WORKING GROUP 4 REPORT TO CCT: May 2003

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Terms of reference : thermodynamic temperature determinations and extension of the ITS-90 to lower temperatures

1. Introduction

The 8th Temperature Symposium in Chicago (October 2002) included several papers of relevance to Working Group 4. It provided the opportunity for some members of the group to meet to review progress and to decide what should be presented in the review of thermodynamic thermometry at the Workshop 'Toward the ITS-XX'. Section 2 of this report summarises this review and includes some information on more recent developments. Section 3 reports activity on the low-temperature extension of the ITS-90. Where papers are expected to appear in the proceedings of the Temperature Symposium, they are indicated by (TS8).

2. Thermodynamic temperature determinations

This section is a short resumé of work in progress which will lead to new thermodynamic temperature values above 1 K. It is grouped according to the technique used: gas thermometry, noise thermometry and radiometry.

As far as we are aware, no experiments in **constant-volume gas thermometry** are in progress other than as interpolations for realising the ITS-90 below 24.5561 K, at NMIJ, KRISS and PTB, and possibly elsewhere.

Two papers were presented at TS8 on **acoustic gas thermometry** in spherical resonators at NIST. Results for ($T - T_{90}$) to date are given as (4.7± 0.6) mK at 302.9 K, (8.8 ± 1.5) mK at 429.7 K and (10.8 ± 3.0) mK at 505 K (Ga, In and Sn points respectively, uncertainties at k = 1). Work continues up to a target temperature of 800 K. Pitre of BNM-INM and Moldover of NIST have begun a co-operative project at NIST to make measurements below 300 K in a 0.5 litre resonator using helium and argon, and below 90 K using helium.

The joint acoustic thermometry project between IEN (Torino) and IMGC in the range 234 K to 380 K (Benedetto *et al*, Tempmeko 2001) continues, and first results are available in CCT/03-18. They are consistent with the NIST results and the earlier low-temperature results of Ewing and Trusler.

There has been no publication on the NPL experiment in **Rayleigh-scattering gas thermometry** since that by Edwards and Boyes in Tempmeko '99. In this technique the elastic scattering from a laser beam passing through a gas is observed and related to the gas density. Two gas cells have been assembled to allow simultaneous measurements at unknown and reference temperatures at equal pressures, and these are being tested to reduce extraneous scattering to an acceptable level (M. de Podesta, private communication). The experiment is planned to run with argon in the range 173 K to 300 K.

Measurement of the thermodynamic temperature of the melting point of copper by **noise thermometry** at PTB was reported at TS8 (Edler *et al*). The method is based on comparisons with a reference source near room temperature, or at the triple-point of water, and used a two-channel arrangement to eliminate the parasitic noise by cross correlation. The result was 1357.69 K ± 0.12 K ($k = 2$).

Progress with the project using a programmable ac Josephson quantised-voltage noise source (QVNS), by NIST and MSL. Accuracy of 0.01 % has been demonstrated in the noise thermometer electronics when using ratio mode, but intermodulation distortion of the QVNS currently limits the accuracy when this is used as the reference. The goal is to measure temperature in the range 84 K to 700 K.

MSL believes it has solved the interference problems in its noise thermometer. It has developed a test based on a zero ohm sensor which indicates that residual EMI problems are below 2 mK at 95 % confidence. Work on the measurement of the indium point will commence shortly.

NIM has begun a project in noise thermometry. Details are not yet available, but it is likely to use the cross-correlation method and initially cover the range from 300 K to 900 K.

New **radiometric measurements** of thermodynamic temperature were presented at TS8 by PTB (Taubert *et al*). These extend the previous data to longer wavelengths (up to 1595 nm) and give new information at temperatures down to about 700 K (zinc point).

No other new radiometric results have been reported, though further experiments are projected or in progress at PTB, NIST and NPL.

At TS8 Reesink *et al* presented progress at NRC with the Fourier transform technique to measure thermodynamic temperatures in the range 873 K to 1273 K. By using a wide wavelength range and a strategy for checking for self-consistency over both wavelength and temperature, it should be possible to obtain results which are thermodynamically valid, with uncertainties perhaps as low as 0.1 K for the Al-Ag interval.

The potential of using metal-carbide eutectic fixed points for the calibration or comparison of radiation thermometers up to about 3000 K, or for re-defining the ITS at high temperatures, was extensively discussed at TS8. Some values for freezing temperatures have been presented, and the topic is under investigation in WG5.

