THE REFLECTING POWER OF VARIOUS METALS

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CONTENTS

INTRODUCTION

The present observations are the result of an attempt to obtain a more thorough knowledge of the optical properties of the metals used in incandescent lamps. Several other elements on the border line between the metals and nonmetals, not heretofore examined, are included, since the data are of general interest.

In a paper on the radiation constants of metals [1] attention was called to the fact that all the pure metals thus far examined have

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[1] This Bulletin **5**, p. 339; 1908. So also this Bulletin, **2**, p. 470; 1907, for illustration of the reflectivities of various metals.

the common property of a low reflecting power in the ultra-violet and in the visible spectrum, which rises more or less abruptly to very high values beyond 2μ in the infra-red, and that it was therefore not unreasonable to assume that the unexamined metals, such as tungsten and osmium, have this same property. This follows from the fact that all the members of a group of chemically related substances have similar physical properties. As will be noticed on a subsequent page, this assumption of a low reflectivity in the visible spectrum has been verified to a degree far beyond expectation.

Since the reflectivity of metals is a smooth and continuous function of the wave length in the infra-red, there is reason for expecting the reflectivity curves of these heretofore unexamined metals (tungsten, tantalum, etc.) also to be smooth and continuous. Their spectral energy curves must therefore be smooth and continuous in the infra-red (no indentations or protuberances), and experimental curves showing such indentations are to be regarded with suspicion as to the accuracy of the observations.

It is difficult to show experimentally this selective emission in other than colored metals (e. g., gold and copper) by means of emission spectra, and since the emissivity in the short wave lengths appears to have only a small temperature coefficient it is possible to gain some knowledge of the emissivity of the metal at high temperatures by determining its reflectivity at low temperatures. That it is permissible to apply data obtained at low temperatures to the same substance operated at high temperatures follows from the recent work of Hagen and Rubens,[2] in which it is shown that for wave lengths less than 4μ the optical constants of metals vary but slightly, if at all, with change in temperature, which is the region of the spectrum of interest on the question of the selective emission of incandescent lamps with metal filaments. We have therefore a positive qualitative proof of the much discussed and much overworked application of "selective emission" (combined with a high operating temperature) to explain the high luminous efficiency of metal filament lamps. As will be noticed in the appended illustrations, the selective emission must lie in

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[2] Hagen & Rubens, Phys. Zs., **11**, p. 139, 1910; Verh. Phys. Gesell., **10**, p. 710; 1908.

the visible spectrum. Here the emissivity is almost 50% (for tungsten) while in the infra-red it is only from 4 to 10% that of an ideal radiator, or "black body."

In the present experiments a fluorite prism, a mirror spectrometer, and a new vacuum bolometer were used. The unknown metal was compared with a new silvered glass mirror of which the reflecting power is known. The absolute value of the reflectivity of the unknown metal was obtained by multiplying the observed reflectivity by the reflectivity of silver given in Table II (data from Hagen and Rubens).

A Nernst glower was used as a source of radiation, which permitted making observations in the extreme blue and at 10μ where the fluorite prism is almost opaque. Since the glower is very narrow it is necessary to have a very accurate adjustment of its images, reflected from the two mirrors upon the spectrometer slit, so as to avoid a systematic error in the reflectivity. The observations in the infra-red were further verified by using a Nernst "heater" instead of the glower.

In the blue and beyond 8μ in the infra-red the accuracy is of the order of 2 to 3%, while in the intervening region the accuracy is of the order of 1 per cent. There is no difficulty in obtaining high accuracy since we are concerned only with ratios of two numbers (galvanometer readings) which are of nearly the same value, and which are subject to the same errors of observation. In view of the physical nature of the material, and especially of the size of the specimens obtainable, and also of the indirect comparison with silver, it would be illusory to attempt to attain a higher accuracy for the absolute values. This is especially true of tungsten and molybdenum in which the mirror surface was ground upon one face of a rectangular prism of the pure metal 20 x 6 x 6 mm on an edge, kindly prepared for us by the General Electric Company. The narrowness of the specimen does not permit the grinding and polishing of an optically plane surface. The dimensions of the tantalum mirror were 15 x 10 x 1 mm; it was prepared by Siemens and Halske and was optically plane and highly polished. The close agreement between the observed reflectivity of tungsten and molybdenum at 12μ and the theoretical value obtained from a knowledge of the electrical conductivity is therefore to be regarded as somewhat accidental. The angle of incidence of the light upon the mirrors was from 12 to 15 degrees, which is sufficiently small to be considered normal incidence, and hence the loss by absorption (100-reflectivity) is a measure of the emissivity of the metal.

From his observations on the optical constants (the refractive index *n*, and extinction coefficient *k*), at 0.579μ Wartenberg[3] computed the reflecting power of various metals, some of which are included in the present paper. It will be noticed in Table I that the results obtained by the two methods are in excellent agreement in all samples having a good polish.

TABLE I

Substance	Reflecting Power	Substance	Reflecting Power
Manganese............	63.5 p. c.	Tungsten............	48.6; *51
Chromium............	69.7; *55	Palladium............	65.0
Vanadium..............	57.5; *57.5	Rhodium............	78.3; *77.5
Tantalum............	43.8; *45	Platinum............	72.5
Niobium..............	41.3	Iridium..............	74.6; *75
Graphite..............	22.3; *23	Silicon..............	35.7; *32

*Observations by W. W. C.

It will be noticed that even in the visible spectrum the same magnitude of the reflectivity is to be found within a group of metals. For example, in the platinum group the reflectivity does not fall below 70 per cent, while in the chromiun group the reflectivity centers about the 60 per cent point. However, only beyond 12μ is this relationship true in general.

TUNGSTEN

The area of the mirror examined was 5 mm x 17 mm. This specimen was made from the pure material, which is somewhat brittle and did not permit a polished surface perfectly free from pores, except in the center. This causes a slight scattering for wave lengths up to 3μ (see discussion under graphite).

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[3] Wartenberg, Verh. Deutsch. Phys. Gesell., **12**, p. 105; 1910. Hennig. Zeit. Instk 30, 61, 1910; gives similar data on the reflectivity observed by direct measurement.

TABLE II

Wave length in μ=.001 mm	Reflecting Power													
	Silver	Platinum	Rhodium	Tungsten	Molybdenum	Iron	Tantalum (Wartenberg's sample)	Chromium	Vanadium	Antimony	Silicon	Magnesium	Tellurium	Graphite
.40μ	84.0	48	......	47.0	44.0	......	....	......	......	......	......	....	......	21
.46	89.0	55	......	48.2	44.6	......	....	......	......	......	......	....	......	22
.5	90.0	58.4	76	49.3	45.5	55.0	38.0	55	57.0	......	34	72.0	......	22.5
.6	92.5	64.2	......	51.3	47.6	57.5	45	......	......	53	32	73.0	49	23.5
.7	94.2	69.0	79	54.0	49.8	59.5	56	56	58.5	......	30	....	......	24.0
.8	95.1	70.3	81	56.3	52.3	61.5	64.5	......	59.5	......	29.2	....	48	25.0
1.0	96.4	73.0	84	62.3	58.2	65.0	78.5	57	61.3	55	28	74.0	49.5	26.8
1.2	97.2	75.0	86.5	68.2	63.6	68.5	84	......	63	......	......	....	50	28.3
1.4	97.6	76.8	88.3	73.8	69.0	71.5	86.5	59	64.5	......	28	75	.....	30.0
1.6	97.8	78.0	89.5	78.0	74.2	74.3	88	61	66	58	......	....	51	32.0
2.0	97.9	80.6	91	84.6	81.6	78.0	90.5	63	69	60	28	77	52	35.2
2.5	97.9	......	91.6	89.2	85.5	81.5	91.6	66	71.7	......	......	79	53	39.5
3.0	98.0	88.8	92	90.5	87.6	84.5	92.3	70	74.3	65	28	80.5	54	43.0
3.5	98.3	......	......	92.0	89.2	87.5	92.8	......	76.7	......	......	....	55	46.0
4.0	98.4	91.5	92.5	92.8	90.5	89.5	93.0	76	78.8	68	28	83.5	57	47.5
5.0	98.5	93.5	93	94.0	92.0	91.5	93.0	81	82	......	......	86	60	50.5
6.0	98.6	......	93.5	94.6	93.0	93.0	....	85	85	70	28	88	63	52.0
7.0	98.6	95.5	93.5	95.1	93.3	94.0	93.5	......	87.8	......	......	91	68	53.5
8.0	98.8	95.1	94	95.6	93.7	94.0	93.8	89	89.8	......	......	93	72	55.5
9.0	98.9	95.4	94.5	95.5	94.0	93.8	....	92	92	72	28	93	78	57.5
10.0	99.0	95.9	......	95.5	94.5	......	....	93	......	......	......	....	......	59.0
12.0	98.9	96.5	......	96.3	95.2	......	95.0	......	......	......	......	....	......	......
12.0 μ	......	......	......	*97.2	*97.3	......	*95.3	*97	......	......	......	....	......	......

