International comparison of radiation temperature scales among five national metrological laboratories using a transfer standard radiation thermometer

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Abstract. Round-robin measurements with a transfer standard radiation thermometer were organized by the NRLM in the framework of a three-year joint research agreement with the NIST, the IMGC and the PTB: the NPL also took part in this exercise. The aim of the study was to assess the mutual traceability of the ITS-90 temperature scales established by the different laboratories in the high-temperature range (above 1000 °C). The thermometer was a monochromatic (0,65 μm) silicon-detector thermometer belonging to the NRLM. It was circulated in the period from May to July 1993 and was calibrated by all the participants against their local reference thermometers. The temperature interval from 1000 °C to 2000 °C was covered by all the participants, but some extended the range down to 800 °C or up to 2700 °C. The results indicate that all the calibrations agree to within 0,5 °C at 1000 °C and to within 2 °C at 2000 °C.

1. Introduction

Demands for accurate temperature scales at high temperature exist in many fields, such as space, nuclear energy and advanced materials. In order to meet these demands, the major national metrological laboratories realize their own temperature scales above the silver point (962 °C) using accurate monochromatic thermometers that are calibrated using fixed-point black bodies according to the procedure contained in the formal definition of the ITS-90 [1]. Because this procedure implies an extrapolation process above a reference temperature, which may be the freezing point of silver, gold (1064 °C), or copper (1085 °C), international comparisons at high temperatures are the only means to disclose possible discrepancies in the temperature scales. The type of research described here is relevant for work that is oriented towards establishing official positions on the mutual agreement of the scales at the various national laboratories.

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International comparisons of radiation scales were carried out in the 1970s and 1980s [2, 3] using tungsten strip lamps as transfer standards. Recent comparisons have taken place between the NPL and the NIST [4] and among seven European laboratories using, in both cases, a silicon-detector infrared thermometer as transfer standard [5]. The NRLM began a three-year joint project in 1993 with the NIST, the IMGC and the PTB concerning radiation thermometry in the ultra-high temperature range (above 2000 °C). During the first year of collaboration, a 0,65 μm silicon-detector thermometer belonging to the NRLM was transported to the three laboratories in the joint project, and to the NPL, for a comparison of measurements of variable temperature black bodies using the silicon-detector thermometer. The comparison was carried out from May to July 1993 from 1000 °C to 2000 °C at all laboratories; at some laboratories it was possible to extend the calibration range to 800 °C and/or to 2700 °C. The results of the comparisons are described in this paper.

2. Characteristics of the transfer standard radiation thermometer (TSRT)

Figure 1 shows the optical layout and Table 1 the specifications of the transfer standard radiation thermometer (TSRT) belonging to the NRLM. The thermometer was manufactured by Topcon and is an upgraded version of a commercially available model.

Table 1. Specifications of the transfer standard radiation thermometer.

Temperature range	800 °C to 3000 °C
Measuring distance	200 mm to infinity
Minimum target size	0,75 mm at 200 mm measuring distance
Detector	Silicon photodiode Hamamatsu Photonics model S1336-5BK
Interference filter for defining the central wavelength	
Measured centre wavelength	651 nm
Measured bandwidth	13 nm
Interference filter for suppressing the spectral transmission in the far wings	
Measured centre wavelength	649,2 nm
Measured bandwidth	100,4 nm
Feedback resistance	100 kΩ, 1 MΩ, 10 MΩ, 100 MΩ
Diameter of objective lens	50 mm
Field-of-view	0,215 °
Ambient temperature sensor	Integrated circuit temperature sensor

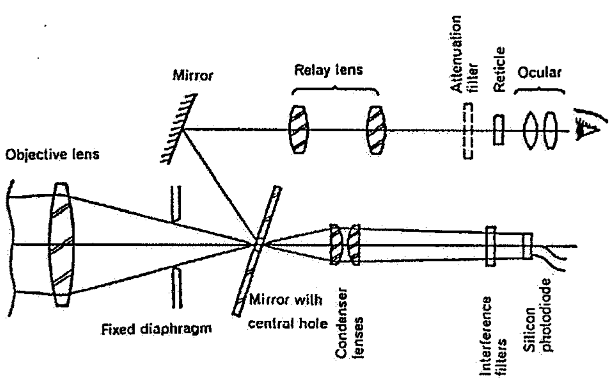

Figure 1. Optical layout of the transfer standard radiation thermometer.

