SELECTIVE RADIATION FROM THE NERNST GLOWER.

By W. W. Coblentz.

INTRODUCTION.

The measurement of very high temperatures is based upon an extrapolation of the laws governing the energy emitted by a body with change in temperature. Our knowledge of these laws is confined to the radiation from platinum and from a hollow inclosure (so-called "black body"), which is the nearest approach to a complete radiator. The remarkable progress that has been made in the development of processes requiring an accurate knowledge of the temperatures involved makes it imperative to study the laws of radiation of various substances with variation in temperature. In order to determine these radiation laws, it is generally necessary to study the spectral energy curves, using for the purpose a prism that is transparent to heat rays and some sort of very sensitive heat measuring device, such as, for example, a bolometer or a thermopile. It is also possible to study the total radiation emitted. The chief difficulty in establishing the so-called radiation constants of substances lies in determining the exact temperature of the radiating surface.

The distribution of radiant energy in the normal spectrum of all solid bodies thus far studied is unsymmetrical about the maximum of the energy curve, having the appearance of a probability function modified by suitable constants. The solids heretofore studied,[1] in which it was possible to determine the approximate temperature, have spectral energy curves, which are represented fairly well by the function,

(1) $$E = c_1 \lambda^{-a} e^{-c_2'/\lambda T}$$

[1] Paschen, Ann. der Phys., (3) **58**, p. 455; **60**, p. 663; 1897; (4) **4**, p, 277; 1901. Lummer and Pringsheim, Verh. d. Deutsche Phys. Gesell., **1**, p. 215; 1899.

In the case of the complete radiator, or so-called black body, the exponent $a = 5$, while for platinum, $a = 6$.

In order to determine the constants of the above equation from the spectral energy curves, it is necessary to know the temperature of the radiator. Fortunately the exponent, a, may also be obtained from the spectral energy curve in which the temperature, T, is constant without knowing the actual temperature, for it can be shown from eq (1) that the ratio of the emissivities (the observed bolometer-galvanometer deflections) for any two wave-lengths λ and λmax, is:

$$\frac{E}{E_{max}} = \left\{ \frac{\lambda_{max}}{\lambda} e^{\frac{\lambda - \lambda max}{\lambda}} \right\}^a \tag{2}$$

from which a may be determined. It was found by Paschen, that for carbon, platinum, etc., the value of a obtained in this way was in agreement with that obtained from a knowledge of the temperature of the radiator.

With this equation it is possible to obtain some idea of the probable total emissivity of a radiating body, as to whether it is proportional to the 4th power ($a - 1 = 4$ for a black body, $a - 1 = 5$ for platinum) or to some higher power of the absolute temperature.

Of course the assumption is made that the emissivity function is similar to that of platinum and of a black body. How far this assumption falls short of the observed facts is brought out in the present paper, in which it is shown that the observed radiation curve of a Nernst filament, which at high temperatures gives an apparently continuous spectrum, is in reality the composite of numerous sharp emission bands, which increase in intensity and broaden out with rise in temperature.

The constant a for various substances has not been extensively investigated, and it is purposed in this, and in subsequent reports, to state the results of a study of various substances (including incandescent filaments) together with the redetermination of the constants of a complete radiator, or so-called black body.

The study of the metal lamp filaments is of interest in connection with the speculations as to whether the great light emissivity (high

luminous efficiency) is due to an abnormal emission in the visible spectrum, with a corresponding suppression of the radiation in the infra-red, or whether the effect is due to the high temperature at which the lamp is burning. In the latter case the distribution of energy in the spectrum may be uniform (no discontinuities), but a larger portion of it will lie in the visible spectrum than at low temperatures. From a theoretical consideration of the fact that the filaments are metallic, electrical conductors with a high reflecting power in the visible, and probably reflecting uniformly high in the infra-red,[2] one would expect the distribution of energy in the spectrum to follow a law similar to that of platinum, but with different constants. The results obtained thus far from a study of such metals as tungsten and osmium support this hypothesis. On the other hand, in the case of oxides, which conduct electrolytically at high temperatures, there is not sufficient data from which to form even a working hypothesis. All of the oxides thus far examined have no strong absorption bands near the visible spectrum; the only exceptions being the oxides of the rare earths, such as cerium, thorium, lanthanum, didymium, erbium, etc., the compounds of which have strong, sharply defined absorption bands in the visible spectrum, and at least some of these have absorption bands in the infra-red. A low reflecting power seems to be characteristic of the oxides (like transparent media, electrical nonconductors) throughout the infra-red to about 8μ, beyond which point they have strong bands of selective reflection. In this region the emission will be suppressed in proportion to the reflecting power.[3] In the rest of the spectrum the emission will be proportional to the absorbing power (general absorption), while at the point where there is a band of selective absorption in the transmission spectrum there will be an emission band in the emission spectrum, provided the radiation is a purely thermal one, following Kirchhoff's Law.

In the case of the Auer mantle the emission spectrum is a series of emission bands at 1 to 2μ, with practically no emission in the region from 4 to 7μ, while beyond 9μ the spectrum is continuous,

[2] Aschkinass, Ann. d. Phys., (4) **17**, p. 960; 1905; Einstein, Ann. d. Phys., (4) **17**, p. 132; 1905; **22**, p. 181, 569, 800; 1907.

[3] Aschkinass, Verh. d. Deutsch. Phys. Ges. **17**, p. 101; 1898; Rosenthal, Ann. der Phys., (3) **68**, p. 791; 1899.

and is apparently as intense as that of a complete radiator at the same temperature.[4]

In the case of the Nernst filament, which is a combination of the oxides of cerium, thorium, and zirconium, the compounds of which are noted for their strong absorption bands, one would hardly expect the emission to follow the same general law of energy distribution known for metals. This assumption, however, has been made in the past, notably by Lummer and Pringsheim[5] and by Mendenhall and Ingersoll.[6] The first two investigators, from a rather cursory examination of the Nernst filament, under normal power consumption, found a smooth continuous curve, with a maximum at wave-length of 1.2μ. From this and from the Wien displacement law, $\lambda_{max} =$ const. (this constant is 2940 for a black body and 2630 for platinum), assuming that the Nernst glower belongs to the same class of radiators as platinum and a black body, Lummer and Pringsheim computed the maximum temperature and found it to be 2450° Abs. and the minimum temperature 2200° Abs. Their computed energy curve of a black body having its maximum emission at 1.2μ departs considerably from the observed curve.

