Report on NIST/NRLM infrared thermometer intercomparison to 3000 °C

Report to fulfil NMS milestone Q311d8

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ISSN 1369-6769

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17/2/98

Approved on behalf of Managing Director, NPL
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1. INTRODUCTION

The ITS-90 above the silver point is realised using a freezing point blackbody cavity (of silver, gold or copper) and a radiation thermometer in conjunction with a fundamental equation of physics, Planck's law, in ratio form.

This portion of the ITS-90 is realised, using a great variety of equipment, across the (National Measurement Institute) NMI community. It is therefore vital that intercomparisons between NMI's are undertaken on a regular basis to ensure scale equivalence at a level required for trade purposes is maintained and also that no systematic errors have crept in unnoticed into the laboratories realisation.

2. INTERCOMPARISON WITH NRLM

Details of the intercomparison and results can be found in the attached paper that my Japanese colleague presented at Tempbeijing recently.

The key elements are as follows: NRLM organised a round of intercomparisons with NPL, NIST, PTB and IMGC. This involved NRLM circulating calibrated, high stability, silicon photodiode based radiation thermometers. These were hand carried to the participants due to their sensitive nature. The intercomparison at NPL was performed in August 1995, these results are summarised on the attached diagram and in "Comparison results Section 3A" in the attached paper. It should be noted that NPL and NRLM performed the widest range intercomparison of any of the participants (900 °C to 2800 °C), NRLM was not able to achieve the desired 3000 °C. The other participants top intercomparison temperatures were as follows: IMGC, 2000 °C; PTB, 2300 °C and NIST 2700 °C.

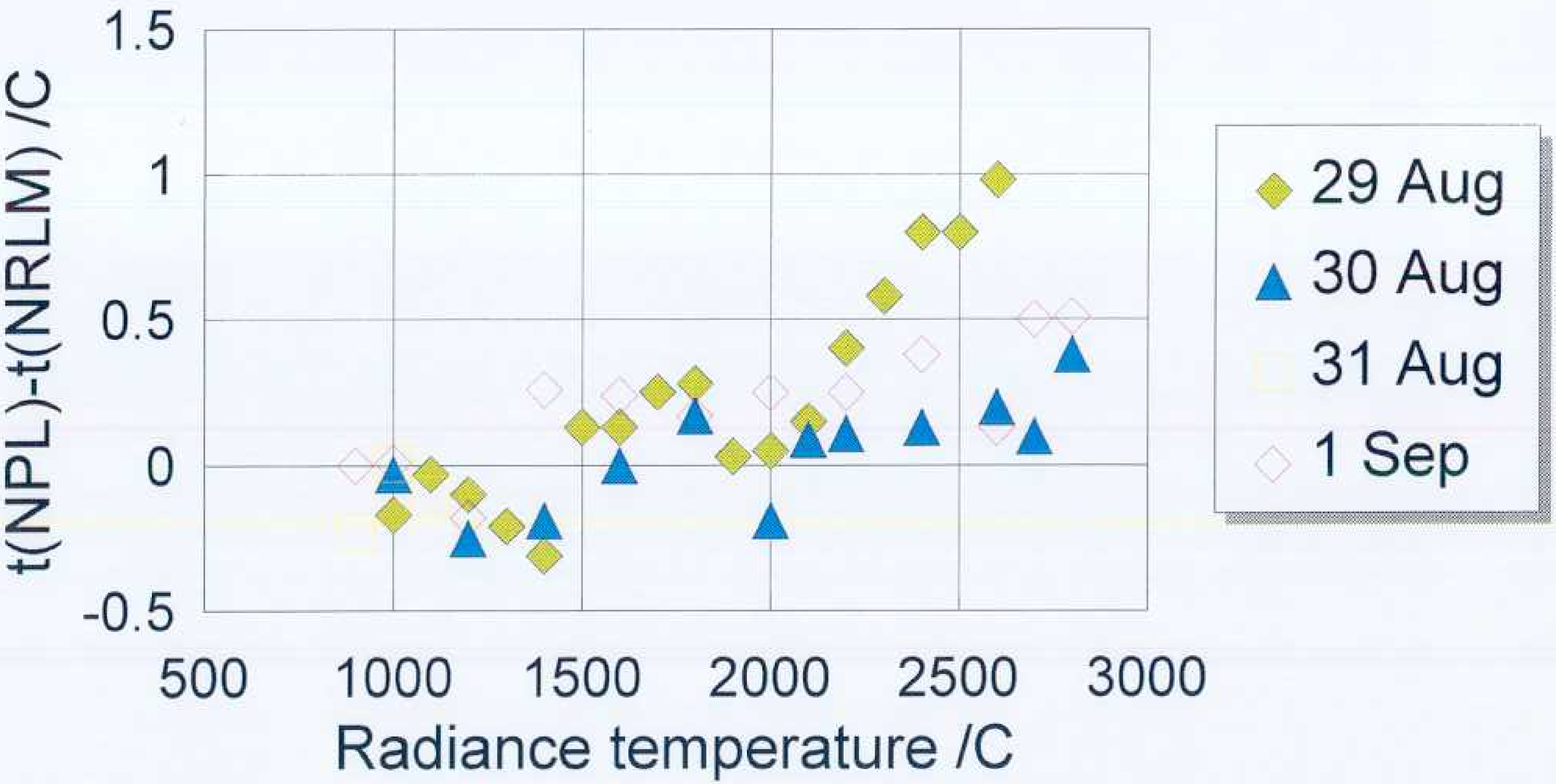
The results between NRLM and NPL can be summarised as follows: the average difference between NRLM and NPL was less than 0.2 °C at 1000 °C and less than 1 °C at 2800 °C. This result is very satisfactory and is probably the best that can be achieved with the currently available equipment.

