Int J Thermophys (2010) 31:1779–1788
DOI 10.1007/s10765-010-0834-5

Practical Implementation of the *Mise en Pratique* for the Definition of the Kelvin Above the Silver Point

G. Machin · P. Bloembergen · K. Anhalt · J. Hartmann · M. Sadli · P. Saunders · E. Woolliams · Y. Yamada · H. Yoon

Received: 1 March 2010 / Accepted: 22 September 2010 / Published online: 24 October 2010

Abstract The "*Mise en pratique* for the definition of the kelvin" (*MeP*-K) was established in April 2006 to be the repository of information required to perform a "practical measurement of temperature in accordance with the International System of Units (SI)." This article describes the progress made by the *MeP*-K HT (High Temperature Task Group) of CCT-WG5 (radiation thermometry) in drawing together the appropriate methods for accessing thermodynamic temperature above the silver point involving direct radiometric measurements on the one hand and indirect extrapolation, interpolation, and least-squares fitting on the other. An examination of the uncertainties

G. Machin (✉) · E. Woolliams
National Physical Laboratory (NPL), Teddington, Middlesex, UK
e-mail: graham.machin@npl.co.uk

P. Bloembergen
National Institute of Metrology (NIM), Beijing 100013, China

K. Anhalt · J. Hartmann
Physikalisch-Technische Bundesanstalt (PTB), Abbestr. 2-12, 10587 Berlin, Germany

M. Sadli
Laboratoire Commun de Métrologie LNE-Cnam, 61 Rue de Landy, Paris 93210, France

P. Saunders
Measurement Standards Laboratory of New Zealand (MSL), Industrial Research Ltd, P.O. Box 31-310, Lower Hutt, New Zealand

Y. Yamada
National Metrology Institute of Japan (NMIJ), AIST, AIST Tsukuba Central 3, 1-1-1 Umezono, Tsukuba, Ibaraki 305-8563, Japan

H. Yoon
National Institute of Standards and Technology (NIST), Gaithersburg, MD, USA

and a brief discussion of the advantages and disadvantages of the various approaches are given. A summary of the remaining issues to be resolved concludes the article.

Keywords *Mise en pratique* for the definition of the kelvin · *MeP-K* · High temperatures · Radiometry · Radiation thermometry · Primary thermometry methods

1 Introduction

In April 2006, the Consultative Committee for Thermometry (CCT) adopted the "*Mise en pratique* for the definition of the kelvin" (*MeP*-K) with the purpose of providing information necessary for a practical realization of temperature according to the *Système International d'Unités* (SI) [1,2]. The *MeP*-K included direct realization of thermodynamic temperature, independent of the defined International Temperature Scale, ITS-90, where the techniques of primary thermometry had advanced sufficiently to confer benefit. This was thought to apply at very low and very high temperatures.

A task group of CCT-WG5 (radiation thermometry) was established in May 2008 to examine the different methods of direct measurement of thermodynamic temperature above the silver point, and, in particular, to write the text for the *MeP*-K for this temperature range. Although the ITS-90 is experimentally simple to implement, other methods could convey significant advantages, either in terms of lower uncertainties or improved robustness/security of realization. The methods are: (a) absolute radiometry linked to the appropriate radiometric units and (b) high-temperature fixed points (HTFPs) as defining points or as radiometric reference standards for the realization/dissemination of thermodynamic temperature.

The WG5 task group has prepared text for the *MeP*-K [1], together with a larger background document [3] that describes the possible methods of realizing/measuring temperatures above the silver point: absolute radiometry ($n = 0, T$), or via high-temperature fixed points ($n \geq 1, T$ or T_{90}), with n referring to the number of fixed points that are used in the realization/dissemination of temperature. Note, the $n = 1$ case is equivalent to the traditional ITS-90 method, which uses fixed-point blackbody cavities immersed in freezing Ag, Au, or Cu as its foundation.

