measurements were made using nominally the same central wavelength but an uncertainty of 0.0005 in the emissivity was included to account for uncertainties in the emissivities of the HTBB and the fixed points.

5. Results and conclusions

The thermodynamic melting temperatures of Co-C, Pt-C and Re-C fixed points were measured with a pyrometer that had been calibrated with traceability to a cryogenic radiometer. The uncertainties for this measurement were calculated at each of the fixed-point melting temperatures. The melting temperatures and uncertainties for each of the fixed points are given in Table 5. The values for the melting temperatures determined at NRC are in agreement with those determined by the other NMIs that participated in Work Package 4 [7] within the uncertainties of the measurements. A comparison of NRC's results to an average (weighted by the uncertainties) of the temperatures determined in Loop 2 is shown in Figure 9.

The measurements presented here are NRC's first attempt to measure the absolute melting temperatures of high temperature M-C eutectic fixed points. During this work, we have found some areas where we feel we can reduce our uncertainties for future measurements. Many users of the BB3500M/pg-type furnaces have improved their fixed-point measurements by measuring the resistivity of each of the pyrolytic graphite rings that make up the heater tube and ordering them to minimize the temperature gradient in the vicinity of the fixed point [12–14]. The measurements reported here were acquired using a furnace that had not been optimized. We intend to complete this optimization with the hope of improving the fixed-point measurements. Work is also underway to reduce the uncertainties in the calibration of the transfer standard using the cryogenic radiometer. We believe that the measurements of the fixed points would benefit from having a feedback control system to aid in setting repeatable melt and freeze offset temperatures. While the temperature of the FR was controlled, it was not monitored and the uncertainty in the FR's responsivity due to the uncertainty in how well the temperature was controlled was likely larger than necessary. The filter radiometer contained an encapsulated platinum resistance thermometer and for future measurements this thermometer will be monitored to ensure that the FR's temperature is stable.

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References

- [1] Machin G, Bloembergen P, Anhalt K, Hartmann J, Sadli M, Saunders P, Woolliams E R, Yamada Y, and Yoon H 2010 *Int. J. Thermophys.* **31** 1779-88
- [2] Yamada Y, Sakate H, Sakuma F and Ono A 2001 *Metrologia* **38** 213-19
- [3] Woolliams E R, Machin G, Lowe D H and Winkler R 2006 *Metrologia* **43** R11-R25
- [4] Machin G, Anhalt K, Bloembergen P, Hartmann J, Sadli M, Saunders P, Woolliams E R, Yamada Y, and Yoon H 2012 Realisation and dissemination of thermodynamic temperature above the silver point (1234.93 K) http://www.bipm.org/cc/CCT/Allowed/25/MeP_HT_v9.1.doc
- [5] Anhalt K, Hartmann J, Lowe D H, Machin G, Sadli M and Yamada Y 2006 *Metrologia* **43** S78-S83
- [6] Machin G, Yamada Y and Bloembergen P 2006 M(C)-C eutectic research plan - the next steps <http://www.bipm.org/wg/CCT/CCT-WG5/Allowed/Miscellaneous/CCT-WG5-docs-01.pdf>
- [7] Anhalt K, Machin G, Dury M, Yoon H, Sadli M, Khlevnoy B, Ballico M, Jahan F, Woods D J and Todd A D W 2012 A comparison of absolute radiometry by metal-carbon eutectic fixed-point. Presentation at *Temperature: its Measurement and Control in Science and Industry (ITS9)*, Anaheim California, 19-23 March 2012
- [8] Ogarev S A, Khlevnoy B B, Samoylov M L, Shapoval V I, Sapritsky V I and Sakharov M K 2004 New high-temperature pyrolytic graphite blackbody sources for precision measurements in radiation thermometry *Proc. 9th Symposium on Temperature and Thermal Measurements in Industry and Science (Tempmeko, 2004) (Dubrovnik-Cavtat Croatia)* (Zagreb, Croatia: Laboratory for Process Measurement, Faculty of Mechanical Engineering and Naval Architecture) pp 569-74
- [9] Fisher J, Neuer G, Schreiber E and Thomas R Metrological characterisation of a new transfer standard radiation thermometer *Proc. 8th Symposium on Temperature and Thermal Measurements in Industry and Science (Tempmeko, 2001) (Berlin, Germany)* pp 801-06
- [10] Boivin L P and Gibb K 1995/96 *Metrologia* **32** 565-70
- [11] Boivin L P, Bamber C, Gaertner A A, Gerson R K, Woods D J and Woolliams E R 2010 *J. Modern Optics* **57** 1648-60
- [12] Khlevnoy B, Sakharov M, Ogarev S, Sapritsky V, Yamada Y and Anhalt K 2008 *Int. J. Thermophys.* **29** 271-84
- [13] Sadli M, Anhalt K, Bourson F, Schiller S and Hartmann J 2009 *Int. J. Thermophys.* **30** 69-76
- [14] Salim S G R, Woolliams E R, Dury M, Lowe D H, Pearce J V, Machin G, Fox N P, Sun T and Grattan K T V 2009 *Metrologia* **46** 33-42

Tables

Table 1. Relative uncertainties ($k = 1$) for the filter radiometer calibration.

