INTRODUCTION.

When a substance becomes heated, it is generally supposed that, however small the consequent rise in temperature above the absolute zero, energy will be lost by radiation from its surface. For solids and liquids, in which the adjacent molecules affect each other, the radiant energy so lost consists of all wave lengths from zero to infinity; but at a given temperature a certain frequency of molecular vibration is more energetic than all the others, which are less and less energetic the farther they are removed from the preponderating vibration. With rise in temperature the maximum of this preponderating vibration shifts toward the shorter wave-lengths, and eventually energy is emitted which is of a frequency affecting the eye.
Only solids and liquids are supposed to emit energy of all frequencies, but of variable intensity, in different parts of the spectrum. The energy emitted may therefore vary uniformly in its distribution throughout the spectrum, or the partition of energy may be in the form of sharp emission bands superposed upon a weak continuous spectrum.

Gases, on the other hand, emit discontinuous spectra, or spectral lines. It is a well-known property that the energy required for excitation is different for different spectral lines, being independent of the wave length of the line.\(^1\)

In the case of spectral lines the energy emitted is proportional to the excitation, while in the case of solids the spectral distribution follows some complex law. In the case of the oxides, etc., it was shown in a previous paper\(^8\) that the partition of energy in the spectrum is generally in the form of sharp emission lines superposed upon a weak continuous spectrum. Some substances were found to emit only a continuous spectrum, with no marked emission bands, but no substance was found in which the spectrum consisted entirely of sharp emission bands. The maximum of the continuous spectrum was found to shift toward the short wave-lengths with rise in temperature. The discontinuous spectrum of many substances was found to merge into a continuous one at high temperatures. On the other hand, the energy emitted by the sharp emission bands was proportional to the energy supplied, and there appeared to be no tendency for a sharp emission band to merge into the continuous spectrum upon which it is superposed. In this respect several of the oxides exhibited an emission spectrum similar to that of a flame, which is a combination of the radiation from solid particles and from a gas.

Furthermore, it was found that the maxima of sharp emission bands do not shift with rise in temperature. Several emission bands were found to be in common with the different oxides studied, but no conclusion was reached as to their cause other than the presence of the oxygen atom. Nothing further than a qualitative proof of Kirchhoff's law of proportionality of emission and absorption could

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\(^1\) See a fuller discussion in this Bulletin, 5, p. 178.

\(^8\) This Bulletin, 5, p. 162.
be established in this search for a law governing the radiation from the oxides, etc., which are known as "transparent media" or "electric insulators."

On the other hand, a uniformly heated cavity, or so-called "black body," and also platinum, have been found, by others, to emit a continuous spectrum of radiant energy. The distribution of this energy is unsymmetrical about the maximum of the energy curve, having the appearance of the probability function modified by suitable constants. With rise in temperature the maximum of the energy curve shifts toward the short wave-lengths. The solids heretofore investigated, and the uniformly heated cavity, or "black body," in which it has been possible to determine the approximate temperature, have spectral energy curves which are represented by the function:

\[(1)\]

\[E = c_1 \lambda^{-\alpha} e^{-c_2 / \lambda T}\]

The shifting of the maximum of the energy curve with rise in temperature is expressed by the law—

\[(2)\]

\[\lambda_{\text{max}} T = \text{const.}\]

With these two equations it is possible to determine the constants of radiation of platinum and of the "black body," provided we know the temperature. For platinum \(a = 6\) and for the "black body" \(a = 5\). There are theoretical reasons for believing that all metals behave like platinum in their emissive properties, since they are electrical conductors and exhibit a high reflecting power in the visible spectrum. The fact that they are electrical conductors of

\(^3\) Paschen, Ann. der Phys. (3) p. 58, 455; 60, p. 663, 1897; (4) 4, p. 277; 1901.


\(^4\) Kirchhoff's Law says that for a given temperature, \(T\), and wave-length, \(\lambda\), the emissivity, \(E\), the absorptivity, \(A\), and the reflectivity, \(R\), of a substance is related to the emissivity, \(e\), of a complete radiator by the equation:

\[E = Ae = (1 - R)e\]

since \(A = 1 - R\). For electrical conductors of the metallic type, the reflective power is related to the electrical conductivity by the relation,

\[100 - R = 36.5 \sqrt{\frac{w}{\lambda}}\]

where \(w\) is the specific resistance. Since this relation is true only for long wave-lengths (beyond \(10\mu\)), and since the value of \(R\) is low and of \(A\) is high in the visible spectrum, such metals as gold, copper, platinum, etc., must show selective emission, however small, in the visible spectrum.

This subject has been thoroughly treated by Aschkinass, Ann. der Phys. (4), 17, p. 960; 1905.
the metallic type indicates that the reflecting power, which increases with the electrical conductivity, is high throughout the infra-red. Hence, it may be assumed tentatively that the emissivity function of such metal filaments as tungsten, tantalum, and osmium is similar to that of platinum and of a complete radiator. The appearance of the contours of the energy curves for various temperatures will give some clue to the admissibility of this assumption, which is nothing more than has been tacitly made by previous observers; and until a better one is suggested, the present method is the only one available, without a knowledge of the temperature of the radiator. Since it is at present impossible to obtain these metals in thin strips, similar to platinum, by means of which it is possible to determine the temperatures, there is certainly no objection in making this assumption and then testing it experimentally by the one remaining method, to see what happens. This method consists in observing the spectral energy curve, in which the temperature, \( T \), is kept constant, without knowing the actual temperature. This gives the value of \( a \), and in this manner we can obtain some idea of the probable emissive power of the filament, as to whether the emissivity (total radiation) is proportional to the fourth power \((a - 1 = 4 \text{ for a black body, } a - 1 = 5 \text{ for platinum})\) or to some higher power of the absolute temperature.

The value of \( a \) is determined from the equation

\[
\frac{E}{E_{\text{max}}} = \left[ \frac{\lambda - \lambda_{\text{max}}}{\lambda_{\text{max}}^\lambda e^{\lambda}} \right] ^a
\]

for it can be shown from equation (1) that the ratio of the emissivities (the observed galvanometer-bolometer deflections, \( E \) and \( E_{\text{max}} \)) for any two wave-lengths is as given in this equation. How far the above assumption falls short of the observed facts was shown in a previous paper on the radiation from the Nernst glower, in which the radiation curve at high temperatures is apparently continuous, but which in reality is the composite of numerous sharp emission bands, which increase in intensity and broaden out with rise in temperature. For the Nernst glower this constant was found to decrease from \( a = 7 \) at low temperatures to \( a = 5 \) at high temperatures.

\[^5\text{This Bulletin, 4, p. 253; 1908.}\]
An investigation of the emissive properties of the metals is of interest in connection with the numerous conjectures offered to account for the high efficiency of the new metal filament incandescent lamps. Some of these conjectures, quoted in a recent paper on this subject, would seem to be but little more than mere guesses, made without considering the experimental data already at hand, from which we can form a reasonable estimate of what to expect of similar substances operated under similar conditions.

From our present knowledge of the similarity of the electrical conductivity and of the absorption and reflection of a majority of the metals extending over the whole range of the Mendelejeff series, it is reasonable to suppose that the few metals remaining uninvestigated will behave similarly in their emissive and other physical properties. Such metals as gold, silver, copper, platinum, etc., which have a low reflecting power (see Fig. 1) throughout or in narrow regions of the visible spectrum, may well be expected, and are known, to have a marked selective emission in this region of the spectrum, but there has not been a single metal investigated which does not have a uniformly high reflecting power throughout the infra-red, from which one could expect to explain a high efficiency due to the entire absence of radiant energy in large regions of the infra-red, such as was found in the oxides, which are electrical insulators. On the other hand, the high efficiency of the new metal filaments has been attributed to the higher melting points, and consequently the higher temperature, at which they can be operated as compared with platinum. This is true in part, since the temperature at which platinum can be successfully operated is only about 1200 to 1400° C, at which temperature even a black body emits only a yellowish-white light.

The great distinguishing characteristics of metals are their uniformly high reflecting power (with the absence of absorption bands)

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6 Waidner and Burgess, this Bulletin, 2, p. 328; 1907.
7 Hagen and Rubens, Ann. der Phys. (4) 8, p. 432; 1902.
8 Hagen and Rubens, Ann. der Phys. (4) 1, p. 352; 1900.
Coblentz, this Bulletin, 2, p. 470; 1906.
9 Lummer, Ziele der Leuchtechnik; Elektrotech. Zs. 28, pp. 787, 806; 1902.
throughout the infra-red, and their low reflecting power, with bands of almost no reflection, in the visible spectrum. The energy not reflected must, of course, be absorbed; hence, from Kirchhoff's law the emissivity, $E_\lambda$, at a given temperature and wave length, must be proportional to the emissivity, $e_\lambda$, of a black body, i. e., $E_\lambda = e_\lambda (1 - R_\lambda)$ where $R_\lambda$ is the reflecting power of the metal. From this, it is evident that the metals must emit selectively in the short wave-lengths (up to $1\mu$) as shown by the reflection curves in Fig. 1. A notable and easily observed example is copper, which has a band of low reflectivity at $0.5\mu$ and a second band at $0.3\mu$, in the ultraviolet.
The band at $0.5\mu$ gives rise to the green color of molten copper, the intensity of the emission being almost half as great as that of a black body at the same temperature. On the other hand, such metals as nickel, cobalt, palladium, platinum, iridium, etc., which have a low reflecting power in the visible (and ultraviolet spectrum) which increases rapidly to a high and uniform reflecting power beyond $1\mu$ but which have no sharp bands of low reflectivity (see platinum, Fig. 1; data from Hagen and Rubens, and from Minor), must also emit an abnormal amount of energy in the visible spectrum as compared with the infra-red. In this case the extra emission is greatest in the violet and decreases uniformly but rapidly toward the infra-red. At high temperatures this will give a more bluish tint to the emitted light than would be the case if the reflecting power were uniformly high throughout the whole spectrum. The latter is a condition for producing a “gray body,” which, by definition, is one in which the emissivity is reduced by the same amount throughout the spectrum. The fact that the reflecting power is uniform in the infra-red indicates that there can not be any emission bands. It is evident that the spectral emissivity function of metals must be far more complex than that given in equation (1). Since the emissivity, $E_\lambda$, is dependent upon the reflecting power, which is a function of the index of refraction and the absorption coefficient, which, in turn, as will be shown later on, are functions of the temperature and the electrical conductivity, it is evident that the emissivity function must contain factors which take account of these phenomena.

