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Construction and comparison of high temperature fixed points at NRC and CEM

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Abstract. This paper describes the collaborative project between National Research Council of Canada (NRC) and *Centro Español de Metrología* (CEM) for the construction and comparison of high temperature fixed points (HTFPs). A hybrid-type crucible that uses the piston method for filling has been jointly developed. A series of 12 high temperature fixed point blackbodies (HTFPBBs) have been constructed, including Cu, Ru-C, Ir-C, Re- C and WC-C covering the temperature range from 1084 ºC to 2750 ºC. All these cells were filled in NRC facilities by CEM and NRC staff. Two cells of each type of fixed point were constructed (except for the WC-C cells), using crucibles from two different suppliers in order to study the influence of the density and emissivity of the crucible in the HTFPs' performance. Moreover, four WC-C cells were made using tungsten powder from two different suppliers, covering all the possible combinations of tungsten powder and crucibles acquired for this project. All cells, and additionally a Pt-C HTFPBB belonging to NRC, have been measured firstly at NRC and, afterwards, at CEM. Both laboratories have calculated the ITS-90 temperatures from their respective measurements and the results have been compared. Differences on the ITS-90 temperatures of the HTFPBBs measured at each lab are within uncertainties of the comparison. After the comparison, CEM kept one Cu cell, one Ru-C cell, one Re-C cell and two WC-C cells. The rest of the fixed points involved in the comparison were sent back to NRC.

Keywords: ITS-90, High Temperature Fixed Points, Comparison.

1. Introduction

Since their inception in 2001 by Yamada et al. [1], Metal (carbide)–carbon eutectic fixed points have provided the basis for new temperature references for the calibration of radiation thermometers at temperatures above the freezing point of silver (961.78 ºC).

Because of their common interest in the development of HTFPs, NRC and CEM decided to collaborate by constructing and measuring a set of HTFPs. This article describes outputs obtained from this bilateral collaborative project.

National Metrology Institutes (NMIs) across the world have been working on the design, construction, temperature determination and how to improve the robustness and the length of their melting plateaus of HTFPs. Using a hypoeutectic powder composition, around 1% below the eutectic composition, to fill the cells and the introduction of a thin lining of high purity graphite on the inside of the cell to act as a sacrificial layer have improved HTFP performance [2]. The most commonly used design of HTFP cells, introduced in [3] and named hybrid design, includes a double layer structure of carbon/composite (C/C) sheet and graphite sleeve between

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the inner graphite tube and the outer wall in order to avoid contact between the metal ingot and the graphite outer wall.

The piston method, introduced in [4] was used to fill the cells in this work. This method reduces the risk of contamination by total confinement of the metal-carbon mixture and minimizing the number of loads and melts required for the complete filling of the cell, which reduces the possibility of impurities present in the environment becoming part of cell's ingot.

For this project, it was decided to design a hybrid-type crucible able to be filled using the piston method, in order to obtain cells that could be considered as part of the state-of-the-art in this field.

The final part of this international project consisted in the determination of the melting temperature of the cells in both institutes and the comparison of the t_{90} values obtained and, thus, provide quantitative information to determine the validity and quality of the cells built.

2. NRC-CEM cells

2.1 Cell design

The design of NRC-CEM cells was developed between staff from both Institutes by exchanging numerous design sketches and comments on those drawings. Fig. 1 shows the final design on its filling arrangement.

Dimensions of the cartridge used to introduce the cells into the filling furnace restricted the length of the extension so two filling steps were normally required to fill the crucibles completely, drastically reducing the number of melts required to fill a cell applying the classic drop method, which could reach up to 20 cycles [5]. Both the piston and the pushing rod have a cavity along their axis that allow to evacuate gases present on the powder mixture out of the crucible during its melt and, once the cell is filled and solidified, the excess of ingot present on the mentioned cavity can be used as a sample that can be analyzed using the Glow Discharge Mass Spectrometry (GDMS) technique in order to obtain a quantitative determination of the impurities present on the fixed point.

NRC-CEM cells have space for 3.65 cm^3 of ingot, a black body cavity with a diameter of 3 mm, an external diameter of 24 mm and, once filled and closed with their cap, they have a total length of 45 mm. Edges of the BB in contact with the alloy are rounded in order to avoid stress concentration and so improve melt's length and cell's robustness. The blackbody (BB) cavity part is fixed to the crucible with a press fit in order to improve cell's robustness as well. Once the design phase was completed, several sets of cells were ordered to two different suppliers of high purity graphite parts, the NRC obtained their parts from Mersen Carbon in U.S.A and the CEM ordered their corresponding set of parts to SGL Carbon in Germany. Given parts of both suppliers have the same nominal dimensions and they are completely interchangeable, weighing of the parts evidenced SGL SIGRAFINE graphite is slightly denser than Mersen high purity graphite and, possibly, provides slightly higher emissivity. Carbon powder and metals required to fill the cells, listed in Table 1, were provided by NRC, along with the Toyo Tanso carbon/composite (C/C) fabric.

