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LUMINOUS EFFICIENCY.

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The problem of determining the efficiency of the artificial processes of light production has engaged the attention of investigators ever since the definite beginnings of the science of illumination, early in the last century. The problem is a complicated one, almost solely because one of its chief factors is not physical, but physiological. The product of the process of conversion of energy,—light,—is something the quantitative measurement of which, in the case of illuminants, depends upon subjective sensation. The difficulties imposed by the nature of light, considered as a subjective sensation, have been such that the quantities most generally used in attempting to make scientific comparisons of illuminants have been at best approximations. These quantities have in fact been arrived at by largely disregarding the physiological side, and, just in proportion to the amount of this disregard, are they unsatisfactory.

Within the last few years considerable work has been done on the relation between radiation and light. Following the pioneer work of Langley and Koenig, such men as Fery, Guillaume, Eisler, Drysdale, Nutting, and others have made contributions to the general problem. As a consequence, it is now possible to make definite and satisfactory comparisons of the efficiencies of artificial light sources, where by "efficiency" is understood the ratio employed in the measurement of any transformation of energy, namely, the ratio of the useful work rendered by the process to the energy put in, each being measured in appropriate units. Curious as it may seem, in the estimation of efficiencies the method of electrical engineering has been more scientific than the methods generally used by scientific writers. "Lumens per watt" is an exact measure of efficiency, while "Luminous efficiency" is not. It has only been by coordinating the conception of luminous efficiency with lumens per watt measurements, by including the physiological factors, that progress has been made possible in the scientific study of efficiencies. As an illustration, it is now possible to express the common candles per watt of the commercial incandescent lamp in terms of an absolute efficiency. The "4-watt" carbon lamp, for instance, has an efficiency of 0.4 per cent. The standard of comparison is the most efficient possible light source; and the ratio of the lumens (or candles) per watt of two illuminants is the ratio of their absolute efficiencies. This is obviously as it should be, but in the "luminous efficiencies" which have figured in scientific investigation, such has not been the case.

In the present paper are outlined the scientific methods which have been employed at one time and another in comparing the efficiencies of light sources. The methods of estimating and the values obtained for "luminous efficiency" and for the "mechanical equivalent of light" are noted as briefly as possible, chiefly for the purpose of showing in what way they are inadequate for our present more exact needs, and in how far they have assisted toward the more satisfactory idea of efficiency now possible. The writings and experimental work of several men are drawn upon freely, in particular the excellent discussion of Drysdale.[1] The object here is not so much to present original work, of which there is very little, as to aid in clearing up the confusion which exists at present, and to bring to the solution of the scientific side of the problem some pieces of work which have only recently become available, or whose availability has not heretofore been realized.

The discussion centers about four topics. 1st, "Radiant Luminous Efficiency," the most frequently used basis of comparison of light sources. 2nd, "Total Luminous Efficiency." 3rd, "The Mechanical Equivalent of Light." 4th, "Reduced Luminous Efficiency," the term applied by Drysdale to the more rational and exact basis of comparison which it is the object of this paper to present and emphasize.

Before considering the subject in detail, warning should here be given that a multiplicity of similar sounding terms will be met with. The resulting confusion is painful. Only after making a special study of the subject can these terms be clearly

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[1] Illuminating Engineer, London, Vol. 1, 1908.

differentiated by the mind, and used correctly. At the conclusion, the suggestion will be made that the majority of these confusing terms be altogether discarded.

RADIANT LUMINOUS EFFICIENCY

The term "luminous efficiency" is usually applied to the ratio of a certain fraction of the radiated energy to the total radiated energy. It is also sometimes applied to the ratio between this fraction of the radiated energy and the total applied energy,—a more or less different quantity. In order to make clear the relationship of the various quantities involved in either use of the term "luminous efficiency," let us consider the transformations undergone by the energy supplied to a light source.

The total applied energy is given out in three forms, represented below:

Total applied energy	*Conduction*, as through supports, piping or wiring. *Convection*, heat carried off by currents in the surrounding medium. *Radiation*, electro-magnetic waves in the ether.

Of these, conduction and convection contribute nothing to the production of light. Radiation has been commonly divided into three parts:

1. The long, infra-red, or heat waves, to which the eye is not sensitive.
2. The intermediate waves, constituting visible radiation.
3. The short waves, called actinic, or ultra-violet, which do not cause the sensation of light in the eye.

These are shown diagrammatically in Fig. 1. If we designate the total applied energy by Q, the total radiated energy by R, and by L that portion of the radiated energy appreciated by

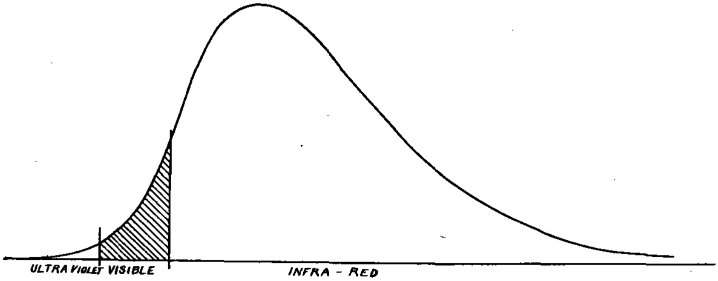

Fig. 1—Energy distribution of black body radiation.

the eye as light, we can express the three efficiencies which have usually been employed, as follows:—

Efficiency of transformation of applied energy into radiation	R/Q
Ratio of visible to total radiation This has been called "radiant efficiency" by Nichols to distinguish it from	L/R
Ratio of visible radiation to energy input, or "total efficiency"	L/Q