This article begins with an outline explaining why high temperatures (above the silver point) were considered the most appropriate for formalizing a primary realization of temperature. It goes on to give a summary of the WG5 task group text for the *MeP*-K, with an outline of the proposed approaches, including a discussion of the advantages and disadvantages of the possible methods. This article serves as an introduction to linked papers by the task group members on absolute radiometry methods, comparative uncertainty studies, and interpolation schemes.

2 *Raison d'être* for the *MeP*-K at High Temperatures

Temperatures above the silver point were thought the prime candidate for recommending (or at least providing a regularized basis for) a primary realization of thermodynamic temperature as an alternative to the ITS-90. There were several reasons for this; the main three are:

- Absolute radiometry can already be implemented in several NMIs, and at high temperatures, achieves uncertainties competitive with, or somewhat better than, ITS-90. In addition, absolute radiometry can be free of other issues that beset the ITS-90 above the silver point (see the two points below). In addition, high-temperature fixed points, although still the subject of research, could, in the future, be used to implement indirect methods of realizing T with uncertainties competitive with ITS-90, and probably more reproducible than absolute radiometry.
- The extrapolation of the ITS-90 from the defining fixed points to higher temperatures means that there are inherent limits to the scale realization uncertainty that can be achieved. The ITS-90 definition means that the uncertainty associated with scale realization increases (approximately) as T^2 from the reference fixed-point temperature.
- It is clear that the ITS-90 is not uniquely defined. Fixed-point blackbody cavities at the Ag, Au, or Cu freezing-point temperatures are all allowable reference sources for the basis of an ITS-90 realization. If the defined temperatures for these fixed points are not thermodynamically correct, the choice of fixed point would inevitably lead to different temperatures being realized.

Finally, an additional reason for considering alternatives to the ITS-90 above the silver point is that in practice the formal definition of the ITS-90 in this regime cannot be implemented, though this is certainly not an exception among the SI units. The ITS-90 formalism calls for the use of Planck's law in ratio form with strictly monochromatic blackbody radiation in vacuo. Neither of these conditions is achievable in practice: integral or mean effective wavelength forms of Planck's law are used to allow for the finite bandwidth of the radiation thermometer, and measurements of thermal radiation are usually made through a gas rather than a vacuum.

3 Direct Thermodynamic Methods

There are two primary radiometric methods that are appropriate for temperatures above the silver point, at least in principle; these are absolute total radiometry and absolute spectral-band radiometry. Both the methods require well-characterized blackbody sources (with high emissivity) and a precise measurement of total (or spectral) radiance of the blackbody traceable to the foundation SI quantities. In turn, the determination of radiance requires precise knowledge of the configuration factor (also known as the geometric factor or form factor), which depends upon the dimensions of the blackbody and detector apertures, and their separation. More details can be found, for example, in [3,4].

3.1 Absolute Total Radiometry

Total radiometry is so-called because it seeks to accurately measure the total power (given by the Stefan–Boltzmann law) emitted from a blackbody of uniform and stable temperature. The lowest uncertainty implementation of the method is through the use of a cryogenic electrical substitution radiometer [4]. Here, the total radiant power of the blackbody is first measured by irradiating a black cavity detector, through a known geometric system, and measuring the thermal-radiation-induced temperature rise with a sensitive thermometer. The thermal radiation from the blackbody is then blocked by a liquid-helium cooled shutter and substituted by electrical power supplied through superconducting leads to the black cavity detector. The electrical power is adjusted until it gives the same temperature rise as that caused by the optical power. By equating the electrical power with the optical power, the temperature of the radiating cavity can be determined. The earliest and most successful implementation of the method as a primary thermometer was by Quinn and Martin [5] at NPL in the 1980s.

However, given the major complexities of total radiometry, the method is not routinely practiced for thermometry, certainly not at high temperatures, and will not be discussed further in this article. The method is, for completeness, discussed in the background document for the *MeP*-K at high temperatures [3], but, due to its lack of routine implementation, is not discussed in the *MeP*-K itself.

