DEPARTMENT OF COMMERCE

BULLETIN
OF THE
BUREAU OF STANDARDS

VOLUME 9
1913

SELECTIVE RADIATION FROM VARIOUS SUBSTANCES, IV

By W. W. Coblentz

CONTENTS

I. RADIATION CONSTANTS OF PLATINUM

In a previous paper[1] the most important so-called constant, α, of spectral radiation of various metals was investigated, on the assumption that the spectral energy distribution followed a law similar to that of a perfect radiator, but with different constants. It was found that the supposed constant, α, had a temperature coefficient; and the investigation was continued.

In a subsequent paper[2] the problem was undertaken from the standpoint of the spectral reflecting power of various metals; and an explanation was given of the cause of the variability of α with temperature. This explanation is based upon the fact that if the reflecting power (and hence the absorptivity) were uniform throughout the whole spectrum, the emission would be that of a "gray body." Hence the position of the maximum emission, λ_{max}, should shift uniformly with rise in temperature toward the shorter wave lengths, and the intensity of the maximum emission should increase according to the equation, $E_{max} = BT^{\alpha}$. But the reflecting power of metals has a temperature coefficient[3] which is quite marked in the infra-red, beyond 30μ, and which decreases to a negligible quantity at 3μ to 4μ. Furthermore the reflecting

---

[1] This Bulletin, **5**, p. 339; 1909.

[2] This Bulletin, **7**, p. 197; 1910.

[3] Hagen and Rubens, Phys. Zs., **11**, p. 139; 1910.

power of metals is low in the visible spectrum and increases rapidly to a fairly constant value beyond 3μ. For the temperatures at which the investigation was made the maximum emission, E_{max}, shifted from the region of 2.5μ to 3.5μ, where the reflecting power is uniform and the temperature coefficient of reflection is negligible, to the region of 1.2 to 1.5μ where the reflecting power decreases (absorptivity and hence emissivity increases) very rapidly with wave length. Consequently, at low temperatures, when λ_{max} is in the region of 2.5 to 3.5μ, the E_{max} should increase as required by Wien's equation ($E_{max}=BT^{\alpha}$); but at high temperatures, with the λ_{max} in the region of 1.2μ, the E_{max} will have increased by BT^{α} plus the increment resulting from the decrease (i. e. increase in emissivity) in spectral reflecting power. In other words, the value of E_{max} is larger than it would be if the reflecting power at 1.2μ were the same as at 3μ, and consequently the value of α varies (decreases) with rise in temperature.

In renewing the investigation there was therefore no expectation of determining a radiation constant, α; but it was purposed to determine a series of spectral energy curves as accurately as possible, and to determine, if possible, one or more temperature coefficients, which applied to the constants of the Wien equation would cause the theoretical curve to fit the observed energy curve at both low and high temperatures.

In order to determine the temperature of the radiating metal (platinum, tungsten, etc.) it was the intention to use a long tube of elliptical cross section and to sight into the interior by means of an optical pyrometer somewhat after the methods carried out by Waidner and Burgess.[4] It was difficult to attain a high temperature because on heavy currents the electrical stresses caused the tubes to collapse. In the meantime, Mendenhall[5] published results indicating that the temperature determined by sighting an optical pyrometer into a V-shaped fold in a strip of metal is closely the true temperature of the metal. This procedure is much simpler than the use of a long hollow tube, and it was deemed sufficiently accurate, for the problem in hand, to measure the temperatures by sighting an optical pyrometer into the V-shaped

---

[4] Waidner and Burgess: This Bulletin, 3, p. 163; 1907.

[5] Mendenhall: Astrophys. J., 33, p. 91; 1911.

space which was given an aperture of a little less than 10°. At high temperatures, the electrical stresses decreased the opening still further; and on account of this difficulty it was not possible to operate strips that were more than 3 cm in length on a current of more than 30 amperes. The radiating strip of metal was 4 mm wide; formed by folding a strip 8 mm wide and 0.02 mm in thickness. It was held securely and vertically between two heavy brass terminals. To the lower terminal, which was movable to take up the expansion, a small weight was usually attached to keep the strip taut. No radiation other than that from the central portion of the strip, 1 to 1.5 cm in length, could fall upon the prism face.

The spectral energy curves were determined by means of a vacuum bolometer,[6] mirror spectrometer, and a fluorite prism. The bolometer strip was 0.6 mm wide and subtended an angle of 4′.

Three series of spectral energy curves were obtained in which the temperatures were measured with an optical pyrometer. In the first series, I to X, inclusive, the length of the platinum strip, between the terminals, was 4.8 cm and the temperature varied from 1004° to 1442° C. In the second series, XI to XV, inclusive, the length of the strip was 2.7 cm and the temperature varied from 1353° to 1691°. This series gave higher values of the constant product $\lambda_{max}T$ than the third series, XVI to XVIII, inclusive, in which the length of the strip was 2.8 cm and in which the temperatures were all lower, varying from 1056° to 1337°. This indicates that the value of the "constant" was affected only by the surface condition (i. e., not the length) of the platinum strip—which becomes rough at high temperatures—and not by the radiation from the cooler ends, for it is to be understood that the temperature of the short radiators is uniform over only about 10 to 15 mm of the central part of the strip. The strips attained their maximum temperature in a few minutes and were easily maintained at a given temperature by means of an ammeter in series with the storage battery. Owing to the thinness of the metal, air currents caused the temperature of the strip to fluctuate several degrees, so that, although a higher accuracy was attainable with the pyrometer, the errors in measuring the temperatures were

---

[6] This Bulletin, 7, p. 197; 1910; 9, p. 7; 1912.

estimated at 3° to 5° at low temperatures and 8° to 10° at high temperatures. These errors are of course dependent upon the width of the opening of the V-shaped aperture, which had a tendency to decrease at high temperatures, thus affecting slightly the "blackness" of the radiation and especially the accuracy in matching the filament of the pyrometer upon the smaller V-shaped opening in the platinum strip. It will be noticed presently that other difficulties enter into the work which are of greater importance than those involved in the temperature measurements.

Because of the defects in this method of using the platinum strip, and hence of temperature measurement, a series of 12 energy curves was obtained, in which the temperatures were measured by means of a potentiometer and a Heraeus thermocouple, of wires 0.1 mm in diameter. The thermocouple was surrounded with a sheet of mica 0.04 mm in thickness, and no leakage could be detected at high temperatures which ranged from 746° to 1509° C. To preclude any error due to the cooling effect on the junction by thermal conduction along the wires, the thermocouple was folded back and forth several times in order to heat a considerable length of the wires. The same kind of platinum was used as in the preceding method. The strip, 3.5 cm in length, was mounted in the V-shaped form previously used. After inserting the thermocouple, the strip was pressed flat and its edges united. Thus all the operations were the same as before, excepting that the temperatures were measured with a thermocouple instead of an optical pyrometer.

In this series the greater heat capacity of the radiator and the smaller exposed surface reduced the temperature fluctuations caused by air currents; but a new difficulty arose in that the temperature of the radiator did not remain constant when the heating current was constant. This was most marked at high temperatures when evaporation of the platinum became more rapid. As in the preceding series in which the temperatures were measured with an optical pyrometer, the "radiation constants" were found to depend on the temperature. The variation in the value of $\lambda_{max}T$ with temperature is more uniform than in the preceding series owing to the increased accuracy in measuring the relative temperatures, as may be noticed in Fig. 3.

TABLE I

Energy Distribution of Platinum—Temperature Determinations With a Holborn & Kurlbaum Pyrometer

Spectrometer circle	λ	Correction divisors		Energy distribution, corrected and reduced to normal spectrum									
		$s. w. \times R^3$	$\frac{(1-r_1)^2}{(1-r_2)^4}$	V 880° C	XVI 1056° C	XVII 1174° C	VII 1216° C	VIII 1271° C	XIII 1353° C	IX 1442° C	XI 1481° C	XII 1625° C	XV 1691° C
° ′													
5 00	0.589μ	0.0284	0.8067	....	....	....	....	....	....	43.30	37.38	126.0	162.4
4 57	.646	.0375	.8073	....	....	....	....	....	....	118.4	94.80	257.1	295.0
55	.698	.0473	.8081	....	....	....	31.51	36.42	34.92	187.9	154.6	348.9	461.9
53	.757	.0630	.8087	....	....	16.49	55.73	55.02	65.60	293.6	237.3	549.5	724.7
51	.836	.0820	.8094	....	11.52	31.19	101.3	105.0	107.8	501.1	382.4	830.3	1064
49	.934	.1033	.8100	6.58	26.79	56.85	200.1	212.6	201.6	772.1	581.9	1176	1436
47	1.054	.1273	.8106	10.08	52.46	101.7	319.5	339.9	314.0	1141	859.2	1639	1815
45	.197	.1498	.8112	29.01	85.60	167.2	459.1	494.1	425.0	1395	1073	1840	2096
43	.357	.1631	.8118	45.40	126.7	234.8	603.1	615.6	514.2	1544	1217	1929	2225
41	.526	.1710	.8124	67.48	166.4	275.2	680.4	692.1	569.8	1560	1225	1901	2140
39	.698	.1710	.8128	88.94	176.9	289.2	676.1	682.0	567.6	1409	1143	1728	1885
37	.868	.1665	.8132	98.39	188.5	287.0	646.0	658.3	528.1	1302	1047	1528	1675
35	2.033	.1600	.8137	106.5	187.8	276.9	617.7	614.1	492.3	1135	932.4	1238	1442
33	.190	.1515	.8141	107.1	176.2	253.9	548.3	559.9	441.5	1014	830.3	1156	1279
30	.410	.1414	.8148	103.5	158.5	225.4	462.0	469.1	380.2	835.8	699.8	869.0	1015
28	.546	.1332	.8154	92.08	141.1	197.4	399.7	408.1	350.0	712.2	624.0	811.4	841.7
24	.801	.1227	.8164	77.87	115.1	152.5	321.7	313.0	251.2	538.6	444.8	599.5	640.5
22	.921	.1183	.8169	73.39	103.4	139.4	284.2	279.3	224.2	464.3	394.0	530.5	563.0
20	3.037	.1140	.8175	70.73	94.76	123.1	252.0	255.4	206.9	426.6	364.0	460.0	497.3
18	.150	.1109	.8181	64.80	84.61	115.9	232.1	235.9	191.0	384.5	318.8	432.5	445.6
14	.367	.1045	.8193	60.40	77.10	99.78	211.6	202.3	158.3	328.1	270.8	358.0	362.8
10	.569	.0980	.8205	52.10	70.93	89.82	178.0	174.7	137.7	283.5	238.5	292.9	315.0
6	.760	.0930	.8216	49.62	64.54	75.19	149.6	155.6	120.0	252.2	206.0	265.0	273.2
4 00	4.031	.0873	.8234	45.10	50.80	67.03	121.2	125.7	103.6	198.5	168.8	225.1	217.2
3 50	.446	.0785	.8263	35.91	40.09	47.78	96.99	96.80	74.86	147.2	123.8	152.0	158.7
45	.638	.0750	.8278	31.50	35.78	42.84	84.12	85.05	65.90	129.3	105.0	140.0	140.8
40	.827	.0716	.8293	28.99	29.50	38.06	74.64	72.13	55.93	111.4	92.60	125.3	114.2
35	5.001	.0687	.8307	25.70	28.30	34.00	62.53	64.46	50.40	101.1	80.22	105.0	107.4
30	.168	.0663	.8321	22.10	25.20	30.63	56.00	57.26	46.92	88.60	75.79	90.61	98.79
20	.486	.0623	.8349	18.28	....	26.52	40.39	48.46	36.32	75.35	61.34	69.20	78.81
2 54	6.240	.0542	.8419	....	....	....	27.61	30.59	25.12	41.72	35.81	38.66	44.92
30	.852	.0487	.8481	....	....	....	....	....	....	....	22.50	25.64	29.28
2 00	7.546	.0433	.8520	....	....	....	....	....	....	....	....	....	....