To the writer it has seemed that an explanation of the high efficiency of the new metal filament lamps is to be sought for in the value of the so-called emissivity constant $a$ (which, as will be shown presently, is most effective in suppressing the energy in the long wave-lengths) and in a possible selective emission (i.e., abnormally high but uniform emission, due to the higher value of the absorption coefficient) in the visible spectrum, so that the operating temperatures may or may not be so very different for filaments made of various metals. All the metals investigated show a low reflecting power in the visible and ultraviolet spectrum. This lowering of the reflecting power is much greater than can be accounted for by the scattering due to lack of polish of the surface. This is particularly true of the “white” metals such as platinum, magnesium,
aluminum, cadmium, zinc, etc., to which class osmium appears to belong. In the case of platinum, Hagen and Rubens\(^\text{10}\) found that the absorption coefficient is unusually high in the visible spectrum, and decreases uniformly toward the infra-red, being only four-fifths its former value at 1.4\(\mu\). Such a large variation in the absorption coefficient (and index of refraction) must necessarily cause a selective emission, however small, in the visible spectrum, where the absorption is the greatest. This selective emission is augmented by the rapid rise in the reflecting power beyond 1\(\mu\) (absorption unknown) which suppresses the radiation in proportion to the reflecting power, and which is uniform throughout the infra-red, thus making it highly improbable that there are bands of selective emission in the infra-red.

The fact that these metal filaments emit a white light indicates that the high emissivity, if present, must extend over a wide region of the visible spectrum, as compared with zinc oxide which emits a yellowish light when heated, and with (molten) copper which emits a greenish light.

On the other hand, if the emission function of the metals is of the form given in equation (1), as has been shown to be true for platinum, then the exponent \(a\) is more effective in suppressing the infra-red radiation than one might suppose. This is shown in Table I, in which the first horizontal line gives the wave lengths for which the computations are made. In the second, third, and fourth lines these wave lengths are raised to the power of \(a = 5, 6, \text{ and } 7\), corresponding, respectively, with a complete radiator, platinum, and tungsten. In the fifth and sixth lines, the computations are given for the logarithmic function. The seventh line is obtained by dividing the values in the third line by the corresponding values in the second line; similarly, the eighth line is obtained from the fourth and second lines, and the ninth line from the sixth and the fifth lines.

The point of interest in this table is the preponderence of the \(\lambda^{-a}\) factor over the \(e^{-c_{i}A\lambda T}\) factor in suppressing the infra-red radiation. For example, the ninth line shows that at 5\(\mu\) the \(e^{-c_{i}A\lambda T}\) factor reduces the emissivity of platinum to 0.87 that of a complete radiator, while (seventh line) the \(\lambda^{-a}\) factor reduces the emissivity to 0.2 its former value. In the case of tungsten (eighth line) the

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\(^{10}\) Hagen and Rubens, Ann. der Phys. (4) 8, p. 450; 1902.
λ—a factor reduces the emissivity to 0.04 that of a complete radiator at 5μ. In other words, if the complete radiator gives a bolometer deflection of 100 mm at 5μ, then, for platinum and tungsten, at the same temperature, the λ—a factor reduces the deflections to 20 mm and 4 mm respectively.

TABLE I.

This table shows the preponderance of the factor λ—a over the factor $e^{-c_2/\lambda T}$ in decreasing the emissivity, $E_\lambda$, beyond 1μ. These values are computed from the equation $E_\lambda = c_1 \lambda^{-a} e^{-c_2/\lambda T}$, using $T=2000^\circ$ Abs.

<table>
<thead>
<tr>
<th>1. Wave length, $\lambda$</th>
<th>0.5μ</th>
<th>1μ</th>
<th>2μ</th>
<th>3μ</th>
<th>4μ</th>
<th>5μ</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Value of $\lambda^{-a}$ for $a=5$ (complete Radiator)</td>
<td>32</td>
<td>1.0313</td>
<td>0.00412</td>
<td>0.000978</td>
<td>0.00032</td>
<td></td>
</tr>
<tr>
<td>3. Value of $\lambda^{-a}$, for $a=6$ (Platinum)</td>
<td>64</td>
<td>0.01565</td>
<td>0.00137</td>
<td>0.000244</td>
<td>0.000064</td>
<td></td>
</tr>
<tr>
<td>4. Value of $\lambda^{-a}$ for $a=7$ (Tungsten)</td>
<td>128</td>
<td>0.0078</td>
<td>0.000457</td>
<td>0.000611</td>
<td>0.0000128</td>
<td></td>
</tr>
<tr>
<td>5. Value of $e^{-c_2/\lambda T}$ for $a=5$ (complete Radiator, $c_2=14500$)</td>
<td>5.05</td>
<td>0.00638</td>
<td>0.027</td>
<td>0.0894</td>
<td>0.164</td>
<td>0.235</td>
</tr>
<tr>
<td>6. Value of $e^{-c_2/\lambda T}$ for $a=6$ (Platinum, $c_2=15600$)</td>
<td>1.43</td>
<td>0.00378</td>
<td>0.0195</td>
<td>0.073</td>
<td>0.139</td>
<td>0.204</td>
</tr>
<tr>
<td>7. Reduction of $E_\lambda$ by $\lambda^{-a}$ in changing from $a=5$ to $a=6$ (complete Radiator to Platinum)</td>
<td>2</td>
<td>1</td>
<td>0.5</td>
<td>0.33</td>
<td>0.25</td>
<td>0.20</td>
</tr>
<tr>
<td>8. Reduction of $E_\lambda$ by $\lambda^{-a}$ in changing from $a=5$ to $a=7$ (complete Radiator to Tungsten)</td>
<td>4</td>
<td>1</td>
<td>0.25</td>
<td>0.11</td>
<td>0.067</td>
<td>0.04</td>
</tr>
<tr>
<td>9. Reduction of $E_\lambda$ by $e^{-c_2/\lambda T}$ in changing from $a=5$ to $a=6$ (complete Radiator to Platinum)</td>
<td>0.284</td>
<td>0.596</td>
<td>0.723</td>
<td>0.824</td>
<td>0.848</td>
<td>0.87</td>
</tr>
</tbody>
</table>
From this it is evident that even though the various metal filaments may not have a marked selective emission in the visible spectrum, the one having the highest value of \( a \) will radiate the least in the infra-red. It would therefore appear that unless the value of \( C_1 \), equation (1), is very different for the different metals, the amount by which the temperature must be raised may be very small in order to bring the metal, having the largest value of \( a \), to the same intensity \( E \), in the visible spectrum, as that of another metal having a smaller value of \( a \); and at the same time the former metal may radiate considerably less in the infra-red. The operating temperatures may therefore not be so very different in the metal filament lamps, especially if the one having the higher value of \( a \) has also a selective emission in the visible. The spectrophotometric curves published by Nichols\(^{11}\) show that for tungsten and tantalum, set to equal intensity at 0.589\( \mu \), the intensity is almost 50 per cent greater in the tungsten curve than it is in the tantalum at 0.45\( \mu \), with correspondingly high values intervening. On the other hand, at 0.7\( \mu \), conditions are just the reverse, the tantalum curve being 12.5 per cent greater than that of tungsten. This makes the slant of the curve of tantalum steeper than the tungsten. It should be the steeper (aside from effect due to differences in temperature) at any wave length, for, as will be shown presently, the value of \( a \) is smaller for tantalum than it is for tungsten at the same temperature (estimated by the position of \( E_{\text{max}} \) see Figs. 9 and 10); and as may be seen from eq. (1), the value of \( dE/d\lambda \) is greater the lower the value of \( a \).

Although much has been written on the possible selective emission in the visible, no really conclusive data was at hand\(^{12}\) until experiments were undertaken recently by Drs. Hyde and Middlekauff in this Bureau.