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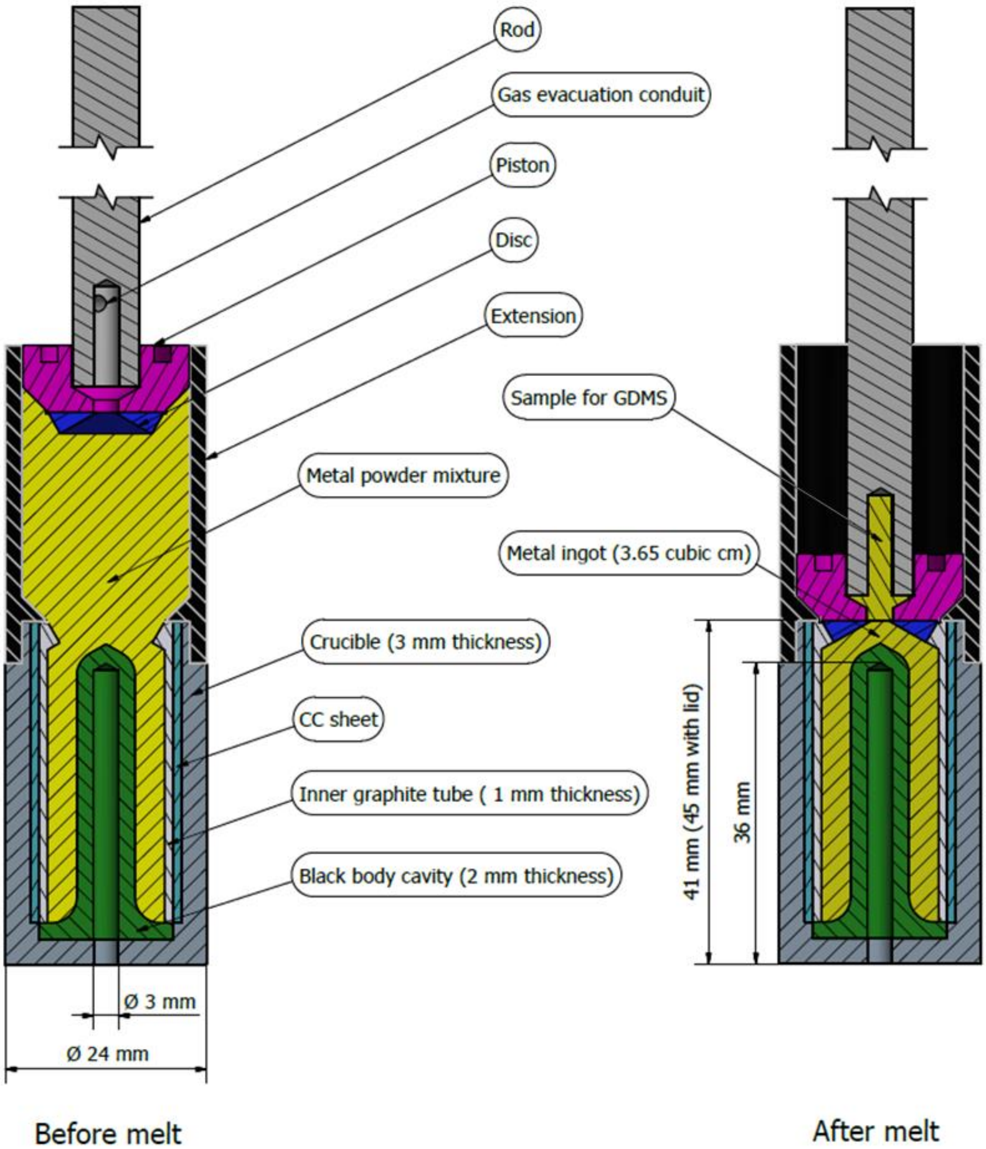

Figure 1: NRC-CEM HTFP filling assembly.

2.2 Filling the cells

It was decided to construct cells corresponding to five different fixed points: Cu, Ru-C, Ir-C, Re-C and WC-C. Cu and Re-C thermodynamic transition temperatures are respectively 1084.62 °C (*U*=0.081 ºC) and 2474.69 ºC (*U*=0.35 ºC). These values were determined in [6] and adopted by the Consultative Committee for Thermometry (CCT) of the *Bureau International des Poids et Mesures* (BIPM). Ru-C, Ir-C, and WC-C approximated transition temperatures, taken from [7], are respectively:1953 ºC, 2291 ºC and 2749 ºC. Ru-C, Ir-C and WC-C thermodynamic transition temperature values are pending to be determined by the CCT Working Group for Non-Contact Thermometry.

The set of HTFPBBs planned to be made would cover the temperature range from 1084 ºC to 2750 ºC allowing the dissemination of ITS-90 temperatures and also thermodynamic radiation temperatures by direct and indirect methods in steps of approximately 200 °C over the whole range.

All cells were filled in NRC facilities during a six-week campaign by NRC staff and a researcher from CEM who was kindly invited to stay for two months at NRC as guest worker for this purpose.

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Two cells of each fixed point were constructed (except for the WC-C cells), using a crucible graphite set from Mersen Carbon and a second one from SGL carbon in order to study the influence on HTFPs' performance due to the usage of graphite parts with different densities and, subsequently, different black body emissivity. Moreover, four WC-C cells were made using tungsten powder from two different suppliers, covering all the possible combinations of tungsten powder and crucible suppliers acquired for this project.