Inspection of these ratios shows that in order to express them as percentages L, R and Q should be in the same units. Two consequences of this are to be noted. First, since the property of light with which we are most concerned, namely its visual intensity, is not directly proportional to quantity of radiation, but varies with wave-length, therefore light, considered photometrically, cannot be expressed as a simple energy quantity, as can R and Q. This difficulty has long been realized, but has apparently been regarded either as of no consequence, or as impossible to meet. Consequently the physiological factor entering (visual sensibility) has been considered only to the extent of recognizing certain largely arbitrary boundaries to the radiation which is appreciable by the eye. For L is taken the quantity of radiated energy lying between certain wave-lengths, usually chosen as $.76\mu$ and $.38\mu$, although we find wave-length limits of $.80\mu$, $.70\mu$ and $.40\mu$ sometimes taken. Radiant efficiency then becomes the ratio of that radiated energy between the chosen spectral limits, to the total radiated energy. It is obvious that the values will depend upon what wave-length limits are taken, a serious objection to the method. This visible portion of the radiated energy should be called "light" only in the sense that it is appreciable by the eye; great care should be taken not to think of it as light quantity as derived by photometry. The importance of this caution will become evident as we proceed. It is sufficient to state here that by this criterion two illuminants could each have 100 per cent. efficiency but differ, due to difference in color, in their candle-power per applied watt by several times.

The second consequence of the limitation imposed by the units is that the radiant efficiency L/R is more often determined than the total efficiency L/Q. The two quantities L and R, as we shall see, are measured in the same way, by radiation meters, so that determination of their absolute values is not necessary to obtain their ratio. On the other hand, L and Q are usually measured by different means, L by radiation meters which do not immediately give absolute energy values, Q by watt-meters, in the case of electric lamps, or equivalent methods with other illuminants. To obtain the total efficiency, L therefore, as well as Q, must be obtained in energy units.

Two general methods have been used to determine radiant luminous efficiency.

First,—by exposing a radiation meter (thermopile, bolometer, pyroheliometer, etc.) first to the total radiation R and then to the visible radiation L.

Second,—by measurement of the distribution of energy along the spectrum, and subsequent integration of the whole area as plotted from the observations, and of the visible portion.

In using the first method it is necessary to decide on some means of separating the visible from the total radiation. One of the earliest means was the use of absorbing screens, opaque to the infra-red rays. In this way alum and water, and later ferro-ammonium sulphate have been employed, and numerous values of L/R obtained. At best absorbing screens are unsatisfactory, for their limits of transmission are not well defined, and as is evident from Fig. 1, a slight shift of the line of separation of "visible" and "dark" radiation can make a large change in the value of L. Furthermore it has been found by Nichols and Coblentz that the results obtained by water, alum, and iodine absorption cells are not trustworthy because the transmission coefficients are not as usually assumed. Drysdale finds the ferro-ammonium sulphate solution chemically affected by radiation and hence also unreliable. For these reasons values obtained by the use of absorbing solutions are only of interest historically.

A better method for performing this separation is that of Angstrom. A spectrum is formed, an opaque screen placed over the portion not desired, and the energy re-condensed upon the energy measuring instrument. This has been used by Angstrom and by Ingersoll, and their figures are probably the only ones of value obtained from direct measurement of L and R.

Radiant efficiency by the second or spectrum integration method has been determined by Tyndall, Langley, Nichols and others. The method demands sensitive instruments, as well as considerable time and labor, but it is probably as satisfactory a one as any.

In the table below are a few values of radiant luminous efficiencies, as determined by the means which are apparently exact and reliable.

TABLE I.

"Radiant Efficiencies." Ratio of radiant energy between wave lengths .38μ and .76μ to total radiant energy.

Source.	Observer.	Date.	Method	L/R
Hefner	Angstrom	1903	Opaque Screen..........	.0096
Nernst	Ingersoll	1903	" "	.0417
Acetylene	Angstrom	1903	" "	.055
"	Nichols	1903	Spectrum Integration....	.03 to .04
"4-watt" Carbon lamp	Ives and Coblentz	1909	" "	.018

Before passing on to the discussion of "total efficiency," the exact meaning and limitations of the radiant efficiencies tabulated above must be emphasized.

The value of L/R gives us this information:— The same light, both as to quantity and distribution in the visible spectrum, could be obtained from the fraction L/R of the radiated energy. This information, although of considerable value as giving us an approximate idea of the wastefulness of artificial light production, is incomplete, for it recognizes no difference in the illuminating value of the visible radiation depending on its color or quality. Illuminants in which all the radiated energy lies in the visible spectrum would be rated alike as 100 per cent. efficient. A red light and a yellow light of equal energy output would be rated the same, although the latter could be a hundred times as bright as the former, because of the distribution of sensibility in the eye. Efficiency in an illuminant does not follow simply from its radiation being concentrated in the visible region, but also to a very large degree from that radiation being advantageously placed in the visible region. A practical result of this is that the ratio of the candles per watt of two illuminants is not that of their luminous efficiencies, for the two candlepowers are determined in part by the different distribution in the visible region of the radiation, as well as by the amount of visible radiation.

The 100 per cent. efficiency of this method, to which other efficiencies are compared, therefore, merely expresses the condition that all the radiant energy lies within certain limits. It gives no information as to how advantageously the radiation might be placed in that region. It gives in fact only a rough measure of real efficiency.

TOTAL LUMINOUS EFFICIENCY.

To obtain the radiant efficiency it has only been necessary to know the ratio of luminous to total radiation. If, however, we know L, the luminous energy, in energy units (assuming the energy input similarly measured, as is usual) we are in a position to find the total efficiency L/Q, or the proportion of the total applied energy (as distinguished from the radiant energy) which would be sufficient to give the same light, in quantity and spectral distribution, as the measured illuminant. The total efficiency is, like radiant efficiency, a pure number; the difference being that by making the comparison between L and Q, instead of L and R, we obtain a value in which the losses by conduction and convection are taken account of.

