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Radiance Temperatures (in the Wavelength Range 519–906 nm) of Tungsten at Its Melting Point by a Pulse-Heating Technique[1]

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Radiance temperatures (at six wavelengths in the range 519–906 nm) of tungsten at its melting point were measured by a pulse-heating technique. The method is based on rapid resistive self-heating of the specimen from room temperature to its melting point in less than 1 s; and on simultaneously measuring the specimen radiance temperatures every 0.5 ms with a high-speed six-wavelength pyrometer. Melting was manifested by a plateau in the radiance temperature versus time function for each wavelength. The melting-point radiance temperatures for a given specimen were determined by averaging the measured temperatures along the plateau at each wavelength. The melting-point radiance temperatures for tungsten were determined by averaging the results at each wavelength for 10 specimens (standard deviation in the range 0.5–1.1 K, depending on the wavelength) as follows: 3319 K at 519 nm, 3236 K at 615 nm, 3207 K at 652 nm, 3157 K at 707 nm, 3078 K at 808 nm, and 2995 K at 906 nm. Based on estimates of the random and systematic errors arising from pyrometry and specimen conditions, the total uncertainty in the reported values is about ± 7 K at 653 nm and ± 8 K at the other wavelengths.

KEY WORDS: emissivity; high-speed pyrometry; high-temperature fixed points; melting; multiwavelength pyrometry; radiance temperatures.

1. INTRODUCTION

Earlier measurements, performed at the National Institute of Standards and Technology (NIST) and at the Istituto di Metrologia "G. Colonnetti"

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(IMGC), have indicated that the radiance temperature[3] of a metal at its melting point is essentially constant during the initial melting period and is highly reproducible [1]. These findings suggested that melting-point radiance temperatures of selected metals may provide easily realizable high-temperature references for secondary calibrations of optical pyrometers and for *in situ* checks on complicated measurement systems at high temperatures. However, the earlier measurements of radiance temperature were performed only at wavelengths near 650 and 1000 nm and on a limited number of metals. Since pyrometers generally operate at wavelengths in the range 400–1000 nm, such applications would require an accurate knowledge of melting-point radiance temperatures of the selected metals throughout this wavelength range.

In an effort to explore this possibility, a high-speed multiwavelength pyrometer [2] capable of simultaneously measuring radiance temperatures at six wavelengths was constructed at NIST. Subsequently, the pyrometer was used to measure the melting-point radiance temperatures (at six wavelengths nominally in the range 500–900 nm) of niobium [3] and of molybdenum [4]. It was found that, for both metals, the radiance temperature at each wavelength is essentially constant during the initial melting period and very reproducible for different specimens of the given metal, to within about ± 1 K.

The present paper describes similar measurements, performed with the six-wavelength pyrometer, of radiance temperatures of tungsten at its melting point. The measurement method is based on passing a large electrical current pulse through the specimen causing it to undergo rapid resistive self-heating from room temperature to its melting point in less than 1 s, while measuring simultaneously the specimen radiance temperatures at the six wavelengths every 0.5 ms. The melting-point radiance temperatures for a given specimen were determined by averaging the measured temperatures along the plateau in the radiance temperature versus time function for each wavelength. The melting-point radiance temperatures for tungsten were determined by averaging the results for 10 specimens.

2. MEASUREMENT SYSTEM

The high-speed measurement system used in the present work consists of a pulse-heating system, a high-speed six-wavelength pyrometer, and a

[3] Radiance temperature (sometimes referred to as brightness temperature) of the specimen surface is the temperature at which a blackbody has the same radiance as the surface, corresponding to the effective wavelength of the measuring pyrometer.

digital data acquisition system. Details concerning the design, construction, and operation of the basic pulse-heating system are given in earlier publications [5, 6].