It is quite impossible to make radio-metric observations in the visible spectrum because of the smallness of the radiant energy involved. Recourse must, therefore, be had to the spectrophotometer. Heretofore, these spectrophotometric measurements of one source have been compared with that of another used as a standard,

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\(^{12}\) Except a few experiments by Leder, Ann. der Phys. 24, p. 305; 1907.
of which the distribution of energy is in even greater uncertainty than the one under investigation. The proper method of procedure is to refer all measurements to the black body at a given temperature, which we know, from theory and from experiment, must have a uniformly increasing distribution of energy with increase in wave length, and of which the energy curve may be computed with greater accuracy than it can be observed in the visible spectrum. This is the manner in which the investigation is being carried out in this Bureau.

It is, therefore, a great satisfaction to be able to include here some preliminary spectrophotometric measurements (referred to a black body at a fixed temperature, as a standard of comparison) of the distribution of energy in the spectra of the filaments described in this paper. The black body employed is one constructed with especial care, to be used in the redetermination of the radiation constants. Every precaution was taken to insure accuracy in the temperature measurements, as well as in the uniformity of the temperature distribution within the black body.

In the spectrophotometric comparison of the incandescent lamp with the black body, the difference in the temperatures of the front and the rear surfaces of the radiating wall was less than 0.3 throughout the series of measurements. The temperature of the black body was kept "normal" at 1432° C, with a maximum variation of 0.3 during the whole series of observations. On the other hand, the "substitution method" employed by Drs. Hyde and Middlekauff reduces spectrophotometric errors to a minimum, so that it is felt that the results are reliable and that explanations of disagreements with others are to be sought elsewhere.

The spectrophotometric comparison of the metal and carbon filaments with the black body shows no selective emission. On the other hand, the acetylene flame has a marked selective emission in the region of 0.72μ.

Although the spectrophotometer shows no bands of selective emission, one can not determine by means of such an instrument whether or not the emissivity throughout the visible spectrum is abnormally high as compared with the infra-red, which high emissivity must result from the abnormally low reflecting power in the visible and ultra-violet as compared with the infra-red, as shown in
Fig. 1, and which must merge gradually into the normal emission beyond \(1\mu\) where the reflecting power is uniform.

**II. DETERMINATION OF THE \(\alpha\) RADIATION CONSTANT.**

It is beyond the scope of this paper to fully discuss the relative merits of previous determinations of this "constant." It must be said, however, that present-day investigators working in this field are prone to forget how little was known of the physical properties of prisms, of reflecting mirrors, of the transparency of the atmosphere, etc., at the time (about 1890) when renewed interest in the laws of radiation was awakened by the invention of a workable bolometer by Langley, and a reflection diffraction grating by Rowland, which in turn was applied by Langley to calibrate his rock-salt prism for the infra-red spectrum. At that time nothing very accurate (if at all) was known beyond \(3\mu\) concerning the transparency of the air, fluorite, water vapor, etc., nor of the reflecting power of silver mirrors and of reflection gratings, nor of the dispersion of fluorite, nor of the emission and absorption of gases and water vapor, all of which investigations were carried out (and have served as a starting point by all subsequent observers) by Paschen, before he could proceed with his main problem, viz, the investigation of the laws governing the radiation from solids by means of spectral energy curves.

In his first paper on this subject he examined the radiation from iron oxide heated upon a platinum strip. He found that, with rise in temperature, the maximum of the energy curves shifted according to the often previously announced relation \(\lambda_{\text{max}}T = \text{Const.}\), and that the total radiation followed a law requiring a variation greater than the fourth power of the absolute temperature, as deduced by Boltzmann. The various radiation laws proposed up to that time were found untenable, and he set up a complicated empirical formula which fitted his observations. He found, experimentally, that the value of \(E/E_{\text{max}}\) was best represented by equation (3). At the end of his paper he announced that the simple empirical relation \(E = c\lambda^{-\alpha}e^{-c\mu T}\) with \(\alpha = 5.6\) was fairly well fulfilled by his results, and concluded that it is probably not far removed from the true

\(^{13}\)Paschen, Ann. der Phys. (3) 58, p. 455; 1896.
emission function. He communicated these results to Wien,\textsuperscript{14} who, a month later, published a theoretical deduction of equation (1), with \( a = 5 \) for a complete radiator. In his second paper,\textsuperscript{15} in which he examined the radiation from copper oxide, lampblack, gas carbon, and platinum, Paschen found equation (1) and its subsidiary relations verified in unexpected places, while in expected places the law was not verified. He found that the values varied from \( a = 5.5 \) to \( a = 6 \), depending upon the substance investigated. From the fact that for a given substance the value of \( a \) obtained by three methods gave concordant results when using "blackened bodies," he concluded that the same will be true for an "absolutely black body," when in equation (1) and equation (3) the value of \( a = 5 \), as demanded by theory.

The practical realization of a black body by Lummer and his colleagues came with the development of electrically heated furnaces, when it was shown that \( a = 4 \) for a uniformly heated cavity, or complete radiator, and \( a = 6 \) for platinum.\textsuperscript{16}

It seems to have been overlooked by those who have criticised Paschen's work because the scale of temperature is in doubt, that the value of the constant \( a \) was in all cases computed from equation (3) in the form;

\[
a = \frac{\log E - \log E_{\max}}{\log e - \frac{\lambda_{\max}}{\lambda} \log e + \log \frac{\lambda_{\max}}{\lambda}}
\]

which does not contain the temperature factor.\textsuperscript{17}

The values of \( a \) for iron oxide alone were obtained from an untold number of computations based upon 47 energy curves, the temperature being varied from 117° to 1124° C. In spite of the thoroughness of the work, Paschen did not find a systematic varia-

\textsuperscript{14}Wien, Ann. der Phys. (3) 58, p. 662; 1896.
\textsuperscript{15}Paschen, Ann. der Phys. (3) 60, 662; 1897.
\textsuperscript{17}Of course the value of \( a \) was also computed, using the observed temperatures, the results usually being in close agreement with those obtained from equation (4), but only a few computations were made using temperatures.
tion of \( a \) with rise in temperature (see Fig. 2), which has been found in subsequent investigations, which, as will be mentioned presently, must occur at some stage, and which his other observations (see Ann. der Phys. 60, p. 707, and Table XIX) seem to show.

The determination of \( a \) by this method is an extremely tedious process, rendered more so by the presence of the atmospheric absorption bands. To overcome the latter difficulty, Paschen computed the position of the \( E_{\text{max}} \) in his energy equations by obtaining \( \lambda_{\text{max}} \) from the equation:

\[
\lambda_{\text{max}} = \frac{(\log \lambda_2 - \log \lambda_1) \lambda_1 \lambda_2}{(\lambda_2 - \lambda_1) \log \epsilon}
\]

selecting for the purpose wave lengths on the energy curve where two ordinates were of equal height \( (E\lambda_1 = E\lambda_2) \), but which did not fall within the region of the atmospheric absorption bands.

In all cases, except for platinum, the values of \( a \) determined by equation (3) and those from equation (1) using the temperature were in close agreement. As already mentioned, there is an inconsistency in that some of his results show no variation in \( a \) with rise in temperature. On the other hand, Lummer and Kurlbaum found from the measurement of the total radiation of platinum and of iron oxide that the value of \( a \) underwent a very marked decrease with rise in temperature (see Table IV). This fact seems to have escaped the attention of Lummer and Pringsheim in their investigation of the spectral radiation of platinum.\(^{19} \) (See a discussion of their results on a subsequent page, under "platinum.") The present results confirm the observations of Lummer and Kurlbaum.


Although it seems to have been overlooked heretofore, it is obvious that the so-called constant, $\alpha$, must decrease in value (either abruptly at some temperature or uniformly throughout the range in temperature) and approach that of a complete radiator, otherwise a point would be attainable at which the total radiation is greater than that of a complete radiator at the same temperature. The writer's attention was called to this fact by Dr. C. W. Waidner some years ago, and the subject has since been discussed by Mendenhall and Ingersoll, on the basis of the radiation laws, especially the Stefan law. This same conclusion follows from a consideration of Maxwell's electromagnetic theory of light, which in its original form does not consider the vibratory periods of the molecules, and which demands the existence of analogous relations between the electric conductivities and the transparencies of the metals to radiant energy.

The electromagnetic theory of light requires the "optical constants" (the refractive index, $n$, and the absorption coefficient, $k$), to have a temperature coefficient which increases with the wave length. In the visible spectrum the change in the optical constants of the metals with the temperature is exceedingly small as shown by various observers.

On the other hand, Hagen and Rubens have shown that at $25\mu$ the absorption coefficient undergoes a change which is proportional to the change of resistance which the metals show with increasing temperature. In the case of platinum, in which the temperature coefficient is large, the observed emissive power ($100 - R$) increased from 3.36 (arbitrary units) at $170^\circ$ C to 9.78 at $1500^\circ$ C, which agrees with the same values computed using the specific resistance of the metal.

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   E. Cohn, "Des electromagnetische Feld," p. 444; 1900.
22 Drude, Ann. der Phys. (3) 39, p. 538; 1890.
   Pflüger, Ann. der Phys. (3) 58, p. 493; 1886.
   Laue and Martens, Phys. Zs., 8, p. 853; 1907. The latter observers, working over a range from $800^\circ$ to $1500^\circ$ C, found no marked change in the optical constants of platinum.
In view of the fact that the reflecting power, $R$, of the metals increases with the electrical conductivity, which decreases with rise in temperature, one would expect to find a corresponding increase in the emissivity, i.e., a decrease in the value of $a$, as demanded by the electromagnetic theory of light. This variation of the "optical constants" with temperature being extremely small in the visible spectrum, and very marked at 25$\mu$, is evidently a function of the wave length. It is therefore of interest to investigate their behavior in the intervening region.