Measurement of the radiated energy in absolute units has usually been done in connection with determination of the mechanical equivalent of light, which is treated in the next section. From values for the mechanical equivalent we obtain the energy in visible radiation corresponding to a unit of light flux. Knowing the energy input necessary to give the unit of light flux we are in a position to determine the total efficiency. We will anticipate the results given in the next section to the extent of showing by one illustration, the derivation of "total luminous efficiency." Thus, taking a value given by H. Lux for the consumption of energy by the Hefner, as 115 watts per mean spherical candle, we obtain for its total efficiency .121/115 or .001, as against .009 for the radiant efficiency, indicating large losses by conduction and convection. With an incandescent lamp these losses are quite small, so that total and radiant efficiencies are nearly the same.

Values of total efficiency have much the same limitations as values of radiant efficiency. The standard of comparison, viz., the source of 100% efficiency, is the same quantity and quality of light as the source gives; that is, a part of the source itself. It is not compared with an outside, absolute standard of efficiency. There is too, no direct connection between total efficiency and lumens per watt.

THE MECHANICAL EQUIVALENT OF LIGHT.

Another means of obtaining a measure of the efficiency of light production is by determination of the "mechanical equivalent of light." By the "mechanical equivalent of light" is meant the energy value of the visible portion of the radiation from a source giving a unit of light flux. An equivalent definition is: The energy value of the radiation of a source of 100 per cent. luminous efficiency, giving unit light flux. As the unit of flux the lumen has sometimes been used, more frequently the spherical candle. We shall in this paper as a rule use the spherical candle or 4π lumens, although the final values will be given in both units. The object of so doing is to make a little clearer the connection between current practical measures and the rational basis of comparison we shall derive. The lumen is of course preferable.

The mechanical equivalent of a given light (the necessity for this limitation will appear shortly) is expressed in watts per mean spherical candle. It must not, however, be confused with the total watts per candle, which is also a mechanical equivalent but in a more comprehensive sense.

The mechanical equivalent of a light is obtained in much the same way as radiant efficiency. The visible portion of the radiated energy (as before, an arbitrary line of demarcation must be made) is separated from the invisible and allowed to fall on a measuring instrument. Instead, however, of making a mere comparison of this energy with the total, its actual amount is measured. The same energy is then measured as light quantity with a photometer, and thus the radiant energy corresponding to one spherical candle for the light source in question is determined.

Values for the mechanical equivalent of several lights have been determined by Tumlirz, Angstrom, Drysdale and others. The majority of these were determined by absorbing screen methods; if we discard these, for the reasons given above, there remain the following:

TABLE II.

Mechanical Equivalents of Light as Given by Several Illuminants.

Energy value of radiation from .76μ to .38μ corresponding to one spherical candle.

Source.	Observer.	Watts per Spherical Candle.
Hefner	Angstrom	.121
Arc	Drysdale	.0805
Nernst	"	.119

From this table we learn that the same quantity and quality of light as that given by these several sources could be obtained by the expenditure of the energy quantities given by the figures of the last column. Those quantities are of course much less than those necessary in practice because we cannot restrict the energy transformation to radiant energy in the visible region.

As to the characteristics and limitations of the "mechanical equivalent of light" one of the most important points to note is that the mechanical equivalent, as defined, is different for each light source. This has not been as well understood as it should have been. It has erroneously been assumed that the mechanical equivalent is a constant, and so some experimentors have thought to obtain total and radiant efficiencies simply by dividing the total energy input or total radiation, per mean spherical candle, by the value obtained by Angstrom. Eisler,[1] in an article which seems not to have been so widely noticed as it deserves, considered the distribution of sensibility in the eye, using Langley's values, and showed that the visible portion of the radiation from a black body increases several times in luminosity for the same quantity of radiated energy, as the temperature rises from 1000° to 5000°, due to the more advantageous distribution of the visible energy at higher temperatures. It should, indeed, have been obvious that the energy necessary to give a certain intensity in

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[1] *Electrotechnische Zeitschrift*, 1904, p. 188.

a Hefner, with its very large amount of deep red, nearly useless as luminosity, would be greater than if the energy were concentrated toward the more luminous part of the spectrum. As an illustration of this error, Tumlirz concluded from the mechanical equivalent of the Hefner that the highest possible efficiency of light production must be about six candles per watt, while as we shall see fifty candles per watt is more probable.

It is therefore impressed upon us that the quality or color of the luminous radiation is a matter of the first importance. In consequence of disregarding it there exists no direct connection between radiant or total luminous efficiency, and the practical and satisfactory candles per watt. Nor do we arrive at any universal standard to which to refer efficiencies. The comparisons made possible by the determination of luminous efficiency are only rough. It is true in general that a source having a large value of luminous efficiency will be more efficient than one with a small; that the source having a small mechanical equivalent will be more efficient than one with a large; although in neither case is this necessarily so, and our knowledge is but qualitative. Exact quantitative comparisons of the efficiency of light sources is impossible from mere knowledge of luminous efficiency or the mechanical equivalent, so-called.

It is evident then that we have thus far arrived at no satisfactory basis for the scientific comparison of efficiencies. It is necessary in order to have this to so change our definition of luminous efficiency that it takes into account quality. We must carry the investigation of mechanical equivalents to the point of finding the minimum possible mechanical equivalent. We shall then find a direct relation between the new "luminous efficiency" or a light source, and its candles per watt, and our standard of comparison will be the light having that minimum mechanical equivalent. The manner of doing this is given in the next section.

REDUCED LUMINOUS EFFICIENCY.

Reduced luminous efficiency (so-called by Drysdale) substitutes for the pure energy quantity which represents "light" in radiant luminous efficiency, an energy quantity weighted according to the capacity of the energy to produce the sensation of brightness. This makes the standard to which all efficiencies are referred, the light having the most advantageous possible distribution of energy, from the standpoint of the production of useful light. In place of considering the mechanical equivalents of light we are to be interested only in the mechanical equivalent of that most efficient possible source. With this we then compare, not the mechanical equivalents (in which we are not interested) but the watts per candle of our light sources. We obtain a ratio identical with "reduced luminous efficiency." Also, and as a consequence, the ratios of the candles per watt of two sources, is the ratio of their reduced luminous efficiencies.