Fig. 2 shows NRC's facility for the filling of eutectic HTFPs which consists of a vertically mounted VEGA BB3500M furnace, vacuum and inert gas delivery system. A MIKRON radiation thermometer that can be focused inside the furnace on some part of the cell or powder material helped determine when melting had taken place.

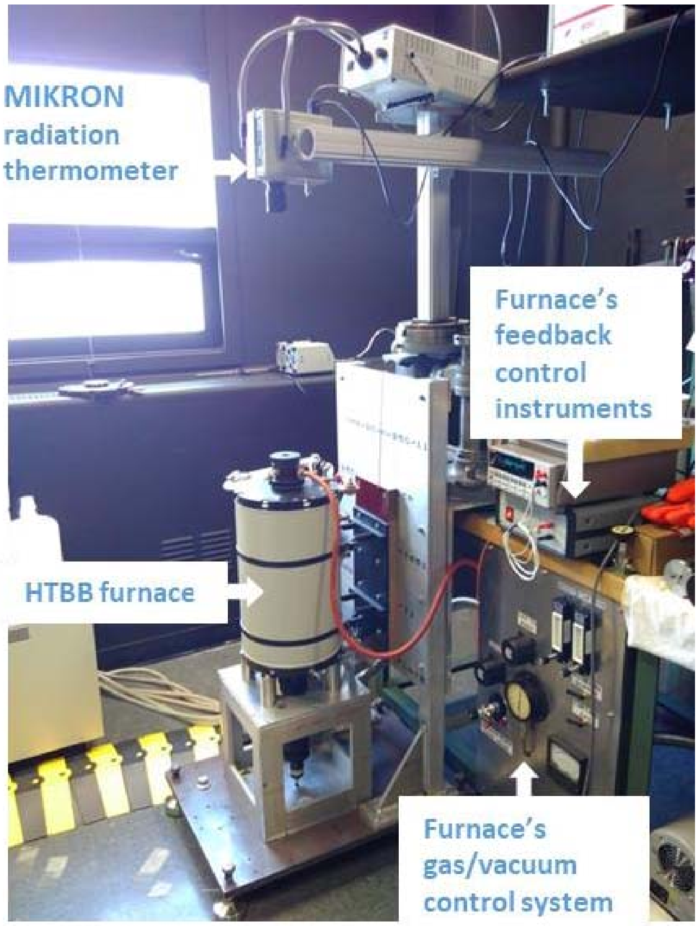

Figure 2. An image of the HTFP filling facility at NRC.

All the crucible materials used for the construction of the eutectic fixed points were baked in vacuum at approximately 100 ºC above their corresponding melting temperature, or for HTFPs that melt above 2000 ºC, in vacuum to 2000 ºC and in flowing argon to approximately 100 ºC above their corresponding melting temperature. Baking of the furnace and materials introduced inside its heating cavity allow to evacuate most of the possible impurities present. The carbon powder used for the eutectic alloys was 200 mesh, with a nominal purity of 99.9999% (Alfa Aesar lot# Q10D086 for the Ir-C cells and lot # B03W022 for the remaining fixed points).

The cell filling procedure was carried out as follows: the powder mixture was introduced inside the cell and an extension. With the materials inside, the furnace was evacuated via a roughing pump and the furnace was heated in vacuum. The furnace was held, in vacuum, at a temperature just below the melting temperature for

Co-C and Ru-C or just below 2000 ºC for the remaining HTFPs. A graphite rod long enough to emerge from the furnace, was inserted inside the furnace and mated with the piston which in turn was in contact with the powder mixture. The rod pushed down the piston when the melt started. During the melt, the excess metal-carbon was forced inside the piston inner funnel through a hole. Figure 3 shows one of the resulting HTFP cells after the filling process.

Figure 3. A filled NRC-CEM cell before threading its closing cap.

Due to its high vapour pressure, the Cu cells were baked and filled in a different facility, using a furnace exclusively dedicated to Cu measurements, the heat pipe furnace described in [8], in order to avoid any contamination of the HTFP filling furnace.

Table 1 summarizes all the HTFP made, plus a NRC's Pt-C cell added to the comparison, with their corresponding parameters. ReS3 and WCCM4 are significantly heavier than others of the same type because they were accidentally overfilled so they were closed with no disc at the bottom (see figure 1).

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Table 1. Summary of the materials used to fill the HTFPs (in order of construction).
*It is worth noting that the Ir metal was obtained from Johnson Matthey in 1955.