The image of a target is focused by an objective lens of 80 mm focal length on to a mirror that has a central hole of about 0,5 mm diameter; this is the field stop of the system. A fixed diaphragm of 10 mm diameter located 25 mm in front of the mirror defines the aperture ratio of the system. Two interference filters are used to limit the wavelength while a commercially available model has one. One of the two interference filters defines the central band while the other suppresses the out-of-band transmission. A silicon photodiode, which generates a photocurrent when illuminated, and an FET operational amplifier with a variable feedback resistor are used to convert radiant flux to voltage. The temperature of the photodiode is monitored by an integrated circuit (IC) temperature sensor that is installed close to the photodiode. The temperature readings are used to correct for the temperature dependence of the radiation thermometer. The light reflected by the mirror is captured by an auxiliary optical system for the purpose of alignment and focusing of the radiation thermometer.

3. Absolute calibration of the thermometer

The TSRT was calibrated at the NRLM according to the definition of the ITS-90, which states that temperatures are to be obtained from measured ratios of spectral radiance between a variable temperature black body and a fixed-point black body. In order to establish the ITS-90 scale on the TSRT, measurements of the relative spectral responsivity and nonlinearity were made, followed by calibration with a fixed-point black body.

Because the TSRT employed narrow-band interference filters, the relationship between the output voltage V and the temperature T can be expressed with the following integral equation:

$$V = a\varepsilon \int L(\lambda, T)\, R(\lambda)\, \mathrm{d}\lambda, \tag{1}$$

where λ is the wavelength, $L(\lambda, T)$ is the Planck function, $R(\lambda)$ is the relative spectral responsivity, ε is the emissivity, and a is a constant that is determined by the fixed-point calibration.

The fixed-point calibration was performed at both the silver and copper points using the apparatus described in [6]. The black-body cavities had apertures of 6 mm and their emissivity was estimated to be 0,9990±0,0005 (expanded uncertainty with coverage factor $k = 2$, equal to twice the standard uncertainty). The departure by 0,1 % from unit emissivity resulted in corrections that ranged from 0,07 °C at 1000 °C to 0,23 °C at 2000 °C and 0,35 °C at 2500 °C. The output voltage at the silver point calculated using (1) with the a factor obtained from the copper-point calibration agreed, in terms of temperature, to better than 0,05 °C with the output voltage measured at the silver point.

The measured spectral responsivity curve, normalized to unity, is shown in Figure 2. The spectral responsivity of the TSRT was measured every 0,1 nm from 640 nm to 660 nm, every 1 nm from 600 nm to 640 nm and from 660 nm to 700 nm, and every 10 nm from 400 nm to 600 nm and from 700 nm to 1200 nm. In each of these wavelength intervals, the instrumental bandwidth of the 300 mm focal length double grating monochromator that was used for these measurements was equal to the step size: 0,1 nm, 1,0 nm, 10 nm. The out-of-band responsivity of the TSRT is less than

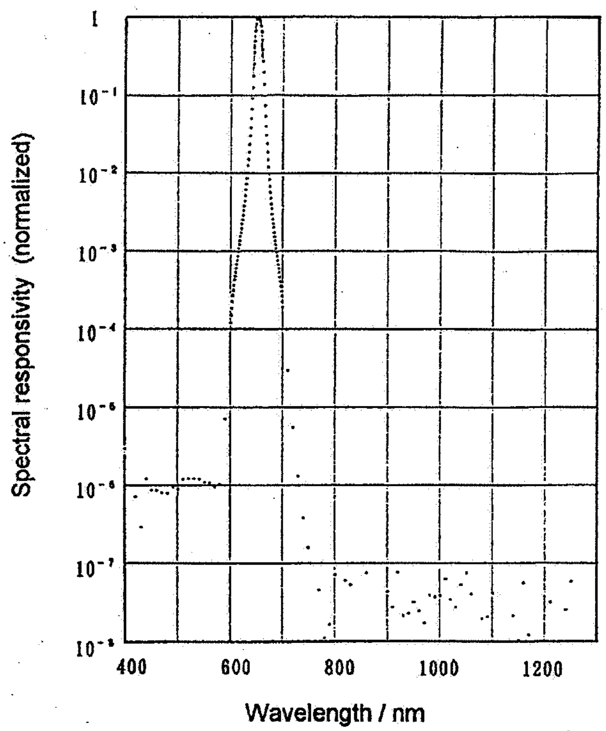

Figure 2. Spectral responsivity of the transfer standard radiation themometer.

