SELECTIVE RADIATION FROM OSMIUM FILAMENTS.

By Ernest F. Barker.

I. Introduction.

THE problem of selective radiation from metals is of especial interest in connection with the study of incandescent lamps because of its direct bearing upon the question of luminous efficiency. If all incandescent sources exhibited the properties of a black body it is clear that luminous efficiency would be a function of temperature only, and any choice between materials for high efficiency illumination would be upon the basis of their relative abilities to withstand high temperatures. Experiment shows, however, that this is not the case. In many, if not all radiators the emissivity is found to vary with the wave-length, the energy curve for pure metals being generally somewhat depressed in the region of longer wave-lengths. The ratio of luminous to total energy radiated is therefore higher than for a black body. The existence of a general effect of this type was anticipated some time ago by Aschkinass[1] in the approximate displacement law for metals

$$\lambda_M T = 2{,}666,$$

derived from Maxwell's equations, in which the constant, and hence the value of λ_M, is lower than for the black body. It has also been shown experimentally for many different filaments, but its magnitude is not readily measurable owing to the lack of a satisfactory method for determining operating temperatures. In 1910 Hyde[2] published a table showing the relative efficiencies of various filaments when operated, not at the same temperature, but at a "color match" with a given standard lamp. This probably arranges them in the proper order, since if there were no selectivity a color match would mean the same temperature of operation. It throws no light, however, upon the question of a possible temperature variation.

If the emissivity E is independent of temperature and the Wien equation is assumed for black body distribution, it should be possible to represent the spectral energy curve of any metallic radiator by the equation

[1] Aschkinass, Ann. d. Phys., 17, p. 960, 1905.

[2] Hyde, Jour. Franklin Inst., 170, p. 32, 1910.

$$J = \frac{c_1 E_\lambda}{\lambda^5 e^{\frac{c_2}{\lambda T}}}. \tag{1}$$

Attempts to fit this relation to experimental data for various spectral energy curves, assuming E to be some simple function of λ, as, for example, $E = k\lambda^a$, have, however, not been entirely successful.[1] Whether the difficulty lies in the choice of the function E_λ, or in a variation of selectivity with temperature, remains to be determined, but Hyde[2] has demonstrated by means of a simple criterion obtained directly from equation (1) that such variations probably do exist in the case of tungsten filaments. Bidwell[3] has found evidence of a similar effect by direct measurements upon a mass of nickel whose temperature could be observed and controlled over a considerable range.

One of the objects of the present investigation is to determine whether or not the osmium filament exhibits a temperature variation of selectivity. Osmium was chosen for study in this connection because, in the first place, its selectivity is probably higher than that of most other metals so that the effects sought will be most easily measurable, and secondly, its characteristics have not been very fully described so that any data obtained from it will be of interest. The lamps, which were obtained through the courtesy of Dr. Hyde, of the Nela Research Laboratory, consume normally about 39 watts at 42 volts, giving approximately .55 candle power per watt. The filaments consist of two separate loops in series, each anchored to the glass bulb at the outer end. The investigation consists of (1) a study of the behavior of three osmium lamps under various operating conditions, with a test for selectivity; (2) a qualitative study, by comparison with carbon lamps, of the characteristic radiation from these filaments, showing variations of emissivity with temperature, and indicating the shape of the energy curve for at least a part of the visible spectrum; (3) a similar investigation of the near infra-red region of the spectrum.

II. Experimental Results in the Visible Spectrum.

1. *Lamp Characteristics.*

As a preliminary study the three osmium lamps were compared with each other and with an untreated carbon lamp for current and power consumption, candle power, and color at various voltages. The photometer measurements were against a secondary standard which was

[1] Coblentz, Bull. U. S. Bureau of Standards, 5, p. 339, 1909.
[2] Hyde, Astrophysical Jour., 36, p. 131, 1912.
[3] Bidwell, Phys. Rev., 3, p. 439, 1914.

several times carefully compared with a lamp furnished by the Bureau of Standards. This lamp had been calibrated at each of eight different voltages, thus making it possible to almost completely eliminate errors due to color differences. All measurements were by the method of

Table I.

Osmium Lamp No. 1.

Volts.	Amperes.	Watts.	Candle Power.	Watts per Candle.
5	.242	1.21		
10	.377	3.77		
13	.441	5.74		
16	.503	8.05		
20	.580	11.60	.91	12.74
23	.637	14.65	1.70	8.62
26	.683	17.76	2.99	5.92
30	.755	22.65	5.55	4.09
33	.800	26.40	8.20	3.22
36	.847	30.52	11.69	2.61
40	.908	36.32	18.00	2.02
42	.938	39.40	21.48	1.835
Normal values. 40.25	.910	36.63	18.30	2.00

substitution, but they represent candle power only in a single direction, since the osmium filaments at incandescence soften sufficiently to preclude the possibility of rotating them. The three lamps were not found to differ materially, and the data for filament No. 1 appears in Table I. and Fig. 1.

It would seem of interest to represent these relations for all the lamps by single algebraic functions, if possible. Middlekauff and Skogland[6] have shown that the variations of amperes, watts, candle power and watts per candle power with impressed voltage, for tungsten lamps of any type, may be expressed by an equation of the form,

$$y = Ax^2 + Bx + C,$$

where x is the logarithm of the ratio of any voltage to a chosen normal voltage, and y is the logarithm of the corresponding ampere, watt or candle power ratio, or the logarithm of the actual watts per candle. The value of C is, then, the logarithm of the normal watts per candle for the last equation, and zero for the first three, since they each represent curves passing through the origin.