Mendenhall and Ingersoll compared the emission of the Nernst glower in terms of a constant comparison lamp, for a certain wave-length in the visible spectrum, at the melting points of gold and of platinum. From this they extrapolated on a straight line (assuming that equation (1), known as Wien's Equation, holds for the glower) and found the temperature at normal or any desired power consumption. This leads to erroneous values, due to the fact that the spectrum is the composite of numerous emission bands, which rapidly increase in intensity, in the short wave-lengths, with rise in temperature. They found the normal temperature to be 2300° Abs., disagreeing with a recent determination by Hartman,[7] who, by means of thermocouples of different thickness placed against the glower, and correcting for heat conduction by extrapolating to a temperature corresponding to an infinitely thin couple, found the temperature to be 1800° Abs. Although this method had previously

[4] Rubens., Phys. Zs., **6**, p. 790; 1904.
[5] Lummer and Pringsheim, Verh. deut. Phys. Gesell, **3**, p. 36; 1901.
[6] Mendenhall and Ingersoll, Phys. Rev., **24**, p. 230, 1907; **25**, p. 1; 1907.
[7] Hartman, Phy. Rev., **17**, p, 65; 1903.

been extensively used with fair success in measuring the temperature of gas flames, it is less suited to the glower in which there is no layer of hot gas to even partially compensate for the heat lost by conduction.

That the Nernst glower emits selectively in the visible spectrum has been shown by Kurlbaum and Schulze,[8] who found a strong emission band at .52μ, which became fainter with rise in temperature and disappeared entirely at high temperatures.

To this brief review of what has been done on the Nernst glower may be added a paper by its inventor,[9] who showed that the conductivity is electrolytic, while Kaufmann[10] showed that in spite of the entirely different inner mechanism of conduction of a gas in a vacuum tube and in a Nernst glower the electrodynamic phenomena are nevertheless very similar.

METHODS AND RESULTS OF PRESENT INVESTIGATION.

In the present investigation of the Nernst glower the distribution of radiant energy in the spectrum was determined at different energy consumption, and hence at different temperatures. For several filaments the apparent black body temperature, corresponding to different values of energy consumption, was measured by Drs. Waidner and Burgess, with an optical pyrometer, for red, green, and blue light. The values given in Table I were obtained from their watt-temperature curve, extrapolated for high temperatures. These values are of interest in showing the variation in selective emission with rise in temperature.

The apparatus used in this work consisted of a spectrometer,[11] having mirrors 10 cm in diameter and of 50-cm focal length, a perfectly clear fluorite prism, having an angle of 60° and circular faces 33 mm in diameter, and a bolometer[12] with a hemispherical reflecting mirror. The bolometer strip and spectrometer slit were 0.6 mm. wide, or about 4′ of arc. The upper part of the spec-

[8] Kurlbaum and Schulze, Verh. d. Deutsch. Phys. Gesell, **5**, p. 428; 1903.

[9] Nernst Zs. für. Electrochemie, **6**, p. 41; 1899.

[10] Kaufmann, Ann. d. Phys., (4) **2**, 158 p..1900; **5**, p. 757; 1901.

[11] For adjustments see "Investigations of Infra-red Spectra," Vol. 1, Carnegie Institute of Washington, 1905.

[12] Described in this Bulletin, **4**, p. 391.

trometer, containing the collimating mirrors, and the Wadsworth mirror-prism table were entirely inclosed by a thin sheet-metal box, lined with black velvet. The spectrometer slit was covered with a clear plate of fluorite. The openings in the top for adjusting the mirrors were closed with soft wax, while the hole admitting the axis for rotating the mirror-prism table was tightened with a nut and packing.

Within the box, and below the level of the mirrors, were placed vessels containing phosphorous pentoxide and sticks of potassium hydroxide, which entirely eliminated the absorption bands of CO_2 and water vapor from the emission curves. A water-cooled shutter was placed before the spectrometer slit and the Nernst glower, inclosed in an asbestos case to prevent air currents, was placed close to the shutter. Observations were also made without inclosing the glower, to prove that the effects observed are not due to stray radiation from the asbestos case.

The auxiliary galvanometer[12a] of 5.3 ohms resistance, with a single swing of 4 to 5 seconds, had a current sensibility of $i = 1.6$ to 1.5×10^{-10} ampere. A greater sensitiveness for the same period would have been possible, by using a lighter suspension. The present suspension of 10 magnets was just heavy enough so as not to be affected by tremors. By reducing the number of magnets from 12 to 10 and by placing the mirror at the center of the suspension the sensibility was increased by 100 per cent. Using a bolometer current of .04 ampere the computed temperature sensibility was $5° \times 10^{-5}$C., which was generally far in excess of that required. The deflections were reduced to 14 to 15 cm by inserting resistance in series with the galvanometer. The individual readings varied by 1 mm, or less than 1 per cent, which is as close as the nature of the work required, since the actual deflections were as high as 2000 cm. Furthermore, at high temperatures (especially when run above normal power consumption) the filament changed in emission by that amount during the series of observations.

[12a] Described in this Bulletin, 4, p. 432. The coils of this instrument are 32 mm in diameter. The proportionality of the deflections with current, at this sensibility, was exact up to 18 cm.

