WORKING GROUP 4 REPORT TO CCT: September 2001

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1. Introduction

The Working Group 4 terms of reference were confirmed at the 20th Session of the CCT as: to review and make recommendations concerning 'thermodynamic temperature determinations and extension of the ITS-90 to lower temperatures'. WG4 met in Berlin in June 2001 to review activities in both areas, to work on a joint publication on the PLTS-2000, and to start preparing this report.

2. Thermodynamic temperature determinations

This section is a short resumé of work in progress which will lead to new thermodynamic temperature values above1 K. It is largely based on reports presented at Tempmeko 2001, with some earlier and additional information.

As an overview, a graph is presented in Figure 1 showing differences between various published measurements of thermodynamic temperature and the ITS-90, ($T - T_{90}$). Two sets of spectral (filter) radiometry are seen to support the gas thermometry of Edsinger and Schooley in the range above 800 K, implying that the results of Guildner and Edsinger are incorrect. The deviation ($T - T_{90}$) for the radiometric measurements is at the level of one standard uncertainty in the values assigned in the ITS-90. There are some indications that the ITS-90 may deviate significantly near 150 K, possibly by 10 mK compared with the uncertainty estimate of ± 2 mK (1s). At lower temperatures the differences and deviations are smaller and are not distinct in this figure.

As was noted in the WG4 report last year, experiments in **constant volume gas thermometry** are in progress only as interpolations in realising the ITS-90 below 24,5561 K, eg at NRC (see Hill, Tempmeko 2001), KRISS, and possibly elsewhere.

Acoustic gas thermometry in spherical resonators in the range up to 800 K is in progress at NIST (Moldover *et al,* Tempmeko 1999). The transducers have now been tested up to about 600 K, and evolution of hydrogen has been monitored. A joint project at IEN (Torino) and IMGC in the range 234 K to 400 K has been initiated (Benedetto *et al*, Tempmeko 2001).

The NPL experiment in **Rayleigh scattering gas thermometry** (Edwards and Boyes, Tempmeko 1999), in which scattering from a laser beam passing through a gas is observed and related to the gas density, continues. The gas cells have been assembled and are being prepared for evaluation. The experiment is planned to run with argon in the range 173 K to 300 K.

A development in **Johnson noise thermometry**, pioneered by NIST and MSL, using a programmable ac Josephson quantised voltage source (JVS), was reported at Tempmeko 2001 by Tew. Theoretical investigations show that the JVS has several significant advantages over conventional noise thermometers using thermal noise references. A thermometer is under construction at NIST's Boulder facility to provide a practical evaluation of the concept. Initial experiments will be carried out at the gallium point, and in the longer term it is intended to measure temperature in the range 84 K to 700 K.

Construction of the MSL noise thermometer is now complete and is operating as designed, although some auxiliary instruments must be replaced to eliminate interference. In the next year MSL plans to measure the indium point and complete a detailed uncertainty analysis. In the longer term, measurements will be carried out at primary and secondary fixed points in the range between the indium and zinc points.

The thermodynamic temperature of the melting point of palladium in air was recently measured by noise thermometry at PTB (Edler *et al*, Tempmeko 1999). The method is based on comparisons with a reference source near room temperature and utilized a two-channel arrangement to eliminate the parasitic noise of electronic components by cross correlation. Three miniature fixed points filled with palladium (purity about 99.98 %, mass 90 g) were used to realize the melts. The measured melting temperature of palladium in air was 1552.95 °C ± 0.21 °C (k = 2). This in good agreement with earlier measurements using radiation thermometry which gave a mean value of 1553.4 °C ± 0.34 °C (k = 2) when adjusted to temperatures in air.

Progress in **radiometric measurements** of thermodynamic temperature was reviewed at Tempmeko 2001 by Fox, who noted that the development of cryogenic radiometers and the availability of high performance detectors has resulted in reductions in the uncertainty of radiometric measurements of nearly two orders of magnitude. Results using absolute (spectral) filter radiometers and total radiometers have been published (see Figure 1), and further developments are in progress at NPL, PTB, NIST. A new project in filter radiometry at the silver point was described at Tempmeko 2001 by Ko *et al* of ITRI, Taiwan.

