WORKING GROUP 4 REPORT TO CCT
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Topic of WG: thermodynamic temperature determinations and extension of the ITS-90 to lower temperatures

Terms of reference: to review and make recommendations concerning thermodynamic temperature determination and the definition of the kelvin

Working Group 4 is **tasked** with continuing to review measurements of T-T_{90} and with monitoring progress on the redefinition of the kelvin in terms of the Boltzmann constant.

Since the preparation of the last report of WG4 to CCT, CCT/08-13/rev, dated 25 June 2008, the members met at the 4th International Workshop on Progress in Determining the Boltzmann Constant, held from 22 to 24 September 2009 at INRiM. The report CCT/08-13/rev had been approved in the meantime by the CCT at 6 February 2009 by email voting. Comments from NPL and INRiM were received and, although the report was agreed unanimously, it was deemed useful to discuss those comments in detail via the respective members of NPL and INRiM at the WG4 meeting of 23 September 2009.

Especially the following points were further evaluated:

Smooth interpolation functions

The report CCT/08-13/rev included a section “Analytical smooth interpolation functions”. Since that date, WG4 reviewed this section, and now recommends a new interpolation function for the temperature range from the triple point of water, T_{TPW}, to the freezing point of copper. The function has the form

$$(T\text{-}T_{90}) / \mathrm{mK} = (T_{90}/\mathrm{K})\ \Sigma_{i=0..4}\ c_i(273.16\ \mathrm{K}/\ T_{90})^{2i}$$

with the coefficients c_i:

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

In comparison with WG4’s original recommendation, the new function had the advantages:

1. It more accurately represents the slope $\mathrm{d}(T\text{-}T_{90})/\mathrm{d}T$ as T approaches T_{TPW} from temperatures above T_{TPW}.
2. It more accurately represents the discontinuity of $\mathrm{d}(T\text{-}T_{90})/\mathrm{d}T$ at T_{TPW} , when it is combined with the recommended function below T_{TPW}
3. the new function more accurately represents $\mathrm{d}(T\text{-}T_{90})/\mathrm{d}T$ near the copper point. A continuation of the differences to higher temperatures can be based on an application of the Planck law.
4. It is less heavily weighted at the high-temperature end where the uncertainties of the estimates of T-T_{90} are larger.
5. It is better-behaved numerically because it has 5 coefficients instead of 6 and because each coefficient is on the order of unity removing the need for large exponents.

The derivative of the high-temperature interpolating function at the triple point of water is 10.1×10^{-5}, resulting in a discontinuity of 3.1×10^{-5} between the low-temperature and the high-temperature interpolation function, which is consistent with the value 4×10^{-5} from Pitre´s recent acoustic gas thermometry.

As T is perfectly continuous, it is clear that the slope discontinuity arises in the ITS-90, i.e. in the calibrations of standard platinum resistance thermometers (SPRTs). The discontinuity in the derivative $d(T\text{-}T_{90})/dT$ is attributable to the reference functions, but subrange inconsistency causes non-uniqueness in the derivative of T_{90}. It therefore varies between SPRTs and the different subrange equations and is biased very slightly away from zero. By evaluating the calibrations of over 40 capsule-type and long-stem SPRTs obtained over a period of more than 20 years, Rusby has found discontinuities in the slope at the triple point of water between 0×10^{-5} and 6×10^{-5} (contribution to TEMPMEKO-ISHM 2010). Given the range of values for different SPRTs, the functions give a satisfactory result.

Extension of recommendations to temperatures below 4 K

The report CCT/08-13/rev gave values for $T - T_{90}$ only above 4.2 K. With the following recommendation the full temperature range of ITS-90, starting from 0.65 K is covered. 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 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 vapour-pressure scale PTB-2006 from 0.65 K to 3.2 K, which is fully consistent with the PLTS-2000. 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 vapour 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. at VSL between 1.1 K and 4.3 K, and that of Meyer and Reilly 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 vapour-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 vapour 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 low temperature smooth interpolation function, Eq. (1) in CCT/08-13/rev, is recommended and below 2 K the vapour pressure polynomial of PTB-2006.

Summary of T-T_{90} review

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). The results of the WG4 report CCT/08-13/rev have been summarized including the aforementioned updates in a paper submitted to TEMPMEKO-ISHM 2010. 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 of the contribution to TEMPMEKO-ISHM 2010 will be listed. In addition, the two smooth interpolation functions will be included for convenience of the user. Clearly, considering the various weaknesses discussed in CCT/08-13/rev, it would be premature to base a new temperature scale on the estimates in Table 2. In the meantime the recommended functions will allow values of T_{90} to be corrected to T, where it is desired to do so.

New measurements on T-T_{90}

During the meeting at CCT-24 in 2008, members of the working group 4 and of the task group TG-SI announced that several new measurements are planned for the near future. The following list is an update as discussed during the meeting at CCT-25.

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 used between the Hg and Ga fixed points.
2) LNE-INM – Acoustic gas thermometry will be extended to the temperature range from 77 K to 4 K. Later, absolute radiation thermometry will be performed at the Cu point.
3) PTB – Dielectric constant gas thermometry will be used to measure around the TPW and below. Absolute radiation thermometry will be used at PTB at the Au and Cu fixed points, and later also at higher temperatures.
4) NPL – Acoustic gas thermometry will be used between the Hg and Sn (Zn) points. Relative radiation thermometry will determine the Ag-Cu interval. Later, absolute radiation thermometry will be performed to measure the Au and Cu fixed points.
5) NIM – measurements are under way with acoustic gas thermometry around the TPW.
6) KRISS – The goal of the experiment is to compare the KRISS realization of the ITS-90 and thermodynamic temperatures determined with acoustic gas thermometry in the range from -40 °C to 110 °C.
7) INRiM – Acoustic gas thermometry will be repeated between the Hg and In points and Doppler broadening thermometry will be established between the TPW and the Ga point.

Unfortunately, so far only the following new measurements could be preformed:

1) Acoustic gas thermometry at LNE-INM between the TPW and 77 K (contribution to TEMPMEKO-ISHM 2010).
2) Dielectric constant gas thermometry at PTB with Helium and Neon between 36 K and 23 K (contribution to TEMPMEKO-ISHM 2010, CCT/10-17) and absolute radiation thermometry between the Zn and Al points with final results [N. Noulkhow, R. D. Taubert, P. Meindl, J. Hollandt, Int. J. Thermophys. 30, 131 (2009)] and at the Au and Cu points with preliminary results (contribution to TEMPMEKO-ISHM 2010).
3) Johnson noise thermometry at NIM at the Ga point [Metrologia **45** (2008) 436–441].
4) Johnson noise thermometry at NIST at the Sn and Zn points (contribution to TEMPMEKO-ISHM 2010).
5) Relative radiation thermometry at INRiM determined the Cu point [Metrologia **47** (2010) 231-238]

This is insufficient to resolve the weaknesses identified in the report CCT/08-13/rev. WG4 is strongly encouraging the NMIs to better support their thermometry sections in performing new measurements of $T – T_{90}$.