*** Values computed from the electrical conductivity.**

In Fig. 1 and in Table II it will be noticed that the reflectivity of tungsten rises abruptly from a low value of 50 per cent in the yellow to 89 per cent at 2.5μ, beyond which point it increases gradually to 96 per cent at 10μ. This is a characteristic of pure metals.

Hagen and Rubens[4] have shown that for long waves (greater than 12μ) the absorption (100-reflectivity) of a metal may be computed from its electrical conductivity by means of the formula $100 - R = \frac{36.5}{\sqrt{c\lambda}}$, where R is the observed reflecting power, c is the reciprocal of the resistance, in ohms, of a conductor 1 m long and 1 sq. mm in cross section, and λ = wave length in μ = .001 mm.

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[4] Hagen & Rubens, Ann. der Phys. (4) **11**, p. 873; 1903. Coblentz, this Bulletin, **2**, p. 470; 1907.

The specific resistance of a squirted rod (hence probably not so pure as the mirror material) of tungsten 20 cm long and 1.2 mm in diameter was determined by Mr. J. H. Dellinger to be 0.000 006 9 ohm per centimeter cube at 21°.8 or 3.99 times that of copper. The sample of tungsten upon which the reflectivity oberservations were made had a specific resistance of 0.000 006 3 at 21°.5 C, or 3.66 times that of copper. Its density was 10 (true value about 19 or 20), which indicates that there were hollow spaces along the axis of prism of metal, which was about 2.5 cm long and had been broken from a longer rod. At one end of this specimen there was a small cavity, but it was not possible to tell how far it extended along the central axis of the specimen. This would cause a higher resistance than the true value. Recent determinations by Fink and by Parani indicate a specific resistance of about 0.000,005 for annealed tungsten. From the specific resistance of this sample of tungsten the computed reflectivity, from the aforesaid formula, using λ = 12μ, is 97.3 per cent, while the value obtained by extrapolating from 10μ is 96.3 per cent. As already stated, this is in closer agreement than is to be expected from the observations and from the size of the mirror employed. It may be noticed in Table II that the infra-red reflectivity of tungsten is the same as that of platinum, and in the visible it is the same as that of steel.

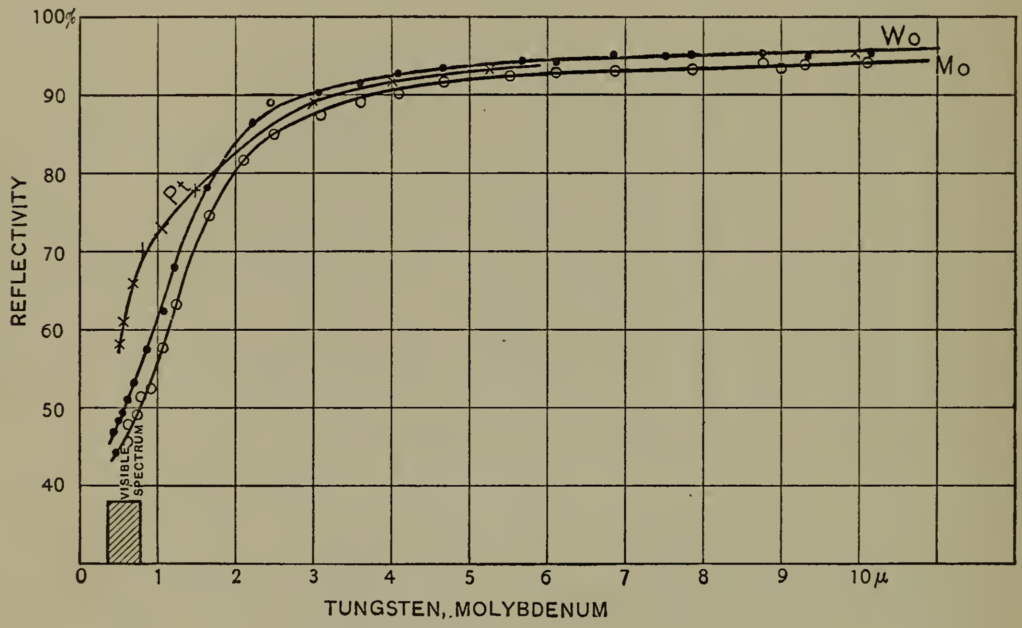

Fig. 1

For a perfectly polished surface, free from pores, the reflectivity of tungsten would be somewhat higher out to 2μ, because of the elimination of the diffuse reflection which obtained in the present sample. (See graphite, which gives an extreme case of diffuse reflectivity.) The results show that in the previous investigation of the radiation constants of metals, it was permissible to assume that the same emissivity function obtains as in platinum, with, of course, different numerical values of the constants.

