SPECTRAL EMISSIVITIES OF TANTALUM, PLATINUM, NICKEL AND GOLD AS A FUNCTION OF TEMPERATURE, AND THE MELTING POINT OF TANTALUM

By A. G. Worthing

Abstract

Spectral emissivities of Ta at 0.665μ and 0.463μ have been determined by (a) the tubular filament, (b) the reflectivity and (c) the comparison at contact methods. For 0.665μ the smoothed values at 300°K, 1500°K, and 2700°K are 0.493, 0.438, and 0.394; for 0.463μ, 0.56, 0.50, and 0.43. While agreeing at 300°K with the results of Wartenberg and of Coblentz, at incandescence the present values are lower than previous values. Probable sources of error in emissivity determinations are such as to indicate that these lower values are the more reliable. *Temperature scale for Ta.*—For 0.665μ, the above emissivities lead to the following differences between brightness temperature and true temperature as a function of the brightness temperature: 57° at 1200°K, 107° at 1600°K, 179° at 2000°K, 278° at 2400°K, and 406° at 2800°K. *Melting point of Ta.*—Two determinations by the contact method, using tungsten as the known material yielded 3300°K. This is higher than previously reported values.

Spectral emissivity of Pt was found to vary linearly with temperature. For 0.665μ, the emissivities at 1200°K and 1850°K are 0.295 and 0.310; for 0.535μ at 1200°K and 1600°K, 0.325 and 0.335; for 0.460μ at 1600°K and 1850°K, 0.375 and 0.390. The emissivity at 0.665μ combined with an observed brightness temperature of 1842°K checks Hoffman's careful melting-point determination exactly.

Spectral emissivity of Ni (98.8% pure) was found not to change with temperature. For 0.665μ, 0.535μ, and 0.460μ, emissivities of 0.375, 0.425, and 0.450 were obtained.

Spectral emissivity of Au for 0.665μ was found to increase from 0.062 at 300°K to 0.145 at 1300°K, for 0.535μ to increase from 0.352 at 300°K to 0.450 at 1300°K, for 0.460μ to remain constant at 0.633.

Introduction

A CONSIDERABLE amount of work has been done, mostly from the standpoint of optical constants, in studying emissivities or reflectivities at room temeratures. A moderate amount of work has been done in studying the variations with temperature. The results show great discrepancies. While in the writer's opinion, the variations in the visible for tungsten and molybdenum are well established, there does not seem yet to be a general agreement as to this among workers using these metals. Some still cherish the belief that the optical constants of metals for the visible region are independent of temperatures.

With a desire to find out further facts regarding the emissivity variations of other metals, and to determine the high temperature scales for certain ones likely to be used in other high temperature studies, a study has been made of tantalum, platinum, nickel and gold.

TANTALUM

Emissivity Methods. Three methods[1] have been employed in determining spectral emissivities, namely, (a) the tubular filament method, (b) the reflectivity method, and (c) the comparison at contact method.

By the first method, a comparison of surface brightness with interior brightness as seen through a hole in the side wall of the tubular filament of tantalum yielded an emissivity directly. As in the study of molybdenum, the tube was formed by winding ribbon in a closed helix. Only one workable tube was thus obtained from the limited supply of pre-war tantalum wire, and only at rather high temperatures did it show a uniformity of surface brightness such as to justify inclusion of the data obtained on it in the final average.

By the second method, a comparison of the brightness of an unreflected image of a bright source with its image formed at and reflected by the polished surface of a tantalum ribbon filament mounted in a lamp bulb, yielded a reflectivity (1.00 − emissivity). When the ribbon filament was incandescent, its natural brightness was first subtracted from the apparent reflected brightness. Polished flat surfaces were obtained by rolling down wire, the final stage being between two polished safety razor blades. With this method surface pittings, resulting from operating at high temperatures, are liable to reduce the apparent brightness of a reflected image and to lead to too high emissivities. Freedom from this source of error may be assumed when the reflected image for the area studied shows no added detail over the unreflected image. While probably not a perfect criterion, its use insures a certain freedom from error. Quite in contrast, excepting cases where the pits are deep, the other methods, through depending on natural brightness measurements, are free from errors of this type.

By the third method, a comparison was made of the brightness of a metal of known emissivity with that of tantalum in contact, when the junction was heated to incandescence. To obtain reliable results by this method, it is necessary to have a fused contact with the boundary layer of alloy very thin. Obtaining such a layer involved

[1] Worthing, (a) Phys. Rev. **10**, 377 (1916); (b) Zeits. f. Physik **22**, 9 (1924); (c) Phys. Rev. **25**, 846 (1925).

considerable preparation and usually, in the case of tantalum, such attempts resulted in failure. In fact, only one lamp was obtained in which the junction layer was sufficiently thin (not over 1/10 the diameter of the filaments) to justify inclusion of emissivity results obtained with it. The metal having the known emissivity in this case was molybdenum. At the melting point of tantalum there was a slight modification of method. In this case, the brightness of a tungsten filament at the contact end to end with a tantalum filament in one