TABLE II

Energy Distribution of Platinum—Temperature Determinations With a Le Chatelier Thermocouple

Spectrometer circle	Correction divisors		λ	Energy distribution, corrected and reduced to normal spectrum									
	$s.w. \times R^3$	$\frac{(1-r_1)^2}{(1-r_2)^4}$		5 855° C	2 976° C	7 1068° C	6 1119° C	3 1152° C	10 1210° C	8 1227° C	9 1327° C	11 1445° C	12 1509° C
° ′													
5 00	0.0284	0.8067	0.589μ	....	....	....	....	....	....	....	10.48	....	30.11
4 57	.0375	.8073	.646	....	....	....	....	....	....	9.58	23.46	44.28	66.30
55	.0473	.8081	.698	....	....	....	5.49	9.08	13.08	16.10	39.75	68.79	111.6
53	.0630	.8087	.757	....	5.69	10.80	13.14	23.95	32.80	32.00	70.21	116.2	192.1
51	.0820	.8094	.836	....	8.75	19.14	31.06	47.17	53.20	65.84	132.9	200.3	284.9
49	.1033	.8100	.934	4.67	18.89	32.99	60.00	86.76	96.64	113.2	215.0	308.0	426.0
47	.1273	.8106	1.054	11.25	44.20	72.19	115.8	161.0	179.9	209.7	368.0	476.0	650.1
45	.1498	.8112	.197	24.70	81.04	128.6	190.5	263.0	280.1	316.5	524.8	649.9	870.0
43	.1631	.8118	.357	46.24	135.3	185.6	275.0	369.2	378.0	446.7	673.7	781.9	987.7
41	.1710	.8124	.526	65.24	176.8	246.6	340.6	431.0	443.9	502.5	730.5	815.8	1013.0
39	.1710	.8128	.698	85.00	205.5	271.0	360.1	457.1	465.7	510.0	735.1	786.6	969.8
37	.1665	.8132	.868	97.20	216.9	279.6	368.7	463.1	451.0	508.0	694.4	708.6	880.0
35	.1600	.8137	2.033	103.5	221.7	270.0	355.0	433.9	432.2	466.1	642.6	663.5	789.4
33	.1515	.8141	.190	106.4	214.4	259.0	335.0	407.0	399.4	435.0	572.4	581.3	702.9
30	.1414	.8148	.410	100.2	194.0	234.9	297.6	362.3	341.6	377.1	500.3	488.1	591.0
28	.1332	.8154	.546	95.13	182.8	221.0	271.1	324.6	317.0	346.4	439.7	434.1	516.0
24	.1227	.8164	.801	80.93	147.9	170.9	213.6	253.0	242.5	262.9	330.8	320.0	371.8
22	.1183	.8169	.921	72.81	131.8	154.0	186.0	219.6	211.7	231.3	288.0	252.2	342.0
20	.1140	.8175	3.037	69.00	123.1	142.4	176.0	204.7	196.5	215.0	266.3	260.0	292.4
18	.1109	.8181	.150	65.25	112.6	131.2	162.0	187.7	188.2	198.0	249.0	235.4	274.9
14	.1045	.8193	.367	58.40	101.5	113.7	138.2	160.4	156.8	167.5	206.0	195.0	228.0
10	.0980	.8205	.569	53.96	91.11	102.0	123.7	140.8	138.6	148.0	178.3	168.0	196.2
6	.0930	.8216	.760	49.61	81.42	89.19	112.8	126.0	122.0	130.0	155.9	149.5	173.0
4 00	.0873	.8234	4.031	41.19	68.06	76.80	92.39	101.6	101.4	105.5	129.5	120.6	135.6
3 50	.0785	.8263	.446	34.52	54.24	56.26	66.59	77.82	78.19	78.00	95.59	87.67	100.8
45	.0750	.8278	.638	30.65	47.69	51.06	60.90	65.23	69.25	70.76	80.58	74.79	89.40
40	.0716	.8293	.827	27.97	41.78	46.82	54.40	59.45	59.30	63.19	73.94	66.70	80.85
35	.0687	.8307	5.001	24.70	39.08	40.12	50.27	55.20	53.80	54.63	65.40	60.00	70.40
30	.0663	.8321	.168	22.30	34.79	36.99	44.76	47.20	48.93	48.40	59.07	53.82	61.80
20	.0623	.8349	.486	18.66	27.16	29.79	37.29	37.40	39.00	40.71	47.83	44.00	51.60
2 54	.0542	.8419	6.240	12.71	16.89	19.06	....	21.04	23.69	24.11	30.70	27.62	29.81
30	.0487	.8481	.852	....	....	....	....	15.96	....	....	17.67	....	19.35
2 00	.0433	.8520	7.546	....	....	....	....	8.10	....	....	....	....	....

A number of the best curves reduced to the normal spectrum are given in Table I and Table II. The correction factors for reduction to the normal curve are also given. These factors include the variation in dispersion (the slit width, "s. w."); the variation in reflecting power (R; R^3 for three mirrors); the variation in reflecting power with angle of incidence upon the prism face (r_1; r_1^2 for two faces); and the loss by reflection at normal incidence from the fluorite bolometer window and the fluorite prism (r_2; r_2^4 for four surfaces). The last two corrections are computed by means of the well-known Fresnel equations, from the refractive indices and the angle of incidence of the energy upon the prism face.

The radiation sensitivity of the bolometer was easily kept constant while observing a given spectral energy curve; but no attempt was made to obtain all the energy curves at the same sensitivity. Hence the relation between curves obtained on different days is not known. Furthermore, it is not required in the computations herein employed. The computations of the constants are based upon the assumption that the mathematical equation of the spectral energy curve is similar to the Wien equation;

$$E = C_1 \lambda^{-\alpha} e^{-C_2/\lambda T}$$

from which it follows that

$$\lambda_{max} T = \text{Const}; \qquad \frac{E}{E_{max}} = \left\{ \frac{\lambda_{max}}{\lambda} e^{\frac{\lambda - \lambda_{max}}{\lambda}} \right\}^{\alpha}$$

The computations of λ_{max} and of α are obtained from equations (4) and (5) of the previous paper[7] and need not be repeated here. It was there shown that there are no real "constants"; in other words, that the equation expressing the spectral energy distribution is more complex than the one assumed in the computations.

In the previous observations the platinum strip was in an evacuated glass bulb. The operating temperatures were not so high, and the platinum strip retained its original high polish. The values of α decreased from 8 to 6.2 for a change in λ_{max} from 2.2μ to 1.9μ, while in the present work, in air with the platinum

---

[7] This Bulletin, 5, pp. 351 and 352; 1909.

surfaces deteriorating (which is supposed to "blacken" the radiation. This would decrease the value of α at any given temperature; but this does not appear to affect the temperature coefficient of α, as may be noticed by the order in which the energy curves were observed—see Fig. 3; XV and XVIII), the values decreased from 6.6 to 6.0 for the same change in λ_{max}, i. e., in temperature. There are several reasons for this difference, the principal one being the highly polished surface of the strip previously used, which would increase the value of α. In Fig. 1 (temperatures by means of optical pyrometer, *A;* thermocouple, *B*) are shown graphically

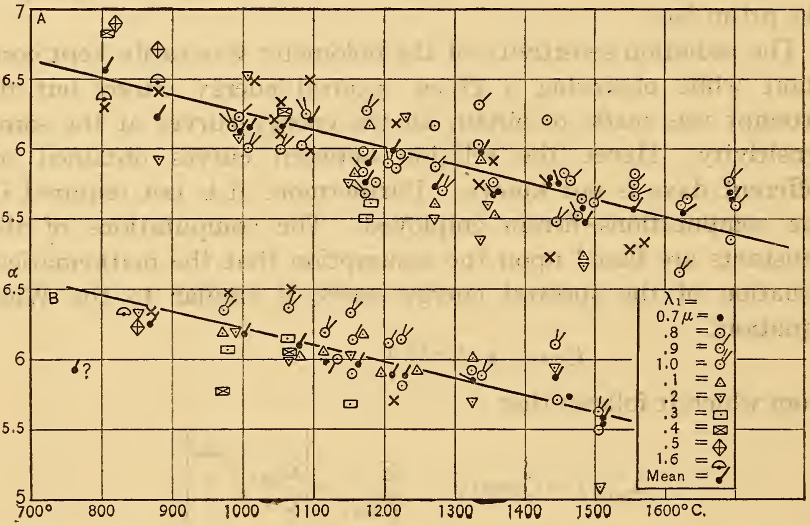

Fig. 1

the results of the computations of α for various temperatures, and for various values of λ_1 taken from the same spectral energy curve; also the mean value, ♂, of all the computations of α, of which only a few of the individual values are shown at each temperature. The variations from the mean are rather large, and occasionally even the mean value lies far from the curve, e. g., Fig. 1–*B*, at 750° for α and Fig. 3–*A* for $\lambda_{max}T$, but in both cases the spectral energy curves were poor, and hence should perhaps not have been computed at all. Both series *A* and *B*, Fig. 1, show that in the temperature range of 1100° to 1400° the value of α is of the order of

5.8 to 6.0. It is difficult to determine how much of this variation in α is owing to roughening of the surface (which is supposed to "blacken", i. e., change the quality of, the emissivity) and how much is the result of the temperature coefficient of emission, which, however, is small in this region of the spectrum. As already mentioned the variation in α is probably affected to the greatest extent by the shift of the maximum emission into the region of the spectrum where the reflecting power decreases rapidly with wave length.