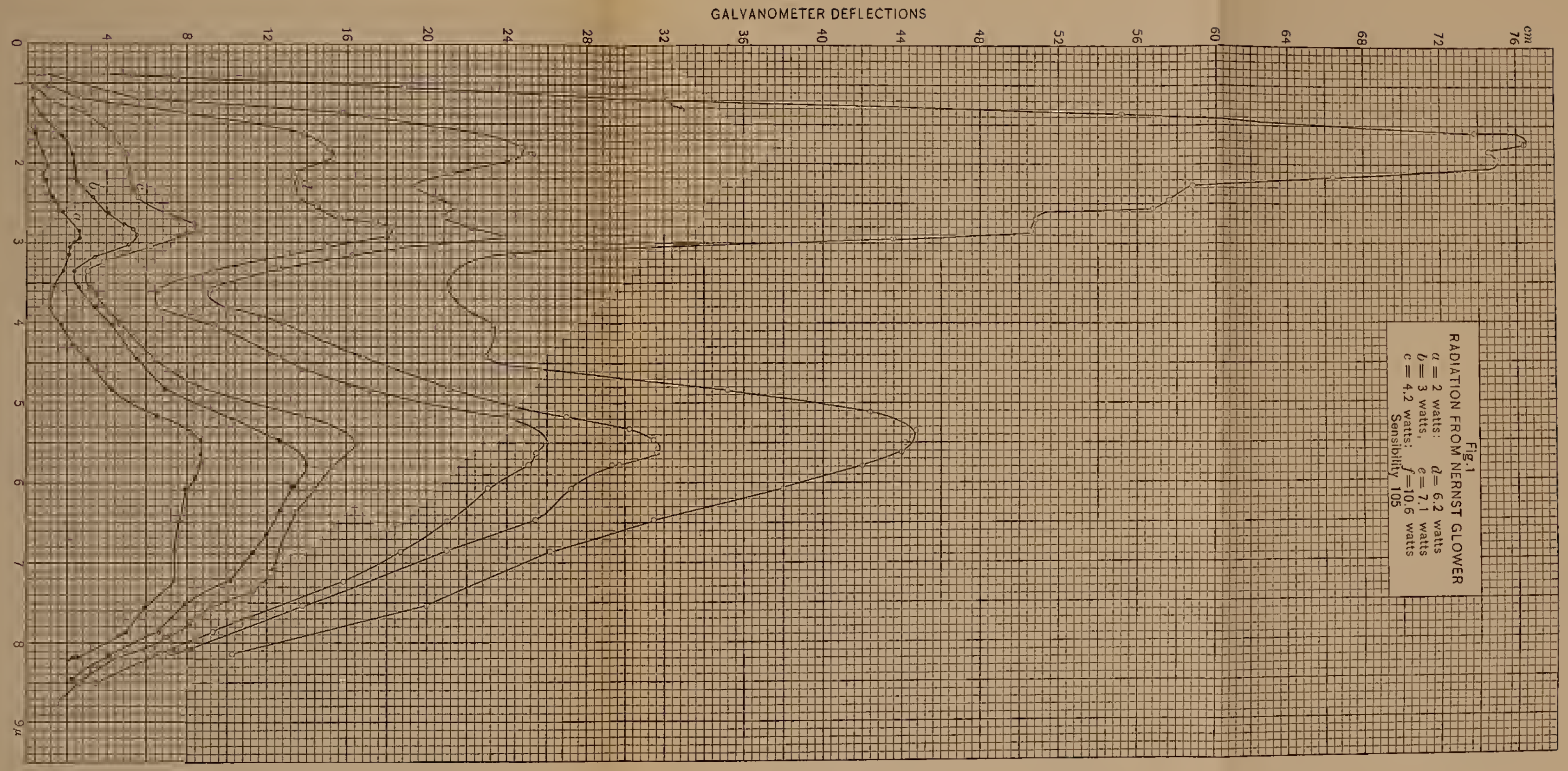

Fig. 1

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The calibration curve of the fluorite prism was constructed from the refractive indices, found by Paschen,[13] which, after plotting all the observations made by different observers, seems to be as close to the most probable values as observation will permit. Unfortunately the dispersion curve passes through a double curvature at 1.5μ, just where the energy spectra have their maxima. In this region the correction for purity (the so-called "slit-width" correction) is a maximum.

The wave-lengths in the calibration curve were plotted to the fourth decimal place, so that there is a certainty of the values to at least the second decimal place. This, however, is of less importance than the value of the slit-width correction, which was made according to Paschen,[14] the values being obtained from a curve plotted on a large scale to insure an accuracy greater than required in the work. In a few cases a correction was made for the reflecting power of the silver mirrors, but it was found negligible except in the visible spectrum.

With this apparatus a series of energy curves was obtained, varying the energy consumption from 16 watts (the lowest at which the glower would conduct without using a transformer) to 123 watts, which is far above the normal. The energy curves, which were continuous, underwent great variations in appearance with rise in temperature. At 2.5 and 3.5μ elevations and depressions would generally appear in the curves, which could not be attributed to experimental errors. Since previous work seemed to show that the spectrum is continuous, an attempt was made to locate the cause of the disagreement in the apparatus, the calibration, or in the slit-width correction curve, but without avail until the filament was run on a 2000-volt transformer which permitted a low heating of the glower. At the lowest temperature the glower was a grayish red. The results given in Fig. 1 are for a 110-volt A. C. glower No. 118, each point being the mean of at least two observations. The ordinates are about three times the observed galvanometer deflections. These results are entirely different from anything hitherto observed in the emission of solids in the infra-red. At the

[13] Paschen, Ann. d. Phys., (4) **4**, p. 299; 1901.

[14] Paschen, Ann. d. Phys., (3) **60**, p. 714; 1897.