10^{-7} on the long wavelength side and less than 10^{-5} on the short wavelength side. In Figure 2, negative values, which arise from noise after subtraction of the background, are not shown.

The nonlinearity of the response of the TSRT was measured using a simple two-aperture flux-doubling method [7]. The measurements were performed with three types of source over four values of the feedback resistor and the results are shown in Figure 3. In order

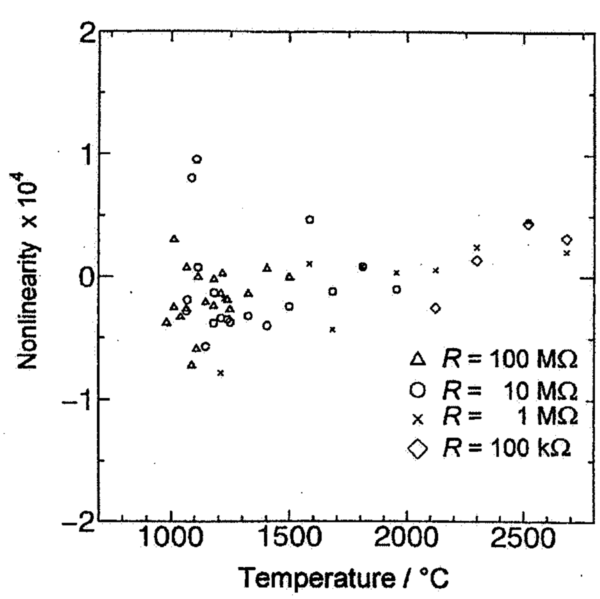

Figure 3. Nonlinearity of the transfer standard radiation thermometer.

to cover the dynamic range of the TSRT, the radiance level of the source was varied. The nonlinearity values on the vertical scale represent the relative departures from linearity at each flux doubling step as a function of the source radiance, which is given in terms of temperature using the observed signal levels and (1). It is evident from the figure that the measured nonlinearity was less than 0,01 % up to 1200 °C and less than 0,005 % for higher temperatures. If one assumes a constant nonlinearity of 0,01 % at each of the flux-doubling steps necessary to cover the range 1085 °C to 2700 °C, the cumulative effect of the nonlinearity at 2700 °C is 0,13 % in terms of signal, which corresponds to about 0,5 °C in terms of temperature. However, because the actual amount of nonlinearity was much less, no corrections were made for this effect.

The function defined in (1) was fitted to the characteristic equation

$$V(T) = \frac{C}{\exp\left(\dfrac{c_2}{AT+B}\right) - 1}. \qquad (2)$$

Here, $c_2 = 0{,}014\,388$ m·K is the second constant of radiation. The coefficients A, B and C are determined by the output voltages calculated from (1) at the three temperatures 1084,62 °C, 961,78 °C and 660,323 °C. The difference between (1) and (2) was less than ±0,02 °C from 500 °C to 2800 °C. This equation is similar to one used for the interpolation of 0,9 μm radiation thermometer scales [8, 9]:

$$V(T) = C \exp\left(\frac{c_2}{AT+B}\right), \qquad (3)$$

in the temperature range 400 °C to 1100 °C. The difference between (2) and (3) is less than 0,01 °C at 2000 °C and 0,3 °C at 2800 °C for a measurement wavelength of 0,65 μm when the same coefficients are used. This Planck-Wien difference reaches 3 °C at 2800 °C for a measurement wavelength of 0,9 μm.

The uncertainty in the scale realized with the TSRT according to this procedure was estimated by combining the uncertainties in the fixed-point calibration, the measurement of the spectral responsivity and the nonlinearity. A further uncertainty, based on repeated observations at the NRLM before and after measurements at the NIST, the PTB, the IMGC and the NPL, was incorporated.

The sources of uncertainty, expressed as expanded uncertainties $(k = 2)$, are:

(a) calibration of the TSRT with the copper-point black body: 0,3 °C;

(b) wavelength obtained from the spectral responsivity: 0,2 nm;

(c) nonlinearity of the TSRT: 0,01 % of the signal values;

(d) stability of the TSRT: 0,3 % of the signal values.