Applying absolute filter radiometry near wavelengths of 800 nm, 900 nm, and 1000 nm, the temperature range for thermodynamic temperature measurements of the PTB large area blackbody has been extended to temperatures as low as the zinc freezing point. Although the inner cavity of the large area blackbody is formed by a sodium heat pipe, it has been shown that it can by used as an accurate source of blackbody radiation at temperatures as low as 400 °C. The achieved standard uncertainty was about 20 mK for thermodynamic temperatures of 419 °C. The new measurements are preliminary in the sense that the non-linearity corrections for the filter radiometers must be confirmed. The obtained temperature differences (T - T_{90}) exhibit an increasing difference with increasing temperature, confirming the general trend observed in the former measurements of 1995. Overall the temperature differences are consistent with an error of about 20 mK in the reference temperature near 730 K (456 °C), which was used in the derivation of the ITS-90 at higher temperatures. This would lead to an error of 57 mK at the silver point, 1235 K.

At NIST, absolute filter radiometry based on electrical substitution radiometry and tunable lasers, has resulted in uncertainties of 0.5 K at 3000 K. A blackbody calibrated using this technique was used to realize spectral irradiance, and the new method resulted in a substantial improvement in the uncertainties assigned to the lamp artifacts that are disseminated by NIST. The next efforts will be on extending this technique to lower temperatures. At cryogenic temperatures, total flux is measured using an electrical substitution radiometer for blackbody sources which are in a vacuum chamber that simulates a 20 K background. Current efforts are focused on dissemination of this scale using radiometers. Recently, a cryogenic filter radiometer with a blocked-impurity-band detector was deployed successfully.

At NPL, the second-generation total radiation thermometer (Absolute Radiation Detector) is being evaluated, especially with respect to the radiation transfer through the aperture system. Temperature measurements are planned for 2002, initially in the range 234 K to 303 K and then extending up to 430 K. The objective is ultimately to link with spectral measurements at 430 K using filter radiometers at about 3.5 µm, so as to establish a radiometric scale from below the triple point of water up to the copper point and beyond.

The possible use of a Fourier transform technique to measure thermodynamic temperatures in the range 500 °C to 1000 °C was presented by Steele and Rowell at Tempmeko 2001. They use a wide wavelength range and overcome some limitations of previous experiments by checking for self-consistency over both the wavelength and temperature ranges. Uncertainties in the region of 0.1 °C seem achievable.

A number of papers at Tempmeko 2001, notably the invited paper by Yamada, were concerned with the development of metal-carbide eutectic fixed points for the calibration or comparison of radiation thermometers up to about 2500 °C. To date they seem to be useful transfer standard devices, but there are some differences in the temperature values due to material variations. This topic is under investigation in WG5.

3. Extension of the ITS-90 to lower temperatures

At its 20th Session, the CCT recommended to the CIPM that it adopt the Provisional Low Temperature Scale from 0.9 mK to 1 K: PLTS-2000. Subsequently the necessary supporting information was prepared and submitted to the CIPM, which duly adopted the scale in October 2000.

Meanwhile, a document was circulated to approximately 200 low-temperature physicists on the mailing list for the Quantum Fluids and Solids conference in June 2000, announcing the development.

Subsequently papers on the scale have been presented at Tempmeko 2001 (Berlin June 2001), and QFS-2001 (Konstanz, July 2001). Preprints of these papers are available electronically from the WG4 chairman. The QFS paper has been accepted for publication in the Journal of Low Temperature Physics.

Formally this concludes this aspect of WG4 activity for the present. However, it is intended to produce ‘Supplementary Information for the PLTS-2000’, in liaison with WG1, to give practical guidance on ^{3}He melting pressure thermometry. A substantial document describing PTB designs and practice has been prepared by Schuster, Hoffmann and Hechtfischer. Further publications are in progress concerning the scale itself (eg a thermodynamic inspection by Reesink, van Beelen and Durieux, submitted to Physica) and the work leading to it (eg from PTB, to be published), and further experimental work is also in progress (by Fogle and Soulen). A European project ‘ULT Dissemination’ is in progress to develop thermometers and superconductive reference points for the dissemination of the scale.