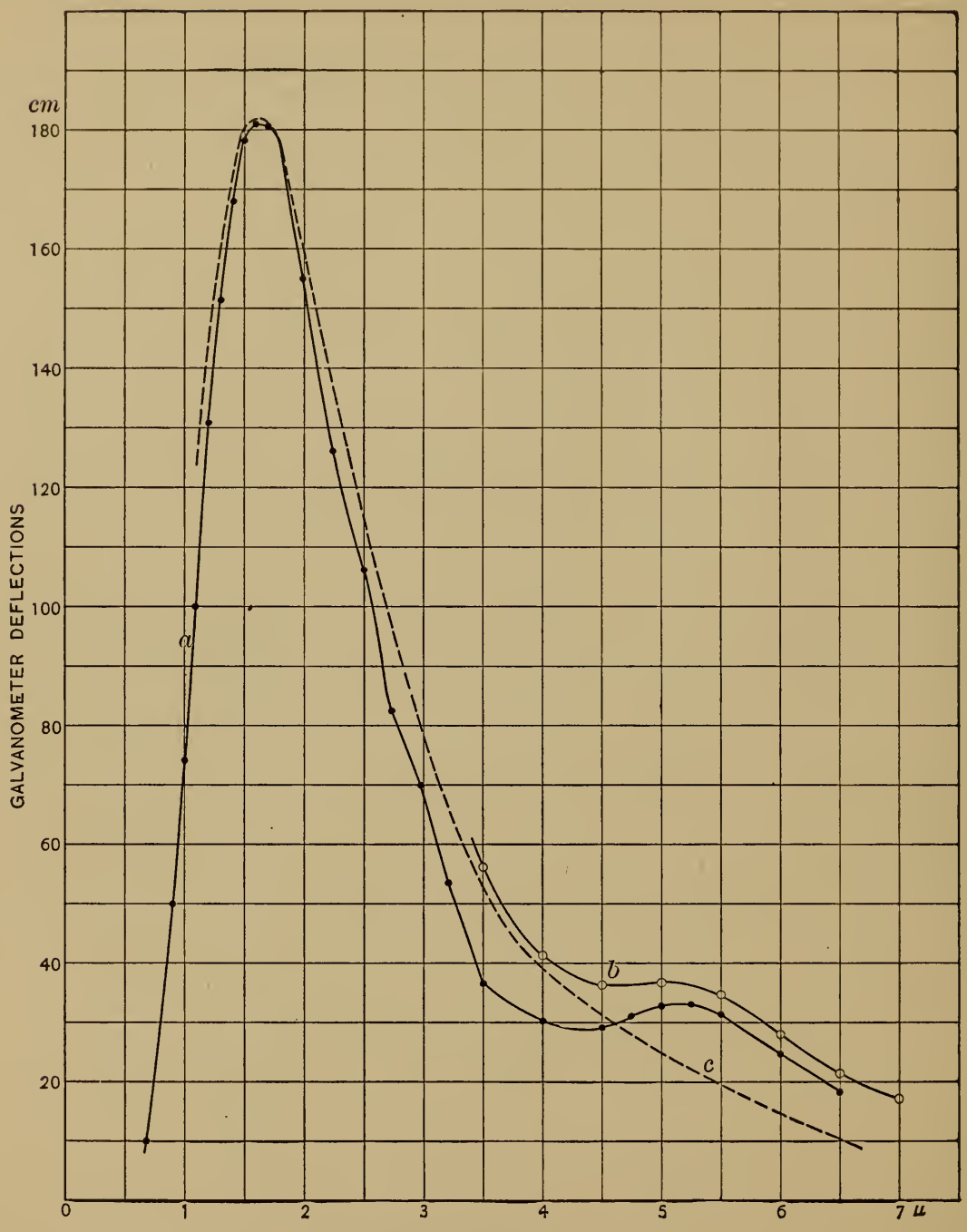


Fig. 2.—*Nernst Glower, No. 118.*

a = 17 watts, b = 21.8 watts, c = "black body."

lowest temperatures (800–900° C.) the bands in the region of long wave-lengths are the most intense. As the temperature increases, the bands in the region of 2.5μ increase very rapidly in intensity, so that by the time the temperature has increased to 1000° to 1100°, the intensity of the group of bands at 2μ is far in excess of that at 5.5μ.

The depression at 3 to 3.5μ persists even at normal energy consumption. The curves at higher temperatures often show a slight depression at 2.5μ not attributable to experimental errors. As the temperature rises (curve *e*, Fig. 1) new emission bands appear, notably at 2.5μ and at 4μ. This shift of the maximum intensity of the bands, with increase in temperature, is to be expected, if the emission is a purely thermal one, following Kirchhoff's law, and is the most conspicuous illustration yet recorded.

In Fig. 2 the emission curves are shown for a 110-volt glower (serial number 118) at 17 and 21.8 watts respectively. It should be noticed that the emission curve has become smooth and continuous, with but two maxima, at 1.4 and 5.5μ respectively. The curve *c* for a black body, having a temperature corresponding to maximum at 1.65μ and of the same intensity as that of the filament at this point, falls far below the emission curve at 5.5μ. This shows that the maximum at 1.65μ is not as high as it should be, if the glower followed a radiation law similar to that of a complete radiator or platinum, as was heretofore assumed.

In Fig. 3 is shown a series of energy curves of a 200-volt filament, at different power consumptions, viz: $a = 15.8$, $b = 17.6$, $c = 19.2$, $d = 22.1$, $e = 27.1$, $f = 34.6$, $g = 43.3$, $h = 52.7$, $k = 62.4$ watts respectively. This illustrates very well the elimination of the emission minimum at 4μ. The curves are for the same sensibility[15], 80, of the galvanometer as compared with the sensibility of 105 in Fig. 1.

The radiation of a 110-volt filament, No. 118, at a power consumption of 77.7 watts is given in Fig. 4, curve *a*. In the same figure, curve *b* represents the distribution of energy of a 220-volt filament (No. 120) at a power consumption of 102.5 watts, which is

[15] For convenience, in practice the sensibility is expressed in arbitrary units which will be described elsewhere.