It will be shown presently that, without a single exception, the metals herein examined show a decrease in $a$ with rise in temperature, as is to be expected. For carbon (a non-metal) which decreases in resistance with rise in temperature, the results are inconclusive, the $a$ decreasing uniformly for the "untreated" carbon and apparently increasing for the "flashed" carbon. For the latter the measurements should extend over a wider range of temperature in order to be conclusive.

### III. METHODS OF PRESENT INVESTIGATION.

In the present investigation it was found that the determination of the value of $a$ is beset with difficulties which precludes great accuracy. The observations of the prismatic distribution of energy can be made with an apparent accuracy of 0.2 to 0.5 per cent, the errors being introduced subsequently in reducing the observations.

The energy spectrum was obtained from about 15 spectrometer settings, between 0.8 and 3$\mu$ (settings every 1' to 2' of arc). The galvanometer deflections were plotted to a scale commensurate with the observations, and from this the normal energy curve was obtained by dividing the observed galvanometer deflections by the width of the bolometer strip expressed in wave lengths, using the first two terms in the function for the slit-width correction, viz:

$$\text{(6) } e f(\lambda) = E(\lambda) - \frac{1}{6} E_1(\lambda) + \frac{2}{45} E_2(\lambda) \ldots \ldots .$$

where $E$ is the observed galvanometer deflection and $\lambda$ is the wave

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24 Paschen, Ann. der Phys., 60, p. 714; 1897.
length. The slit-width correction is difficult to determine in the region where a dispersion curve passes through a point of inflection. In this region (at 1.5\(\mu\)) where, unfortunately, the maxima of the energy curves also occur, the dispersion of fluorite is extremely difficult to observe and probably not known with as great accuracy as in other parts of the spectrum. The dispersion curve (refractive index and wave length) was obtained by plotting all the known observations, and it coincided precisely with the latest and probably the most accurate determination\textsuperscript{25} of the refractive indices of fluorite. From this dispersion curve the prism calibration curve (minimum deviation setting and corresponding wave length) was computed, and from the latter the so-called slit-width correction curve was found by reading from the calibration curve the width which the bolometer strip (0.6 mm) subtended in wave lengths in different parts of the spectrum.

The value of the bolometer strip of 4' of arc is given in Table II, third column, from which it will be noticed that in precision work the slit-width correction for fluorite is a tedious and somewhat uncertain factor at 1.5 to 1.7\(\mu\).

In this respect rock salt (or quartz) would be better adapted to work of this type, because the double curvature in the dispersion curve falls at 3\(\mu\). However, the lack of purity of rock salt, the smaller dispersion at 1 to 2\(\mu\), and particularly the difficulty in keeping the surfaces polished, prohibit its use.

Other errors that enter into the determination of the value of \(a\) are “stray” or “field light,” which is superposed upon the spectrum, and the loss of energy by absorption at the mirrors which is quite marked in the wave lengths from 0.5 to 1.0\(\mu\). The latter may be corrected, thus reducing the values of \(a\) by 2 to 5 per cent. In a few cases in the present work the reflecting power correction was applied, but the uncertainties (introduced after making the observations) in obtaining \(E\) and \(E_{max}\), especially the latter, which amounted to 5 per cent, did not seem to justify the procedure. The “field light,” which comes from the prism surfaces and from scattering internally, can not be eliminated from the energy curve by absorption screens, which it is hoped to apply in finding isochromatic

\textsuperscript{25}Paschen, Ann. der Phys. (4) 4, p. 302; 1901.
Table II.
Calibration Curve of Fluorite Prism, 60°

<table>
<thead>
<tr>
<th>Spectrometer Setting</th>
<th>Wave Length</th>
<th>Slit-width Correction</th>
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<tr>
<td>20°00'</td>
<td>0.5893μ</td>
<td>0.034</td>
</tr>
<tr>
<td>58</td>
<td>0.625</td>
<td>0.0395</td>
</tr>
<tr>
<td>55</td>
<td>0.694</td>
<td>0.054</td>
</tr>
<tr>
<td>53</td>
<td>0.754</td>
<td>0.071</td>
</tr>
<tr>
<td>19°50</td>
<td>0.8875</td>
<td></td>
</tr>
<tr>
<td>49</td>
<td>0.9407</td>
<td>0.102</td>
</tr>
<tr>
<td>48</td>
<td>1.002</td>
<td>0.1230</td>
</tr>
<tr>
<td>47</td>
<td>1.063</td>
<td>0.1318</td>
</tr>
<tr>
<td>46</td>
<td>1.1318</td>
<td>0.1432</td>
</tr>
<tr>
<td>45</td>
<td>1.206</td>
<td>0.1542</td>
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<tr>
<td>44</td>
<td>1.286</td>
<td>0.1640</td>
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<tr>
<td>43</td>
<td>1.370</td>
<td>0.1720</td>
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<tr>
<td>42</td>
<td>1.457</td>
<td>0.1745</td>
</tr>
<tr>
<td>41</td>
<td>1.545</td>
<td>0.1760</td>
</tr>
<tr>
<td>19°40</td>
<td>1.633</td>
<td>0.1743</td>
</tr>
<tr>
<td>39</td>
<td>1.719</td>
<td>0.1715</td>
</tr>
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<td>38</td>
<td>1.8040</td>
<td>0.1682</td>
</tr>
<tr>
<td>37</td>
<td>1.887</td>
<td>0.1647</td>
</tr>
<tr>
<td>36</td>
<td>1.9685</td>
<td>0.1617</td>
</tr>
<tr>
<td>35</td>
<td>2.048</td>
<td>0.1585</td>
</tr>
<tr>
<td>34</td>
<td>2.127</td>
<td>0.1540</td>
</tr>
<tr>
<td>33</td>
<td>2.277</td>
<td>0.1475</td>
</tr>
<tr>
<td>19°30</td>
<td>2.421</td>
<td>0.1407</td>
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<tr>
<td>28</td>
<td>2.558</td>
<td>0.1345</td>
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<tr>
<td>26</td>
<td>2.689</td>
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</tr>
<tr>
<td>24</td>
<td>2.813</td>
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</tr>
<tr>
<td>22</td>
<td>2.934</td>
<td>0.119</td>
</tr>
<tr>
<td>19°20</td>
<td>3.051</td>
<td>0.1147</td>
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<tr>
<td>15</td>
<td>3.328</td>
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<td>10</td>
<td>3.578</td>
<td>0.098</td>
</tr>
<tr>
<td>5</td>
<td>3.806</td>
<td>0.0915</td>
</tr>
<tr>
<td>19°00</td>
<td>4.035</td>
<td>0.086</td>
</tr>
<tr>
<td>50</td>
<td>4.445</td>
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<tr>
<td>40</td>
<td>4.825</td>
<td>0.0707</td>
</tr>
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<td>30</td>
<td>5.169</td>
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<td>15</td>
<td>5.642</td>
<td>0.059</td>
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<tr>
<td>18°00</td>
<td>6.082</td>
<td>0.056</td>
</tr>
<tr>
<td>30</td>
<td>6.864</td>
<td>0.049</td>
</tr>
<tr>
<td>17°00'</td>
<td>7.546μ</td>
<td>0.042</td>
</tr>
</tbody>
</table>
energy curves. The only applicable test is to measure the energy in the ultraviolet where silver has a minimum reflecting power. For the most intense radiation from a Nernst glower the stray radiation determined in this manner was extremely small, and hence negligible in the metal filaments.

The adjustment of the apparatus has previously been described. The adjustments of the spectrometer (the "zero setting" of the bolometer) was made with the yellow helium line.

Great precaution had to be taken to prevent radiation from more than one filament entering the spectrometer slit. To this end the first spectrometer mirror was covered except a narrow portion through the center. The center of the cone of light, which was only about 3 mm wide for the metal filaments, was brought to a fixed mark upon a ground-glass screen placed within the spectrometer; and the adjustment of the lamp, covered with a hood containing a narrow slit, was continued until no light from side (or line of sight) filaments entered the spectrometer. This adjustment is emphasized because the curious results of Sartori, in which he found that a 3.5-watt-per-HK-carbon-filament lamp had the maximum of its energy spectrum at a shorter wave length than that of a 1-watt-per-HK-osmium lamp, seem (to the writer) to be due to a lack of centering the narrow cone of light upon the prism face. The spectrometer-bolometer adjustments were made before and after each series of observations, and the bolometer sensibility was frequently tested while making the series of observations. The energy was taken from a storage battery. The observations were repeated in different parts of the spectrum after measuring through the spectrum, and in general immediately after passing the maximum emission, in order to test any change in emissivity of the filaments due to deterioration.

Every effort was made to avoid errors which would interfere with the accuracy attainable, and it is felt that the explanation of some of the results obtained, which are apparently at variance with those of others—for example, the lack of constancy of the exponent, $a$—must be sought elsewhere, and not in faults in the apparatus.

