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Report on the recent activities of CCT

Dr. Christof Gaiser (chair CCT WG Contact Thermometry)
Prof. Graham Machin (chair CCT WG Non Contact Thermometry)

1. Activities in contact thermometry

Since 2011, when the previous estimates of $(T - T_{90})$ were published by the CCT, there has been a change in the definition of the kelvin, and significant advances in primary thermometry were achieved, yielding much improved measurements of thermodynamic temperature T and at the same time $(T - T_{90})$ over the range from 4 K to 323 K. A published analysis combines the new data with the older data used in 2011 to update the consensus values for $(T - T_{90})$ over the range from 4 K to 323 K. In some temperature ranges, the uncertainty is reduced by an order of magnitude compared to those published in 2011. Furthermore, the uncertainties of the new T data are partially comparable with the uncertainties of the T_{90} realisation. Hence, in combination with T_{90} measurements, the updated estimates offer an important means for achieving a state-of-the-art determination of thermodynamic temperature without the high cost and inconvenience of primary thermometry. In principle, the improved primary thermometers now also allow for a direct dissemination of T in this temperature range. A first feasibility test is part of a recently started project.

Major focus is now on recommendation 1 of the 29th CCT (2021) “Requirement for new determinations of thermodynamic temperature above 400 K”. In this temperature range new data from primary thermometry is expected within the next three years. At the same time this will allow for a future update of T-T_{90} in the higher temperature range and it is a next step towards a direct dissemination of T via primary thermometry in this temperature range.

2. Dissemination of thermodynamic temperature above the silver point

The current temperature scale (ITS-90) above the silver point uses Planck’s law in ratio form to establish the scale. A narrow-band non-contact thermometer (almost invariably silicon detector based) is calibrated at an ITS-90 defining fixed-point (blackbody) at either the Ag, Au or Cu point. Using this calibrated instrument the spectral radiance of a variable temperature blackbody is determined. From the calibration and this measurement the variable temperature blackbody temperature is determined (allowing for suitable corrections if required for emissivity, linearity and so forth).

In more recent times it has become possible to establish thermodynamic temperature directly by a number of what is known as relative primary methods. These approaches are relatively simple to establish, with uncertainties competitive with ITS-90 but yield thermodynamic temperature.

The first approach is simply to take the thermodynamic temperature, rather than the ITS-90 temperature, of the Ag, Au and Cu point and use Planck’s law in ratio form to determine thermodynamic temperatures. The downside with this approach is that it is an extrapolation method and requires the device used for extrapolation to behave in an almost ideal fashion to avoid growth in uncertainties as one extrapolates from the reference temperature.

The second approach, which is much more robust, is to use a parametrised form of Planck's law in conjunction with two or more high temperature fixed points with known thermodynamic temperatures. Such an approach, established in the mise en pratique for the definition of the kelvin (MeP-K) has those major advantages:

- It allows thermodynamic temperature to be established with low uncertainties comparable to the current defined scale
- It is more robust than the ITS-90 formulation because it is essentially an interpolation rather than an extrapolation approach and so intrinsically more robust
- It gives the potential of realising robust low uncertainty thermodynamic temperatures in industrial calibration laboratories
- It is a simple and cost effective way of establishing a fundamental radiance scale

Within the frame of EMPIR project "Realising the redefined kelvin" the thermodynamic temperatures of four more high temperature fixed points were established. These are given in table 1 below with their k=2 uncertainties.

Table 1: Thermodynamic temperatures of four high temperature fixed points

HTFP	T_{POI} (K)	$U(T_{\mathrm{POI}})$ (K)	T_{LIQ} (K)	$U(T_{\mathrm{LIQ}})$ (K)
Fe-C	1426.92	0.15	1427.02	0.15
Pd-C	1765.05	0.16	1765.18	0.16
Ru-C	2226.99	0.22	2227.08	0.24
WC-C	3020.85	0.25	3020.92	0.27

These values will be published in a peer reviewed publication in 2024[1] and then incorporated within the annex of the MeP-K-19 for establishing thermodynamic temperature at high temperatures.

These will join the already known and published Co-C, Pt-C and Fe-C[2] which are already in the MeP-K-19 annex.

It is envisaged that in the second part of the 2020s a key comparison of thermodynamic temperature, established by this approach, will be performed. Thereafter it is envisaged that, due to the utility and robustness of the approach, realisation and dissemination of high temperature thermodynamic temperature will become widespread in the late 2020s to early 2030s.