The high-speed six-wavelength pyrometer [2] is capable of measuring radiance temperatures of a rapidly heating specimen with a time response less than 20 μs. The pyrometer lens system focuses the radiance from a circular target area (0.5-mm diameter) on the specimen onto the head of a fiber-optic bundle, which is randomly hexfurcated in order to distribute nearly equal fractions of target radiance among six channels. In each channel, the radiance is directed through an interference filter onto a silicon photodiode and the photocurrent from the diode is converted by a high-stability amplifier to a proportionate voltage. The principal channel upon which the pyrometer calibration is based has a bandwidth of 26 nm centered at 652 nm; the bandwidths of the other five channels, centered nominally at 500, 600, 700, 800, and 900 nm, are in the range 54–74 nm.

The digital data acquisition system consists of (i) six track-and-hold amplifiers to read simultaneously the voltage signals from the six pyrometer channels at selectable rates up to 15 kHz and (ii) a high-speed voltmeter to scan rapidly the track-and-hold amplifiers, digitize the analog signals with 13-bit (12 bits plus sign) resolution, and store the digital data in its memory (64 kbytes).

3. MEASUREMENTS

The measurements of radiance temperature of tungsten at its melting point were performed on 10 specimens in the form of strips. The tungsten strips were cut from a sheet that had been rolled from a bar manufactured by a powder metallurgy technique. The manufacturer's typical analysis of the powder indicated the presence of the following impurities (ppm, by weight): Ni, 16; Fe, 12; Al, Cr, Mn, Si, and Sn, 6 each; and Ca, Cu, and Mn, 3 each. The purity of the tungsten in its final form (sheet) was reported to be 99.95%.

The nominal dimensions of the strips were as follows: length, 50 mm; width, 6.5 mm; and thickness, 0.25 mm. The surfaces of the specimens were mechanically abraded in order to remove possible surface contaminants. Three different grades of abrasive were used, yielding surface roughnesses of approximately 0.2, 0.4, and 0.5 μm. A few experiments were also performed on specimens with "as received" surface conditions (approximately 0.1 μm in roughness).

Prior to the pulse-heating experiments, the six-wavelength pyrometer was calibrated in two steps. First, the 652-nm channel was calibrated with a secondary standard (tungsten-filament lamp) which, in turn, had been calibrated by the Radiometric Physics Division at NIST. Then the temperature calibration of the 652-nm channel was used to calibrate the other five channels by performing (steady-state) measurements on a graphite tube blackbody furnace. All temperatures reported in this paper, except where explicitly noted otherwise, are based on the International Temperature Scale of 1990 (ITS-90) [7].

In preparation for pulse heating, each specimen strip was mounted vertically between two electrodes inside the experiment chamber; the upper electrode is stationary, whereas the lower electrode is attached to a flexible connection to allow for thermal expansion of the specimen during heating. The chamber was evacuated and then filled with argon gas at a pressure of approximately 0.1 MPa in order to minimize evaporation of the tungsten specimen at high temperatures. Adjustments were made to the battery bank voltage and to a resistor in series with the specimen in the pulse-heating circuit in order to achieve the desired heating rate. The specimen was then rapidly heated from room temperature to its melting point in less than 1 s by passing a large electrical current pulse through it. The heating periods, from room temperature to the melting point, ranged from about 300 to 600 ms in duration. During the experiment, the six pyrometer signals were digitized and recorded simultaneously every 0.5 ms by the data acquisition system. After the experiment, the recorded data were transferred to a minicomputer for subsequent analyses to determine the radiance temperatures.