The idea of reduced luminous efficiencies is arrived at by considering the relative luminosities of different portions of the visible radiation. The yellow-green or middle of the spectrum is the brightest, the red and blue ends, the least bright. Therefore, if we had a light source which not only radiated all its energy in the visible region (100% "radiant efficiency") but radiated it all at the brightest wave-lengths, we would have a source of 100 per cent. "reduced luminous efficiency."

Drysdale, following suggestions of Fery and Guillaume, attacked experimentally the problem of obtaining the mechanical equivalent of yellow-green light. Previously, however, Eisler without specifically mentioning luminous efficiency, had derived a value for this quantity indirectly from Tumlirz's values for the mechanical equivalent of the Hefner, using Langley's data on visual sensibility. The present writer, in calculating the luminous efficiency of the fire-fly, at the time ignorant of Eisler's work, arrived at a value of the mechanical equivalent of yellow-green light by using Koenig's values for visual sensibility, and radiation measurements of a glow lamp. The derivation of this quantity through our knowledge of visual sensibility will be given here, for the two reasons, that it makes possible the derivation of the mechanical equivalent in question from other known mechanical equivalents, and that it gives a method of ascribing values of reduced radiant luminous efficiency to all sources for which the distribution of radiation is known.

The sensibility of the eye to different spectral colors at different illuminations has been studied by Langley and by Koenig. Koenig's values are the more recent and complete. They have been put in convenient form by Nutting, and will be used here. The sensibility curve, according to Koenig, for the normal eye, for high intensities, and for a normal spectrum (uniform energy distribution) is given in Fig. 2. The ordinates give the relative photometric values of the different colors of the spectrum. The maximum at .565μ is for convenience given the value unity. The maximum of this curve shifts toward the blue for low intensities,—the well-known Purkinje effect, and so in using these values the fact must be kept in mind that the results hold only for high intensities above the region where the Purkinje effect is marked.

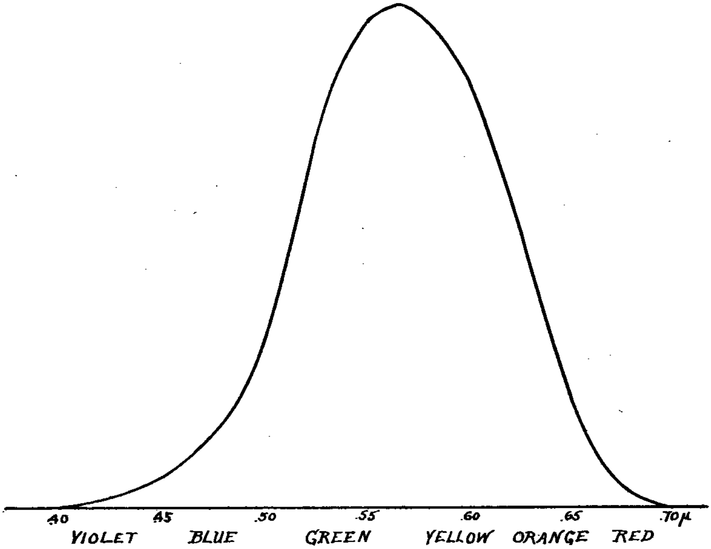

Fig. 2—Sensibility curve of the eye, for a normal spectrum at high intensities.

If we know the complete radiation curve of a source, as determined by a bolometer or thermopile in conjunction with a spectrometer, we can assign to each wave-length its relative luminosity value by merely multiplying its energy value by the ordinate of the sensibility curve at that wave-length. We thus obtain a reduced energy quantity which is proportional at each wave-length to the light value of the energy. The area of the reduced curve is then proportional to the luminosity of the source. Beyond the limits of the visible spectrum the value of the reduced energy is zero. If all the radiated energy were concentrated at .565μ (the most luminous part of the spectrum) the reduced area would be the same as the unreduced. This corresponds to 100 per cent. reduced radiant efficiency. It follows that the ratio of the reduced to the total energy curves gives the "reduced radiant luminous efficiency," where the standard of comparison is the efficiency of a source whose radiation is limited to yellow-green light at .565μ. In Fig. 3 are shown the total and reduced energy distribution curves for a "4-watt" carbon lamp. The ratio of the shaded to the total area is the reduced radiant luminous efficiency. The necessity for restricting the statements to "radiant" efficiencies thus far is obvious.

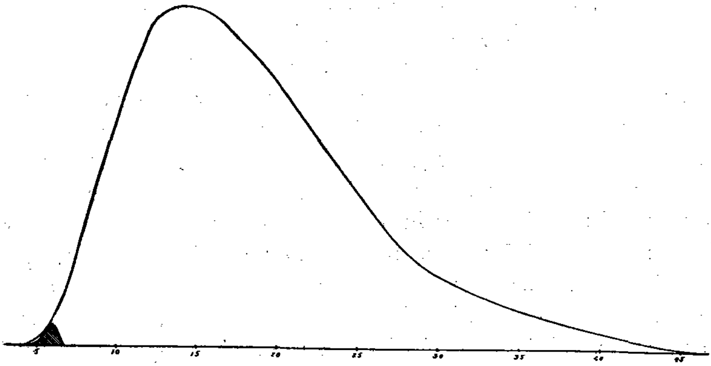

Fig. 3—Reduced luminous efficiency of a "4-watt" carbon lamp.

Before proceeding further the following short table of reduced radiant luminous efficiencies will give an idea of the order of magnitude of this quantity.

TABLE III.

Reduced Radiant Luminous Efficiencies.