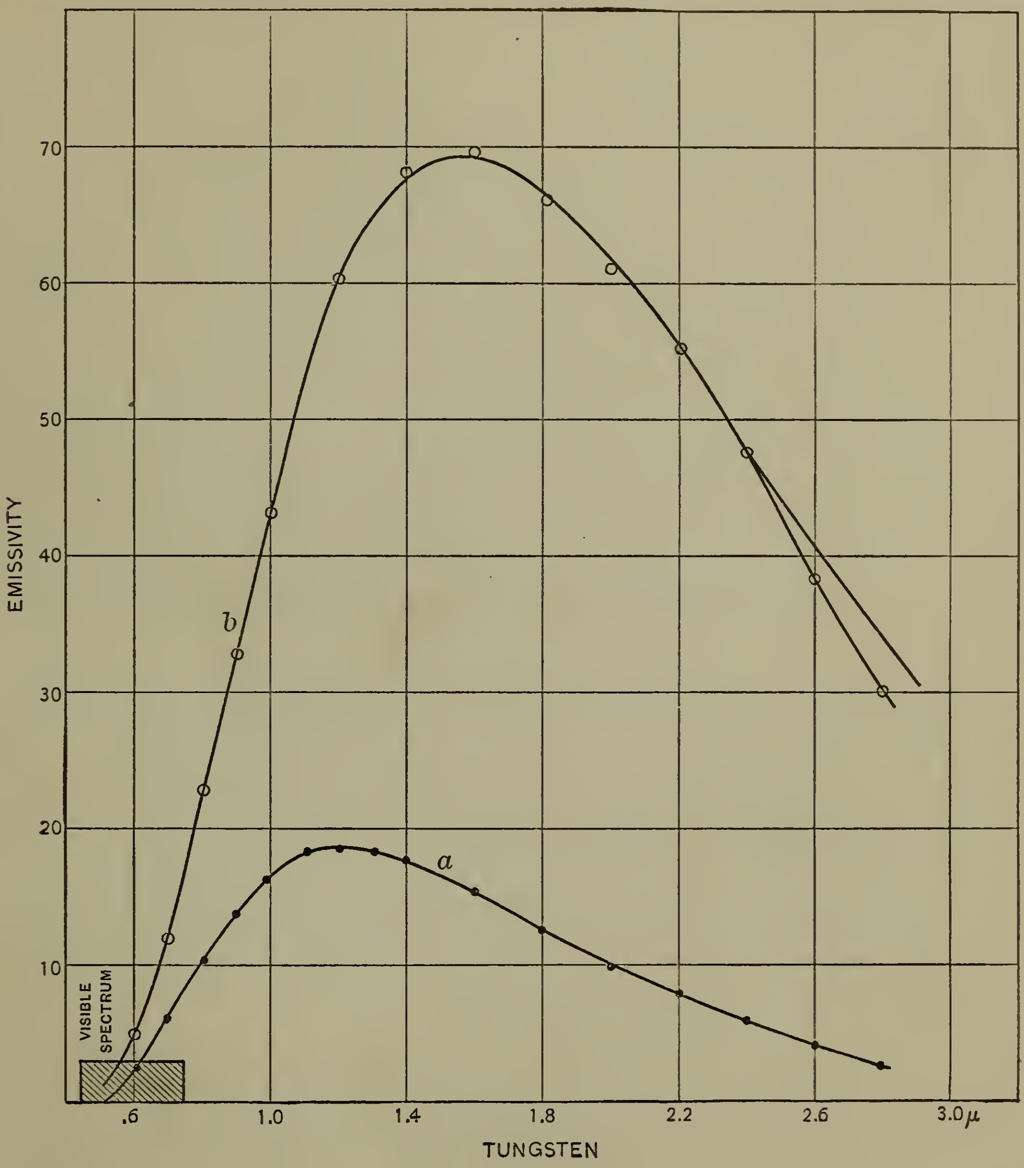

Fig. 2

In Fig. 2, curve *a*, is given the spectral energy curve of a new 110-volt, 32-candlepower tungsten lamp when on a normal operation of 55 watts. The mean value of the radiation constant for this lamp was previously computed[1] to be about $\alpha = 6.5$, the variations in the individual computations being rather large. The spectrometer calibration has just been recomputed, which is more accurate than the one then employed. The new computation of this radiation constant is not sufficiently different from the old one to warrant a revision of the data then published, although the individual computations are in closer agreement. The new value of the $\lambda_{max} = 1.225\mu$ (old $\lambda_{max} = 1.257\mu$) and the new $\alpha = 6.2$, the shift in the new calibration curve being about 0.02μ toward the short wave lengths. On the basis of the new calibration curve the wave lengths of maximum emission are too large by about 0.02μ. The radiation constants are also too large by 3 per cent to 5 per cent. Since the individual computations vary by this amount, and since different samples of the metal filaments seem to be subject to variation, the old values are probably as trustworthy as would be the revised ones. The experimental data does not indicate a variation of the constant "α" with wave length. For, at any temperature, the values of "α" are all high or all low irrespective of the wave lengths selected in the computations.

The reflection curve and the radiation constant ($\alpha = 6.2$) are in close agreement with that of platinum. We are therefore in a position to make comparisons with platinum of which the radiation constants are fairly accurately known. Using the $\lambda_{max} T = 2620$ of platinum, and the observed $\lambda_{max} = 1.225\mu$ of tungsten, the operating temperature of the aforesaid lamp was 1870° C. Féry and Chéneveau (Compt. Rend., 149, 777, 1909) by using radiation methods obtained 1875°.

From the observed radiation curve *a*, Fig. 2, we can obtain the black body curve, *b*, at the same temperature, by dividing the observed emissivities by the observed absorptivities (100-reflectivity) of tungsten given in Fig. 1. The maximum emission lies at about $\lambda_{max} = 1.45\mu$ from which the computed temperature is about 1760° C. This value is no doubt somewhat too low, because no account was taken of the loss by diffusion in the reflection curve at 0.6 to 2μ. Using the reflectivity values of platinum which are in all probability higher than the true values of tungsten, the $\lambda_{max} = 1.38\mu$ in place of $\lambda_{max} = 1.45\mu$ and $t = 1860°$ C, which is probably too high. The computed values of α, from curve *b*, Fig. 2, vary from 4.6 to 5.5 while the experimental value for a "black-body" is $\alpha = 5$. This shows that curve *b* is not a true "black-body" radiation curve. There are two evident reasons for this discrepancy. First, the observed curve *a* has not been corrected for absorption by the glass walls of the lamp, which would give an emissivity at 2.5μ somewhat as shown by dotted lines in Fig. 2. Second, the reflectivity is not known with sufficient accuracy at 1.5 to 2μ (because of diffuse reflection due to the fine pores in the specimen examined) where a small error in the reflectivity has a very large effect in the position of the maximum of the radiation curve. If it were not for this difficulty, this method could be used for estimating temperatures of metal filaments of known reflecting power (using perfect mirrors for determining the reflectivity), but of which it is impossible to measure the temperature directly. Since the emissivity and the reflectivity are functions of the refractive index and of the absorption coefficient, and since in considering the emissivity we are not concerned with the scattering effect, it does not seem necessary to consider the question of the "blackening" of the radiation due to the porosity of the filament, so long as the size of the pores are of the same magnitude as the wave length of the emitted light. This case seems to be different from the experiment in which the mechanical scratches, made in a strip of incandescent metal, show a higher emissivity than the outer surface. The present observations and those of Waidner and Burgess[5] seem to indicate that on "normal" operation the tungsten filament is at a temperature of 1850° C to 2200° C.

MOLYBDENUM

The area of the mirror examined was 5 mm x 17 mm. The reflecting surface had a very much higher polish than the sample of tungsten just described. To the eye it was apparent that the molybdenum had a higher absorption than the tungsten mirror. This is illustrated in the bolometric comparison, shown in Fig. 1, which indicates a reflectivity of only 46 per cent in the yellow,

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[5] Waidner and Burgess, this Bulletin, 2, p. 319.

which rises abruptly to 85 per cent at 2.5μ beyond which point the reflectivity gradually increases to 95 per cent at 10μ. The specific resistance of two samples of molybdenum wire, drawn to a uniform diameter, was determined by Mr. Dellinger. The wires were respectively 15 cm and 20 cm in length, 0.627 mm and 0.815 mm in diameter, and the corresponding specific resistance was .000 006 4 and .000 006 2 at 21°.5. This is about 3.6 times the resistance of copper and practically the same as that of tungsten. From this it appears that the reflectivity of molybdenum should be as high as that of tungsten at 12μ. The observations indicate the opposite condition. No systematic errors could be detected in the observations and the only explanation which can be offered at present is that the size of the reflecting surfaces was too small to establish a true absorption to a greater accuracy than 2 per cent at 12μ. This, however, is not a large discrepancy when it is recalled that in some of the earlier work, using larger mirrors of known curvature, errors almost as large as these are on record.

The reflectivity curves of molybdenum and tungsten are so nearly alike that from a consideration of their emissivities and luminous efficiencies there seems to be no great choice in the use of these two metals in incandescent lamps. On the other hand, from a consideration of their physical properties, the molybdenum filament would be the preferable because it seems to retain its toughness and its ductility, in contrast with tungsten which seems to become crystalline and brittle after being operated, for a while, at a high temperature. The melting point of molybdenum is quite high, and it is principally a question of overcoming certain physical weaknesses, such as disintegration, in order to make this material useful for incandescent lamp filaments.

GRAPHITE

Two samples of graphite were examined, the one being the natural mineral from Siberia. Its reflecting surface was 4 cm x 5 cm. The second sample, curve *b*, Fig 3, was a longitudinal section of a rod, 8 mm in diameter, of Acheson's graphite. It could not be burnished free from pores which were rather large, and which caused a scattering of the radiation, out to 4μ in the infra-red. Beyond this point it reflects as highly as the natural Siberian mineral, shown in curve *a*, Fig. 3. The natural mineral was very compact, but showed the rays and fibrous structure of the original plant or tree from which it was formed. It was burnished or "polished" on a semi-matte piece of plate glass. A thoroughly ground glass was too rough, while the smooth plate was found equally inapplicable. The partly ground glass seemed to hold just sufficient material to work into the softer parts without accumulating sufficient loose material which would roughen the surface. The glass plate was kept wet with clean water and by the application of some pressure it was possible to prepare a very highly polished surface.