Label	type	% C	Ingot weight (g)	Metal provider	Metal nominal purity (%)	Crucible provider	Filling/melting iterations required
RuM1	Ru-C	2.5	43.98	Zhuzhou Kete Ind.	99.95	Mersen	2
RuS2	Ru-C	2.5	42.72	Zhuzhou Kete Ind.	99.95	SGL	2
ReM2	Re-C	1.6	72.06	Zhuzhou Kete Ind.	99.999	Mersen	2
ReS3	Re-C	1.6	82.04	Zhuzhou Kete Ind.	99.999	SGL	2
WCCM3	W(C)-C	5	65.93	Zhuzhou Kete Ind.	99.999	Mersen	2
WCCS4	W(C)-C	5	59.79	Zhuzhou Kete Ind.	99.999	SGL	1
WCCM4	W(C)-C	5	75.70	Alfa Aesar	99.999	Mersen	2
WCCS5	W(C)-C	5	60.06	Alfa Aesar	99.999	SGL	1
IrM5	Ir-C	0.6	80.78	Johnson, Matthey	99.98	Mersen	1
IrS6	Ir-C	0.6	84.22	Johnson, Matthey	99.98	SGL	2
CuM6	Cu	0	21.35	Alfa Aesar	99.9999	Mersen	1
CuS7	Cu	0	21.30	Alfa Aesar	99.9999	SGL	1
PtHRad1	Pt-C	0	68.8	ESPI metals	99.999	Mersen	2

3. Measurements

3.1 Measurements at NRC

The t_{90} measurements of the cells at NRC were made with a KE-*Technologie GmbH* LP5 standard radiation thermometer. The thermometer was calibrated using a Cu fixed point blackbody and the relative spectral response was measured.

Except for Cu cells, which were measured using a dedicated furnace for this type of fixed points, all cells were installed in a VEGA HTBB 3500M furnace with dedicated carriages lined with graphite foil and carbon composite layers. Fig. 4 shows the setup for the measurements at NRC. Graphite foil and Toyo Tanso C/C layers were used to keep the cell tight against the holder to avoid slippage during installation and removal. The cell's position and furnace power offsets were optimized for melting plateau sharpness and well defined inflection points.

The order of measurements was as follows: Ru-C; bake-out in vacuum at 2000 ºC; WC-C; Re-C; Cu; bake-out at 2000 ºC in vacuum, 2500 ºC in Ar; WC-C; Re-C; bake-out at 2000 ºC in vacuum, 2332 ºC in Ar; Ir-C; Pt-C and Cu.

Special care was taken to avoid deep super-cooling of Re-C and WC-C fixed points by avoiding overheating of the Re-C and WC-C cells after the melt had completed.

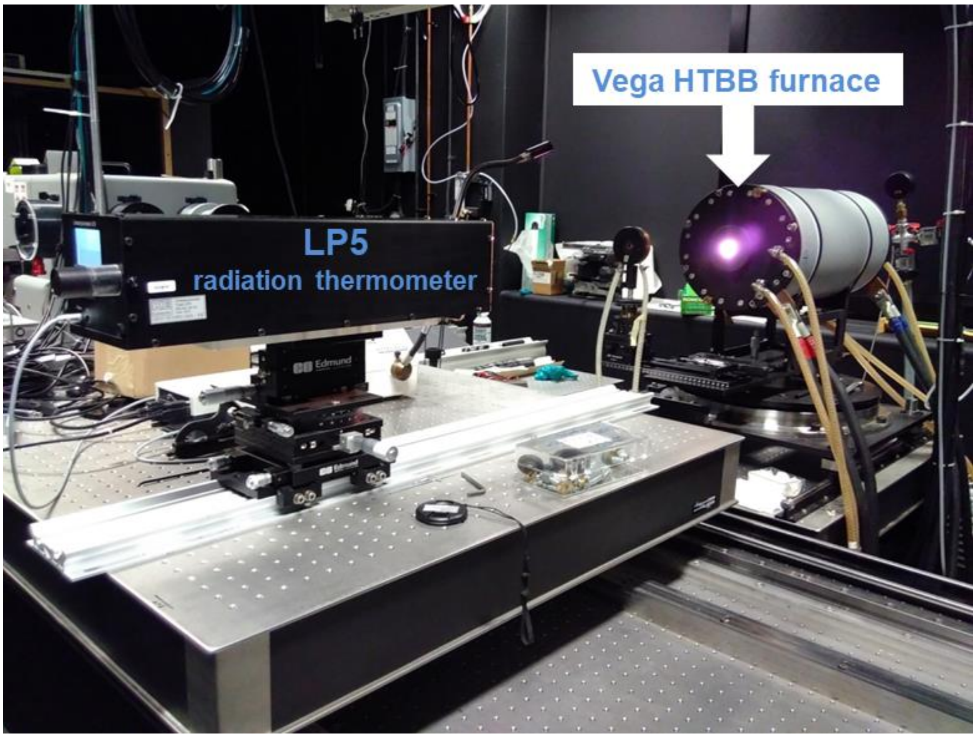

Figure 4. Experimental setup for the HTFP measurements at NRC

3.2 Measurements at CEM

The cells (except WC-C) were installed in a CHINO IR-R80 furnace. The furnace was baked, before the installation of the cells, with an Ar and He purge for about 1 hour, at approximately 2027 ºC, for the cells below Re-C temperature and at 2527 °C in the case of the Re-C. The cells were installed in the furnace wrapped in graphite felt from CHINO (a different wrap for each cell). The furnace window was removed during each measurement and a flow of nitrogen maintained during the measurements.

The fixed point cells were placed in the most homogeneous part of the furnace. This place was determined previously using CEM HTFPs: the best place identified where the longest duration and sharpest ending of the melting plateau were obtained.

