WORKING GROUP 4 REPORT TO CCT
20 May 2014

Members: Joachim Fischer (PTB) chairman, Michael de Podesta (NPL), Ken Hill (NRC), Gennady Kytin (VNIIFTRI), Mike Moldover (NIST), Laurent Pitre (LNE-CNAM), Peter Steur (INRiM), Osamu Tamura (NMIJ), Rod White (MSL), Inseok Yang (KRISS), Jintao Zhang (NIM)
assisted by Richard Rusby

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, document CCT/12-14, dated 25 April 2012, the members met at the BIPM at 20 May 2014.

Uncertainties

In order to recall the capabilities of the different methods to determine thermodynamic temperatures it is useful to review the uncertainties identified and agreed on by WG4 in the 2011 summary paper by J. Fischer, M. de Podesta, K. D. Hill, M. Moldover, L. Pitre, R. Rusby, P. Steur, O. Tamura, R. White, L. Wolber: “Present estimates of the differences between thermodynamic temperatures and the ITS-90”, Int. J. Thermophys. **32**, 12–25 (2011). In figure 1 the uncertainties are shown of all measurements taken into account in the temperature range 4.2 K to 400 K. Depending on the chosen reference temperature the uncertainties of constant volume gas thermometry (CVGT) (Astrov, Kemp, Steur) have different trends. Apart from the reference temperatures, the uncertainties of CVGT are significantly higher than that of acoustic gas thermometry (AGT) (Benedetto, Ewing, Moldover and Ripple, Pitre). Consequently, the weighted mean for T-T_{90} had to be estimated by WG4 close to the values of the acoustic results.

In figure 2 the temperature range below 40 K is shown in more detail. Again the acoustic gas thermometry generally offers lower uncertainties than that of constant volume gas thermometry but Berry´s seminal work of 1979 was very close. In addition, dielectric constant gas thermometry (DCGT) is competing with AGT.