Although not used for primary thermometry, cryogenic electrical substitution radiometers are used regularly in a number of national measurement institutes (NMIs) to provide the traceability to the electrical watt, and these form the basis for the realization and dissemination of spectral responsivity. This, coupled with the advent of ultra-linear stable silicon photodiodes and trap detectors [6], has led to absolute spectral-band radiometry becoming the standard approach for primary high-temperature measurement.

3.2 Absolute Spectral-Band Radiometry

Absolute spectral-band radiometry is a method underlying the measurement of the spectral radiance or irradiance of a blackbody radiator. This requires the construction of a filter radiometer. In principle, these are simple devices composed of a well-characterized aperture, a spectrally selective filter, and (for these temperatures) a silicon photodiode. Although simple in concept, in practice, significant precautions need to be taken in both radiometer design and implementation to obtain optimum performance.

The calibration of filter radiometers requires a means of measuring optical power, usually a cryogenic electrical substitution radiometer, a stable source of monochromatic optical radiation, either a laser (e.g., [7]) or broadband source plus monochromator (e.g., [8]), and a transfer or reference detector, usually a trap detector [6]. The cryogenic radiometer measures the optical power of the monochromatic source traceable to the electrical watt. Once the spectral power of the source is determined, the transfer detector is calibrated using the known source, at that wavelength, in amperes per watt (A/W). This process is then repeated for a range of wavelengths and the absolute calibration of the transfer detector affected. The transfer detector is then used, again in conjunction with a monochromatic source, to absolutely calibrate the spectral response of the filter radiometer.

The actual implementation of absolute spectral-band radiometry to measure the temperature of a blackbody can follow a variety of approaches, which differ in important details. Four different approaches are outlined in [3] and are summarized briefly below:

- A filter radiometer, calibrated for power responsivity, is used to measure the radiance of the blackbody in combination with a detector and source apertures—the "power method" [9].
- A filter radiometer, calibrated for irradiance responsivity, is used to measure the radiance of the blackbody in combination with a source aperture—the "irradiance method" [10].
- A filter radiometer, calibrated for irradiance responsivity, is used to measure the radiance of the blackbody in combination with a lens aperture and a single, simple lens—"the hybrid method" [11].
- An imaging radiometer, calibrated for radiance responsivity, comprising a filter radiometer incorporated within an optical system consisting of several lenses and appropriate baffling, is used to measure the radiance of a blackbody—"the radiance method" [12,13].

The first two methods are non-imaging, and the third and fourth use optics to facilitate the measurement of small sources.

Despite differences in the details of the calibration and subsequent implementation of direct absolute spectral-band radiometry ($n = 0$), the uncertainties attained by the practitioners are similar, and somewhat less than the uncertainties for thermodynamic temperature associated with the indirect methods ($n \geq 1$) referred to below (see Fig. 1). The current international status of radiometry, and the uncertainties that are realistically achievable, are currently being assessed as part of the CCT-WG5 HTFP research plan [14,15].

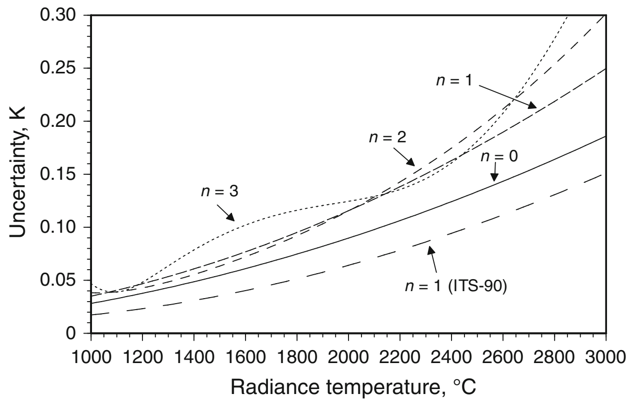

Fig. 1 Comparison of combined standard uncertainties in radiance temperature for each method. Curve labeled $n = 1$ gives the uncertainty in thermodynamic temperature extrapolated from the gold point assuming an uncertainty in the gold-point temperature as determined by absolute radiometry. For $n = 1$ (ITS-90), the thermodynamic uncertainty associated with the gold-point temperature is not included. For $n = 2$, the Au and WC-C fixed points were used; for $n = 3$, the Au, Pt-C (1738 °C), and WC-C points were used