WC-C cells were installed in a VEGA BB3200 furnace. This furnace has been only used with WC-C cell so it is thought that no baking was needed. The cells were installed into the BB3200 furnace wrapped in graphite felt. The furnace window was removed during each measurement and a flow of Ar maintained. The HTFPs were placed in the most homogeneous part of this furnace determine by the manufacturer.

The thermometer used for measuring the HTFP temperatures was a KE-*Technologie GmbH* LP4 standard radiation thermometer. The thermometer reference photocurrent was calibrated just before the measurements with the CEM reference Cu freezing point blackbody. The temperatures were obtained by extrapolation using the relative spectral response of the thermometer which was also measured just before the measurements. The linearity and the size of source effect (SSE) of the thermometer are known and they were included in the uncertainty budget and used as a correction, respectively. The effective radius, R_{ref}, of the HTFPs were calculated [9] measuring the horizontal temperature profiles with the LP4 radiation thermometer. The setup at CEM used for the HTFP measurements is shown in Fig. 5.

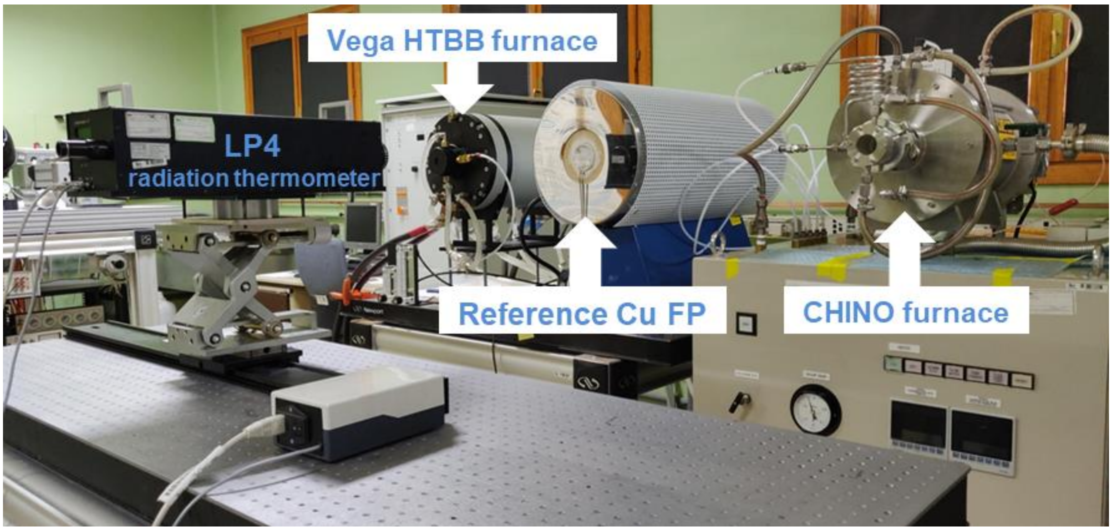

Figure 5. Experimental setup for the measurements of HTFPs at CEM.

The CEM reference Cu freezing point blackbody was measured again after the measurements and the difference between the start and end of the measurements was < 0.03 °C. This value is lower than the drift value for the thermometer considered in the uncertainty budget (0.1 °C).

The melting temperature assigned to each HTFP was the mean of at least three realizations. The point of inflection was obtained from the minimum of the derivative of the 3rd order polynomial fitting of the melting curve, the dispersion of which is included in the uncertainty budget. The steps used respect to the corresponding transition temperature reference values are: ± 30 °C (Re-C); ± 20 °C and -30 °C, +20 °C (Ru-C); ± 30 °C, ±20 °C and ±15 °C (Co-C); ± 30 °C and ± 20 °C (Ir-C); -20 °C,+30 °C, ±20 °C and ±10 °C (Pt-C) and ±20 °C and ±10 °C (Cu). An example of the melting plateaux recorded on a run of measurements of one of the cells is given in Figure 6.

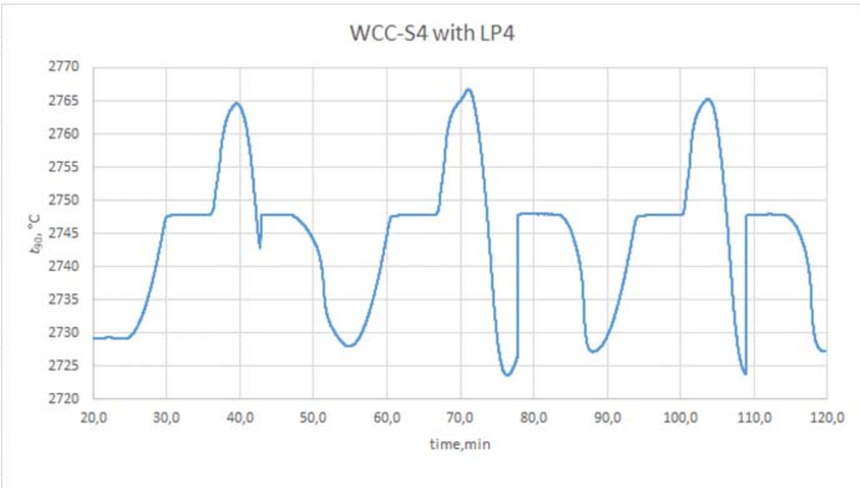

Figure 6. Melting and freezing plateaus from cell WCC-S4.