Figure 1 illustrates the variation of radiance temperature corre-

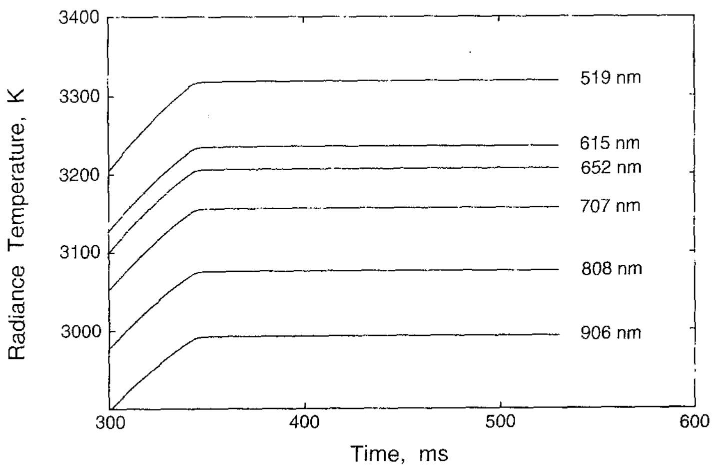

Fig. 1. Variation of the radiance temperatures of a tungsten strip specimen just before and during melting as measured by the six-wavelength pyrometer. The effective wavelength, shown for each channel, was determined by the method of Kostkowski and Lee [8].

sponding to six effective wavelengths as a function of time near and at the melting point of tungsten during a typical pulse-heating experiment. The effective wavelength for each pyrometer channel was determined at the respective radiance temperatures, following the method of Kostkowski and Lee [8]. The melting of the specimen is manifested by a plateau in the radiance versus time function at each wavelength. A more detailed view of the plateau region, presented in Fig. 2, indicates that the plateau radiance

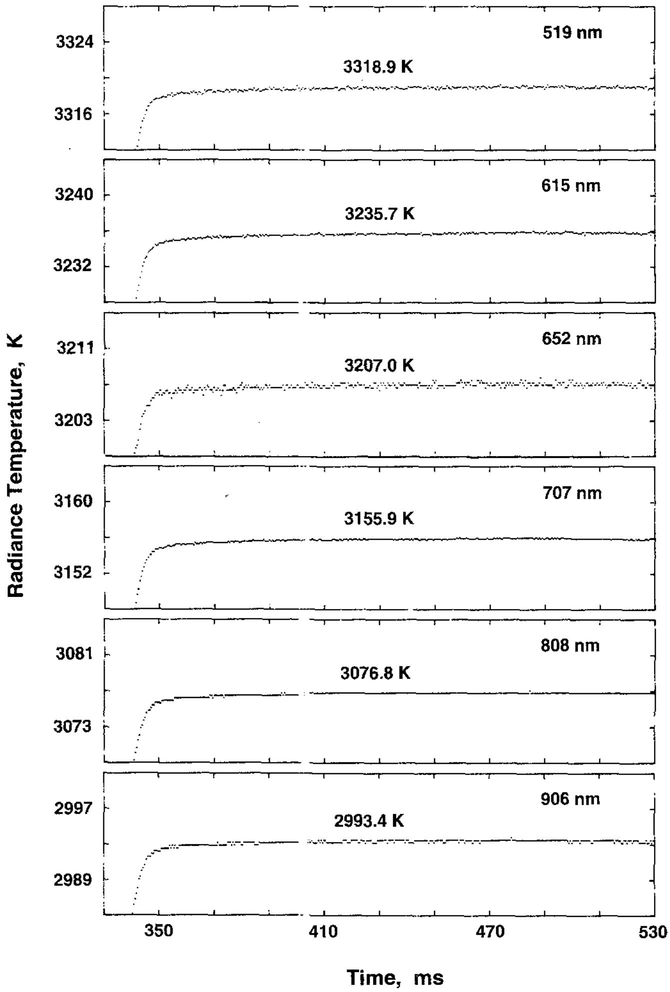

Fig. 2. Expanded plot of the radiance temperature versus time functions shown in Fig. 1. Each labeled temperature indicates the average temperature along the plateau, i.e., the melting-point radiance temperature at a given wavelength.

temperature is essentially constant at each wavelength with a temperature difference between the beginning and the end of the plateau of less than 1 K. Experiments on specimens with an "as received" surface yielded poorly formed plateaus approximately 2 K higher than those obtained from specimens treated with an abrasive, suggesting the possible existence of contaminants (oxides, nitrides, etc.) on the "as received" surfaces. Thus, the data from the latter experiments were not included in the analysis to obtain the final results.

