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Present Estimates of the Differences Between Thermodynamic Temperatures and the ITS-90

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Abstract At the request of the Consultative Committee for Thermometry (CCT), Working Group 4 (WG4) has critically reviewed all available measurements of the differences between thermodynamic and ITS-90 temperatures, $(T - T_{90})$, and documented the conversion of older data to the ITS-90. Particular attention has been given to the uncertainties. Based on this review, we provide consensus estimates of $T - T_{90}$ for selected measurements from 0.65 K to 1358 K. We provide two analytic functions for $T - T_{90}$, one for use from 8 K to the triple point of water (T_{TPW}) and one for use above T_{TPW}. The small discontinuity of the derivative $\mathrm{d}T_{90}/\mathrm{d}T$ at T_{TPW} is discussed.

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We also identify temperature ranges where researchers are encouraged to undertake high-accuracy measurements of $T - T_{90}$.

Keywords Differences $T - T_{90}$ · International Temperature Scale ITS-90 · Primary thermometry · Thermodynamic temperature

1 Introduction

In 2006, the Consultative Committee for Thermometry (CCT) adopted a Mise en pratique for the definition of the kelvin [1] and envisioned that future versions would include recommended values of the differences between thermodynamic temperatures and ITS-90 temperatures ($T - T_{90}$). At the CCT's request, Working Group 4 (WG4) critically reviewed all available measurements of $T - T_{90}$ including constant-volume gas thermometry, acoustic gas thermometry, spectral radiation thermometry, total radiation thermometry, noise thermometry, and dielectric-constant gas thermometry. WG4 also reviewed the uncertainties and the conversion of older data from ($T - T_{68}$) to ($T - T_{90}$) . This paper is an updated summary of the report of WG4 to the CCT [2] and the first complete account of the differences $T - T_{90}$ since the adoption of the ITS-90.

We provide consensus estimates of $T - T_{90}$ for selected measurements from 4.2 K to 1358 K as well as a recommendation for $T - T_{90}$ for the range 0.65 K to 4.2 K. In the temperature range from 25 K to 255 K, the review found unexplained inconsistencies between the uncertainties claimed for specific data sets and WG4's consensus estimates of $T - T_{90}$. This was addressed in part by expanding the uncertainties of the consensus estimates. WG4 needs additional data before it can provide a low-uncertainty estimate of $T - T_{90}$ in this temperature range. Also, more measurements are needed between 550 K and 693 K and at the copper point (1358 K). WG4 strongly encourages researchers to undertake additional high-accuracy measurements of $T - T_{90}$ in these temperature ranges.

2 Overview of Input Data

Table 1 is ordered according to the methods employed, summarizes the experiments taken into consideration above 4.2 K, and specifies the temperature ranges or fixed points. The uncertainties for all data were critically reviewed. We note that no data have so far been reported for measurements of T with respect to the ITS-90 as interpolated by SPRTs at any temperature below 77 K. Instead, some constant volume gas thermometry data which originally provided values of ($T - T_{68}$) have been converted to ($T - T_{90}$), and below 24.5 K the differences are referred to the ITS-90 as *interpolated* by gas thermometry.

Figure 1 gives an overview of measurements considered by WG4, with emphasis on the range above the triple point of water. Constant-volume gas thermometry (CVGT) was the basis for establishing the ITS-90, both directly and by furnishing the reference temperatures for spectral radiation thermometry at high temperatures [29]. Since the adoption of the ITS-90, acoustic gas thermometry has superseded

Table 1 Summary of all experiments taken into consideration above 4.2 K by WG4 identifying the covered temperature ranges or fixed points