Following this suggestion, equations of the same form were tried for

[6] Middlekauff and Skogland, Phys. Rev., 3, p. 485, 1914.

osmium lamps for the volts-watts and volts-candle-power variations. It is easily seen that if such a relation holds for the two cases $y_1 = \log w/w_0$ (log. watt ratio) and $y_2 = \log c/c_0$ (log. candle power ratio), it necessarily

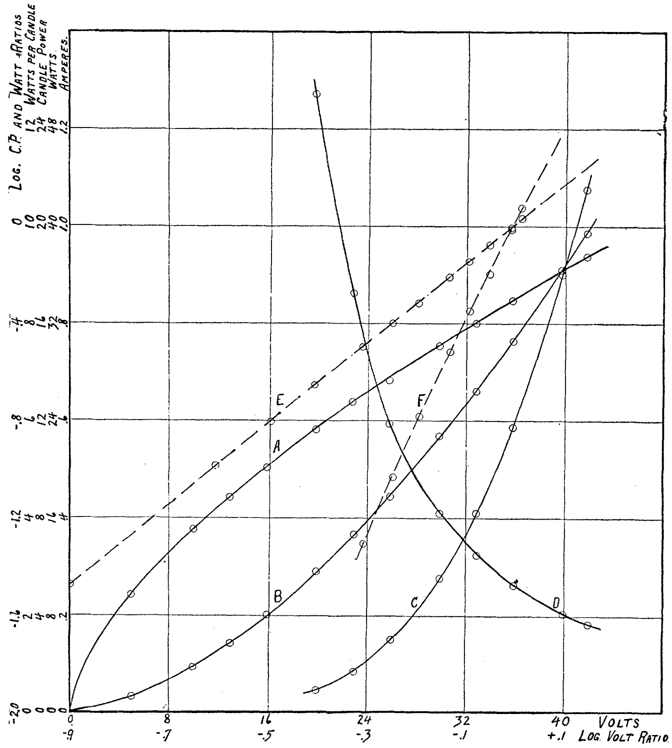

Fig. 1.

Characteristic Curves for Osmium Lamp No. 1. *A*, amperes; *B*, watts; *C*, candle power; *D*, watts per candle; *E*, log. watt ratio; *F*, log. candle power ratio.

holds for $y_3 = \log a/a_0$ (log. ampere ratio) and for $y_4 = \log w/c$ (log. watts per candle), for

$$\frac{w}{w_0} = \frac{a}{a_0} \cdot \frac{v}{v_0},$$

$$\log \frac{w}{w_0} = \log \frac{a}{a_0} + \log \frac{v}{v_0},$$

or

$$y_1 = y_3 + x.$$

But if

$$y_1 = Ax^2 + Bx,$$

then

$$y_3 = Ax^2 + (B - 1)x,$$

a function of the same form. Similarly, taking the logarithm of

$$\frac{w}{w_0} \div \frac{c}{c_0} = \frac{w}{c} \div \frac{w_0}{c_0},$$

we have

$$y_1 - y_2 = y_4 - (y_4)_0,$$

or

$$y_4 = y_1 - y_2 + (y_4)_0$$
$$= (A_1 - A_2)x^2 + (B_2 - B_1)x + C.$$

The normal consumption chosen was 2 watts per candle power, and the corresponding normal values of watts and candle power as they appear in Table I., were taken from the curves. The coefficients were determined by the method of least squares from the data taken upon filament no. 1, and the resulting equations are as follows:

(A) $$y_1 = 0.026609x^2 - 1.65072x$$

where x = log volt ratio, and y_1 = log watt ratio, and

(B) $$y_2 = -1.24490x^2 - 3.91898x$$

where x = log volt ratio, and y_2 = log c.p. ratio.

Table II. shows how nearly these equations represent the desired relations. It is to be noticed that the percentage of error to be expected in the candle power determinations is comparatively large because of the faint illumination at lower voltages.

The three available osmium lamps are all of the same type, so it is not possible to show that these equations are of general applicability. However, having been derived from the data for filament no. 1 only, they were found to apply almost as well to filaments no. 2 and no. 3 when the proper normal values were inserted.

Table II.

(A) Volts-Watts Relation for Filament No. 1.

Volts.	y_1 = Log (Watts ÷ 36.63)		Watt Ratio.		Per Cent. Difference.
	Computed.	Observed.	Computed.	Observed.	
10	−.98857	−.98750	.1027	.1029	+.20
13	−.80380	−.80493	.1978	.1973	−.25
16	−.65708	−.65804	.2203	.2198	−.23
20	−.49894	−.49938	.3170	.3167	−.09
23	−.39962	−.39800	.3985	.3990	+.13
26	−.31235	−.31440	.4871	.4849	−.45
30	−.21028	−.20877	.6162	.6183	+.34
33	−.14219	−.14224	.7208	.7207	−.01
36	−.07995	−.07926	.8512	.8526	+.16
40	−.00447	−.00369	.9898	.9915	+.17
42	+.03051	+.03166	1.0728	1.0756	−.28

(*B*) *Volts-Candle-Power.*

Volts.	y_2 = Log (C.P. ÷ 18.30)		Candle Power Ratio.		Per Cent. Difference.
	Computed.	Observed.	Computed.	Observed.	
20	−1.30518	−1.30341	.0495	.0497	− .40
23	−1.02600	−1.03200	.0942	.0929	+1.40
26	− .78867	− .78678	.1627	.1634	− .43
30	− .52055	− .51816	.3016	.3033	− .56
33	− .34731	− .34864	.4495	.4481	+ .31
36	− .19290	− .19464	.6563	.6537	+ .40
40	− .01063	− .00718	.9758	.9836	− .80
42	+ .07199	+ .06958	1.1803	1.1815	− .10

The curves corresponding to (A) and (B) are plotted with a broken line upon Fig. 1. It will be noted that (A) represents very nearly a straight line. Assuming it to be actually straight, with a slope of $m = 1.65$, the relation could be written in the form

$$W = c_1 V^m,$$

where W = watts radiated and V = volts. Now if

$$W = IV = \frac{V^2}{R}$$

be substituted, where R is the resistance, this becomes

$$W = c_2 R^{\frac{m}{2-m}} = c_2 R^{\beta},$$

and if the resistance be proportional to absolute temperature, as it is very nearly for tungsten at high temperatures,[7]

$$W = c_3 T^{\beta} = c_3 T^{4.71}.$$

The value of this exponent, even though only a rough approximation, is of interest. For a black body its value is 4, and Hyde[8] has found experimentally $\beta = 4.7$ for tantalum and $\beta = 6.0$ for tungsten.