Hefner	.0018
"4-watt" carbon lamp	.0043
Black body at 6,000° absolute	.156
Fire-fly	.965
Monochromatic light, wave-length .565	1.000

The total area of the radiation curve is proportional to watts, the reduced area to luminous flux or spherical candles, the ratio of the two is proportional to watts per candle. If we determine the constant of this proportionality by measuring the radiated watts per candle, corresponding to a known "reduced radiant luminous efficiency" we can deduce the reduced luminous efficiency of any source from knowledge of its watts per candle. Determining this constant amounts to finding the mechanical equivalent of a light of 100 per cent. reduced radiant efficiency; in short, the least amount of radiated energy that will give one spherical candle.

Drysdale, with apparatus similar to Angstrom, made a direct determination with yellow-green light from an arc spectrum. His value was .059 watts per candle. This is the only direct determination thus far made where accuracy was striven for. By using the method employed by Eisler, it is possible to obtain values for this quantity from observations on other sources whose radiation curves or mechanical equivalents are known. Because of the difficulties in measuring the minute energy quantities represented by a narrow portion of the spectrum it is probable in the writer's opinion that more accurate values may be obtained by calculation from quantities that are less difficult to measure. This method of calculation of the quantity, which we shall call M, will now be given.

The simplest way of determining M (apart from a reliable direct measurement) is to know the radiated watts per candle of a source whose reduced luminous efficiency we also know. Thus the writer with Dr. Coblentz determined M from observations on a carbon glow lamp, on the assumption,—which cannot be far from true,—that practically all the applied energy is transformed into radiation. The reduced radiant luminous efficiency being .0043, and the watts per mean spherical candle being 4.83, it follows that a luminous efficiency of 100 per cent. would correspond to .0043 × 4.83 or .021 watts per candle.

Recently through the kindness of Dr. E. P. Hyde the writer has had an opportunity to calculate the value of M from energy distribution measurements on three incandescent lamps whose watts per mean spherical candle-power were known. These were an untreated carbon, a treated carbon, and an osmium lamp, used in an investigation on selective emission of incandescent lamps.[1] The distribution in the visible was obtained by comparison with a black body at known temperature (1690° absolute) whose distribution was computed from Wien's equation. The data were derived from the lamps at low voltages, corresponding to about 8½ watts per spherical candle for the carbon and about 5½ watts per spherical candle for the osmium, so that the proportion of visible to infra-red energy is quite small. As high accuracy cannot be expected under these conditions as when a large amount of energy is radiated in the visible region. The accuracy is also very dependent on the exactness with which the visible and radiometric measurements are joined. But with careful measurements the results should not be greatly in error.

From the osmium lamp, proceeding as with the carbon lamp described above, the value of M is deduced as .016 watt, from the untreated carbon .014, and from the treated carbon as .015 watt.

As far as the writer knows these are the only available experiments in which both the energy distribution and the quantity of energy are given. However, we have practically the same thing in those cases where we know both the mechanical equivalent and the shape of the radiation curve in the visible region. If we have the "radiant luminous efficiency" as well, we can determine the reduced radiant luminous efficiency, although this is not necessary to determine M. Knowledge of these quantities from the work of Tumlirz enabled Eisler to make probably the first recorded determination of M. In Fig. 4 is given the radiation curve of the Hefner lamp in the visible region (.76μ to .38μ). The smaller curve is the reduced area proportional to luminosity. The reduced luminous efficiency of the visible portion of the Hefner radiation is the ratio of these areas or 0.19. (The "radiant luminous efficiency" or the ratio of this visible area to the whole, Angstrom found to be .0096; the product of the two quantities or .0018, is reduced radiant efficiency). Now the "mechanical equivalent" of the Hefner, or the quantity of

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[1] Selective Emission of Inc. Lps. as Determined by New Photometric Methods.

energy radiated between these limits for one spherical candle is .121 watts. The product .19 × .121 or .023 watts is the value of M, in good agreement with the one derived from the

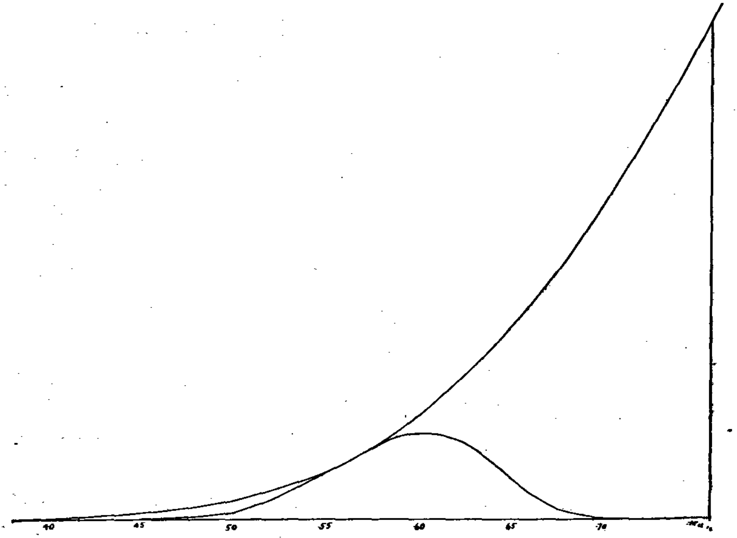

Fig. 4—Visible radiation of Hefner lamp.

"4-watt" incandescent lamp, but not with Drysdale's direct experimental value. Eisler obtained .017 watts. As his value was obtained through Tumlirz's work with absorption cells it does not deserve so great weight as the others, but since the same absorption cell was used to determine both the radiant luminous efficiency and the mechanical equivalent, the errors of the absorption method would be partly compensated for, and the order of magnitude of M cannot be far wrong.

Drysdale with the same apparatus determined the mechanical equivalent of "white light," using both a Nernst and a carbon arc. From these, values of M can be calculated as above, although Drysdale did not do so. For this purpose it is necessary to know the distribution of visible radiation.