3. INTERCOMPARISON WITH NIST

An indirect intercomparison has been performed with NIST as part of this exercise. However a direct intercomparison of very high temperature scales has been delayed because of problems first with NIST not being able to produce a suitable transfer instrument and secondly with the NIST radiation thermometry calibration facility being shut down for long periods for refurbishment and service. It is hoped to undertake the higher temperature intercomparison with NIST in the new programme. In the current programme NPL is joint co-ordinating a CCT key comparison with NMi-VSL in the field of radiation thermometry using tungsten ribbon lamps, to 1700 °C; this includes NIST.

NPL NRLM intercomparison

August 95



Tempbeijing'97

INTERNATIONAL COMPARISONS USING ROUND-ROBIN RADIATION THERMOMETERS ORGANIZED BY NRLM IN THE LAST FOUR YEARS

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ABSTRACT

A three-year joint research project in the field of high temperature radiation thermometry was established in 1993 between the National Research Laboratory of Metrology (NRLM) and the National Institute of Standards and Technology (NIST). the Istituto di Metrologia "G. Colonnetti" (IMGC) and the Physikalisch- Technische Bundesanstalt (PTB). respectively. As a result NRLM organized an extensive set of intercomparison experiments between these institutes to ensure the equality of their scales. In 1993. a 0.65 μm radiation thermometer from NRLM was transported to NIST. IMGC. PTB and the National Physical Laboratory (NPL). and the first intercomparison of temperature was carried out using the blackbodies of each institute in the temperature range from 1000 °C to 2000 °C. At some institutes, the interval from 800 °C to 2700 °C was studied. The agreement of the results was 0.5 °C at 1000 °C and 2 °C at 2000 °C. In 1994. a 0.9 μm radiation thermometer was transported to NIST for comparison of radiation temperature measurements from 420 °C to 2700 °C. A different 0.9 μm radiation thermometer was transported to IMGC for comparisons from 420 °C to 1085 °C. A third 0.9 μm radiation thermometer was transported to PTB for comparisons from 900 °C to 2200 °C. In 1995 and 1996. a new 0.65 μm radiation thermometer and a copper fixed-point blackbody from NRLM were transported to NPL. PTB. and NIST and the intercomparisons were repeated. This paper will present a summary and some results of these intercomparisons.

