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Radiance Temperature (at 653 nm) of Tungsten at Its Melting Point

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The radiance temperature (at 653 nm) of tungsten at its melting point was measured using a subsecond-duration pulse-heating technique. Specimens in the form of strips with initially different surface roughnesses were used. 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 653 nm) at the melting point for 23 tungsten specimens is 3208 K on IPTS-68, with a standard deviation of 0.8 K and a maximum absolute deviation of 1.9 K. The total error in the radiance temperature is estimated to be not more than ±10 K.

KEY WORDS: Melting; normal spectral emittance; pulse heating; radiance temperature; tungsten.

1. INTRODUCTION

A subsecond-duration pulse-heating technique was used earlier to measure the radiance temperatures[2] of niobium [1] and selected other metals (summarized in ref. [2]) at their respective melting points. It was found that the radiance temperature was constant during the initial melting period and was reproducible for different specimens of the same substance. In the present study, the same technique is used to measure the radiance temperature of tungsten at its melting point.

The method is based on rapid resistive self-heating of the specimen from room temperature to its melting point in less than one second by the

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[2]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.

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passage of an electrical current pulse through it; and on measuring specimen radiance temperature (at the rate of 1200 temperatures per second) with a high-speed photoelectric pyrometer [3]. The radiance measurements were performed at 653 nm, which corresponds to the effective wavelength of the pyrometer's interference filter. The bandwidth of the filter was 10 nm. The circular area viewed by the pyrometer was 0.2 mm in diameter. Details regarding the construction and operation of the measurement system are given in earlier publications [4, 5].

2. MEASUREMENTS

The measurements of the radiance temperature (at 653 nm) of tungsten at its melting point were performed on 23 specimens in the form of strips. The tungsten strips were cut from a long strip which 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 in ppm by weight: Ni, 16; Fe, 12; Al, Cr, Mn, Si, Sn, 6 each; Ca, Cu, Mg, 3 each. The purity of the tungsten in its final form (strip) was reported to be 99.95%.

The nominal dimensions of the strips were: length, 75 mm; width, 6.3 mm; and thickness, 0.25 mm. Before the experiments, the surfaces of a number of specimens were treated with an abrasive; two different grades of abrasive were used, yielding two surface roughnesses (approximately 0.2 and 0.5 μm in rms value) for different specimens. Experiments were also performed on specimens with "as received" surface conditions (approximately 0.1 μm in roughness).

All the experiments were performed with the specimen in an argon environment at atmospheric pressure. The heating rates for different specimens were in the range 1100–5400 $K \cdot s^{-1}$, corresponding to specimen heating periods (from room temperature to its melting point) in the range 460 to 170 ms.

Variation of radiance temperature as a function of time near and at the melting point for typical experiments on two specimens, each treated with a different abrasive, is shown in Fig. 1. The high values at the beginning of each plateau are probably related to the degree of initial surface roughness of the specimen. Presence of flat and long plateaus are evident in the results.

Variations of radiance temperature as a function of time near and at the melting point for typical experiments on two specimens, both with "as received" surface condition, is shown in Fig. 2. It may be seen that, while one of the experiments (upper trace) yielded a flat plateau, the other experiment (lower trace) did not produce a very good plateau. In general,