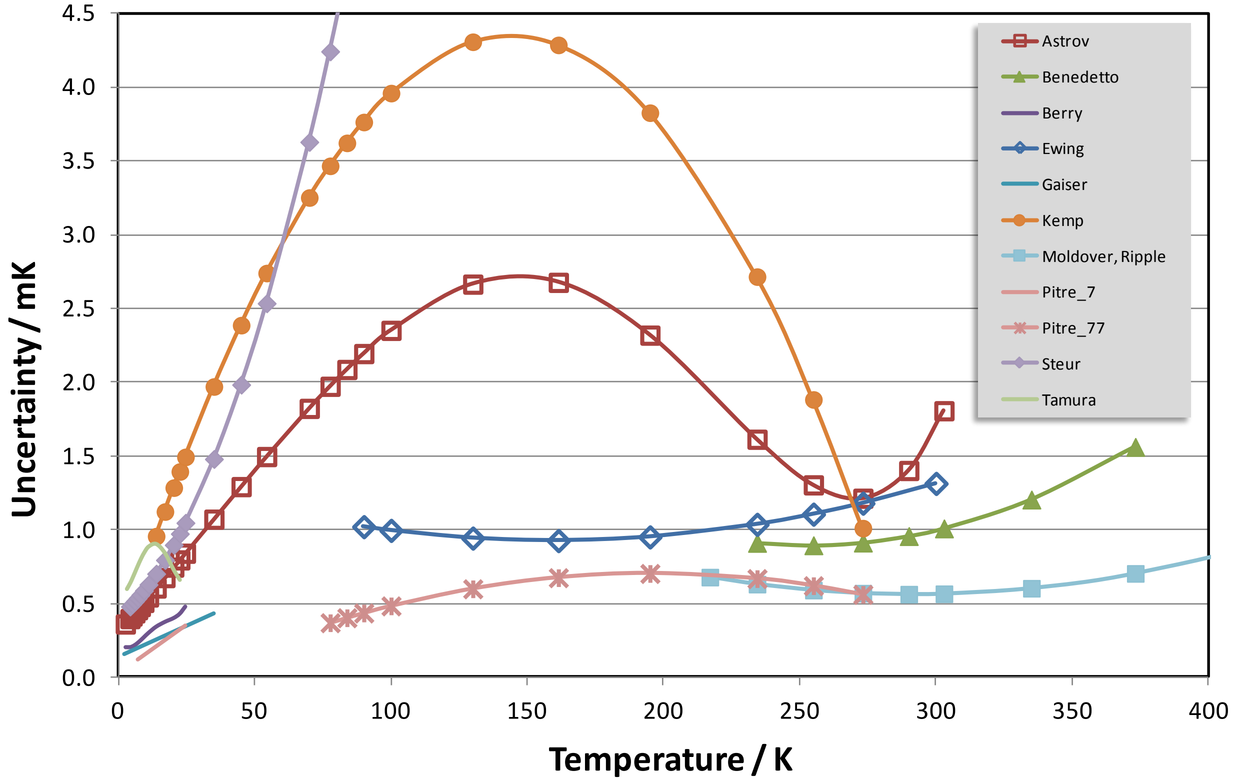


Figure 1 Uncertainties (*k*=1) of thermodynamic temperature determinations considered in Int. J. Thermophys. **32**, 12–25 (2011)

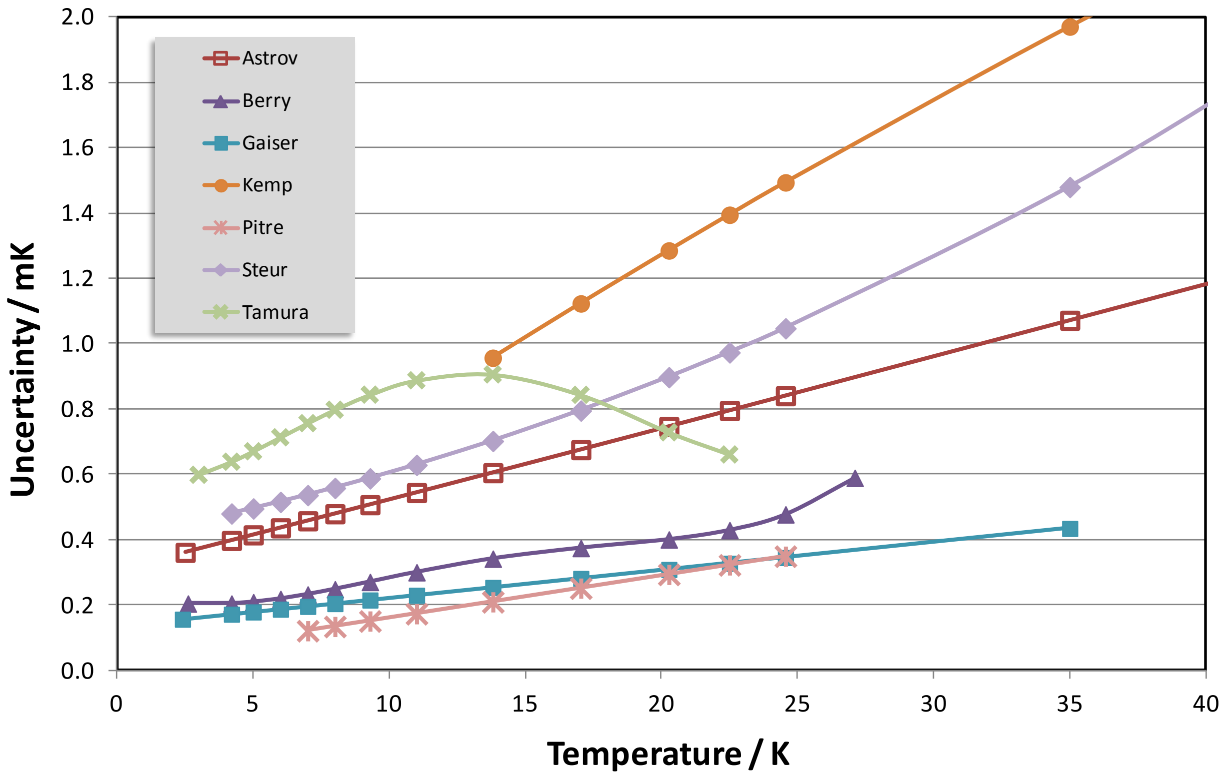


Figure 2 Detail of figure 1 for temperatures below 40 K

New measurements on T-T_{90}

In table 1 all published determinations of thermodynamic temperatures and thus on T-T_{90} since the 2011 consensus estimate of WG4 in Int. J. Thermophys. are listed. From the last column it can be seen that only a few measurements produced valid results for consideration in WG4.