INTRODUCTION

According to the International Temperature Scale of 1990 (ITS-90). temperatures above the freezing point of silver (961.78 °C) are defined in terms of the spectral radiance from a silver. gold (1064.28 °C) or copper (1084.62 °C) fixed-point blackbody source. Intercomparisons among national metrological institutes are conducted to ascertain the accuracy and uncertainty of the temperature scales among nations. Comparisons using vacuum standard lamps. such as the intercomparison organized by the Nederlands Meetinstituut - Van Swinden Laboratorium (NMi-VSL) and NPL, are limited to 1700 °C. In this work, silicon detectors, which are stable in time and linear in response, have been used in a radiation thermometer, which served as the comparison instrument. The upper measurement limit for the radiation thermometer is greater than 2800 °C, which is the highest temperature available among the blackbodies in the comparison. Because the uncertainty in temperature is proportional to T^2, it was desirable to perform the comparison at the highest possible temperatures.

In 1993, a three year joint research project began, with NRLM as the lead laboratory and NIST, IMGC and PTB as the participants. The goal was the intercomparisons of radiation temperature measurements from 1000 °C to 2000 °C or in a wider range using radiation thermometers. NPL also participated in the intercomparison at 0.65 µm. The lowest temperature possible in the intercomparison was extended to 420 °C by including a radiation thermometer with a measuring wavelength of 0.9 µm. The overall methodology, as developed by NRLM, and some of the results are described below.

EXPERIMENTAL

1. Radiation Thermometers

The five Topcon[1] silicon-detector radiation thermometers (RTs) that were used for the intercomparison are identified by a three digit number and listed in Table 1. The RTs use refractive optical elements, are compact in size and have small ambient temperature coefficients. The size of source effect (SSE) was measured to be between 0.14 % and 0.23 % when the target diameter changed from 6 mm to 24 mm. RT 019 and RT 173 had a center wavelength of 0.65 µm and a bandwidth of 13 nm and 17 nm, respectively. A narrow band and a broad band interference filter are used together, in order to reduce the out of band spectral responsivity. These RTs were used for the temperature determinations between 800 °C and 2800 °C. The target diameter at a measurement distance of 250 mm was 1 mm for RT 019 and 0.5 mm for RT 173. The output voltages with a gain of 10^{-} for measurements of the NRLM copper fixed-point blackbody were 15 mV and 6 mV, respectively. RT 173 was prepared especially for the intercomparison because some of the blackbodies at the other institutes had small apertures.

RT 148, RT 062, and RT 130 had a center wavelength of 0.9 µm and a bandwidth of about 80 nm. RT 148 had been used for a domestic intercomparison in Japan. The temperature range for RT 148 is from 400 °C to 2000 °C and for RT 062 the range is from 400 °C to 1400 °C. RT 062 was not used for temperatures above 1500 °C because of the nonlinearity in this region. RT 130 had a small target size and was used from 660 °C to 2300 °C.

2. Calibration

The NRLM RTs were calibrated according to ITS-90 above 962 °C. The spectral responsivity was measured to determine the mean effective wavelength with an expanded uncertainty (coverage factor of two) of 0.2 nm at 0.65 µm and 0.5 nm at 0.9 µm. The nonlinearity was measured with a relative expanded uncertainty of 0.01 % and the absolute responsivity was determined using the

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[1] Certain commercial equipment, instruments, or materials are identified in this paper to foster 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.

Table 1 Characteristics of five NRLM radiation thermometers used for intercomparison
The two interference filters are designated 1 and 2.

