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Radiance Temperatures (at 658 and 898 nm) of Niobium at Its Melting Point[1]

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Radiance temperatures (at 658 and 898 nm) of niobium at its melting point were measured by a pulse-heating technique. A current pulse of subsecond duration was imparted to a niobium strip and the initial part of the melting plateau was measured by high-speed pyrometry. Experiments were performed with two techniques and the results do not indicate any dependence of radiance temperature (at the melting point) on initial surface or system operational conditions. The average radiance temperature at the melting point of niobium is 2420 K at 658 nm and 2288 K at 898 nm, with a standard deviation of 0.4 K at 658 nm and 0.3–0.6 K at 898 nm (depending on the technique used). The total uncertainty in radiance temperature is estimated to be not more than ± 6 K. The results are in good agreement with earlier measurements at the National Institute of Standards and Technology (USA) and confirm that both radiance temperature and normal spectral emissivity (of niobium at its melting point) decrease with increasing wavelength in the region 500–900 nm.

KEY WORDS: high-speed pyrometry; high temperature; melting; niobium; normal spectral emissivity; pulse heating; radiance temperature.

1. INTRODUCTION

A pulse technique for the measurement of the radiance temperature of metals at their melting point was described by Cezairliyan in 1973, reporting results on niobium at 0.65 μm [1]. During a 20-year period, measurements on many metals at different wavelengths using this technique were

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performed as a joint research effort between the National Institute of Standards and Technology (NIST, USA) and the Istituto di Metrologia "G. Colonnetti" (IMGC, Italy). A comprehensive review of this joint effort was presented recently [2], summarizing the experimental results obtained both at NIST and at IMGC and suggesting the use of radiance temperature and of normal spectral emissivity of selected metals at their melting point as possible reference values.

Recent controversial results on the normal spectral emissivity of metals at their melting point obtained by a major research laboratory [3] suggested the necessity to perform additional measurements of the radiance temperature of niobium at its melting point, both to verify and to extend the earlier results [1].

This paper presents results obtained at IMGC on niobium, with measurements performed both near 0.65 μm and near 0.9 μm. The measurements at 658 nm were performed in 1980–1981 and confirmed the earlier results of Cezairliyan [1]. The measurements at 898 nm were performed recently using both the conventional technique and a new measurement technique, described in detail in the preceding paper [4].

The method is based on rapid resistive self-heating of the strip specimen from room temperature to its melting point in less than 1 s by the passage of an electrical current pulse through it and on measuring the specimen radiance temperature with a high-speed pyrometer. The measurements at 658 nm were performed with a microsecond-resolution pyrometer [5]; the bandwidth of the interference filter was 50 nm, and the circular area viewed by the pyrometer was 0.8 mm in diameter. The measurements at 898 nm were performed with a millisecond-resolution pyrometer [6]; the bandwidth of the interference filter was 82 nm, and the circular area viewed by the pyrometer was 0.3 mm in diameter. Details regarding the basic construction and operation of the pyrometers and of the IMGC measurement system are given in earlier publications [7, 8].

The conventional technique of measurement consists of a one-shot pulse experiment where the specimen is destroyed each time. With the new technique [4], the current pulse is interrupted during the melting plateau before the specimen collapses, and repeated melting plateaus are possible with the same specimen. This new technique is particularly useful for materials that are not well annealed and contain residual stresses that disturb one-shot meltings.

2. MEASUREMENTS

The measurements of the radiance temperature of niobium at its melting point were performed on 29 specimens (13 at 658 nm and 16 at

898 nm). The material was obtained from two manufacturers: the measurements at 658 nm were performed on a material (hereafter labeled M1) 99.9+% pure. The manufacturer's typical analysis for material M1 indicated the presence of the following impurities (ppm by weight): Ta, 210; Hf and W, <100 each; Fe, Mo, and Zr, <50 each; Al, Ca, Cr, Co, Cu, Mg, Mn, Ni, Pb, Si, Sn, Ti, and V, <20 each; Cd, <5; O, 42; N, 25; and H, 5.