Direct evidence of the selectivity of the osmium filaments is obtained by comparing the watts per candle power which they radiate with the watts per candle power radiated by a carbon lamp when the two are at a color match, *i. e.*, when the ordinates of the spectral energy curves are proportional throughout the visible spectrum. Under these conditions, if there were no selectivity, both would be at the same temperature and both would have the same luminous efficiency. As appears from Table III., however, the osmium filament is much more efficient than the carbon, indicating that when the energy distribution is the same for

[7] Pirani, Phys. Zeitsch., 13, p. 753, 1912.

[8] *Loc. cit.*

both in the visible part of the spectrum, the curve for the osmium must lie considerably below that of the carbon at longer wave-lengths. This relation will be discussed further in connection with the study of the infra-red radiation.

TABLE III.

Carbon and Osmium Filaments at Color Match.

Carbon No. 1.		Osmium No. 1.		Ratio Watts per Candle.
Volts.	Watts per Candle.	Volts.	Watts per Candle.	
180	9.35	26.0	5.92	.633
190	7.15	28.3	4.75	.665
200	5.61	30.8	3.81	.679
210	4.51	33.3	3.15	.697
220	3.72	35.8	2.65	.713

2. *Variations of Emissivity with Temperature.*

Under the caption of "Criterion I" Hyde[9] has described a comparatively simple method for investigating qualitatively the temperature variations in emissivity from any source, as follows: Equation (1) may be considered as defining emissivity E, which we will assume to be independent of temperature.

$$J = \frac{c_1 E}{\lambda^5 e^{\frac{c_2}{\lambda T}}}. \tag{1}$$

Suppose a black body B, and any other substance A having an emissive power E and radiating in accordance with this equation, are at such temperatures that for a chosen pair of wave-lengths each has the same relative intensities, *i. e.*,

$$\left[\frac{J_{\lambda_1}}{J_{\lambda_2}}\right]_A = \left[\frac{J_{\lambda_1}}{J_{\lambda_2}}\right]_B. \tag{2}$$

Let the temperature of B be increased by a given small amount, and the temperature of A by such an amount that the same condition again holds, and

$$\left[\frac{J_{\lambda_1} + dJ_{\lambda_1}}{J_{\lambda_2} + dJ_{\lambda_2}}\right]_A = \left[\frac{J_{\lambda_1} + dJ_{\lambda_1}}{J_{\lambda_2} + dJ_{\lambda_2}}\right]_B. \tag{3}$$

Differentiating (1) and combining with (2) and (3) we obtain

$$\left[\frac{dJ_{\lambda_1}}{J_{\lambda_1}}\right]_A = \left[\frac{dJ_{\lambda_1}}{J_{\lambda_1}}\right]_B \quad \text{and} \quad \left[\frac{dJ_{\lambda_2}}{J_{\lambda_2}}\right]_A = \left[\frac{dJ_{\lambda_2}}{J_{\lambda_2}}\right]_B,$$

i. e., for either wave-length the relative change of intensity due to the increase in T is the same for A as for the black body B. This may be written

[9] *Loc. cit.*

$$\left[\frac{J_{\lambda_1}+dJ_{\lambda_1}}{J_{\lambda_1}}\right]_A = \left[\frac{J_{\lambda_1}+dJ_{\lambda_1}}{J_{\lambda_1}}\right]_B \tag{4}$$

with a similar relation holding for wave-length λ_2. Equations (2), (3) and (4) constitute criterion I., (4) following from (2) and (3) necessarily if (1) properly represents the energy distribution in the spectrum of A, *i. e.*, if the emissivity is independent of the temperature. Equation (4) is a necessary, though not a sufficient condition for this constancy of E with respect to T. Hence if the radiation from any substance does not obey criterion I., its emissivity is a function of temperature. The application of criterion I. may be made directly with a spectrophotometer by measuring the various intensities at two wave-lengths for the radiators which are to be compared.

If, for given temperatures of A and B, equation (2) holds, not simply for two particular wave-lengths, but for any arbitrarily chosen pair of wave-lengths in the visible spectrum, then each source radiates the same proportionate amount of energy for each spectral region. Equation (2) is thus the condition for what may be called an integral color match. With a Lummer-Brodhun contrast photometer it is possible to adjust two sources quite accurately for such a color match, and this affords a satisfactory and somewhat less laborious method of applying criterion I., by measuring the relative variations in total intensity.

Data are here presented for the comparison of the osmium filaments with two untreated carbon filaments. The latter, though not black bodies in the strict sense, form very convenient reference standards, and are sufficiently non-selective to be quite acceptable. Direct measurements against a standard electrically heated black body are, in fact, very difficult owing to the impossibility of obtaining temperatures comparable with those of the incandescent filament, and also because the highest temperatures available can scarcely be kept constant while the comparison is being made. Criterion I. has been tested, both with the photometer and with the spectrophotometer, using a range of temperatures for the carbon lamps corresponding to impressed voltages from 180 to 220. In every case it has been shown that there is actually a change of emissivity with temperature.

Photometric Data.—A Lummer-Brodhun contrast photometer of the ordinary type was used, with an adjustable bench about seven meters in length. The two sources to be compared were carefully screened, and two diaphragms with apertures about ten by fifteen centimeters were mounted between the photometer and each lamp. All light not coming directly from the lamps was excluded as completely as possible, and in order to eliminate any effects due to construction and arrangement of the system, a part of the observations were taken with the reference standard at each end of the bench. The three test lamps were each carefully color matched against both carbon filaments at voltages for the latter ranging from 220 to 180 volts in ten volt intervals, the corresponding relative intensities being recorded (Table IV., *B*). *Criterion I. is fulfilled if these relative intensities are constant for each set of observations,*

TABLE IV.

Voltages and Relative Intensities for Integral Color Match.

A, Mean color match voltage of test lamp. *B*, Mean relative intensities of test lamp and comparison lamp. *C*, Ratio of relative intensities in terms of values corresponding to normal voltage of comparison lamp.

Series I. Photometer length 400 cm. Comparison lamp carbon No. 2.