RT	019	148	062	130	173
Manufactured	Nov. 1977	Oct. 1990	Mar. 1981	Dec. 1987	Mar. 1994
Revised	Jan. 1993		Feb. 1990	Feb. 1995	
1 Band center [nm]	651.6	901.5	902.7	906.0	650.3
1 Band width [nm]	13.1	79.0	78.8	82.5	16.9
2 Band center [nm]	649.2				648.3
2 Band width [nm]	100.4				97.1
Target Diam. [mm]	1 at 250	3 at 400	3 at 400	0.4 at 400	0.5 at 250
SSE 24 mm [%]	0.19	0.20	0.14	0.21	0.23
Temp. coeff. [%/°C]	-0.044	+0.023	+0.023	+0.020	+0.013
Output at Cu [mV]	14.316	15 555.	14 630.	640.74	623.7
A [nm]	650.87	900.09	901.61	902.24	649.83
B [nm K]	662.4	5333	5361	5869	1366
C [V]	166290	1917030	1767340	76410	73460

copper point blackbody with an expanded uncertainty of 0.3 °C. The silver point blackbody was used to confirm the calibration. The 0.9 μm RTs were checked using aluminum and zinc point blackbodies. The agreement at the fixed points, other than the copper point, was usually better than 0.1 °C. In Table 1, *A*, *B* and *C* are the coefficients of the interpolation equation. They were determined using output signals at the copper point, 2000 °C and 3000 °C for 0.65 μm RTs and those at the zinc and copper points and 2000 °C for 0.9 μm RTs calculated from the measured spectral responsivity and the measurements of the copper point.

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

Here V is the output signal, T is the temperature and c_2=0.014 388 m·K is the second radiation constant. Equation (1) was used to determine the temperature from the measured signals.

Table 2 shows the expanded uncertainty for k=2 of the 0.65 μm and 0.9 μm RTs calibrated at NRLM (first and third rows), and the expanded uncertainty of the 0.65 μm for measurements made at the host laboratories with a portable NRLM copper point blackbody (second row).

Table 2 Estimated expanded uncertainty for k=2 in °C for the 0.65 μm and 0.9 μm RTs

T [°C]	420	600	800	1000	1085	1500	2000	2500	3000
0.65 μm RT			0.37	0.35	0.40	0.69	1.16	1.75	2.48
0.65 μm RT with Cu			0.32	0.24	0.27	0.48	0.82	1.27	1.82
0.9 μm RT	0.23	0.23	0.28	0.35	0.40	0.74	1.39		

3. Comparison Blackbodies

Heated graphite blackbodies were used for the temperature ranges from 1000 °C to 2800 °C. In 1993, PTB used a vacuum tungsten strip lamp from 1000 °C to 1500 °C. Inconel blackbodies or heat pipe blackbodies were used for temperatures below 1200 °C.

4. Method of Transport

The RTs were delivered to each institution in person, in many cases as hand luggage. RT 062 was hand carried from NRLM to IMGC for the comparison from 420 °C to 1085 °C, and then it was shipped back to NRLM. RT 130 was shipped to PTB for the comparison from 900 °C to 2300 °C. In 1995, a copper point blackbody was hand carried and RT 173 was sent as checked luggage. In 1995, the output of RT 173 at the NRLM copper point changed by 1 % during transportation from PTB to NIST. In 1996, RT 019 was hand carried and the copper point blackbody was shipped.

5. Laboratory Requirements

A transformer was used at each institute to obtain 100 V AC as required by the RTs and the NRLM copper point. Argon gas flow was used to reduce oxidation of the NRLM copper point blackbody. Two signals were recorded for each RT: the output of the photodiode amplifier and the output of an integrated circuit sensor that monitored the ambient temperature. Two digital voltmeters at the host institute were used to measure these signals. The data were stored on a computer and the target temperature was calculated from Eq. (1).

Table 3 . Summary of the intercomparison measurements.

Month and year	Wavelength µm	RT	Institute	Range	Blackbody
May 1993	0.65	019	NIST	1000 °C~2700 °C	
July 1993	0.65	019	NPL	800 °C~2500 °C	
July 1993	0.65	019	IMGC	900 °C~2000 °C	
July 1993	0.65	019	PTB	800 °C~2200 °C	
May 1994	0.9	148	NIST	420 °C~2000 °C	
March 1995	0.9	062	IMGC	420 °C~1085 °C	
March 1995	0.9	130	PTB	900 °C~2200 °C	
August 1995	0.65	173	NPL	900 °C~2800 °C	Copper
September 1995	0.65	173	PTB	900 °C~2300 °C	Copper
September 1995	0.65	173	NIST	1000 °C~2700 °C	Copper
February 1996	0.65	019	NIST	1000 °C~2700 °C	Copper
December 1996	0.65	019	NIST	1000 °C~2700 °C	Copper