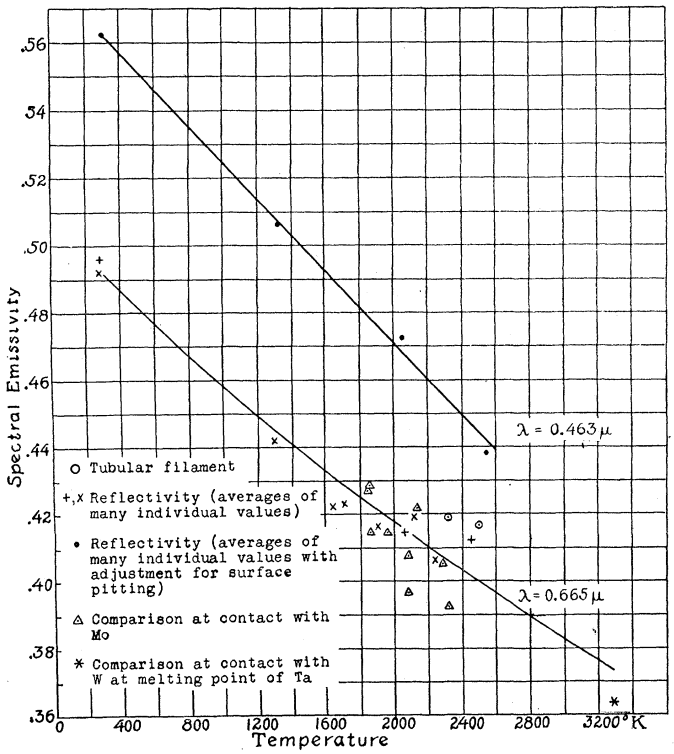

Fig. 1. Spectral emissivities of tantalum as obtained from various methods.

lamp was compared with the surface brightness of a short all tantalum filament at the melting point in another lamp.

Residual gases in the lamp bulb and gases apparently emitted by the tantalum on heating had to be guarded against much more than in the case of tungsten or of molybdenum. Except when the tantalum filament had been operated at a high temperature, say 2400°K, for a considerable time while connected to a mercury condensation pump, there was a tendency for the tantalum surface to lose its luster and to

deteriorate rather rapidly. This was not due to mere surface pittings, for the natural luster of the surface once dimmed as judged by reflectivity measurements, could be largely restored by repeating the above heating and evacuating process.

Emissivity results. Emissivities obtained for 0.665μ and 0.463μ are shown in Fig. 1. As shown, only two determinations were obtained under satisfactory conditions by the tubular filament method. For the most part the reflectivity method was used. Further, all such points represent averages of many determinations. In this work, for 0.665μ, the errors due to shallow pittings have presumably been largely eliminated by limiting the accepted results to that period for which no appreciable changes were noticeable in the measured reflectivities at room temperature. The emissivities for 0.463μ, however, were determined on tantalum showing distinct pitting. Corrections were made, however, in accord with some reflectivities for 0.665μ measured at the same time. Emissivities for 0.463μ are less dependable than those for 0.665μ.

The few results obtained by the comparison at contact method are all shown in Fig. 1. The molybdenum emissivities used were taken from recently published result. The single value plotted at the melting point represents the result obtained from the averages of two tungsten and of two tantalum brightnesses, the tantalum and tungsten brightnesses being obtained in different lamps, as explained above. Due to the actual brightness settings on the tantalum being slightly off from the place where melts actually occurred, the computed spectral emissivity is expected to be low.

Altogether, the data are not as satisfactory as were similar data obtained for tungsten and molybdenum. However, it is probable that the curve for 0.665μ as drawn is correct to within 0.01 or at most 0.02. For 0.463μ the uncertainty is probably over twice as great. It is interesting to note that tantalum shows not only the same type of variation with temperature that tungsten and molybdenum show, but that its actual variation is of the same order. Between room temperature and the melting point for 0.665μ, each shows a decrease, tungsten about 14.5 prcent, molybdenum 22 percent, and tantalum 24 percent.

Comparisons with published results. Previously published results on tantalum for the visible region together with those here presented are shown in Table I. At room temperature, considering the range of interpolation using Coblentz's data, it seems that the results of Wartenberg, Coblentz and the present writer are in fair agreement.

Henning's results do not fit well with the others. How much of the differences is due to impurities is difficult to say. Coblentz found great variations in his specimens. The present writer's specimens, however, obtained at two different times (once from Siemens and Halske) of pre-war origin, and intended for incandescent lamp filaments, yielded essentially the same results. Perhaps their operation several times at very high temperatures, through freeing them from absorbed gases and cleaning the surfaces may have been the determining factor.

TABLE I

Published data on spectral emissivities of tantalum in the visible region.