Some of the experiments at 898 nm were also performed on material M1. The rest of the measurements at 898 nm (including repeated experiments on five specimens) were performed on another material (hereafter labeled M2), 99.9% pure, obtained from a different source. The manufacturer's typical analysis for material M2 indicated the presence of the following impurities (ppm by weight): Ta, 2000; Fe, 200; Ti, 30; O, 100; N and C, 50 each; and H, 5.

Material M1 was obtained from the Subsecond Thermophysics Group of NIST and is the same material used at NIST for the measurement of the radiance temperature of niobium at its melting point [1, 9].

The specimens were in the form of strips with the following nominal dimensions: length, 25–50 mm; width, 6.3 mm; and thickness, 0.13 and 0.25 mm. Before the experiments performed with the conventional technique, the surface of most of the specimens was treated using an abrasive; different grades of abrasive were used, yielding three different surface roughnesses (ranging from approximately 0.2 to 0.5 μm in rms value) for different specimens. In some experiments, specimens with "as-received" surface conditions (approximately 0.1 μm in rms value) were also used. All the specimens used with the conventional technique were destroyed during melting at the end of the experiment.

Some of the specimens used for the experiments at 898 nm were not treated with abrasive. These measurements were performed with a different technique, in which several melting plateaus are possible using the same specimen [4]. In this new technique the surface structure of the specimen is permanently modified in the first melting, which is reached by gradually increasing the duration of the current pulse until the melting plateau appears. Consequently the repeated melting plateaus are measured on a surface different from the original one, and the original conditions of the specimen are of limited importance [4].

All the experiments described in this work were performed with the specimen in vacuum at approximately 10^{-3} Pa. Additional experiments were performed in argon at atmospheric pressure and with specimens of different thicknesses. Details of these complementary measurements are reported in another publication [4]. The heating rate for different specimens (just before their melting) was in the range 1600–4650 $K \cdot s^{-1}$.

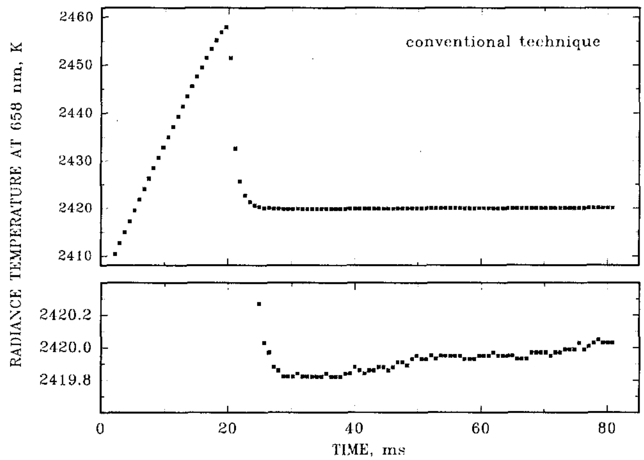

Fig. 1. Variation of radiance temperature (at 658 nm) as a function of time near and at the melting point of niobium for a typical experiment with the conventional technique (specimen 4). One temperature of five is plotted.

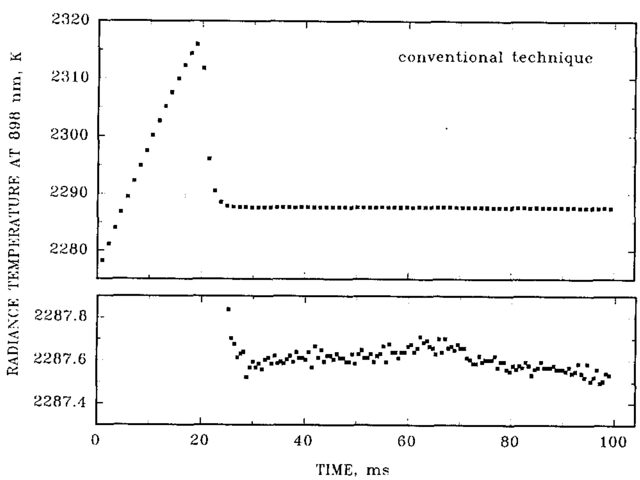

Fig. 2. Variation of radiance temperature (at 898 nm) as a function of time near and at the melting point of niobium for a typical experiment with the conventional technique (specimen 9). In the upper graph, 1 temperature of 120 is plotted; in the lower graph, 1 temperature of 60 is plotted.