4. RESULTS

Pulse-heating experiments were carried out on 10 tungsten specimens. For a given specimen, the plateau radiance temperature, at each effective wavelength, was determined by averaging the measured temperatures along the flat portion of the corresponding plateau. The number of temperatures used for averaging ranged from 201 to 741, depending on the heating rate and the behavior of the specimen during melting. The standard deviation of an individual temperature from the average is in the range 0.1–0.5 K for all 10 experiments.

The trend of radiance temperature along each plateau was determined by fitting the measured temperatures by a linear function of time with the least-squares method. The slope of the linear function takes values between -5.1 and $12.3\ K \cdot s^{-1}$. The temperature difference between the beginning and end of the plateau, as determined from this slope, is in the range -1.5 to 1.2 K.

The specimen heating rates were determined by fitting linear functions of time to the radiance temperatures measured during the premelting period. The heating rates (slopes of the linear functions approximately 15 K below the melting plateaus) range from 440 to $2290\ K \cdot s^{-1}$. The plateau radiance temperatures (corresponding to 10 specimens/experiments) at each effective wavelength are plotted against heating rate in Fig. 3. As may be seen, the plateau radiance temperature does not depend on the heating rate or on the initial roughness of the specimen surface.

Table I presents the final results for the radiance temperature of tungsten at its melting point that were obtained by averaging, at each effective wavelength, the values of plateau radiance temperature for each of the 10 specimens. The standard deviation of an individual plateau radiance temperature from the average is in the range 0.5–1.1 K, depending on the wavelength, and the maximum absolute deviation is 1.4 K. Also given in Table I are the corresponding values for the normal spectral emissivity of tungsten at its melting point that were calculated by means of Planck's law, based on the present results for radiance temperature and the value 3693 K for the melting point of tungsten [9]. This value for true melting temperature of tungsten was measured about two decades ago in our laboratory via subsecond pulse-heating of tubular specimens, each with a blackbody hole through the wall of the tube.