Author	Method	λ	e_λ	Remarks
		At room temperature		
Wartenberg[2] (1910	Optical constant	.579μ	56.2%	
Henning[3] (1910)	Spectral pyrometer	.665	55	Interpolated from curve
Coblentz[4] (1911)	Thermocouple	.665	48	Interpolated from curve (Wartenberg's sample)
Worthing (1925)	Optical pyrometer	.665	49.3	
		At incandescent temperatures		
Pirani[5] (1910)	Various	.65(?)μ	49%	Assumed constant—disregarded in later work
Mendenhall and Forsythe[6] (1913)	Open wedge	.658	61	1400°K
			49	2100
			47	2800
McCauley[7] (1913)	Open Wedge	.658	59	1400
			47	2100
			46	2800
Worthing (1925)	Tubular filament	.665	44.2	1400
	Reflectivity		41.5	2100
	Mo-Ta contact		39.0	2800

At incandescent temperatures, as also shown in Table I, there are great variations. Pirani had little faith in his determinations and later used for all temperatures 56 percent, the average of Wartenberg's and Henning's results at room temperature. Mendenhall and Forsythe, and also McCauley working under Mendenhall, using the open wedge method, obtained results considerably higher than those presented in this paper. Since all ordinary errors in pyrometry measurements, such as those due to residual gases (Mendenhall and Forsythe do not mention trouble of this kind), pitted surfaces, and failure to obtain complete blackness for the black body radiation, separately

[2] Wartenberg, Verh. Deut. Phys. Gesell. **12**, 105 (1910).
[3] Henning, Zeits. f. Instrumentenk **30**, 61 (1910).
[4] Coblentz, Bull. Bur. Standards, **7**, 197 (1911).
[5] Pirani, Verh. Deut. Phys. Gesell. **12**, 301 (1910).
[6] Mendenhall and Forsythe, Astrophys. J. **37**, 380 (1913).
[7] McCauley, Astrophys. J. **37**, 164 (1913).

tend toward emissivities that are too high, it follows that, other things being the same, the lower values (in this case the present writer's) of emissivity are the more probable. Data on the rate of variation of radiation intensity with temperature, as will be noted in the following paper, point to the same conclusion.

Henning,[3] on the supposition of constancy for his factor θ, obtained at incandescence a minimum value for emissivity, which at about 2500°K in the case of his tantalum band amounted to 30 percent. (His 27 percent for tantalum wire must be discarded because of the errors due to diffraction[8] in pyrometry which may have entered in that case.) This minimum is really an approximation to what is now termed color emissivity,[9] and is in close agreement with the 29 percent which may be deduced from Forsythe's[10] color temperature-brightness temperature data, and with the 32 percent which may be deduced from the above data by means of the equation

$$\log e_c = \frac{\lambda' \log e' - \lambda'' \log e''}{\lambda' - \lambda''}$$

where e_c is the color emissivity and e' and e'' the spectral emissivities at wave-length λ' and λ''.

As a whole, the data of Table I do not show satisfactory agreement. However, for the establishing of a temperature scale at incandescence a selection must be made. In doing so the present author has disregarded previously published results. He has felt justified in so doing (1) because his different methods have checked reasonably well, and (2) because, on the basis of errors at incandescent temperatures arising from imperfect black body conditions, pitted surfaces, and surfaces altered by residual gases, his results seem to be the more nearly free from suspicion.

Temperature scale. The temperature scale of tantalum which follows from the foregoing emissivity at 0.665μ is shown in curve A, Fig. 2. The corresponding color temperature scale (curve B), however, fairly closely in accord beyond $S=1600$°K with a constant color emissivity of 0.29, is taken from data referred to above obtained by the writer's colleague, W. E. Forsythe.

Melting Point. Only two melting point determinaions have been made. Both have depended upon the determination of the tempera-

[8] Worthing and Forsythe, Phys. Rev. **4**, 163 (1914).

[9] Worthing, Bull. Am. Inst. Mining Met. Eng. No. 153, 1925 (1919); Forsythe and Worthing, Astrophys. J. **61**, 146 (1925).

[10] Forsythe, J.O.S.A. **7**, 1115 (1923).

ture of tungsten filaments at the contact end to end with tantalum filaments as the tantalum was heated to the melting point. These values were 3275°K and 3315°K, the latter having the greater certainty. They give an approximate average of 3300°K.

Previous data are summarized in Table II. Taken altogether there is not a reasonable agreement. Extended extrapolations, based on determinations of currents of small filaments at burnouts, are always subject to considerable uncertainty. Pirani and Meyer's result assumed an emissivity of 0.56 at 0.64μ to apply at all temperatures, but they concluded that the tantalum, when once melted, had a much lower apparent emissivity. This probably means that their