Method and author	Year of publication	Temperature
Constant-volume gas thermometry		
Berry	1979 [3]	4.2 K to 24.6 K
Kemp et al.	1986 [4]	14 K to 287 K
Steur and Durieux	1986 [5]	4.2 K to 100 K
Astrov et al.	1995/96 [8]	4.2 K to 309 K
Guildner and Edsinger	1976 [6]	273 K to 730 K
Edsinger and Schooley	1989 [7]	505 K to 904 K, Al
Tamura et al.	2008 [9]	4.2 K to 22.5 K
Acoustic gas thermometry		
Ewing and Trusler	2000 [10]	90 K to 301 K
Moldover et al.	1999 [11] and	
Ripple et al.	2007 [12]	217 K to 552 K
Strouse et al.	2003 [13]	Ga, In, Sn
Benedetto et al.	2004 [14]	234 K to 380 K
Pitre et al.	2006 [15]	7 K to 24.6 K,
		77.7 K to TPW
Spectral radiation thermometry		
Fischer and Jung	1989 [16]	Al, Ag, Au
Fox et al.	1991 [17]	Al, Ag, Au
Stock et al.	1995/96 [18] and	
Taubert et al.	2003 [19] and	
Noulkhow et al.	2009 [20]	692 K to 1235 K
Yoon et al.	2004 [21]	Ag, Au
Goebel et al.	2004 [22]	Cu
Various other sources	2008 [23]	Cu
Total radiation thermometry		
Martin et al.	1988 [24]	144 K to 375 K
Noise thermometry		
Edler et al.	2003 [25]	Cu
Labenski et al.	2008 [26]	Zn
Dielectric-constant gas thermometry		
Luther et al.	1996 [27] and	
Gaiser et al.	2008 [28]	4.2 K to 24.6 K

this method and has identified significant differences $(T - T_{90})$. The various CVGT measurements are denoted in Fig. 1 with green symbols. The acoustic measurements denoted by blue or brown symbols can be seen in more detail in Fig. 2. Meanwhile, new spectral radiation thermometry has provided information on $(T - T_{90})$ in the

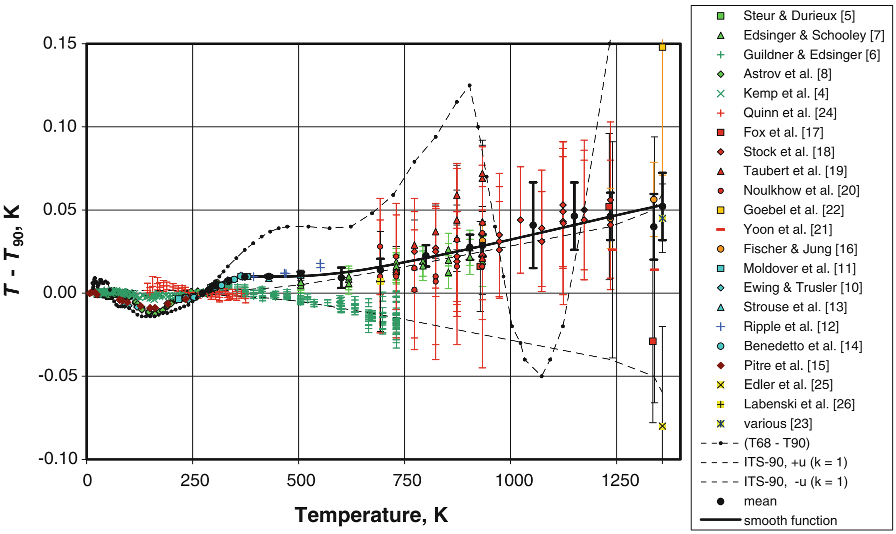

Fig. 1 Overview of measurements of $T - T_{90}$ with emphasis on the range above the triple point of water. The smooth function (Eq. 2, *solid black line*) interpolating the mean values (*bold black dots*) is recommended above the triple point of water. The difference from the former scale IPTS-68 is shown by *small black dots* and a *dashed line*. All error bars represent uncertainties with $k = 1$. The initial uncertainty bounds of the ITS-90 with respect to thermodynamic temperature are given by *dashed lines*

region above 730 K, denoted in Fig. 1 by red and orange symbols. For further details, see the discussion in the following sections.

3 Special Problems

By inspecting Figs. 1 and 2, it is evident that certain measurements deviate from the others beyond their combined uncertainties. These cases are treated in more detail in this section.