In figure 3 the consensus estimate of WG4 between 4.2 K and 80 K is shown by black dots and by the smooth interpolation function. The new low temperature CVGT results obtained at NMIJ are in good agreement with the results already included in the 2011 consensus estimate and are not shown here. The extension of DCGT measurements of PTB up to 36 K (diamonds) is so far not following the negative values of T-T_{90} obtained by AGT which shows significant deviations beginning at the neon point and is represented here by the consensus estimate. Before a revision, WG4 will wait for a further extension of DCGT to even higher temperatures, for the results of the new method refractive index gas thermometry (RIGT, see below), and for the repetition of AGT.

In figure 4 the determinations of T-T_{90} above the triple point of water are depicted. In detail, the NIST noise thermometer results between 693 K and 800 K, a radiometric determination of the gold point at NMIA, and determinations of the copper point by radiation thermometry at INRiM and at NPL/LNE are to be included in the next consensus estimate of WG4. The radiation thermometry work of PTB and NIM will be improved and the preliminary data listed in table 1 are not shown in figure 4. So far, all new measurements seem to confirm the consensus estimate of WG4 in this temperature range, however only with large uncertainties.

It is evident that more measurements of thermodynamic temperatures are required before WG4 can make a new consensus estimate. To make the situation more transparent in figure 5 an overview is given on the temperature ranges of past, present and future determinations. The measurements having contributed to the 2011 consensus estimate are labeled with a green bar, present repetitions and/or extensions of those measurements are in red and completely new approaches presently under development are denoted with a blue bar.

Beginning with low temperatures, NMIJ has repeated CVGT from 3 K to 22.5 K as mentioned above. At PTB, besides the described ongoing extension of DCGT to 303 K, the design for a new experiment to cover temperatures up to 500 K is under consideration. With this experiment an independent confirmation of AGT – besides Doppler broadening thermometry (see below) – would be available in the important temperature range above the triple point of water. An important role in the low temperature range will play RIGT, presently under development at NRC in the temperature range 5 K to 297 K and at NIM between 110 K and 380 K. With RIGT microwave resonances of a metal quasi-sphere are used to determine the refractive index of the working gas, the electromagnetic physics being similar to DCGT.

Many laboratories are extensively enhancing AGT to cover broader temperature ranges. LNE and INRIM are repeating and extending their AGT measurements performed between 2003 and 2006 with new improved instrumentation. VNIIFTRI is going to measure thermodynamic temperature with AGT between 4.2 K and 273 K. At NPL a complete new set up is under preparation for the temperature range from 125 K to finally 1000 K. A joint NIM/NIST project is developing new cables and antennas for microwave measurement and cylindrical cavities using Nickel-Chromium alloy to extend the temperature range of AGT up to the 1358 K. University of Valladolid (UVa) is going to measure thermodynamic temperatures with AGT between 90 K and 505 K.

As a further outcome of the determination of the Boltzmann constant a completely new optical method, the Doppler broadening thermometry is gaining importance. University of Naples will measure thermodynamic temperatures between 234 K and 429 K. Johnson noise thermometry is developed at NMIJ and at NIM which is in the first instance aiming at a temperature range from 273 K to 303 K.

The NIST noise thermometry and the new spectral radiation thermometry measurements have been described in the 3rd paragraph above. Many of the new experiments are effectively supported by the EMRP-Project “Implementing the new kelvin” running between 2012 and 2015.

The members concluded that with all these new experiments successfully finished hopefully a sufficiently broad base will be available for a new consensus estimate on T-T_{90} and finally a new improved international temperature scale with significantly higher thermodynamic precision.