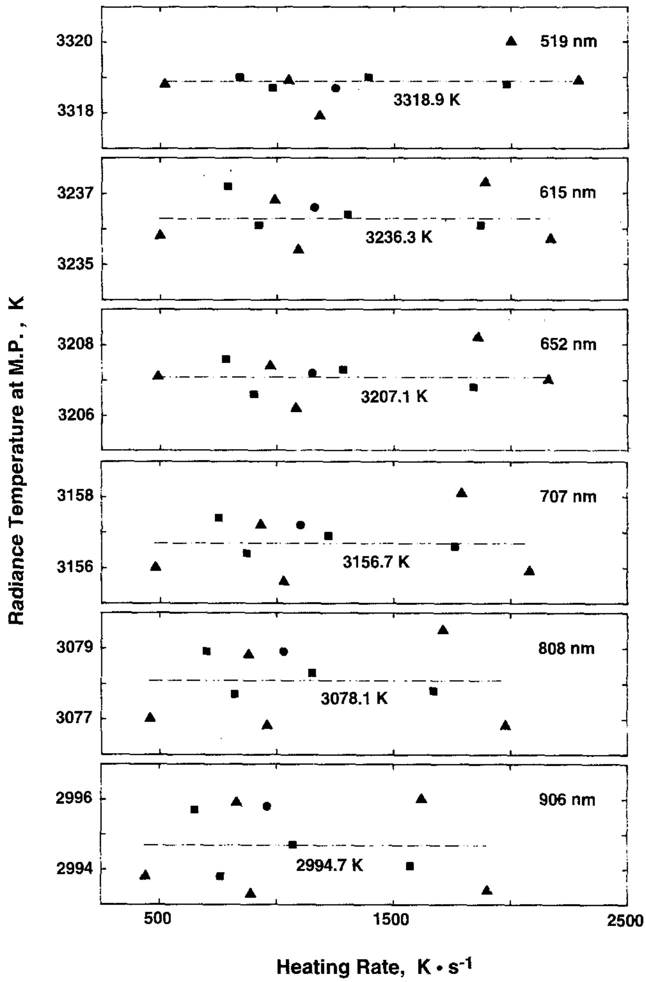

Fig. 3. Melting-point radiance temperatures as a function of the heating rate used in 10 experiments. Each dashed line and labeled temperature indicates the average melting-point radiance temperature at a given wavelength for the 10 tungsten specimens. The different symbols refer to typical surface roughness of the specimens prior to melting, as follows: ●, 0.2 μm; ■, 0.4 μm; ▲, 0.5 μm.

Table I. Final Results for the Average Radiance Temperature and Normal Spectral Emissivity, at Six Wavelengths, of Tungsten at its Melting Point

Effective wavelength (nm)[a]	Radiance temp. (K)[b]	SD (K)[c]	Max. abs. dev. (K)	Norm. spectral emissivity[d]
519	3318.9	0.5	1.1	0.429
615	3236.3	0.6	1.0	0.409
652	3207.1	0.6	1.1	0.404
707	3156.7	0.8	1.4	0.391
808	3078.1	1.0	1.4	0.380
906	2994.7	1.1	1.4	0.364

[a] Determined at the respective radiance temperature by the method of Kostkowski and Lee [8].
[b] Average of the plateau radiance temperatures at each effective wavelength for 10 tungsten specimens.
[c] Standard deviation of an individual plateau radiance temperature from the average plateau radiance temperature.
[d] Determined by means of Planck's law from the average plateau radiance temperature and the value 3693 K for the melting point of tungsten [9].

5. ESTIMATE OF ERRORS

A detailed analysis of sources and magnitudes of the random and systematic errors in temperature measurements with the six-wavelength pyrometer is given elsewhere [2]. The major error sources arise from (i) the calibration and operation of the pyrometer and from (ii) the physical/chemical conditions and melting behavior of each specimen. A summary of the estimated uncertainties in the reported radiance temperatures is presented in Table II.

6. DISCUSSION

Although the radiance temperature and normal spectral emissivity of tungsten have been studied extensively, primarily in connection with the development of tungsten strip lamps as standard radiation sources, only a few investigations have reported data at the melting point. These melting-point data are listed along with the present results in Table III. A comparison (based on ITS-90) of the literature data on radiance temperature of tungsten at its melting point with the present work is given in Fig. 4. In general, the reported values for normal spectral emissivity of tungsten at its melting point were obtained from measured surface radiance temperatures

Table II. Sources and Magnitudes of Uncertainties in the Measurement of Radiance Temperatures of Tungsten at Its Melting Point with the Six-Wavelength Pyrometer at NIST

	Uncertainty (K) at effective wavelength (nm)					
Source	519	615	652	707	808	906
Pyrometer related						
Secondary standard	3	3	3	3	3	3
Geometry differences[a]	1	1	1	1	1	1
Effective wavelength[b]	3	3	3	3	3	3
Nonlinearity[b]	0.5	0.5	0.5	0.5	0.5	0.5
Calibration transfer[b]	2	2	1	2	2	2
Radiance source align.[b]	3	3	3	3	3	3
Noise and digitization[b]	0.5	0.5	0.5	0.5	0.5	0.5
Measurements related						
Secondary std. drift	1	1	1	1	1	1
Window calibration[b]	1	1	1	1	1	1
Pyrom. calib. drift[b]	2	2	2	2	2	2
Neutral-density filter calib.[b]	3	3	3	3	3	3
Specimen impurities	2	2	2	2	2	2
Melting behavior	3	3	3	3	3	3
Total uncertainty[c]	8	8	7	8	8	8

[a] The estimated uncertainty due to differences in solid acceptance angle of the six-wavelength pyrometer and the pyrometer used by the Radiometric Physics Division to calibrate the secondary standard.

