ART. XXXVI.—*Magnesium as a Source of Light;* by FREDERICK J. ROGERS, M.S.

[Contributions from the Physical Laboratory of Cornell University. No. 9].

I.

Quality of Magnesium Light.

THE light produced by the combustion of magnesium is brilliantly white. It is whiter than the arc light and almost rivals sunlight itself. When the spectrum of the magnesium light is formed side by side with that of ordinary gaslight, the former is immediately seen to be relatively much stronger in the more refrangible rays. It gives a continuous spectrum, superimposed upon which are the ever present sodium lines D_1 D_2 and the magnesium lines b_1 b_2 b_4 as well as four or five oxide bands.

In the experiments to be described in the first part of this paper the brightness of magnesium light in different parts of its spectrum was compared with the corresponding components of gaslight from an Argand burner by means of the "horizontal slit" photometer.* This is a spectrophotometer movable along a photometer bar. It furnishes, side by side, spectra of the two sources of light to be compared, the two

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* Described by Dr. E. L. Nichols, in Trans. Am. Inst. of E. E., vol. vii.

spectra being viewed in the usual manner by means of an observing telescope. The advantage of this form of spectrophotometer is that there is no polarizing device, equality of the particular portions of the spectra compared being obtained by movement along the photometer-bar.

The light to be studied was produced by the combustion of magnesium-ribbon $2\frac{1}{2}^{mm}$ wide, supplied at a uniform rate by means of clock-work. The light was very variable, a fact which greatly increased the difficulty of determining its quality. Even when a diaphragm with an opening of 2×5^{mm} was placed immediately in front of the burning ribbon this variation in intensity was quite marked. The best that could be done was to take the mean of a large number of observations. The comparison was made at eight points very nearly equidistant in the normal spectrum. Five sets of observations were made making in all fourteen readings for each of the eight points in the spectrum. Table I gives the ratios, magnesium light: gaslight, reduced to unity at the D line, as obtained by taking the mean of these five sets of observations.

TABLE I.

Wave-lengths.	$\frac{\text{Mg. light.}}{\text{gaslight.}}$	Wave-lengths.	$\frac{\text{Mg. light.}}{\text{gaslight.}}$
·450	8·77	·574	1·21
·479	5·33	·606	0·83
.506	3·43	·635	0·66
·536	2·07	·670	0·53

The full curve in fig. 1 represents graphically the relation between wave-lengths and relative intensity in the case of the magnesium light. The standard gaslight is arbitrarily taken to be unity in all parts of the spectrum. Curve II*, fig. 1, represents the relative intensity of the arc light for different wave-lengths as obtained by Dr. Nichols in 1888. Curves III and IV, fig. 1, represent the relative intensity of daylight as compared with the standard. III represents daylight from a cloudless sky and IV, daylight from a heavily clouded sky. In the latter case the cloudiness happened to be just sufficient to make daylight almost identical in character with the magnesium light. For these dotted curves the standard light was a sixteen candle power incandescent lamp which, however was found to give a light nearly identical in quality with the light from an Argand gas burner. The stars in the figure for $\lambda =$ ·656, ·527, and ·450 represent the values for magnesium light obtained by Prof. Pickering in