COMPARISON RESULTS

1. 0.65 µm in 1993[1]

Most institutes used a 0.65 µm RT and a graphite blackbody. IMGC used a 0.9 µm RT and estimated the emissivity of the graphite blackbody to be unity. PTB used a strip lamp for the comparisons from 1000 °C to 1500 °C. Figure 1 (from Ref.1) illustrates the temperature differences of the four institutes with respect to NRLM. The results of NIST, NPL and IMGC were in good agreement. The scales of five institutes agreed within 0.4 °C at 1000 °C and 2 °C at 2000 °C. The difference between NIST and NRLM did not exceed 1.5 °C even at 2700 °C.

2. 0.9 µm in 1994 and 1995

A. NIST

From 800 °C to 2000 °C, NIST used the same 0.65 µm radiation thermometer as in 1993, and the emissivity of the graphite blackbody was taken to be 0.99 at 0.9µm. The preliminary results show the difference between NIST and NRLM was about 0.3 °C at 1000 °C and 1.6 °C at 2000 °C. Sodium and cesium heat pipe blackbodies were used at 960 °C, 660 °C, 500 °C and 420 °C. The preliminary results at these temperatures show differences between 0 °C to 0.7 °C.

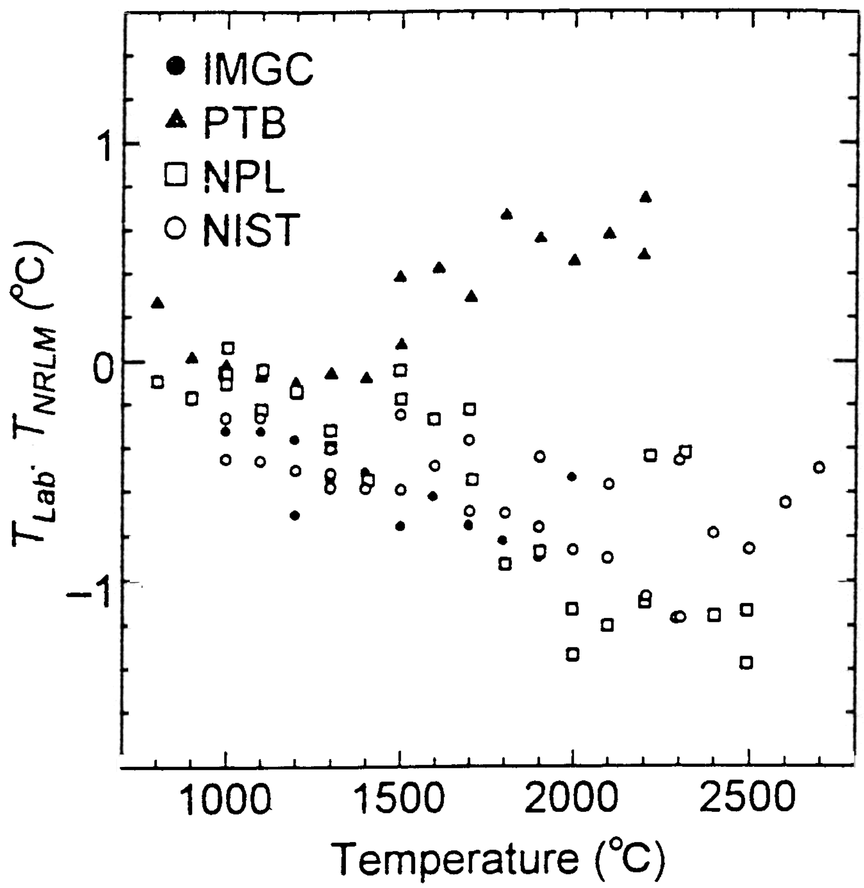

Fig. 1 0.65 μm intercomparison result in 1993

B. IMGC[2)]

IMGC's calibration of the 0.9 μm RT was based on a multi fixed point (MFP) technique. The IMGC and NRLM RTs were compared by using an inconel blackbody at eight points from 420 °C to 1085 °C, and the agreement was better than 0.1 °C in the whole range. IMGC discovered that RT 062 had a large size of source effect when the source size changed from 50 mm to 80 mm in diameter. This was confirmed later at NRLM. The other four 0.9 μm radiation thermometers from NRLM did not show this effect.