Test Lamp.		Comparison Lamp Voltages.				
		180	190	200	210	220
Osmium no. 1	A	26.0	28.6	30.9	33.1	35.8
	B	.837	.837	.824	.781	.776
	C	1.08	1.08	1.06	1.01	1.00
Osmium no. 2	A	26.0	28.4	30.8	33.6	36.2
	B	.817	.815	.800	.794	.779
	C	1.05	1.05	1.03	1.02	1.00
Osmium no. 3	A	26.1	28.7	31.4	33.5	36.2
	B	.851	.826	.837	.791	.783
	C	1.09	1.05	1.07	1.01	1.00

Series II. Photometer length 500 cm. Comparison lamp carbon No. 1.

Osmium no. 1	A	26.0	28.3	30.8	33.3	35.8
	B	.798	.767	.755	.743	.733
	C	1.09	1.05	1.03	1.01	1.00
Osmium no. 2	A	26.5	28.8	31.3	33.9	36.3
	B	.819	.789	.788	.783	.764
	C	1.07	1.03	1.03	1.02	1.00
Osmium no. 3	A	26.6	28.7	30.9	33.4	36.1
	B	.851	.814	.772	.755	.753
	C	1.13	1.08	1.03	1.00	1.00

Series III. Photometer length 500 cm. Comparison lamp tantalum No. 1.

		70	80	90	100	110
Osmium no. 1	A	32.1	36.8	41.3	45.7	49.8
	B	1.619	1.530	1.480	1.405	1.358
	C	1.19	1.13	1.09	1.03	1.00

as follows from equation (4), or, in other words, if the ratio of the relative intensities corresponding to two different temperatures (Table IV., C) is unity. Since the carbon lamps cannot be operated at a temperature sufficiently high to match in color the osmium filaments near their normal temperature, a comparison was also made between osmium filament no. 1 and a tantalum lamp, tantalum having been found to very nearly fulfill criterion I.[1] This appears in the table as Series III.

Considerable difficulty was encountered at the lower temperatures in making the color match because of the faint illumination, so that the first series of readings was taken with the photometer bench at 400 cm. Series II., with a length of 500 cm., is probably more accurate for the higher voltages, but less accurate for the lower, as appears from the variations in C, Table IV. While the results are not quite as consistent as might be desired, they show without exception that *there is a considerable departure from the conditions upon which criterion I. depends.*

It must be understood that there is a certain assumption underlying these conclusions, viz., that when a color match is obtained as above the ordinates of one spectral energy curve are actually proportional to the corresponding ordinates of the other curve, not simply in the brighter portion, but throughout the visible spectrum. This is the condition represented by equations (2) and (3), which must be satisfied before equation (4) is to be applied. Further investigation with a spectrophotometer, therefore, seemed desirable.

Spectrophotometric Data.—The instrument used was of the Lummer-Brodhun type, manufactured by Schmidt and Haensch, and was equipped with a variable sectored disc as designed by Hyde, giving a continuous range of transmissions from about 60 per cent. down to 0 per cent. This was calibrated in position by comparison with several standard discs. The slit width used on each collimator was .4 mm., and before each slit diffusing screens of ground glass were mounted. The method of substitution was employed throughout, two lamps being compared by successive balancing against a fixed comparison source, and the latter frequently tested for changes in temperature and color by comparison with a standard. During the course of some months the variation of the comparison source was almost imperceptible. Under these conditions no slit width corrections are necessary for the relations expressed by equations (2), (3) and (4), so long as the width of the collimator and ocular slits is not changed, because the correction factor, depending only upon the wave-lengths and the shape of the energy curve under investigation, cancels out in each case. The conclusions to be deduced are, therefore, quite independent of the purity of the spectra compared.

[1] Hyde, *loc. cit.*

The preliminary observations involved a comparison of the spectral energy curves for osmium and carbon at various color match temperatures, through as wide a range of wave-lengths as possible. No marked differences between them were noted, the agreement being sufficiently close to indicate that no particular region of the spectrum demands special attention. Hence the conclusion seemed justified that if the curves are matched at four or five wave-lengths about equally spaced across the visible region, they will show satisfactory agreement throughout. As a matter of fact, however, there was some tendency, scarcely greater than the necessary experimental error, toward larger ratios in the middle region of the spectrum, indicating an elevation of the osmium curve with respect to the carbon, and later observations show the same effect. This conclusion is not in agreement with a statement published by Hyde,[1] for he found "slight evidence in the case of osmium that the curve of the latter when showing the same relative distribution between the energy emitted at 0.7 μ and that emitted at 0.5 μ as compared with carbon, dropped a little below that of the carbon at intermediate wave-lengths." These variations are not, however, of sufficient magnitude to noticeably affect the results here presented.

Test for Variations of Emissivity with Temperature.—In order to avoid the tedious process of spectrophotometric color matching by repeated trials with slightly varying voltages in each of the temperature regions

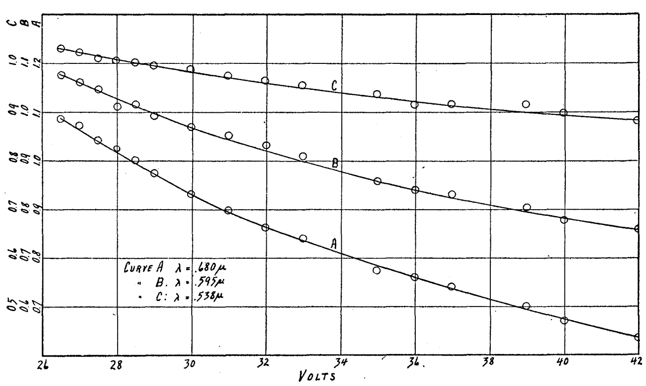

Fig. 2.
Color Ratios for Osmium No. 1.

to be studied, the following method was adopted. Measurements upon each lamp of the intensities for wave-lengths .680 μ, .595 μ, .538 μ and .500 μ in terms of the corresponding intensities of the comparison source

[1] Hyde, Jour. Franklin Inst., 170, p. 31, 1910.

were taken for a number of different voltages at arbitrary intervals. A set of ratios, which will be referred to as "color ratios," were then computed and plotted. These represent the quotient of the intensity for the shortest observed wave-length, $\lambda = .500\ \mu$, by the intensities at the same temperature for the other three wave-lengths. The three numbers so obtained may be used as an index of the color of the test

TABLE V.