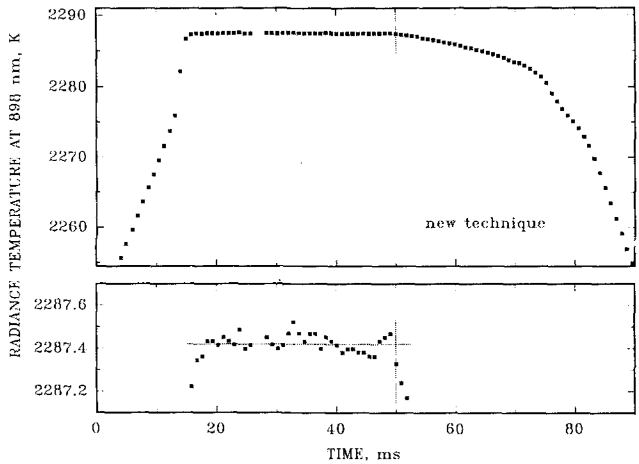

Fig. 3. Variation of radiance temperature (at 898 nm) as a function of time near and at the melting point of niobium for a typical experiment with the new technique (specimen 3, experiment 3-S1). All temperatures are plotted; the data gap in the initial part of the plateau is due to the suppression of data caused by electromagnetic inteference from the switch coil. The vertical dashed line indicates the time of current interruption.

Variation of the radiance temperature as a function of time near and at the melting point of niobium for typical experiments is presented in Fig. 1 (658 nm, conventional technique), in Fig. 2 (898 nm, conventional technique), and in Fig. 3 (898 nm, new technique). For specimens treated with abrasive (Figs. 1 and 2), the magnitude of the spikes before the melting plateau is probably related to the degree of initial surface roughness of the specimen. The peak temperatures of the spikes were higher than the plateau temperatures in various experiments by about 3–40 K. However, regardless of the magnitude of the spikes, the radiance temperature at the melting plateau is approximately the same for all the specimens at a given wavelength.

3. EXPERIMENTAL RESULTS

All temperatures reported in this paper are based on the International Temperature Scale of 1990 (ITS-90) [10]. Measurements at 658 nm performed several years ago were done according to IPTS-68 [11]; experimental results were converted as necessary to ITS-90.

For experiments performed with the conventional technique, the radiance temperature of niobium at its melting point and other pertinent

Table I. Summary of Measurements of the Radiance Temperature (at 658 nm) of Niobium During Melting (Conventional Technique)

		Premelting period		Melting period				
Specimen No.[a]	Surface roughness[b]	Heating rate $(K \cdot s^{-1})$[c]	SD (K)[d]	Number of temperatures[e]	Slope at plateau $(K \cdot s^{-1})$[f]	Plateau temperature difference (K)[g]	Radiance temperature (K)[h]	SD (K)[i]
1	C	2800	0.1	737	1.8	0.2	2419.6	0.1
2	C	3700	0.1	322	6.5	0.3	2420.1	0.1
3	B	3300	0.1	299	8.2	0.4	2420.3	0.1
4	B	3000	0.1	375	4.0	0.2	2419.9	0.1
5	C	4200	0.1	270	3.2	0.1	2419.6	0.1
6	D	3000	0.1	519	5.1	0.4	2420.0	0.1
7	A	3400	0.1	372	9.9	0.6	2420.0	0.2
8	D	2800	0.1	776	10.8	1.3	2420.7	0.4
9	A	4100	0.1	276	8.5	0.4	2420.0	0.1
10	D	3400	0.1	400	9.2	0.6	2420.3	0.2
11	B	1600	0.1	262	−0.7	−0.1	2419.7	0.1
12	A	1900	0.1	727	5.7	1.3	2420.9	0.5
13	A	1700	0.1	133	3.6	0.1	2420.2	0.1

[a] Also represents the experiments in chronological order.

[b] The notations used for surface conditions correspond to the following typical roughnesses (rms) in μm: A, 0.1; B, 0.2; C, 0.4; and D, 0.5.