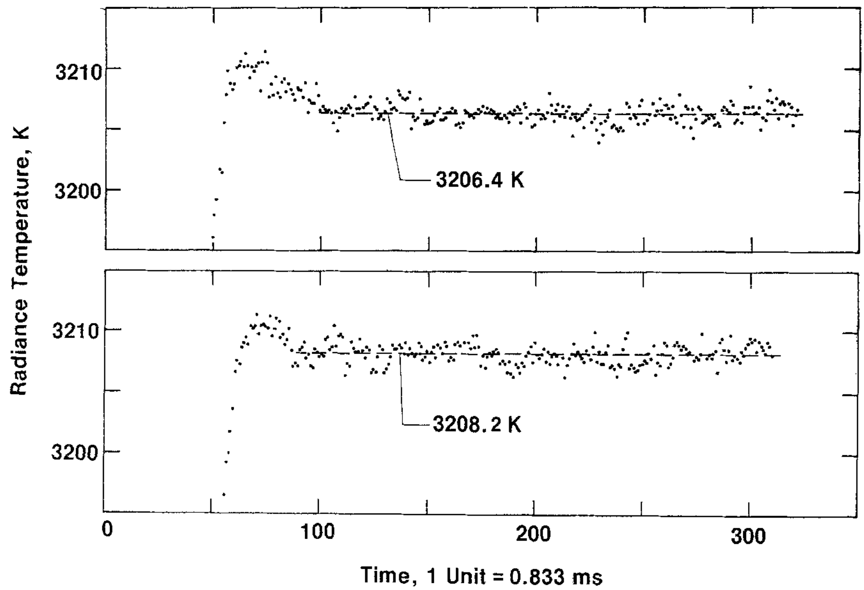

Fig. 1. Variation of radiance temperature (at 653 nm) of tungsten as a function of time near and at its melting point for typical experiments on two specimens, each treated with a different abrasive, yielding surface roughnesses of about 0.2 μm (upper trace, specimen 5) and 0.5 μm (lower trace, specimen 9).

the results of the experiments on specimens with "as received" surface condition exhibited somewhat inferior plateaus in comparison to those obtained on specimens treated with an abrasive. Existence of a thin oxide layer on the surface of the specimens in the "as received" case might have been partially responsible for this behavior. Since the differences in the results of experiments with "as received" specimens are within the imprecision of the measurements, the results of all experiments were included in the final analysis.

3. RESULTS

The radiance temperature at the melting point (or radiance melting temperature) of 23 tungsten specimens and other pertinent results are presented in Table I. All temperatures reported in this paper are based on the International Practical Temperature Scale of 1968 [6].

The single value for the radiance temperature at the plateau for each specimen was obtained by averaging the temperatures at the plateau. The number of temperatures used for averaging ranged from 75 to 371, depend-

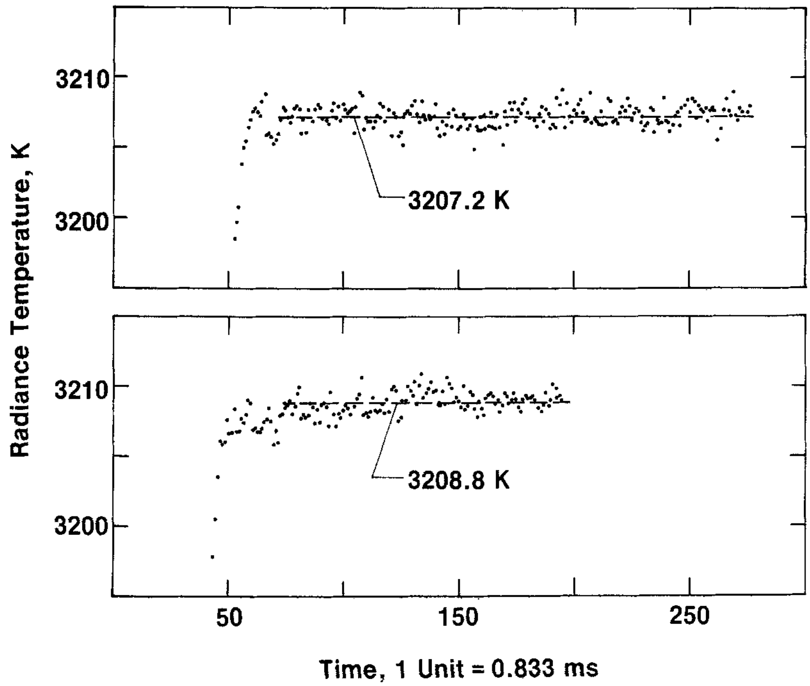

Fig. 2. Variation of radiance temperature (at 653 nm) of tungsten as a function of time near and at its melting point for typical experiments on two specimens both with "as received" surface condition (roughness about 0.1 μm). Upper trace is for specimen 3, and lower trace is for specimen 22.

ing both on the melting rate and on the behavior of the specimen during melting. The standard deviation of an individual temperature from the average was in the range 0.7–0.9 K for all the experiments.