3.1 Low-Temperature Constant-Volume Gas Thermometry

Results from acoustic gas thermometry (AGT) [10,11,15] indicate significant deviations of the ITS-90 from thermodynamic temperatures in the range below 273 K, with absolute values of almost 10 mK at 150 K. These values seem to be broadly consistent with (revised) results from Astrov's [8] CVGT. Two other CVGT experiments in the range (Steur [5], up to 100 K and Kemp [4], up to 287 K), together with the original Astrov [30] CVGT and Quinn and Martin's [24] total radiation thermometry, constituted the main ingredients for the construction of the ITS-90. The principal problem in this temperature range is the disagreement between the gas thermometry work of Astrov and of Kemp, see Fig. 2. WG4 examined several effects that could have contributed to the difference.

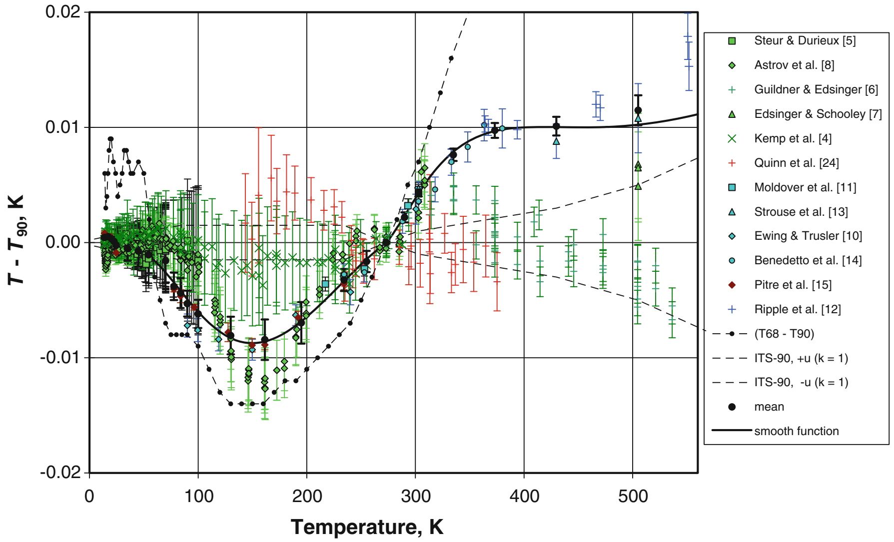

Fig. 2 Measurements of $T - T_{90}$ in the temperature range from the hydrogen point to 550 K. Data reported in terms of IPTS-68 have been converted to ITS-90 using $T_{90} - T_{68}$ differences derived from stable capsule-type SPRTs. The smooth function (Eq. 1, *solid black line*) interpolates the mean values (*bold black dots*) below the triple point of water. Above 273.16 K, the polynomial of Eq. 2 is recommended (shown by the *same symbols*). The difference with respect to the former scale IPTS-68 is shown by *small black dots* and a *dashed line*. All error bars represent uncertainties with $k = 1$. The initial uncertainty bounds of the scale ITS-90 with respect to thermodynamic temperature are given by *dashed lines*

Changes in the linear thermal expansion coefficient due to cold working ought to apply to all low-temperature gas thermometry experiments, since all used (oxygen-free high-conductivity) copper bulbs. It is estimated to contribute 0.3 % to the uncertainty in the linear thermal expansion coefficient, equivalent to about 1 % in the change of volume. This corresponds to about 1 mK at 150 K. Thus, the differences between the data of Astrov and of Kemp cannot be reconciled by this mechanism.

Starting with the NPL gas thermometry of Berry [3], bulbs used at low temperatures (<30 K) have been gold-plated to reduce as much as possible adsorption effects that occur at the lowest temperatures. Gold plating was used by both Steur and Kemp, but *not* by Astrov. It may be that gold plating alters the natural expansion of copper; resulting in a relative error in bulb volume, $\Delta V/V$, and hence in $\Delta T/T$, which is approximately linear with $T - T_{\mathrm{TPW}}$, and hence quadratic when expressed in mK. This is roughly the observed tendency, assuming that the AGT data is a better representation of thermodynamic temperature. The gold layer of Kemp's NML bulb has a thickness of 0.05 mm while Steur's KOL gas thermometer has double that amount. These values were used to estimate an upper limit for the effect of gold-plating, amounting to no more than 2 mK at 100 K.