[c] Heating rate evaluated at a temperature approximately 15 K below the plateau temperature.

[d] Standard deviation of an individual temperature as computed from the difference between the measured value and that from the smooth temperature versus time function quadratic) obtained by the least-squares method. Data extend approximately 30 K below the melting point.

[e] Number of temperatures used in averaging the results at the plateau to obtain an average value for the radiance temperature at the melting point of the specimen.

[f] Derivative of the temperature versus time function obtained by fitting the temperature data at the plateau to a linear function in time using the least-squares method.

[g] Maximum radiance temperature difference between the beginning and the end of the plateau based on the linear temperature versus time function.

[h] The average (for a specimen) of measured radiance temperatures at the plateau.

[i] Standard deviation of an individual temperature as computed from the difference between the measured value and the average plateau radiance temperature.

results corresponding to wavelengths 658 and 898 nm are presented in Tables I and II, respectively. For experiments performed at 898 nm with the new technique, Table III presents a summary of the radiance temperature of niobium at its melting point obtained in repeated experiments on different specimens, and Table IV presents detailed experimental results for a typical specimen.

A single value for the radiance temperature at the plateau was obtained by averaging the temperatures at the plateau. An overview of the most significant experimental results obtained in these measurements is presented in Table V. The final results corresponding to measurements at the two wavelengths are summarized in the following discussion.

3.1. At 658 nm

The average radiance temperature at the melting point for 13 niobium specimens (conventional technique) is 2420.1 K with a standard deviation of 0.4 K and a maximum absolute deviation of 1.3 K. The results are presented in Fig. 4. It may be concluded that the radiance temperature (at 658 nm) of niobium at its melting point is 2420 K.

3.2. At 898 nm

For measurements performed with the conventional technique (specimen destroyed in each experiment), the average radiance temperature at the melting point for nine niobium specimens is 2287.8 K, with a

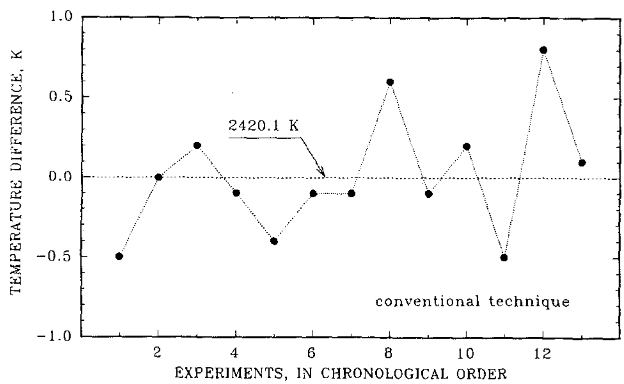

Fig. 4. Difference in radiance temperature (at the melting point of niobium, at 658 nm) for individual experiments from their average value of 2420.1 K. Experiments performed with the conventional technique.

Table II. Summary of Measurements of the Radiance Temperature (at 898 nm) of Niobium During Melting (Conventional Technique)

		Premelting period		Melting period				
Specimen No.[a]	Surface roughness[b]	Heating rate $(K \cdot s^{-1})$[c]	SD (K)[d]	Number of temperatures[e]	Slope at plateau $(K \cdot s^{-1})$[f]	Plateau temperature difference (K)[g]	Radiance temperature (K)[h]	SD (K)[i]
1	C	4650	0.2	3600	0.0	0.0	2287.7	0.2
2	C	4370	0.2	460	−44.7	−0.2	2287.8	0.2
3	A	4030	0.3	10200	6.2	0.6	2288.2	0.3
4	A	3920	0.2	5600	−5.7	−0.3	2288.0	0.1
5	A	3420	0.2	5700	−2.8	−0.2	2288.3	0.1
6	C	3510	0.3	6900	−5.8	−0.4	2287.7	0.1
7	A	3930	0.1	11050	−3.0	−0.4	2287.7	0.1
8	A	3350	0.2	2800	−1.9	0.1	2287.5	0.1
9	C	3340	0.1	7000	−1.1	−0.1	2287.6	0.1