The value of λ_{max} is given in Fig. 2 for the optical pyrometer temperatures and energy curves (I to XVIII) and the thermocouple (1 to 12) temperatures and energy curves. In this curve the ordinates are the computed values of λ_{max} which result from taking different values of λ_1 (and λ_2) as explained in the previous paper.[1] All of these curves show a minimum which shifts toward the shorter wave lengths with rise in temperature.

If we take a "black body" spectral energy curve (at 1500° C) and multiply its ordinates (= emissivity) by the absorbing power (100 − Reflection) of platinum, then, from the resulting curve, compute the value of λ_{max} for different values of λ_1 (and λ_2) we obtain the heavy curve shown in Fig. 2, Pt. This likewise has a minimum, which would be still more marked if we had assumed a temperature coefficient of emission for the values of λ_2 in the region of 4μ to 7μ as observed by experiment.

This minimum in λ_{max}, which usually lies in the region of 3.0μ to 3.2μ, is not in the region of atmospheric absorption bands (at 2.7μ to 3.0μ) and it is not to be found in the spectral energy curves of a uniformly heated inclosure, or so-called "black body." The explanation offered for its occurrence is based upon the high temperature coefficient of emission in the region of 4μ to 7μ and the rapid change in emissivity which must follow a shifting of the maximum of the spectral energy distribution into the region of 1.5μ to 1.2μ, where the reflecting power of platinum undergoes a rapid decrease with wave length. In the region of 3.0μ to 3.5μ there is no marked temperature coefficient of emission, and the reflecting power is fairly uniform. Hence in this region of the spectrum there is no marked change in the emission with rise in temperature, other than that which would result if platinum were

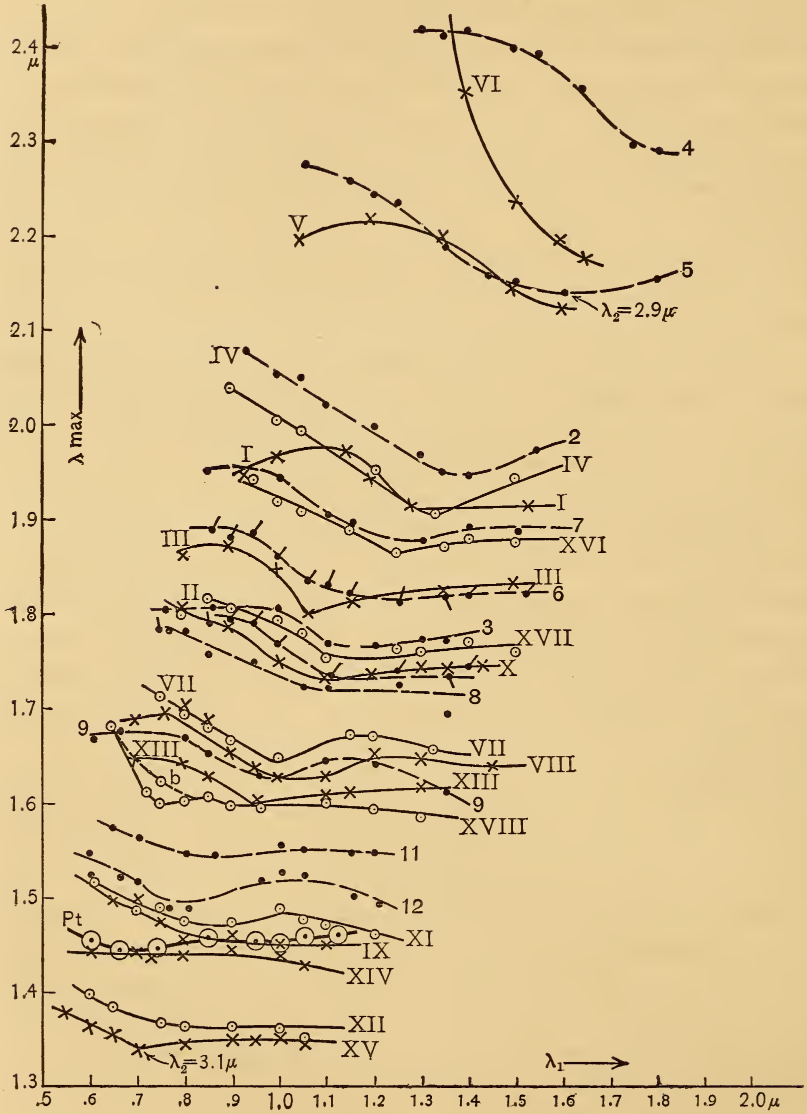
2.4 μ
2.3
2.2
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
λ max
.5
.6
.7
.8
.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0μ
λ₁
VI
4
V
5
λ₂=2.9μ
IV
2
IV
I
I
7
XVI
III
III
6
II
3
XVII
X
8
VII
9
XIII
b
VII
VIII
XIII
9
XVIII
11
12
Pt
XI
IX
XIV
XII
XV
λ₂=3.1μ

Fig. 2

a "gray body." The emissivity should therefore be a minimum in this region, and when computing λ_{max} from a value of λ_1 in which the corresponding value of λ_2 falls in the region of 3.2μ there follows a low value of λ_{max}. For the same reason, the values of α are very irregular when computed for various values of λ_2. It is, of course, to be understood that the low value of λ_{max} for values of λ_2 in the region of 3μ is owing partly to atmospheric absorption bands at 2.7μ. The observed energy curves are more or less distorted, depending upon the temperature; and to a more marked degree than seems possible as the result of experimental errors. Whether this is the true explanation remains to be determined.

The various values of $\lambda_{max}T$ are given in Fig. 3 for the optical pyrometer temperatures A and the thermocouple temperatures B. In each series the mean values (⊙ ⊙ ⊙) of all the computations (from 4 to 8 on each curve) of λ_{max} and also the aforesaid minimum values (. . .) are given. The value of $\lambda_{max}T$ increases gradually from 2400 (mean value) at 700° to 2620 (2690 for thermocouple) at 1500° C. These values are independent of the order in which the energy curves were determined, showing that the change in the quality (the "blackening") of the radiation is a true temperature effect and not one resulting from the roughening of the surface with evaporation. To the writer the latter explanation seems far-fetched, because the optical constants of each particle of the roughened surface are the same as before (viz, that of platinum), and the roughening is not of sufficient depth to produce a cavity within which the radiation can become "blackened" by internal reflection.

In the lower part of Fig. 3 are shown the different values of $\lambda_{max}T$ as observed by Paschen.[8] They increase in a line parallel with those herein described. Paschen did not, however, consider this a real variation. The numerical values are 4 per cent lower, owing probably to a difference (50°) in the temperature scale, and especially to a difference (0.09μ) in the dispersion curve of fluorite. An examination of his "Table XIV" shows that the values of λ_{max} pass through a minimum in the same manner as found in the present work, Fig. 2.

---

[8] Paschen: Ann. d. Phys. (3), **60**, p. 696; 1896.

The theoretical curves for platinum computed on the basis of Wien's equation, using $\alpha = 6$ at 1100° C and $\alpha = 5.6$ at 1500° C, agree fairly well with the observed curves in both cases, being too high in the region of 3μ, intersecting them in the region of 4.5μ, and hence falling below the observed curves in the region of 5μ to 6μ.

The spectral energy curves obtained by the two methods of operation are given equal weight; for in the optical pyrometer series (e. g., energy curve *X*) the temperature sometimes changed or the platinum strip collapsed, while in the thermocouple series the temperature changed as already explained. The errors in the work are not to such a great extent owing to the difficulty in making the temperature measurements as in heating the platinum strip. The values of $\lambda_{max}T$ are somewhat higher by the thermocouple measurements. This might be the result of one or more of several causes: (1) Lack of "blackness" of the radiation from the platinum strip, which would give pyrometer readings which are too low; (2) the surface of the platinum in the thermocouple measurements being colder than the center, would give a λ_{max} which is too large for the true temperature; (3) the greater roughness of the platinum surface in the thermocouple series would increase the "blackness" of the radiation, thus giving a λ_{max} which is too large.

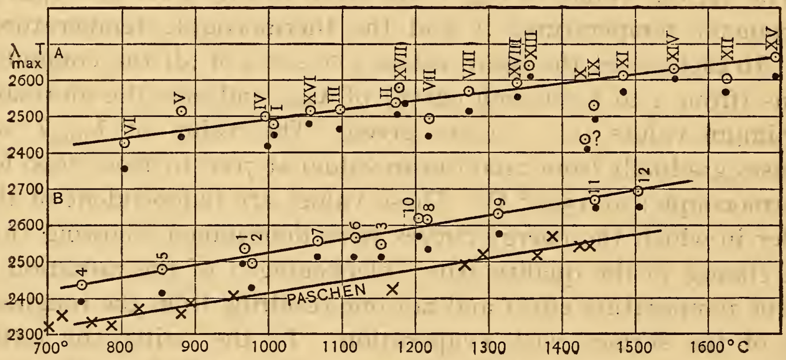

Fig. 3

The lack of "blackness" of the radiation from the V-shaped opening might have been tested by determining the melting point of the strip by means of the optical pyrometer. But the strip collapsed when heated above 1700°, and the nature of the radiating properties of platinum did not appear to warrant an attempt to establish accurate numerical values of these constants.

It is to be noticed that the values of α are obtained by a method which is independent of the temperature measurements. The mean value of α for a given temperature is not markedly different for the two methods of determination.

It is to be noticed that sometimes the same energy curve gave a good value of α and a poor value of $\lambda_{max}T$. This is owing to the fact that (e. g., the value of curve X, Fig. 3–A) the energy curve was poor in the region of 3μ to 5μ, which affected the λ_{max}, but was good in the region of 1μ to 2μ, from which region was obtained the value of E_{max} used in computing α.

The two independent methods used in investigating the so-called radiation constants (α, which is obtained without a knowledge of the temperature, and $\lambda_{max}T$) lead to the same conclusion that there are no real "constants" for metals (platinum), as announced in the previous communication. The value of $\alpha = 6$ and $\lambda_{max}T = 2600$ are therefore applicable only in work which does not require high accuracy.

It is purposed to inquire into the total radiation of metals to learn whether it is possible to obtain a more accurate temperature coefficient of emission for α than it is possible to obtain from the data herewith presented.