Discussion

Results are presented in Figure 1, which shows differences between various published measurements of thermodynamic temperature and the ITS-90, ($T - T_{90}$). They include results which were available in 1989 and used in the derivation of the ITS-90. Colour printing is recommended.

The most striking feature is the further support given to the gas thermometry of Edsinger and Schooley (*Metrologia*, 1989, **26**, 95-106) in the range above 800 K by the new NIST and IEN/IMGC acoustic data, and the new extended absolute spectral radiometry of PTB (in addition to the earlier data of PTB and two NPL values). The earlier results of Guildner and Edsinger (*J Res Nat Bur Stand*, 1976, **80A**, 703-738) increasingly seem discrepant.

The uncertainties ($k = 1$) in the PTB radiometric measurements are almost as large as the differences ($T - T_{90}$) and the uncertainties (at $k = 1$) originally assigned to the ITS-90 values. Hence the deviations are strongly indicated but not conclusively determined.

On the other hand, the PTB value for the copper point using noise thermometry is 0.08 K *below* the ITS-90. This implies either a large error (of about 0.13 K) in the Au-Cu interval in the ITS-90, or some experimental offset (the PTB uncertainty is 0.12 K, at $k = 2$), or a combination of the two.

The uncertainties in the NIST acoustic data are not only small compared with ($T - T_{90}$), but the differences at the Ga, In and Sn points are also larger than their ITS-90 uncertainty values (1, 3 and 5 mK, $k = 1$). Hence the discrepancies are clearly significant, and are with respect not just to the data of Guildner and Edsinger, but with the consensus as it was in 1989 (gas thermometry of Astrov *et al*, Kemp *et al*, acoustic thermometry of Moldover and Trusler, total radiometry of Quinn and Martin).

Positive differences ($T - T_{90}$) above 273.16 K must be expected to continue as negative differences below 273.16 K, since any lack of continuity in the ITS-90 is known to be relatively small (about 1 mK between 234 K and 303 K). According to recent acoustic thermometry the differences reach - 0.01 K near 150 K, but the 'recovery' to substantially zero differences below 100 K, seen in the constant-volume gas thermometry, seems fortuitous. New data are needed to confirm the behaviour of (T - T_{90}) in this region also.

The experiments in progress and referred to earlier give good reason to hope that a new consensus may emerge in the next few years. One result of particular significance will be a new acoustic determination of the zinc point: if this can be achieved with an uncertainty of only a few millikelvins, one of the major weaknesses in deriving the ITS-90 will be substantially reduced. Given that, the most accurate values for the Al, Ag, and Au points may simply follow from renormalising the *relative* spectral radiation thermometry of Fischer and Jung (*Metrologia*, 1989, **26**, 245-252).

3. Extension of the ITS-90 to lower temperatures

The extension of the ITS-90 below 0.65 K takes the form of an equation for the melting pressure of ^{3}He, in the Provisional Low Temperature Scale from 1 K to 0.9 mK, PLTS-2000. This was approved by the CIPM in October 2000, and an account of its derivation has been published (*Journal of Low Temperature Physics* **126**, 633-642, 2002, see WG4 report of September 2001). A further report was presented at TS8, which included tables of values of melting pressure, p_m, and the first derivative, dp_m/dT_{2000}, at convenient increments of temperature T_{2000}.

The TS8 paper also discusses how the region of overlap between the PLTS-2000 and the ITS-90 should be considered. New measurements of ^{3}He vapour pressures were reported at TS8 by Engert and Fellmuth, which support theoretical evidence that the ITS-90 vapour-pressure equation is in error below 1 K, by up to 1 mK at 0.65 K. It is recommended that the PLTS-2000 should be used for preference, or that corrections should be applied to vapour-pressure measurements where the highest accuracy is required. Guidance on this point will be included in the *Supplementary Information for the realisation of the ITS-90 and PLTS-2000*.

A first draft of the *Supplementary Information for the Realisation of the PLTS-2000* has been prepared using the document PTB-ThEx-21 by Schuster *et al*, a paper by Adams at TS8, and other sources in the literature. It has been circulated in the group for comment, and will be amended and submitted to WG1 for incorporation in the *Supplementary Information for the Realisation of the ITS-90*, now under revision.