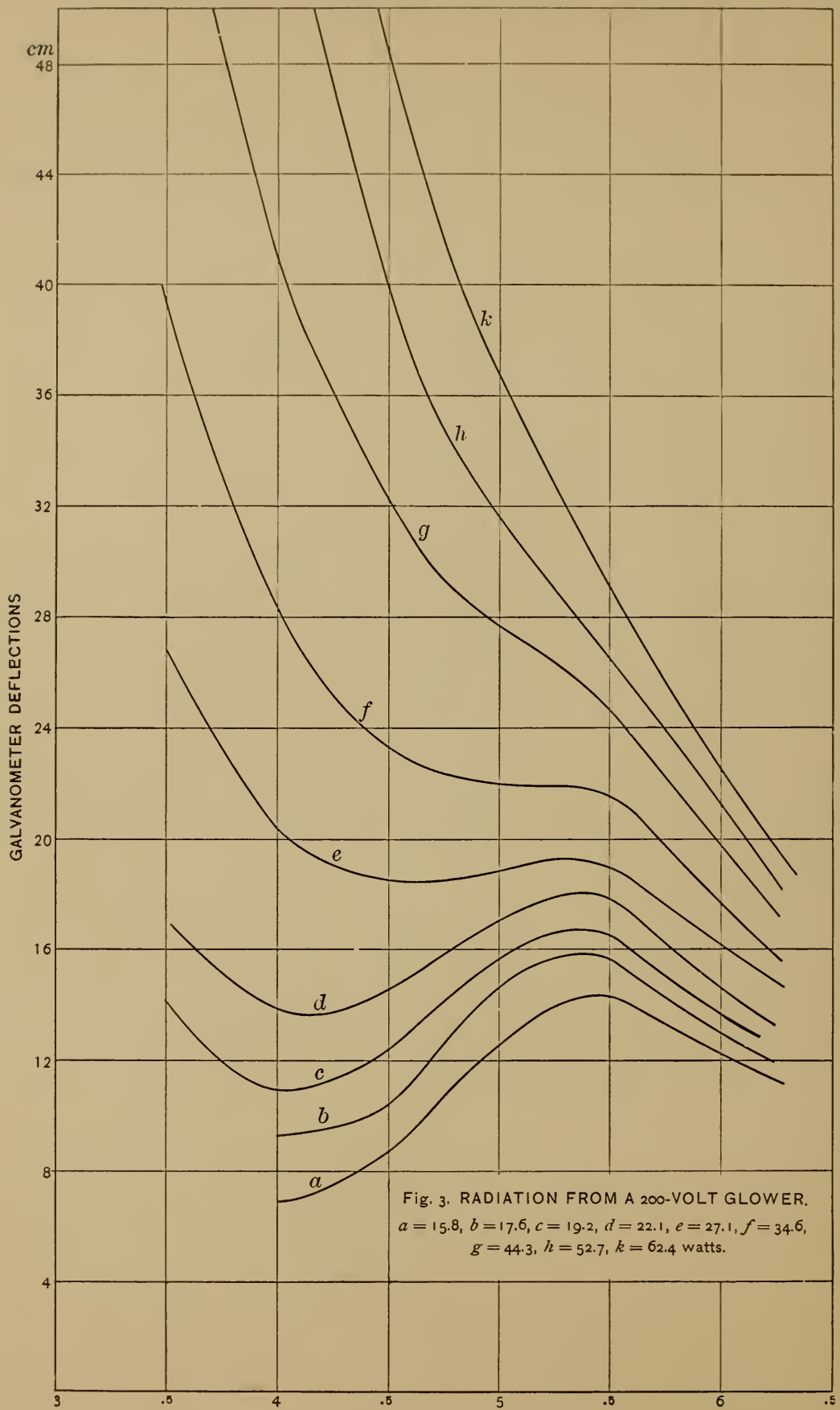


Fig. 3. RADIATION FROM A 200-VOLT GLOWER.
$a = 15.8$, $b = 17.6$, $c = 19.2$, $d = 22.1$, $e = 27.1$, $f = 34.6$, $g = 44.3$, $h = 52.7$, $k = 62.4$ watts.

somewhat above the normal. The energy distribution is irregular, with an abnormal increase in intensity at 0.75 μ due no doubt to the sudden increase in intensity of an emission band, as illustrated in