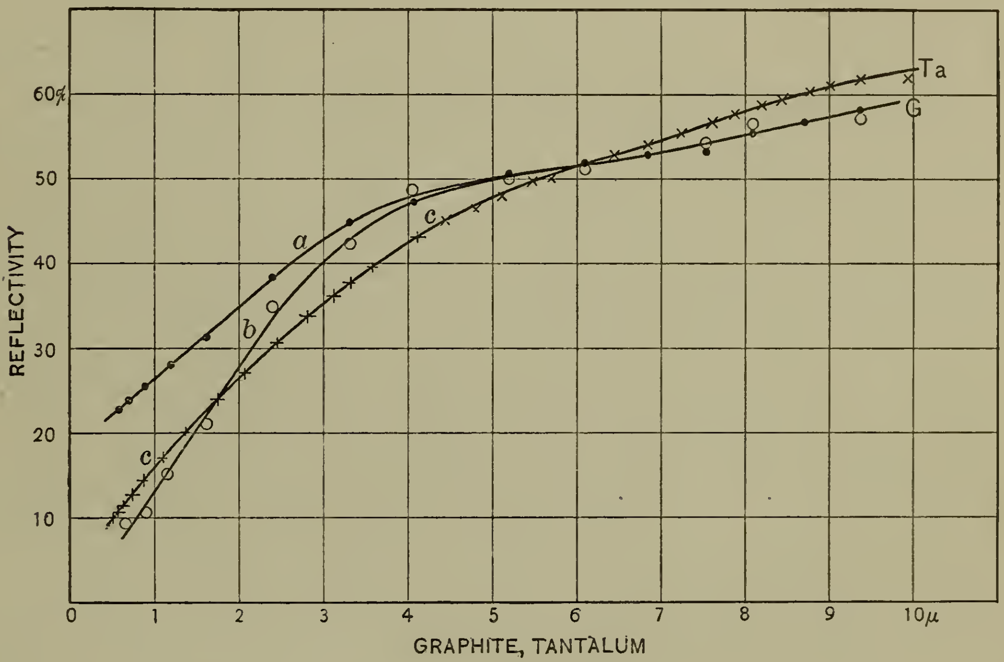

Fig. 3

The reflectivity is 23 per cent in the yellow, gradually increasing to 63 per cent at 10μ. From the low reflectivity at 2μ in the infra-red there results a high emissivity (in contrast with the metals), hence the graphatized carbon filament can not have the same luminous efficiency as the tungsten lamp at the same temperature, although it has the higher emissivity in the visible spectrum.

TANTALUM

The utilized area of the tantalum mirror was 9 mm x 14 mm. In spite of its excellent polish, it showed an exceedingly low reflectivity throughout the spectrum, as compared with pure metals.

The curve *c*, in Fig. 3 represents three series of observations, using different adjustments, the measurements usually agreeing to one part in 100 to 200. In the visible spectrum the reflectivity is only 10 per cent, which gradually increases to 63 per cent at 10μ. There is no indication of an approach to constant reflectivity, in in the infra-red, such as obtains in pure metals. Subsequent correspondence with the maker showed that this surmise of an impure metal was correct. The surface was rendered impure by working and polishing which, by the action of gases, formed an exceedingly hard surface layer. From the writer's experience it appears that the ease with which a tantalum mirror becomes contaminated in polishing depends upon the previous history of the metal. For example, the regulus of tantalum obtained from Von Wartenberg [6] had never been rolled or hammered, and it was found that, in polishing it, any contamination, such as for example, the blackening caused by a film of oil, was easily removed. On the other hand, a film of oil on the mirror just described, which had evidently been worked down from a regulus (Fig. 3, *c*) formed a brown coating which was removed with great difficulty.[7] The rear side of this mirror was therefore ground flat on fine emery paper, which for the final polish was covered with a layer of alcohol and graphite. By stroking lightly and lifting the mirror soon after the alcohol had entirely evaporated, a clean surface was produced which was almost free from scratches. The old surface, of which the reflectivity is given in Fig. 3, was so hard that it could not be polished by this method.

The contrast between the reflectivity of the old contaminated surface and the new surface, polished as just described, is shown

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[6] Von Wartenberg, Verh. Phys. Gesell., **12**, p. 121; 1910. He found that tantalum was not contaminated by polishing.

[7] See further a recent investigation by Parani, Verh. Phys. Gesell., **12**, p. 301, 1910, who likewise finds that tantalum is easily contaminated by gases.

in Fig. 4. Curve *c* gives the reflectivity of the new surface as produced by the fine dry emery paper, the scratches being quite deep. Curve *a* gives the reflectivity of the same mirror after giving it the final polish with graphite and alcohol, when only very fine scratches remained. In the latter case the scattering is almost eliminated, and the reflectivity rises abruptly from 39 per cent in the yellow to 85 per cent at 2.5μ, beyond which point the rise is gradual to 94 per cent at 9μ. The theoretical reflecting power, at 12μ, computed from the electrical conductivity, is about 95.7 per cent.

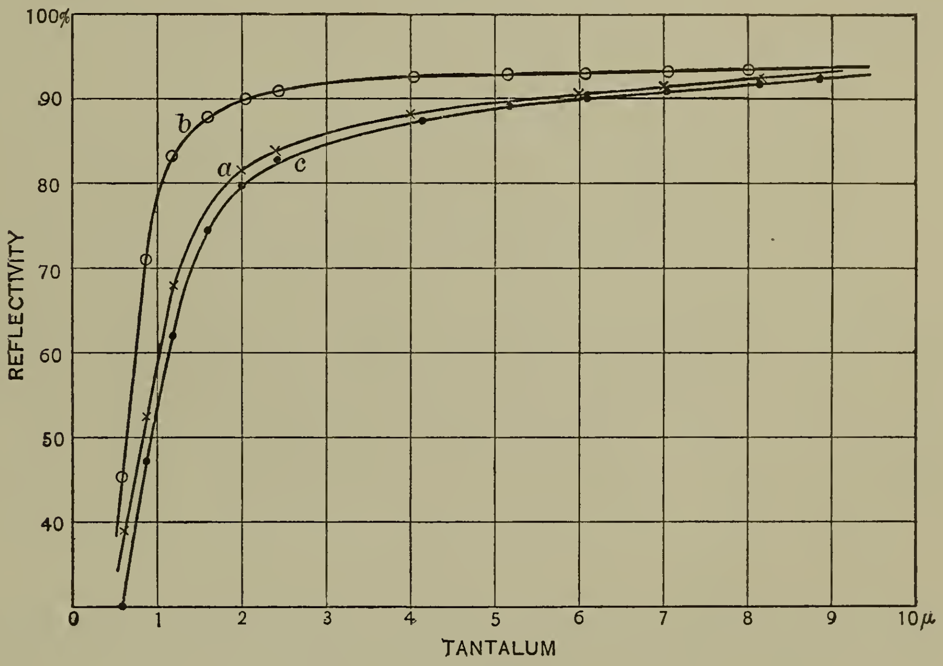

Fig. 4

Through the kindness of Dr. Von Wartenberg an opportunity was granted to examine the tantalum regulus mirror used by him in determining the optical constants in the visible spectrum. The area of surface which could be used was only about 2.5 mm x 3 mm, and hence it was impossible to obtain the absolute reflectivities with high accuracy. There was no difficulty in obtaining the relative values for different parts of the spectrum, which is the point of most interest. The surface of the mirror was perfectly free from scratches. The reflectivity, which is shown in curve *b*, Fig. 4, rises even more abruptly to high values than was found in the first sample. In this respect, pure tantalum, zinc, and silver stand unique among the metals. Because of the steepness of the reflectivity curve, the emissivity of tantalum in the visible spectrum must be more selective than obtains in tungsten and molybdenum. Furthermore, since the reflectivity of pure tantalum is higher than that of tungsten at 1 to 2μ, it must have the higher luminous efficiency.

The reflectivity of the regulus of pure tantalum as observed by two methods (Wartenberg computed R from the "optical constants") is about 45 per cent in the yellow. The other mirror appeared much darker, so that the lower reflectivities as shown in Fig. 4 are to be attributed to impurities. The tantalum regulus appeared as bright as the prism of tungsten already described. The most casual observation shows that the tungsten filament has a much whiter metallic luster than a tantalum filament. This may be due to contamination in drawing the tantalum wire, especially if drawn with oil as a lubricant. It appears that in tungsten all the impurities can be driven off at high temperatures. This is not necessarily true of tantalum, which occupies an anomalous position in the scale of luminous efficiencies of metals.

From the observations of Waidner and Burgess, who found that the "normal" operating temperature of tantalum is about 2000 C, it is evident that its low luminous efficiency is not due to a low operating temperature, such as would be necessary with platinum.

Incandescent lamps of tungsten and osmium have an efficiency of about 1.25 watts per candle, while for no apparent reason tantalum must be classified with graphitized carbon with an efficiency of about 2 to 2.5 watts per candle.

The foregoing data on the reflectivity of tantalum and graphite (Fig. 3) shows that this classification is consistent. The radiation constants of these two substances are almost the same (total radiation; tantalum proportional to the 5.3-power of temp.; graphitized filament proportional to the 5.1-power of temp.), and the manner in which they differ is in the right direction, since graphite is a nonmetal. Hence, while it was somewhat contrary to expectation to find such a low reflectivity in the infra-red for impure tantalum, this is not inconsistent with other data such as the radiation constants.