Since these two illuminants have practically the visible energy distribution of a black body at appropriate temperatures, it will be sufficient to know the reduced luminous efficiency of the visible portion of the black body radiation for various temperatures. Because of their general interest and application, the writer has worked out by this method the reduced luminous efficiencies of the black body for a series of temperatures, calculating the radiation curves from the equation of Wien. The values for the visible portion alone are given in Fig. 5. It is at once evident why the mechanical equivalent of light depends upon the character of the visible radiation, since the ordinates here represents quantities of light corresponding to the same energy quantity.

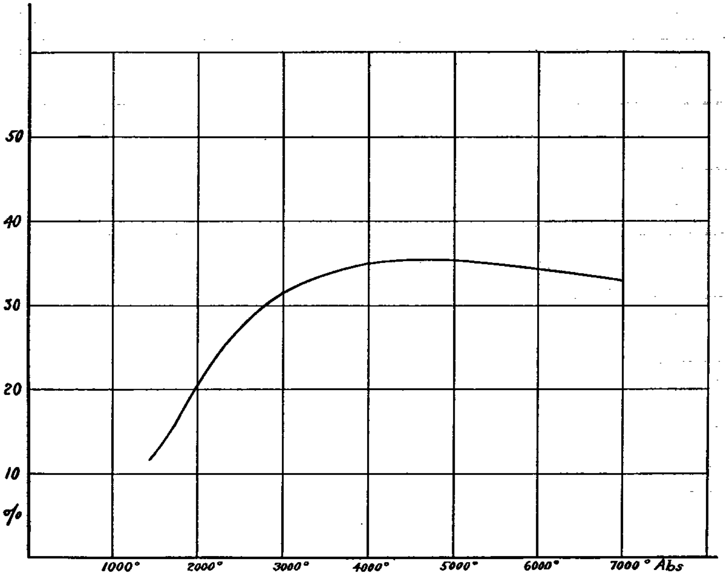

Fig. 5—Reduced luminous efficiency of visible radiation of black body.

The values just obtained can be used in conjunction with the older "radiant luminous efficiency" to determine reduced values for the total black body radiation and illuminants of similar visual energy distribution. Drysdale has calculated the radiant luminous efficiencies of a black body (L/R), and the values are shown by the dotted line in Fig. 6. These have each been reduced according to Fig. 5, and the resulting reduced radiant efficiencies are given by the full line. The maximum efficiency

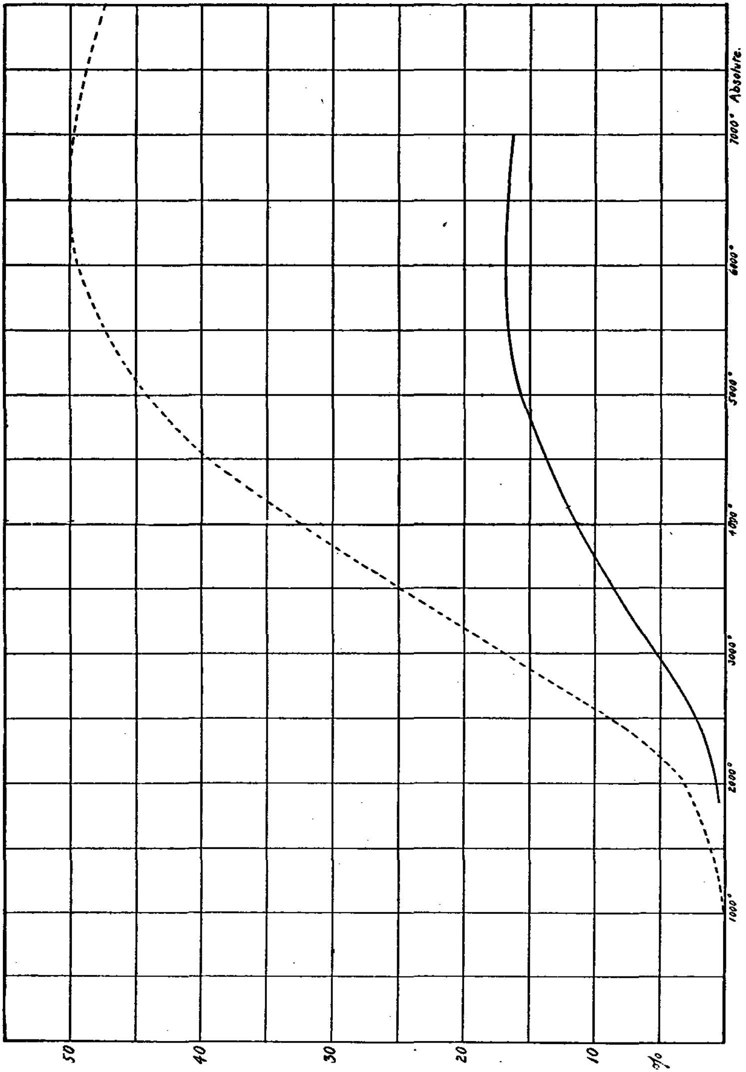

Fig. 6—"Luminous efficiency" and "reduced luminous efficiency" of black body.

is given at about 6000°. The radiation of the sun corresponds in its visible region closely to the black body at about 5000°, but the difference in color of the black body between 5000° and 6000° is so slight that we may say that the most efficient light a black body can give is white light. We shall return to the discussion of these values later.

To use these computations we note that the Nernst corresponds closely in visual distribution to an acetylene flame, which in turn is practically that of a black body at 2330° absolute.[1] Repeating the process we have applied to the Hefner, we find for the reduced efficiency of the visible radiation .255. This applied to the mechanical equivalent found by Drysdale for the Nernst gives .255 × .119 or .03 watts. Taking the arc as equivalent visually to a black body at 3000° absolute[2] we obtain .30 × .0805 or .024. These values are not consistent with the directly obtained value .059; probably, in the writer's opinion, because the chances of error in measuring the energy in the small band of green light were far greater than in measuring the whole visible spectrum.