With regard to the agreement between the ITS-90 and the PLTS-2000 in the range of overlap, 0.65 K to 1 K, definitive comparisons between ^{3}He vapour pressures and ^{3}He melting pressures have not yet been reported. The possible implications of deviations of the ITS-90 from the PLTS-2000 remain as detailed in the April 2000 report, as follows :-

‘to overcome the anomaly, if it is substantiated, the vapour pressure equation could be revised, but this would entail a (minor) revision of the ITS-90 itself and might not be acceptable. On the other hand, the ITS-90 already includes sub-ranges which may be expected to differ by amounts up to 0.5 mK, so the new anomaly could be viewed as a somewhat larger sub-range inconsistency. Alternatively, the use of the vapour pressure equation could be restricted to temperatures above 1 K, or 0.8 K, or the application of corrections could be recommended.

‘In any case, Supplementary Information… ...could state a preference to use melting pressures rather than vapour pressures below 1 K. There was general discussion on this issue at the NIST meeting [in January 2000], and it was commented that a melting pressure realisation would not only be more accurate but, in view of experiences to date, could also be regarded as the more practical option. It was agreed to raise the issue in this report for discussion by the CCT, but to not to make any recommendation at this stage.’

This discussion was carried over to the coming Session.

Figures

Figure 1: Graph of differences between published thermodynamic temperature determinations from the ITS-90 up to 1235 K (J V Nicholas, 2000).

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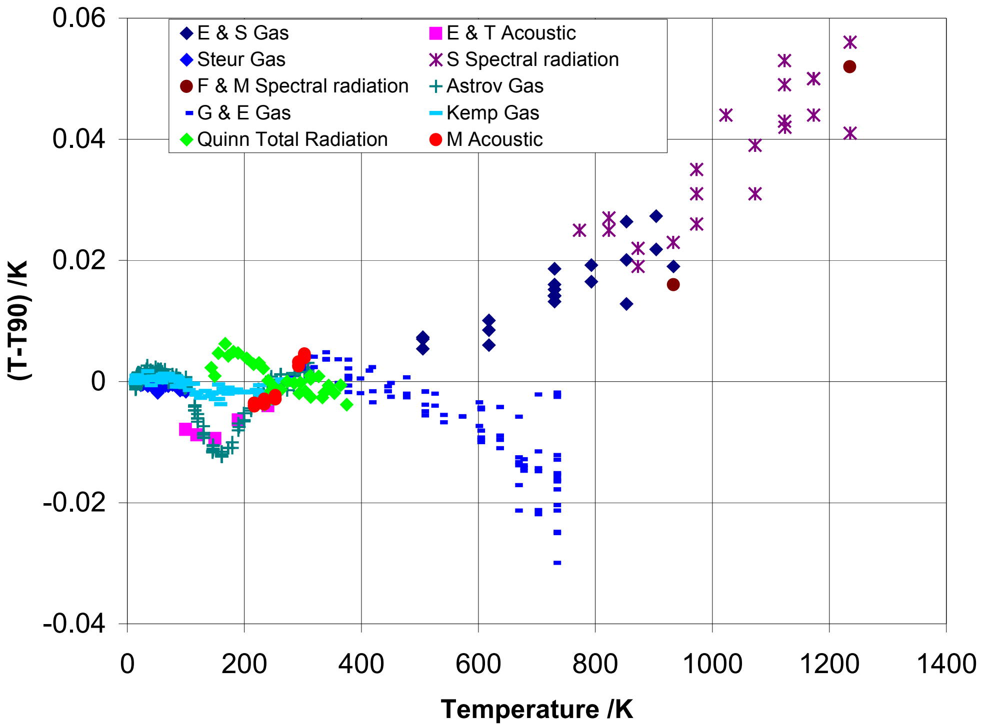

Figure 1: Graph of differences between published thermodynamic temperature determinations from the ITS-90 up to 1235 K (J V Nicholas, 2000). Attributions are as follows.

E & S: Edsinger and Schooley, Metrologia **26**, 95-106, 1989
Steur: Steur and Durieux, Metrologia **23**, 1-18, 1986
F & M: Fox, Martin and Nettleton, Metrologia **28**, 357-374, 1991
G & E: Guildner and Edsinger, J Res Nat Bur Stands **80A**, 703-738, 1976
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S: Stock, Fischer, Friedrich, Jung, Wende, Metrologia **32**, 441-444, 1995/96
Astrov: Astrov, Belyansky and Dedikov, Metrologia **32**, 393-395, 1995/96
Kemp: Kemp, Kemp and Besley, Metrologia **23**, 61-86, 1986
M: Moldover, Boyes, Meyer and Goodwin, Tempmeko 1999, 412-417.