[a] Also represents the experiments in chronological order.
[b] The notations used for surface conditions correspond to the following typical roughnesses (rms) in μm: A, 0.1; and C, 0.4.
[c] Heating rate evaluated at a temperature approximately 10 K below the plateau temperature.
[d] Standard deviation of an individual temperature as computed from the difference between the measured value and that from the smooth temperature versus time function (quadratic) obtained by the least-squares method. Data extend approximately 200 K below the melting point.
[e] Number of temperatures used in averaging the results at the plateau to obtain an average value for the radiance temperature at the melting point of the specimen.
[f] Derivative of the temperature versus time function obtained by fitting the temperature data at the plateau to a linear function in time using the least-squares method.
[g] Maximum radiance temperature difference between the beginning and the end of the plateau based on the linear temperature versus time function.
[h] The average (for a specimen) of measured radiance temperatures at the plateau.
[i] Standard deviation of an individual temperature as computed from the difference between the measured value and the average plateau radiance temperature.

Table III. Summary of Experiments Performed to Determine the Radiance Temperature (at 898 nm) of Niobium at Its Melting Point (New Technique) (All Temperatures in K)

Experiment No.[a]	Specimen 1[b]	Specimen 2	Specimen 3[c]		Specimen 4	Specimen 5[c]		Specimen 6[c]		Specimen 7[c]	
			First set	Second set		First set	Second set	First set	Second set	First set	Second set
1	2288.3	2287.3	2287.5	2287.0	2286.2	2287.3	2287.6	2288.1	2287.5	2286.1	2288.4
2	2288.2	2287.2	2287.6	2287.0	2286.1	2287.4	2287.5	2288.0	2287.7	2287.3	2288.3
3	2288.3	2287.3	2287.5	2287.1	2286.4	2287.4	2287.5	2288.0	2287.5	2287.3	2288.2
4	2288.0	2287.2	2287.5	2287.1	2286.4	2287.4			2287.6	2287.1	2288.4
5	2288.0	2287.2	2287.4	2287.1	2286.4	2287.8					2288.4
6	2288.1	2287.3	2287.5		2286.4	2287.9					
7		2287.0	2287.4		2287.2						
8			2287.4								
Average (K)[d]	2288.2	2287.2	2287.5	2287.1	2286.4	2287.5	2287.5	2288.0	2287.6	2287.0	2288.3
SD (K)[e]	0.14	0.11	0.07	0.05	0.36	0.25	0.06	0.06	0.10	0.57	0.09
Material[f]	M2	M2	M2		M2	M1		M1		M2	

[a] The experiment number refers to repeated experiments performed under the same conditions and also represents the chronological order.
[b] The specimen number identifies each specimen and also represents the chronological order.
[c] For some specimens experiments were performed in two data sets with different calibrations.
[d] The average (for each data set) of radiance temperatures measured under identical conditions.
[e] Standard deviation of each data set of radiance temperatures measured under identical conditions.
[f] Experiments were performed with materials from two different sources.

Table IV. Summary of Typical Measurements of the Radiance Temperature (at 898 nm) of Niobium During Melting (New Technique, Repeated Meltings of Specimen 3)

	Premelting period		Melting period				
Experiment No. and set[a]	Heating rate ($K \cdot s^{-1}$)[b]	SD (K)[c]	Number of temperatures[d]	Slope at plateau ($K \cdot s^{-1}$)[e]	Plateau temperature difference (K)[f]	Radiance temperature (K)[g]	SD (K)[h]
1-S1	2065	0.2	5	0	0	2287.5	0.1
2-S1	2064	0.1	8	−17.9	−0.1	2287.6	0.1
3-S1	2064	0.1	15	−3.1	−0.1	2287.5	0.1
4-S1	2050	0.1	15	0	0	2287.5	0.1
5-S1	2097	0.1	30	−2.6	−0.1	2287.4	0.1
6-S1	2121	0.1	30	2.7	0.1	2287.5	0.1
7-S1	2156	0.2	29	0	0	2287.4	0.1
8-S1	2155	0.1	35	0	0	2287.4	0.1
9-S2	1969	0.1	27	−4.6	−0.1	2287.0	0.1
10-S2	1981	0.1	24	−6.2	−0.1	2287.0	0.1
11-S2	2159	0.1	22	−4.8	−0.1	2287.1	0.1
12-S2	2194	0.2	24	−2.0	−0.1	2287.1	0.1
13-S2	2184	0.1	24	−1.9	−0.1	2287.1	0.1