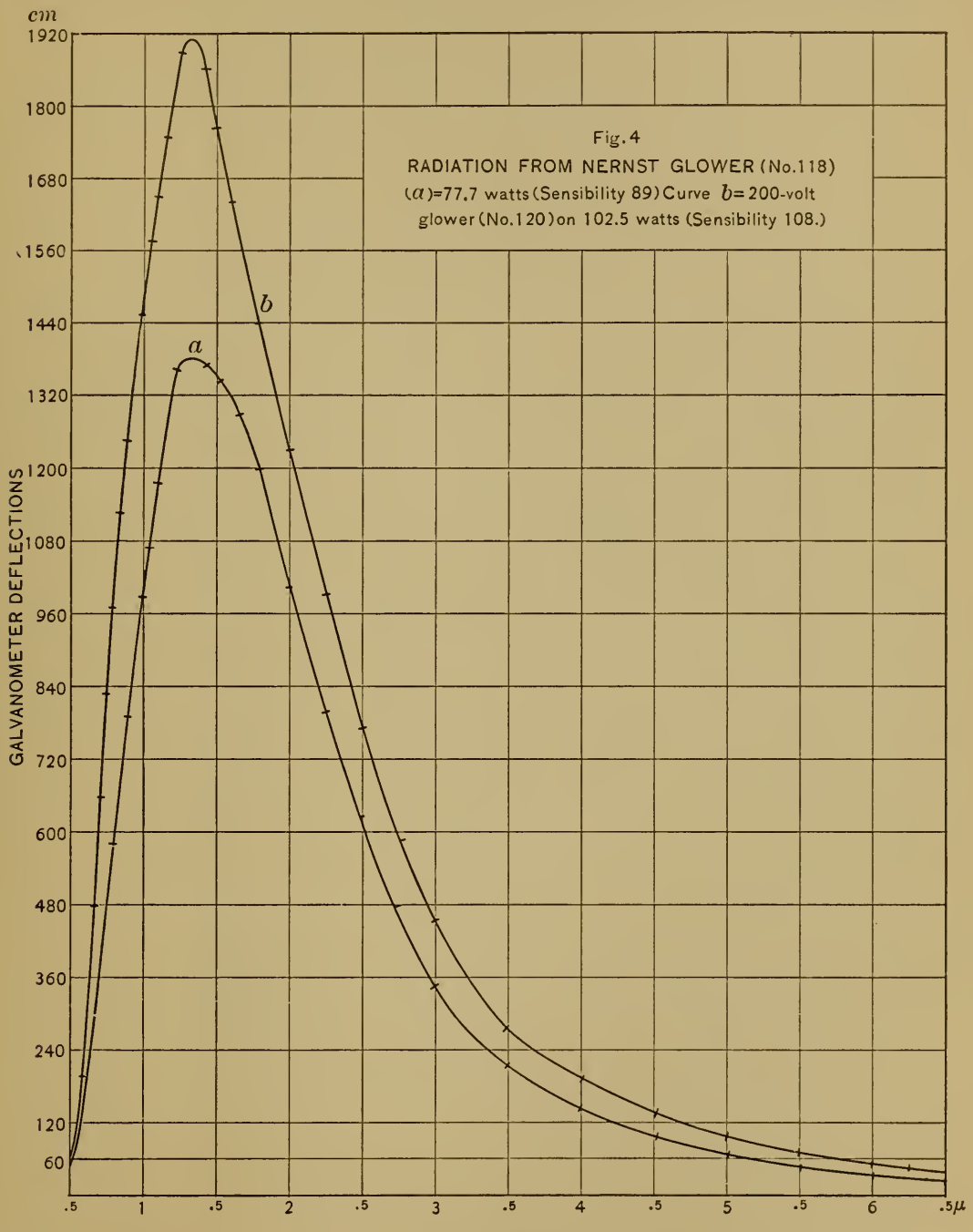
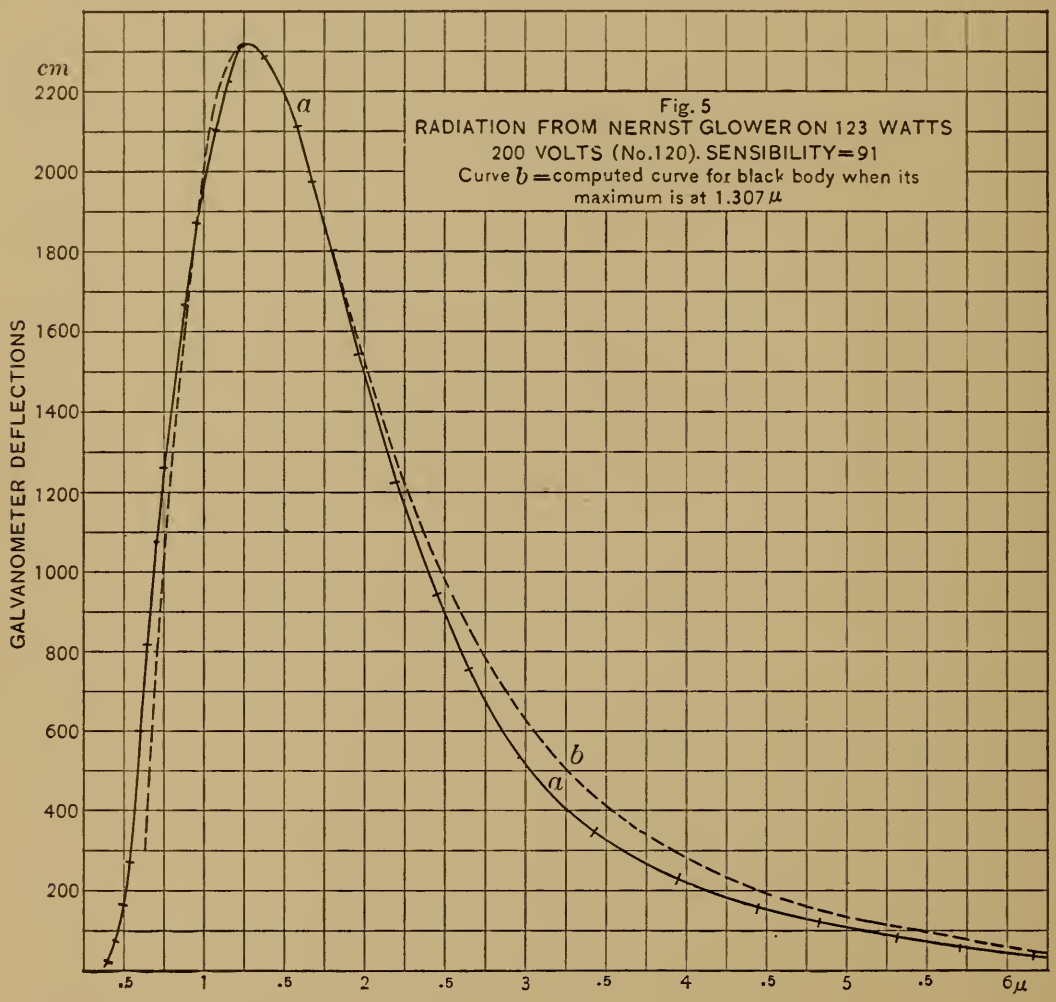


Fig. 1. Fig. 5 shows the radiation curve of the 220-volt filament (No. 120) at 123 watts, which is far above the normal. The emissivity decreased rapidly in intensity, probably due to the evapora-

tion and decrease in diameter of the filament. Within the experimental errors of observation the results indicate that the emissivity is abnormally increased in the visible. The theoretical curve of a "black body," having a maximum emission coinciding with that of the glower at 1.3 μ ($t = 1975°$ C.) falls below the observed curve in the visible, and is higher than the observed curve at 5 μ, which is



just the reverse of the results obtained when using 16.8 watts. (See Fig. 2 for a similar case.) Since the galvanometer deflections were as high as 2000 cm and since errors as great as 25 to 30 per cent would be necessary to account for this discrepancy, it is evident that the radiation from the glower can not be compared with that of a complete radiator. The data obtained at low temperatures (Fig. 1), which indicate selective emission, are a further proof of this conclusion. An attempt was made to find the transmission of a thin

section made of the material which constitutes the glower, but without success, due to the inhomogeneity of the material. As a substitute, the radiation from (and through) a 0.5 mm layer of this

Fig. 6. *Radiation from Nernst (A. C.). Material.*

Curves *a* and *b*. Curve *c* = radiation from a Nernst heater tube.

material was found when placed on a strip of platinum heated electrically, or placed on a "heater tube" of a Nernst lamp from which the covering of kaolin had been removed. The surface was a deep

red, temperature about 900° C., similar to the filament in Fig. 1. The platinum was probably at a temperature of 1200? In Fig. 6 is given the emission curves, *a* and *b*, of the glower material on the "heater tube." The emission bands at 2, 2.7, and 6 μ are similar to those found in Fig. 1, but there is no great depression at 4 μ, from which it would appear that this region is filled up by the radiation from the platinum wires, transmitted through the glower material. This is to be expected from the conditions indicated in Fig. 1. Curve *c*, Fig. 6, shows the radiation from a Nernst "heater tube," the covering being a refractory clay. An examination of the material separately will be necessary to show whether or not the maxima are true emission bands. The importance of such a radiator is evident in investigations in which a more uniform distribution of energy is desired than obtains in the glower, e. g. in searching for reflection bands of substances.