These sources of uncertainty were evaluated at a number of temperatures according to [10], and the combined uncertainties for the scale realization were calculated by combining them in quadrature: the results are shown in Table 2.

Table 2. Estimated expanded uncertainties for $k = 2$ in the NRLM calibration of the transfer standard radiation thermometer.

Temperature/°C	1000	1085	1500	2000	2500	3000
Source	Uncertainty/°C					
Fixed-point black body	0,26	0,30	0,51	0,84	1,25	1,74
Effective wavelength	0,02	0,00	0,17	0,47	0,89	1,42
Detector nonlinearity	0,01	0,00	0,08	0,22	0,42	0,67
Output stability	0,22	0,25	0,43	0,70	1,04	1,45
Combined uncertainty	0,34	0,39	0,69	1,21	1,90	2,76

4. Apparatus used in the comparison

After the TSRT was calibrated at the NRLM according to the procedure described in the preceding section, it was used to realize a temperature scale in the other participating laboratories by measurement of their black-body sources. This temperature scale was compared with that maintained in the laboratory, which is realized with reference radiation thermometers, fixed-point black-body sources and transfer sources such as tungsten strip lamps.

4.1 Reference thermometers

The basic features of the reference thermometers and the transfer or reference sources are shown in Table 3. The NIST photoelectric pyrometer, a filter radiation thermometer, was calibrated at the gold-point temperature and the temperature of a variable temperature black body was determined from the measurements of the ratio of spectral radiance. A tungsten strip lamp at 1255 °C was used to check the stability of the radiation thermometer during the comparison. The NPL radiation thermometer was a commercial unit; model LP2 manufactured by IKE (Germany). The procedure used was the same as at the NIST except that no additional sources were used to check the stability. The IMGC reference thermometer was the primary standard thermometer, and in this comparison it was used to compare the radiance of the black body with that of a pair of tungsten strip lamps, which hold the scale at the IMGC. The PTB also used a model LP2 IKE thermometer, but the calibration was not performed using a fixed-point black body directly. Instead it was calibrated using tungsten strip lamps as transfer sources calibrated against the PTB primary standard thermometer. Because the PTB used tungsten strip lamps to realize the ITS-90 for temperatures below 1500 °C, the results of this comparison had to be referred to a given wavelength due to the wavelength dependence of the radiance temperature of the lamps. Therefore, the LP2 thermometer was calibrated with two different interference filters, for wavelengths 548 nm and 657 nm. In this way, it was possible to interpolate the radiance temperature to the TSRT wavelength of 651 nm.

4.2 Transfer sources

The transfer sources used in the comparison are listed in Table 4. All four institutes used graphite black bodies to cover at least part of the measured temperature interval. The protective windows that are sometimes used in graphite black bodies were removed during the measurements except at the PTB where an Infrasil (TM) window was used. The transmittance of this window was measured separately and the data were used to correct the measurement results. Other radiance sources were used in addition to the graphite black bodies in the temperature ranges where they could provide better temperature stability and uniformity. An Inconel (TM) sodium heatpipe black body, an Inconel black body in a tubular furnace, and a vacuum tungsten strip

Table 3. Characteristics of the reference thermometers used at the four institutes.

Institute	Designation	Centre wavelength/nm	Bandwidth/nm	Detector	Transfer or reference source	Target size (measuring distance)
NIST	Photoelectric pyrometer	655,3	4,2	Photomultiplier	Gold point; vacuum lamp at 1255 °C	0,6 mm × 0,8 mm (640 mm)
NPL	IKE LP2	650,35	12	Silicon photodiode	Gold point	1 mm diameter (840 mm)
IMGC	IMGC primary standard	900	12,7	Silicon photodiode	Vacuum lamp 800 °C to 1500 °C Gas-filled lamp 1500 °C to 2000 °C	1 mm diameter (500 mm)
PTB	IKE LP2	657	10,1	Silicon photodiode	Vacuum lamp 1000 K to 1800 K Gas-filled lamp 1800 K to 2300 K	0,8 mm diameter (580 mm)

Table 4. Characteristics of the radiation sources used at the four institutes.