[a] Measurements were performed in two sets (S1 and S2) with different calibrations. The number represents the experiments in chronological order in each data set.
[b] Heating rate evaluated at a temperature approximately 17 K below the plateau temperature.
[c] Standard deviation of an individual temperature as computed from the difference between the measured value and that from the smooth temperature versus time function quadratic) obtained by the least-squares method. Data extend approximately 450 K below the melting point.
[d] Number of temperatures used in averaging the results at the plateau to obtain an average value for the radiance temperature at the melting point of that experiment.
[e] Derivative of the temperature versus time function obtained by fitting the temperature data at the plateau to a linear function in time using the least-squares method.
[f] Maximum radiance temperature difference between the beginning and the end of the plateau based on the linear temperature versus time function.
[g] The average (for an experiment) of measured radiance temperatures at the plateau.
[h] Standard deviation of an individual temperature as computed from the difference between the measured value and the average plateau radiance temperature.

Table V. Summary of the Most Significant Experimental Results

Experimental results	Unit	Data	Data	Data
Experiments at		658 nm	898 nm	898 nm
Measurement technique[a]		Conventional	Conventional	New
Details in		Table I	Table II	Tables III, IV
Number of temperatures at plateau[b]		133/776	460/11,050	5/35
Range of standard deviation[c]	K	0.1/0.5	0.1/0.3	0.1
Range of slopes[d]	$K \cdot s^{-1}$	−0.7/10.8	−44.7/6.2	−17.9/2.7
Range of temperature differences[e]	K	−0.1/1.3	−0.4/0.6	−0.1/0.1
Average of rad. temp. determinations[f]	K	2420.1	2287.8	2287.5
Standard deviation of determinations[g]	K	0.4	0.3	0.6
Maximum absolute deviation[h]	K	1.3	0.8	1.9

[a] Conventional, one-shot experiment with the destruction of the specimen; new, repeated meltings of the same specimen.

[b] Number of temperatures used in averaging the results at the plateau to obtain an average value for the radiance temperature at the melting point of the specimen.

[c] Range of standard deviations of an individual temperature as computed from the difference between the measured value and the average plateau radiance temperature.

[d] Range of the derivatives of the temperature versus time functions obtained by fitting the temperature data at the plateau to a linear function in time using the least-squares method.

[e] Range of the maximum radiance temperature difference between the beginning and the end of the plateau based on the linear temperature versus time function.

[f] The average (for each data set) of the plateau radiance temperature.

[g] Standard deviation (for each data set) as computed from the difference between the plateau values and their average.

[h] Maximum absolute difference (for each data set) among plateau radiance temperatures.

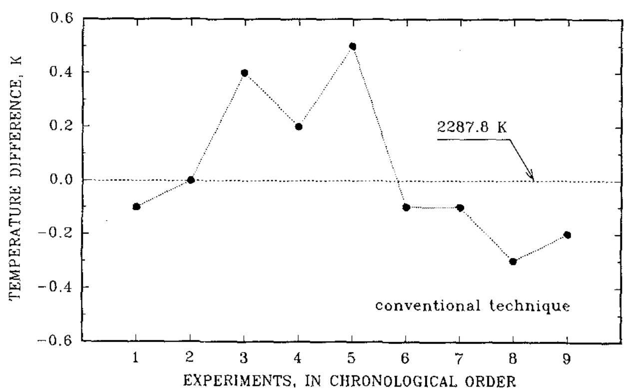

Fig. 5. Difference in radiance temperature (at the melting point of niobium, at 898 nm) for individual experiments from their average value of 2287.8 K. Experiments performed with the conventional technique.