4 Indirect Methods

The ITS-90 above the silver point is realized by one defining fixed-point blackbody (of either Ag, Au, or Cu), $n = 1$, and the use of Planck's law in ratio form to develop the temperature scale by extrapolation [16]. This is the case because at the time when ITS-90 was formulated, no reliable HTFPs existed above the Cu point. However, with the advent of HTFPs [17,18], this situation no longer persists and it will soon become possible to develop indirect methods of realizing thermodynamic temperature above the silver point by interpolation between two or more fixed points on the basis of Planck's law.

Two fixed points ($n = 2$) are the minimum required for such interpolation [19–21]. If the two fixed points have phase transition temperatures as far from each other as practically feasible (e.g., the Ag point and the highest available HTFP with well known thermodynamic temperature), then the scheme will have a wide range with low uncertainty. Some extrapolation beyond the calibration points may also be acceptable. The development of very high-temperature HTFPs such as WC-C (2749 °C) will allow the scheme to be successfully implemented over the range from about 1000 K to 3300 K. In this scheme, accurate knowledge of the relative spectral responsivity function is not required (just an estimate of the bandwidth), and the effect of the uncertainty associated with non-linearity is strongly reduced as compared to that affecting schemes using fewer fixed points: $n = 1$ (with ITS-90 as a special case) or $n = 0$ (direct measurement of T via primary methods). The uncertainties associated with interpolation and extrapolation will clearly depend on the temperatures of the calibration points in question and their associated uncertainties.

An alternative option is through following flexible multi-point interpolation schemes ($n = 3$) or a least-squares approach ($n > 3$). The redundancy of HTFPs in a least-squares scheme provides additional security in scale realization. For schemes with $n \geq 3$, in principle, knowledge of the spectral responsivity function is no longer needed.

The situation regarding the use of HTFPs in high-temperature metrology is still the subject of research, as the HTFPs do not yet have internationally agreed temperatures by the CCT. However, an international project is currently underway [14], and it is anticipated, at the conclusion of that project, that agreed values with uncertainties will be assigned to a selected set of HTFPs. Once thermodynamic temperatures for HTFPs are established, they can then be used with interpolation procedures, based upon Planck's law, to establish thermodynamic temperatures from Ag to 3300 K. It is in anticipation of this that HTFPs and interpolation schemes are included in Sect. 4 of the main *MeP*-K document.

5 Uncertainties of the Respective Methods

The derivation of uncertainties outlined in this section is described in detail in [3,19]. A generalized framework for the propagation of uncertainty for all the different approaches to radiometric high-temperature realization—direct via absolute radiometry ($n = 0$, T), or indirect via high-temperature fixed points ($n \geq 1$, T or T_{90})—has been developed [19]. This framework is based on an analytical equation that is used to model the integral of Planck's law over the radiometer's spectral responsivity. The model, while not exact, has an accuracy well within the combined measurement uncertainty, and allows analytical uncertainty equations to be derived, which can be used to compare the uncertainty associated with each approach. These equations allow additional insight into the uncertainty relationships to be gained. The model unifies the uncertainty analyses for each method without sacrificing accuracy in the estimated uncertainty values.

Uncertainty components for the different approaches to temperature measurement—primary radiometry, one-point (including ITS-90), two-point, and three-point extrapolation/interpolation schemes—contain different components of differing significance, the details of which are found in [3,19].