[b] These estimated uncertainties, which are somewhat dependent on wavelength, are rounded to one significant figure.

[c] The square root of the sum of squares of the various individual uncertainties.

on the basis of Planck's law or Wien's approximation and an independent knowledge of melting temperature. For intercomparison, the reported values for emissivity were adjusted to a common melting temperature (3693 K). The adjusted emissivity values are given in Table III and are also plotted as a function of wavelength in Fig. 5.

A little more than a decade ago, we used a single-wavelength high-speed (photomultiplier-based) pyrometer to measure the melting-point radiance temperature of tungsten at 653 nm, obtaining a value of 3206 K (on ITS-90) [12]. The agreement of this value with the present results is well within the measurement uncertainties involved and is particularly noteworthy since the high-speed pyrometers used in the two investigations were of very different design. Based on our earlier measurement of the true melting temperature of tungsten (3693 K on ITS-90) [9] and Planck's law,

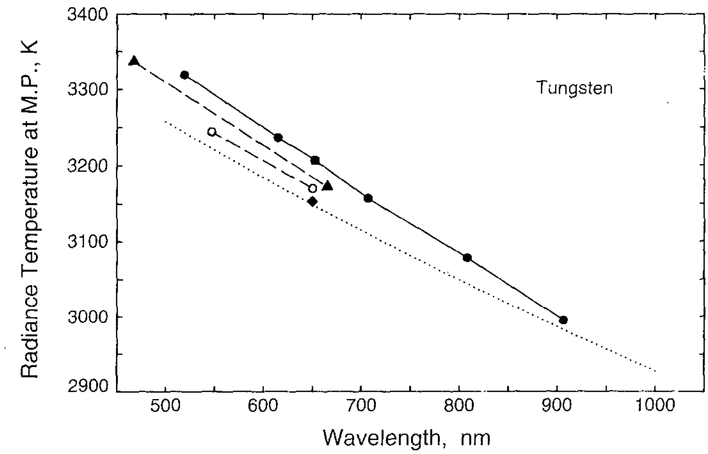

Fig. 4. Comparison (on ITS-90) of literature values and present results for the radiance temperature of tungsten at its melting point. The different symbols refer to different methods used for specimen heating, as follows: filled symbols, resistive self-heating; open symbols, electromagnetic levitation/induction heating; dotted curve, laser pulse heating. ○, Arpaci and Frohberg [13]; ▲, Worthing [10]; ■, Cezairliyan and Miiller [12]; ···, Hiernaut et al. [14]; ◆, Allen et al. [11]; ●, present work.

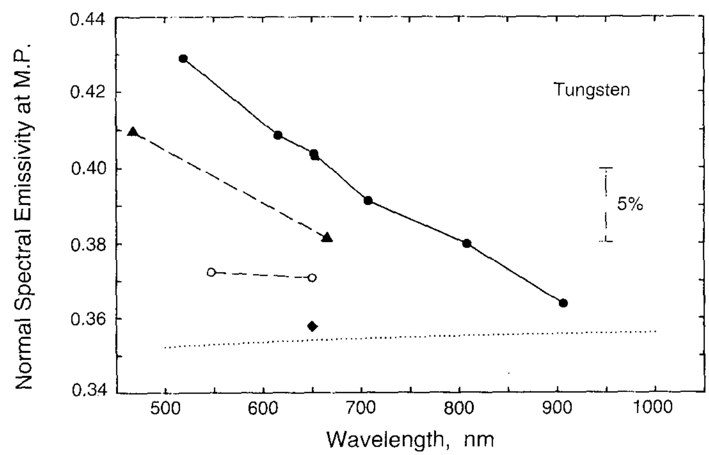

Fig. 5. Variation of the normal spectral emissivity of tungsten at its melting point as a function of wavelength. The symbol designations are the same as those given in the caption in Fig. 4. The plotted data correspond to emissivity values adjusted for a common melting temperature of 3693 K (on ITS-90) [9].

