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On the uncertainties in the realization of the kelvin based on thermodynamic temperatures of high-temperature fixed-point cells

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Abstract. In July 2016 the Consultative Committee for Thermometry's Non-Contact Thermometry Working Group formed a task group to compile a complete list of uncertainties for high-temperature fixed points, categorize them as well specified or not, and recommend areas of future research. We describe herein two paths to realizing T by indirect primary radiometry using high-temperature fixed-point blackbody cells: one in which published values for the metal-carbon eutectic material transition temperatures are used and the other where a set of cells has their transition temperatures determined directly. The uncertainty components that need to be considered for each path are given together with typically achievable values and how well those values are known. This work concentrates on Co-C, Pt-C and Re-C.

Keywords: radiation thermometry, high-temperature fixed-point cells, thermodynamic temperature

1. Introduction

The redefinition of the kelvin in terms of the Boltzmann constant allows for new methods to realize thermodynamic temperature traceably to the SI. For non-contact thermometry §4.2 of the *mise-en-pratique* for the definition of the kelvin (*MeP-K-19*), [1] describes absolute and relative methods of primary radiometric thermometry, with relative methods: “extrapolation from one fixed point, which requires only knowledge of the relative spectral responsivity of the detector and filter; interpolation or extrapolation on the basis of two fixed points, which requires only the bandwidth of the responsivity; interpolation or extrapolation from three or more fixed points, for which detailed measurements of responsivity are not required”. The relative method requires at least one fixed-point cell[‡] with a known thermodynamic phase transition temperature. At present, the *MeP-K-19* appendix lists thermodynamic temperatures for cobalt-carbon (~ 1597 K), palladium-carbon (~ 1765 K), platinum-carbon (~ 2011 K) and rhenium-carbon (~ 2748 K). In contrast to the ITS-90, the uncertainty of each fixed-point temperature is given. It is expected that in the future this list will be expanded. These fixed points, possibly in conjunction with one or more of the silver, gold or copper fixed-points, can be used to establish a thermodynamic temperature above the silver fixed point (~ 1235 K). If combined with ITS-90 specified fixed points and documented differences with uncertainties of $T - T_{90}$ there is considerable flexibility in setting up a thermodynamic scale. This paper considers the uncertainties that need to be taken into account when using the high-temperature fixed-points. Uncertainties and descriptions of the methods for absolute primary radiometric thermometry are given in [1] and [2].

Research into the fabrication, use, and determination of the thermodynamic melting temperatures of high-temperature metal-carbon or metal carbide-carbon eutectic and peritectic alloys has been intense since they were first suggested by Yamada *et al* in 1999 [3]. These are known generically as high-temperature fixed-points (HTFPs) and a summary of the history, construction, performance and applications of HTFP cells is given by Machin [4].

This paper is a summary of the report of the Consultative Committee for Thermometry’s Non-Contact Thermometry Working Group (CCT WG-NCTh) Task Group on high-temperature fixed-point uncertainties (HTFPU.) We describe the methodology of gathering and reporting the uncertainty components and values (Section 2), discuss the uncertainty components and their values intrinsically related to the HTFPs (Section 3), suggest uncertainties to be considered when HTFPs are used in practice (Section 4), present other considerations (Section 5), and recommend areas that require further research (Section 6). This work follows and complements earlier work on the uncertainties in realising ITS-90 using radiation thermometry where a CCT report [5] was subsequently published [6] so as to make the information for users as widely available as feasible. This work can be used as a guide to future reviews of

[‡] In this paper we distinguish “fixed-point” as a concept from “fixed-point cell” as an artifact that implements that concept.

calibration and measurement capabilities (CMCs).

2. Methodology

Since the goal of this work was to determine a definitive list of uncertainties for HTFP cells and classify them as being either well known or in need of further research we confined ourselves to the types of HTFP cells that are in common use now: small-aperture fixed-point blackbody cells with diameters ~ 24 mm and lengths from 43 mm to 50 mm. This work is also limited to those furnaces used for realizing HTFP cells for non-contact thermometry at the time the CCT report was being prepared.