In conclusion, acknowledgment is due Mr. U. F. Rosen for the computations involved in this research, the experimental part of which was carried out about eight months ago.

II. EMISSION SPECTRA OF NEON, HELIUM, AND MERCURY

The spectral-energy distribution of the radiation from various gases in vacuum tubes and from metalic vapors in the carbon arc was given in a previous paper.[9] The main object of the investigation was to determine the location of the strongest emission lines in the spectrum. It was found that in all cases the most intense lines lie just beyond the red (in the region of 0.8μ to 1.0μ) and that in the region of 1.5μ to 3.5μ there was a complex radiation

---

[9] Physical Review, 22, p. 1; 1906. Carnegie Publication No. 35; 1909.

which was weak in intensity and, usually, unresolved with the spectrometric apparatus employed. Subsequent experimenters, using a larger dispersion, have succeeded in resolving this latter region into separate lines, which in their spectral-series relations are found to be a continuation of the lines in the visible spectrum. The dispersion of the present spectro-bolometric apparatus (mirror spectrometer, fluorite prism, and vacuum bolometer) was not sufficient to enable one to locate the individual lines. However, a vacuum tube containing neon being available, it was deemed of interest to continue the inquiry as to the location of the most intense emission lines. At the present stage of our knowledge of the subject but little can be said of the application of these data. The subject may be summarized by stating that in spark spectra the most intense lines are situated in the ultra-violet; that in arc and vacuum tube spectra the most intense lines are situated just beyond the red; and that in the spectra of solids the maximum emission lies far in the infra-red but shifts rapidly toward the visible with rise in temperature.

The prismatic (x x x) and the normal (. . .) spectral energy curves of neon are given in Fig. 4, from which it may be noticed that the maximum emission lies within the group of lines in the red of which the line at 0.64μ is the brightest to the eye. The intensity of the line or group of lines in the region of 0.8μ is only about one-twentieth that of the red. A slight emission was observed at 1.1μ. Beyond this point no radiation was observed for the current (0.008 ampere, capillary tube 1 mm diameter) at which the tube was operated. No doubt more lines will be observed on more intense excitation, but this will not modify the observations as to the location of the maximum emission. From the data at hand it appears that the maximum emission at 0.64μ is not due to the lack of resolution of a group of lines, as compared with the maximum at 0.86μ, but that it is a property of this gas. This appears to be the only gas on record in which this property obtains.

The spectrum of helium consists of fewer lines than that of neon, the most prominent one (visually) being the yellow line at 0.5876μ. Radiometrically, however, conditions are quite different. The red lines are then found to be as intense as the yellow line.

The most intense line lies at 1.083μ, as shown in Fig. 4. The intensity of a weak line at 2.05μ is only 0.05, and the yellow line (0.587μ) is only 0.1 the value of the line at 1.083μ.

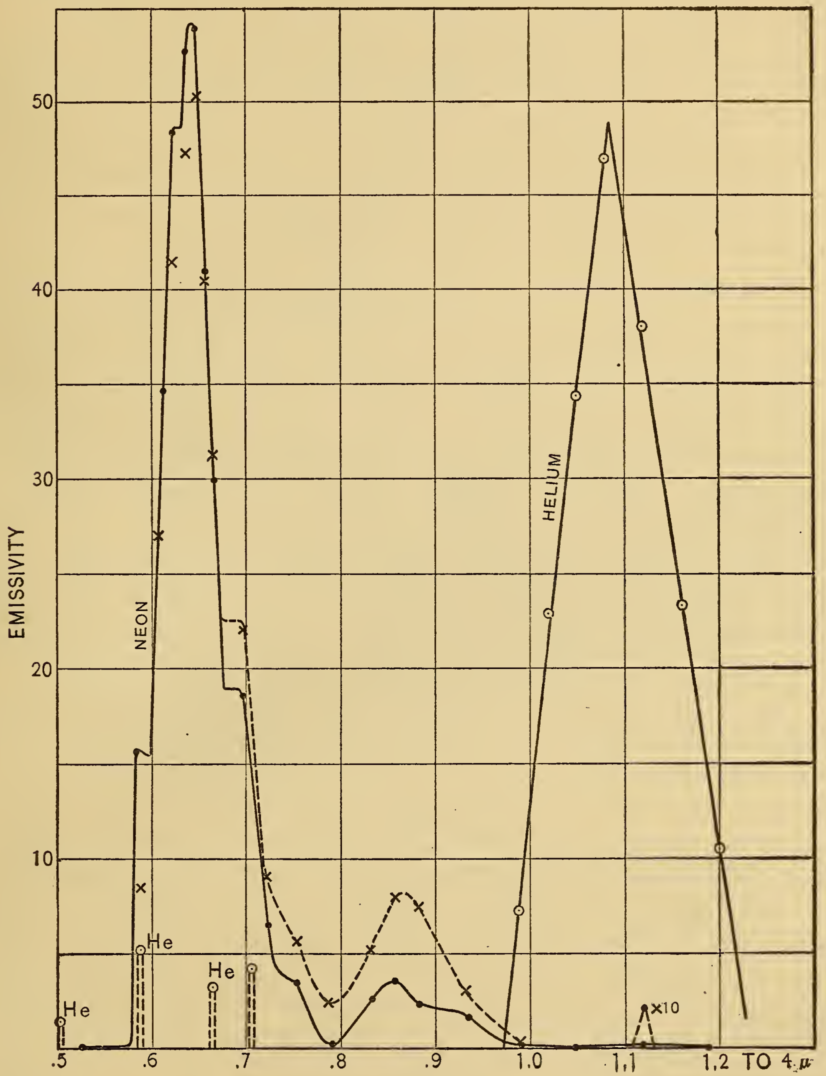

Fig. 4

It is well known that only a small fraction of the energy expended in such gases as helium, xenon, etc., is required to excite neon to light emission. Since the energy put into the gas must come out again in some manner (mostly as radiation of various wavelengths) and since but little of the radiation emitted by neon is in the infra-red, an explanation is at hand of the small energy input (high efficiency) required to excite this gas to light emission.

The luminous efficiency of vacuum tube radiation (air,[10] nitrogen, carbon dioxide, helium, etc.) is of the order of 15 to 20 per cent, or perhaps even much lower, owing to the great amount of infra-red radiations emitted. In marked contrast with these gases is neon, in which the infra-red is almost entirely absent, so that its luminous efficiency is of the order of 80 to 90 per cent. The color of this light is a rich crimson.

In conclusion, it may be noticed that the spectrum of neon is composed of numerous fine lines, more than 60 of which lie between the red and yellow helium lines (0.5876μ and 0.7065μ). With a larger dispersion the shape of the curve will necessarily change until, when final resolution is attained, each spectral line will give a more symmetrical energy curve, as observed (Fig. 4) at 1.083μ for helium. There is sufficient reason for believing that the emission lines in neon are just as numerous at 0.8μ to 1.0μ as they are in the visible spectrum, so that whatever the dispersion, the same energy distribution will obtain as here observed, viz, that the strongest lines occur in the region of 0.6μ to 0.7μ of the visible spectrum. In this respect, as already stated, neon is unique.

The prismatic energy distribution of a Heraeus quartz-mercury lamp is given in Fig. 5 for different values of energy consumption. The lamp used (end on) was of the 110-volt type, being 7 cm in length, the electrodes having cooling wings of thin sheet copper. With the fluorite prism and mirror spectrometer used in making the observations the green and yellow lines (0.546μ and 0.576μ, respectively) are completely resolved so that the relative intensities are as shown in Fig. 5. The two lines at 1.014μ and 1.128μ are not resolved, as shown in curve *a*, so that apparently the intensities are as great as is the yellow line. In the normal spectrum the intensities of these lines would be much less than one-fourth (slit width at 1.0μ is about 4 times the value at 0.58μ) the yellow line. The mercury spectrum is therefore similar to the

---

[10] Drew: Phys. Rev. 17, p. 321; 1903.

neon spectrum in having the strongest emission lines in the visible spectrum.

It is well known that the green mercury line is easily excited to light emission so that the hot mercury shaken back and forth in the quartz lamp emits a beautiful greenish light. On excitation the yellow line increases rapidly in intensity. This is well

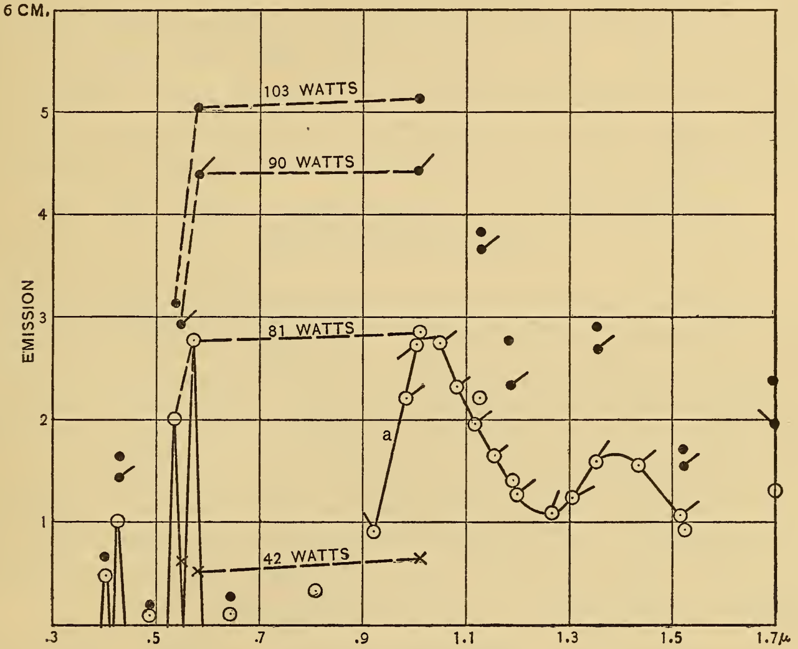

Fig. 5.—*Mercury vapor*

illustrated in Fig. 5. Using an energy input of 42 watts the green, the yellow, and the line at 1.01μ (unresolved), are of practically the same intensity. On 81 watts the yellow line is 1.4 times and on 103 watts it is 1.7 times the intensity of the green line (the observations are joined by dotted lines for convenience in illustration) while the infra-red grows in proportion with the yellow line. It is of course known from the work of Küsch and Retschinsky,[11] and of Pflüger [11] that lines belonging to a given

---

[11] Küsch and Retschinsky: Ann. der Phys. (4), **20**, p.563; 1906. Pflüger: Ann. der Phys. (4), **26**, p. 789; 1908.

spectral series increase in intensity in the same proportion; and that for different spectral series lines the increase in intensity is different for the same energy input. The present data, however, furnish instructive information, not previously at hand, as to the cause of the decrease in luminous efficiency, after exceeding a given energy input, which according to Küsch and Retschinsky is about 0.185 w. p. m. h. c. This is owing to the rapid increase in intensity of the emission lines in the infra-red as compared with the blue and green lines. The intensity of the yellow line, increasing as it does in the same proportion as the infra-red, is not sufficient to counterbalance the loss by radiation in the infra-red, and the result is a decrease in the ratio of the luminous to the total radiation.