We conclude that the error for Kemp's bulb might reach a maximum of about 3 mK around 150 K, which increases the original uncertainties by about 50 %. Although this shows that the effect cannot fully explain the larger difference between Kemp and Astrov, it is significant in the context of the work of WG4. Therefore, WG4 remains concerned about the effect of the interface between the copper and gold. However, the data sets of NML and KOL [4,5] cannot be excluded from consideration, because no published data are available on the effect of gold-plating on thermal expansion.

3.2 NBS/NIST Constant-Volume Gas Thermometry

In his 1990 publication [31], Schooley reviewed the history and the results of CVGT at NBS/NIST that began in 1928 and concluded in 1990, with significant publications in the archival literature including [6] and [7]. Schooley's review shows that the NBS/NIST gas thermometer underwent several stages of improvements, particularly as problems were discovered when the thermometer was operated at the higher temperatures. He emphasized that CVGT results are very sensitive to the thermal expansion of the bulb. Edsinger and Schooley constructed two cylindrical bulbs and in the range 505 K to 933 K they discovered a temperature-dependent drift in the apparent volume of their first gas bulb [31]. Because they were aware of drifts, they returned the gas thermometer to 0 °C after each test temperature. In contrast, Guildner and Edsinger [6] detected no drift up to 730 K and they measured successively higher test temperatures without returning to 0 °C.

In the region of overlap (505 K to 730 K, see Fig. 1), the more recent NBS/NIST gas thermometry results [7,31] are inconsistent with the earlier results [6]. Because of the continuity of the NBS/NIST program and because of the progressive discovery and mitigation of gas bulb-related problems, the most recently published results [7,31] must be regarded as superseding earlier results [6]. As the earlier data [6] below 505 K were acquired with apparatus and procedures similar to those that led to the inconsistent results at 505 K, the uncertainties claimed for the NBS/NIST gas thermometry results below 505 K are unreliable.

3.3 Total Radiation Thermometry of Quinn and Martin

In the original Quinn and Martin paper [32] and the subsequent Martin et al. paper [24], errors were made in determining some of the factors that enter into the calculation of σ, the Stefan-Boltzmann constant. Based on what is known now, the estimate for σ, some 3.5 parts in 10^4 below the CODATA [33] value, would be revised. Error in estimating the coupling of the calorimeter and the radiator suggests a value of σ that is too small. In contrast, the efficiency of the light trap appears to have been overestimated—resulting in a value of σ that would be too large.

In retrospect, it appears that there were errors of the second kind, and since their estimate for σ is low (if we assume that the CODATA value is correct), we can infer that there must have been other errors that have an effect similar to the errors of the first kind. A correction to the data beyond the bounds of any known error would be required to bring the total radiation thermometry temperature estimates into line with the more recent acoustic data. Neither the authors nor other experts are able to give a plausible explanation for the discrepancy. It seems likely that the acoustic data are less subject to systematic bias, but it is a concern that the evidence suggesting the total radiation thermometry work is in error rests on a single technique, albeit with different implementations and gases and many internal consistency checks. Therefore, the total radiation thermometry data are retained with uncertainties as published when reporting surveys of experiments, even if we now believe that either the data or the uncertainty estimates are unreliable. However, because we lack a reliable estimate for the uncertainty of the data, the total radiation thermometry data [24] are excluded from calculations of a consensus estimate of $T - T_{90}$.

3.4 Copper Point

There have been only two recent measurements at the copper point, Goebel's absolute radiation thermometry [22] being 148 mK above ITS-90, and Edler's noise thermometry [25] 80 mK below. Therefore, various other data [34–37] have been included to take into account the older relative radiation thermometry exhibiting low uncertainties. The result of Edler [25] is excluded from the averaging process due to a recently detected statistical bias [38].

4 Consensus Estimate of $T - T_{90}$ by Averaging of Data

The upper limit of the WG4 averaging process is the copper point (higher temperatures are under discussion in CCT WG5 [39]). The treatment of $T - T_{90}$ below 4.2 K is given in Sect. 6. It was agreed to exclude the Quinn and Martin [24] total radiation measurements and the gas thermometry measurements of Guildner and Edsinger [6] from the averaging procedure as explained above, while those of Edsinger and Schooley [7] are retained. The gas thermometry results of Kemp, Steur, and Astrov [4,5,8] are retained for the averaging, but with recalculated uncertainties. The relative radiation thermometry of Fischer and Jung [16] at the Al, Ag, and Au points and of various other sources at the Cu point [23] are included to benefit from their low uncertainties.