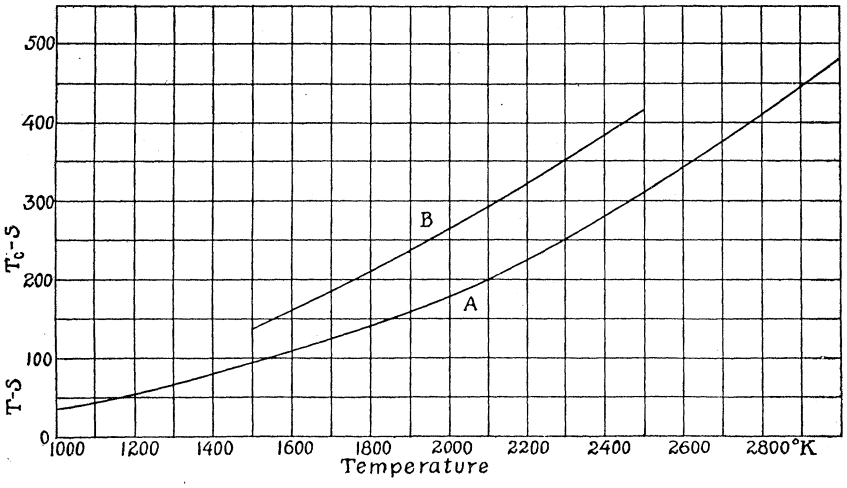

Fig. 2. Temperature scales for tantalum. A. (T−S) scale represents result of present study. B. (T_c−S) scale represents results published by Forsythe.

specimens had roughened surfaces, in which case the application of any supposed emissivity is questionable. The method used by Forsythe seems fundamentally sound. But it is to be said that a discussion of the results for both molybdenum and tantalum emissivities (tungsten also, though the cause for difference in that case was very apparent) obtained by the open wedge method, in contrast to those obtained by the tubular filament, the reflectivity and the contact methods, leads to the belief that the open wedge has not yielded completely black radiation. For this reason Forsythe's 3160°K is probably too low. It is interesting to note that if a lack of blackness of the open wedge radiation occurred, sufficient to account for a measured 0.47 near the melting point as determined by Mendenhall and Forsythe instead

of the present author's 0.375, Forsythe's value for the melting point when corrected would be 3270°K as against the present author's

TABLE II

Published values for the melting point of tantalum.

Observer	Method	c_2	M.P. of Pt.	No. of Trials	Melting Point.	Average Deviation	Melting point $c^2=14330\mu$ deg $T_{Au}=1336$°K or $T_{Pd}=1829$°K
Waidner and Burgess[11] (1907)	Extrapolation	14500	2026°K	5	3180°K	..	3230‡
Pirani[5] (1910)	Extrapolation	14200	2018	..	3270	..	3230‡
Pirani and Meyer[12] (1911)	Brightness temp. at melt.	14200	*	14	3123	30°K	3106
Forsythe[13] (1911)	Open wedge	14500	2028	8	3071	13	3160#
Worthing (1925)	Contact with tungsten	14330	....	2	3300	20	3300

*M.P. of Pd taken as 1828°K
#Correction made for change in effective wave-length (Hyde, Cady, Forsythe, Astrophys. J., **42**, 294 (1915))
‡Adjusted for change in c_2 only

3300°K. Regarding his own result, the writer feels that the temperature scale for tungsten is so nearly agreed upon that the greatest objection to his 3300°K is the smallness of the number of trials. A reasonably precise value for the melting point cannot be stated.

SPECTRAL EMISSIVITY OF PLATINUM

A portion of the platinum used was obtained from Heraeus. Originally in wire form, it was rolled into a ribbon and wound into a tube as had previously been done with molybdenum. Another portion of the platinum was obtained from Baker & Co. Ltd. It was originally tubular. Small holes were drilled through the side walls. These tubes were much like those previously used in the study of tungsten. In all cases the tubes were mounted as filaments in incandescent lamp bulbs with commercial argon as used in incandescent lamps as the contained atmosphere. No reflectivity measurements were made in the case of platinum.

The spectral emissivities obtained for platinum for wave-lengths 0.665μ and 0.460μ by three observers are shown in Fig. 3. The agreement is not good. Nevertheless, for 0.665μ, there is sufficient definite-

[11] Waidner and Burgess, J. Phys. **6**, 830 (1907).
[12] Pirani and Meyer, Verh. Deut. Phys. Gesell. **13**, 540 (1911).
[13] Forsythe, Astrophys. J., **34**, 353 (1911).

ness to justify their presentation. With increase in temperature, there seems to be an increase in spectral emissivity. If this is real, platinum differs in this respect from tungsten, molybdenum, and tantalum for which decided decreases have been found.

As a whole, published results for platinum as presented in Fig. 4 show a wide variation. Relatively, the writer's results are low at low temperatures and about an average at high temperatures.