There seems to be a prevailing notion that the polish of the metal filament is of great importance, but it is not apparent how roughness or scratches can cause a "blackening" of the radiation by successive reflection within the cavities so long as the latter are of the order of the wave length emitted. It is the absorption coefficient and the refractive index that must be considered. This is especially conspicuous in tantalum filaments. When new they have a brownish luster, while the filaments of old lamps are decidedly black. Similar filaments of osmium retain their gray appearance even after becoming crystalline. Under the microscope the crystalline tantalum filament appears much darker than tungsten, although the actual polish of the crystal surfaces of the latter is much higher. Some crystals appear as dark as highly polished jet or fine grains of stibnite, which has a reflectivity of only about 35 per cent. This low reflectivity in the visible spectrum produces a high emissivity, but, contrary to the properties of the pure material, the reflectivity continues low (emissivity high) in the infra-red, which tends to lower the luminous efficiency.

The ideal solid illuminant must fulfill the conditions of a high operating temperature, and a high emissivity in the visible spectrum. As shown in Fig. 1, of all the metals thus far examined, tungsten approaches nearest to the fulfillment of these conditions.

ANTIMONY

It was found impossible to produce a perfect mirror of antimony, so that the absolute values obtained have little weight. Since the main object in the present work is to show the relative values of reflectivities in the visible as compared with the infra-red, the results obtained on several antimony mirrors are here recorded. As with all the other metals, larger surfaces, either plane or of known curvature, must be used for high accuracy in the absolute values.

Two samples of antimony were examined, the one being a mirror (5 mm x 17 mm) polished upon a cleavage plane of a large crystal of the metal (from Kahlbaum), the other being a mirror formed in vacuo by cathode disintegration. The reflectivity of the polished cleavage piece is shown in curve *a* of Fig. 5. The reflectivity is low, due to the presence of numerous large-sized pores which resulted in the polishing. Two cathode mirrors were also examined. The first one contained small holes caused by dust particles on the glass surface, which seemed to permit radiation from the rear surface of the glass (2 mm in thickness) to return on its path, thus causing a wavy reflection curve with maxima of about 65 per cent at 1.2μ, 2.5μ, and 4μ, and minima of 55 to 60 per cent at 2μ, 3.3μ, and 6μ, beyond which point the reflectivity increased gradually to 68 per cent at 9μ. On removing the rear mirror surface the maxima and minima were destroyed. A second mirror (5 mm x 17 mm), free from dust holes, and with the rear surface of glass free from metal, was examined, the data being plotted in curve *b*, Fig. 5. The reflectivity rises from 53 per cent in the yellow to a fairly uniform value of 72 per cent at 9μ.

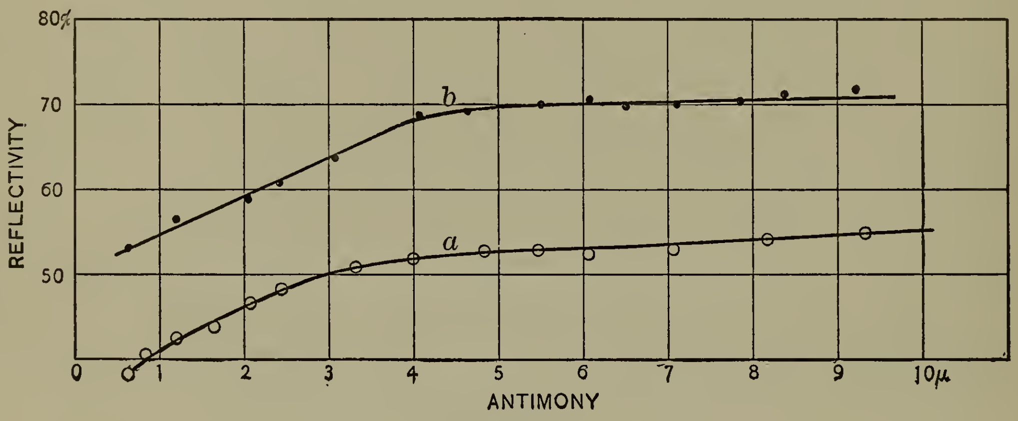

Fig. 5

In view of the difficulty in producing a mirror which is free from carbon, by the cathode discharge, and in view of the fact that the mirror seemed darker than one would expect, judging from the appearance of the crystals, it seems probable that the reflectivity is somewhat higher than here recorded. However, in view of the fact that antimony departs considerably from the true metals, the low reflectivity throughout the spectrum is probably to be expected, as will be noticed presently in several other metals which lie on the border line between the electrical conductors and the insulators.

In conclusion, it may be added that cathode mirrors of antimony are easily produced in 5 to 7 minutes, by using a heavy current. The tendency is for one to continue the discharge for a longer period than this, with the resultant oxidization of the central part of the mirror. By using a residual atmosphere of hydrogen and a low current, excellent large-sized mirrors are produced in half an hour.

RHODIUM

The sample examined was kindly loaned by Dr. Von Wartenberg. The area of the surface examined was 5 mm x 5 mm. Several small blowholes were present, which, with the smallness of the surface, did not permit high accuracy in the absolute values of the reflectivities. The reflecting power (Fig. 6), *Rh*, rises abruptly from 77 per cent in the yellow to 92 per cent at 2.5μ, beyond which point the rise is gradual to about 94 per cent at 9μ.

IRIDIUM

The mirror examined was a thick plate of the metal, which in the polishing had not been perfectly freed from pores, which caused scattering. The reflectivity in the yellow was only 53 per cent, which increased to 75 per cent at 2μ and to 90 per cent at 8μ. This same plate was examined several years ago[8] when it had a finer polish. The reflectivity, Fig. 6, *Ir*, was found to increase from 79 per cent at 1μ to 95 per cent at 9μ. Its reflectivity seems to be somewhat higher than platinum in the visible spectrum.

IRON

The sample of iron examined had a purity of 99.8 per cent. The chief impurities were .15 per cent copper, .02 per cent manganese, and .02 per cent carbon. The sample took a high polish and reminded one somewhat of palladium in its general appearances. The reflectivity, Fig. 6, *Fe*, rises gradually with increase in wave length and, throughout the spectrum, the values are about 2 per cent higher than the values previously observed on steel by Hagen and Rubens.

MAGNESIUM

The mirror examined had a surface of about 1.2 cm x 2.5 cm. It was polished with considerable difficulty. A highly polished surface free from scratches was finally obtained by wet-grinding

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[8] See this Bulletin, **2**, p. 470, 1907, where the reflectivity data of this and numerous other metals is tabulated.

on fine emery paper, using tin oxide ("putty powder") and then (dry) polishing the surface on chamois skin with a little putty powder. This procedure prevented the formation of a film of oxide. However, the surface was not entirely free from blisters, so that the reflectivities are somewhat higher than recorded in Fig. 6, *Mg*. The reflectivity curve is somewhat different from that of a pure metal, especially of aluminum. (See this Bulletin, vol. 2, p. 470.) The alloy of aluminum and magnesium, magnalium, has a reflectivity curve which falls between these two metals.