First, smooth interpolating functions for each of the different data sets were constructed. These functions allowed easy averaging of the values of $T - T_{90}$ at a predefined set of temperatures, including the fixed points of ITS-90 and additional points that are often secondary reference points. Where such points were not available, the temperatures were arranged to cover the scale in approximately equidistant steps, the intervals being narrower in the low temperature range (see Table 2). Then, the mean was formed using the inverse of the squares of the uncertainties identified by WG4 as weighting factors. The individual uncertainties were propagated according to the paper of Cox [40]. As WG4 has spent considerable efforts to update the uncertainties of the measurements, there is confidence that these are (to the extent possible) reliable and scientifically justified. The resulting uncertainties for the mean of $T - T_{90}$ are displayed in Figs. 1, 2, and 3 as error bars of the points denoted "mean."

The inconsistency between the CVGT and AGT results below the triple point of water and the absence of recent measurements in the region between the neon point and 77 K required additional consideration. Kinks should not appear (except at the triple point of water) in a smooth interpolation function of $T - T_{90}$ representing the consensus estimate. However, in the region between the neon point and 77 K, only older CVGT data are available that seem inconsistent with recent AGT results. Therefore, a type B

Table 2 Current best estimates of $T - T_{90}$ between 4.2 K and the copper point

T_{90} (K)	$T - T_{90}$ (mK)	u (mK)	T_{90} (K)	$T - T_{90}$ (mK)	u (mK)
4.2	−0.02	0.12	161.405	−8.43	1.8
5	0.10	0.12	195	−6.97	1.8
6	0.04	0.13	234.3156	−3.25	1.0
7	−0.08	0.09	255	−1.64	0.9
8	0.01	0.10	273.16	0	0
9.288	0.13	0.11	290	2.19	0.4
11	0.27	0.12	302.9146	4.38	0.4
13.8033	0.44	0.14	335	7.62	0.5
17.035	0.51	0.16	373.124	9.74	0.6
20.27	0.32	0.17	429.7485	10.1	0.8
22.5	0.10	0.18	505.078	11.5	1.3
24.5561	−0.23	0.20	600.612	9.21	6.1
35	−0.53	1.0	692.677	13.8	6.9
45	−0.75	1.4	800	22.4	6.4
54.3584	−1.06	1.6	903.778	27.6	7.6
70	−1.57	1.9	933.473	28.7	6.6
77.657	−3.80	1.2	1052.78	40.9	26
83.8058	−4.38	1.3	1150	46.3	20
90	−5.30	1.1	1234.93	46.2	14
100	−6.19	1.2	1337.33	39.9	20
130	−8.07	1.6	1357.77	52.1	20

The uncertainties u are for $k = 1$

uncertainty on the unknown bias due to uncorrected systematic effects was introduced following the methodology of Levenson et al. [41]. In this way it was possible to average across the old and new data from 35 K to 70 K. The low-temperature CVGT data of Tamura et al. [9] and of Steur and Durieux [5] were renormalized, referenced to the mean value of all other measurements at their upper bounds, the neon point and 100 K, respectively. The latter was especially valuable in providing a thermodynamically sound interpolation up to 100 K, overlapping with the upper branch of the acoustic gas thermometry. Above 77 K, the usual weighted mean was used. However, the uncertainties were expanded according to the limited degrees of freedom for the averaging process to account for some remaining discrepancy with respect to Kemp's CVGT [4].