In the tradition of [5] and [6] we have attempted to include *best* and *normal* values for each uncertainty component. *Best* and *normal* are defined as those that “can be obtained with considerable effort by the small number of leading workers in the field” and those that “can easily be obtained at present in National Metrology Institutes”, respectively. Some uncertainty components – those requiring further research – are not sufficiently well understood to be categorized in this way and thus simple “worst case” values are given.

Additionally, the components and uncertainties herein are based upon the most studied HTFP cells, namely Co-C, Pt-C and Re-C. To compile this list of uncertainties and their values we relied heavily on work done in establishing definitive melting temperatures as part of the CCT WG-NCTh/InK project, which is summarised in [4], [7], [8], [9].

When using HTFP cells to realize a temperature scale, there are two slightly different schemes which depend on how the temperature is assigned to the local cell or cells.

- Scheme 1. A given high-temperature fixed-point cell is taken to have the temperature value, within the stated uncertainty, given by the *MeP*-K-19. The stated uncertainty of each high-temperature fixed-point is included as a component in the full uncertainty budget, as summarized in Tables 1 and 2.
- Scheme 2. A high-temperature fixed-point cell is taken to have the temperature value determined by a primary thermometric method such as described in [2]. It is the uncertainty of that determination that is included in the full uncertainty budget.

It is possible to combine these two schemes to produce a hybrid scale where one HTFP - or more - uses values with uncertainty(ies) as Scheme 1 and one or more as Scheme 2. Most of the uncertainty components herein apply to both methods but some may only apply to one scheme, for example if the temperature of a local cell is assigned by primary radiometry at the same wavelength it will be used at, the uncertainty in the emissivity of the cell does not need to be considered.

Figure 2 shows a graphical representation of the hierarchy of relative and absolute primary radiometric thermometry and of the two relative HTFP schemes.

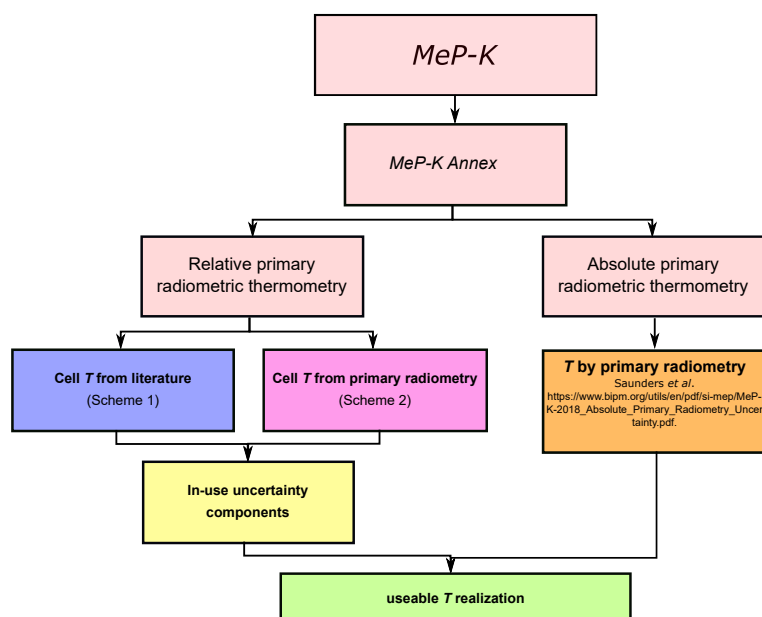


Figure 1. A roadmap from the *MeP-K-19* to a realized high temperature scale

3. Uncertainties intrinsic to HTFP cells

In contrast to the fixed points used in ITS-90, which have zero uncertainty by definition, the high-temperature fixed-points in the *MeP-K-19* each have an associated uncertainty in the assigned temperature which has to be combined with the uncertainty of the physical realization of the actual fixed-point cell being assessed. The uncertainty components discussed in this section are considered to be intrinsic to the HTFP cell itself. Some components, for example the size-of-source effect, are considered in Section 4 as they are a function of not only of the fixed point, but also the furnace and radiometer performance.

The uncertainty components to be considered are: temperature drop, structure effect (for Co-C and Fe-C), identification of the point-of-inflection (POI) or identification of the liquidus point, HTFP stability, impurities, furnace effect, emissivity and uncertainties of unknown origin (“unknown” uncertainties).