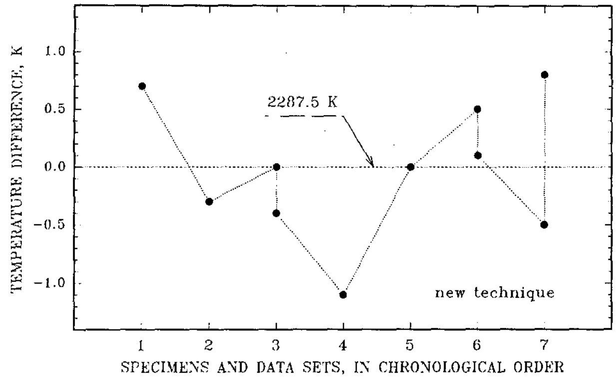

Fig. 6. Difference in radiance temperature (at the melting point of niobium, at 898 nm) for individual data sets (groups of repeated experiments in identical conditions) from their average value of 2287.5 K. Experiments performed with the new technique.

standard deviation of 0.3 K and a maximum absolute deviation of 0.8 K. The results for the conventional technique are presented in Fig. 5.

Measurements performed with the new technique were divided in groups of repeated experiments on the same specimen in the same conditions, called data sets. For these measurements the average radiance temperature at the melting point for seven niobium specimens (11 data sets, 58 experiments) in 2287.5 K, with a standard deviation of 0.6 K and a maximum absolute deviation of 1.9 K. The results for the new technique are presented in Fig. 6.

Considering the results obtained with the two measurement techniques, it may be concluded that the radiance temperature (at 898 nm) of niobium at its melting point is 2288 K.

4. ESTIMATE OF UNCERTAINTY

The details of sources and estimates of uncertainties in temperature measurements in high-speed experiments using the IMGC system are given in earlier publications [5, 6, 8]. Specific items in the uncertainty analysis were recomputed whenever the present operational conditions differed from those in the earlier studies.

The uncertainty resulting from the monochromatic operation of the pyrometers at the various wavelengths is estimated to be no more than 4 K. Additional uncertainties that may result from misalignment and specimen behavior during melting are estimated to be less than 3 K. The effect of the impurities in the specimen is estimated to contribute less than

2 K. It may be concluded that the uncertainty in the reported radiance temperatures (at 658 and 898 nm) of niobium at its melting point is not more than ± 6 K.

5. DISCUSSION

The present results have shown the constancy and the reproducibility of the radiance temperature of niobium at its melting point for a number of specimens with different initial conditions in experiments performed under different operational conditions. Experiments performed with two measurement techniques (conventional and new) provided similar results, with the difference between the two techniques (0.3 K) being of the same order of magnitude of the standard deviation of measurements with each technique (conventional technique, 0.3 K with 9 experiments; new technique, 0.6 K with 58 experiments).

Some of the experimental results discussed in detail in this work were reported in earlier papers [2, 9, 12] as unpublished data. The data presented here are identical for experiments at 658 nm (performed several years ago), while a small correction (less than 1 K) has been applied to the data at 898 nm, due to effective wavelength calibrations of the pyrometers that were performed recently and were not available at the time of the earlier publications.

A detailed survey of the literature results on the radiance temperature and normal spectral emissivity of niobium at its melting point was presented recently by the research group at NIST, while discussing results obtained by high-speed multiwavelength pyrometry [9]. This survey included a partial summary of the present results (as unpublished data). A further discussion of the literature results seems unnecessary, since no new results have been published in the meantime. But it is useful to review briefly the data obtained on the radiance temperature and on the normal spectral emissivity of niobium at its melting point both at NIST and at IMGC for the following reasons:

(a) the results were obtained over a 20-year period;

(b) experiments were performed with two systems, making use of four high-speed pyrometers of different characteristics;

(c) pyrometers were operated monochromatically at different wavelengths (range, 500–900 nm);

(d) the calibration schemes of the pyrometers were widely different; and

(e) the results were obtained on niobium from two sources and part of the experiments were performed according to two techniques (conventional and new).

Figure 7 presents the most recent NIST–IMGC results on the wavelength dependence of the radiance temperature of niobium at its melting point. The straight line is a least-squares fit of recent NIST multiwavelength pyrometry results [9], with the circles being the results of the present work (filled circle, conventional technique; open circle, new technique). The same data are presented on a more sensitive scale in the two small graphs on the right-hand side, for the wavelength regions near 0.65 and 0.9 μm.