We obtain therefore a number of values in the neighborhood of one fiftieth of a watt per candle, (with the exception of Drysdale's value of one-seventeenth). These values because of the manner in which they are obtained must be too high. We have assumed in deducing them that the candle-power measurements were made at high intensities, and, in the case of the incandescent lamps, that no energy is lost by conduction and convection. In practice photometric work is carried out at moderate illuminations,[3] where more energy is required, with illuminants of the kind we are considering, to give a certain amount of light measured by any of the present standards than at higher illuminations. The energy input would therefore need to be less under the high illumination conditions we have assumed. The amount of this connection is difficult to determine, being a function of the colors of the standard and the light tested. From some calculations made by means of Koenig's visibility curves for various

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[1] In a direct comparison by Dr. E. P. Hyde, the value 2,326 was obtained.

[2] Obtained by spectrophotometric comparison of 10 amp. D. C. arc with acetylene.

[3] If a medium illumination were taken as standard, a sensibility curve with a maximum nearer the blue should be used. This would give smaller values for M.

intensities, using a "4-watt" lamp as the standard (*i. e.,* considering its candle-power a constant at all illuminations) the amount of this correction for any illuminant and conditions here considered would not appear to exceed 10 per cent. With regard to the losses by conduction and convection, they would also operate in the direction of making the energy assumed necessary for a certain light flux too large. These latter losses would be proportionally greater in the lamps run at lower temperatures.

The errors in the calculation of the quantity M being therefore all in the direction to make the obtained values large, the mean of these, viz., .024 watt per mean spherical candle is probably an upper limit. Giving small weight to the values obtained by Eisler and by Drysdale, for reasons already given, it appears that we can assign with some show of probability to the quantity M the value of one-fiftieth of a watt per mean spherical candle, or .0016 watt per lumen. Future work may determine this more accurately.

TABLE IV.

Values for the Mechanical Equivalent of the Most Efficient Light.

Method.	Watts per candle.
Application of Langley's sensibility data to Tumlirz's figures for the Mechanical Equivalent of the Hefner (Eisler) ..	.017
Direct measurement of yellow-green light (Drysdale)	.059
Application of Koenig's sensibility data to energy distribution curves or to mechanical equivalents (Ives)—	
Hefner (Angstrom's value of mechanical equivalent)	.023
Nernst (Drysdale's value of mechanical equivalent)	.030
Arc (Drysdale's value of mechanical equivalent)	.024
"4-watt" carbon lamp (distribution curve obtained by Coblentz)	.021
Untreated carbon lamp at 8.6 w. p. s. c. (distribution curve furnished by E. P. Hyde)	.014
Treated carbon lamp at 8.0 w. p. s. c. (distribution curve furnished by E. P. Hyde)	.015
Osmium lamp at 5.5 w. p. s. c. (distribution curve furnished by E. P. Hyde)	.016

This quanity is one of prime importance in comparing efficiencies. The derivation of "reduced luminous efficiency" has given us a rational basis of estimating efficiencies, but it is largely a means to an end. One object of studying efficiencies is to know what efficiency should be attainable, and to compare our present ones with it. Future investigation should therefore devote itself not as formerly to accumulating values of luminous efficiency, but to obtaining more accurate values of M.

It would seem to the writer that the most promising method for doing this would be direct measurement of the light and energy of the very intense radiation from the green line of the quartz mercury arc. This gives much more energy for measurement than does a strip of continuous spectrum and may be easily separated from the other mercury emission lines by the use of absorbing screens. This line, wave-length .546μ, does not correspond exactly to the maximum of sensibility according to Koenig, but is near enough so that only a small correction would be necessary. If this direct method proves unreliable, values can still be obtained through mechanical equivalents of "white" illuminants, by the use of the sensibility curve. These would always be subject to the errors of the sensibility curve, but a comparatively large change in the latter is necessary to make much difference in the resultant value.

Using this value of M, namely .02 watts per spherical candle, we can obtain some figures of interest. Referring to the values of reduced luminous efficiency for the black body, we see that about 17 per cent. is the maximum value at 6000°. Using Planck's equation instead of Wien's, a slightly smaller value results, namely 15.6 per cent. This, the most efficient black body, corresponds to .13 watts per candle or 7½ candles per watt. If all the radiation of the black body were confined to the visible region (.76μ to .38μ) the reduced efficiency would be 34 per cent. (Fig. 5), or 17 candles per watt. The limits taken are however wider than necessary. A white light would be obtained from the radiation between wave-lengths .40μ and .70μ. The reduced efficiency of this radiation is 42 per cent., or 21 candles per watt. It is therefore evident that the development of higher efficiencies is dependent on finding substances which not only will stand a high temperature but will radiate selectively in the visible region.

In the following table are collected figures for reduced luminous efficiencies and for candles per watt and lumens per watt.

Since the (total) reduced efficiencies are proportional to the candles (or lumens) per watt, it is only necessary to know accurately the reduced efficiency of one illuminant, for then the ratio of the candles (or lumens) per watt of other illuminants to it gives their reduced efficiencies. The reduced efficiencies of the last four on the list were so obtained.

It may be noted here that the definition of reduced luminous efficiency might be put in a slightly different form than we have used. Drysdale's manner of putting it is that the reduced luminous efficiency expresses the percentage of the applied energy which would be sufficient to give the same light quantity, had the energy been radiated as yellow-green light. The two modes of describing the quantity are exactly equivalent.

TABLE V.