Lamp.	Voltage.	Color Ratios.				Observed Transmission.			
		$\lambda = .680\mu$	$.595\mu$	$.538\mu$	$.500\mu$	$.680\mu$	$.595\mu$	$.538\mu$	$.500\mu$
O no. 1	35.97	.759	.844	.925	1.00	.1839	.1658	.1520	.1396
O no. 2	36.12	.759	.843	.917	1.00	.1597	.1437	.1320	.1211
O no. 3	35.70	.759	.849	.925	1.00	.1610	.1431	.1325	.1227
	mean	.759	.845	.922	1.00				
C no. 1	220.2	.759	.850	.925	1.00	.1000	.0906	.0831	.0761
C no. 2	222.2	.759	.846	.925	1.00	.1216	.1090	.0991	.0910
	mean	.759	.848	.925	1.00				
O no. 1	33.50	.820	.891	.946	1.00	.2404	.2210	.2086	.1985
O no. 2	33.45	.820	.888	.938	1.00	.2105	.1960	.1852	.1743
O no. 3	33.35	.820	.895	.950	1.00	.2074	.1888	.1775	.1690
	mean	.820	.891	.945	1.00				
C no. 1	210.0	.820	.890	.937	1.00	.1309	.1214	.1145	.1091
C no. 2	212.8	.820	.886	.941	1.00	.1580	.1458	.1380	.1303
	mean	.820	.888	.939	1.00				
O no. 1	31.00	.895	.947	.971	1.00	.3234	.3042	.2974	.2900
O no. 2	30.90	.895	.946	.965	1.00	.2850	.2700	.2650	.2555
O no. 3	31.00	.895	.945	.975	1.00	.2707	.2553	.2491	.2422
	mean	.895	.946	.970	1.00				
C no. 1	200.0	.895	.940	.960	1.00	.1774	.1684	.1634	.1579
C no. 2	202.4	.895	.936	.965	1.00	.2150	.2055	.1990	.1926
	mean	.895	.938	.962	1.00				
O no. 1	28.93	.978	.996	.995	1.00	.4160	.4080	.4088	.4060
O no. 2	28.78	.978	1.002	.992	1.00	.3750	.3675	.3667	.3650
O no. 3	28.76	.978	1.000	.998	1.00	.3597	.3504	.3535	.3520
	mean	.978	.999	.995	1.00				
C no. 1	190.0	.978	1.002	.994	1.00	.2459	.2341	.2404	.2409
C no. 2	191.6	.978	.991	.990	1.00	.3075	.3045	.3032	.3015
	mean	.978	.997	.992	1.00				
O no. 1	26.75	1.075	1.069	1.028	1.00	.5500	.5555	.5785	.5947
O no. 2	26.50	1.075	1.067	1.024	1.00	.5040	.5040	.5325	.5425
O no. 3	26.50	1.075	1.066	1.024	1.00	.4900	.4935	.5087	.5225
	mean	1.075	1.067	1.025	1.00				
C no. 1	180.0	1.075	1.073	1.016	1.00	.3497	.3538	.3706	.3744
C no. 2	182.4	1.075	1.058	1.017	1.00	.4200	.4278	.4428	.4527
	mean	1.075	1.065	1.016	1.00				

lamp, since two lamps will match in color only when these ratios are the same for each. Fig. 2 shows the variations in color ratios for osmium filament no. 1, and makes it possible to find the voltage corresponding to any desired color.

The voltage of each lamp when at color match with carbon no. 1 at 180, 190, 200, 210 and 220 volts may be read from these curves immediately, and the exactness of the color match determined by the agreement of the corresponding color ratios. The figures appear in Table V. The average ratios for carbon and for osmium at each temperature show that a very nearly perfect match has been obtained, the differences between corresponding values for different filaments being not much greater than those for two similar filaments. The osmium ratios for yellow and green (.595 μ and .538 μ) seem to run slightly higher than those for carbon,

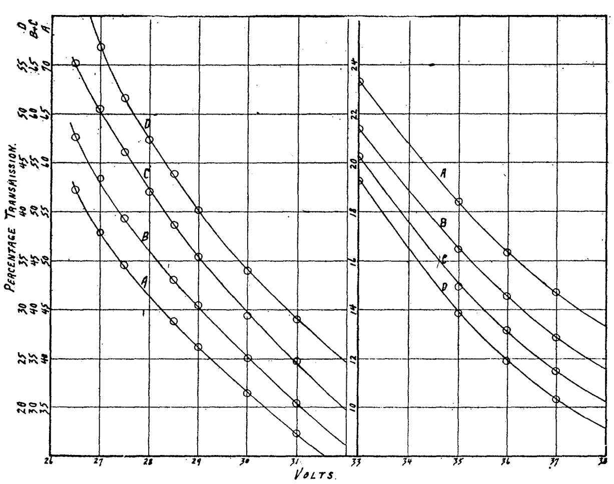

Fig. 3.

Isochromatic Curves for Osmium No. 1. Curve *A*, .680 μ; Curve B, .595 μ; Curve C, .538 μ; Curve D, .500 μ.

which agrees with the previous conclusion regarding the relative shapes of the curves. The agreement of these pairs of ratios constitutes the fulfillment of equation (3).

The same observations from which the above color ratios were computed may also be plotted in the form of isochromatic transmission-voltage curves, as in Fig. 3, the disc transmissions varying inversely as the intensities relative to the comparison source. From Fig. 3 we may determine the intensities for each of the four wave-lengths considered, at such voltages for osmium no. 1 (found from Fig. 2) as correspond to a color match with carbon no. 1 at the chosen voltages. These intensities, the reciprocals of the disc transmissions appearing in Table V., *are precisely the data necessary for the application of criterion I.*

TABLE VI.

Intensity Ratios for Each Lamp when at a Color Match with Carbon Lamp No. 1.