26 This Bulletin, 4, p. 533; 1908.
27 Sartori: Illuminating Engineer (London), 1, p. 601; 1908, contains an abstract of this paper.
Although, as previously described, the apparatus was practically free from absorption, a very weak, narrow absorption band seemed to be present at 1.45 \( \mu \), which may be due in part to the prism. Although it was perfectly free from flaws and almost colorless, the prism belonged to what is known as the "green" variety of fluorite, which has been found to have a very narrow, shallow absorption band at 1.42\( \mu \) (see Fig. 1, which gives the transmission of a very light-yellowish-green sample 3.85 mm thick, and also the transmission of a clear white fluorite 2.28 mm thick). To simplify the computations, which were long and tedious, the value of \( \alpha \) was computed (see equation (3) ) for those wave lengths which were used in computing \( \lambda_{\text{max}} \) in equation (5). The wave length \( \lambda_1 \) was selected, which would not occur in possible absorption bands, which was quite removed from the correction for reflection, and which did not place \( \lambda_2 \) too far into the infra-red (beyond 2.5\( \mu \)) where, for the incandescent lamps, the glass walls begin to absorb heavily (see Fig. 1 for the transmission of a sample of glass 0.75 mm thick). The value of \( \lambda_{\text{max}} \) found in this manner from equation (3) would vary from the mean by 1 to 3 (very rare) units in the second decimal place. The main difficulty was in the uncertainty in taking the values of \( E \) and \( E_{\text{max}} \), especially the latter, from the energy curves, so that in spite of all the precautions taken the variation in the value of \( \alpha \) for any one energy curve, using different values of \( \lambda_1 \) and \( \lambda_2 \), is of the order of 3 to 5 per cent. However, the values are consistent, all being high or low, which is the point of principal interest in this investigation. Moreover, the values of \( \alpha \) so determined are compared with platinum, of which the remaining constants are fairly well known.

IV. COMPARISON OF THE SPECTRAL ENERGY CURVES OF VARIOUS SUBSTANCES.

One method of demonstrating the great difference in the emissivity in the infra-red as compared with the visible spectrum, due to the difference in the value of \( \alpha \), is to set the various filaments to the same intensity in the visible and observe their energy curves. In order to do this it is necessary to keep the bolometer at the same sensibility
throughout the examination, and to have the same energy flux, i.e.,
the same area of the prism face covered by the different filaments.
The latter will depend upon the diameter of the radiating filament
and its distance from the spectrometer slit. Then, with these two
factors constant, the energy supply is regulated in the various lamps
so that they all give the same deflection at a certain wave length;
for example, 0.5μ. The problem is simplified and sufficiently
approximated by setting the different lamps to a color match with
an ordinary photometer, or, better still, with a spectrophotometer,
and noting the voltages of the different lamps. The radiation
curves are then observed at these voltages, regardless of the area of
the prism face covered or the sensibility of the bolometer, and the
deflections in the various energy curves are reduced by a fixed
amount, which is determined by the factor which must be applied
to make the deflections equal for all the lamps for a certain wave
length—say the yellow or red. With the cooperation of Dr. E. P.
Hyde, a series of energy curves were made for several commercial
incandescent lamps, including untreated carbon (curve a), flashed
carbon (curve b), tungsten (curve c), and osmium (curve d), all
shown in Fig. 3. In all the lamps the radiation was observed
through the glass walls, hence no comparison can be made of the
curves beyond 2.5μ. Great care was taken to shield the lamps so
that the radiation from only one filament entered the spectrometer
slit. The cone of energy covered only about 3 mm of the prism
face, thus greatly reducing the deflections, which consequently
could not be determined with great accuracy in the visible. Hence,
while the observations demonstrate conclusively the very different
emissivity of these lamps, the curves cannot be used to estimate the
value of the so-called constant a. For example, the curves for
tungsten and osmium, according to the other determinations of a,
should be closer together, with the tungsten curve perhaps the
lower of the two. (See, however, discussion under osmium.) The
suppression of the infra-red radiation in the two metals with a high
value of a is very marked in comparison with the radiation from the
carbon filaments. A mere glance at Fig. 3 shows that the carbon
lamps emit about one-third more infra-red energy than the metal
filaments. This alone is sufficient to explain the high efficiency of
the latter, without introducing the question of a selective emission
Fig. 3.—Spectral Radiation Curves.
in the visible, the term "selective emission" being used to indicate an abrupt change in the energy curve with change in wave length, such as was found in the oxides.\(^\text{28}\)

The estimation of the temperature of these filaments based upon the shift in the maximum is hardly admissible, for a change from \(a=5\) to \(a=6\) introduces a change of 20 per cent in the maximum, \(\lambda_{\text{max}}\), while the value of \(C_s\) changes but 7 per cent. Increasing the value from \(a=5\) to \(a=7\) (tungsten) introduces a change of almost 40 per cent in the maximum \(\lambda_{\text{max}} = C_s/Ta\).

As a further illustration, in the present curves the value of \(a=5.9\) for the flashed carbon \(\lambda_{\text{max}} = 1.54\mu\) and \(a=7.1\) for tungsten. The change in \(a\) is 18 per cent, which for the same temperature would make \(\lambda_{\text{max}} = 1.25\mu\) for tungsten, when in reality the value is \(\lambda_{\text{max}} = 1.47\mu\). Evidently, it is impossible to say what the temperature is without measurements with a thermocouple, to determine the other constants which enter the energy equations.

V. RESULTS OF THE DETERMINATION OF THE "CONSTANT, \(a\)," FOR VARIOUS METALS.

In this investigation the filaments to be examined were in the form of commercial incandescent lamps with glass walls, and also in the form of especially made lamps with fluorite windows, secured with Khotinsky cement, as shown in Fig. 4. The latter lamps were about 15 cm long, 5 cm in diameter, and admitted a filament about 5 to 7 cm long. The filaments for the lamps with fluorite windows were taken from commercial lamps. All the filaments were heated to incandescence by means of direct current from storage batteries, hence there was no difficulty in keeping the current constant.

The results obtained with the lamps with fluorite windows are not very satisfactory for the metal filaments, owing to the fact that they could not be properly treated in exhausting them. The exhausting was done with a mercury pump, and was continued for several days, the pressure being reduced to less than 0.01 mm. The results are of interest in showing that the energy curves are

\(^{28}\text{This Bulletin, 5, p. 159.}\)
smooth and continuous throughout the infra-red examined; they also show the great influence of the methods of exhaustion upon the constant $a$ and upon the life of the filament.

In the commercial lamps care must be taken to operate them at a sufficiently high temperature so that the maximum emission is far removed from the increased absorption of the glass wall. In Fig. 4 is given the transmission curve of a fragment of the glass wall, 0.75 mm thick, of an incandescent lamp. The absorption increases very rapidly beyond $2.5\mu$, so that without a knowledge of the absorption of each lamp no comparisons beyond $2.5\mu$ can be made of the various energy curves.

In the following illustrations the values of the so-called radiation constant, $a$, are platted for a given energy consumption. They are characterized by various signs (circles, dots, triangles, etc.), to indicate at what wave length the $E_{\text{max}}$ was taken to compute $a$.

The wave lengths ($\lambda_{\text{max}}$) of $E_{\text{max}}$ are also shown as being of value in estimating the probable value of $a$ from a knowledge of the location of $E_{\text{max}}$ with respect to a possible small absorption band at $1.45\mu$. The various lamps were operated on a storage battery and no difficulty was experienced in maintaining a constant radiation.

1. **UNTREATED CARBON.**

The so-called radiation constant $a$ was found for a filament about 5 cm long and 0.1-mm diameter, mounted in an exhausted glass vessel, as shown in Fig. 4. At the highest energy consumption the filament appeared as bright as a normal burning incandescent carbon lamp. The apparent black-body temperature, corresponding to the different values of energy consumption, was measured by Doctors Waidner and Burgess with an optical pyrometer for red, green, and blue light. The values given in Table III were obtained from their watt-temperature curve extrapolated for high temperatures. The observed and the computed temperatures are at greater variance the greater the energy supplied. It is of interest to note that the selective emission as found by the optical pyrometer (which is in reality a photometer in which the temperature of the comparison lamp is varied) is highest in the red, which is just the opposite of the
metals and of the Nernst glower. On the other hand the acetylene flame emits selectively like an oxide.

From the values of $a$ shown in Fig. 5, it appears that there should be a better agreement in these temperatures at the higher temperatures. The various computations of $a$ for any given energy consumption are in close agreement, are uniformly high at low temperatures, and decrease with rise in temperature. At about $1200^\circ a=6.5$, at about $1500^\circ a=5.7$, and at about $1700^\circ a=5.2$.

![Graph](image)

**Fig. 5.**—Untreated Carbon.

The value of $a$ was also determined for a 110-volt incandescent lamp with glass walls when operated on 99.2 volts, 43.5 watts (see Fig. 5). The energy curve is shown in Fig. 3, curve $a$. The value of $a=5.49$, which is in agreement with the previous results when the energy curve has its maximum at $1.58\mu$, i. e., when the filament was at the same temperature.

In this series of measurements a commercial lamp with glass walls, and one with a fluorite window and short filament were used. Nevertheless, the value of $a$ for the same $\lambda_{\text{max}}$ are in excellent agreement.

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29 This Bulletin, 2, p. 319; 4, p. 548.
TABLE III.