C. PTB

A graphite blackbody was used from 900 °C to 2200 °C. PTB calibrated their 0.9 μm thermometer according to ITS-90. The difference of the two 0.9 μm thermometers was less than 0.4 °C at 1000 °C and 1.1 °C at 2000 °C, and was within the uncertainty of the RT 130 radiation thermometer. PTB extensively studied the focusing of RT 130. The focal point was about +17 mm different from that selected by the human eye due to the chromatic aberration at the measuring distance of 630 mm.

3. 0.65 μm in 1995 and 1996.

A. NPL

During the two years since the 1993 experiment, NPL improved the air conditioning of the laboratory, prepared a new graphite blackbody, and a translation stage for the comparison. Both RTs measured NRLM's copper point and NPL's gold point blackbodies. The differences between the copper and gold points from ITS-90 values were about 0.1 °C. The difference of scales between NRLM and NPL was less than 0.2 °C at 1000 °C and less than 1 °C up to 2800 °C. NPL's RT predicted lower temperature than NRLM's, which was also observed in 1993, but the difference was smaller in 1995. The intercomparison results agreed within 1σ of the overall intercomparison uncertainties.

B. PTB

PTB improved the control of the graphite blackbody so the blackbody could be used from 900 °C to 2300 °C. As in the former comparisons PTB used a reference RT to determine the temperature of the graphite blackbody. This reference RT was calibrated according to the ITS-90 by means of variable temperature tungsten strip lamps which were traceable to the PTB gold fixed-point. In addition, for this comparison PTB for the first time tested an alternative calibration procedure for the reference RT. This calibration was similar to the NRLM procedure based on the measurements of the relative spectral responsivity of the RT and the photocurrent signal at one fixed-point of the ITS-90. To evaluate the potential of this method the NRLM copper point blackbody was used to determine the reference value of the spectral responsivity. Both PTB calibration methods agreed within ± 0.3 °C in the temperature range of the comparison. The difference between NRLM and PTB was 0.1 °C at 1000 °C and less than 1 °C at 2300 °C. PTB's RT predicted higher temperatures than NRLM's RT, which was also observed in 1993.

C. NIST

In September 1995, the comparison was carried out with the graphite blackbody from 900 °C to 2700 °C. The difference of NIST and NRLM RTs was not reproducible. The preliminary result for the difference in the RTs is about 1 °C at 1000 °C and about 2 °C at 2000 °C. In February 1996, RT 019 and a copper point blackbody were brought to NIST instead of RT 173, and a comparison was done from 1000 °C to 2700 °C. These preliminary results were also not reproducible, as in the September 1995 measurements. In December 1996, RT 019 and a copper point blackbody were brought to NIST and the comparison was done from 1000 °C to 2700 °C with a larger separation between RT 019 and the blackbody. The preliminary results were satisfactory, with the difference less than 1 °C at 2700 °C. The reason for the unsatisfactory results in 1995 and 1996 is not clear, but may be due to instability in the NRLM RT at NIST. The NIST RT was consistent with respect to the NIST standard sources for the entire measurement sequence.

CONCLUSION

Intercomparisons of radiation thermometer scales between five national institutes over four years have been described. The first intercomparison using 0.65 μm RT in 1993 was encouraging, especially for the first experiment. Comparisons using 0.9 μm RTs in 1994 and 1995 demonstrated that the temperature range could be extended. The second intercomparison at 0.65 μm showed agreement of 1 °C in temperature up to 2800 °C.

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