To determine the trend of measured temperatures at the plateau, temperatures for each experiment were fitted by a linear function in time with the least-squares method. The detailed results are reported in Table I. The temperature difference between the beginning and the end of the plateau (corresponding to the slope in the plateau) is in the range -0.9 to 0.9 K.

In order to observe the possible effect of specimen heating rate on the results, the single values for the radiance temperature at the melting plateau for the specimens were plotted against heating rate. As may be seen from Fig. 3, no significant dependence of radiance melting temperature on specimen heating rate is observed.

The single values for the radiance temperature at the melting plateau for the specimens were grouped according to specimen surface roughness. An average value for radiance melting temperature was obtained for each group. From the results summarized in Table II, it may be concluded that there is no evidence of any significant trend in the radiance melting temperature with respect to the initial surface roughness of the specimens.

The average radiance temperature at the melting point for the 23 tungsten specimens is 3207.9 K with a standard deviation of 0.8 K and a maximum absolute deviation of 1.9 K. The deviation of the individual results from the average radiance melting temperature is presented in Fig. 4; it may be seen again that there is no significant bias with respect to the initial surface roughness of the specimen.

4. ERRORS

A detailed analysis of the sources and magnitudes of the errors in temperature measurements with the present system is given in an earlier publication [4]. The major error sources arise from (1) calibration and operation of the pyrometer, and (2) physical and chemical conditions of each specimen.

A summary of estimated maximum uncertainty (combined random and systematic errors) in radiance temperature measurements due to pyrometry pertinent to the present work is presented in Table III. Specific items in the error analysis were recomputed whenever the present operational conditions differed from those in the earlier study. It may be seen that the estimated maximum uncertainty in temperature arising from pyrometry is 6 K.

The variation of measured radiance temperatures for different specimens from the reported average lies within 2 K. Also, impurities in the specimen are not likely to change (decrease) the melting point of tungsten by an amount exceeding 2 K. Therefore, the maximum error attributable to the specimen conditions is estimated to be not more than 4 K.

Thus, the total estimated uncertainty (errors due to pyrometry and specimen conditions) in the reported radiance melting temperature is not more than ± 10 K. It may be concluded that the radiance temperature (at 653 nm) of tungsten at its melting point is 3208 ± 10 K.

5. DISCUSSION

The present results have shown the constancy and reproducibility of the radiance temperature of tungsten at its melting point for a number of

Table I. Summary of Measurements of Radiance Temperature (at 653 nm) of Tungsten During Melting

			Melting period				
Specimen[a]	Typical surface roughness (μm)	Premelting heating rate[b] ($K \cdot s^{-1}$)	Number of temperatures[c]	Slope at plateau[d] ($K \cdot s^{-1}$)	Plateau temp. difference[e] (K)	Radiance melt. temp.[f] (K)	Standard deviation[g] (K)
1	0.1	2500	155	6.8	0.9	3208.6	0.7
2	0.5	2300	176	− 2.2	− 0.3	3207.3	0.8
3	0.1	2400	204	1.2	0.2	3207.2	0.8
4	0.1	2300	105	3.2	0.3	3209.0	0.7
5	0.2	2200	222	− 0.6	− 0.1	3206.4	0.8
6	0.5	2200	218	− 2.3	− 0.4	3207.6	0.8
7	0.1	2100	187	3.2	0.5	3208.2	0.8
8	0.2	2200	199	0.5	0.1	3207.3	0.7
9	0.5	2200	220	0	0	3208.2	0.8
10	0.1	2100	189	− 2.5	− 0.4	3208.6	0.8
11	0.2	3600	96	− 9.7	− 0.8	3207.5	0.9
12	0.5	3500	121	− 9.2	− 0.9	3208.8	0.8
13	0.2	1100	293	2.0	0.5	3207.2	0.8
14	0.5	1200	268	− 1.7	− 0.4	3208.4	0.8