Table III. Radiance Temperatures and Normal Spectral Emissivities at Wavelengths (λ) in the Range 500–1000 nm of Tungsten at its Melting Point as Reported in the Literature

Investigator	Ref. No.	Year	Purity (wt.%)	Heating method[a]	λ (nm)	Radiance temperature (K) As reported	Radiance temperature (K) On ITS-90	Normal spectral emissivity As reported	Normal spectral emissivity Ajusted for a common m.p.[c]
Worthing	10	1917		R	467	3341 ± 15	3336 ± 15	0.434	0.409
					665	3176 ± 15	3172 ± 15	0.398	0.381
Allen et al.	11	1960	99.95	R	650	3149	3153	0.360	0.358
Cezairliyan and Miiller	12	1982	99.95	R	653	3208 ± 10	3206 ± 10	0.404	0.403
Arpaci and Frohberg	13	1984	99.9+	E	547	3245	3244	0.381	0.372
					650	3171	3170	0.378	0.371
Hiernaut et al.	14	1989	99.96	L	500		3257[b]	0.36	0.352
					650		3149[b]	0.36	0.354
					1000		2927[b]	0.36	0.356
Present work			99.95	R	519		3319 ± 8		0.429
					615		3236 ± 8		0.409
					652		3207 ± 7		0.404
					707		3157 ± 8		0.391
					808		3078 ± 8		0.380
					906		2995 ± 8		0.364

[a] Method used to heat the specimen (specimen geometry in parentheses): R, resistive self-heating (flat strip); E, electromagnetic levitation/induction heating (sphere); L, laser pulse heating (sphere).

[b] Based on the constant emissivity (0.36 for the wavelength range 500–1000 nm) and the melting temperature (3687 K on ITS-90) reported by the investigators.

[c] Adjusted values for emissivity are based on the reported melting-point radiance temperatures (on ITS-90) and a melting temperature of 3693 K (on ITS-90) for tungsten [9].

our earlier and present measurements of melting-point radiance temperatures yield respective values of 0.403 (at 653 nm) and 0.404 (at 652 nm) for the normal spectral emissivity of tungsten at its melting point.

The earliest experiments appear to be those reported by Worthing [10], who utilized conventional disappearing-filament optical pyrometry in conjunction with quasi-steady-state resistive heating of tubular specimens to measure both melting-point radiance temperatures and true melting temperature of tungsten, yielding values that are, respectively, about 20 and 25 K lower than results obtained in our laboratory. Although rather large, these differences are within the combined uncertainties for temperature measurement in the two laboratories. From his temperature measurements, Worthing obtained a melting-point emissivity of 0.398 at 665 nm, which is less than 1% below an interpolation of the present results (see Table III). This difference is exaggerated in Fig. 5 in which the "adjusted" emissivity values are presented.

Other quasi-steady-state measurements involving slow resistive heating of long thin rod specimens by Allen et al. [11] and electromagnetic levitation/induction heating of small spherical specimens by Arpaci and Frohberg [13] have yielded melting-point radiance temperatures for tungsten that are about 40 K or more lower than the present results. These large differences are possibly due to problems associated with specimen evaporation and contamination, large heat transfers, etc., which may arise when specimens are exposed to elevated temperatures for long periods of time (minutes to hours) during steady-state or quasi-steady-state experiments. A literature value for the melting temperature of tungsten (3683 K) was used in both investigations to determine emissivity of tungsten at its melting point, yielding values that are more than 6% lower than the present results.