This introduces the issue of mixed traceability, where parts of the temperature scale will be realised by ITS-90 and other parts through direct linkage to the kelvin definition and hence thermodynamic temperature will be realised. However, as ITS-90 is only an approximation to thermodynamic temperature this development is not of great concern but will require monitoring by CCT to ensure that the transition is seamless and effective.

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[1] Sadli, M., Bourson, F., Lowe, D., Anhalt, K., Martin, M.J., Mantilla, J.M., Girard, F., Florio, M., Pehlivan, Ö., Nasibli, H., Kňazovická, L., Sasajima, N., Lu, X., Kozlova, O., Briaudeau, S., Machin, G., "**Assigning thermodynamic temperatures to a set high-temperature fixed points in the range 1400 K to 3000 K** *International Temperature Symposium Proceedings in press 2024*

[2] Lowe, D.H., Todd, A. D. W., Van den Bossche, R., Bloembergen, P., Anhalt, K., Ballico, M., Bourson, F., Briaudeau, S., Campos, J., Cox, M.G., del Campo, D., Dury, M., Gavrilov, V., Grigoryeva, I., Hernanz, M. L., Jahan, F., Khlevnoy, B., Khromchenko, V., Lu, X., Machin, G., Mantilla, J.M., Martin, M. J., McEvoy, H.C., Rougié, B., Sadli, M., Salim, S.G.R., Sasajima, N., Taubert, D., van der Ham, E., Wang, T., Wei, D., Whittam, A., Wilthan, B., Woods, D., Woodward, J.T., Woolliams, E.R., Yamada, Y., Yamaguchi, Y., Yoon, H., Yuan, Z., "**The equilibrium liquidus temperatures of rhenium-carbon, platinum-carbon and cobalt-carbon eutectic alloys**" *Metrologia*, **54**, 390–398 (2017) https://doi.org/10.1088/1681-7575/aa6eeb

3. Direct traceability to the kelvin

Since the redefinition of the kelvin several developments have arisen in the field of thermometry that challenge the traditional concept of traceability.

Classically traceability to the kelvin has been through an unbroken chain of measurements to the user from the national standard of temperature (almost invariably the defined scale, the ITS-90) – which itself is validated by international key comparisons.

However new approaches to delivering reliable temperature measurement in-process are being developed. These fall into two main categories:

1) Self-validation approaches. Here a traditional thermometer (for e.g. a thermocouple) would incorporate a fixed-point of reference temperature – for example a small fixed-point . Then each time the process in which the sensor was embedded passed through the melting/freezing temperature of the fixed-point a re-calibration of the sensor (and of all those in the same thermal environment) could be performed.
2) Practical primary thermometry. Here the temperature sensor is a primary or relative primary thermometer. This could be an electron-based (e.g. Johnson Noise[3]) or photon-based (such as Doppler Broadening or Photonic Resonators[4]).

Such sensors could directly challenge the conventional approach to traceability. Those with incorporated fixed-point/s would, with the right algorithm, calibrate themselves. Practical primary thermometry approaches would, in principle, need no calibration of the sensor because it works on fundamental physical principles. Calibration of the measurement system would likely be required – but that would be an electrical or frequency calibration (both based on quantum standards) not a temperature one.

Such approaches to traceability are in their infancy, are likely to be niche in application when first introduced. However, that may well change when the benefits of "always-right" sensors become apparent. When that happens the question "What does temperature traceability mean?" in such a scenario becomes a pressing one.

To anticipate this question this is an active topic of discussion within CCT and the thermometry community more widely at the moment. A workshop will be held at CCT in May 2024 to begin discussing how to address this question and further community consultation will be held in Feb 2025 at a Royal Society workshop "Progress with the redefined kelvin" in Glasgow.

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[3] Pearce, J.V., Veltcheva, R.I., Tucker, D. L., Machin, G., "**Progress towards in-situ traceability and digitalization of temperature measurements**", *Acta IMEKO,* **12 (1)**, pp. 1 - 6 (2023) *ISSN: 2221-870X* https://doi.org/10.21014/actaimeko.v12i1.1386

[4] Dedyulin, S., Ahmed, Z., Machin, G., "**Emerging technologies in the field of thermometry**", *Meas. Sci. & Technol.* **33** 092001 (26pp) (2022) https://doi.org/10.1088/1361-6501/ac75b1