Due to the high economical value of Ir-C cells, only one of them, IrS6, was sent to CEM for the comparison and, after the measurement campaign, it was returned back to NRC. Since this work was focused on metal-carbon fixed points, only one Cu cell participated in the comparison.

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4. Uncertainties in the measurements

4.1 Uncertainties in the t_{90} realization above 1084.62 °C at NRC

Uncertainties in the t_{90} realization about the silver point at NRC using the LP5 where calculated following the CCT03-03 document [10]. Table 2 shows the components and their sensitivity coefficients and Table 3 shows the uncertainties scaled to the HTFP temperatures in this work.

Table 2. Components and sensitivity coefficients from [10] used in the calculation of the t_{90} uncertainties at NRC

Component	Unit	Standard uncertainty	Sensivity coefficient
Cu Point Total	ºC	0.069	$(T/T_0)^4$
Wavelength	nm	0.058	$(T/\lambda)^2(T/T_0\text{-}1)^2$
Reference detector calibration	nm	0.130	$(T/\lambda)^2(T/T_0\text{-}1)^2$
Scattering, polarization	nm	0.001	$(T/\lambda)^2(T/T_0\text{-}1)^2$
Drift	nm	0.150	$(T/\lambda)^2(T/T_0\text{-}1)^2$
Out-of-band transmittance	nm	0.007	$(T/\lambda)^2(T/T_0\text{-}1)^2$
Interpolation and integration	nm	0.007	$(T/\lambda)^2(T/T_0\text{-}1)^2$
Size of source effect	A	0.000	$(\lambda T^2/c_2)^2$
Non-linearity	----	0.001	$(\lambda T^2/c_2)^2$
Drift	ºC	0.069	$(T/T_0)^4$
Ambient conditions	----	0.000	$(T/T_0)^4$
Gain ratios	A	0.000	$(\lambda T^2/c_2)^2$
Repeatability/Noise	A	0.001	$(\lambda T^2/c_2)^2$

The uncertainty in the Cu point is calculated from impurities (10 mK), emissivity (52 mK), temperature drop (5 mK), plateau identification (7 mK) and repeatability (44 mK). The repeatability component is attributed to our ability to re-align and place the fixed-point within the furnace [10].

The wavelength related uncertainties were estimated as follows. The wavelength and reference detector uncertainties were estimated from the calibration of the wavelength scale of the monochromator, and the reference detector used to measure the relative responsivity. The scattering and polarization uncertainty was taken from the 'normal' value in [10]. The drift in wavelength was estimated from repeated measurements of the relative responsivity (and is likely more related to alignment than actual drift). Measurement of the relative responsivity were made from 400 nm to 900 nm and the responsivity was found to drop below 10^{-5} this value was used as the uncertainty.

The SSE of the LP5 was measured using the direct method with apertures in front of the HTBB. The non-linearity was estimated to be no worse than 0.05% over the range. The drift was estimated from repeated measurements of the copper point. The ambient conditions in which the LP5 operates did not deviate from 21 ºC to 25°C so the effect is assumed to be negligible. The LP5 using three gain setting over its range and the difference between these were measured and found to also be negligible. We estimate the repeatability in the signal from the worst case noise measurement.

Table 3. NRC uncertainties scale to the HTFP temperatures measured.

Component (ºC)	Cu	Pt-C	Ru-C	Ir-C	Re-C	WC-C
Cu Point Total	0.005	0.023	0.035	0.061	0.080	0.118
Wavelength (nm)	0.000	0.007	0.016	0.041	0.062	0.108
Reference detector calibration	0.000	0.037	0.081	0.207	0.316	0.547
Scattering, polarization	0.000	0.000	0.000	0.000	0.000	0.000
Drift	0.000	0.050	0.108	0.275	0.421	0.728

Out-of-band transmittance	0.000	0.000	0.000	0.001	0.001	0.001
Interpolation and integration	0.000	0.000	0.000	0.001	0.001	0.001
Size of source effect	0.013	0.029	0.036	0.047	0.055	0.066
Non-linearity	0.000	0.000	0.000	0.000	0.000	0.000
Drift (°C)	0.069	0.152	0.186	0.247	0.284	0.343
Ambient conditions	0.000	0.000	0.000	0.000	0.000	0.000
Gain ratios	0.000	0.000	0.000	0.000	0.000	0.000
Repeatability/Noise	0.000	0.000	0.000	0.000	0.000	0.000
Total (°C)	**0.071**	**0.169**	**0.236**	**0.432**	**0.609**	**0.988**

4.2 Uncertainties in the t90 realization above 1084.62 °C at CEM.

Uncertainties in the t_{90} realization about the silver point at CEM using the LP4 where calculated following the CCT03-03 document [10].

CEM calibrates the standard radiation thermometer with direct ITS-90 realization. This calibration is developed in the following steps:

1. Cu fixed point reference;
2. measurement of the linearity with high stability tungsten lamps and a high temperature furnace up to 2800 °C;
3. measurement of the relative spectral response using a monochromator;
4. measurement of the size of source effect using an integrated sphere with the differential method.