15	0.1	1200	336	− 1.3	− 0.4	3208.6	0.8
16	0.2	1300	241	1.0	0.2	3207.5	0.7
17	0.5	1200	335	1.5	0.4	3207.9	0.8
18	0.1	1300	371	− 0.2	− 0.1	3209.0	0.9
19	0.1	4200	86	− 5.6	− 0.4	3206.0	0.9
20	0.2	3900	123	− 0.8	− 0.1	3207.7	0.8
21	0.5	3800	129	− 8.1	− 0.9	3208.5	0.9
22	0.1	3800	123	7.8	0.8	3208.8	0.8
23	0.2	5400	75	− 10.9	− 0.7	3207.3	0.9

[a] Also represents the experiments in chronological order.
[b] Heating rate evaluated at a temperature approximately 10 K below the melting point.
[c] Number of temperatures used in averaging the results at the plateau to yield an average value for the radiance temperature at the melting point of the specimen.
[d] 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.
[e] Radiance temperature difference between the beginning and the end of the plateau based on the linear temperature vs time function.
[f] The average value (for a specimen) of measured radiance temperatures at the plateau.
[g] Standard deviation of an individual temperature as computed from the difference between the measured value and the average plateau radiance temperature.

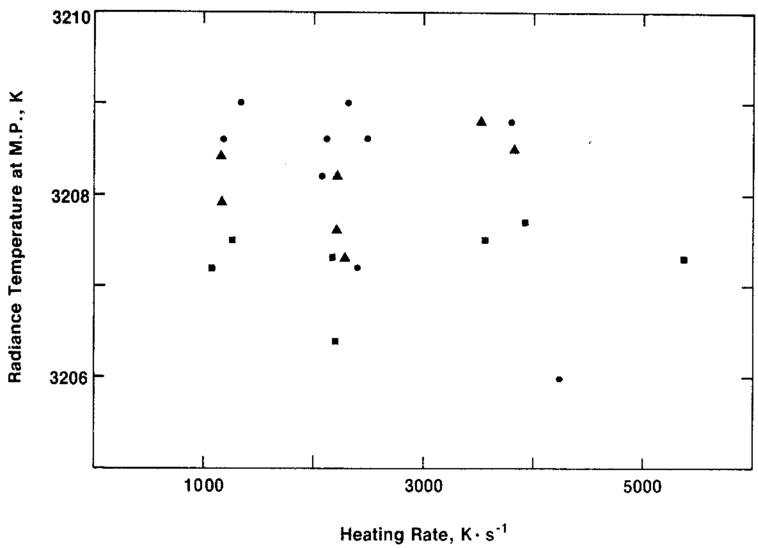

Fig. 3. Radiance temperature (at 653 nm) of tungsten at its melting point as a function of specimen heating rate. Each symbol represents the average plateau temperature for a specimen as tabulated in Table I. The symbols ●, ■, and ▲ correspond to experiments in which the surface roughnesses were about 0.1, 0.2, and 0.5 μm, respectively.

specimens with different initial surface conditions. This substantiates similar earlier results on several other refractory metals [1, 2].

We were unable to locate in the literature other measurements on radiance temperature of tungsten at its melting point. However, some normal spectral emittance data have been reported, primarily at temperatures below 3000 K [7]. On the basis of the value 3695 K for the melting point of tungsten [8] and the present value 3208 K for the radiance melting

Table II. Average Radiance Melting Temperature (at 653 nm) of Tungsten Specimens According to Surface Roughness

Surface roughness (μm)	Number of specimens	Average rad. melt. temp. (K)	Standard deviation (K)	Max. abs. deviation (K)
0.1	9	3208.2	1.0	2.2
0.2	7	3207.3	0.4	0.9
0.5	7	3208.1	0.5	0.8
All above	23	3207.9	0.8	1.9

