THE REFLECTION FACTORS OF TUNGSTEN AT INCANDESCENT TEMPERATURES.

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Synopsis.

A direct method has been developed for measuring the reflection factors of substances at incandescent temperatures. Curves are given showing the variation in the reflection factor of tungsten for wave-lengths from 0.67 μ to 4.0 μ and for temperatures up to 2067° K.

The reflection factor of tungsten was found to increase with temperature for wave-lengths less than about 1.27 μ and to decrease with temperature for wave-lengths longer than this. The transition from the approximately constant positive temperature coefficient in the visible to the approximately constant negative coefficient in the infra-red takes place in the rather narrow region lying between about 0.7 μ and 2.0 μ. The numerical values of the reflection factor agree fairly well with Worthton's values in the visible and with the theoretical equation first applied to long wave-lengths by Hagen and Rubens, beyond 2 μ in the infra-red.

THIS study of the reflection factors of tungsten was made as part of the general study of the properties of tungsten undertaken by Nela Research Laboratory. Closely related papers on the emissive powers in the visible and ultra-violet have already been published by Worthing[1] and Hulburt[2] respectively. The present paper deals with the reflection factors at incandescent temperatures in the red end of the visible spectrum and the near infra-red. The most direct method of attack was adopted, involving spectral energy measurements of a beam reflected from a polished tungsten surface both when hot and when cold.

Apparatus and Method.

The success of the method depended entirely on obtaining a tungsten mirror that could be heated without appreciable warping. A few trials were made with massive mirrors, including an attempt to heat such a mirror by means of an electronic discharge impinging upon its back; but it was found simpler and entirely practicable to use smaller mirrors that could be heated by means of an electric current passing through them. Three different types of such mirrors were made: (*a*) squirted filament, circular hole along axis, outer surface hexagonal, width of face 0.75 mm.; (*b*) swaged filament 1.16 mm. in diameter, central portion

[1] Phys. Rev., 10, 1917, p. 377.

[2] Astrophys. Jour., 45, 1917, p. 149.

rolled flat and bent into a form resembling that of the old-fashioned paper fasteners known to the trade as "flat heads," mirror face 25 x 2 mm.; (*c*) drawn wire, 0.9 mm. in diameter, bent so as to form three sides of a long narrow rectangle, ground flat so that its section became a semicircle. All were heated in vacuo to a temperature higher than that used in the experiments, were rough-polished on cloth with sulphur-flour and rouge, and finished on a pitch surface with the finest rouge; and were mounted in evacuated glass bulbs. The part of the polished surface used was always sufficiently removed from the lead-in wires so that its temperature was uniform. The data taken on mirrors *a* and *b* were considered preliminary; those on *c* are recorded below. All mirrors showed the same general behavior. In this connection two experimental difficulties should be mentioned: (1) it was very difficult to make stem seals that would not check, due to the frequent changes in the large heating currents; (2) it was found that the mirror surface developed furrows, which, however, obliterated only a small percentage of the surface, the parts between the furrows retaining their polish.

The spectrobolometer was of the Wadsworth fixed arm type; instrumental dimensions are given in the legend accompanying Fig. 1. The bolometer and galvanometer were provided with auxiliary apparatus so that the galvanometer could be used either as a deflection or as a zero

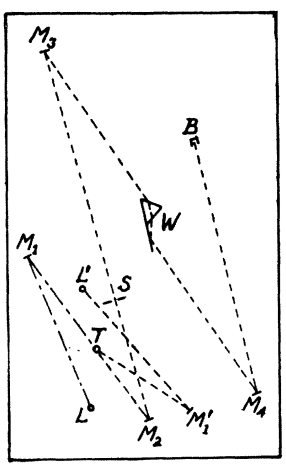

Fig. 1.
Diagram of Apparatus.

L, *L'*, two positions of flat filament (0.2 × 2.5 cm.) tungsten lamp in cylindrical bulb, operated at 15 amp.