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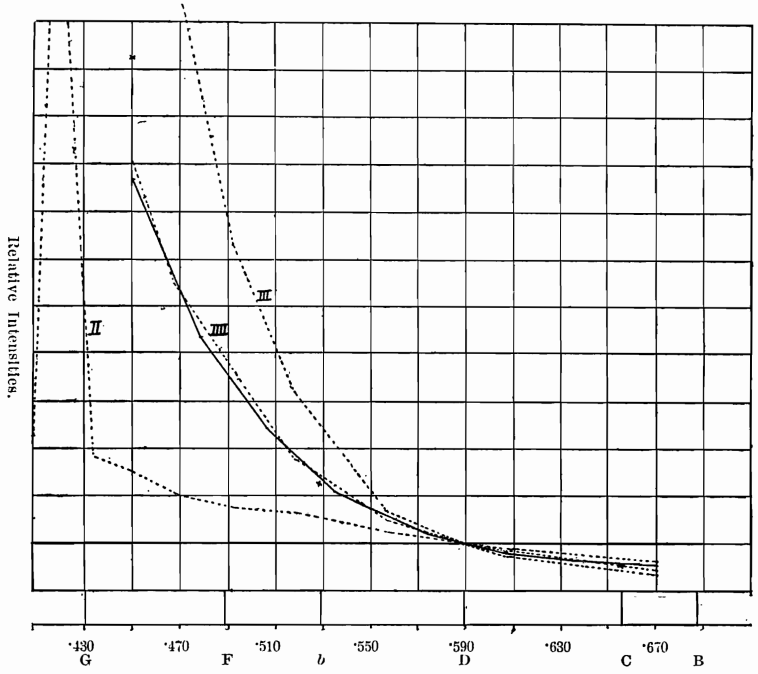
* This Journal, vol. xxxvii, p. 100.

1879.* It will be seen that the results from Table I, are quite in accordance with those of that observer and sustain his statement that of all artificial illuminants the magnesium light approaches sunlight much more nearly than does any other.

1.



II.

Temperature of Burning Magnesium.

An important question in regard to the magnesium light is that of the temperature at which combustion takes place. Flame temperatures are not well known. Rossetti† has found 1350° for the hottest part of a Bunsen flame and 640° to 940° for a stearine candle flame. As I knew of no experimental data whatever on the subject of the temperature of burning magnesium, I attempted to measure it by means of the E. M. F. produced in a thermo-element composed of platinum and platinum-iridium, when the element was placed in the flame. A thermo-element of those materials had been previously cali-

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* Proc. Am. Acad. of Arts and Sciences. 1879–80. p. 236.

† Annalen der Physik, Beiblätter, I, p. 615, II, p. 333.

brated* using as known temperatures the melting points of metals, for high temperatures,† silver 954°, gold 1035°, copper 1054°. As the melting point of copper is far below the temperatures to be measured it is necessary to prolong the calibration curve beyond the points determined by observation. But as this curve is almost exactly a straight line from 700° to 1050° it is probably safe to prolong it to, at least within 200° or 300° of the melting point of platinum.

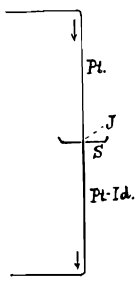
It was soon found that burning magnesium almost instantly destroyed the small platinum wire used (·01 inch diameter), apparently by some chemical action, as there was no evidence of fusion. To determine the temperature in the ordinary way, by noting the permanent deflection of a galvanometer needle when the thermo-junction was held in the magnesium flame, was clearly impossible. To obviate this difficulty several indirect methods were employed, in all of which the temperature of burning magnesium was determined by comparison with other flame temperatures.

The temperatures of the flames to be used as standards in this work, were determined by the writer by means of the E. M. F. produced by them in the above mentioned thermo-junction. These flames were air blast flame, Bunsen flame, luminous gas flame (Bunsen burner with the air holes closed) and candle flame. In all cases the object was to get the temperature of the hottest part of the flame. No galvanometer readings were taken, until by repeated trial, the deflection was as great as could be obtained. The final results of three sets of observations are given in Table II.

Three methods employed in the estimation of the temperature of combustion of magnesium are described below.

First method.—The wire of the thermo-element was passed through a small hole in a porcelain screen which protected the junction as shown in fig. 2. The platinum-iridium wire was then heated as closely as possible to the screen by the different flames, including the magnesium flame and the corresponding galvanometer "swings" were noted. Three determinations by this method are given in Table II.

2.



Second method.—It was found that after the platinum-iridium wire had been heated a short time by the magnesium-flame, a *negative* deflection of the galvanometer was obtained. An investigation proved that the burning magnesium formed a black compound with the wire and that this substance formed with the platinum-iridium a thermo-element whose

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* By Mr. Ernest Merritt in the course of an investigation not yet published.

† "Physikalische-Chemische Tabellen." Landolt und Börnstein.