For the future, WG4 will keep under review both the acceptance of the PLTS-2000 in the ultra-low temperature community and evidence which may help resolve the uncertainties in the lower parts of the range. Within Europe, a project called 'ULT Dissemination' is nearing completion, and new devices for ensuring traceability to the PLTS-2000 are being evaluated. These include a current-sensing noise thermometer, a Coulomb-blockade thermometer, a second-sound thermometer, Pt and ^{3}He NMR thermometers, and a Superconductive Reference Device to replace the NBS SRM 768. It is hoped that this work will in due course also lead to new indications on the accuracy of the scale.

Finally, a recent development which we have noticed is the presentation at a meeting of the American Physical Society of a tunnel-junction noise thermometer by Spietz *et al* of Yale University (see report in *Science* **299**, 1641, 14 March 2003). This is not essentially a low-temperature device but, with absolute uncertainties currently at about 0.1% of T, it has considerable potential for cryogenic use, especially below 1 K.

Figures

Figure 1: Graph of differences between published thermodynamic temperature determinations and the ITS-90 up to 1235 K

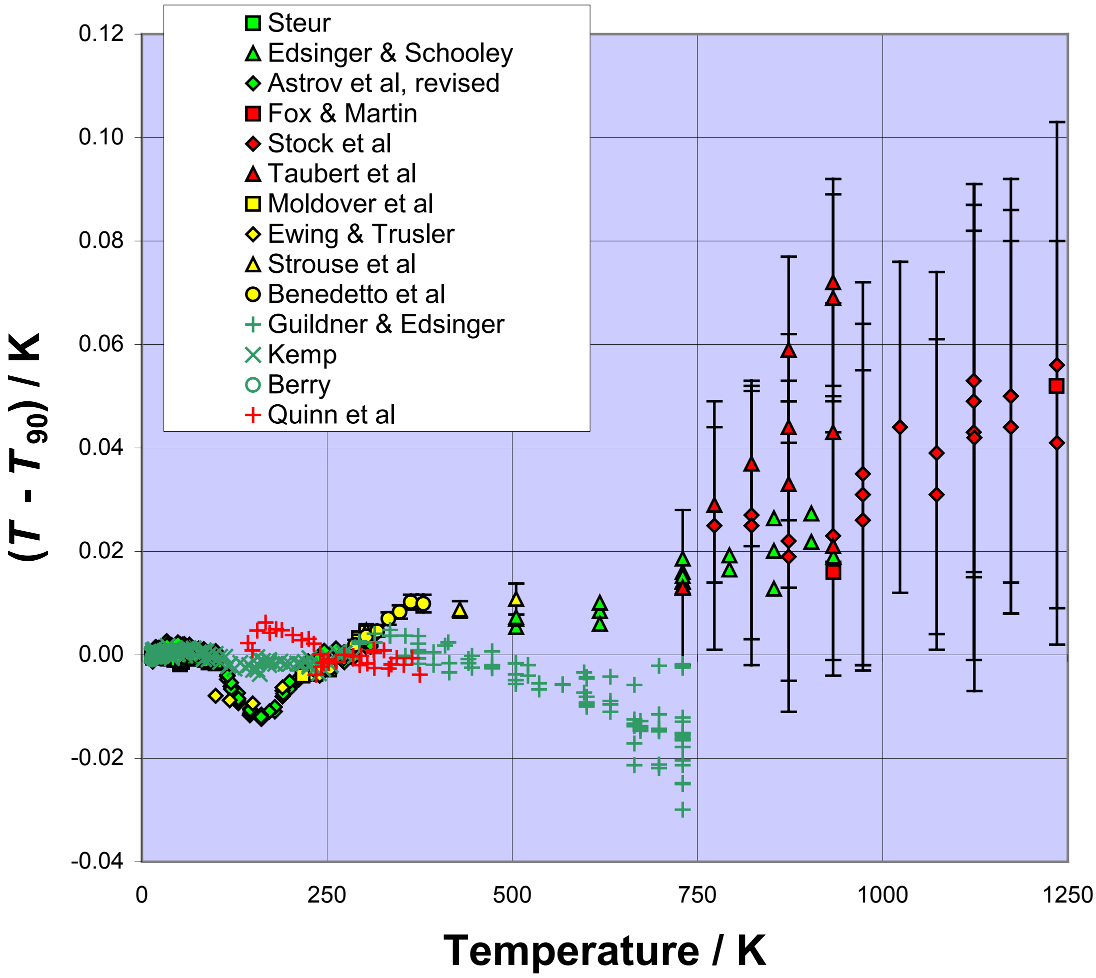

Figure 1: Graph of differences between published thermodynamic temperature determinations and the ITS-90 up to 1235 K. Some uncertainty bars are given, at k = 1. References are as follows.

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