Figure 1 shows a comparison of the combined standard uncertainty in measured radiance temperature for examples of the methods, introduced above, excluding the least-squares methods. The ITS-90 shows the lowest uncertainty because the assigned ITS-90 temperatures of the defining fixed points have zero uncertainty. When the uncertainty associated with the thermodynamic temperature assignment of the defining fixed point is taken into account, the uncertainty for the $n = 1$ extrapolation method is somewhat higher than that for primary radiometry. It should be stressed that T_{90} and T are different quantities, and there is a systematic difference between T and T_{90}, which increases nearly proportionally to T^2. Care should be exercised whenever the uncertainties given for T and T_{90} are compared as the uncertainties for T_{90} are for a defined scale, whereas the other methods are for a realization of thermodynamic temperature and of necessity include additional uncertainty components.

It should be noted that the uncertainties for realizing thermodynamic temperature by indirect methods are slightly higher than both the $n = 0$ and $n = 1(T)$ methods. However, weighed against this should be the fact that the actual realization of temperature by these approaches is likely to be more robust because of the use of more than one fixed point, which gives extra security in the realization. Use of the least-squares approach is probably the most secure but is more time-consuming to implement. Also, by adopting a least-squares strategy, the uncertainty associated with the calibration of the radiometer is reduced by approximately a factor of $\sqrt{n/3}$ as compared with that resulting from a three-point interpolation [20].

As with all uncertainty analysis, conclusions change as the understanding in the method grows. In particular, it is likely that the uncertainties of thermodynamic temperature realization following the HTFP methods ($n \geq 1$) will decrease as the key uncertainty components, such as those associated with the furnace effect, are better understood and accounted for.

6 Discussion

The direct method by primary radiometry ($n = 0$) has the advantage that it intrinsically has lower uncertainties than any indirect method relying upon one or more HTFPs ($n \geq 1$). The ITS-90 ($n = 1$) above the silver point remains an excellent approximation to T for most practical applications. But as pointed out above, a direct comparison of the achievable uncertainties between ITS-90 and thermodynamic temperature is not strictly possible because the ITS-90 defining fixed points have zero uncertainty by definition.

For primary radiometry, there remains the issue of cost of implementation and the background NMI capability required to realize a primary radiometric scale with these low uncertainties. In addition, regular checking of the $n = 0$ method should be undertaken because of the potential for unpredictable drift that may occur in radiometer output—due to either amplifier changes or unpredictable change in the wavelength of the filter. This, however, may easily be done by periodically testing the radiometer output against a qualified HTFP.

The indirect methods ($n \geq 2$) require validated HTFPs. These are in the process of being established as temperature references and should be fully established as such in the next few years [14,18]. Although these methods have slightly larger uncertainties than the direct and $n = 1$ methods, they also have some distinct advantages.[1] They are more flexible and very simple to implement, not requiring particularly expensive equipment to establish a very low-uncertainty radiance-temperature scale. If two fixed points are used, only basic knowledge of the spectral responsivity of the radiometer or radiation thermometer is required [21,22]. If more than two are used, then the uncertainty in temperature realization may be reduced and the radiation thermometer can be calibrated with no knowledge of the spectral response. This is similar to the way a standard platinum resistance thermometer (SPRT) is calibrated today according to the ITS-90, with the scale being established on the thermometer, and interpolation equations (empirical, in the case of a SPRT) used to realize temperatures between the measured fixed points. One further advantage is that a scale can be established in any range of interest—so, if the experimenter were only interested in establishing a scale between 1500 °C and 2500 °C, then they would only need to use an appropriate number of HTFPs in that range to establish a low-uncertainty scale. It should also be noted that the $n = 2$ method can be easily implemented with either the Ag, Au, or Cu point taken as the lower temperature value and the choice of the upper fixed point (a eutectic or peritectic) depending on the application [22–24].