E. M. F. was negative, the E. M. F. in the original element being considered positive. To eliminate this accidental E. M. F., the thermo-junction was made in the form of a **T** as in fig. 3 and the projecting portion which passed through a porcelain screen was heated as before by the different flames. Two determinations by this method are given in Table II.

Third Method. — In this case a rather large bead of metal was formed at the junction. The junction was then *directly* heated by the different flames, last of all by the magnesium flame, and the galvanometer "swings" were noted as before. The thermo-element was not so quickly destroyed as before; nevertheless, only one reading for the magnesium flame could be obtained before making a new junction. Two determinations were made by this method.

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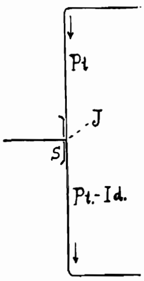
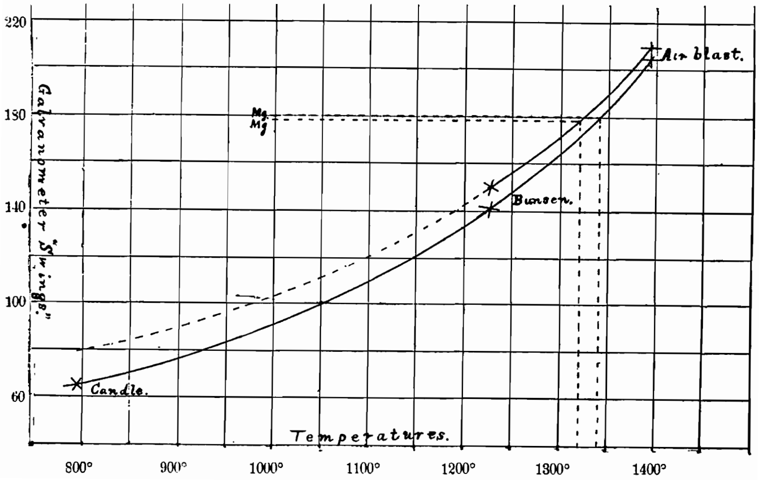


TABLE II.

Candle flame.	Luminous gas-flame.	Bunsen flame.	Air blast flame.	Method.	Magnesium flame.	
827°	----	1227°	1398	First	1345° 1375 1280	1333°
765	992°	1233	1382	Second	1350 1333	1342
792	1018	1222	1404	Third	1320 1345	1332

The values for the flame temperature of magnesium, given above, were obtained by a graphic method which is illustrated

4.



in figure 4. The previously determined temperatures of the other flames were plotted as abscissæ and the corresponding galvanometer "swings" as ordinates. The ordinate on these curves, corresponding to the "swing" due to the magnesium flame was taken as indicating the position of that flame upon the curve. The abscissa reading of this point gave the flame temperature to be inserted in the table. In figure 4 are given the curves for the third method. The galvanometer "swings" for the same flame in the two cases were not exactly the same on account of the bead of metal at the junction being larger in one case than in the other.

Whatever question may be raised touching the accuracy of the absolute values of the above determinations of flame temperatures; there can be little doubt that they are relatively nearly correct; and we may be sure that the temperature of burning magnesium is a little below that of the hottest part of an air blast flame.

When the quality of the light from sources of different temperature is examined, it is almost uniformly found that the light from the sources of higher temperature is richer in the more refrangible rays. Prof. Pickering, in the course of the series of investigations on the quality of the light from different sources already cited, has made use of this fact to calculate flame temperatures. The following passage from his paper will serve to indicate the basis of his estimates: "Then if the temperatures we adopted were correct, this would give us a very simple empirical law, viz: The temperature is always proportional to some function of the ratio of any two assumed wave-lengths. For artificial sources for the wave-lengths ·585 and ·455 it varies directly as this ratio. . . . . Upon this principle the temperature of the magnesium-light, perhaps the highest terrestrial temperature we have yet attained, would be 4900° C." As direct measurement shows this estimate to be altogether too high, it might be inferred that the magnesium light, unlike that of most sources, is not solely due to incandescence, but that it is in part due to something like fluorescence by heating. Further evidence in favor of this view will be presented in the course of the following study of the efficiency of the magnesium light.