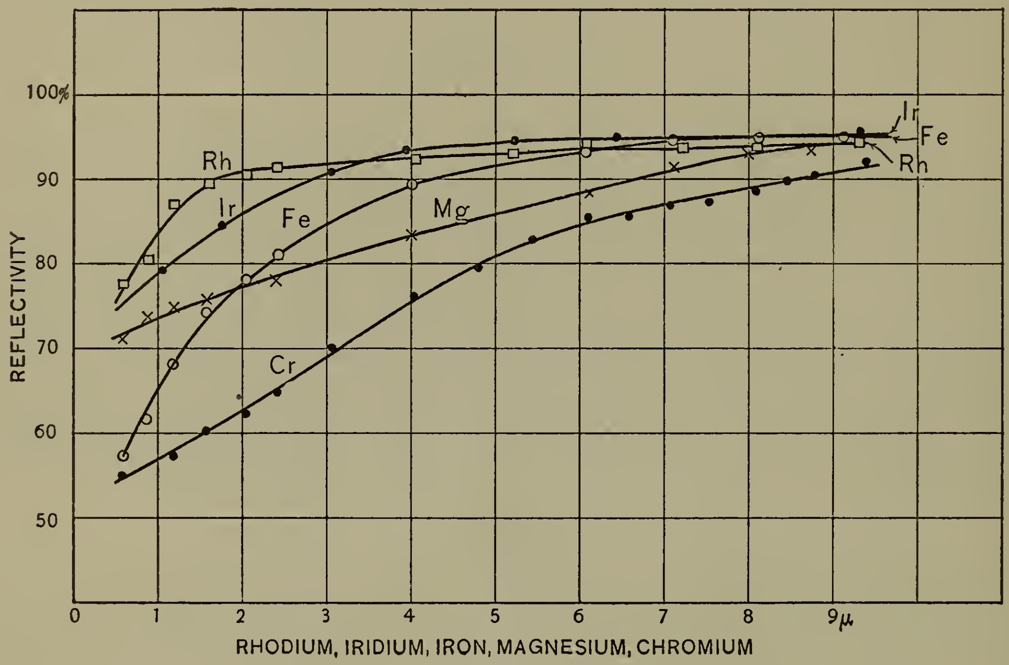

Fig. 6

CHROMIUM

The sample of chromium was sawed from a lump of the metal made by the Goldschmidt process. The material was quite crystalline, but took a fairly high polish, excepting the usual pores which were rather large as compared with those of the sample of tungsten, just described. The reflection curve, Fig. 6, *Cr*, increases gradually from 55 per cent in the yellow to 91 per cent at 9μ. Judging from previous experience with other metals, it seems quite certain that, for a perfect mirror surface of noncrystalline material, the reflectivity of chromium would be higher in the yellow, as observed by Wartenberg. While part of the low reflectivity of chromium is no doubt due to diffuse reflection, out to 5μ, it is to be noted that this metal produces acid compounds, just as was observed with antimony, and in its general properties can not be classed with the true metals. Hence its unusual reflection spectrum is to be expected.

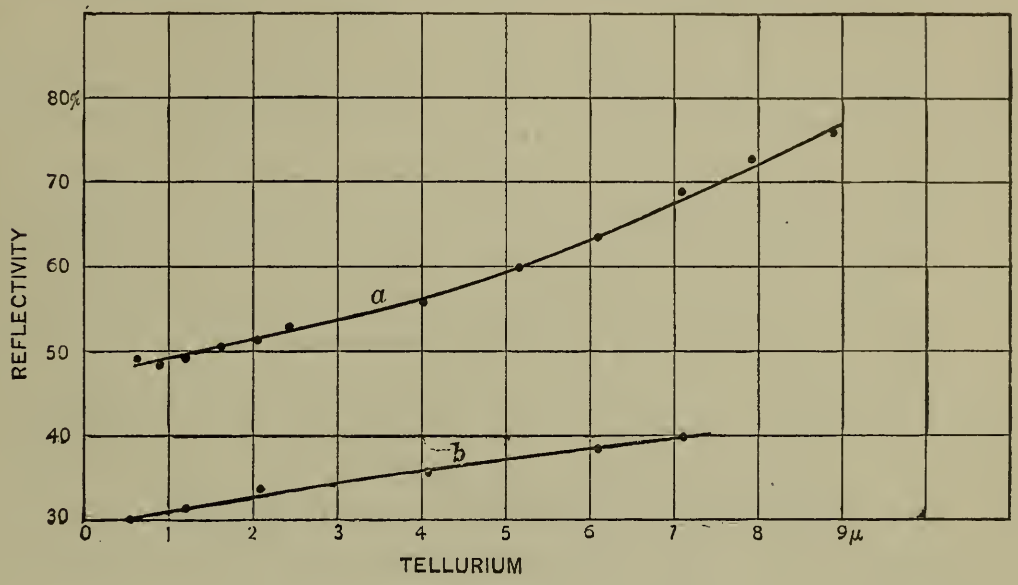

Fig. 7

VANADIUM

The sample examined was kindly loaned by Dr. Von Wartenberg. The surface was plane, highly polished, and the area examined was about 5 mm x 5 mm.

The reflecting power, curve *c*, Fig. 8, rises gradually from 58 per cent in the yellow to 92 per cent at 9μ. In this respect it is very similar to chromium and iron, Fig. 6. This is to be expected since they fall in the same group in the Mendelejeff series.

TELLURIUM

A knowledge of the reflectivity of tellurium is of interest because it occurs on the border line between metals and nonmetals and has a high electrical resistance. It is usually found in a highly crystalline state, and it is therefore difficult to polish a surface free from pores. The reflectivity curve of such a mirror is given in curve *b*, Fig. 7. It is of interest only in showing the general trend of the reflectivities in various parts of the spectrum. The absolute values would be very much higher if a correction could have been made for the loss by scattering caused by the roughness of the surface..

The best mirror used in the present examination was produced by the cathode discharge in hydrogen. It was found that unusually large-sized mirrors can be deposited in this manner, the time required being about half an hour. Thin deposits of tellurium transmit a reddish-brown light, which would indicate a low reflection beyond the red or a minimum reflection in the red. This is illustrated in curve *a*, Fig. 7, where at $.8\mu$ the reflectivity, after repeated observations, was found to be slightly less than in the yellow. While this might be due to the lack of knowledge of the true value of the reflectivity in the visible spectrum of the silver comparison mirror, the color of the transmitted light seems to indicate such a minimum. The occurrence of a reflectivity minimum so far in the red is unusual in the true metals. However, the characteristics of tellurium are so different from the usual ones of true metals, that such an unusual reflecting power is probably to be expected.

The construction of a thermopile having large surfaces usually results in a sluggish instrument because of its great heat capacity. It has been suggested to deposit by cathode discharge two metals (for example, Te-Cu) upon some material which can afterwards be removed. These two films of metal are to overlap along one edge, which forms the active junction. The thermoelectric power of tellurium is very high; and in view of the ease with which a film of this metal can be deposited, it might prove satisfactory as a surface thermopile.

SILICON

A knowledge of the reflectivity of this element is of interest because it belongs to the nonmetals or insulators. Two samples were examined. The polishing was done on a fine grade of emery paper covered with a mixture of tin oxide and a little graphite. The one sample, from Kahlbaum, curve *b*, Fig. 8, was quite homogeneous and took a very high polish, free from scratches. The second sample from the Carborundum Company, curve *a*, Fig. 8, was less homogeneous, its hardness was greater and it took a poor polish. The crystals as they come from the furnace are of a bluish color, as was also true of the highly polished remelted sample here examined. This causes a high reflectivity in the visible ($R=34$ p. c. at .5μ; 30 p. c. at .75μ; 28 p. c. at 1μ) spectrum, which decreases rapidly to a uniform value of 28 per cent beyond 1μ in the infra-red. The lower value of 24 per cent in curve *a* is due to the porosity and to the consequent diffuse reflection by this sample of silicon. From an examination of these two samples it appears highly improbable that the absolute values of the reflectivities, to 10μ in the infra-red, are much greater than 30 per cent. It was noticed in Fig. 3 that the reflectivity of graphite continues to rise gradually with increase in wave length. The carbide of these two elements, carborundum SiC, as well as the oxide SiO_2, have the most remarkable[9] reflection spectra yet observed, with bands of selective reflection which are as high in value as the reflectivity of pure metals.

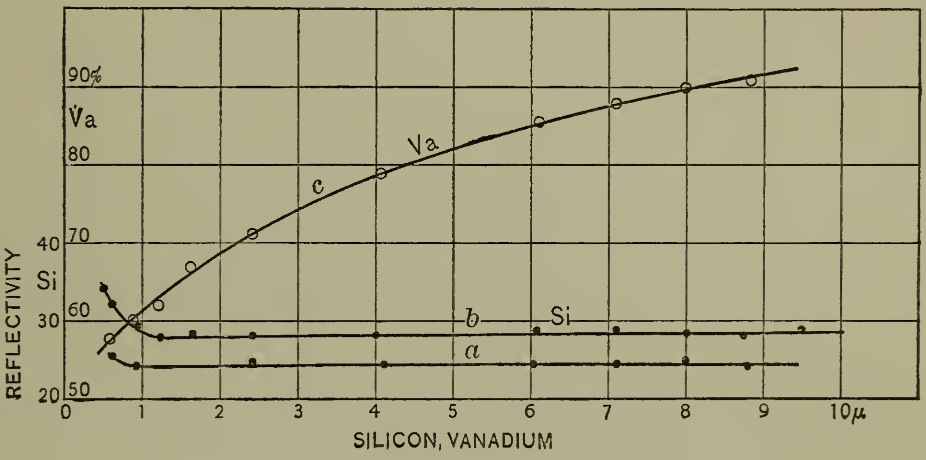

Fig. 8

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[9] This Bulletin, **2**, p. 476; 1907.