3.1. Temperature drop

Because of heat exchange between parts of the fixed-point cell and a furnace, there is a heat flux and thus a temperature gradient, across the wall of the cell cavity from the solid/liquid interface in the melting ingot to the cavity surface. The temperature drop uncertainty refers to our lack of knowledge of this temperature gradient. While the gradient can be calculated given knowledge of the dimensions and materials, the actual thickness of the cavity is not so well known since some of the graphite wall is consumed during the formation of the alloy ingot. The present best-estimates come from modelling the cells used in the CCT-WG5-High Temperature Fixed Point Research

Plan/Implementing the new kelvin project (InK) [10] and are: for Co-C, Pt-C, and Re-C the uncertainties after correction are 0.004 K, 0.011 K and 0.048 K, respectively. Corrections from [10] were divided by 2 (as in [8]) to account for the thinning of the wall and these values were used as both the correction and uncertainty for the assigned values in the *MeP-K-19*, and these values correspond to the *best* uncertainty. The temperature drop uncertainty does not need to be taken into account when the HTFP cell's temperature has been determined directly for that HTFP cell under Scheme 2. But note that the temperature drop might depend on the furnace wherein the HTFP cell is subsequently used, which might be different from the one in which the HTFP cell was calibrated. However, this effect is small compared to the overall temperature drop uncertainty [10].

To estimate the *normal* uncertainty, Eq. 8 of [5] was used and it was assumed that the wall thickness was between 2 mm and 1 mm. Using typical graphite properties (thermal conductivity $81 \text{ W m}^{-1} \text{ K}^{-1}$; emissivity 0.85) and assuming a rectangular distribution, we obtain 0.009 K, 0.023 K and 0.080 K for Co-C, Pt-C and Re-C, respectively.

3.2. Structure effect

The microstructure of a binary eutectic alloy is formed during solidification, and the scale and degree of undercooling – the solid-liquid interface being at lower temperature than would be found in equilibrium – depends on the velocity of the interface. The effect that the previous freeze rate has on the subsequent melting temperature has been termed the structure effect [11]. This effect is small and has been observed only in Fe-C and Co-C. The smaller dispersion of the melting temperature with varying rate of the preceding freeze observed for Co-C is because the diffusion of carbon in the liquid state during the building up of the eutectic structure during solidification is significantly faster for Co-C than for Fe-C, given the higher eutectic temperature of Co-C. Note that the diffusion coefficient in question increases rapidly with temperature. As a consequence, at a given freezing rate we expect the eutectic structure of Co-C to be coarser than that of Fe-C.

On the other hand, at a given growth rate the melting range of the Co-C sample appeared to be larger than that of the Fe-C sample, since the impurity content of Co-C in [11] was significantly larger than that of Fe-C. This led to the structure effect uncertainty appearing to be larger for Co-C than for Fe-C: uncertainty values of 0.010 K and 0.014 K for Fe-C and Co-C, respectively, were arrived at in [11]. The value for Co-C is used here as both the best and normal uncertainty. Note that the uncertainties here were arrived at considering the POI and not the liquidus temperature. The uncertainty for the structure effect should be taken into account for both Scheme 1 and Scheme 2.

3.3. Identification of the point-of-inflection and the liquidus point

It is well known that HTFP cells do not have the well defined, minimal temperature range melting and freezing that can be achieved with the fixed-point cells used for ITS-90. Whether this is due to the microstructure of a binary alloy compared to pure metal, the difficulty of getting the very best purity (6N) material, the difficulty of getting good thermal uniformity at higher temperatures or some other reason is not well established. As defined in [11], the liquidus point should be determined as being halfway between the upper-limit point (the intersection of a line fitted to the slope of the melting curve at the inflection point, and a line fitted to the run-off after the melt) and the point-of-inflection (POI). This procedure, known as the specific limits approach, was described in [8]§

The uncertainty in the liquidus temperature should be taken as the difference between the upper-limit and point-of-inflection temperatures divided by $2\sqrt{3}$. In [8], this amounted to, on average, 0.024 K, 0.044 K and 0.069 K for Co-C, Pt-C and Re-C, respectively, although values can be calculated for each individual plateau. These values are taken to be both the *best* and *normal* uncertainties.