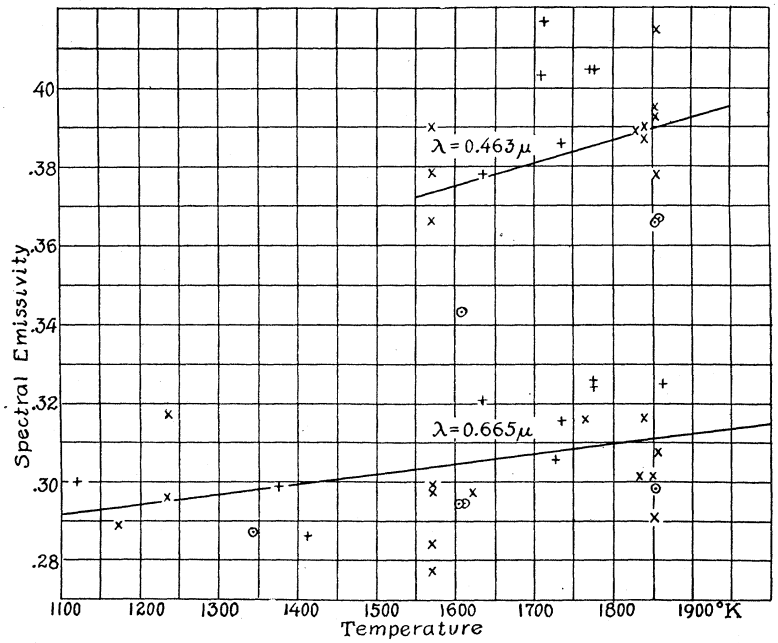

Fig. 3. Spectral emissivity of platinum. Results by three different observers, using the tubular filament method.

There are certain indications, however, which show that considerable confidence may well be given the writer's data. These are his determinations of the melting point which are based in part on the line of Fig. 3 for 0.665μ extrapolated to 2040°K of thereabouts. Using short platinum wires mounted in Λ-shape with the peak considerably reduced in cross-section to make the location of melt definite, eight determinations of the brightness temperature at melt gave 1842°K,*

* At melt the emissivity of platinum, as has been pointed out by Burgess and Waltenberg, increases by about 15%. With wire shaped as stated, it was possible to keep a short length of wire in a semi-molten state. About the small area under observation a boundary line between a dark and a bright portion could be seen to shift slowly back and forth. The dark portion was taken to be the solid phase. Brightness temperature readings on this solid phase were apparently affected by the shifting, for the readings on the liquid phase, which gave a brightness temperature of 1864°K, showed only an average deviation of 2°.

the average deviation being 6°. With 0.316 as the emissivity at 0.665μ, a melting point temperature of 2043°K is obtained. This is in

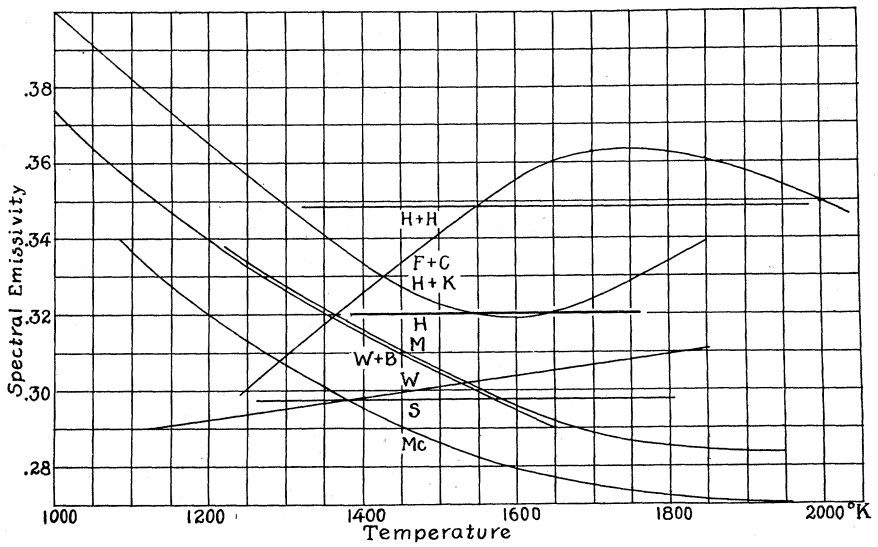

Fig. 4. Published spectral emissivities of platinum for red light at incandescent temperatures as obtained by various experimenters.

Curve	Author	Year	λ
H & K	Holborn and Kurlbaum	1903	.65μ
W & B	Waidner and Burgess	1907	.66
L & M	Laue and Martens	1907	.63
F & C	Fery and Cheneveau	1909	.629
H	Henning	1910	.665*
M	Mendenhall	1911	.658
Mc	McCauley	1913	.658
S	Spence	1913	.658
H & H	Henning and Heuse	1923	.647
W	Worthing	1925	.665

* Interpolated from results for 0.680μ and 0.627μ.

excellent agreement with the value recently obtained by Hoffman[2] in a very careful study. His 2044°K when corrected for a change in[1] c_2 from 14300μ deg. to 14330μ deg. yields 2043°K. On the other hand,

[14] Holborn and Kurlbaum, Ann. d. Physik **10,** 225 (1903).
[15] Waidner and Burgess, Bull. Bur. Standards **3,** 163 (1907).
[16] Laue and Martens, Physik Zeits **8,** 853 (1907).
[17] Fery and Cheneveau, Comptes Rendus **148,** 401 (1909).
[18] Mendenhall, Astrophys. J. **33,** 91 (1911).
[19] Spence, Astrophys. J., **37,** 194 (1913).
[20] Henning and Heuse, Zeits f. Physik **16,** 63 (1923).
[21] Hoffman, Zeits. f. Physik **27,** 285 (1924).

there are the results of Nernst and Wartenberg[22] and of Waidner and Burgess[15] which point to 2035 °K. To check this value either the brightness temperature 1842 °K must be reduced by 6°, the emissivity must be increased to 0.330, or some combination of their partial changes must be made. Further study of platinum is needed.