Source.	Spherical candles per applied watt.	Lumens per applied watt.	Reduced luminous efficiency.
Ideal yellow-green source	about 50	about 625	100%
Fire-fly	?	?	96.5
Black body at 6000°	7½	95	15.6
Black body at 6000 between .70μ and .40μ	21	265.0	42.0
"4-watt" carbon lamp	.21	2.6	0.43
Tungsten	.63	7.9	1.3
D. C. Arc	1.1	13.8	2.2
Yellow flame arc	3.0	37.8	6.0
Quartz mercury arc	3.4	42.8	6.8

As was the case with so-called "luminous efficiency" it is necessary in giving "reduced luminous efficiencies" to note whether the efficiency is "radiant" or "total;" that is, whether we have considered merely the energy radiated, or the whole applied energy. In practice our knowledge is as a rule of the applied energy. In cases, however, where we are interested in the efficiency of the radiated energy we can obtain the radiant "reduced luminous efficiency" by measuring the radiated energy. In the case of the fire-fly for instance, we can study its radiation, but we do not know how much energy it has to apply to obtain a certain amount of radiation, *i. e.*, we cannot determine its total efficiency as applied watts per candle. Usually the knowledge we desire is of the total efficiency, or the ratio of the candles per watt to that of the most efficient light. If, however, there is reason to believe that a large amount of energy is lost in the transformation from applied energy into radiation it becomes of interest to know the efficiency of the radiated energy alone. In such cases the radiant and total efficiencies are related to each other by the factor giving the efficiency of transformation of applied energy into radiated energy. This is a quantity easier to determine than either the so-called "luminous efficiency" or the "mechanical equivalent" for it is only necessary to measure the total radiation in watts,—not a small and difficultly measurable fraction of it.

As a consequence of developing the idea of reduced luminous efficiencies we find that in order to know all that is usually of significance about an artificial illuminant,—once the value of the constant M is determined,—we should determine—

1. Mean spherical candle-power.
2. Energy input.
3. Radiated energy.

From 1 and 2 we obtain the candles per watt, which we can compare with the candles per watt of the ideal source, or of the most efficient in white light. This comparison will usually be sufficient to answer our questions about relative efficiency. In certain cases it will be of importance to know where the chief waste of energy takes place. We learn this from "2" and "3."

SUMMARY AND CONCLUSION.

The meaning and values of the various quantities employed in the comparison of the efficiencies of light sources have been reviewed and criticized. It has been pointed out that the common technical measure of efficiency "candles per watt" or preferably "lumens per watt," is exact and satisfactory as far as it goes, while the usual scientific measure "luminous efficiency" is not. The weakness of the quantities "luminous efficiency" and "mechanical equivalent of light" is that they take no adequate account of the relation between the quality of the radiation and the efficiency, and that the values indicating the highest efficiency possible refer not to any common standard, but only to the particular lights measured. As a consequence there is no direct relationship between "luminous efficiency," and "candles per watt." The luminous efficiency and the mechanical equivalent of a source are only rough measures, unsuitable for comparisons.

By taking into consideration the quality of the visible radiation, the idea of "reduced luminous efficiency" has been developed. Here the standard of comparison is the light which, owing to the sensibility of the eye, is the most efficient. By determining the minimum energy necessary to give one spherical candle of this most efficient possible light, a quantity is obtained to which the watts per candle of any illuminant may be referred, thus giving a rational measure of efficiency. This measure of efficiency if expressed in percentage is identical with "reduced luminous efficiency."

What are the useful conclusions to be drawn from this survey?

In order to make a complete discussion of this subject it has been necessary to use a large number of terms, "radiant luminous efficiency," "total luminous efficiency," "the mechanical equivalent of light," "reduced radiant luminous efficiency," "reduced total luminous efficiency." So many similar terms are altogether too confusing to be preserved in use. One conclusion that might well be reached would be that we should cease using the term "luminous efficiency" in its older sense of the ratio of visible to total radiation, using this term to designate the more rational "reduced luminous efficiency." This should certainly be done if possible. It is probable though that the term "luminous efficiency" has been too long attached to the former quantity to offer much hope of its being transferred. The confusion of finding the same term used in different senses would be very undesirable.

In the writer's opinion the best solution of the difficulty is to discard the term "luminous efficiency" altogether. The quantity formerly meant by "luminous efficiency" should be stated explicitly. In place of so many per cent. "luminous efficiency" it is more exact and satisfactory to state that such a percentage of the total energy radiated lies inside or outside the visible spectrum. This is a rough measure of efficiency, and should be so considered. The "mechanical equivalent" of a light can just as well be given without using this name. State that the visible portion of the radiation has such an energy value for unit light flux. Instead of applying the term "luminous efficiency" to that quantity we have discussed as "reduced luminous efficiency," confine ourselves to "efficiency," meaning lumens per watt. If we wish to compare the efficiencies of two illuminants, compare their lumens per watt, or candles per watt, depending on which unit of flux we have used. If we wish to know how an illuminant stands with respect to the highest possible efficiency, compare its lumens per watt with the lumens per watt of yellow-green light, or if preferred, to that of the most efficient white light. There is no real need for a "luminous efficiency" giving values in percentages. If a percentage value is given it can be stated explicitly that the efficiency of the illuminant is so many per cent. the efficiency of the standard yellow-green or white as preferred. But the writer's belief is that it is best to avoid the use of percentages in this connection. On this view, the figures of the "Lumens per Watt" column of Table IV give all that is usually necessary in the comparison of illuminants. Make direct comparison of candles or lumens per watt, and know the goal of efficiency in light production.

The mechanical equivalent of the most efficient light, with which we make comparisons, is a quantity for future investigation to determine more exactly. The final value will depend upon conventions yet to be decided upon as to the standard conditions of illumination under which we shall consider our standards of intensity to hold their values. In short, it is bound up with the whole question of color photometry. For the present the efficiency of the yellow-green source is so much higher than any practically obtainable efficiency that the existing uncertainty in its value is of no great moment, if we use it as here urged.