The uncertainty in determining the point-of-inflection was estimated to be 0.003 K, 0.005 K and 0.001 K for Co-C, Pt-C and Re-C, respectively, from [8]. These values were the average differences between the original determination of the points-of-inflection from [7] and the reanalysis of the same data in [8]. But in practice other methods can be used to determine the POI, so a value (for all HTFPs) of 0.006 K ($0.010\text{ K}/\sqrt{3}$) should be considered achievable. In the case where the POI is used, and temperatures of the cells are not directly measured, one must also consider how different the cells are from the set for which the temperature determination was made. Including an uncertainty component based upon the measured melting range could be used to estimate this. For example, the difference between the POI and the upper limit temperature measured on the local cell could be used to estimate the uncertainty in the difference between the local set and the set for which the temperature was determined. This uncertainty component should be accounted for when using both Scheme 1 and Scheme 2.

3.4. Stability

There is the possibility of changes in a fixed-point cell as, for example, the ingot dissolves some of the graphite crucible or impurities segregate given repeated melting and freezing. A re-assessment of cells used in [7] was performed in [12] and these values constitute our current best estimates for drift. Here, the worst-case drift from [12], divided by $2\sqrt{3}$, was used and amounts to: 0.038 K, 0.070 K and 0.031 K for Co-C, Pt-C and Re-C, respectively. These values were taken as the *best* uncertainties. These values are

§ “At each iteration a cubic function is fitted to the new data range, keeping the fitted range centred on the point of inflection from the previous iteration: The point of inflection is identified; The analytical slope at the point of inflection is found; A linear function is fitted to a fixed fraction of the cubic fitted data set (the effect of choice of fraction having been evaluated and found not to affect the outcome)”

consistent with, albeit slightly larger than, the results from [13]. An increase in the melting range of a fixed-point cell should be taken as an indication that a cell has drifted and requires verification. There has been a case [14] where a drift of 0.5 K was observed with a Re-C cell. As reported in [7], one Re-C cell was similarly observed to have drifted by 0.5 K. For the *normal* uncertainty for Re-C a value of $0.5/2\sqrt{3}$ K = 0.144 K was used.

The uncertainty component related to the stability of the HTFP should be considered for both Scheme 1 and Scheme 2.

3.5. Impurities

Materials with impurities at the level of $10 \mu\text{g g}^{-1}$ (“5N”) or better are recommended [6]. In the determinations of the liquidus temperatures for Co-C, Pt-C, and Re-C [8] uncertainty values for the effect of impurities of 0.038 K, 0.037 K and 0.106 K, respectively, were used. These values were estimated from the glow discharge mass spectrometry (GDMS) assays of some of the metals used to fill the cells, with additional components added to account for the lack of knowledge of the purity of the other cells based on the comparison carried out as part of the pre-selection [15] of the cells for the CCT-WG5-High Temperature Fixed Point Research Plan/Implementing the new kelvin project [8]. These values were taken to be the *normal* uncertainties. To estimate the *best* uncertainties, an Overall Maximum Estimate (OME) [16] was assuming that 5N pure materials are used. For Co-C, Pt-C and Re-C the OMEs obtained were 0.008 K, 0.010 K and 0.011 K, respectively.

For Co-C and Fe-C, impurities have been covered in detail in [11]. In [17] impurity parameters m (liquidus slope) and k (distribution or partition coefficient) were calculated for a range of impurities by means of the software package Thermo-Calc; estimated uncertainties are included. In calculating the correction $T_E - T_{liq}$, and the associated uncertainty $u(T_E - T_{liq})$ (where T_E is the equilibrium transition temperature), three schemes underlying the uncertainty analysis were compared and the hybrid SIE-IE-IRE (which combines the sum of individual estimates (SIE), individual estimates (IE) and individual random estimates (IRE)) approach was shown to be a reasonable compromise [17].

Since in Scheme 2 each HTFP has had its temperature determined directly, there is no need to account for the effect of impurities. For Scheme 1 the uncertainty associated with the impurities needs to be accounted for since the temperature associated with the HTFP used this way is the published liquidus temperature.