<table>
<thead>
<tr>
<th>Energy Consumed</th>
<th>Temp. K. Red</th>
<th>Temp. K. Green</th>
<th>Temp. K. Blue</th>
<th>$\lambda_{\text{max}}$</th>
<th>$T_{\text{max}} = \frac{2930}{\lambda_{\text{max}}} - 273^\circ$</th>
<th>$T_{\text{min}} = \frac{2520}{\lambda_{\text{max}}} - 273^\circ$</th>
<th>Radiation Constant, $a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.47 Watts</td>
<td>1200°</td>
<td>1160°</td>
<td>1120°</td>
<td>1.986µm</td>
<td>1202°C</td>
<td>1044°C</td>
<td>6.5</td>
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<td>.085 Amp.</td>
<td>1390</td>
<td>1340</td>
<td>1284</td>
<td>1.911µm</td>
<td>1262</td>
<td>1097</td>
<td>6.0</td>
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<td>3.38 Watts</td>
<td>1675</td>
<td>1610</td>
<td>1557</td>
<td>1.692µm</td>
<td>1457</td>
<td>1275</td>
<td>5.7</td>
</tr>
<tr>
<td>4.94 Watts</td>
<td>2030</td>
<td>1950</td>
<td>1895</td>
<td>1.582µm</td>
<td>1572</td>
<td>1372</td>
<td>5.35</td>
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<tr>
<td>.125 Amp.</td>
<td>2135</td>
<td>2040</td>
<td>1985</td>
<td>1.507µm</td>
<td>1672</td>
<td>1462</td>
<td>5.2</td>
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<tr>
<td>7.63 Watts</td>
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<td>8.5 Watts</td>
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<td>.17 Amp.</td>
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<td>CARBON (Untreated)</td>
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<tr>
<td>.96 Watts</td>
<td>1314</td>
<td>1322</td>
<td>1327</td>
<td>1.556µm</td>
<td>1507</td>
<td>1407</td>
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<td>.8 Amp.</td>
<td>1422</td>
<td>1435</td>
<td>1440</td>
<td>1.521µm</td>
<td>1562</td>
<td>1447</td>
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<tr>
<td>1.53 Watts</td>
<td>1607</td>
<td>1632</td>
<td>1640</td>
<td>1.414µm</td>
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<tr>
<td>.9 Amp.</td>
<td>1692</td>
<td>1724</td>
<td>1733</td>
<td>1.371µm</td>
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<td>1637</td>
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<tr>
<td>2.44 Watts</td>
<td>1850</td>
<td>1895</td>
<td>1910</td>
<td>1.303µm</td>
<td>1977</td>
<td>1742</td>
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<tr>
<td>1.1 Amp.</td>
<td>2000</td>
<td>2060</td>
<td>2080</td>
<td>1.267µm</td>
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<tr>
<td>5.04 Watts</td>
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<td>1.2 Amp.</td>
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<td>1.4 Amp.</td>
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<td>7.28 Watts</td>
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<tr>
<td>1.6 Amp.</td>
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<tr>
<td>OSMIUM (Short filament, fluorite window)</td>
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<td></td>
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<td></td>
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<tr>
<td>.6 Watts</td>
<td>1357</td>
<td>1450</td>
<td>1475</td>
<td>1.457</td>
<td>1650</td>
<td>1507</td>
<td>1407</td>
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<tr>
<td>.8 Amp.</td>
<td>1522</td>
<td>1762</td>
<td>1593</td>
<td>1.825°</td>
<td>1695</td>
<td>1547</td>
<td>1447</td>
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<tr>
<td>METALLIZED AND FLASKED CARBON.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

The "metallized" carbon examined consisted of a 110-volt "Gem" incandescent lamp (glass walls) which at normal operation required 50 watts. The mean value of the "constant," $a = 5.85$. There seems to be a slight tendency for the value of $a$ to increase with energy consumption (see Fig. 6), but this may be due to the fact that on
36 watts the $E_{max}$ occurs at $1.47 \mu$, where there is a small absorption band which prevents the accurate measurement of the maximum deflection. The value may therefore be more nearly $a = 6$.

A 110-volt "flashed" carbon lamp with glass walls (on 84.75 volts—watts not determined; see curve b, Fig. 3) was also investigated. The $E_{max}$ occurs at $\lambda_{max} = 1.54 \mu$ as compared with $\lambda_{max} = 1.57 \mu$ for the untreated carbon filament (Figs. 3 and 5) having the same color. The mean value of $a = 5.88$ was found from three closely agreeing computations. (See Fig. 6.)

Paschen found that the value of this "constant" for carbon rods heated in the air was about $a = 5.6$, while for the same carbons heated in a vacuum $a$ varied from 5.0 to 5.3. Since we do not know the condition of the surfaces, the results obtained by various observers can not be compared.

3. THE HELION FILAMENT.

The helion filament consists of a carbon filament covered with a thin coating of silica. The samples examined were unmounted experimental ones (single loop 10 cm long), kindly presented by the inventor, Prof. H. C. Parker.

The filaments were mounted in bulbs with fluorite windows, and an examination was made without seasoning them. It was found
that the filaments became covered with black spots, so that an extensive examination could not be made. On first starting, the value of \(a = 8.2\), which is unusually high. On 17 watts (87 volts) the filament was as bright as an ordinary 110-volt 16-c p flashed carbon lamp, and \(a = 7\), Fig. 7. On 21 watts the value of \(a = 6.4\), and on examination it was found that the filament was covered with black spots where the silica had disappeared. But even in this condition the value of \(a\) is high and comparable with platinum. The results

![Diagram](image)

**Fig. 7.** "Helion" (Silica coated carbon).

show that if the covering of silica can be made stable the efficiency of such a filament will be unusually high, due to the high value of \(a\); but, unfortunately, on account of chemical decomposition of the silicon carbide surface it will probably not be possible to operate the filament at such high temperatures as is possible with tungsten. Hence, when perfected, the two may not be so very different in their efficiency as a light producer, which in the case of the helion filament is due to the fact that its operating temperature must be kept low, and in the case of the tungsten filament is due to smaller value of \(a\), which places it closer to a complete radiator, although its operating temperature may be higher than for helion.
In order to obtain an estimate of the probable value of $a$ of the various metal filaments, it is necessary to compare them with platinum, of which the "constant," $a$, was supposed to be fairly well established.

Paschen's values of $a$ seem to increase slightly with temperature, which may be due to an increase in smoothness of surface. Lummer and Pringsheim also record a change in the emissivity of platinum due to a change in the surface. The values of $a$ for platinum found by Paschen (in marked contrast with all the other substances examined by him) differ by 18 per cent, being $a = 5.536$ when he used equation (3) and $a = 6.423$ when computed from two equations requiring a knowledge of the temperature. For the oxides of iron and of copper the values, computed by these same three methods, are in agreement within 2 to 3 per cent. On the other hand, Lummer and Pringsheim did not make the tedious computations, but assumed a value of $a = 6$ and computed the temperatures corresponding with the observed temperatures, evidently assuming that the temperature scale is sufficiently reliable for that purpose. Although there is no systematic variation there is in some instances (especially at high temperatures), a considerable discrepancy between the computed and the observed temperatures. This method of procedure does not show how constant the value of $a$ is with rise in temperature, and it is unfortunate that the computations of $a$ were not made for each energy curve. They concluded that the observed temperatures are too low and that the more probable value is $a = 5.85$. The difference between their observed and their computed (using $a = 6$) energy curves differ more and more, at 2 to 5$\mu$, the higher the temperature. This would seem to indicate that in addition to the fact that equation (1) does not hold for long wave-lengths, unless the temperatures are seriously in error the value of $a$ decreased with rise in temperature, thus increasing the values of $E$ at 3 to 4$\mu$. In the total radiation measurements by Lummer and Kurlbaum the constant, $\sigma$, of the Stefan law was found to

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30 Paschen, Ann. der Phys., (3) 60, p. 662; 1897.

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increase from \( \sigma = 4.28 \) to \( \sigma = 19.64 \) (in arbitrary units), while for a
"black body" investigated at the same time the value of \( \sigma = 109 \)
(about) throughout the whole range of temperatures. (See Table IV.)