III. EMISSIVITY OF DIFFERENT PARTS OF AN ACETYLENE FLAME

In a previous paper[12] it was shown that in the spectral energy curve of an acetylene flame viewed flatwise, the maximum emission at 1.25μ is twice the height of the maximum at 4.35μ; and that for the flame viewed edgewise the ratio is 5.5. The emission maxima of the flame viewed edgewise are shifted about 0.05μ toward the longer wave lengths, viz, at 1.30μ and 4.40μ, respectively.

In the visible spectrum the spectral energy curves of the flame viewed flatwise and edgewise were found to be superposable, as one would expect; for the color of the flame appears to be independent of the thickness of the radiating layer.

In a subsequent examination made by Messrs. Beatty and Crittenden, using the same apparatus (vacuum bolometer, fluorite prism, and spectrometer) the spectral energy curve given in Fig. 6 was obtained. The lower part of the flame radiated flatwise into the spectrometer slit. The chief interest in this curve is that the maximum at 1.15μ which is caused by the radiation from the carbon particles is only about 0.7 the height of the CO_2 maximum at 4.35μ. The shift of the latter maximum from 4.40μ to 4.35μ is to be ascribed to a lower temperature; for the position of this maximum is a function of the temperature. The shift in the maximum from 1.25μ to 1.15μ is the result of the rapid decrease in emissivity with thickness of the radiating layer, in the spectral

---

[12] This Bulletin, 7, p. 243; 1911.

region from 1.5μ to 2.5μ, where the radiation is far less saturated than in the visible spectrum. This brings out the small emission band of CO_2 at 2.75μ which was obliterated by the more intense emission of the thicker radiating layer of carbon particles, observed in the previous paper. In Fig. 6 the crosses (x x x) illustrate the relative heights of these two emission maxima when the flame radiated edgewise into the spectrobolometer. Here the ratio of the two maxima is 3, as compared with the values of 0.7 to 2, when the flame was viewed flatwise.

Fig. 6.—*Acetylene flame*

Evidently the wide variations in the radiant efficiency of the acetylene flame, as obtained by various observers by integrating the spectral energy curves, is to be explained on the basis of such evidence as herewith presented.

It was deemed of interest to investigate this subject further in connection with the question of the combustion of gases in flames. The question investigated was the relative intensities of these two maxima (carbon particles and carbon dioxide) in different regions of the flame. Because of the lack of intensity it is very difficult to observe the complete spectral energy curve of a small part of the flame. Accordingly only the (prismatic) maxima of emission were observed. A flat and a cylindrical flame were examined. In the burner used (Von Swarz "Perfection," previously described) the flat flame is produced by two cylindrical jets of ignited gas impinging at an angle of 90°. This leaves a (transparent) nonluminous region 4 to 5 mm in diameter at the base of the flame, as shown in Fig. 7–*A*.

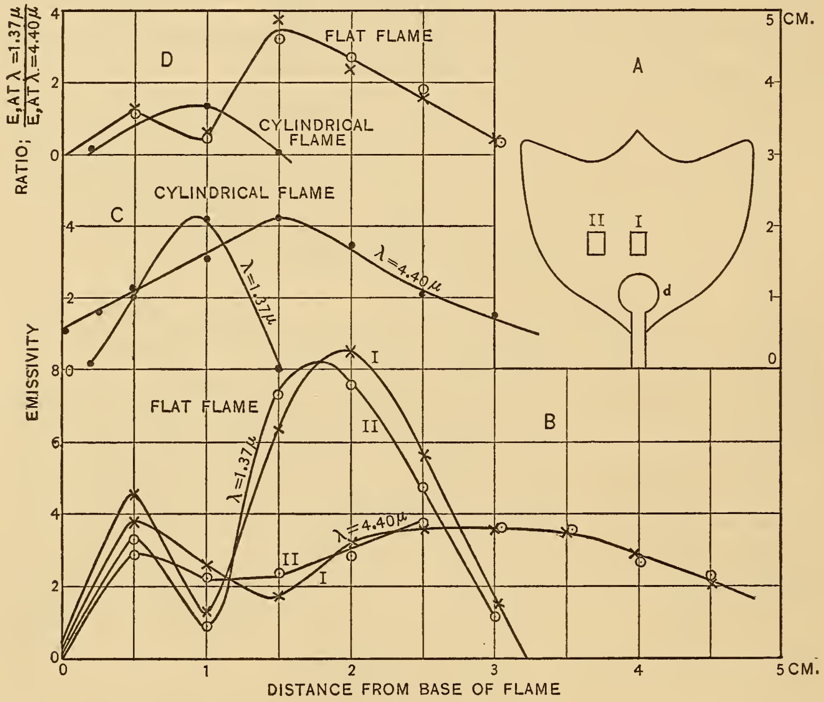

Fig. 7.—*Acetylene flame*

The flame was placed back of a metal screen with a hole in it 3 mm high and 2 mm wide. An image of the illuminated slit was projected upon the spectrometer slit by means of a short focus mirror. The flame was mounted upon a carrier having a graduated scale, which enabled the operator to raise or lower the flame before the opening in the metal screen.

Two series of observations were made on the flat flame on the regions shown by the small rectangles (I, II) in Fig. 7–*A*. Starting with the slit at the base of the flame, with the spectrobolometer set on $\lambda = 1.37\mu$ and gradually lowering the flame, a series of observations was made as shown in the lower part of Fig. 7–*B*. Resetting the flame (slit at the base of the flame) and placing the bolometer in the region of 4.40μ a similar series of observations was obtained. The first maximum emission, at 5 mm from the base of the flame, comes from the cylindrical jets, and the lowest emission comes from the dark spot, *d*, of the flame, Fig. 7–*A*. The carbon particles have their maximum emission 2 cm above the base while the CO_2 emission continues very strong several centimeters above the luminous flame. The minimum emission of the CO_2 at 4.40μ appears to be situated several millimeters above the nonluminous spot, *d*, Fig. 7–*A*.

The radiation from the cylindrical flame was similarly observed, Fig. 7–*C*. It is of interest to note that at the base, where combustion begins but where the flame is almost nonluminous, the CO_2 (CO ?) already emits considerable energy. Furthermore, the carbon particles emit but little in the hazy region 2 cm above the base, where the luminosity seems to be somewhat similar to the radiation from incandescent carbon dioxide in vacuum tubes. Of course there is no discontinuous spectrum as found in the vacuum tube discharge through CO_2. Perhaps it would therefore be better to consider this glow similar to the hazy outline at the base of a Bunsen flame. The CO_2 emission continues strong for some distance above the luminous part of the flame.

In the upper part of Fig. 7–*D* is given the ratio of emission of these two curves (7–*B* and 7–*C*; E at $1.37\mu \div E$ at 4.4μ)) from which it is easy to see how, in integrating over a large area as was done in obtaining the spectral energy curves of Fig. 6, the relative height of the two maxima depends upon the position of the flame before the slit.

The data at hand are too meager to consider the question of "luminescence" in the hazy luminous region at the top of the flame, where the emission of the carbon particles became immeasurably small. From this preliminary survey it appears highly desirable to have a more thorough examination of various kinds of flames.

IV. VARIATION OF EMISSIVITY WITH THICKNESS OF THE RADIATING LAYER—OXIDES

In a previous paper[13] experimental data were given on the radiating properties of various metals in which only the superficial conditions (refractive index, reflecting power, etc.) were involved.

In a later paper[14] experiments were described on the variation in the spectral emission with variation in thickness of the radiating layer, as exemplified in the acetylene flame and in the Welsbach mantle. Attention was called to the fact that in nonmetals the emissivity is dependent mainly upon the absorptivity which in turn depends upon the thickness of the radiating layer. The investigation included a study of the acetylene flame radiating flatwise and edgewise into the spectrobolometer; also the Welsbach mantle heated to incandescence in the usual way and the same material formed into a solid rod and heated electrically.

In connection with these experiments it was of course desirable to obtain quantitative data on the variation in emissivity of some (pure) oxides with thickness. For this purpose samples of the same kind of glower material, squirted into rods of various diameters, were prepared under standard conditions.

The glowers described in the present experiments were squirted and baked by the Westinghouse Nernst Lamp Co., after which suitable platinum terminals were attached and covered with regular glower paste. After this the glowers were seasoned by operating them at a high temperature for five to six hours. The lengths of the glowers, determined experimentally, were such that they could be started on a 118 volt a. c. circuit by preheating with a blast lamp. The generator (rotary converter) was operated on a storage battery to insure a constant voltage. The alternating current was used instead of direct current to avoid the transference of platinum from the terminals into the glower, which occurs with heavy glowers. Suitable ballast rheostats were placed in series with the glowers, the lengths of which varied from 8 mm for the one which was 0.385 mm diameter to 18 mm for the glower which was 2.150 mm diameter. After starting the

---

[13] This Bulletin, 5, p. 339; 1909.

[14] This Bulletin, 7, p. 243; 1911.

glower, the terminal voltage dropped to 99 volts (0.20 ampere) for the thinnest glower, and to 70 volts (1.86 amperes) for the thickest glower. A voltmeter was kept across the terminals and an ammeter was in series with the glowers.

All the glowers were set to the same emissivity against a standard Nernst glower which in previous work[14] had been set to the same color as a 1.2 w. p. m. h. c. tungsten lamp. By placing the thin glowers one at a time in front of a thick glower, which was kept at a constant voltage, it was an easy matter to vary the voltage of the former until they disappeared against the thick glower. In this calibration the glowers were set to the same emissivity by viewing them through red, green, and blue glass. Usually there was no marked variation in the voltage readings when making these settings, using differently colored glass.

All these glowers were intercompared at the completion of the investigation, and it was found that the calibration had not changed. This was to have been expected, for the filaments had been thoroughly seasoned and each one had been operated but a short time.