Table 2 summarizes the result of the averaging process for measurements of $T - T_{90}$ above 4.2 K and represents the present best estimate of the experts in WG4. It is noted that there must be an uncertainty in establishing the reference temperature in primary thermometry, such as CVGT or AGT, because one relies on an SPRT to transfer the value from a physical realization of the reference (triple-point-of-water cell) to the environment of the gas thermometer bulb or resonator. All the uncertainties in this

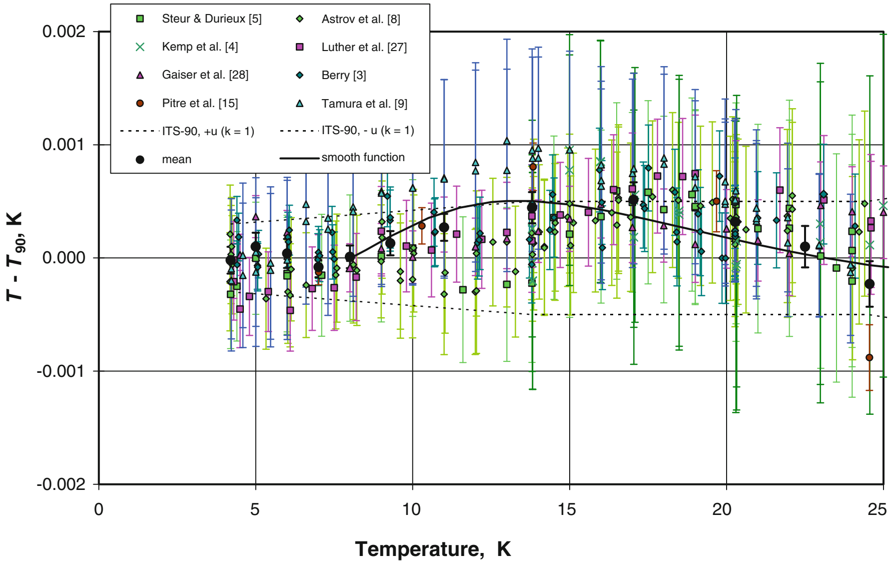

Fig. 3 Measurements of $T - T_{90}$ with respect to interpolating CVGTs in the temperature range from 4.2 K to the neon point. The data of Astrov, Berry, and Steur in terms of NPL-75 have been converted to ITS-90 based on data from stable Rh–Fe thermometers. The smooth function (Eq. 1, *solid black line*) interpolates the mean values (*bold black dots*) above 8 K. All error bars represent uncertainties with $k = 1$. The initial uncertainty bounds of the scale ITS-90 with respect to thermodynamic temperature are given by *dashed lines*

process lead to components of uncertainty in measured values of T/T_{ref} and hence T, but they do not affect the uncertainty of the reference temperature, T_{ref}, itself (which is zero in the case of the triple point of water, by definition). In a similar way, the uncertainty of the calibration of the SPRT is identically zero at $W = 1$. Hence, there is no uncertainty in stating that $T - T_{90} = 0$ at the triple point of water. For a discussion of the implications of the redefinition of the kelvin, see [42].

Comparing the uncertainty of the mean of $T - T_{90}$ with the initial estimated thermodynamic uncertainty of ITS-90, there is significant progress in the low-temperature range from 4.2 K to the neon point (see Fig. 3) with a lot of recent and consistent measurements now available. This is not the case between 35 K and 77 K as shown in Fig. 2, where we must still rely on Kemp, Steur, and Astrov [4,5,8]. Therefore, WG4 has presently no other solution beyond applying the described formalism that leads to considerably higher uncertainties of the mean values between 35 K and 70 K.

Above 77 K, there is again considerable progress as Pitre et al. [15], Ewing and Trusler [10], and others at higher temperatures contributed new acoustic gas thermometry data. These results confirm the discontinuity in the slope of $T - T_{90}$ at the triple point of water. However, there is the unexplained inconsistency in the CVGT of Kemp which was accounted for by expanding the uncertainties of the mean. WG4 strongly encourages researchers to undertake additional high-precision measurements of thermodynamic temperatures in this range. Another gap exists between 550 K and the zinc point, where we still have only Schooley's CVGT results [7] (Fig. 1). We hope to see this gap closed by acoustic gas thermometry, radiation thermometry, or possibly by advanced noise thermometry. A new value for the zinc point would almost connect with the relative spectral radiation thermometry of Fischer and Jung [16] and should immediately lead to new values for the aluminum, silver, and gold points with lower uncertainties. More measurements are also urgently required at the copper point.