$I_{v_1}/I_{v_2} = T_{v_2}/T_{v_1}$, I = intensity of emission, $v_1 < v_2$. T = fractional transmission of disc.

Lamp.	Color Match Voltages.		Wave-lengths. .680μ	.595μ	.538μ	.500μ
A. Color match with carbon No. 1 at 180 and 220 volts.						
O no. 1	26.75	35.97	.334	.298	.263	.235
O no. 2	26.50	36.12	.317	.285	.248	.223
O no. 3	26.50	35.70	.328	.290	.260	.234
		mean	.326	.291	.257	.231
C no. 1	180.0	220.0	.286	.256	.224	.203
C no. 2	182.4	222.2	.289	.255	.224	.201
		mean	.287	.255	.224	.202
B. Color match with carbon No. 1 at 190 and 220 volts.						
O no. 1	28.93	35.97	.441	.406	.372	.343
O no. 2	28.78	36.12	.425	.391	.360	.332
O no. 3	28.76	35.70	.447	.409	.375	.348
		mean	.438	.402	.369	.341
C no. 1	190.0	220.0	.407	.387	.346	.316
C no. 2	191.6	222.2	.395	.358	.327	.302
		mean	.401	.372	.336	.309
C. Color match with carbon No. 1 at 180 and 210 volts.						
O no. 1	26.75	33.50	.436	.397	.361	.332
O no. 2	26.50	33.45	.419	.390	.348	.321
O no. 3	26.50	33.35	.424	.382	.349	.324
		mean	.426	.390	.353	.326
C no. 1	180.0	210.0	.374	.344	.309	.291
C no. 2	182.4	212.8	.376	.340	.312	.288
		mean	.375	.342	.310	.289

The ratio of two intensities, or the inverse ratio of two transmissions, at any wave-length and a chosen pair of voltages for a given lamp, forms one member of equation (4). The other member is a similar intensity ratio for the other lamp at color match voltages and the same wave-length. These ratios for each lamp for various wave-lengths and various pairs of voltages appear in Table VI.; to satisfy equation (4) the values for the osmium lamps at any wave-length should equal those for the carbon lamps at the same wave-length, in any one of the three groups. The mean values show a very wide deviation from equality, however, and always in the same direction. *Hence criterion I. is not fulfilled*, and there is a change of emissivity with temperature, even at the short wave-lengths within the visible spectrum.

III. Comparison of the Infra-red Spectra of Carbon and Osmium.

The marked depression of the energy curve of osmium with respect to that of carbon filaments in the longer wave-lengths suggests at once the application of criterion I. in the infra-red. This has been done, using a fixed arm mirror spectrometer with a quartz prism, set up according to Wadsworth's[1] method for minimum deviation. The Cornu quartz prism, with faces 74 × 110 mm., was supplied by A. Hilger, Ltd., and its indices of refraction for various wave-lengths were determined from measurements by Paschen[2] upon a similar prism. The detector was a sensitive thermopile constructed by Coblentz, with a Leeds and Northrup high sensitivity galvanometer. With the scale at 128 cm. it

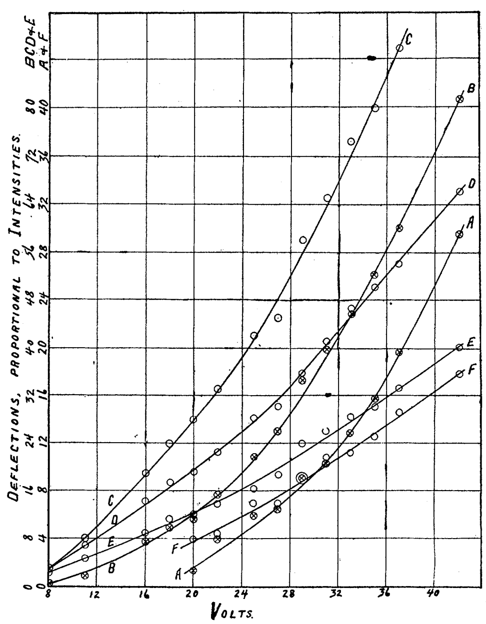

Fig. 4.

Isochromatic Curves for Osmium No. 1. Curve A, .608 μ; Curve B, .726 μ; Curve C, 1.068 μ; Curve D, 1.750 μ; Curve E, 2.098 μ; Curve F, 2.400 μ.

[1] Wadsworth, Phil. Mag., 38, p. 337, 1894.

[2] Paschen, Ann. d. Phys., 35, p. 1005, 1911.

gave a deflection of 80 mm. for a standard candle at one meter. The thermopile slit was .38 mm. in width, and so placed that it received an average spectral range of about 185 Ångstrom units.

The data consists of observations of the energy distributions at various temperatures for osmium lamp no. 1 and carbon lamp no. 1, from the extreme red of the visible spectrum to the longest wave-lengths giving appreciable deflections. The results for repeated trials were quite consistent, and are shown graphically for osmium no. 1 in Fig. 4. From such curves the mean galvanometer deflections of Table VII. were obtained. This table also shows the ratios of the intensities at various wave-lengths to those at $\lambda = 2.098\ \mu$ for each different temperature, which correspond to the color ratios for the visible spectrum. The intensity ratios are plotted in Fig. 5.

TABLE VII.

Galvanometer Deflections, and Intensity Ratios.