III.

Radiant Efficiency of Magnesium light.

By radiant efficiency of a source of light I mean the ratio of *luminous energy* to total *radiant energy.* This ratio has often been rather ambiguously called, *net* efficiency.

The method employed for the determination of this ratio was to note the galvanometer deflections produced by the direct radiation of the source upon the face of a thermopile in circuit with a galvanometer, and then the effect of radiation from the same source when the “dark” heat is cut off by a glass cell containing a saturated solution of alum. Two alum cells were used in all cases. The second cell eliminated the effect of the warming up of the first one due to the absorption of radiant heat. The total thickness of the two alum cells was 72^{mm}. The E. M. F., produced in a thermopile by radiation on its face, varies directly as the intensity of the radiation. Therefore the ratio of the galvanometer deflection obtained when the alum cells are interposed, to the deflection produced by the unobstructed radiation, properly corrected if there has been a change in the resistance of the galvanometer circuit, gives the ratio of the radiation through the alum cells to the total radiation. When this ratio is corrected for the light absorbed and reflected by the alum cells and for the “dark” heat which passes through them, we have the radiant efficiency of the source of light.

The amount of light absorbed and reflected by the alum cells was determined photometrically. The candle power of a constant source of light was measured both when the two alum cells were and were not interposed between it and the photometer, and it was found that ·641 of the light incident upon the face of the first alum cell passed through both. The “dark” heat transmitted by the alum cells was measured with the aid of a cell containing an opaque solution of iodine in bisulphide of carbon. This transmitted the “dark” heat but intercepted the light. In the case of a gas flame ·004 of the incident “dark” heat was transmitted through both alum cells.

For the sake of comparison the radiant efficiency of candle light and gaslight was determined. The final results of a number of measurements are as given below.

TABLE III.

Radiant efficiency of candle-light,		·0153
“ “ “ gaslight,	Bat’s wing burner,	·0128
	Argand “	·0161

Julius Thomsen* found the efficiency of petroleum flame to be about ·02. His method was similar to the above except that he used distilled water instead of a solution of alum and disregarded the heat transmitted. S. P. Langley† by a very different method, namely by measuring the intensity of the

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* Poggendorff's Annalen, cxxv, p. 348.

† Science, vol. i, p. 483.

radiation for the different wave lengths of the luminous and heat spectrum, found the radiant efficiency of gaslight from an Argand burner to be ·024.

Considerable difficulty was experienced in measuring this ratio for magnesium light on account of the great variability of the magnesium flame. The galvanometer needle instead of moving steadily or by steps to a maximum and then remaining there, was almost constantly in motion. Furthermore the radiation with and without the alum cells had to be measured successively, and there was no certainty that the condition of the flame was the same in the two cases. The best that could be done was to take a large number of observations and discard a few that were very far from the mean.

TABLE IV.

	Galvanometer deflections.				
No. of Experiment.	Two alum cells R. of circuit =803.	Direct radiation R. of circuit=8030.	Light transmitted through alum cells divided by total radiation.	Preceding ratio corrected for heat transmitted.	Radiant efficiency (preceding ratio corrected for light reflected and absorbed.)
No. 1	67·4	76·5	·088	·085	·133
" 2	77·5	83·5	·093	·090	·140
Same as above but with diaphragm.					
No. 3	16·5	17·9	·092	·089	·139
" 4	21·7	22·7	·095	·092	·144
Same as above but with galvanometer No. 2.					
	R. of circuit=37·46	R. of circuit 147·46.			
No. 5	18·0	48·6	·094	·091	·142
" 6	17·8	49·1	·092	·089	·139
" 7	12·4	40·8	·077	·074	·115
" 8	14·1	41·2	·087	·084	·131
Same as above, sensitiveness of galvanometer changed.					
	R. of circuit=20·46	R. of circuit 207·46			
No. 9	31·0	40·5	·076	·073	·114
Average by method of permanent deflections,					·133