A number of experiments might be performed with these glowers. One might, for example, study the candle power, efficiency, etc. For the present, experiments were made only on the shape of the spectral energy curves as modified by the change in thickness of the radiating layer. This gives the loss in efficiency resulting from the preponderating increase in emission in the infra-red spectrum. (Other methods will be necessary to determine the losses by conduction.) For this purpose the glowers were adjusted at a suitable distance before the slit of the vacuum spectrobolometer. No attempt was made to secure the same solid angle of radiation upon the prism face, for all the glowers had been set to the same emissivity in the visible spectrum, by optical methods, and the only requirement was to use the glowers at the voltages observed in obtaining the same emissivity and to obtain suitable factors with which to superpose the spectral energy curves of the various glowers, in and near the visible spectrum.

The results are shown in Fig. 8, which gives the normal spectral energy distribution of the various glowers. For the thin glowers (1 to 4) the spectral energy curves superpose over practically the

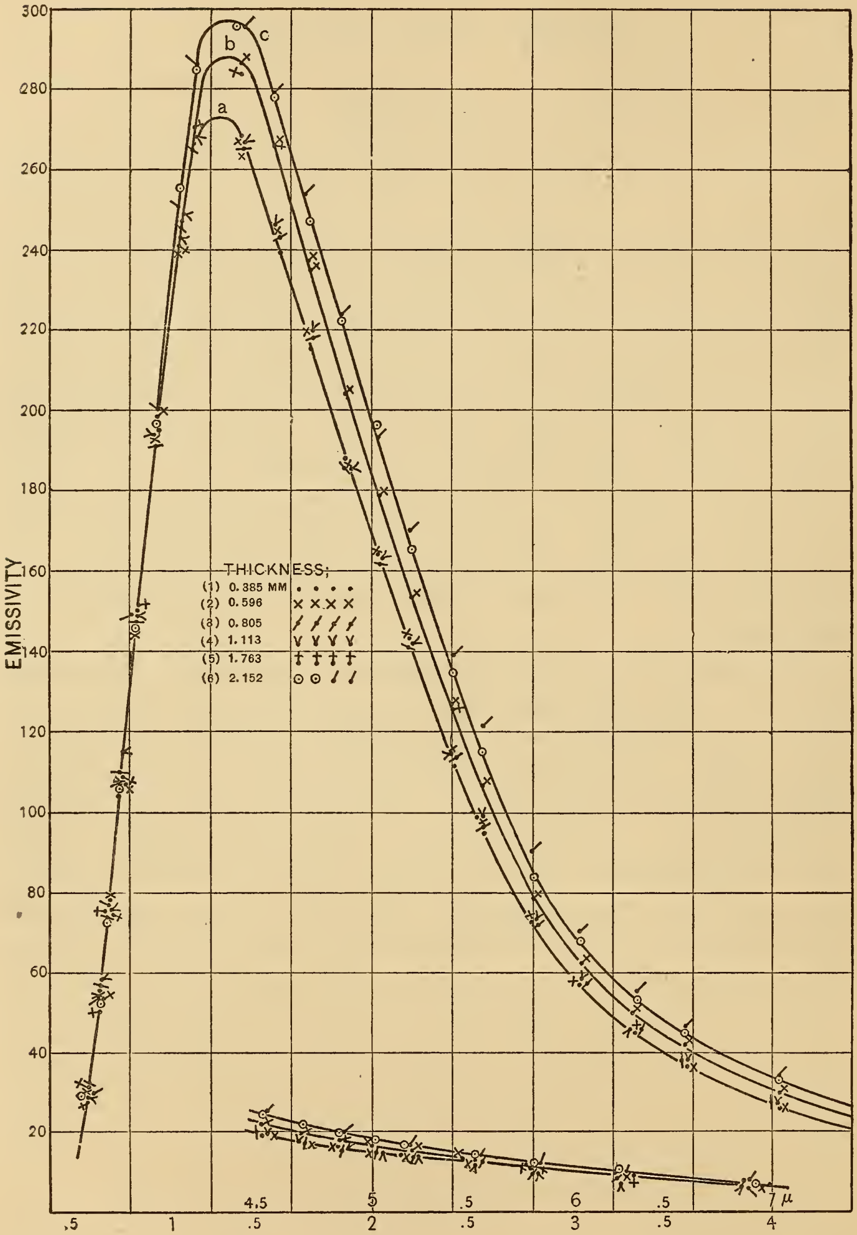

Fig. 8.—*Nernst glower*

whole length of the curve. The latter glower (4) shows a slight increase in emissivity at 1.5μ to 4μ. These form curve *a*, in Fig. 8. In curve *b* are given two series of observations on a glower 1.763 mm diameter. In the same manner, curve *c* shows two series of observations on a glower 2.152 mm in diameter, the observations being made on different days.

The increase in the emissivity, extending from 1.5μ to 6μ, is very marked in these two curves and is so great that it can not be attributed to experimental errors. An integration of these curves gives the ratio of the areas of $a : b : c = 1 : 1.071 : 1.134$. From this it appears that in order to obtain the same emissivity in the visible spectrum, the thickest filament radiates 13.4 per cent more infra-red energy than obtains in the thinnest filament. There is, of course, also a much greater loss of heat by conduction from the ends of the thick filament than from the thin filaments; but for the present the extent of this loss remains undetermined. The ordinary solid glower, 1.1 mm diameter, is represented by the higher values in curve *a*, which represents a loss of 2 per cent more infra-red radiation than obtains in the thinnest glowers.

The commercial A. C. glower is a hollow cylinder which is more efficient than a solid glower of the same diameter. To manufacturers it is a well-known fact that the very thin glowers are the most efficient. The data previously presented on the Welsbach mantle and the data herewith presented on the emissivity of various solid glowers show why this is the case. The efficiency can be increased somewhat by operating several glowers near together. This is owing to the fact that it requires about 18 to 20 watts to keep an ordinary 110-volt glower warm and conducting, unless operated on a high voltage transformer, as was found on a previous investigation of the selective emission[15] of the Nernst glower. The proximity of several glowers increases the surrounding temperature and decreases the losses by convection with a consequent rise in temperature for the same energy input.

The thicker the glower the more nearly its radiation approaches that of a black body. For the thinnest glower the maximum emission lies at about $\lambda_{max} = 1.25\mu$ and for the thickest filament the maximum emission is at about $\lambda_{max} = 1.32\mu$, although it is at the same emissivity in the visible.

---

[15] This Bulletin, 4, p. 533; 1908.

The value of $\lambda_{max}=1.32\mu$ and $\lambda_{max}T=2930$ would make the temperature about 2230° Abs. No doubt the operating temperature is lower than this value, for the glower is not a black body as here assumed on the basis that the radiating layer is of sufficient thickness to emit completely all frequencies.

The above-mentioned filling up of the spectral energy curve between 1.5μ and 3μ, with increase in thickness of the radiating layer, is especially marked in the energy curve of the acetylene flame, an illustration of which is given on another page.

The data herewith presented confirms the previous conclusions that the radiation constant, α, of the Nernst glower varies with the thickness of the radiating layer.

V. RADIATION FROM A UNIFORMLY HEATED CAVITY AND FROM ITS INCLOSING WALLS

In the ideal radiator or so-called "black body" the walls of the inclosure are assumed to be opaque to all radiations. The energy emitted, of all wave lengths, is then independent of the nature of the material forming this opaque envelope. In practice such an opaque inclosure is not readily obtained and experimenters have to use radiators made of highly refractory porcelain, or graphite tubes, the latter being operated in a vacuum. Porcelain tubes may of course be blackened with nickel oxide, etc., but many objectionable features are then encountered.

During the course of experiments upon such radiators, in the construction of which every attempt was made to approach the ideal, the question arose as to whether or not the observed distribution of energy was independent of the composition of the radiating inclosure. Radiators constructed of ordinary porcelain appeared to have a slightly different spectral energy distribution from similar tubes of a more refractory "Marquardt" porcelain. The latter appeared to be slightly selective in its emission in the infra-red. When one considers the extraordinary way in which the frequencies emitted by the porcelain are modified when emitted from within the uniformly heated inclosure, the difficulties to be encountered in producing such a radiator become apparent. In Fig. 9, curve *a*, is shown the spectral energy distribution from the surface of a thin rod of Marquardt porcelain, rendered conducting

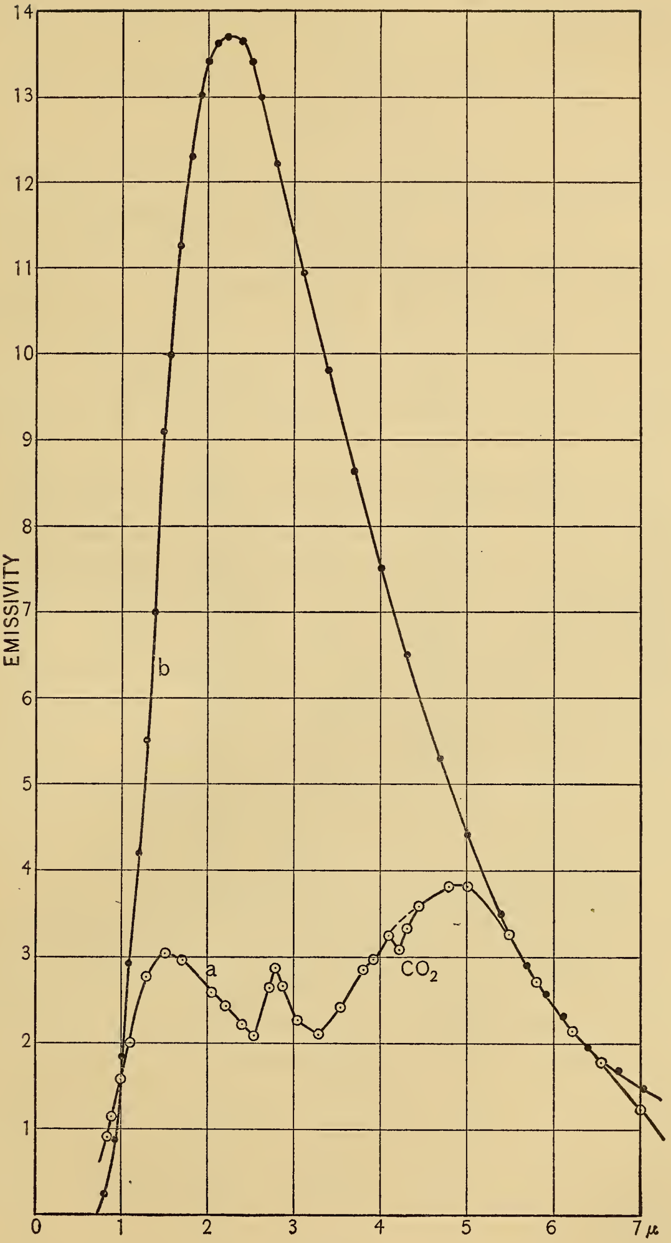

Fig. 9

by heating with a blast lamp and then heated to a bright red by means of an electric current from a 2000-volt transformer. There are three distinct emission bands. In this figure curve *b* represents the spectral energy distribution of the radiation from an experimental "black body" made of Marquardt porcelain and heated to 1032° C. The curve is perfectly smooth, but, in comparison with similar curves obtained from different "black bodies," made of a lower melting point porcelain, this curve appears to emit a slight excess of radiation in the region of 4μ to 5μ, as compared with the region of 3μ. Curve *a* is given simply as an illustration of an infinite number of curves, having different contours depending upon the composition of the material, and upon the temperature of operation, as was shown in previous investigations.