The radiation "constant," *a*, was found for several glowers, using equation (2). In order to do this it is necessary to accurately find the wave-length (λ_{max}) corresponding to the point of maximum emission. This is possible from equation (1) by selecting two wave-lengths, λ_1 and λ_2, corresponding to the points where the value of E, the galvanometer deflections, is the same. This gives:

$$\lambda_{max} = \frac{(\log\lambda_2 - \log\lambda_1)\lambda_1\lambda_2}{(\lambda_2 - \lambda_1)\log\epsilon} \qquad (3)$$

In Table I are given the mean values of λ_{max} determined from several points on each curve. The maximum and minimum temperatures computed on the assumption that the glower follows a radiation law similar to that of a complete radiator and that of platinum, respectively (which of course is not true), are also given in this table. The apparent temperatures, determined with the optical pyrometer are included, to indicate changes in selectivity with rise in temperature. The values of *a* are plotted in Fig. 7, the wave-lengths being selected to correspond with those used in finding λ_{max} (eq. 3) in order to facilitate computation. For the 200-volt filament the so-called constant, *a*, drops from 7.5 at an energy consumption of 16 watts to a uniform value of 5.3 at 80 to 120 watts.[16] For the

[16] Excepting the curve for 102 watts, which is very irregular, showing unresolved bands of selective emission.