To account for these potential improvements and alternatives, the main text of the *MeP*-K will incorporate primary radiometry and, in due course, indirect methods for realizing and hence disseminating thermodynamic temperature using HTFPs.

7 Outstanding Issues

Two administrative issues remain to be addressed, one concerning the issue of certification and traceability, and the other concerning the conducting of key comparisons in a manner that enables key comparisons of like quantities to be undertaken.

[1] Note the final paragraph in the uncertainty section. It is likely that the uncertainties associated with the practical realization of the HTFPs will decrease over time.

7.1 Certification and Traceability

Calibration certificates issued by the temperature departments of NMIs often contain statements such as "traceable to ITS-90." As dissemination of T becomes a reality, this statement will have to be modified. T_{90} is a defined quantity and, therefore, only an approximation to T. Through access to T, users will be getting traceability to the fundamental quantity thermodynamic temperature, with comparable or lower uncertainties than those achievable by the ITS-90. One approach could be to include a statement such as "traceable to a realization of thermodynamic temperature, T, following procedures endorsed by CCT, specified in the *MeP*-K." A more direct approach would be to simply state "traceable to the SI." This transition may be of concern to some users and, if this is likely to be the case, then a covering note explaining the transition to T from T_{90} should be included with such certificates.

7.2 Potential for Ambiguity in Key Comparisons

It is clear that multiple approaches to the realization and dissemination of thermodynamic temperature at high temperature are emerging: direct methods through different incarnations of primary radiometry, and soon indirect methods via HTFPs with interpolation or least-squares fitting, or through measuring T_{90} and applying *a priori* known values of $T - T_{90}$ (T directly measured) with the associated uncertainties. When a key comparison is undertaken, care needs to be exercised to ensure that equivalent quantities are compared. For example, if some NMIs are realizing T by a number of methods, while others are realizing T_{90}, then the comparison protocol needs to be clear about exactly what quantity is being compared and if all values be reduced to T or T_{90}. This issue will have to be addressed in the next few years, as a key comparison is already due in this field.

8 Summary

This article summarizes the progress made by the WG5 task group in formulating the *MeP*-K for the kelvin at high temperatures.

Direct primary radiometric thermometry in a few laboratories is already at the stage where, above the silver point, thermodynamic scale uncertainties are comparable with or better than any indirect method ($n = 1, n \geq 2$ involving HTFPs) when the uncertainties of the transition temperatures of the HTFPs are taken into account. There is no reason why these laboratories should not realize and disseminate T directly, rather than still relying on ITS-90 ($n = 1$), provided care is taken to maintain the worldwide integrity of the realization of the SI quantity at these temperatures. This will be tested by a key comparison in the coming years.

Once their temperatures are established, HTFPs will be an efficient and cost effective means of realizing a very low-uncertainty high-integrity radiance temperature scale by a number of indirect methods, including two-point, three-point, or least-squares ($n > 3$).

Acknowledgments The authors gratefully acknowledge the support given them by their respective funding bodies. In addition, thanks is offered to all the members of CCT-WG5, CCT, and CCPR who have commented on various drafts of the documents from which this article was constructed.