VI. STANDARD SPECTRAL ENERGY CURVES

In Table III are given the emissivities in the normal spectrum of a Nernst glower set to a color match with a tungsten lamp which was operated on 1.2 w. p. m. h. c. This is not far removed from the commercial operation of the Nernst glower. The glower (length 13 mm, diameter 1 mm, well seasoned and quite crystalline in appearance) was purchased about 5 years ago, hence of different stock from the others herein described. This fact, however, does not cause any difference in the emissivity in the visible spectrum, but there appears to be some difference in the infra-red where the emissivity appears to be as high as that of the 2 mm glower, Fig. 8, discussed on a previous page.

The spectral energy distribution from 0.45μ to 0.67μ of a tungsten lamp operated on 1.2 w. p. m. h. c. is given in Table III. The spectral energy curve was obtained with a mirror spectrometer and a fluorite prism. At some future time it is hoped to provide further and more accurate data in the violet, so that the whole may be used as a standard spectral energy curve, such as was given in a previous paper for acetylene,[16] see Table IV. In the infra-red, however, the variation of emissivity with thickness is too marked to permit the use of the acetylene flame as a standard of radiation.

---

[16] This Bulletin, 7, p. 261; 1911.

The data in Table III are useful also in considering the minimum concentration of a solution of cupric chloride as a filter to absorb all the infra-red, as described on a subsequent page.

TABLE III

Spectral energy distribution from 0.45μ to 0.67μ of a tungsten lamp operated on 1.2 w. p. m. h. c. and of a Nernst glower from 0.45μ to 9.00μ set to a color match with the tungsten lamp

Wave length in μ= 0.001 mm	Emissivity	Wave length in μ= 0.001 mm	Emissivity
0. 449	7. 6	2. 033	408. 1
. 466	10. 8	2. 189	345. 2
. 485	15. 2	2. 410	282. 6
. 506	20. 4	2. 546	250. 1
. 530	29. 0	2. 801	189. 4
. 558	40. 4	3. 037	140. 9
. 589	59. 0	3. 367	107. 4
. 606	73. 0	3. 569	83. 6
. 646	103. 2	4. 031	64. 1
. 697	151. 5	4. 445	49. 2
. 757	213. 6	4. 827	40. 5
. 835	311. 9	5. 485	30. 2
. 934	409. 0	6. 240	20. 9
1. 054	524. 1	6. 852	14. 6
1. 197	608. 0	7. 546	10. 5
1. 357	635. 7	8. 170	5. 3
1. 526	605. 9	8. 737	2. 5
1. 698	534. 0	9. 090	1. 4
1. 868	464. 1		

TABLE IV

Spectral Energy Distribution of an Acetylene Flame

[Reprinted from Bulletin Bureau Standards, Vol. 7, p. 261, 1911]

Wave length in μ= 0.001 mm	Emissivity	Wave length in μ= 0.001 mm	Emissivity
0. 36	3. 5	0. 56	43. 7
. 38	4. 4	. 58	54. 0
. 40	5. 8	. 60	66. 3
. 42	7. 2	. 62	80. 5
. 44	9. 7	. 64	96. 5
. 46	12. 5	. 66	112. 8
. 48	16. 5	. 68	130. 1
. 50	21. 7	. 70	147. 0
. 52	27. 6	. 72	163. 8
. 54	34. 8	. 74	181. 5

The data in Table III on the Nernst glower show that this form of radiator can not be used as a standard of infra-red without rigorously defining the dimensions. There is also difficulty in defining the mode of operation of the glower; and in the present work it has been used by setting it to a color match with a tungsten lamp operated on 1.2 w. p. m. h. c. The latter may be easily rated photometrically.

As already mentioned, the glower used in obtaining the data in Table III was a well-seasoned one (made at least five years ago) which had a crystalline appearance, and it was 1.02 mm in diameter. The peculiar property of its energy curve is that it coincides throughout the spectrum with the energy curve of the glower of new material 2.152 mm in diameter, except at 2μ to 3μ, where the emissivity is higher than any of the glowers presented in Fig. 8. Whether this is the result of a difference in the composition of the material or in the physical structure is an interesting question. From the data presented in the previous paper on the Welsbach mantle material in the form of a solid rod, it appears that this difference in emissivity is owing to a difference in composition of the glowers. However, it is possible that with age the chemical structure of the material undergoes a change, which would produce a different radiating property of the material.

Note I.—LIGHT FILTERS WHICH ABSORB ALL THE INFRA-RED

Under the above title [17] experiments were described on the transmission of various solutions of copper salts, the object being to determine the minimum concentration which will absorb all the infra-red and at the same time give a high transmission in the visible spectrum.

Having in mind a discontinuous spectrum of the mercury vapor type in which the intensity of the radiation at 1.2μ is weak, a 2-cm layer of a 2 per cent solution of cupric chloride was recommended as being sufficiently opaque for eliminating the infra-red rays. Such a solution is of course inadequate as an absorption screen for eliminating all the invisible radiation from a source having an

---

[17] This Bulletin, 7, p. 655; 1911.

extremely large amount of infra-red such as obtains in incandescent solids of the Nernst glower type. On integrating the spectral energy curve of a Nernst glower (used on normal operation) after transmission through such a solution, it is found that the amount transmitted in the infra-red might cause an appreciable error in the measurement of the (total) radiation in the visible spectrum. Further experiments were therefore undertaken to determine the proper concentration which will reduce to a negligible quantity the energy transmitted in the infra-red.

In view of the fact that a copper sulphate solution changes from a bluish to a greenish yellow color on dilution, a further examination was made of this substance in solution to compare with cupric chloride in solution. It was found that a solution of copper sulphate of the same color as a 2.5 per cent solution of cupric chloride was considerably more transparent than the latter, in the region of 1.2μ. There is therefore no advantage in employing copper sulphate as a radiation filter for eliminating the infra-red.

The transmission of an accurately prepared 2.5 per cent solution of cupric chloride (2.5 grams $CuCl_2 + 2H_2O$ in 97.5 grams of water and 2 drops of HCl) is given in Fig. 10, the absorbing layer being exactly 2 cm in thickness, the cell walls being of clear white optical glass (each) 1 mm thick. An old and a newly prepared solution were examined. The maximum transmission at 1.15μ to 1.20μ is of the order of 0.35 per cent. The transparency was slightly increased on adding several drops of HCl. The depression at 0.51μ is caused by the dichroism of the solution.

The transmission of an accurately prepared 3 per cent solution (3 gr $CuCl_2 + 2H_2O$ in 97 grams of water and 2 drops of HCl) is also given in Fig. 10. The maximum transmission at 1.2μ is of the order of 0.16 per cent, with a possibility that the value is still lower. Using a 3.5 per cent solution of $CuCl_2$ (3.5 gr $CuCl_2$, 96.5 gr H_2O, and 2 drops of HCl), the infra-red spectral energy curve of the Nernst glower is reduced to a narrow band at 1.2μ, Fig. 10, which is entirely negligible in comparison with the curve of the visible spectrum.

Fortunately in the case where green and violet radiation are desired a still more concentrated solution (say 4 per cent) may be employed, which eliminates the infra-red still more completely.

This is an important fact, for a small amount of infra-red added to the green and blue radiations, which have a low energy value, may cause an appreciable error. On the other hand, when it is desired to obtain considerable radiation in the yellow and orange, because of the high energy value of these radiations, the use of a weaker solution (3.5 per cent) is permissible, since the slight addition of infra-red is negligible in comparison with total energy to be measured.

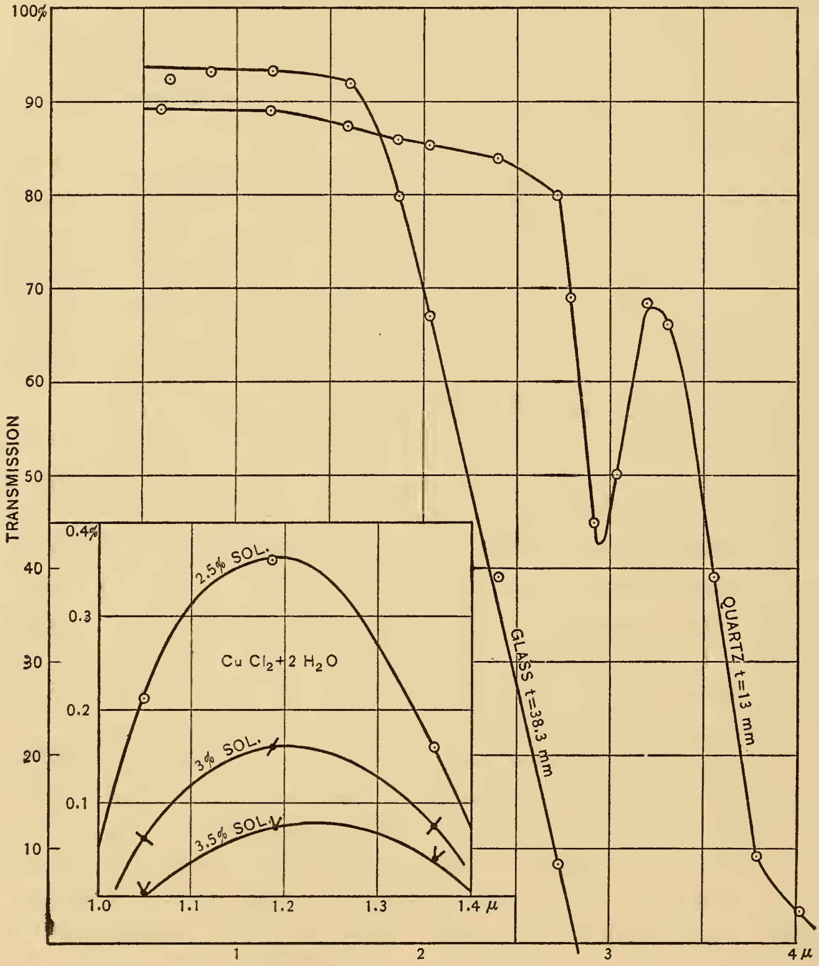

Fig. 10

TABLE V

Concentration of solution	2.5%	3.0%	3.5%
λ	Ratio of energy transmitted		
1.05μ	0.0021	0.0006	0.00003
1.20μ	0.0036	0.0016	0.00075
1.36μ	0.0015	0.0007	0.00040

It is of course to be understood that this screen is useful only to eliminate the infra-red and that, in order to obtain red, green, or blue, etc., it is necessary to use a suitable monochromatic color screen in addition to the aforesaid standard solution of cupric chloride.