5 Analytical Smooth Interpolation Functions

To disseminate the differences $T - T_{90}$ via the Mise en pratique in a convenient form, simple analytic expressions have been developed. The general idea is to approximate the differences with only two functions. Below 273.16 K, fitting with a logarithmic temperature parameter $x = \log_{10}(T)$ down to 8 K (see Figs. 2, 3) proved to be the best interpolation:

$$(T - T_{90})/\text{mK} = \Sigma_{i=0\ldots7} b_i (\log_{10}(T_{90}/273.16\,\text{K}))^{i+1} \tag{1}$$

with the coefficients b_i:

$$b_0 = 4.42457 \times 10^1 \quad b_1 = -1.76311 \times 10^2 \quad b_2 = -1.53985 \times 10^3$$
$$b_3 = -3.63685 \times 10^3 \quad b_4 = -4.19898 \times 10^3 \quad b_5 = -2.61319 \times 10^3$$
$$b_6 = -8.41922 \times 10^2 \quad b_7 = -1.10322 \times 10^2$$

By forming the ratio with respect to the temperature of the triple point of water T_{TPW} in the argument of the logarithm, the function is forced to go through the definition point of the kelvin. The derivative $\text{d}(T - T_{90})/\text{d}T_{90}$ at the triple point of water is 7.0×10^{-5}.

From the triple point of water to the copper point, a polynomial in the dimensionless variable $x \equiv (T_{\text{TPW}}/T_{90})$ is recommended to represent the dimensionless difference $(T - T_{90})/T_{90}$ as a function of T_{90}. The function has the form,

$$(T - T_{90})/\text{mK} = (T_{90}/\text{K})\,\Sigma_{i=0\ldots4} c_i (273.16\,\text{K}/T_{90})^{2i} \tag{2}$$

with the coefficients c_i:

$$c_0 = 0.0497 \quad c_1 = -0.3032 \quad c_2 = 1.0254 \quad c_3 = -1.2895 \quad c_4 = 0.5176$$

The derivative at the triple point of water is 10.1×10^{-5}, resulting in a discontinuity of 3.1×10^{-5} between Eqs. 1 and 2, which is consistent with the value 4×10^{-5} from recent acoustic gas thermometry [15]. The accumulated inconsistency between the Hg and Ga points would be about 1.1 mK, whereas experiments based on the resistance ratios of platinum resistance thermometers [43] suggested a higher value of 1.5 mK. Although it is difficult to measure the slope discontinuity, in principle, it must arise in the ITS-90, i.e., in T_{90} not in T. By evaluating the calibrations of over 40 capsule-type and long-stem SPRTs obtained over a period of more than 20 years, Rusby [44] has found discontinuities in the slope at the triple point between 0×10^{-5}

and 6×10^{-5}. If new thermodynamic experiments are undertaken around TPW, the expected discontinuity is known as soon as the SPRT is calibrated. Given the range of values for different SPRTs, the functions give a satisfactory result.

6 The Temperature Range Below 4.2 K

The backbone of ITS-90 in the low-temperature range between 2.6 K and 27.1 K is Berry's gas thermometry [3] embodied in the scale NPL-75. Rusby and Swenson [45] extended Berry's scale using CMN thermometry from 3.1 K down to 0.4 K. The vapor-pressure/temperature relations of the ITS-90 are based on this extension and the work of El Samahy [46] from 1.8 K down to the lower limit of the ITS-90 at 0.65 K.

However, since the adoption of the ITS-90, deviations of the ITS-90 from thermodynamic temperature have been detected below 1.5 K. It is currently considered best to rely on the Provisional Low Temperature Scale of 2000, PLTS-2000 [47] over its applicable range, 0.9 mK to 1 K, and to make a smooth connection to the ITS-90 at about 2 K. This approach was followed for the new ^{3}He vapor-pressure scale PTB-2006 from 0.65 K to 3.2 K, which is fully consistent with the PLTS-2000 [48], see Fig. 4. The temperatures according to PTB-2006 are equal to those of PLTS-2000 in the range from 0.65 K to 1 K: $T_{2006} = T_{2000}$. The temperatures T_{2006} in the range 1 K to 2 K are thermodynamically sound as they are calculated using thermodynamic vapor-pressure relations and are in agreement with T_{2000} at 1 K and with T_{90} at 2 K. We note that the work of de Groot et al. [49] at VSL between 1.1 K and 4.3 K, and that of Meyer and Reilly [50] at NIST between 0.65 K and 5.2 K gave similar indications. However, they could only compare their wire scales as represented by Rh–Fe thermometers traceable to the scale NPL-75 and T_{90} realized using helium vapor-pressure/temperature relations, thereby leading to higher uncertainties.