Spectral Emissivity of Nickel

The nickel used is the same as that used for leads in commercial vacuum incandescent lamps (98.8 percent Ni, 0.75 percent Fe, 0.15 percent each of Cu, Mn, and Si and traces of S, P, and C). The impurities may well affect the melting point but probably are of little consequence in affecting spectral emissivities. For incandescent temperatures, the nickel was formed into tubes as in the case of molybdenum. For room temperature reflectivity measurements, the nickel was in polished ribbon form. In all cases the nickel was mounted as filaments in lamp bulbs baked out in a furnace at a temperature of about 275 °C. Finally the bulbs were filled with commercial argon.

At incandescence, spectral emissivities were taken over the range 1300 °K to 1660 °K. No indication of a change with temperature was found, the average, in fact, agreeing with the two values obtained at room temperature by reflectivity. For 0.665μ, eight determinations gave $0.375 \pm .006$ (average deviation from the mean); for 0.535μ, five determinations gave $0.425 \pm .006$; for 0.460μ, fifteen determinations gave $0.450 \pm .013$.

The above together with previously published spectral emissivities are shown in Table III. The fact that the two single values obtained by the reflectivity method at room temperature are higher than all other values may mean that there was some deterioration of polish due to heating; though, in contrast with others, it may have produced a surface freeer from impurities. The uncertainty in the measurements could hardly by themselves account for the difference.

At incendescence there is a complete failure to check the results of Bidwell. From the standpoint of probable errors of pyrometry, Bidwell's lower values might seem preferable; but in substatiation of the present author's results, some melting point determinations may be quoted. A single determination sighting on the hole of a nickel tube gave 1723 °K, while the average of five groups using the method described for platinum gave 1720 ± 3 °K. Considering impurities this is not a bad check with 1725 ± 2 °K, which the work of

[22] Nernst and Wartenberg, Verh. Deut. Phys. Gesell. **8**, 48 (1906).

TABLE III

Published data on spectral emissivities of nickel in the visible region.

Author	Method	Red		Green		Blue		Remarks
		λ	e_λ	λ	e_λ	λ	e_λ	
		Roon temperatures						
Quincke[23] (1874)	Optical constant	.650μ	.336	.525μ	.396	.450μ	.437	As reported by Rubens.
Rubens[24] (1889)	Bolometric	.665	.340	.535	.385	.460	.390	From smoothed curve.
Drude[25] (1890)	Optical constant	.63	.363	.59	.380	....	....	
Hagen and Rubens[26] (1902)	Thermocouple	.665	.326	.535	.380	.460	.408	From smoothed curve
Hagen and Rubens[26] (1903)	Thermocouple	.65	.328	....	....	....	....	
Bernoulli[27] (1909)	Optical constant	....	....	.535	.365	.460	.378	From smoothed curve.
Henning[3] (1910)	Spectral-pyrometer	.665	.365	.535	.430	....	....	From smoothed curve.
Meier[28] (1910)	Optical constant	.665	.318	.535	.367	.460	.413	From smoothed curve.
Tool[29] (1910)	Optical constant	.665	.333	.535	.383	.460	.430	From smoothed curve.
Ingersoll[30] (1910)	Optical constant	.65	.322	....	....	....	....	
Bureau Standards[31] (1920)		.665	.340	.535	.377	....	....	From smoothed curve.
Worthing 1925)	Pyrometer	.665	.375	....	....	.460	.450	From smoothed curve.
		Incandescent temperatures						
Bidwell[32] (1914)	Pyrometer	.660	.250	....	....	....	....	T=1200°K (solid)
		.660	.215	....	....	....	....	T=1700°K (solid)
		.660	.215	....	....	....	....	Liquid at M.P.
Worthing (1925)	Pyrometer	.665	.375	.535	.425	.460	.450	1200°K<T<1650°K.

Holborn,[33] Day and Sosman,[34] and Burgess and Waltenberg[35] has standardized. To have obtained this value in the present case would

[23] Quincke, Ann. d. Physik **1,** 336 (1874).
[24] Rubens, Ann. d. Physik **37,** 249 (1889).
[25] Drude, Ann. d. Physik **39,** 481 (1890).
[26] Hagen and Rubens, Ann. d. Physik **8,** 1 (1902); **11,** 873 (1903).
[27] Bernoulli, Ann. d. Physik, **29,** 585 (1909).
[28] Meier, Ann. d. Physik **31,** 1017 (1910).
[29] Tool, Phys. Rev. **31,** 1 (1910).
[30] Ingersoll, Astrophys. J. **32,** 265 (1910).
[31] Bureau of Standards, Chem. Met. Eng. **24,** 73 (1921).
[32] Bidwell, Phys. Rev. **3,** 439 (1914).
[33] Holborn, Ann. d. Physik **56,** 361 (1895) (corr. by Ruer, Zeits. anorg. Chem. **51,** 224 (1906).
[34] Day and Sosman, Am. J. Sci. **29,** 93 (1910).
[35] Burgess and Waltenberg, Bull. Bur. Standards **10,** 79 (1914).