3.6. Furnace effect

The “furnace effect” is where differences are seen with the same fixed-point cell in different furnaces which are larger than can be explained by the uncertainty assessment [18]. The furnace effect is an area that requires more work to understand its origins and magnitude. The most recent estimate of the uncertainties due to the furnace

effect comes from [19], which gives 0.08 K, 0.125 K and 0.240 K for Co-C, Pt-C and Re-C, respectively. These values were taken as both the *best* and *normal* uncertainties. Thermal inertia [20] and the temperature gradient [21] over the crucible length probably contribute to the furnace effect. Results from [18] suggest that the furnace effect is still not fully understood. Note that in addition the furnace co-determines the effective emissivity, temperature drop and the impact of the SSE. The furnace effect should be accounted for in both Scheme 1 and Scheme 2 (although the use of the same furnace for all measurements could reduce or eliminate this component).

3.7. Emissivity

Present best estimates, based on steady state and taken from [7] for Co-C, Pt-C and Re-C, give equivalent uncertainties of 0.014 K, 0.018 K and 0.025 K, respectively. These values were taken as both the *best* and *normal* uncertainties. Emissivity should be accounted for when using both Scheme 1 and Scheme 2. However, if, using Scheme 2, the temperatures for each HTFP were determined at the same wavelength as they will be used at, the emissivity does not need to be accounted for.

There is a need to investigate how the effective emissivity changes dynamically as the temperature in the cavity changes.

3.8. Unknown uncertainties

Ideally, the uncertainty in the temperature of a HTFP can be characterized by the components listed above. However, in practice the differences between cells can be larger. The analysis in [7] identified that the uncertainties given by participants for the determination of thermodynamic temperature were inconsistent with the model used. This could be because one or more of the components of uncertainty is actually larger than current estimates, or there could be additional sources of uncertainty as yet unidentified. An additional uncertainty component is required. This uncertainty component was estimated from the cell selection work [15] done prior to the thermodynamic measurements of Co-C, Pt-C and Re-C [7]. To estimate the *best* value the full range of the deviation of qualified and spare cells (i.e. excluding the disqualified and broken cells) divided by $2\sqrt{3}$ was used, resulting in 0.016 K, 0.012 K and 0.044 K for Co-C, Pt-C and Re-C, respectively. To estimate the *normal* uncertainty values, all the cells (including the disqualified and broken cells) were included, resulting in values of 0.061 K, 0.069 K and 0.070 K for Co-C, Pt-C and Re-C, respectively. These “unknown” uncertainties only need to be considered for Scheme 1.

3.9. Temperature

The uncertainty in the temperature of the HTFP cells used must also be taken into account. If the values for the liquidus or POI temperature from *MeP-K-19* [22] are used, the uncertainties given there can be used for Co-C, Pt-C and Re-C as 0.07 K, 0.11 K

and 0.22 K, respectively and for the point-of-inflection, the uncertainties are somewhat lower at 0.065 K, 0.090 K and 0.175 K.

If the local HTFP cells have their temperatures determined directly, then this uncertainty component is derived from the primary radiometric uncertainty. In [7], this ranged from 0.10 K to 0.22 K for Co-C, 0.15 K to 0.32 K for Pt-C and 0.28 K to 0.57 K for Re-C.

3.10. Summary of the uncertainty components pertaining to the HTFP cells

Tables 1 and 2 summarize the uncertainty values associated with the HTFP cells when using the values and uncertainties for liquidus temperature, T_{liq} , given in the *MeP*-K-19.

Table 1. For scheme 1, a summary of the components for the use of T_{liq} of HTFP cells and present best and normal estimates of their uncertainties

Item	Source	Present best estimates of uncertainty ($k=1$) / mK					
		Co-C		Pt-C		Re-C	
		Best	Normal	Best	Normal	Best	Normal
Temperature drop		4	9	11	23	48	80
Structure effect		14	14	N/A	N/A	N/A	N/A
Identification of T		24	24	44	44	69	69
Stability		38	38	70	70	31	144
Impurities		8	38	10	37	11	106
Furnace effect		80	80	125	125	240	240
Emissivity		14	14	18	18	25	25
Unknown		16	61	12	69	44	70
Liquidus T		70	70	110	110	220	220
Total		119	138	188	204	342	393

4. Uncertainties related to the use of HTFP cells

In addition to the uncertainties intrinsic to the fixed points described in Section 3, there are additional uncertainty components that need to be considered when implementing HTFP cells. The components may depend on the specific way the HTFP cells are used and often are determined by the HTFP cells and other factors that arise when HTFP cells are used.