After calibration at the Cu FP, the LP4 is used to measure the other fixed points. The photocurrent measured at each fixed point is corrected by dark current and SSE. The t_{90} is calculated applying paragraph 2.5 from the BIPM Guide to the Realization for the ITS-90.

The uncertainty components considered are:

1. the calibration of the thermometer at the Cu fixed point, which includes: dark current; repeatability; multimeter's resolution, calibration and drift; furnace's non-uniformity and emissivity of the blackbody;
2. the measurement of the thermometer photocurrent with a multimeter measured at the fixed point, which includes: dark current; repeatability and multimeter's resolution, calibration and drift);
3. the uncertainty due to the SSE correction;
4. the emissivity of the FPBB;
5. the wavelength of the thermometer, from the calibration of the monochromator, its drift and the drift of the thermometer filter;
6. the non-linearity of the thermometer.

Table 4 shows the standard uncertainties corresponding to CEM's LP4 ITS-90 calibration uncertainty components and their sensitivity coefficients. Table 5 shows uncertainties in temperature units and scaled to the temperatures of the HTFP involved in this comparison.

Table 4. CEM's LP4 t_{90} calibration uncertainty budget

Component	Unit	Standard uncertainty	Sensitivity coefficient
Cu point calibration	ºC	0.04	T^2/T_x^2
Photocurrent measurements	A	0.0010 to 0.0022	$\lambda_e T^2/c_2$
Size of the Source Effect	----	4.62 10^{-5}	$\lambda_e T^2/c_2$
HTFP emissivity	----	0.00058	$\lambda_e T^2/\varepsilon c_2$

Wavelength (nm)	nm	0.085	$T^2(T_x^{-1}-T^{-1})/\lambda_e$
Non Linearity	----	0.001	$\lambda_e^{T^2/c_2}$

*λ_e is the effective wavelength of the standard radiation thermometer

Table 5. CEM's LP4 t_{90} uncertainties scaled to the temperatures of the fixed points measured.

Component (ºC)	Cu	Pt-C	Ru-C	Ir-C	Re-C	WC-C
Cu point calibration	0.002	0.008	0.012	0.020	0.027	0.039
Photocurrent measurements	0.007	0.002	0.002	0.005	0.006	0.008
Size of the Source Effect	0.000	0.000	0.000	0.000	0.000	0.000
HTFP emissivity	0.002	0.011	0.017	0.029	0.039	0.057
Wavelength	0.000	0.016	0.035	0.088	0.135	0.234
Non Linearity	0.007	0.033	0.050	0.050	0.116	0.170
Total	**0.13**	**0.26**	**0.34**	**0.44**	**0.57**	**0.71**

4.3 Uncertainties in the comparison

Comparison uncertainties, represented by the uncertainty bars in figure 7, are the combined uncertainties in the t_{90} measurement at each lab. Besides standard thermometer calibration uncertainties, CEM adds in use uncertainty components for each cell measured. This measurement uncertainties are dominated by the standard deviation of the transition temperatures of all the cycles performed for each cell. Table 6 lists the combined uncertainty obtained for each cell measured at NRC and CEM within this project.

Table 6. Combined uncertainty of each cell measured during the bilateral comparison of t_{90} transition temperatures determination between NRC and CEM.

Cell label	Combined uncertainty (ºC)
RuM1	0.84
RuS2	0.84
ReM2	1.71
ReS3	1.71
WCCM3	2.48
WCCS4	2.48
WCCM4	2.55
WCCS5	2.48
IrS6	1.40
CuM6	0.33
PtHR	0.60

5. Results

Results of the transition temperature determination at NRC and CEM of the HTFPs involved in this comparison are shown in Table 7 and the differences between the NRC and CEM measurements ($t_{90,NRC}$-$t_{90,CEM}$) are shown in Fig. 7. Measurements of the comparison, first at NRC and later CEM, are the first that were carried out after constructing the cells and served to validate them. Melting plateaus observed had a shape, length and measured transition temperatures, considering their associated uncertainties, were comparable with any other state of the art HTFPBB cell constructed by NMIs around the world. No cell breakage was observed, proving NRC-CEM HTFP design robustness.

Although all measurements are within comparison's combined uncertainties, differences between NRC and CEM temperatures measured of Ru-C and Re-C cells are larger than the rest. Since Ru-C and Re-C transition temperatures are between values of other fixed points measured, these differences can't be justified by a discrepancy in the ITS-90 realization at each Institute. Moreover, CEM and NRC measurements at the Re-C fixed point have the same uncertainty. Neither the presence of impurities inside the cells and can be considered as an explanation of the mentioned differences considering transition temperature of contaminated cells drifts positively and CEM measurements were carried out after NRC and provided lower values. Another aspect to consider to discard contamination is that NRC Re-C temperature values match the value for this fixed point determined in [6] and Ru-C measurements at CEM and NRC are both higher than the value in [7]. Hence, discrepancies in measured temperatures for Ru-C and Re-C cells must be attributed to an experimental or data processing error covered by comparison's combined uncertainty.