During the course of these experiments a number of samples of (old and new) 3 per cent solution were examined, all of which gave nearly the same transmission, showing that by exercising care in preparing these solutions there will be no marked uncertainity as to the amount of infra-red radiation that is transmitted. The use of more concentrated solutions is of course to be recommended whenever the nature of the problem permits it. The present experiments simply show the minimum concentration and permit a calculation of the error from infra-red radiation, provided the spectral energy curve is known. For this purpose is included the transmission (Figs. 10 and 11, and Tables III and V) of the solutions of cupric chloride, just described, the absorption cell being exactly 20 mm thick. For determining these ratios a Nernst glower was used as a source of radiation. The glower was set to the proper voltage (practically on normal operation) to give a color match with a tungsten lamp operated on 1.2 w. p. m. h. c. The galvanometer deflections in the region of 1.0μ to 1.3μ without the absorption cell were equivalent to 8000 to 11 000 mm, and through the solution they were from 0.2 to 6 mm. Only the great steadiness of the vacuum bolometer permitted measurements of such small magnitudes as were observed through the solutions. In Fig. 11 is shown the spectral energy curve as observed through the solutions just described. For the 3 per cent solution the total energy transmitted in the region of 1.05μ to 1.35μ is 4 per cent of the energy transmitted in the visible spectrum, from 0.44μ to

0.68µ. The energy transmitted at 1.05µ to 1.35µ by a 3.5 per cent solution of $CuCl_2$ is less than 1 per cent of the energy transmitted in the visible spectrum. Whether the infra-red can be separated as thoroughly from the visible spectrum by mechanical means (Ångström's knife-edge screen) as by this method, remains undertermined. Possibly a combination of the two methods would be still better, for in this case a weaker solution could be used to eliminate the infra-red rays scattered over the spectrum by the screen. In this case the screen would not have to be set

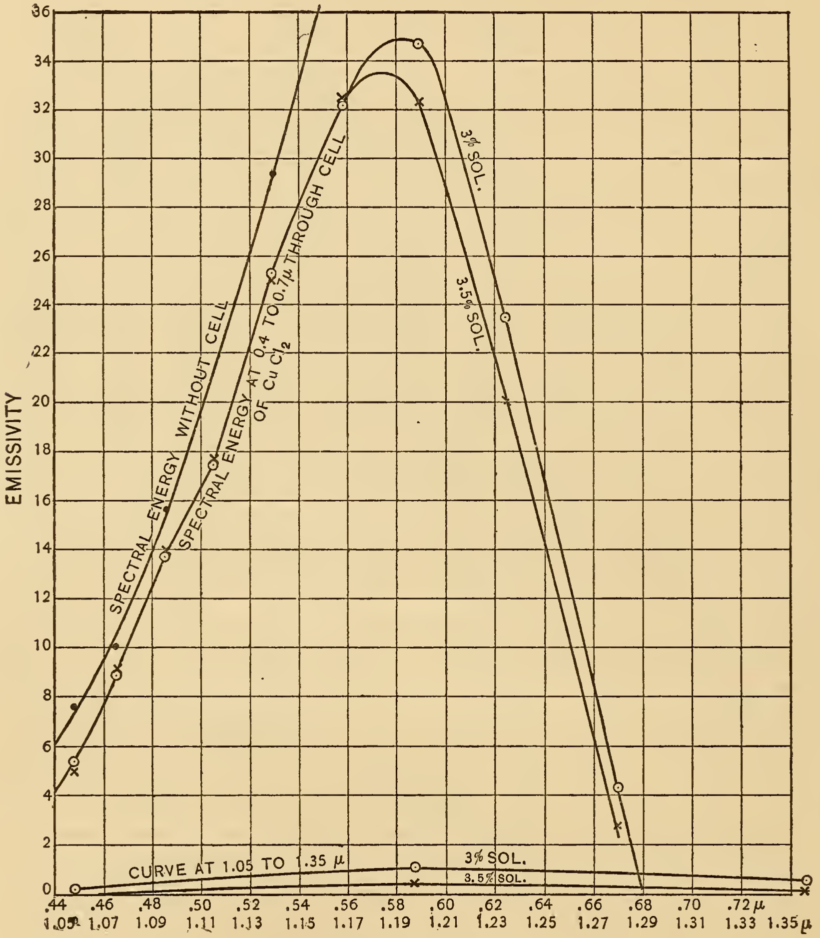

Fig. 11.—*Nernst glower*

so accurately at 0.7μ to separate the infra-red from the visible, for the solution would absorb the radiations lying between 0.7μ and 0.9μ and the small amount remaining of the radiations at 1.05μ to 1.35μ would be situated so far from the edge of the screen that none could pass by and into the radiometer.

From the data herewith presented it is evident that for sources of radiation having a high emissivity at 1.2μ to 1.5μ the 2 per cent solution of $CuCl_2$ described in the previous paper is not sufficient to eliminate to a negligible amount all the infra-red; that a 3.5 per cent solution is necessary to reduce the infra-red to 1 per cent of the visible radiations; and that for producing green and blue radiations it is desirable to eliminate the infra-red still further by using a solution of 4 per cent of cupric chloride.

In conclusion it is desirable to emphasize the importance of using exactly the same thickness 20.0 mm to obtain the results herewith presented. For example a cell 21 mm in thickness of a 2.5 per cent solution transmits 0.28 to 0.30 per cent as compared with a transmission of 0.35 per cent by the 20-mm cell, see Table V, which gives the ratios of the energy transmitted by the solution to the direct radiation falling upon the radiometer.

Ångström separated the visible spectrum from the infra-red by means of a knife-edge screen. One objection to this method is the uncertainty as to the amount of stray infra-red, especially of wave lengths just beyond the visible, that is superposed upon the visible spectrum. As already mentioned a combination of Ångström's spectrum knife-edge screen and a weak (1 per cent) solution of $CuCl_2$ would remedy this defect without seriously reducing the intensity in the red. The amount of infra-red transmitted by this solution at 1μ is so small and it is located so far from the edge of the screen that there is no danger of an appreciable amount of infra-red being superposed upon the visible spectrum.

As a final summary it may be stated that the method of obtaining monochromatic radiation by means of filters is very inefficient when concentrated solutions must be employed. For example, the 3 per cent solution transmits 58 per cent, and the 3.5 per cent solution transmits only 55 per cent at 0.589μ. The transmission is, of course, much higher in the blue and in the green.

Note II.—TRANSMISSION OF PRISM MATERIAL

In order to learn the applicability of glass and quartz prisms in spectral energy work at high temperatures, the transmission of thick samples of these materials was examined, as shown in Fig. 10. The plate of quartz, 13 mm in thickness, increases rapidly in opacity beyond 1.2μ, so that it is unsuitable in spectral energy work (other than isochromatics) involving wave lengths greater than 1.2μ. The same is true of crown glass, the transmission of which is shown in Fig. 10, thickness 38.3 mm.

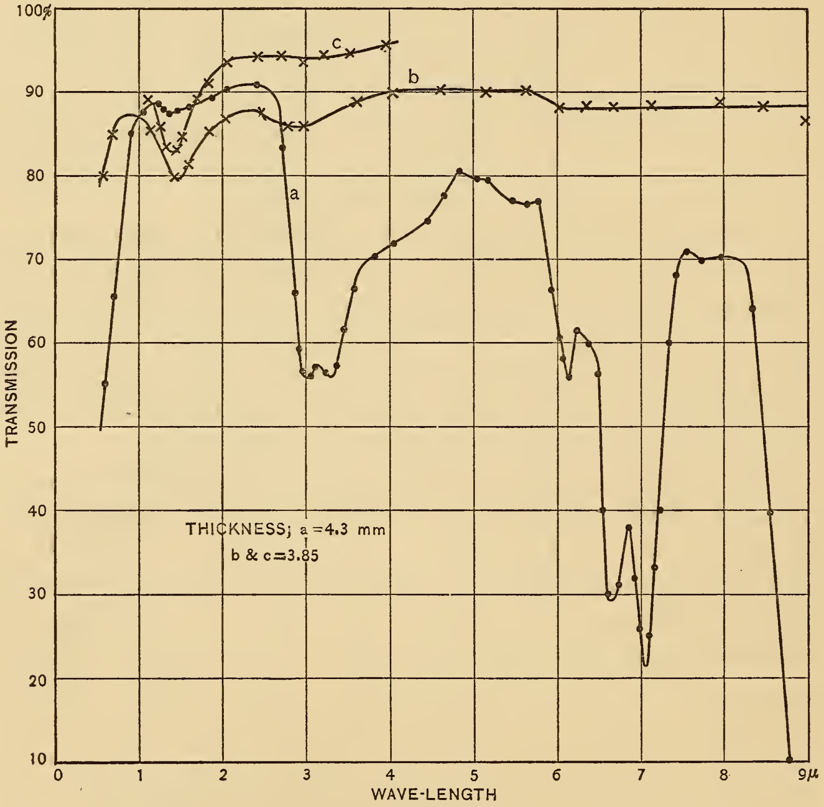

Fig. 12.—*Fluorite*

Owing to the increased scarcity of fluorite it is important to learn the utility of the green varieties of this material. In Fig. 12, *a* is shown the transmission of a sample of deep green fluorite

(4.3 mm in thickness) which showed a strong violet fluorescence in ordinary light. The transmission curve is conspicuous for numerous absorption bands, the maxima of which occur at 1.4, 3.0, 3.3, 4.2, 5.6, 6.1, 6.63, 7.03μ, respectively. The transmission of a light yellowish green sample is shown in Fig. 12, *b* and *c*. Here the prominent bands at 3μ and 7μ appear to be entirely absent, while the band at 1.4μ is very marked as compared with a similar absorption band in the deep green sample.

WASHINGTON, June 5, 1912.