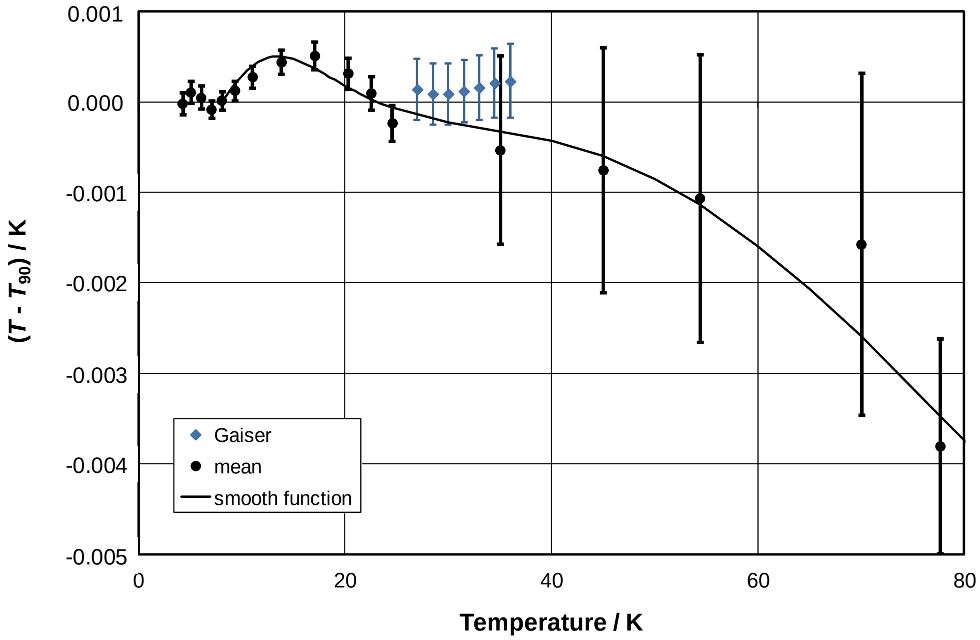


Figure 3 Numerical values and uncertainties (k=1) of consensus estimate of WG4 for T-T_{90} published in Int. J. Thermophys. **32**, 12–25 (2011) and of recent DCGT work (Gaiser).