Table 2. For scheme 2, a summary of the components for the use of T_{liq} of HTFP cells and present best and normal estimates of their uncertainties

Item	Source	Present best estimates of uncertainty ($k=1$) / mK					
		Co-C		Pt-C		Re-C	
		Best	Normal	Best	Normal	Best	Normal
Structure effect		14	14	N/A	N/A	N/A	N/A
Identification of T		3	6	5	6	1	6
Stability		38	38	70	70	31	144
Furnace effect		80	80	125	125	240	240
T (Radiometer)		96	221	150	316	280	567
Total		131	239	207	347	370	632

The size-of-source effect (SSE) is important to the measurement of HTFP cells since the blackbody typically has a small ~ 3 mm aperture and the fixed-point cell is housed inside a furnace which is 5 K to 30 K hotter than the fixed-point transition temperature. If used to calibrate an instrument, the SSE needs to be accounted for when measuring radiance sources of different sizes. For guidance and *best* and *normal* uncertainties, see [5]. For an approach tailored to calibration of radiation thermometers by fixed point blackbodies see [20, 23, 24]. In [24], an uncertainty between 0.012 K and 0.015 K was arrived at for the SSE at the Re-C point.

Related to the radiation thermometer, the HTFP cell and the furnace used, the SSE should be considered for both scheme 1 and scheme 2. In principle, the cell-furnace-radiometer combination determines the SSE uncertainty.

To use HTFP cells to calibrate an instrument, interpolation between or extrapolation beyond the available fixed points is required. The various schemes have been described in [22], or its extensions [25] and [26], and these documents should be used as guides for the laboratory to evaluate the uncertainty in interpolation/extrapolation appropriate to the scheme it has chosen. The use of the Planck version of the Sakuma-Hattori equation is recommended where one, two or three fixed points are used ($n = 1$, $n = 2$ or $n = 3$), or a least squares approach where more than three are used (fixed points can be a mixture of HTFP and pure metal fixed points).

The case where two HTFP cells are used (the $n = 2$ scheme) has been studied by Bloembergen and Yamada [27] and Saunders *et al.* [28], although the temperatures for the Co-C, Pt-C and Re-C fixed points need to be updated using the most recent temperatures from [8] and [7]. As an example, at present using the $n = 2$ scheme with Cu and WC-C, the uncertainty ranges from approximately ~ 0.05 K to ~ 0.5 K over the range from 1200 K to 4000 K [27]. While related to both the choice of HTFP cells

used and the radiation thermometer used, the uncertainty due to interpolation and/or extrapolation should be considered in both schemes.

The sensitivity coefficients required to evaluate the propagation of uncertainties from each of the fixed points can be found in [25] and [26].

5. Other considerations

5.1. Cell evaluation

The way HTFP cells have been filled and the extent to which voids and/or graphite inclusions are present in the ingot can significantly affect the plateau shape and the melting range, and consequently the point-of-inflection position on the plateau as well as the form and position of the run-off at the end of the plateau. In the case of incomplete filling, the most obvious effects would be: a lack of reproducibility of the melting temperature of the cell; a pronounced run-off before full melting was attained; and the sensitivity of the POI to changing the thermal environment (such as furnace set-point temperature, temperature gradients, etc.). The tests below can be used to evaluate the quality of a HTFP cell. Of course, it is up to the user to decide what is considered sufficiently high quality for their purpose.

5.1.1. Cell melting range In the cell selection process [15] conducted prior to the measurements in [7], selection criteria were established to ensure that only the best HTFP cells were chosen for the definitive thermodynamic temperature assignment. Three main criteria had to be respected for the cell selection: small melting range, high purity of the metals and high melting temperatures, i.e., close to the melting temperature of the pure alloy system (which is most probably correlated with the first two criteria given that for most impurities the distribution coefficient, k , is less than one.) Therefore, in order to ensure high-quality HTFPs, it is important to ensure that the cells to be used as temperature references present the following characteristics: completeness of filling (though the density of the M-C eutectics is not very well known, experience in filling cells can help determine the filling procedure and ensure that the cell is filled to over $\sim 95\%$ of its volume); high purity of the metals (99.999%); and small melting range. The melting range is a reliable indication of the: purity of the materials; adequacy of the positioning of the cell inside the furnace (effect of the temperature distribution); and filling of the cell (an imperfectly filled cell with voids will show poor plateaus with large melting ranges in the case of large melt initiation temperature steps). For HTFP cells to be of the highest quality, it is recommended to ensure that the melting range obtained with a reference cell is compliant with the selection criteria in [15], namely about 0.12 K at Co-C, 0.30 K at Pt-C and 0.35 K Re-C.