have necessitated using an emissivity 0.360 in place of 0.375 for 0.665μ. Were Bidwell's spectral emissivities used, a value of about 1800°K would have been obtained for the melting point. No other conclusion seems possible than that Bidwell's results are considerably in error, and that the present writer's results at incandescence, together with published careful determinations of the melting point, have a consisency which indicates their substantial correctness.

Spectral Emissivity of Gold

The gold used in this study was obtained in sheet form from Eimer and Amend. It was stated to be very pure and suitable for temperature standardizing. The gold for direct emissivity determinations was formed from a portion of the sheet rolled into a closed tube; the gold for reflectivity determinations was formed from small polished strips. All specimens tested at incandescence were mounted and operated like gas-filled lamp filaments. The results obtained for gold are shown in Fig. 5.

Much difficulty was experienced in handling gold. In polishing with rouge, the polishing material became embedded in the gold; and when such a polished strip was heated to incandescence, the presence of the embedded material was manifested at first by numerous bright specks on a comparatively dark background. These rapidly disappeared when the temperature was increased to about 1200 or 1300°K. It has been assumed for the filaments so polished that with such heating the embedded material was either driven off or diffused into the body of the ribbon leaving an essentially pure gold surface. In this report all values for rouge polished filaments refer to surfaces thus cleaned. When operated at about 1200°K, gold etches rapidly due to uneven vaporization, the surface tends to become mottled, and true reflectivity determinations are made difficult even when the etching lines are shallow. All reflectivity determinations made on rouge polished filaments in this work were subject to this difficulty. No such difficulty, however, is experienced in the direct emissivity determinations (*points of Fig. 5) using the tubular filament. The only error due to shallow etching lines would result from the variation from Lambert's cosine law, and for gold, when the lines are shallow, that error is negligible.

In a test of a suspected change in emissivity with heat treatment of gold (none was found), a great many careful reflectivity measurements at room temperature were made. In these cases the surface of the gold was scraped or shaved with a sharp razor blade and then the

specimen was rolled between two other polished razor blades. In all cases the surface was highly polished and under a high power microscope showed no indications of any embedded particles. The average of twelve determinations for 0.665μ gave for the reflectivity $0.938 \pm .010$ (average deviation from mean); the average of two for 0.535μ gave 0.648 ± 0.018; and the average of twelve for 0.460μ gave $0.367 \pm .014$.

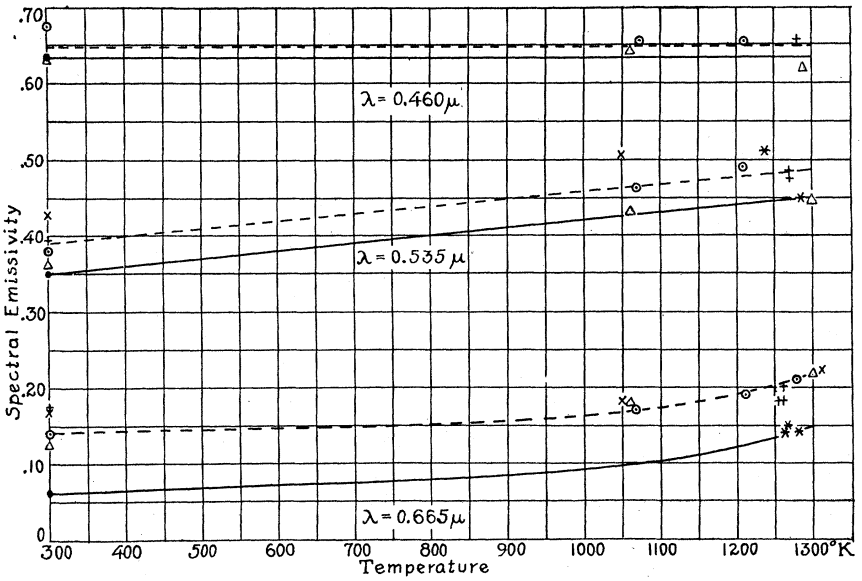

Fig. 5. Spectral emissivity of gold as a function of temperature.

X,Θ,+,Δ values obtained by reflectivity method on rouge polished ribbon filaments showing etching due to heating

* values obtained by direct method on tubular filament

•averages of many determinations by reflectivity method using ribbon filaments, which though highly polished were not contaminated with polishing material

---- averages of X,Θ,+, and Δ values, no corrections being made for effects due to etching

———expected averages for uncontaminated material

These results (*points of Fig. 5) have been assumed to be the correct reflectivities for gold at room temperature.