References

1. Mise en Pratique for D of the Kelvin. http://www.bipm.org/utils/en/pdf/MeP_K.pdf
2. D.C. Ripple, R. Davis, B. Fellmuth, J. Fischer, G. Machin, T. Quinn, P. Steur, O. Tamura, D.R. White, Int. J. Thermophys. doi:10.1007/s10765-010-0837-2
3. G. Machin, P. Bloembergen, K. Anhalt, J. Hartmann, M. Sadli, P. Saunders, E. Woolliams, Y. Yamada, H. Yoon, *Realization and Dissemination of Thermodynamic Temperature Above 1234.93 K*. CCT/10-12rev1 (2010). http://www.bipm.org/cc/CCT/Allowed/25/D12r_MeP-HT_v8.pdf
4. Z.M. Zhang, B.K. Tsai, G. Machin (eds.), *Radiometric Temperature Measurements: I. Fundamentals*, Chap. 2, Sects. 2.2.4–2.2.6. Experimental Methods in the Physical Sciences Series, vol. 42 (Academic Press, Elsevier, Amsterdam, 2010)
5. T.J. Quinn, J.E. Martin, Philos. Trans. Roy. Soc. **316**, 85 (1985)
6. E.F. Zalewski, C.R. Duda, Appl. Opt. **22**, 2867 (1983)
7. S.W. Brown, G.P. Eppeldauer, K.R. Lykke, Metrologia **37**, 579 (2000)
8. J. Hartmann, Phys. Rep. **469**, 205 (2009)
9. H.W. Yoon, C.E. Gibson, P.Y. Barnes, Appl. Opt. **41**, 5870 (2002)
10. H.W. Yoon, C.E. Gibson, G.P. Eppeldauer, A.W. Smith, S.W. Brown, K.R. Lykke, Thermodynamic Radiation Thermometry Using Radiometers Calibrated for Radiance Responsivity, Int. J. Thermophys. (submitted)
11. E. Woolliams, M. Dury, T. Burnitt, P. Alexander, R. Winkler, W. Hartree, S. Salim, G. Machin, Primary Radiometry for the Mise-en-Pratique for the Definition of the Kelvin: The Hybrid Method, Int. J. Thermophys. (submitted)
12. J. Hartmann, K. Anhalt, D.R. Taubert, J. Hollandt, Absolute Radiometry for the MeP: The Irradiance Measurement Method, Int. J. Thermophys. (submitted)
13. S. Briaudeau, M. Sadli, F. Bourson, B. Rougié, Primary Radiometry for the Mise en Pratique: The Laser-Based Radiance Method Applied to a Pyrometer, Int. J. Thermophys. (submitted)
14. G. Machin, P. Bloembergen, J. Hartmann, S. Sadli, Y. Yamada, Int. J. Thermophys. **28**, 1976 (2007)
15. K. Anhalt, J. Hartmann, G. Machin, E. Woolliams, H. Yoon, Absolute Radiometry of Metal-Carbon Eutectic Fixed Points for a New Temperature Scale, Int. J. Thermophys. (submitted)
16. H. Preston-Thomas, Metrologia **27**, 3 (1990); 107 (1990)
17. Y. Yamada, H. Sakate, F. Sakuma, A. Ono, Metrologia **38**, 213 (2001)
18. G. Machin, Acta Metrol. Sinica **29**, 10 (2008)
19. P. Saunders, Uncertainties in the Realization of Thermodynamic Temperature Above the Silver Point, Int. J. Thermophys. (submitted)
20. P. Saunders, Metrologia **40**, 93 (2003)
21. P. Bloembergen, Y. Yamada, N. Yamamoto, J. Hartmann, Realizing the High-Temperature Part of a Future ITS with the Aid of Eutectic Metal-Carbon Fixed Points, in *Temperature: Its Measurement and Control in Science and Industry*, vol 7, part 1, ed. by Dean Ripple (AIP, New York, 2003), pp. 291–296
22. P. Saunders, P. Bloembergen, D.R. White, Uncertainty in temperatures realized by radiation thermometry using two fixed points, in *Proceedings of TEMPMEKO 2004, 9th International Symposium on Temperature and Thermal Measurements in Industry and Science*, ed. by D. Zvizdić, L.G. Bermanec, T. Veliki, T. Stašić (FSB/LPM, Zagreb, 2004), pp. 1149–1154
23. Y. Yamada, Uncertainty of radiation thermometers calibrated by interpolation between fixed points, in *Proceedings ICROS-SICE International Joint Conference* (2009), pp. 3812–3815
24. P. Bloembergen, Y. Yamada, Indirect Thermodynamic Temperature Measurements at High Temperature Based Upon Two Reference Points, Int. J. Thermophys. (submitted)