**TABLE IV.**

<table>
<thead>
<tr>
<th>Absolute Temperature</th>
<th>( \sigma = \left( \frac{E}{T_a - 1} \right) )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Black Body</td>
</tr>
<tr>
<td>( T )</td>
<td>( T_e )</td>
</tr>
<tr>
<td>372.8</td>
<td>290.5</td>
</tr>
<tr>
<td>492</td>
<td>290</td>
</tr>
<tr>
<td>654</td>
<td>290</td>
</tr>
<tr>
<td>795</td>
<td>290</td>
</tr>
<tr>
<td>1108</td>
<td>290</td>
</tr>
<tr>
<td>1481</td>
<td>290</td>
</tr>
<tr>
<td>1761</td>
<td>290</td>
</tr>
</tbody>
</table>

In Table IV the value of \( \sigma \) is obtained by dividing the observed
total radiation by the difference between the observed temperatures
of the radiating substance and the shutter raised to the fourth power
\( (a-1 = 4 \) for a black body). This test of the constancy of the value
of \( \sigma \) for platinum is not a fair one, since it is known that its emis-
sivity is of the order of the fifth power of the temperature. In the
fifth column of Table IV, under platinum, the writer has com-
puted (from the values of \( \sigma \) and the corresponding temperatures
which gave the value of \( E \)) the value of \( \sigma \) on the assumption that
the total radiation of platinum is as the fifth power of the absolute
temperature, i. e., for \( a = 6 \). The variation in \( \sigma \) is much less than
for \( a = 5 \), and it appears that for a value of \( a = 6.5 \) (about) the value
of \( \sigma \) would remain constant throughout this range of temperature.
But a value of \( a = 6 \) seems to be the upper limit and for this value
the coefficient, \( \sigma \), increases 40 per cent, which seems to indicate
quite conclusively that part of this variation in \( \sigma \) is due to an
actual variation (decrease) in the "constant" \( a \).
From this it is evident that the value of $\sigma$ is decreasing with rise in temperature. It would therefore appear that the change in $a$ ought to be detected in the spectral energy curve, for it is inconceivable that, assuming a selective emission in the extreme infrared, the energy can increase sufficiently to affect the total radiation and not be observable in the spectral radiation curve at 1 to 3$\mu$. This inconsistency, of a variation of $a$ in their observations on total radiation and of its assumed constancy in the spectral radiation curves, seems to have been overlooked by Lummer and his collaborators.

The variation in $a$ with change in temperature was entirely unexpected, and was not found until most of the observations had been made and the computations plotted, as shown in the accompanying illustrations.

At first it was suspected that the variation is due to an increase in stray light, but the observations of $E_{max}$ for platinum lie at such long wave lengths (as compared with those of the other metals) that the change in $a$ appears to be real. The platinum examined was the purest made by Heraeus. The strip was 50 by 1.5 by 0.02 mm in a glass bulb with fluorite window, as shown in Fig. 4. The strip was welded to thick platinum wires, which were in turn welded to the copper supports. This procedure was found necessary to prevent the hot platinum strip from fluxing with the copper leads. In order to work under constant conditions the platinum was aged by heating it for a short time to a higher temperature than it was used in the experiments. The small deflections at the low temperatures introduces great variations in the value of $a$, but the important point brought out is that the values of $a$ are uniformly high or uniformly low, depending upon the temperature. This is illustrated in Fig. 8. A slight variation in taking the $E_{max}$ and the $E$ from the energy curve causes a variation of 2 to 5 per cent in $a$, as shown at different parts of the curve where more than one value of $a$ for any given wave length (for example at 0.9 and 1.6$\mu$) is plotted. The abscissa is represented by the observed current in amperes (squared) instead of the usual "watts." Estimating temperatures from the equation $\lambda_{max}T=2620$, it may be said that the constant decreases from $a=8.5$ at 900° C to $a=6.3$ at 1100° C. For some unexplained reason all the values are higher than than those found by Paschen
using the same method. This, however, is of minor importance, for we are concerned with this value relative to that of the other metals.

In Fig. 1 is shown the reflecting power of platinum, which increases rapidly from a low value of 65 per cent at 0.5μ to 94 per cent at 5μ, beyond which the reflecting power is uniform and equal to 96.4 per cent at 14μ.

The absorption of a thin film of platinum decreases rapidly with wave length, being much less than that of gold and silver in the infra-red. From the rapid change in the absorption (and reflection) curves it seems evident that platinum must show selective emission (being uniformly high but not necessarily broken into bands) in the visible spectrum, as compared with the infra-red.

5. OSMIUM.

One series of measurements of a was made on a short (3-cm) piece of osmium, which was taken from an osmium lamp. A series of five energy curves, the λmax varying from 1.26μ to 1.52μ, gave concordant values of a = 6.3 (mean of 14 computations), with no definite decrease with rise in temperature. In Table III are given

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33 Hagen and Rubens, Ann. der Phys., (4) 11, p. 873; 1903.
34 Hagen and Rubens, Ann. der Phys., (4) 8, p. 432; 1902.
the apparent temperatures of this filament as found with an optical pyrometer and the corresponding $\lambda_{\text{max}}$. In fact, the value of $a$ seemed to increase on first operation, which is in accord with general experience in the manufacture of new filaments.

The color of the filament remained a silver-gray in appearance, but the surface was pitted and rough, showing bright patches. These defects were of sufficient magnitude to affect the emissive power, making it lower than one would expect from a highly polished surface of the same material. In addition to this, the filament was short and affected by heat conductivity from the ends. The results can not be given great weight in considering the value of $a$.

The work was repeated, using a Siemens & Halske's commercial 55-volt, 32-cp lamp ("Auer Oslampe"). The energy curve when operated on 38.6 volts (28 watts) is given in Fig. 3. Here the $E_{\text{max}}$ falls within the region of a possible absorption band, and $a = 6.77$ (mean of six computations; see Fig. 9 for the variation in $a$)

![Fig. 9.—Osmium.](image)

which is greater than usual for any given wave length, e.g., at $1\mu$. This same lamp, when operated on 50 volts (10 per cent below normal) 34 watts, gave a very concordant value of $a = 6.96$ as the mean of four computations. Here the $E_{\text{max}}$ falls outside of the questioned region of absorption. Two computations (equation 5) gave $\lambda_{\text{max}} = 1.4002\mu$ and $\lambda_{\text{max}} = 1.4015\mu$, and on the whole it is believed that the latter value is the more nearly correct. These two series
of measurements give a mean value of \(a = 6.86\). This lamp was calibrated for photometric work, and hence was not operated at higher temperatures.

The value of \(a\) of osmium appears to be somewhat larger than that of tungsten (thick filament) for the same \(\lambda_{\text{max}}\), and is of the same magnitude as that of tungsten when the filaments are thin, hence probably more homogeneous. The emissivity of osmium should therefore be equal or slightly less than that of tungsten throughout the infra-red, as indicated in Fig. 3.

According to Lummer and Pringsheim,\(^{35}\) the high efficiency of the osmium lamp is due to its selective emission in the visible spectrum. It is a "whiter" metal than tungsten, but whether or not this has a marked effect the emission remains undetermined.

The measurements with the spectrophotometer do not show a selective emission in the visible spectrum. The present measurements indicate (for a color match in the visible spectrum, Fig. 3), that osmium has its \(\lambda_{\text{max}} = 1.425\mu\) and tantalum has its \(\lambda_{\text{max}} = 1.472\mu\).

From this it appears that the so-called "radiation constant, \(a\)," of osmium must be higher than that of tungsten; and hence the working temperature of osmium must be higher than that of tungsten (unless the constant \(e_1\) is greater in the former, which can hardly be possible). This alone would account for the much-discussed cause of the high light-efficiency of osmium filament lamps.

6. TUNGSTEN.

The first measurements were made upon a thin filament of tungsten, 3 cm long, placed in a lamp with a fluorite window, as shown in Fig. 4. The conduction from the ends caused it to be spindle-shaped when heated. The examination was made to show that the spectrum is not discontinuous, as mentioned on a previous page. The mean value of \(a = 7.28\) was found from four computations, which is unusually high considering the fact that the \(\lambda_{\text{max}} = 1.301\mu\), while in all subsequent observations the value of \(a\) is much less for the \(\lambda_{\text{max}}\) at 1.2 to 1.3\(\mu\). (See Fig. 10.)

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\(^{35}\)Quoted in Liebenthal's Praktische Photometrie, pp. 54 and 340. The original paper by Lummer (Ziel der Leuchttechnik) does not mention the experimental work upon which the evidence of selectivity is based.
A series of measurements was then made on a 110-volt, 32-cp, 60-watt (General Electric) lamp having a fine filament. The values of $a$ vary considerably at the lowest energy consumption, but they are all high—about $a = 7.8$. At about normal operation the value dropped to $a = 6.5$. Another 110-volt lamp of the same make was examined on 60 volts (see Fig. 3 for its energy curve). Two computations gave concordant values of $a = 7.14$ and $a = 7.18$, respectively, as shown at $a$ in Fig. 10, the $E_{max}$ being at $1.472\mu$.

A further study of $a$ was then made, using for the purpose a General Electric Company 10-volt single-loop tungsten lamp, the filament being at least 0.2 mm in diameter. The thick filament gave much larger galvanometer deflections. For the highest energy consumption (given in amperes, "squared," Fig. 10) the brightness was somewhat below normal. The values of $a$ are somewhat lower for the same $\lambda_{max}$ as compared with the thin filaments, decreasing
from $a = 7.1$ to 6.2. The values of $a$ found from these four filaments differ considerably from each other, especially for the thick filament, but the important fact remains that all the values are much higher than those of platinum, when the energy curves have the $E_{\text{max}}$ at the same wave length. From this it would appear that the high efficiency of tungsten is due not only to the high operating temperature, as concluded by Grau, but also to the high value of $a$.

7. TANTALUM.

The measurements were made on a 110-volt, 16-cp, lamp. In the first series, the radiation entering the spectrometer slit formed an image which was about 4 mm wide, and evidently came from two filaments. The values of $a$ are plotted (I) in Fig. 11. The lamp was then readjusted, giving a sharper, narrower image upon the prism face. The values of $a$ thus obtained are somewhat higher (II) in Fig. 11, but in both cases there is a tendency for $a$ to decrease with rise in temperature.