Item	Source	FR Response/ %
1	Calibration of Si transfer detectors	0.04
2	Wavelength (0.1 nm)	0.03
3	Ageing and repeatability of the Si transfer detector calibration	0.03
4	Temperature of Si transfer detector (2 °C)	0.01
5	Temperature of FR (± 0.5 °C)	0.05
6	Electrical Measurements	0.02
7	FR spatial non-uniformity	0.02
8	FR aperture area	0.03
9	Spectral truncation	0.02
	Combined	0.09

Table 2. Uncertainties ($k = 1$) in terms of temperature for the FR.

Temperature/ K	Uncertainty in FR Calibration/ K
1597	0.12
2011	0.18
2747	0.33

Table 3. Uncertainties ($k = 1$) in the LP3 Calibration.

Item	Source	Uncertainty near Co-C/ K	Uncertainty near Pt-C/ K	Uncertainty near Re-C/ K
1	FR calibration	0.115	0.179	0.329
2	HTBB stability	0.033	0.006	0.042
3	FR to HTBB aperture distance	0.031	0.094	0.141
4	FR optical alignment	0.077	0.120	0.220
5	Standard deviation in FR signal	0.043	0.031	0.046
6	Standard deviation in LP3 signal	0.048	0.031	0.061
7	HTBB aperture area	0.026	0.040	0.073
8	HTBB radiance non-uniformity	0.050	0.050	0.050
	Combined	0.17	0.25	0.44

Table 4. Uncertainties ($k = 1$) for fixed point measurements.

Item	Source	Uncertainty near Co-C/ K	Uncertainty near Pt-C/ K	Uncertainty near Re-C/ K
1	LP3 calibration	0.169	0.248	0.438
2	Inflection point determination	0.000	0.001	0.002
3	Inflection point repeatability	0.005	0.072	0.029
4	Emissivity	0.064	0.100	0.183
	Combined	0.18	0.28	0.48

Table 5. Temperatures and uncertainties for the fixed point measurements.

Fixed Point	Melting inflection point temperature/ K	Uncertainty, $k = 2$ / K
Co-C (CoC-7ST-7)	1597.776	0.36
Pt-C (PtCH16)	2011.390	0.55
Re-C (Re66S11)	2748.056	0.95

Figures

Figure 1. Schematic of the approach to calibrate the LP3 at approximately 1597 K, 2011 K, and 2747 K: a) calibration of the Si transfer detector using the cryogenic radiometer; b) calibration of the spectral responsivity of the FR using the transfer detector and; c) using the FR and the HTBB to calibrate the LP3 near each of the fixed point transition temperatures.

Figure 2. Temperature difference between the LP3 and the filter radiometer near the melting temperatures of the Co-C, Pt-C and Re-C fixed points. The $\circ$ indicate the differences between the FR temperature and the temperature indicated by the LP3 before the fixed point measurements and the + indicated the differences after the fixed point measurements.

Figure 3. A typical melting plateau measured for the Co-C fixed point. The temperature has been modified to include the correction determined by the LP3-filter radiometer transfer calibration

Figure 4. Melting inflection point temperatures determined for the Co-C fixed point. The average of the 20 measurements is shown as a solid line.

Figure 5. A typical melting plateau measured for the Pt-C fixed point using the LP3. The temperature has been modified to include the correction determined by the LP3-filter radiometer transfer calibration.

Figure 6. Inflection points determined from the Pt-C melting plateaux.

Figure 7. A typical melting plateau measured for the Re-C fixed point using the LP3. The temperature has been modified to include the correction determined by the LP3-filter radiometer transfer calibration.

Figure 8. Inflection points determined from the melting plateaux of the Re-C fixed point. The temperature has been modified to include the correction determined by the LP3-filter radiometer transfer calibration. Only points 12 through 29 were used to calculate the melting temperature of the fixed point.

Figure 9. Difference between the NRC value and a weighted mean of all the values determined in loop 2 of work package 4. $k = 1$ uncertainties for the NRC measurements are indicated by the error bars.