In Table IV, are given nine determinations of the radiant efficiency of magnesium light. In the first two no diaphragm was used, but in every other case a diaphragm of 10×15^{mm} opening was placed in front of the ribbon of burning magnesium. This reduced the fluctuations caused by the varying length of the incandescent strip of magnesia.*

It has been proved† that when a galvanometer and thermopile are used together the "first swing" of the galvanometer

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* It is perhaps a misnomer to call this strip of incandescent magnesia a "flame." Neither the combustible nor the product of combustion is a gas and the burning magnesium unlike a flame hangs downward.

† Ernest Merritt, note on galvanometer used with thermopile, this Journal, xli, p. 417.

needle due to the face of the thermopile being suddenly exposed to a source of radiation is proportional to the final permanent deflection. Use was made of this fact in obtaining the results given in Table V. In this case there was no difficulty in determining the limit of the "first swing." The difficulty still remained, however, that the magnesium might be giving out a maximum of radiation at the instant of exposing the thermopile to it while at the next exposure it might be far from a maximum. A mean of the results by the method of permanent deflections and "first swings" gives ·135 as the radiant efficiency of magnesium light. The only artificial light whose efficiency is greater than this is the light from a Geissler tube* of which the radiant efficiency is about ·34. L. B. Marks† finds the radiant efficiency of the arc light to vary from ·08 to ·127 depending upon the character of the carbons.

Table V.

No. of Experiment.	Galvanometer "swings."		Light transmitted through alum cells divided by total radiation.	Preceding ratio corrected for heat transmitted.	Radiant efficiency (preceding ratio corrected for light reflected and absorbed.)
	Two alum cells. R. of circuit 7·46	Direct radiation R. of circuit 7·46			
No. 1	3·8	47·0	·081	·078	·122
" 2	3·5	40·0	·088	·085	·133
" 3	2·9	31·8	·092	·089	·139
Sensitiveness of galvanometer changed.					
No. 4	4·9	55·1	·089	·086	·134
" 5	5·2	57·0	·091	·088	·137
" 6	5·0	48·3	·103	·100	·156
" 7	5·4	56·3	·096	·093	·145
" 8	4·6	54·9	·084	·081	·126
" 9	4·3	45·3	·095	·092	·144
Average by the method of "first swings."					·137

H. Nakano,‡ in a series of experiments to determine the relation of the size of carbons to efficiency, found that in the case of carbons ·25 in. in diameter and a potential difference of 38 volts the "spherical efficiency" was ·166 but with carbons of the usual size the efficiency was about ·10.

The radiant efficiency of incandescent lamps is much less than that of the arc light. Ernest Merrit§ found the radiant efficiency of incandescent lamps under the best conditions compatible with their continued existence to be about ·06.

In all the experiments above referred to, the efficiency was measured in the same way, viz: by taking the ratio of the

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* Beiblätter zu den Annalen der Physik, xiv, page 538.

† Am. Inst. of E. E., 1890, vol. vii.

‡ Am. Ins. of E. E., vol. vi, p. 308.

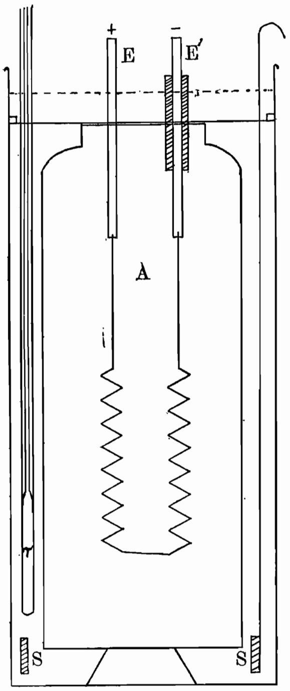
§ This Journal, vol. xxxvii, p. 167.

radiation through an alum cell to the unobstructed radiation and correcting for light absorbed and heat transmitted.

IV.

Heat of Combustion of Magnesium.

5.