Assuming 2749 K for the melting point of niobium on ITS-90 [13], the normal spectral emissivity of niobium at its melting point may be computed from the radiance temperature data. The results are presented in Fig. 8, which includes all the measurements performed at NIST (open and filled squares) and at IMGC (open and filled circles) over a 20-year period. The data at 650 nm were measured at NIST in 1973 and those at 658 nm were measured at IMGC in 1980, while the rest are more recent measurements (after 1990) at both laboratories. The straight line in Fig. 8 is a least-squares fit of all the data (measurements performed at both

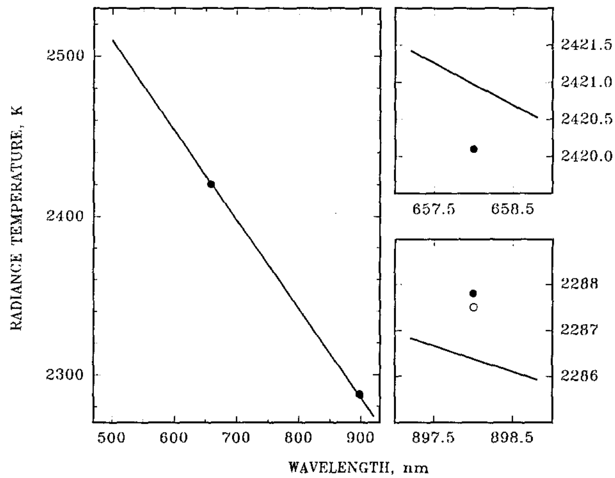

Fig. 7. Recent results on the radiance temperature of niobium at its melting point as a function of wavelength. The results of the present work (●, conventional technique; ○, new technique) are compared with a least-squares fit (straight line) of data obtained recently at NIST by high-speed multiwavelength pyrometry (from Ref. 9). The graphs on the right give details in the wavelength regions near 0.65 and 0.9 μm.

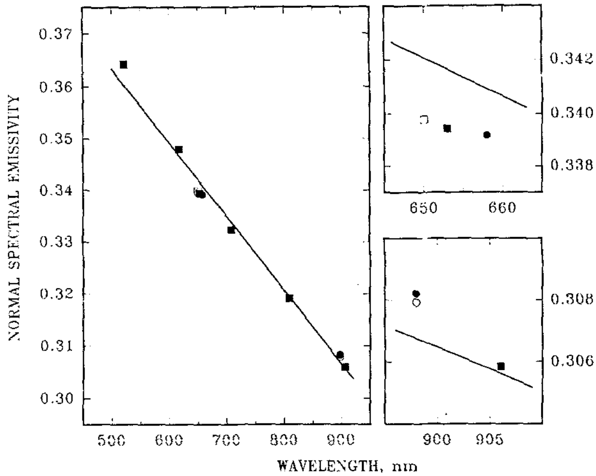

Fig. 8. Results obtained at NIST (□, from Ref. 1; ■, from Ref. 9) and at IMGC (this work; ●, conventional technique; ○, new technique) on the normal spectral emissivity of niobium at its melting point as a function of wavelength. The straight line is a least-squares fit of all the data from both laboratories. Details for the wavelength regions near 0.65 and 0.9 μm are shown in the graphs on the right.

laboratories). From this figure, it is clear that the experimental results both at NIST and at IMGC indicate a pronounced negative slope for the wavelength dependence of the normal spectral emissivity of niobium at its melting point in the range 500–900 nm.

6. CONCLUSIONS

The experimental results of this work confirm the data obtained at NIST on the radiance temperature of niobium at its melting point. The analysis of the normal spectral emissivity of niobium at its melting point, taking into account all measurements performed at NIST and at IMGC in the last 20-years, shows a pronounced negative dependence on wavelength in the range 500–900 nm.

A new measurement technique to perform repeated measurements at the melting point using the same specimen was demonstrated, with experimental results not differing from those obtained in experiments where the specimen is destroyed. The main advantage of this new technique is the possibility of repeated use of the same specimen at different times, eliminating the uncertainties due to specimen behavior in repeated in-situ checks of complex experimental apparatus.

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