Institute	Type of source	Measured temperature interval/°C	Measuring distance/mm	Source size/mm	Percentage correction factor for the size-of-source effect	Window
NIST	Graphite black body (Thermogage type 2 dual)	1000 to 2700	732	Ø 25	0,2	No
NPL	Inconel/sodium heatpipe black body	800 to 1000	500	Ø 75	0,4	No
	Graphite black body (IKE)	1000 to 2500	500	Ø 15	0,1	No
IMGC	Home-made Inconel black body	900 to 1200	500	Ø 25	0,2	No
	Graphite black body Pereco model CT-215	1200 to 2000	500	Ø 10	0,07 to 0,09	No
PTB	Tungsten strip lamp (vacuum)	800 to 1500	200	3 wide	0 No corrections applied	Yes
	Graphite black body (IKE)	1500 to 2200	580	Ø 15	0,1	Yes

lamp (Polaron high-stability type) were used at the NPL, the IMGC and the PTB, respectively. The sixth column in Table 4 shows the corrections, in terms of percent radiance, that were applied to account for the size-of-source effect of the TSRT, as described below.

5. Results and discussion

The TSRT was carried by hand, not as checked baggage, to the four laboratories on two separate trips: to the NIST in May 1993 and then to the NPL, the IMGC and the PTB in July of the same year. Measurements were performed for one week in each laboratory. The temperature intervals covered by each laboratory are given in column three of Table 4.

The preliminary results of the comparison, i.e. without considering the effects of the source size or ambient temperature, are shown in Figure 4. The temperature differences on the vertical axis represent the differences found in each laboratory with respect to the NRLM calibration of the TSRT, or $T_{\mathrm{Lab}} - T_{\mathrm{NRLM}}$. These measurements agree to better than 0,7 °C at 1000 °C and 2,5 °C at 2000 °C. The preliminary results were adjusted to account for the ambient temperatures in the different laboratories during the measurements, for the different sizes of the black body apertures and for the different temperature distributions beyond the apertures.

The ambient temperature, as measured by the IC temperature sensor inside the TSRT, varied from 27 °C to 29 °C during the calibration of the TSRT using the copper point at the NRLM. The ambient temperature in the other four laboratories varied from 20 °C to 27 °C during the measurements. The temperature

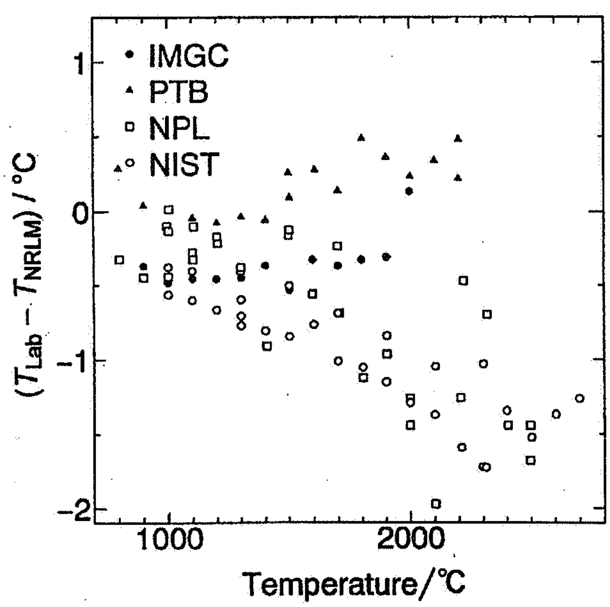

Figure 4. Uncorrected results of the comparison.

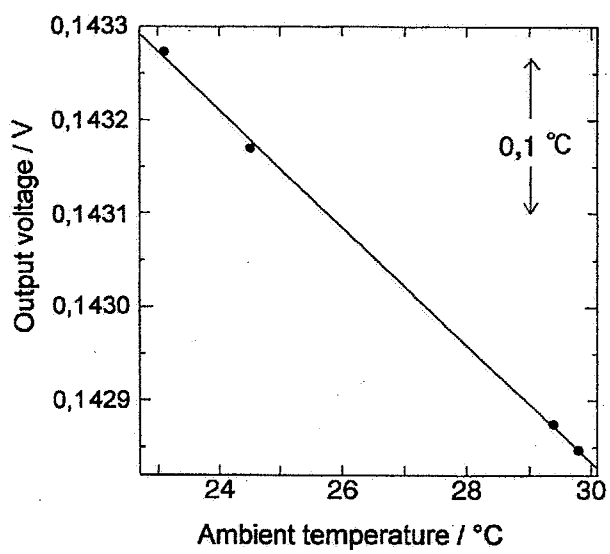

Figure 5. Ambient-temperature dependence of the output voltage of the transfer standard radiation thermometer at the copper point.