The recommendation of WG4 is therefore to keep the results of Rusby and Swenson and El Samahy between 2 K and 4.2 K, $T - T_{90} \equiv 0$, and to use PTB-2006 between 0.65 K and 2 K, $T - T_{90} \equiv T_{2006} - T_{90}$. As the ^{3}He vapor-pressure polynomial of PTB-2006 has exactly the same definition range and form as that of the ITS-90, users can replace the coefficients and there is no need for a correction function. In summary, from 2.0 K to 8.0 K, WG4 recommends that the ITS-90 be used according to its definition. Above 8 K, the smooth interpolation function, Eq. 1, is recommended, and below 2 K, the vapor-pressure polynomial of PTB-2006 [48].

7 Outlook

The results of [2], summarized and updated in this paper, have been approved by the CCT and WG4 is providing them for inclusion in the Mise en pratique for the definition of the kelvin. The differences $T - T_{90}$ and the corresponding uncertainties as stated in Table 2 will be listed. In addition, the smooth interpolation functions, Eqs. 1 and 2, will be included for convenience of the user. Clearly, considering the various weaknesses discussed in Sect. 4, it would be premature to base a new temperature scale on the estimates in Table 2.

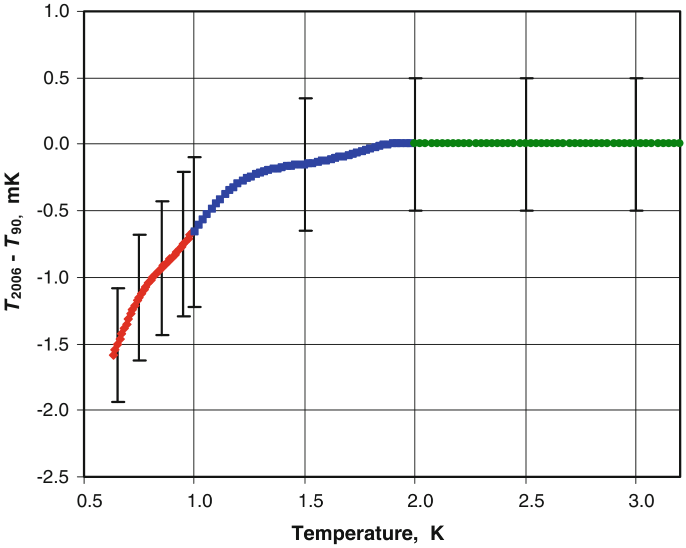

Fig. 4 Differences between the scales PTB-2006 and ITS-90. The temperature scale PTB 2006 is based on the PLTS-2000 (*red symbols, left*), on a thermodynamic vapor-pressure relation (*blue symbols, middle*) and on the ITS-90 (*green symbols, right*). The error bars represent uncertainties for $k = 1$ (Color figure online)

Several new measurements are planned for the near future:

(1) NIST—Acoustic gas thermometry will be extended to the range between 550 K and 700 K. In addition, noise thermometry is planned at 77 K and between 700 K and 930 K. Refractive index gas thermometry at microwave frequencies is planned at the Hg and Ga fixed points.
(2) LNE-INM—Acoustic gas thermometry will be repeated between 77 K and the TPW and extended to the temperature range from 77 K to 4 K. Absolute radiation thermometry will be performed at the Cu point.
(3) PTB—Dielectric-constant gas thermometry will be used in the framework of the Boltzmann project to measure around the TPW and below. Absolute radiation thermometry will be used at PTB between the Zn and Al fixed points, at the Au and Cu fixed points, and later also at lower temperatures.
(4) NPL—Related to the Boltzmann project, acoustic gas thermometry will be employed to measure thermodynamic temperatures around the TPW. Absolute radiation thermometry will be performed at NPL to measure the Au and Cu fixed points.
(5) NIM—measurements are under way with acoustic gas thermometry around the TPW.

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