SUMMARY

The reflecting power of various metals has been examined, including tungsten, tantalum, and molybdenum. By comparing these metals with silver, of which the reflectivity is known, the absolute reflectivities have been determined.

Each individual substance required a special mode of polishing in order to produce a smooth surface free from contamination. These methods are indicated in the text.

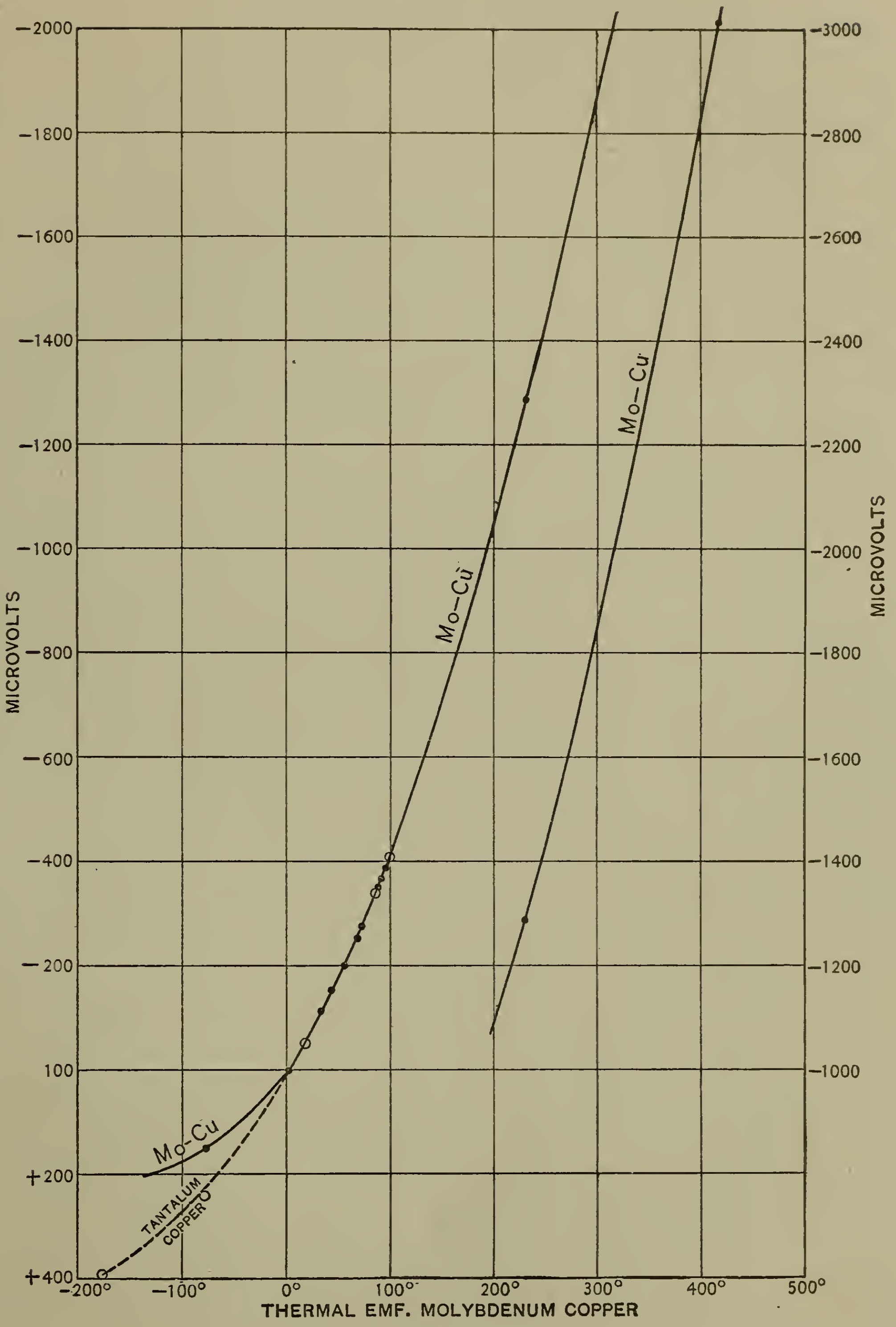
It is shown that, in common with all the other pure metals previously examined, the present series has a low reflectivity in the visible spectrum which increases rapidly to high values in the infra-red. The reflectivity curves of tungsten and of molybdenum are so nearly alike that from a consideration of their optical properties there is no great choice in the use of these two metals in incandescent lamps. Since molybdenum is tough and tungsten is brittle (i. e., becomes brittle after being operated at high temperatures), it remains to be seen whether other physical difficulties can be overcome in the former metal to enable its introduction as an illuminant.

The reflectivity curves show that the high efficiencies of the metal filament lamps is due to their low reflectivity (true absorption, and not diffuse reflection, is meant) in the visible spectrum and to a high reflectivity in the infra-red.

A high operating temperature is also necessary for a high luminous efficiency in metal filament lamps. This is exemplified in the difference in the efficiencies of platinum and tungsten lamps.

In tungsten the low reflectivity in the visible spectrum results in an emissivity of almost 50 per cent, while in the infra-red the emissivity is less than 10 per cent of an ideal radiator.

The ideal solid illuminant giving a high luminous efficiency must fulfill the condition of a high operating temperature, a high reflectivity (hence low emissivity) in the infra-red and a low reflectivity (high emissivity) in the visible spectrum. The pure metals, tungsten and molybdenum fulfill these conditions more exactly than any other known metals, excepting tantalum, which as a lamp filament, however, does not have the optical properties of the samples described in this paper.


−2000
−1800
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−600
−400
− 200
100
+200
+400
MICROVOLTS
−3000
−2800
−2600
−2400
−2200
−2000
−1800
−1600
−1400
−1200
−1000
MICROVOLTS
Mo–Cu
Mo–Cu
Mo-Cu
TANTALUM
COPPER
−200°
−100°
0°
100°
200°
300°
400°
500°
THERMAL EMF. MOLYBDENUM COPPER

Fig. 9

Thus far it has been impossible to obtain a large-sized sample of pure osmium, to determine its reflectivity.

In conclusion, the writer expresses his appreciation of the courtesy of Dr. Von Wartenberg in submitting his samples of tantalum, rhodium, and vanadium for examination.

NOTE I

ON THE THERMOELECTRIC PROPERTIES OF MOLYBDENUM

Having the requisite apparatus and pure wire at hand, it seemed of interest to determine and place on record the thermoelectric behavior of molybdenum. This seemed especially true since its physical properties do not warrant a separate and extensive investigation; and yet this data is of importance for comparison with other metals.

The methods and instruments here employed were described in a previous paper on the thermoelectric properties of tantalum and tungsten.[10] The wire used (specific resistance given on a previous page) was .627 mm in diameter and about 25 m long. Copper wires .2 mm in diameter were wound tightly around the ends of the molybdenum wire and soldered with tin. For the melting points of zinc and tin the junction was in a thin glass tube. Above 600° the molybdenum oxidized so rapidly that no measurements were made on its emf. For temperatures as high as 419° (m. p. zinc) the metal shows no oxidation. The observations were extended to −78°.5 C, which temperature was obtained with a thick solution of carbon dioxide snow and ether. The results are given in Fig. 9, which includes tantalum. Between 0° and 100° these two metals have almost the same thermoelectric power. It is to be noticed, however, that they are *opposite in polarity*. In a copper-tantalum couple the direction of the current is the *same* as in copper-constantan, while in copper-molybdenum the direction of the current is *opposite* to that of a copper-constantan couple. Between 0° and 100° the thermoelectric power of the molybdenum-copper couple is 4.4, between 100° and 200° it is 6.6, and between 200° and 400° it is 9.3 microvolts per degree. The thermoelectric power, between 0° and 100°, is about one-tenth the thermoelectric power of copper-constantan.

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[10] This Bulletin, 6, p. 107; 1909.