Deflections at Wave-lengths.						Volts.	$I_{2.098\mu} \div I_\lambda$					
$\lambda = .608\ \mu$	$.726\ \mu$	$1.068\ \mu$	$1.750\ \mu$	$2.098\ \mu$	$2.400\ \mu$		$.608\mu$	$.726\mu$	1.068μ	1.750μ	$2.098\ \mu$	$2.400\ \mu$
						Osmium No. 1.						
	.6	3.1	3.0	2.3		8		3.83	.742	.766	1.00	
	3.3	10.7	8.2	5.6		12		1.70	.521	.683	1.00	
	7.1	19.0	13.7	9.0		16		1.27	.474	.656	1.00	
1.4	12.1	27.8	19.6	12.7	3.5	20	9.08	1.05	.457	.649	1.00	3.63
4.3	19.3	38.4	26.1	16.5	5.8	24	3.79	.855	.430	.632	1.00	2.84
7.6	29.2	52.0	33.5	21.2	8.2	28	2.79	.726	.408	.633	1.00	2.58
11.5	41.9	68.0	42.4	26.3	10.7	32	2.29	.629	.387	.621	1.00	2.46
17.4	56.5	85.5	51.8	31.6	13.3	36	1.82	.560	.370	.610	1.00	2.38
25.0	72.6	104.8	61.2	37.2	16.2	40	1.49	.512	.355	.608	1.00	2.30
29.5	81.5	114.5	66.0	40.2	17.8	42	1.36	.494	.351	.610	1.00	2.26
						Carbon No. 1.						
12.2	51.0	145.5	109.0	76.3	31.3	180	6.25	1.50	.525	.700	1.00	2.43
14.2	63.6	168.5	122.8	84.7	34.1	190	5.96	1.33	.503	.690	1.00	2.48
18.3	78.2	191.5	136.5	93.0	36.8	200	5.09	1.19	.485	.681	1.00	2.53
23.1	96.2	214.4	150.5	101.3	39.6	210	4.39	1.05	.473	.674	1.00	2.56
29.7	119.0	240.0	166.0	109.6	42.4	220	3.68	.935	.456	.660	1.00	2.58

The variation of any intensity ratio with increasing voltage is an indication of the rate of increase of intensity with temperature for the given wave-length, relative to that for $\lambda = 2.098\ \mu$. Thus, in the case of the carbon lamp, the ratios for each wave-length shorter than $2.098\ \mu$ decrease (Table VII.), showing that the corresponding I_λ increases more rapidly than does $I_{\lambda=2.098\mu}$, and the rate of decrease becomes more rapid with shortening wave-lengths. For $\lambda = 2.400\ \mu$ the ratios increase, showing that here I_λ increases more slowly than at $2.098\ \mu$. This is exactly as would be expected for black body radiation, according to Wien's displacement law. In the case of osmium, I_λ increases more rapidly for each shorter wave-length than for $2.098\ \mu$, but the last column shows a more rapid increase for $2.400\ \mu$ than for $2.098\ \mu$, which is quite an unexpected result. This cannot be explained by absorption effects, since they would influence the carbon radiation equally; neither does it seem to be a mere observational error since there is a definite and smooth progression. Possibly the explanation is to be found in a peculiarity of the energy curve such as an emission band in this neighborhood, but further investigation will be necessary before definite conclusions can be reached.

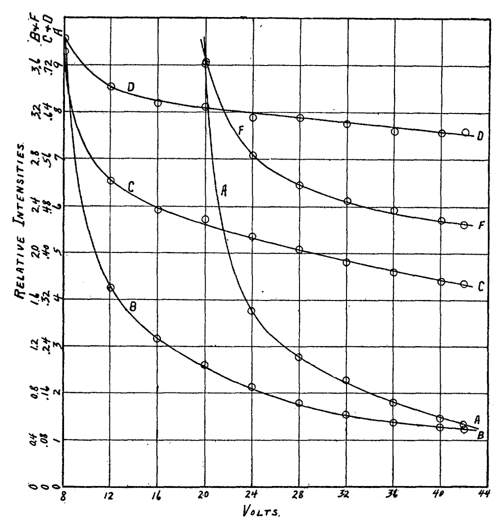

Fig. 5.

Energy Distribution, Osmium No. 1. Intensities relative to $I_{\lambda=2.098\mu}$. Curve A, .608 μ; Curve B, .726 μ; Curve C, 1.068 μ; Curve D, 1.750 μ; Curve F, 2.400 μ.

Application of Hyde's Criterion.—From Fig. 5 showing the variations of intensity ratios for the osmium lamp it is at once apparent that no voltage can be found at which the energy curve from this lamp will be of the same shape as that from the carbon lamp at any of the measured voltages. Hence criterion I. cannot be applied to this spectral region as a whole, but only at particular pairs of wave-lengths and temperatures.

Choosing $\lambda = 2.098\ \mu$ for comparison with each of the other wave-lengths, and, as before, temperatures corresponding to voltages for

TABLE VIII.

Isochromatic Intensity Ratios for Wave-Lengths and for Pairs of Voltages at which the Ratios $(I_{\lambda=2.098\mu} \div I_{\lambda'})$ are the Same for Both Lamps.

Wave-length.	Intensity Ratios $(I_{\lambda=2.098\mu} \div I_{\lambda'})$		Carbon Lamp Voltages.		Osmium Lamp Voltages.		$I_{\lambda'}$ for Carbon No. 1.			$I_{\lambda'}$ for Osmium No. 1.		
	At Lower Voltage.	At Higher Voltage.	Lower.	Higher.	Lower.	Higher.	Lower.	Higher.	Ratio.	Lower.	Higher.	Ratio.
.608	6.25	3.68	180	220	21.20	24.30	12.2	29.7	.410	1.55	4.60	.337
	5.96	3.68	190	220	21.35	24.30	14.2	29.7	.478	1.60	4.60	.348
	6.25	4.39	180	210	21.20	22.90	12.2	23.1	.528	1.55	3.50	.443
.726	1.50	.935	180	220	13.60	22.20	51.0	117.0	.436	4.7	15.7	.299
	1.3	.935	190	220	15.45	22.20	63.6	117.0	.544	6.5	15.7	.414
	1.50	1.05	180	210	13.60	19.90	51.0	96.2	.531	4.7	12.0	.392
1.068	.525	.456	180	220	11.90	19.20	145.5	240.0	.606	10.4	26.0	.400
	.503	.456	190	220	13.50	19.20	168.5	240.0	.702	13.7	26.0	.527
	.525	.473	180	210	11.90	16.80	145.5	214.4	.678	10.4	20.7	.502
1.750	.700	.660	180	220	10.85	15.40	109.0	166.0	.657	6.6	13.0	.508
	.690	.660	190	220	11.55	15.40	122.8	166.0	739	7.5	13.0	.577
	.700	.674	180	210	10.85	13.12	109.0	150.5	.725	6.6	9.8	.674
2.400	2.43	2.58	180	220	33.30	28.25	31.3	42.2	.740	10.6	8.4	1.26
	2.48	2.58	190	220	31.25	28.25	34.1	42.4	.805	10.	8.4	1.21
	2.43	2.56	180	210	33.30	28.80	31.3	39.6	.790	10.6	8.7	1.22