dependence of the TSRT is shown in Figure 5 and was obtained by repeating the copper-point calibration during a day on which the ambient temperature was changed. The temperature coefficient α of the TSRT obtained from a linear regression of these data was $-4,4 \cdot 10^{-4}/°C$. This small and negative value could be caused by the temperature characteristics of the silicon photodiode, which has almost zero temperature coefficient below 900 nm and a positive coefficient at longer wavelengths [11], or by some other effect such as the temperature dependence of the amplifier circuit.

The corrected output voltage V_c was calculated from the raw voltage V_r using the following equation:

$$V_c = V_r/[1 + \alpha(t_{am} - 23)], \quad (4)$$

where t_{am} represents the ambient temperature in each laboratory.

In all cases, the correction on V_r was less than 0,4 %, equivalent to less than 0,30 °C at 1000 °C and less than 0,93 °C at 2000 °C.

The size-of-source effect of the TSRT was measured using an integrating-sphere apparatus that provided a uniform radiance source with a variable diameter at the exit aperture. Diameters of 6 mm, 12 mm, 24 mm and 50 mm were chosen. Two independent measurements were made at each aperture setting and the results are shown in Figure 6. The values on the vertical axis represent the ratios of the signals measured with the smaller diameters to that measured with the 50 mm diameter exit aperture. The output of the TSRT changed by less than 0,3 % when the diameter of the source was varied from 6 mm to 50 mm. The difference of 0,3 % corresponds to 0,22 °C at 1000 °C or 0,70 °C at 2000 °C. The data from each laboratory were corrected for the size-of-source effect by using the curve in Figure 6, the known sizes of the sources

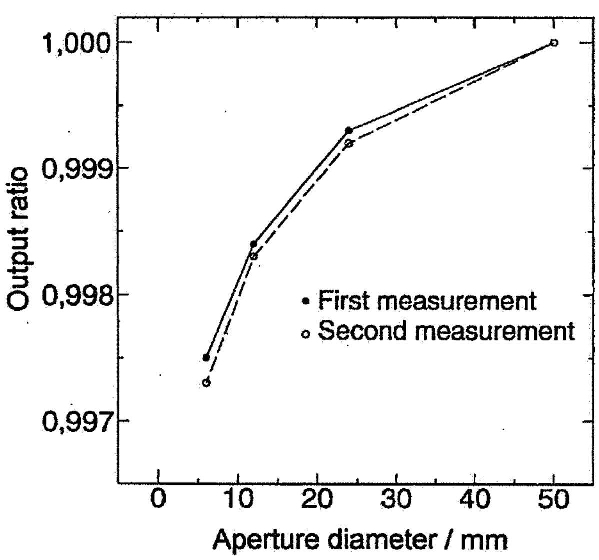

Figure 6. Size-of-source effect of the transfer standard radiation thermometer. The lines represent a fit to the data.

that were measured (Table 4) and the 6 mm aperture of the copper-point black body of the NRLM. The results are summarized in Table 4. It should be noted that most corrections were calculated simply on the basis of the differences in the diameters of the cavity apertures assuming uniform temperature distributions and neglecting possible contributions from the area outside the aperture. Only for the IMGC black bodies were the temperature distributions for the surroundings available, so a more precise calculation could be made. The correction was 0,12 °C at 900 °C and 0,20 °C at 1200 °C for the Inconel black body and 0,07 °C at 1200 °C and 0,22 °C at 2000 °C for the graphite black body.

The results of the comparison, after applying the above corrections, are shown separately for each laboratory in Figures 7 to 10. In Figure 7 the value $T_{NIST} - T_{NRLM}$ is plotted. The figure shows the results of the two measurement runs performed during two days at the NIST. The closed circles represent the data of the first day and the open circles those of the second day. The difference between the two runs was 0,2 °C at 1000 °C and 0,5 °C at 2000 °C. The agreement between the NIST and the NRLM was better than 0,8 °C between 1000 °C and 2000 °C and remained better than 1,5 °C at 2700 °C.