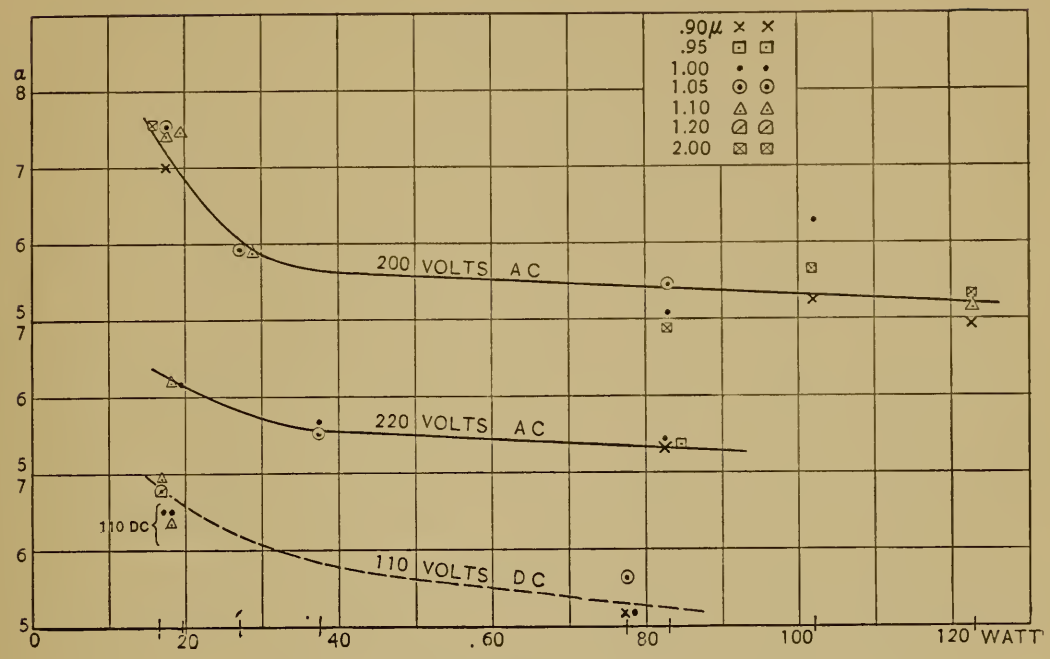


Fig. 7. *Radiation constant, a, of Nernst Glower.*

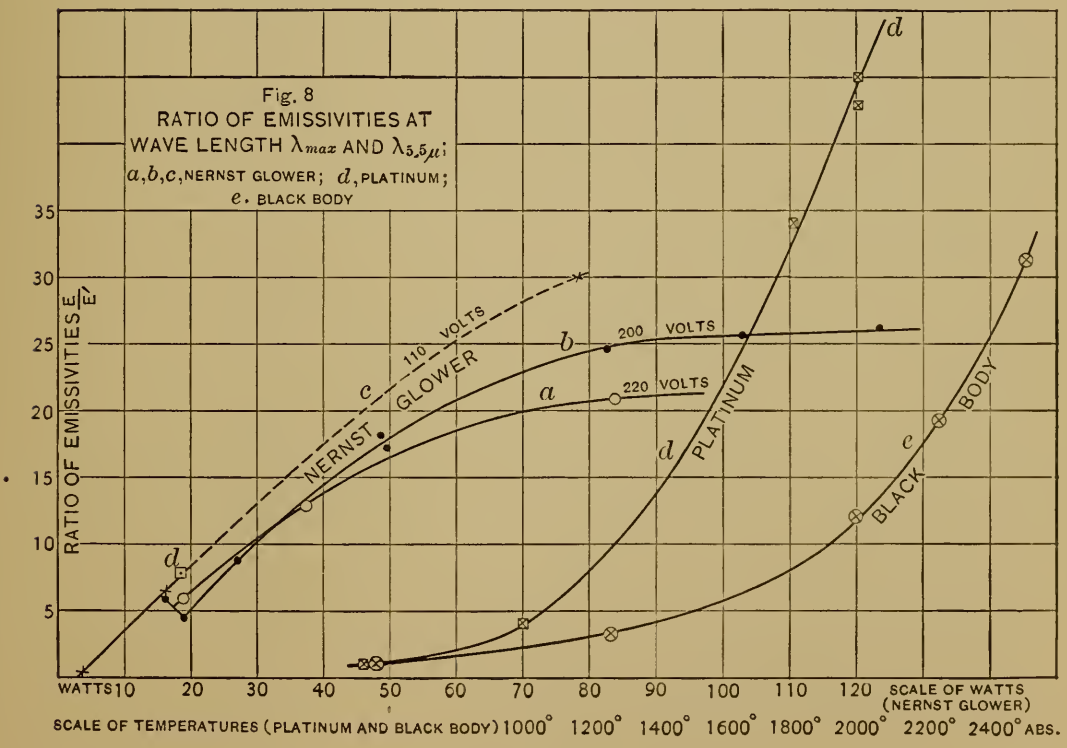


TABLE I.

Watts amp.	Temp. K. red	Temp. K. green	Temp. K. blue	λ_{max}	$T_{max}=\frac{2930}{\lambda_{max}}-273^{\circ}$	$T_{min}=\frac{2620}{\lambda_{max}}-273^{\circ}$
Nernst 200 Volts, No. 120.						
16.8 watts	1400° C					
0.11 amp.	9452°	1490	1517	1.458μ	1737	1517° C
19.6 watts	1460			(1.433)		
0.12 amp.	1490	1527	1550	1.45μ	1747	1532
27.7 watts	1602					
.167 amp.	1627	1659	1677	1.445μ	1757	1544
83.2 watts	1985					
.412 amp.	2027	2052	2064	1.366μ	1877	1647
102.5 watts	2055			1.317	1950	1715
0.5 amp.	2120	2148	2158			
123. watts				1.307μ	1972	1735
.6 amp.						
Nernst 110 Volts, No. 118.						
17. watts	1400° C			1.621μ		
.2 amp.	1438	1470	1484		1537	1342
77.7 watts	2110			1.388		
.80 amp.	2135	2170	2988		1842	1612
Nernst 110 D. C., No. 121.						
18.4 watts	1468	1507	1528	1.560	1607	1406° C
.2 amp.	1465					
Nernst 220 Volts.						
19.6 watts				1.583	1577	1382
.115 amp.						
37.2 watts				1.448μ	1747	1537
.20 amp.						
83. watts				1.360μ	1879	1652
.4 amp.						


Fig. 9
RADIATION FROM A NERNST GLOWER (110 VOLT)
a = 7.6 watts
b = 9.5 watts
c = 12 watts (not to same scale as a and b)
EMISSIVITY
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6
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2
a
b
c
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2
3
4
5
6
7
8 μ

220-volt glower (No. 120) the value of a decreases from 6.3 to 5.3, while for a 110-volt D. C. glower the value changes from 6.9 to 5.30. In other words, the total emissivity drops from the 6th power to the 4.3th power of the absolute temperature. By taking the total radiation of the glower, Mendenhall and Ingersoll found the value of a to be about 9, with no consistent evidence of a variation of a with temperature. These results were obtained before the emission spectrum was resolved into separate bands, Fig. 1. From the latter it is evident that it is not permissible to apply this method of determining the "constant." In Fig. 8 is given a comparison of the ratio of the intensities of the emissivities of various glowers at various values of energy consumption for wave-lengths of 5.5μ (the position of the apparently second maximum, Fig. 2) and of λ_{max}, which, of course, varies with temperature. The thicknesses of the filaments were: a=.63 mm, b=.71 mm, c=.98 mm, d=1.05 mm, respectively. The ratio rises from a value of 5 at 18 watts to a fairly constant value of about 25 at normal power consumption, i. e., the point on the potential-current curve where the potential is fairly constant. This ratio is a function of the thickness, and is an exact analog of what is found in the discharge of electricity through gases. In this figure this same ratio is plotted for a complete radiator and for platinum at various temperatures, from which it will be observed that the ratio is far from approaching an asymptotic value.

From whatever point of view we consider the data at hand, it is evident that even after the emission spectrum has become apparently continuous it does not follow so simple a law as has been established for solids emitting continuous spectra. It is also evident that any estimations of the temperature of the glower, based on these laws, will lead to erroneous results. From a commercial point of view, the efficiency of such a radiator, in which the emissivity is abnormally high at .6 to .7μ, while the maximum at 1.2μ is abnormally low, must be much higher than that of substances having a radiation law similar to that of platinum, in which case, in order to attain a similar intensity in the visible spectrum, the maximum at 1.2μ rises to extremely high values.

By integrating the energy curve and taking the ratio of the visible to the infra-red radiation (it has been customary to take the dividing line at .76μ) it is possible to obtain a rough estimate of the luminous (white light) efficiency for a given energy consumption. This gives values from 3.6 per cent at 27.7 watts, 5.5 per cent at 83 watts to 7.4 per cent at 123 watts. The total areas can not be compared, particularly for different filaments, because the cone of energy which enters the spectrometer slit does not cover more than about one-half of the prism face, and varies with the diameter of the filament and its distance from the slit. This will change the size of the galvanometer deflections uniformly throughout the spectrum. Thus in Fig. 4 the areas of the curves can not be compared, because they are for different filaments; but curve *b* might be compared with Fig. 5. This is of minor importance, for the curves are given to show the change in the relative distribution of energy with rise in temperature.

The results described in this paper are for filaments made from different lots of material, the 220-volt glower being at least 5 years old. The observations have been made at different dates, all in duplicate, some quadruplicate.

An examination of other filaments may show a variation in the minor details of the two groups of emission bands, as shown in Fig. 9, but the general results can hardly be modified without employing a much larger dispersion and a narrower bolometer. This, however, is of minor importance in considering the selective emission of the Nernst glower. The manner in which some of these emission bands are suppressed while others are intensified in different substances will be described in a subsequent paper.

WASHINGTON, February 10, 1908.