![Graph of Tantalum](image)

A series of observations was made on a filament about 6 cm long placed in a lamp, as shown in Fig. 4. The filament seemed to be affected by the residual gas in the bulb, and its behavior was so unsatisfactory that the results were discarded entirely. The results,

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36 Grau, Illuminating Eng., 1, p. 186; 1908.
on the whole, seem to indicate that the "constant" \(a\) of tantalum is somewhat higher than for platinum.

On "normal operation" the \(a\) of tungsten and of tantalum are about the same value, but for tungsten the \(\lambda_{\text{max}} = 1.23 \mu\) while for tantalum the \(\lambda_{\text{max}} = 1.34 \mu\), from which it would appear that the tungsten filament is at a higher temperature.

In Table V are given approximate values of the "constant" \(a\) of the aforesaid metals, as used in the 110-volt lamps investigated, when under "normal operation," which seems to admit of rather wide variations. For example, the 55-volt osmium lamp has a \(\lambda_{\text{max}}\) which is at variance with the preceding lamps in which the \(a\) is smaller. Although the osmium lamp was operated on 50-volts (only 10 per cent below normal) the \(\lambda_{\text{max}}\) is larger than for tungsten. In Fig. 3 the comparison is a fairer one and the position of the \(\lambda_{\text{max}}\) is consistent with the value of \(a\). The "normal" operating temperatures, computed on the assumption that the constants are the same as for platinum, are given in the third column of this table. The values, of course, are only approximations, and are all much lower (300 to 500° less) than found by Waidner and Burgess,\(^37\) using an optical pyrometer. This is of course due in part to the assumption made that these metals have the same constants as platinum, which is contrary to observation.

**TABLE V.**

<table>
<thead>
<tr>
<th>Constants of 110-Volt Lamps Burning Normally.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\lambda_{\text{max}})</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>Metallized Carbon</td>
</tr>
<tr>
<td>Tantalum</td>
</tr>
<tr>
<td>Tungsten</td>
</tr>
<tr>
<td>Osmium (55-volt lamp on 50 volts)</td>
</tr>
</tbody>
</table>

\(^37\) Waidner and Burgess, this Bulletin, 2, p. 327; 1907.
8. THE ACETYLENE FLAME.

It is hardly legitimate to apply the foregoing method of computation of \( a \) for the acetylene flame, and much less for the sun, but it seemed of interest to make computations.

That the emissivity of the acetylene flame must depart far from a complete radiator is evident from the very intense emission band of \( \text{CO}_2 \) at 4.4\( \mu \) superposed upon that of the incandescent carbon particles which have their maximum at 1.05\( \mu \). For computing \( a \) the energy curve of the acetylene flame found by Stewart\(^{38} \) was used. For the wave lengths, \( \lambda = 0.75, 0.9, 0.95, 1.2, \) and 1.3\( \mu \) the values of \( a = \{0.3, 1.1, 1.4, 1.7, \) and 9.5, respectively. This gives a mean value of \( a = 11 \), and is an extreme example, showing that \( a \) and not temperature may cause a high luminous efficiency; for the mean temperature of the acetylene flame is about 1900° C, while the \( \lambda_{\text{max}} = 1.05\mu \). The temperature of a complete radiator would have to be 2500° C in order to have its maximum emission at \( \lambda_{\text{max}} = 1.05\mu \).

Spectrophotometric comparisons by Nichols\(^{39} \) and by Blaker\(^{40} \) of the spectra of carbon filaments with acetylene shows a marked selective emission at 0.6 to 0.7\( \mu \) in the carbon filament. It is difficult to conceive how a radiator like carbon (of the type lying between insulators and electrical metallic conductors) of the thickness of the filament used, can emit such an unsaturated radiation. As mentioned on a previous page, the selective emission is due to the unsaturated radiation from the acetylene flame. The maximum of the selective emission of acetylene lies in the region of the apparent minimum found by Nichols and by Blaker at 0.7 to 0.72\( \mu \) in the solid carbon.

It will be interesting to investigate the change in selectivity with increase in thickness of the flame. Whether the selective emission at 0.72\( \mu \) is due to a true emission band at this point, or due to a more transparent region in the infra-red, 0.76 to 0.8\( \mu \), remains to be determined. The latter seems more probable. Stewart's energy curves of the visible spectrum do not rise as rapidly as one would expect, in order to become a maximum at 1.05\( \mu \), which would indicate a discontinuity at 0.7 to 0.8\( \mu \). That the transparency of the

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\(^{40}\) Blaker, Phys. Rev., 13, p. 345; 1901.
acetylene flame must increase rapidly in passing from the visible into the infra-red is evident from the smallness of the radiometer deflections at the maximum of the energy curve, at 1.05\(\mu\), as compared with the large deflections in the visible spectrum. For a Nernst glower, which on normal operation emits somewhat like a complete radiator (due to its low reflecting power and its great thickness), the deflections at 1.05\(\mu\) would have been 40 to 50 times as great as those observed by Stewart. Further evidence of the very rapid increase in transparency of extremely thin films of carbon (lampblack) is to be found in a paper by Ångström,\(^{41}\) and also in an investigation by Ladenburg\(^{42}\) of the transmission of a flat acetylene flame and of a Hefner flame. The latter was much more opaque than acetylene, at 0.7\(\mu\), while beyond 2.5\(\mu\) they were of about the same opacity.

9. THE SUN.

For computing the value of \(a\) for the sun, Abbot's\(^{43}\) data was employed. First of all, it was found that no consistent value of \(\lambda_{\text{max}}\) could be found (eq. 5), the values varying from \(\lambda_{\text{max}} = 0.49\mu\) to \(\lambda_{\text{max}} = 0.52\mu\), due, no doubt, to the lack of data in the ultraviolet, assuming that the composite radiation is similar to the Nernst glower. The difficulty in computing the value of \(a\) lies in the lack of knowledge of the value of \(E_{\text{max}}\), of which different values were used. Taking \(\lambda_{\text{max}} = 0.46\mu\), and \(\lambda_1 = 0.4, 0.5, 0.6, 0.7, \) and 1.2\(\mu\), respectively, the values of \(a = 21.9, 15.6, 11.0, 7.8, \) and 5.4, respectively. The values of \(a\) vary uniformly over so great a range that it seems evident that we can not apply the radiation laws of a complete radiator, as has been done heretofore, in discussing the emissivity of the sun.

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\(^{41}\)Ångström, Ann. der Phys., (3) 36, p. 717; 1889.

\(^{42}\)Ladenburg, Phys. Zs., 7, p. 697; 1906.

\(^{43}\)Abbot, Smithsonian Miscell. Coll., 45, p. 74; 1903.

Also: Annals Astrophys. Obs., 2; 1908.
VI. SUMMARY.

The object of this investigation was to obtain some estimate of the emissivity of incandescent metal filaments, e.g., tantalum, tungsten, and osmium, the assumption being made that their spectral energy distribution follows the same general law as that of platinum and of a complete radiator. With substances whose energy spectra undergo no change in contour with change in temperature it does not seem unreasonable to apply our knowledge gained from the behavior of platinum under similar conditions, especially since the filaments are metals—electrical conductors—which, theoretically, should have similar emissive properties. That the method is open to criticism is admitted, but there is nothing novel about it, and until a better one is suggested the present method is the only one available without a knowledge of the temperature of the radiator. The results obtained, considered quantitatively, are not very satisfactory, and perhaps this should hardly be expected. The filaments are generally made from discrete particles of metal, mixed with a "binder," and squirted into a thin thread, after which the binder is removed, leaving the metallic particles welded together in various degrees of homogeneity and purity. The results, therefore, can not be as conclusive, neither can the accuracy be as great as will be possible when wide strips are obtainable, made from these metals, melted into a homogeneous mass, and rolled and hammered into shape, such as obtains for platinum. The nature of the material now obtainable did not appear to warrant a further continuance of the present investigation.

The results obtained show that the so-called radiation constant, \(a\), of all the metals examined is higher than that of platinum at the same temperature. Osmium seems to have the highest value, \(a = 7\).

Although the individual computations of the "constant, \(a\)," vary from 3 to 5 per cent, the results thus far obtained are concordant in being uniformly high or uniformly low for a given energy consumption and as compared with platinum.

Contrary to the results of the previous investigations, the present work shows that the so-called "radiation constant, \(a\)," decreases uniformly with rise in temperature, i.e., the \(a\) has a temperature
coefficient probably similar to that of electrical resistance. Theoretically, this decrease must occur, but whether the change takes place abruptly or whether it is a gradual change, as indicated in the present results, remains undetermined.

It is, therefore, an open question whether or not there is a "radiation constant, $a$," for metals (total radiation, $S=\sigma T^{a-1}$). This is of vital importance in the application of optical pyrometers, although the "optical constants" of the metals show no appreciable temperature coefficient in the visible spectrum. The present observations, and some of those of previous experimenters, indicate a variation in this so-called constant with temperature.

The investigation will, therefore, have to be undertaken anew, and it is proposed to examine the total radiation of platinum (and other metal strips, if obtainable), using the temperature scale to as high a point as its accuracy will admit. Further spectro-bolometric work will also be necessary, although the latter is subject to greater instrumental errors. An investigation of the infra-red reflecting power of platinum, with change in temperature, will also aid in proving or disproving this variation in emissivity constants of metals.

WASHINGTON, August 22, 1908.