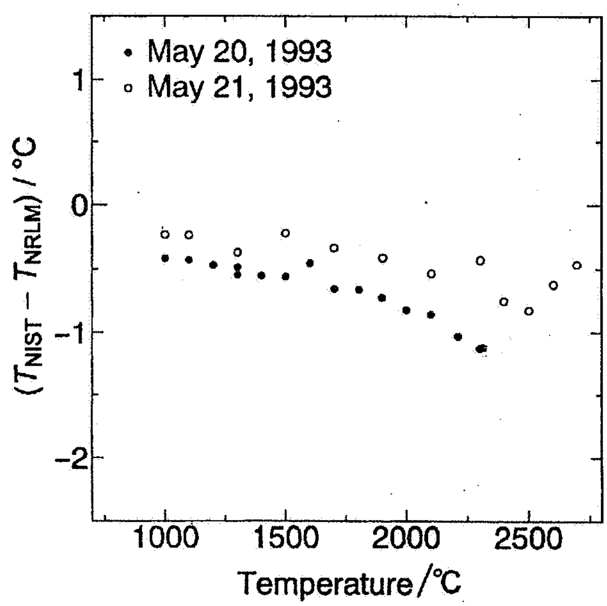

Figure 7. Differences between the NIST and the NRLM radiance temperature measurements.

The results of the NPL measurements are shown in Figure 8. The measurements were performed over three days and the open circles, triangles and squares represent the measurements of the first, second and third day, respectively. The closed squares refer to the measurements with the heatpipe black body while all the other symbols refer to the graphite black body. The scatter of the data was larger than for the other

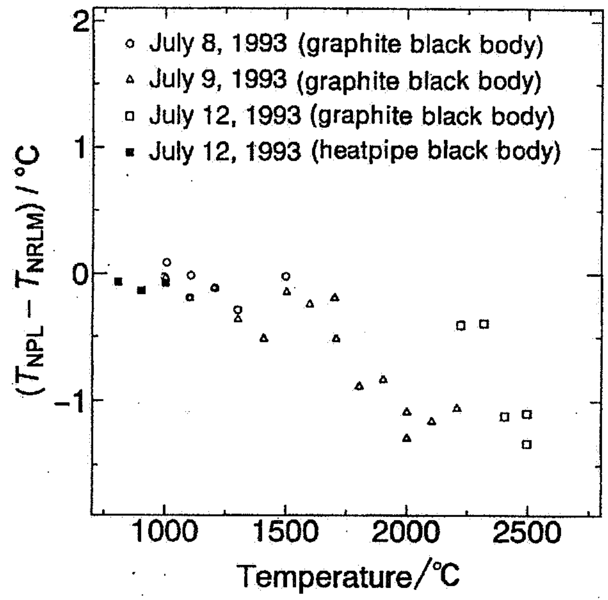

Figure 8. Differences between the NPL and the NRLM radiance temperature measurements.

laboratories, about 0,5 °C. The cause may be that a tripod was used to mount the TSRT at the NPL, while it was mounted on a translation stage in the other laboratories. Poorer repeatability of the alignment of the TSRT may have resulted. The agreement between the NPL and the NRLM was better than 0,2 °C at 1000 °C and better than 1,5 °C at the higher temperatures between 2000 °C and 2500 °C

The closed and open circles in Figure 9 represent the results obtained at the IMGC in a single run with the Inconel black body and the graphite black body,

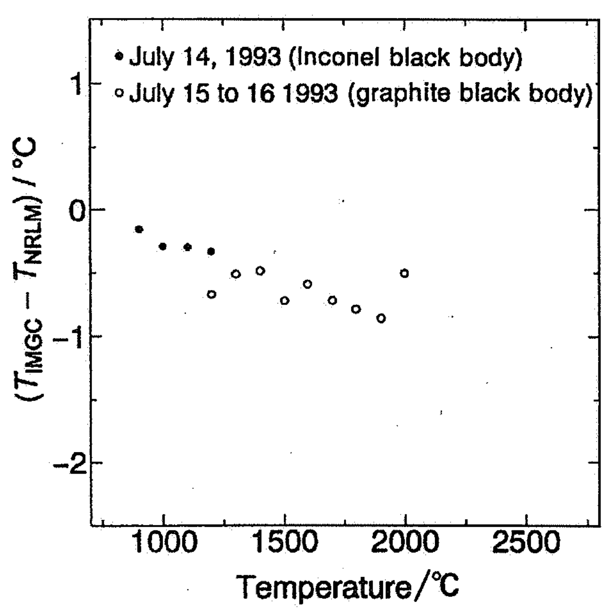

Figure 9. Differences between the IMGC and the NRLM radiance temperature measurements.

respectively. Only the point at 2000 °C was measured three times and the three values agreed to within 0,15 °C. The agreement between the IMGC and the NRLM was better than 0,3 °C at 1000 °C and better than 1 °C at 2000 °C. As at the NIST and the NPL, most departures from the NRLM were negative.