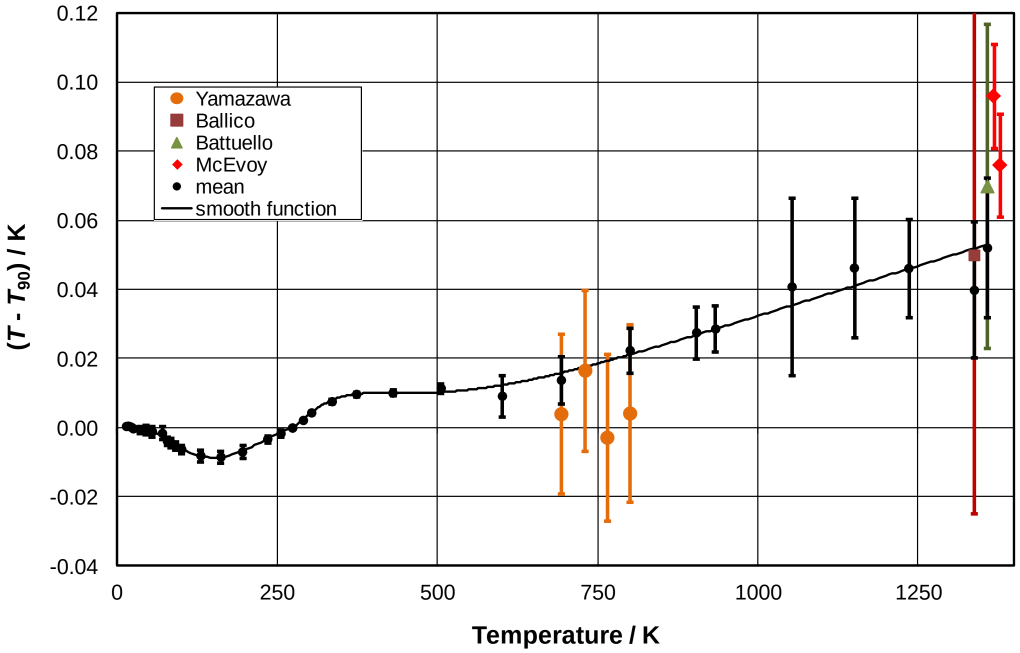


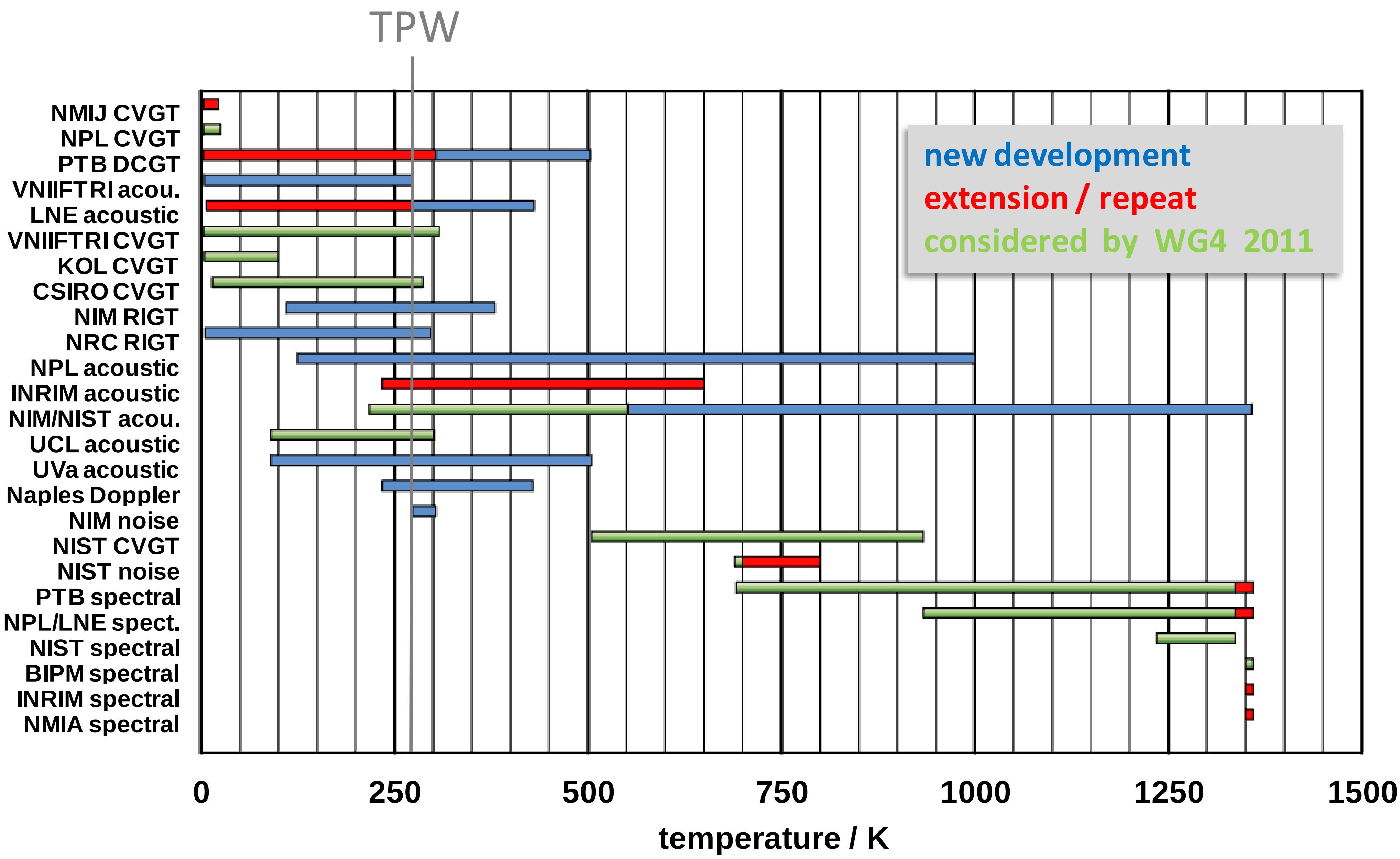
Figure 4 Numerical values and uncertainties (k=1) of consensus estimate of WG4 for T-T_{90} published in Int. J. Thermophys. **32**, 12–25 (2011) and of recent noise (Yamazawa) and radiation thermometry work (Ballico, Battuello, McEvoy). The two results of McEvoy et al. obtained at NPL and at LNE have been moved to the right for better visibility.

Table 1 Published determinations of thermodynamic temperatures since the WG4 consensus estimate in Int. J. Thermophys. (2011) in chronological order, all uncertainties with k=1.