In order to determine the total efficiency of magnesium light it is necessary to know its heat of combustion. In determining this quantity a new form of colorimeter was used. In this case the magnesium ribbon was burned in an entirely closed vessel containing oxygen, not allowing *any* of the products of combustion to escape. Figure 5 represents a vertical section of the calorimeter. The smaller vessel, A, holds something over half a liter. This vessel is provided with an air-tight cover through which pass two electrodes E, E′, one of which is insulated from the calorimeter. The outside vessel is just large enough to allow room between it and the inner vessel for a stirrer, S, and a thermometer T.

The process was as follows: About three fourths of a gram of magnesium was coiled into a spiral and a very small quantity of phosphorus fastened to it. The terminals of the spiral were then connected to the electrodes. Before putting the magnesium into the vessel, A, the latter was filled with oxygen. After the inner vessel had been closed, water was poured into the calorimeter until it was a centimeter deep over the top of the former vessel. The ribbon was then ignited by the instantaneous application of a current of electricity. This calorimeter gave quite uniform results. In Table VI, are given

TABLE VI.

No.	Lesser calories per g. of Mg.	No.	Lesser calories per g. of Mg.
1	6246	5	6020
2	6081	6	6072
3	5760	7	6011
4	5878	Average	6010

the results of seven determinations by this method. A mean of these gives 6010 lesser calories as the heat developed by the combustion of one gram of magnesium in oxygen.

Julius Thomsen* gives 6077 as the heat of combination of magnesium and oxygen. He arrived at this result indirectly by means of the heat developed in the formation of the hydrate.

V.

Total efficiency of magnesium light.

By total efficiency is meant the ratio of luminous energy to the total energy expended in the production of the light. In order to determine this ratio it is necessary to know the ratio of radiant energy to total energy of combustion. The method of obtaining the energy of combustion of a gram of magnesium in lesser calories, has just been described, and next must be indicated that of obtaining the radiant energy from a gram of burning magnesium in the same units. The method of obtaining this result was by calibrating the galvanometer and thermopile for lesser calories of spherical radiation from a source 24^{cm} from the face of the thermopile. The known source of heat was a spherical brass vessel coated with lamp black and filled with hot water. Its loss of heat was known by its fall in temperature. The loss by convection and conduction was determined by noticing the rate of cooling in air and in a vacuum, under otherwise similar circumstances. By this means it was found that a galvanometer "swing" of one scale division corresponded to a spherical radiation of 2·53 calories per minute. Next the thermopile was exposed to the radiation from burning magnesium, the ribbon being supplied at a uniform rate. From a mean of 24 observations it was found that the burning of one gram of magnesium produced 4630 calories of radiant energy. As above shown ·135 of this radiant energy is light. The total energy of combustion of one gram of magnesium is 6010 colories, therefore the total efficiency of magnesium as a producer of luminous energy is $\frac{\cdot 135 \times 4630}{6010} = \cdot 1025$. It is assumed in this computation that the radiation from burning magnesium is of the same intensity in all directions. Experiments were made for determining the validity of this assumption, in which it was found that the candle power showed but little diminution up to 70° from the horizontal plane.

It is very remarkable that nearly ·10 of the total heat of combustion of any artificial illuminant is expended in producing light. The radiant efficiency of magnesium, as we have

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* Journal für praktische Chemie, 1875.

seen, is very high and what is still more surprising, the ratio of radiant energy to total energy is not far from ·75. The small loss by convection which renders this ratio possible is partially explained by the fact that the product of combustion is a solid. It may be also that this unusually high percentage of radiation is in some way related to the fact that so large a proportion of the radiant energy itself is luminous.

The final experiments in my study of magnesium as a source of light consisted in the determination of the amount of light produced by burning one gram of the metal. Measurements were made by means of the "horizontal slit" photometer. The standard for four determinations was an Argand lamp with a Methven slit, which allowed two candle power to pass through. In these measurements the comparison was made at the D line. In four other determinations the standard was an incandescent lamp; in which case the measurements were made at two points on opposite sides of the D line and their mean taken. In Table VII are given the final results of these eight determinations.