The full line curves, representing expected emissivities, have been drawn in accord with the assumption that the observed reflectivities using etched filaments (dashed curves) should be increased throughout by the ratio necessary to yield the more dependable values at room temperature. It is quite satisfying to note that the curve thus obtained for 0.665μ agrees very well at incandescence with the directly

observed emissivities using the tubular filament. At 0.535μ one of the two directly observed emissivities falls on the corrected curve, but the other falls considerably off. A possible explanation is that, in this case, the orientation of the tubular filament, along whose length there ran a narrow slit, was such in this particular instance as to prevent the complete blackening of the radiation from the interior in the direction from which it was viewed.

TABLE IV

Published data on spectral emissivities of gold in the visible region.

Author	Method	Red		Green		Blue		Remarks
		λ	e_λ	λ	e_λ	λ	e_λ	
		Room temperature						
Quincke[23] (1874)	Optical constant	.65 μ	.086	.525μ	.293	.450μ	.652	As reported by Rubens.
Rubens[24] (1889)	Bolometric	.665	.128	.535	.335	.460	.566	From smoothed curve.
Drude[25] (1890)	Optical constant	.63	.105	....	....	....	....	
		.59	.149	....	....	....	....	
Hagen and Rubens[26] (1902)	Thermocouple	.665	.098	.535	.330	.460	.650	From smoothed curve.
Hagen and Rubens[26] (1903)	Thermocouple	.650	.108	....	....	....	....	
Meier[18] (1910)	Optical constant	.665	.120	.535	.335	.460	.565	From smoothed curve.
Tool[29] (1910)	Optical constant	.665	.082	.535	.315	.460	.640	From smoothed curve.
Tate[36] (1912)	Photometric Opt. const.	.665	.160	.535	.395	.460	.635	From smoothed curve.
Försterling and Friederickz[37] (1913)	Optical constant	.67	.045	....	....	....	....	
Worthing (1925)	Pyrometer	.665	.062	.535	.352	.460	.635	
		Incandescent temperatures						
Stubbs and Prideaux[38] (1912)	Photometric	.665	.120	.535	.410	.495	.531	Solid just below M.P.
		.665	.208	.535	.405	.495	.473	Liquid just above M.P.
Bidwell[32] (1914)	Pyrometer	.660	.125	....	....	....	....	Solid and liquid near M. P.
Burgess and Waltenberg[39] (1914)	Pyrometer	.650	.145	.550	.38	....	....	Solid at 1275°K
		.650	.219	.550	.38	....	....	Liquid just above M.P.
Worthing (1925)	Pyrometer	.665	.140	.535	.448	.460	.632	Solid at 1275°K

A comparison of the emissivities obtained with previously published data is shown in Table IV. At room temperature, viewed from the reflectivity standpoint (unity less emissivity), there is general excellent

[36] Tate, Phys. Rev. **34**, 321 (1912).

[37] Försterling and Friederickz, Ann. d. Physik **40**, 201 (1913).

[38] Stubbs and Prideaux, Proc. Roy. Soc. **87A**, 451 (1912).

[39] Burgess and Waltenberg, Bull. Bur. Standards **11**, 591 (1914).

agreement between published values. From the emissivity standpoint, however, the checks on a percentage basis are not good. The present author's value for 0.665μ with a single exception is lower than that of others. Whether or not the polishing by pressure, rather than by means of the more common method employing rouge with its possibilities of embedding polishing material in the gold, is the explanation cannot well be stated. That the differences shown in the table for 0.535μ should not only relatively but numerically be generally less and those for 0.460μ still less, is in agreement with the supposition of embedded polishing material as a source for discrepancies. Thus, some unintentional confirming tests with rouge-embedded gold specimens indicated an apparent change in emissivity for the specimens which at 0.655μ was over five times as great as at 0.460μ.

At incandescence, at 0.665μ, there is a moderately good agreement in published emissivities. For the green and blue regions of the spectrum the agreement does not seem to be quite so good, though due to the diversities of wave-lengths it is difficult to say so definitely. Altogether, the writer has considerable confidence in the results which he has presented.

An interesting point which may be with or without significance is to be seen when comparisons of emissivity variations with temperature are made for gold and tungsten. Weniger and Pfund[40] found for tungsten that at 1.27μ there was no change in emissivity with temperature, while for longer wave-lengths there was a definite progressive increase in emissivity with increase in temperature, and for shorter wave-lengths, as was known before, a definite progressive decrease. The present work suggests a similar relation for gold with 0.460μ as the wave-length corresponding to 1.27μ; and it is interesting to note, though it may be a mere coincidence, that these wave-lengths are in direct proportion to the melting point temperatures. Thus $1.27\mu/0.46\mu$ equals 2.76, while $3655°K/1336°K$ equals 2.74.

In conclusion the writer wishes herewith to acknowledge his indebtedness at different times in the progress of the work to Lester Boss, Ruth Sublett Haas, Pauline Perkins, and John Kirschner.

NELA RESEARCH LABORATORY,
August, 1925.*

[40] Weniger and Pfund, Phys. Rev. **14**, 427 (1919).

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