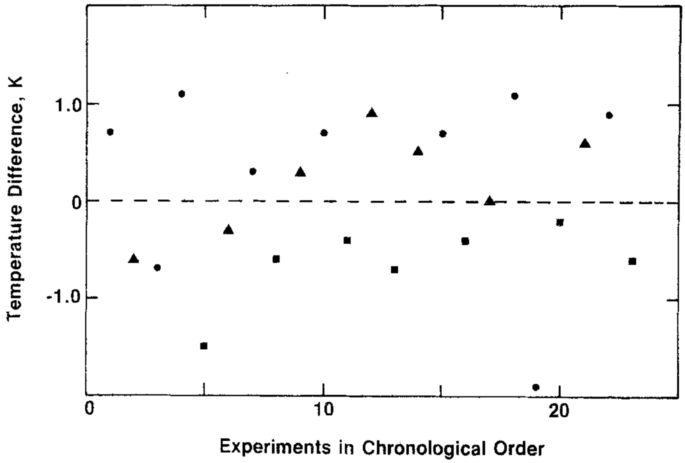

Fig. 4. Difference of radiance temperature (at the melting point of tungsten, at 653 nm) for individual experiments from their average value of 3207.9 K (represented by the "zero" line). The symbols ●, ■, and ▲ correspond to experiments in which the surface roughnesses were about 0.1, 0.2, and 0.5 μm, respectively.

temperature, Wien's law yields a value of 0.404 for the normal spectral emittance (at 653 nm) of tungsten at its melting point.

For approximate comparison purposes, emittance data by selected investigators were extrapolated (linearly) to the melting point and were interpolated (linearly) for the wavelength of the present work. The results are presented in Table IV. It may be seen that the normal spectral

Table III. Estimated Maximum Uncertainty in Measurements of Radiance Temperature (at 653 nm) at 3200 K

Source	Uncertainty (K)
Standard lamp calibration	3
Drift in standard lamp calibration	1
Radiation source alignment	2
Neutral density filter calibration	3
Window calibration	1
Pyrometer calibration stability	2
Effective wavelength calibration	2
Total uncertainty (root sum square of above items)	6

Table IV. Normal Spectral Emittance (at 653 nm) at the Melting Point of Tungsten Estimated from the Data of Various Investigators; Extrapolated from Lower Temperatures and Interpolated Between Adjacent Wavelengths

Investigator	Ref.	Year	Temp. Range[a] (K)	Bracketing wavelengths[b] (nm)	$\epsilon_{N,653}$
Forsythe and Worthing	[9]	1925	300–3300	467, 665	0.405
De Vos	[10]	1954	1600–2800	653[c]	0.411
Larrabee	[11]	1959	1600–2400	640, 660	0.398
Latyev et al.	[12]	1970	1200–2600	650, 656	0.391
Present work					0.404

[a]Temperature range in which measurements of normal spectral emittance are reported.
[b]Bracketing wavelengths, closest to 653 nm, at which measurements are reported.
[c]Emittance obtained from the smooth curve of emittance vs wavelength given by the investigator.

emittance values are in the range 0.391–0.411, while the value of the present work is 0.404. The greatest difference between the emittance value of the present work and the values reported in the literature (from Table IV) is about 3%, which corresponds to about 15 K in radiance temperature at the melting point of tungsten. Considering the assumptions made and extensive extrapolations involved in the estimation process, the agreements seem to be satisfactory.

The pulse heating technique used in this study has demonstrated the capability of measuring radiance temperature of metals during their initial melting period. It was not possible to follow the entire melting process because the specimen collapsed and opened the main electrical circuit prior to the completion of melting.

In conclusion, the results of the present work in addition to earlier results on other metals suggest the possibility of using the radiance temperature at the melting point of selected metals for secondary calibration and checking of optical temperature measuring equipment in high temperature systems. Tungsten, having the highest melting point among metals, is likely to play an important role in this. However, the final assessment will require additional accurate work on a select group of metals, which should include the measurement of radiance melting temperature at several wavelengths, in the range 0.4–1 μm, generally used in high temperature pyrometry.

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