TABLE VII.

Standard=Argand lamp.		Standard=Incandescent lamp.	
No.	C. p. minutes per g. of Mg.	No.	C. p. minutes per g. of Mg.
1	248	1	233
2	252	2	236
3	228	3	288
4	250	4	272

A mean of the above eight measurements gives 251 candle-power-minutes produced by the combustion of one gram of magnesium.

This measurement of the candle-power-minutes produced by one gram of magnesium may serve as a check on the determination of the total efficiency. Assuming that the efficiency is ·10, one gram produces 601 calories of luminous energy; therefore the thermal equivalent of one candle-power-minute of magnesium light is $\frac{\cdot 10 \times 6010}{251} = 2\cdot 39$ calories. Even in the most unfavorable circumstances, namely, by using the maximum heat of combustion from Table VI and the minimum candle power minutes from Table VII we have, thermal equivalent $= \frac{\cdot 10 \times 6246}{228} = 2\cdot 74$ lesser calories. In 1865 Julius Thomsen[*] published some determinations of the thermal equivalent of light, which he found to vary from 4·4 calories in the case of

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[*] Annalen der Physik und Chemie, vol. cxxv, page 348.

a sperm candle to 3·7 calories in the case of gas. His values are too high, for he used distilled water to absorb the radiant heat instead of an alum solution, and made no correction for the heat transmitted. Dr. Nichols* puts the thermal equivalent of the light from an incandescent lamp at 3·6 calories. Magnesium-light is much richer than gaslight in those rays (green) which are most effective in producing vision. Nevertheless it is highly improbable that its thermal equivalent is much less than two-thirds that of the incandescent lamp or in other words, that it is much less than 2·4 calories. But if the total efficiency of magnesium light is considerably less than ·10 then its thermal equivalent must be considerably less than 2·4 calories.

It may be interesting to compare magnesium with gas as a producer of luminous energy. The radiant efficiency of gaslight is about ·015; but of the total energy of combustion in the case of gas only ·15 or ·20 is radiant energy. Therefore the total efficiency of gaslight is ·0022 or ·003. This means that potential energy in the form of uncombined magnesium and oxygen is from 30 to 40 times more effective as a producer of luminous energy than the same quantity of potential energy in the form of illuminating gas and oxygen. Even this statement does not give the full measure of the superiority of magnesium light. If the thermal equivalents of gaslight and magnesium light are 3·6 and 2·4 respectively, the same quantity of luminous energy in the form of the latter will produce 50 per cent more candle power than if it were luminous energy in the form of gaslight.

The results of this investigation may be summed up as follows:

1. The spectrum of burning magnesium, as has already been pointed out by Pickering, approaches much more nearly that of sunlight than does the spectrum of any other artificial illuminant.
2. The temperature of the magnesium flame, about 1340° C., lies between that of the Bunsen burner and that of the air blast lamp, although the character of its spectrum is such as would correspond to a temperature of nearly 5000° C. were its light due to ordinary incandescence.
3. The "radiant efficiency" is 13½ per cent; a value higher than that for any other artificial illuminant (excepting perhaps the light of the electric discharge in vacuo for which Dr. Staub of Zürich has found an efficiency of about 34 per cent.
4. The radiant energy emitted by burning magnesium is about 4630 calories per gram of the metal burned or 75 per

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* American Inst. of E. E., vol. vi, p. 173.

cent of the total heat of combustion; as compared with 15 per cent to 20 per cent in the case of illuminating gas.

5. The thermal equivalent of one candle-power-minute of magnesium light is about 2·4 lesser calories, as against 3·5 to 4·0 for other artificial illuminants.

6. The total efficiency of the magnesium light is about 10 per cent; as compared with ·25 per cent [a quarter of one per cent], for illuminating gas.

7. Taking into consideration the greater average luminosity of the rays of the visible spectrum of the magnesium flame, it is certain that *per unit of energy expended, the light-giving power of burning magnesium is from fifty to sixty times greater than that of gas.*

Physical Laboratory of Cornell University, June, 1891.