In a recent study of several high-temperature metals (including V, Nb, Mo, Ta, and W) involving rapid laser pulse heating of small spherical specimens, Hiernaut et al. [14] used a different approach to obtain values for normal spectral emissivity ($\varepsilon_{n,\lambda}$) from measurements of specimen radiance with a high-speed six-wavelength pyrometer. They assumed $\ln \varepsilon_{n,\lambda}$ to be a linear function of wavelength and introduced this expression into Planck's radiation equation, resulting in six equations for six wavelengths. The pairwise combination of these equations leads to an overdetermined system of 15 equations from which true temperature and $\varepsilon_{n,\lambda}$ were determined by least-squares fitting techniques. Their "fitted" results indicate that $\varepsilon_{n,\lambda}$ at the melting point of not only tungsten but all the high-temperature metals studied is constant, independent of wavelength, over the wavelength range 500–1000 nm. As may be seen in Fig. 4, the radiance temperatures (dotted curve), which were calculated via Planck's law from their "fitted" results for melting temperature and emissivity of tungsten, are systematically lower (by as much as 80 K at 500 nm) than the present results. Unfortunately, Hiernaut et al. did not report any radiance temperatures, which, in principle, could have been determined from their measurements of specimen radiance.

The constant emissivity value of 0.36 reported by Hiernaut et al. for tungsten is in significant disagreement with the present results (Table I), which show that the melting-point emissivity of tungsten changes more than 15% between wavelengths 519 and 906 nm, a difference which is significantly larger than could be realistically attributed to temperature measurement error. For example, an uncertainty of 6 K in radiance temperature corresponds to an uncertainty of less than 3% in emissivity. Furthermore, a recent review [15] of literature data has concluded that the normal spectral emissivities of several high-temperature metals (Ni, Ti, V, Nb, Mo, Ta, and W) at their melting point are clearly not constant but all decrease monotonically with increasing wavelength in the range 400–1000 nm.

Two important factors that affect the measurement of radiance temperature of a specimen surface are (i) surface topology and (ii) surface contaminants (oxides, nitrides, etc.). In the present work, very reproducible results (within ± 2 K) were obtained from measurements on specimens with surfaces that had been mechanically abraded to different roughnesses. The good agreement suggests that, after the onset of melting, the surface topology was relatively independent of the initial surface roughness and that preexisting surface contaminants on the tungsten strip specimens (if any) were removed by the surface treatment. In addition, our measurements were performed at heating rates ranging from 440–2290 $K \cdot s^{-1}$, thereby exposing the specimens to elevated temperatures for short yet different durations (from several tens to a few hundred milliseconds). The excellent agreement among results obtained at different heating rates suggests that there was minimal contamination of the specimen surface by residual impurities in the argon gas environment during the short-duration experiments.

7. CONCLUDING REMARKS

The present work on tungsten has shown that pulse-heating experiments, when repeated on strip specimens, yield highly reproducible results (within ± 2 K) for the melting-point radiance temperatures at six wavelengths in the range 500–900 nm. Similar pulse experiments, performed earlier in our laboratory, on strip specimens of niobium [3] and molybdenum [4] have also yielded melting-point radiance temperatures in the same wavelength range with a similar high degree of reproducibility (± 1 K).

Because of the simplicity and ease of performing pulse experiments on metal strips, radiance temperatures at the melting point of selected metals are likely to form the necessary foundation for temperature references that can be easily realized for high-temperature optical pyrometry. This would be particularly attractive for rapid secondary calibrations of pyrometers in environments where lengthy primary calibration procedures are either undesirable or not possible (microgravity research, industrial high-temperature technologies, etc.). However, applications to conventional pyrometry (time response, 1 s or slower) would require the development of techniques for maintaining a stable specimen surface for several seconds during melting.

In order to establish secondary temperature reference points over a sufficient temperature range, accurate measurements of radiance temperature (over a wavelength range 500–1000 nm) at the melting point of several other high-temperature metals will be required.

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