Authors	**Title**	**Journal**	**Method**	**T Range / K**	**Ref. Temp.**	**Results and comments**	**Include results in next WG4 estimate**
C. Gaiser, B. Fellmuth, N. Haft	Dielectric-Constant Gas-Thermometry Scale from 2.5 K to 36 K Applying 3He, 4He, and Neon in Different Temperature Ranges	Int J Thermophys (2010) **31**, 1428–1437	DCGT	27.0 28.5 30.0 31.5 33.0 34.5 36.0		T-T_{90} = (0.14 ± 0.34) mK (0.09 ± 0.34) mK (0.09 ± 0.34) mK (0.12 ± 0.35) mK (0.16 ± 0.36) mK (0.21 ± 0.38) mK (0.23 ± 0 41) mK	no, wait for extension to higher temperatures; here only results ≥ 27 K not measured previously are listed
M. Battuello, M. Florio, F. Girard	Indirect determination of the thermo-dynamic temperature of the copper point by a multi-fixed-point technique	Metrologia (2010) **41**, 231–238	Radiation Thermometry	Cu	Ag	T-T_{90} = (70 ± 47) mK	**yes**
O. Tamura, S. Takasu, T. Nakano, H. Sakurai	Constant-Volume Gas Thermometry with Different Helium-3 Gas Densities at NMIJ/AIST	Int J Thermophys (2011) **32**, 1366–1377	CVGT	3 to 24.5	Ne TP	use instead of older data which are consistent with the new ones	**yes**
T. Keawprasert, K. Anhalt, D. R. Taubert, J. Hartmann	Monochromator-Based Absolute Calibration of Radiation Thermometers	Int J Thermophys (2011) **32**, 1697–1706	Monochro-mator based radiation thermometry	Au, Cu		T-T_{90} = 52 mK (Au) T-T_{90} = -50 mK (Cu); u = 158 mK	no, uncertainties too high
M. Ballico	Thermodynamic Temperature Measurements Traceable to Photometric Standards	Int J Thermophys (2011) **32**, 2206–2216	Radiometry	Au		T-T_{90} = (50 ± 75) mK	**yes**
K. Yamazawa, W. Tew, S. Benz, H. Rogalla, P. Dresselhaus, A. Pollarolo	Improvements to the Johnson noise thermometry system for measurements at 505-800 K	TIMCSI, Vol. 8, AIP Conf. Proc. (2013) **1552**, 50-55	Noise Thermometry	692.6 730.0 764.4 799.9	505 K	T-T_{90} = (4.0 ± 23.0) mK (16.6 ± 23.3) mK (-2.8 ± 24.1) mK (4.2 ± 25.7) mK	**yes**
Z. Yuan, X. Lu, X. Hao, W. Dong, T. Wang, Y. Lin, J. Wang, Y. Duan	Thermodynamic temperature measurements of silver freezing point and HTFPs	TIMCSI, Vol. 8, AIP Conf. Proc. (2013) **1552**, 56-59	Radiation Thermometry	Ag		*633 nm:* T-T_{90} = (280 ± 120) mK 900 nm: T-T_{90} = (-90 ± 170) mK	no, discrepancies between 633 nm and 900 nm filters
H. C. McEvoy, M. Sadli , F. Bourson, S. Briaudeau, B. Rougié	A comparison of the NPL and LNE-Cnam silver and copper fixed-point blackbody sources, and measurement of the silver/copper temperature	Metrologia (2013) **50**, 559–571	Radiation Thermometry	Cu	Ag	*NPL:* T-T_{90} = (96 ± 15) mK *LNE:* T-T_{90} = (76 ± 15) mK	**yes**

	interval						

Figure 5 Overview on temperature ranges of past, present and future thermodynamic temperature determinations


TPW
NMIJ CVGT
NPL CVGT
PTB DCGT
VNIIFTRI acou.
LNE acoustic
VNIIFTRI CVGT
KOL CVGT
CSIRO CVGT
NIM RIGT
NRC RIGT
NPL acoustic
INRIM acoustic
NIM/NIST acou.
UCL acoustic
UVa acoustic
Naples Doppler
NIM noise
NIST CVGT
NIST noise
PTB spectral
NPL/LNE spect.
NIST spectral
BIPM spectral
INRIM spectral
NMIA spectral
new development
extension / repeat
considered by WG4 2011
0
250
500
750
1000
1250
1500
temperature / K