Figure 10 shows the results of the PTB measurements. The circles, triangles, squares and diamonds show data obtained on different days and the closed and open symbols indicate the results with the tungsten strip lamp and the graphite black body, respectively. The departures from the NRLM calibration were generally of opposite sign from those of the other laboratories, although the absolute values of the differences were comparable over most of the temperature interval. In fact, the agreement between the PTB and the NRLM was better than 0,2 °C in the range of the tungsten strip lamp from 900 °C to 1500 °C and better than 1 °C up to 2200 °C. During the calibration of the reference thermometer at the PTB it was found that the apparent radiance of the lamps used to transfer the scale from the primary standard showed a strong dependence on the angle of observation. A steep increase of radiance, at the rate of about 1 % per angular degree, made the alignment of lamps very critical and could possibly explain the different trend of the PTB results above 1500 °C.

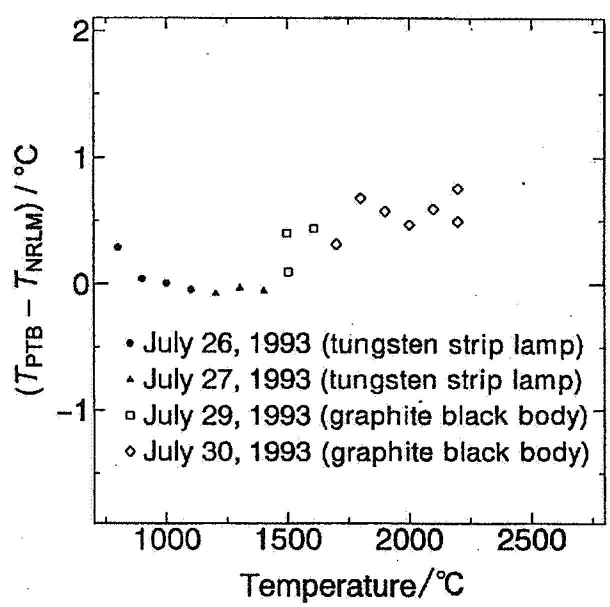

Figure 10. Differences between the PTB and the NRLM radiance temperature measurements.

By comparing these partial results, we conclude that the TSRT measurements performed in the five laboratories agree in the temperature interval from 1000 °C to 2000 °C, where all laboratories have a temperature scale, to better than 0,5 °C at 1000 °C and 2 °C at 2000 °C.

6. Conclusion

A transfer standard radiation thermometer was calibrated according to the ITS-90 procedure at the NRLM and then used to measure the radiation temperature of variable temperature sources at four national metrological institutes. At the same time the reference thermometers at these institutes were used to measure the radiation temperature giving the results shown in Figures 7 to 10. The results of this international comparison show that the five laboratories were in agreement to within 0,5 °C at 1000 °C and to within 2 °C at 2000 °C. Also at 2500 °C the agreement among the three laboratories that extended the calibration up to this temperature (NRLM, NIST and NPL) was within 2 °C. It must be stressed that the departures of all laboratories from the original NRLM calibration were within the estimated uncertainties of this calibration.

This result is particularly encouraging considering that the variety of apparatus and approaches used in the different laboratories could have led to systematic differences which were much larger. We conclude that careful calibrations of radiation thermometers in the high-temperature range meet the accuracy demands required by most practical applications. Furthermore, this international comparison has indicated suggestions for further improvements. These include full evaluation of the size-of-source effect and proper alignment of the radiation thermometer when using tungsten strip lamps or black bodies with strong radial temperature gradients.

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Note. Certain commercial equipment, instruments or materials are identified in this paper to aid understanding. Such identification does not imply recommendation or endorsement by the authors or their home institutions, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

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