NOTE II

PRESERVATION OF SILVER MIRRORS

Silver-on-glass mirrors and especially mirrors made by grinding and polishing the metal itself become tarnished and turn brown very rapidly when exposed to the air in the laboratory. The question naturally presents itself whether or not the slight difference in reflectivity of molybdenum and tungsten, described on a previous page, is caused by a systematic error due to a gradual deterioration of the silver comparison mirror. The electrical conductivity indicates that the reflectivity of molybdenum should be slightly higher than tungsten. Since the two metals were examined in rapid succession on the same day, the question of deterioration of the silver mirror is negligible. This silver-on-glass mirror was prepared just before the observations were made, but no difference could be detected between it and mirrors now almost two years old. The latter mirrors, some of them 15 cm in diameter, also a mirror of solid silver, were prepared in the earlier part of 1908 and were at once placed in a large desiccator containing vessels of phosphorous pentoxide and potassium hydroxide. When not in use the mirrors are kept in this manner. A large mirror spectrometer has its optical parts similarly inclosed and the mirrors appear as white as when made two years ago. This simple device of keeping the mirrors in dry air seems to preserve them indefinitely, in marked contrast with mirrors standing in the open, when the surface tarnishes in a very short time.

NOTE III

COMMENTS ON RADIATION LAWS OF METALS

In a previous paper [11] the spectral radiation constant, "α," of various metals was described. This "constant" was found to vary with the temperature and theoretical reasons were given to account for this variation. The data presented in the present paper support the experimental data then obtained, but lead to a different and a more plausible explanation of the cause of the variation in "α" with temperature. If in the previous experiments the equation representing total radiation had been

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[11] Coblentz, this Bulletin, 5, p. 339; 1909. See p. 367 for a discussion of the radiation from platinum.

considered, $S=\sigma T^{\alpha-1}$, then we would have had to consider the constant "σ" as well as the constant "α." The constant "c_2," in the equation $c_2=\alpha\lambda_{max}T$, also involves the temperature, as well as other factors, so that "α" was the only constant that could be investigated, as described in the aforesaid paper.

Assuming [11] a value of $\alpha=6$, the radiation from platinum observed by Lummer and Kurlbaum [12], shows a variation in the constant of total radiation from $\sigma=8.24$ to $\sigma=11.16$ for an increase in temperature of about 1275 degrees.

It seems apparent that "σ" can not be considered constant, for it indicates the emissivity per unit area of a surface radiating under specific conditions. Now if those conditions vary, as is true of the metals in which the absorptivity (at any wave length) is a function of the temperature, it would seem that the "σ" can not remain constant, but must increase with rise in temperature. The coefficient of emissivity, "σ," must therefore be rigidly defined, just as is true of the resistivity.

The constant, α, in the Wien equation $E=c_1\lambda^{-\alpha}e^{-c_2\lambda/T}$ and as tentatively assumed in the aforesaid computations, relates to a specific region of the spectrum; and irrespective of the writer's published data, experiments by others show that the emissivity of metals at any wave length in the infra-red is affected by the temperature, i. e., it has a temperature coefficient. But this is not all. At low temperatures the maximum emission, E_{max}, falls in the region of 3 to 6 μ where the reflecting power at a given temperature is practically constant and we have to consider only the change in the radiation constant, "α," due to the temperature coefficient of the reflectivity. At high temperatures the E_{max} falls in the region of 1.5 μ (see Fig. 1), where at any given temperature the reflectivity changes rapidly with wave length; and as it shifts toward the short wave lengths the E_{max} must increase by a different law (from the Wien equation $E_{max}=B\,T^{\alpha}$) from what it did when at 3 to 6 μ. In the region of 1.5 μ the temperature coefficient is small, but the absorption (100-reflectivity) varies

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[12] Lummer and Kurlbaum, Verh. Phys. Ges., Berlin, **17**, p. 106; 1898. They assumed a value of $\alpha=5$ and found a variation of $\sigma=4.28$ to $\sigma=19.64$ for a temperature change of about 1275°.

rapidly with wave length, while beyond 3 μ the conditions are exactly the reverse. In both cases the emissivity, E_{max}, increases in a different manner than postulated by the simple radiation formulas.

Now, from the Wien equation, $E^{\lambda}=c_1\lambda^{-\alpha}e^{-c_2/\lambda T}$, the radiation constant "α" is computed from the equation (Eq. 1)

$$a=\frac{\log E-\ \log E_{max}}{\log e-\frac{\lambda_{max}}{\lambda}\log e+\log\frac{\lambda_{max}}{\lambda}} \qquad \text{(Eq. 1)}$$

where E and E_{max} are the emissivities at the wave lengths λ and λ_{max}, respectively. It will be noticed that the temperature of the filament does not enter into this equation. From the most recent work of Hagen and Rubens, (Phys. Zeit. 2, p. 139, 1910) it appears that in the region extending from the visible to 3 μ the temperature coefficient of emissivity is extremely small, and the observed variations in "α" with temperature, as computed from the above equation, must be due to some other cause than a true temperature coefficient of emissivity. This cause is not difficult to find if we turn to the reflectivity curves, Fig. 1. At low temperatures, when λ_{max} falls in the region of 2 μ, the E_{max} is but slightly affected by the temperature coefficient of emissivity, and since the reflecting power varies but slowly with the wave length, the E_{max} will be closely that required by the Wien equation ($E_{max}=B\ T^{\alpha}$). At high temperatures when the λ_{max} falls in the region of 1.2 μ, the E_{max} falls in the region where the reflectivity changes rapidly with wave length, and consequently the value of E_{max} must increase at a higher rate than required by the equation $E_{max}=B\ T^{\alpha}$. The difference between $\log E-\log E_{max}$ (Eq. 1) must therefore be less than would otherwise be the case, due to this fact, and the decrease in "α" with temperature when computed from the above equation must necessarily follow, as observed.

From the reflectivity curves this seems a plausible explanation. Hence, an accurate value of "α" cannot be computed from the Wien equation as expressed in (Eq. 1). However, from the close agreement between the values of "α" of platinum by this and by more direct methods, it is evident that the errors resulting from the use of Equation 1 are not serious. The aforesaid work has shown in a fairly quantitative way that the constant "α" of tungsten is much higher than that of platinum and of carbon. The great suppression of the radiation of tungsten as compared with carbon in the infra-red is another proof of this. The Wien spectral energy curves, using different values of "α," illustrate this same behavior, as may be easily verified by plotting the data given in Table I, this Bulletin, 5, p. 347.

It seems evident that any spectral radiation formula which can be set up must contain factors which will take into consideration not only the variation in emissivity with temperature, but also the variation in the absorptivity, which is a function of the wave length and the temperature. Whether the constant "α" really varies [13] as found in my previous paper where the Wien equation was tentatively assumed, or whether the constant "σ" varies, or whether both vary, is not the all important question at this stage of our knowledge. The most important thing for the present is to get further experimental data [13] on total and spectral radiation, using wide strips of such metals as platinum and tungsten, and suitable means to measure the temperatures. In this manner it is hoped to contribute more accurate data in the near future.

Summary.—For metals the physical facts are:

(1) An extraordinary variation in their reflectivity, from the visible to about 2μ, beyond which point the reflectivity increases but slowly with wave length.

(2) A small temperature coefficient of emissivity from the visible to 3μ, beyond which point the temperature coefficient increases rapidly with wave length.

(3) For the black body the position of maximum emission in the spectral energy curve shifts, with the rise in temperature, toward the short wave lengths by a given amount, because only the temperature enters the problem and $\lambda_{max}T = \text{const}$. Furthermore the height of the maximum emission increases by a fixed amount $E_{max} = BT^{a}$. The total radiation progresses as $S = \sigma T^{a-1}$. The constants "α" and "c_2" are concerned in the slope of the

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[13] This conclusion was evident in my previous paper. This Bulletin, 5, p. 379; 1909.

spectral energy curve, while "σ" defines the total emissivity per unit area of the radiator. In the pure metals, the variation in E_{max} and λ_{max} will be affected (by opposite amounts) by (1) and (2), and as already mentioned in the text, these formulæ, just mentioned, must be modified to take account of these facts.

(4) The cause of the constancy of "α," as found in the visible spectrum and of its variability as found in the infra-red, is probably due to the fact that in the very limited region of the visible spectrum λ_1, and λ_2 are close together, and, in the computations, they are *taken the same at different temperatures.* Moreover no temperature coefficient of emissivity has yet been definitely established in this region. On the other hand, in the infra-red, λ_1 and λ_{max} are far apart, and λ_{max} *is different for different temperatures.* Furthermore, the λ_{max} is affected by a temperature coefficient of emission, and by a rapid change in emissivity due to a rapid variation in the reflecting power, especially in the region of 1 to 1.5μ.

WASHINGTON, May 28, 1910.