M_1, M_1', two positions of concave mirror, $f = 20.0$ cm., diam. $= 9.3$ cm. *L* and *M* were mounted on a single tripod which could be placed in either one of two sets of hole-slot-plane plates. The primed position served for measurements of the beam reflected from *T*, and the unprimed for measurements of the beam incident on *T*.

T, tungsten mirror, mounted as a lamp filament in a selected tubular glass bulb; see text. Angle of incidence of beam on mirror 10°.

M_2, concave mirror, $f = 16.0$ cm., diam. $= 15$ cm.

S, slit, 0.5 mm. × 20 mm. Subtends 0.13 μ in the most condensed part of the spectrum near 1.63 μ.

M_3, M_4, concave mirrors, $f = 76$ cm., diam. $= 15$ cm.

W, fluorite prism in Wadsworth mounting. Prism angle 59° 59.8'.

B, bolometer, platinum strips (0.5 × 25.0 mm.) Smoked above acetylene flame. Resistances when total bolometer current is 0.12 amp., are 5.303 and 5.296 ohms. Balance coils 10 ohms each, part of Wolff five dial bridge. Galvanometers: Four-coil, astatic, 7-sec. period, volt sensitivity, 670 mm. per microvolt at a scale distance of 1 meter. *S-H* d'Arsonval, critically damped, volt sensitivity, 10 mm. per microvolt at a scale distance of 1 meter. Galvanometer scale actually used at distances of 2.5 m. from the four-coil instrument and 5 m. from the d'Arsonval.

instrument. When used as a deflection instrument, its sensibility could be reduced by a group of shunts, but when used as a zero instrument it was always kept at full sensibility. For use in the latter manner, the exposed strip of the bolometer was shunted by a high variable resistance (10,000 Ω in parallel with the strip and 3,000 of this 10,000 in parallel with from 1 to 110,000 Ω) so that at a balance with the exposed strip illuminated, the current in each of the four arms of the bridge was the same as when the shunt was disconnected and the strip shaded. The changes in current due to exposures of the strip, as is customary, were assumed proportional to the incident radiant flux and their values were calculated from the experimentally determined values of the shunt resistance necessary to bring this current back to its normal value.

The path of the beam before reaching the slit of the spectrometer is indicated in Fig. 1 by $L'M_1'TM_2S$. To insure that the tungsten mirror T was in exactly the same position in the image of the source formed by M', when hot as when cold, two telescopes were mounted permanently, one near M_2 giving a view of the front of the mirror, and the other off at right angles, giving a view of the edge of the mirror, the cross hairs of both being set on marks that could be easily identified. A shutter was placed near M_1'. The natural radiation from the tungsten mirror was allowed to enter the slit at all times and the increase in the galvanometer deflection due to opening the shutter was recorded. Readings were usually made in this order: mirror at room temperature, mirror incandescent, mirror at room temperature.

The actual galvanometer deflections or resistance readings varied in magnitude from day to day, due to using different currents in the bolometer and in the source, etc., and are, therefore, not recorded below. Between 0.7 μ and 3.0 μ no deflections less than 2 cm. nor greater than 20 cm., were used; readings were made to 0.1 mm.; each figure recorded is based on the mean of at least ten deflections. Spectrometer settings were checked at the beginning and end of each run by the yellow and red lines of helium and occasionally by the carbon dioxide emission band at 4.4 μ. The temperature-current relations for the tungsten mirrors were determined with a Holborn Kurlbaum optical pyrometer by Dr. Worthing of this laboratory.

Data and Discussion.

The data are recorded in Table I. and plotted in Figs. 2 and 3. In a narrow region bounded approximately by the wave-lengths 0.7 μ and 2.0 μ a change of temperature produces a striking change in the relation between reflection factor and wave-length. Within this interval an

TABLE I.