5.1.2. Effect of melt initiation temperature step on the melting range During the assessment of the effect on the plateau melting range with different melt initiation

steps, as above, HTFP cells that show large differences in their melting temperature between plateaus realized with different offset temperatures, for example 10 K, 20 K and 30 K, should be considered inadequate for use as high quality reference cells. In the authors' experience with Co-C, Pt-C and Re-C, differences in the melting ranges between the different offset temperatures of 0.07 K, 0.10 K and 0.15 K, respectively, should be considered as limits for the highest quality cells.

For less demanding applications, these criteria can be relaxed with correspondingly larger uncertainties.

5.2. Comparison of methods

Using the point-of-inflection as the reference point rather than the liquidus is likely to have smaller uncertainties, but does require knowing that the realization has been made under the same or sufficiently similar conditions as during the assignment of temperature. For this reason the point-of-inflection is well suited to scheme 2. If the values for point-of-inflection listed in the *MeP-K-19* are to be used, this means the same construction requirements need to have been met and also comparable realisation conditions, such as what type of furnace is used, and how well it has been optimized. Alternatively, a direct chain of comparison measurements to one of the HTFP cells used in [7] would be needed.

The use of the liquidus overcomes these limitations. The liquidus is bounded by limits, which gives larger uncertainties, but the limits are valid regardless of the conditions of use: poorer realisations will increase the spread of possible values but will still include the reference value albeit with a larger uncertainty. This method is thus best suited to new cells where there is no or limited suitable radiometric temperature assignment capability. There is a trade-off between the uncertainty in the published value compared to the local thermodynamic capability, and the need to assess the effect of impurities in a new cell.

5.3. Limitation of scope

Finally, it should be noted that the information here refers to eutectic alloys and the use of melting to identify the liquidus or a proxy for it. A number of peritectic alloys have also been investigated and at least one is under investigation for addition to the *MeP-K-19*. It may be possible that in evaluating the peritectic based HTFP the freeze is preferred to the melt. In that case additional uncertainties may need to be added to those considered in this paper.

6. Recommendations for further study

The materials used for HTFPs and the way references are realized have not been studied in as much depth as pure metal fixed points. There are aspects that relate to assessing uncertainties that are not fully understood. The two most important areas that need

research are to better understand the furnace effect and to determine the temperatures of other HTFP.

- Further work to understand the furnace effect is the most important area of study. The observed effect should be investigated to fully clarify its physical origin. Some recent work [29] has already been published.
- As previously mentioned, Co-C, Pt-C and Re-C are the most studied HTFPs. Future work should include determination of the thermodynamic temperatures of other HTFP types such as the WC-C and Pd-C points. This could be carried out using scales derived from the published values for Co-C, Pt-C and Re-C or via a direct radiometric determination.

There are additional areas that would benefit from further investigation and might reduce or better characterize uncertainties.

- Results of the stability tests in Work Package 1 of the CCT-WG5-High Temperature Fixed Point Research Plan/Implementing the new kelvin project only detected drift for one cell. There is work presently underway to better understand HTFP stability. An update to the stability uncertainties should be made once this work is complete.
- If possible, experimental confirmation of the temperature drop calculations in [10] and further simulations should be attempted.
- The correlations between the temperatures of the fixed points used in any interpolation/extrapolation scheme should be considered. Uncertainties due to interpolation/extrapolation should be reconsidered given the present knowledge of fixed-point melting temperatures and their uncertainties.

7. Conclusion

The uncertainty components and their magnitudes discussed in this work represent the state of knowledge at the time of writing. The authors acknowledge that this is an incomplete picture and expect that these values will be become refined as the high-temperature metrology community gains more experience implementing, testing through comparisons, and reviewing calibration and measurement capabilities [30] based on relative primary thermometry.

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