The fulfillment of Criterion I would be indicated by the agreement of the ratios in columns 10 and 13.

carbon no. 1 of 180 and 220, 180 and 210, and 190 and 220, the intensity ratios which form the right hand members of equations (2) and (3) respectively may be found in Table VII. These are rearranged for convenience in Table VIII., columns 2 and 3. From Fig. 5 the voltages of the osmium lamp for which the same ratios hold may be determined, so that equations (2) and (3) are satisfied at these voltages (Table VIII., columns 6 and 7). Fig. 4 and similar curves give the intensities for the two lamps for these voltages at the chosen wave-lengths, and the isochromatic ratios of these intensities for any two temperatures form the two members of equation (4), which constitutes criterion I. These ratios appear in columns 10 and 13 of Table VIII., which should agree, according to equation (4). The wide discrepancy shows marked changes of emissivity with temperature, the greatest relative differences occurring in the neighborhood of the maximum of the energy curve, which is about 1.0 μ.

The peculiarity of osmium radiation at 2.400 μ already noted is here again evident, for at this wave-length when the carbon voltage is increased, that of osmium must be decreased in order to maintain the same relative intensities for wave-lengths 2.098 μ and 2.400 μ.

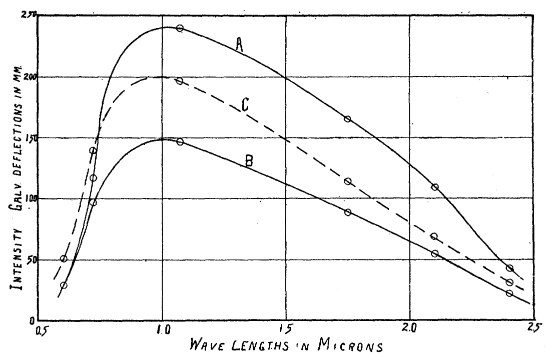

Fig. 6.

Approximate Spectral Energy Curves for Osmium and Carbon. Curve *A*, Carbon No. 1 at 220.0 volts; Curve *B*, Osmium No. 1 at 35.97 volts; Curve *C*, Osmium No. 1 at 42.00 volts; Curves *A* and *B* at color match temperatures.

Relative Selectivity of Osmium and Carbon.—The isochromatic curves of Fig. 4 supply the data necessary for a comparison of the energy curves for osmium and carbon when the two are at a color match in the visible region. Table IX. shows the deflections at various wave-lengths for both lamps corresponding to a color match with the carbon at 220 volts. All the deflections for the observations on osmium were reduced to the

Table IX.

Comparison of the Spectral Energy Distribution in the Infra-red for Carbon No. 1 and Osmium No. 1.

Lamp.	Volts.		Deflections at Wave-lengths.					
			.608μ	.726μ	1.068μ	1.750μ	2.098μ	2.400μ
C no. 1	220		29.7	117.0	240.0	166.0	109.6	42.4
O no. 1	35.97	Observed:	17.25	56.4	85.3	51.7	31.6	13.3
		Reduced:	29.7	97.0	147.0	89.0	54.4	22.9
O no. 1	42.00	Observed:	29.5	81.5	114.5	66.0	40.2	17.8
		Reduced:	50.8	140.5	197.2	113.8	69.3	30.6

same scale as the carbon deflections by a constant factor, viz., the ratio of the deflections at $\lambda = .608\ \mu$, since, the visible spectra matching, these ordinates should be equal. The deflections for carbon and the reduced deflections for osmium are plotted in Fig. 7. The curve for osmium at 42 volts is also plotted to the same scale. No attempt has been made to locate exactly the maxima of these curves, nor have corrections been made for absorption, but the very large effect of selectivity is at once apparent in the depression of the osmium curves relative to those of carbon throughout the infra-red region. Even at 42 volts the osmium radiates less than the carbon for wave-lengths greater than 0.8 μ, although the former is far above the temperature for color match in the visible spectrum.

IV. Summary.

Three incandescent lamps with osmium filaments have been studied. Data are presented and equations derived for the variations with voltage of the power consumed and the candle power radiated, and the functional dependence of current and watts per candle power upon voltage is indicated.

The luminous efficiencies of osmium and carbon lamps at color match voltages are compared, showing that osmium as a radiator is highly selective. Hyde's criterion for the detection of variations of emissivity with temperature has been applied both photometrically and spectrophotometrically, carbon lamps being used as comparison sources. Without exception all the results show that the emissivity is a function of both wave-length and temperature. A method is described for determining the relative shapes of the energy curves for two filaments when the best possible color match has been obtained, and the color ratios computed under various conditions indicate that, when the extremes are matched, the curve for osmium is somewhat depressed relative to that for carbon in the middle portion of the visible spectrum.

Energy curves for both radiators have been obtained in the infra-red region out to wave-lengths of 2.4 μ, and the observations show that the two cannot be brought into coincidence at any voltage. An application of criterion I. to these data again shows marked changes of emissivity with temperature. The relations of the energy curves in the infra-red at voltages corresponding to a color match in the visible spectrum are shown, the osmium radiation being very noticeably deficient in energy of the longer wave-lengths.

It has been shown that, within the range of observations presented, the rate of increase of intensity with temperature increases from the longer toward the shorter wave-lengths for the carbon filament, but that for the osmium in the neighborhood of 2.4 μ the rate of increase is greater than for wave-lengths 2.098 μ or 1.750 μ. An explanation of

this effect as indicating an emission band is suggested, though this has not been verified.

In conclusion the writer wishes to express his indebtedness to Dr. K. E. Guthe for his continual interest and helpful suggestions; also to Dr. E. P. Hyde for loaning the osmium lamps used and the standard sectored discs for calibration purposes.

Physical Laboratory,
University of Michigan,
May 1, 1915.