Relative Reflection Factors of Tungsten,

$$i.e., \frac{\text{Reflection factor at high temperature}}{\text{Reflection factor at room temperature}}.$$

Wave-length in μ.	1380° K.	1632° K.	1859° K.	2067° K.
0.67	1.06	1.074	1.087	1.098
0.70				1.090
0.76				1.089
0.82				1.080
0.90				1.065
1.05				1.040
1.10				1.026
1.16				1.014
1.20				1.012
1.27	1.000	1.000	1.000	1.000
1.39				0.976
1.50				.954
1.63				.928
1.76				.909
1.90	0.933	0.919	0.902	.890
2.00	.925	.908	.891	.877
2.23				.876
2.44				.876
2.90	.923	.906	.889	.876
2.99				.878
4.00				.880

increase in temperature causes an increase in the reflection factor for wave-lengths less than about 1.27 μ and a decrease for wave-lengths

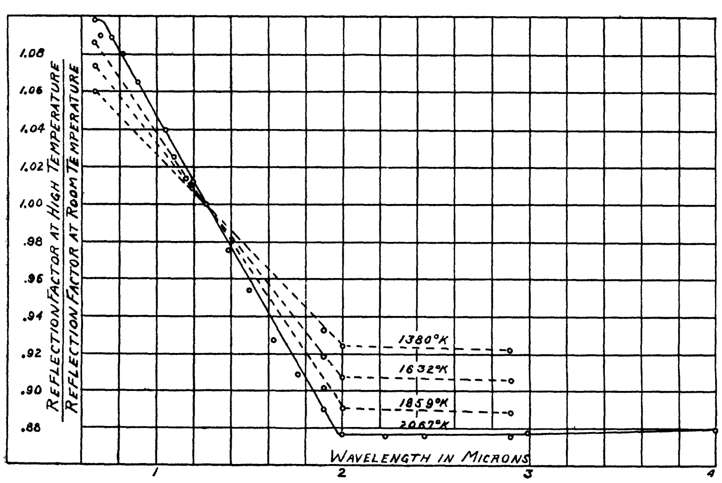

Fig. 2.

Relative Reflection Factor.

greater than this, the change in each case being greater the higher the temperature.

Previous experimental work has shown that in the visible part of the spectrum, the reflection factor of tungsten increases with temperature; thus Worthing[1] for wave-length 0.665 μ using an optical pyrometer method which for this region of the spectrum is much more delicate than that employed by the present authors, gives data yielding a change in

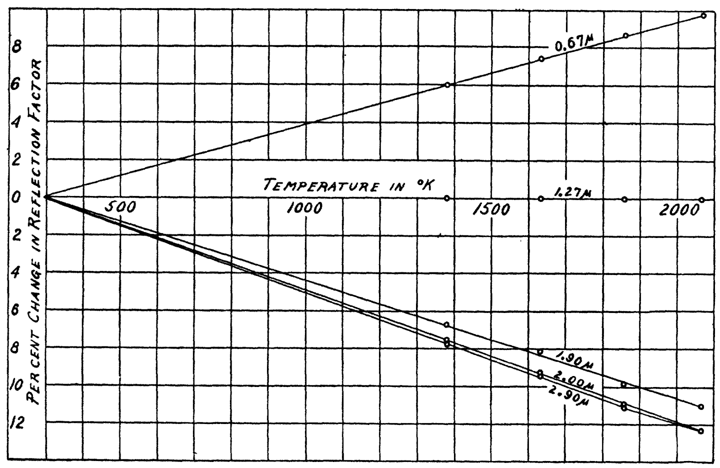

Fig. 3.

Change in Reflection Factor with Temperature.

the reflection factor of 5.0, 6.2, 7.3, and 8.2 per cent. at temperatures of 1380, 1632, 1859, and 2067° K. respectively; the corresponding values found here are 6.0, 7.5, 8.7, and 9.9 per cent.