WC-C cells are the most meaningful of the set of cells constructed in order to evaluate the effects of the graphite parts and metal powder sources. Average temperatures corresponding to WCC3 and WCCS4 filled with W powder provided by Zhuzhou Kete Ind. are 77 mK higher than average temperatures of WCC4 and WCCS5, filled with Alfa Aesar W powder. Regarding graphite suppliers, in accordance with SGL graphite higher density and subsequent higher emissivity compared with Mersen graphite, average temperature of WCCS4 and WCCS5 is 260 mK higher than the average temperature corresponding to WCC3 and WCC4. Nevertheless, considering the uncertainties involved, differences observed can be considered negligible; future work involving several days of thermodynamic temperature measurements of each cell would be required to obtain consistent conclusions.

Table 7. Summary of NRC-CEM HTFP's comparison results.

Cell	CEM t_{90} (ºC)	CEM $U(t_{90})$ (ºC)	NRC t_{90} (ºC)	NRC $U(t_{90})$ (ºC)	NRC t_{90} -CEM t_{90} (ºC)
CuM6	1084.62	0.3	1.084.603	0.14	-0.02
PtHR	1738.22	0.5	1738.264	0.34	0.04
RuM1	1953.25	0.7	1953.922	0.47	0.67
RuS2	1953.34	0.7	1.953.936	0.47	0.60
IrS6	2289.48	1.1	2.289.548	0.86	0.07
ReM2	2474.14	1.2	2.474.678	1.22	0.54
ReS3	2474.10	1.2	2.474.704	1.22	0.60
WCCM3	2747.76	1.5	2747.57	1.98	-0.19
WCCS4	2747.88	1.5	2747.94	1.98	0.06
WCCM4	2747.57	1.6	2.747.652	1.98	0.08
WCCS5	2747.85	1.5	2.747.825	1.98	-0.02

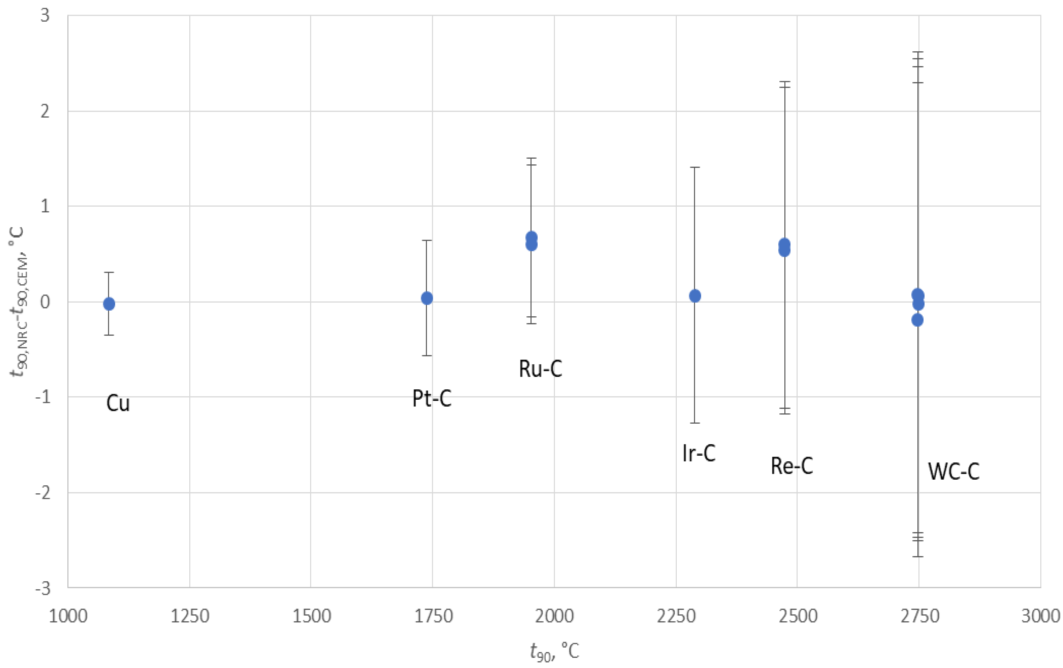

Figure 7. Differences in the t_{90} measurements for each HTFP between NRC and CEM.

6. Conclusions

A set of 12 HTFPs covering the temperature range from the copper point at ~1084 °C to the WC-C point at ~2750 °C has been constructed allowing the dissemination of ITS-90 temperatures and also thermodynamic radiation temperatures by direct and indirect methods.

Ten of those cells, along with Pt-C previously made at NRC HTPS were measured at both NRC in Canada and CEM in Spain. These measurements were used to evaluate cell's performance and compare the ITS-90 temperature scale of the respective NMIs over this temperature range and they were found to be in agreement considering comparison's uncertainty budget.

After the comparison, constructed cells were distributed between the participant institutions: CEM kept Ru-C, Re-C, Cu and the two WC-C made with SGL carbon parts and NRC kept the rest. Further measurements of the constructed HTFPs will be required along time in order to check their stability and longevity.

The set of cells made and the bilateral comparison carried out along this bilateral collaboration project has created a strong link between both institutions. Measurements carried out in the future by each institute in the temperature range from 1084 ºC to 2750 ºC can be related and the research collaboration in the field of radiation thermometry between NRC and CEM is expected to continue over time.

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