As is well known, Hagen and Rubens,[2] showed that for long wavelengths the reflection factors of metals obey the formula derived by Drude,[3] from Maxwell's theory:

$$R = 100 - 3650\sqrt{\frac{\rho}{\lambda}}$$

R is the reflection factor in per cent., ρ is the resistivity in ohm-cm., and λ the wave-length in μ. That this formula fits the present data fairly well beyond 2.0 μ may be seen from Table II.

The resistivities are taken from Langmuir's table.[4] The values of "R Observed" at room temperature (293° K.) are taken from Coblentz'[5]

[1] Phys. Rev., 10, 389, 1917.

[2] Ann. d. Phys., 4F, 11, 873, 1903; Phys. Zeitschr., 11, 139, 1910.

[3] Lehrbuch der Optik, 2d ed., p. 349.

[4] Phys. Rev., 7, 154, 1916.

[5] B.B.S., 14, 312, 1918.

TABLE II.

Comparison of Observed and Theoretical Values of the Reflection Factor of Tungsten for long Wave-Lengths.

Temperature.	Resistivity Ohm·Cm.	Change in R (Fig. 2).	R Observed.	R Computed.	$\frac{R \text{ Computed}}{R \text{ Observed}}$.
		$\lambda = 2.0\,\mu$			
293° K.	5.51 x 10^{-6}		90.0%	94.0%	1.045
1380	37.46	− 7.5%	83.3	84.2	1.011
1632	46.01	9.2	81.8	82.5	1.009
1859	54.19	10.9	80.3	81.0	1.009
2067	61.99	−12.3	79.0	79.7	1.009
		$\lambda = 2.5\,\mu$			
293° K.	5.51 x 10^{-6}		93.8%	94.6%	1.009
1380	37.46	− 7.6%	86.6	85.9	.992
1632	46.01	9.3	85.0	84.3	.992
1859	54.19	11.0	83.5	83.0	.994
2067	61.99	−12.3	82.3	81.8	.994

most recent table; the rest of the numbers recorded in these columns are the result of applying to these values the percentage changes determined by the present investigation. The columns headed "R Computed" are obtained directly from the formula written above. The approximate constancy of the ratio of the computed to the observed values, which holds also at 3 μ, indicates that the formula holds for tungsten at considerably shorter wave-lengths than for other metals previously studied. In fact it appears that the formula holds up to the point at which the sharp break occurs in the curves in Fig. 3, that is up to the region in which the rapid transition takes place from a decrease to an increase in the reflection factor with an increase of temperature.

The general character of the changes found in the reflection factor of tungsten are not peculiar to this metal; McCauley[1] using an indirect method based on Kirchhoff's law, $E/\epsilon = 1 - R$, in which he measured E, the radiant flux emitted by the substance at a certain temperature and wave-length and obtained ϵ, the flux emitted by a black body at the same temperature and wave-length, from Planck's equation, found similar changes in the reflection factors of platinum, palladium and tantalum.

NOTE ON THE REFLECTION FACTOR AT ROOM TEMPERATURE.

The authors measured the reflection factor of tungsten at room temperature by a direct method with the apparatus in front of the slit

[1] Astrophys. Jour., 37, 164, 1913.

arranged as indicated in Fig. 1, so that the transition from a measurement of the incident beam to that of the reflected beam could be made readily, with the two optical paths identical except for the reflection from the tungsten mirror.

A curve showing the relation between reflection factor and the wave-length plotted from data taken after the conclusion of the high temperature experiments differs markedly from a similar curve taken when the mirror was new. Not only does the earlier curve show slightly higher values of the reflection factor, as might be expected on account of the fissures that appeared in the surface during use, but the earlier curve also shows the two depressions at about 0.8 μ and 1.4 μ shown by Coblentz,[1] whereas these seem to be absent in the later curve. As the actual behavior of the metal throughout the infra-red and particularly in this region of the spectrum is of considerable interest, a further study, using this direct method and greater dispersion, is contemplated.

Nela Research Laboratory,
Cleveland, Ohio,
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[1] *Loc. cit.*