

## The Estimation of High Temperatures by the Method of Colour Identity

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XIX. *The Estimation of High Temperatures by the Method of Colour Identity.* By CLIFFORD C. PATERSON and B. P. DUDDING, A.R.C.Sc. (*From the National Physical Laboratory.*)

*Synopsis.*

1. Preliminary experiments are described on the method of "colour identity" adapted to the estimation of the temperature of incandescent substances such as metal or carbon radiating in the open; by this method the "true" temperature of certain bodies as distinct from their "black body" temperatures can be arrived at with a very fair degree of accuracy.

2. By the colour identity method the total luminous radiation (white light) from a black body is made identical in colour with that from the incandescent metal under examination by adjusting the temperature of the black body until there is colour identity in the field of a Lummer Brodhun photometer.

3. Comparisons are made of the results so obtained with those obtained by other methods, and the colour identity method is shown to give the correct result for melting platinum.

4. Formulæ are deduced, based on the fundamental theories of energy radiation and the sensitivity of the eye, connecting the temperature of carbon and tungsten filaments with their lumens per watt, and it is shown that these expressions hold from the lowest to the highest values of lumens per watt.

5. It is shown that the colour identity method of determining filament temperatures is practically independent of the cooling at the ends of the filaments of ordinary lamps.

6. An explanation is given of the principal factors and limitations of the colour identity method in which it is shown that accurate results should be obtained so long as the bodies under consideration act as "grey" bodies throughout the visible spectrum, and that there will be a tendency to error to the extent that they depart from the grey body condition in the *visible spectrum*.

7. The colour of the radiation from melting platinum is shown to be the same as that from a carbon filament lamp operating at 2.6 $\frac{1}{2}$  lumens per watt, or 4.7 $\frac{1}{2}$  watts per mean spherical candle, or approximately 3.8 watts per mean horizontal candle.

The work described in this Paper is not in the nature of a complete investigation of the subject. It had for its original

object the determination of the colour of the light from molten platinum under the open radiation conditions which prevail in the realisation of the Violle standard of light. A good primary standard of light must not only be constant and accurately reproducible, but the colour of its light should approximate to that of the sources which are ordinarily used in practice, so that large colour differences will not be involved in the photometric measurements for which such a standard is used. The object for which the investigation was started was completed over two years ago, but the progress of the work indicated some unexpected phenomena which it was intended to investigate further. Pressure of other work has up to now prevented this being done, and the authors desire at this stage to publish this preliminary note on the subject. The accuracy of the work is the accuracy of preliminary experiments in which all reasonable precautions have been taken. Values given for temperature certainly have not an absolute accuracy of more than 1 or 2 per cent., but the methods described are capable of a higher precision, and this will undoubtedly be attained in the fuller investigation which it is intended to undertake.

### *General Discussion.*

Optical pyrometry is almost exclusively concerned with the *intensity* of the light emitted by a luminous body in any given wave-length. The colour of the light thus dealt with is fixed by the wave-length or wave-lengths chosen for the measurements, and colour differences do not occur.

In ordinary photometry the sum of the intensities of the light emitted by a source in all wave-lengths over the visible spectrum is compared against the sum of the intensities of the light emitted by another source. The radiation from each source has thus a composite colour whose characteristics will depend on the relative intensity of the light in each wave-length. Although both sources may radiate according to the law of a black body, if there should be a difference of temperature between them the composite colour or hue of the radiations from the two bodies will differ, and it becomes necessary to compare intensities which are not of the same colour. For most solid radiators the colour of the light is a perfectly definite quality, and forms a criterion of the state of incandescence of such bodies. Most bodies are more or less selective in their radiation, but there is a certain group, consisting mainly of metallic substances, which although appa-

rently selective in favour of the visible spectrum *as a whole*, emit light throughout that spectrum without any appreciable deviation from the distribution to be found in the visible spectrum of a black body.\* For instance, consider a tungsten filament adjusted to a suitable temperature, and compared spectrophotometrically against a carbon filament. The one is mainly selective in favour of the visible spectrum as a whole, and the other acts in this respect as a black body. The spectrophotometer, dealing only with the visible spectrum, cannot detect any relative difference between the two at different wave-lengths throughout the portion of the spectrum with which it deals, and thus a comparison of the total visible radiation is possible with an ordinary photometer, exact identity of colour being obtainable. That is to say, these substances virtually radiate as "grey" bodies, as far at least as the visible spectrum is concerned, and it is this close approximation to grey body radiation in the visible spectrum which lies at the root of the method discussed in this Paper. Hence, identity of colour can be obtained not only when comparing one tungsten lamp against another, but also when comparing a tungsten lamp against a black body. If the temperature of these bodies is pushed to an extreme value a very slight difference of colour is perceptible at the point where the colour balance is closest, but such differences are too small to prevent an observer obtaining consistent results in judging the colour balance between two radiations.

A comparison of colour is made similarly to photometric comparisons of intensity. The current in the comparison lamp is varied so that the colour of the light fluctuates on both sides of the mean, first inclining to be redder and then to be bluer than the light from the test source. The current in the lamp is then readily determined at which the observer judges the colour balance to occur. It must be remembered that in these comparisons it is the hue of so-called white light which is under consideration, and not that of spectral or other colours.

The colour identity method depends on the combined effects of the light emitted in all wave-lengths in the visible region. If the intensity is relatively greater at the red end than at the blue end, the hue of the resulting radiation will tend to be red, and vice versa. The radiation from a black body at  $1,750^{\circ}\text{C}$ .

\* Coblenz, "Radiation Constants of Metals," "Bull." B.S., Vol. V, p. 359. Hyde, "Selective Emission of Incandescent Lamps," "Trans.," Ill. Eng. Soc., 1909.

has a definite hue depending on the relative proportions of the energy in the red, green and blue regions, and any other radiator emitting light in the same *relative proportions* will have the same hue of radiation, no matter what the absolute intensity of the radiations. Thus, it is that the radiation from a grey body will be identical in hue with that of a black body, and compared on the colour identity basis the grey body will be given its true temperature. The optical pyrometer, on the other hand, only takes account of the relative *intensities* of the light from the black and grey bodies, and, therefore, estimates the temperature of the grey body at a value far below its true temperature. It follows, therefore, that the measure of the accuracy of the colour identity method is the extent to which bodies radiate as *grey (or black) bodies throughout the visible spectrum*.

Throughout this Paper the usual conception of a grey body is adopted—*i.e.*, one which, at any temperature, does not radiate as much energy in the various wave-lengths as a black body at the same temperature, but in any wave-length the intensity per unit area of the surface is a constant fraction of that of the black body in the same wave-length.

By a selective body is meant one in which the amounts of energy radiated in the various wave-lengths throughout the whole spectrum do not bear a constant proportion to those in the same wave-lengths for a black body at the same temperature.

Section 1 of this note deals with the establishment of electric sub-standards of colour, which are intended to serve for defining the colour of the radiation from any incandescent bodies compared against them, and so to fix the temperature of such bodies in terms of the temperature of a black body whose radiation is identical with theirs in colour.

Section 2 gives the determination of "colour identity" temperatures of carbon and tungsten glow lamps when burning at different efficiencies, and contains expressions for such efficiencies in terms of temperature based on Wien's equation for intensity of energy distribution and Nutting's equation for the sensitivity of the human eye.

Section 3 discusses the accuracy of such determinations, and deals with the "colour identity" temperature of platinum at the melting point, showing that even for a selective radiator such as platinum this temperature is a measure of the true

temperature of the platinum filament, although it is glowing under open radiation conditions. Filament temperatures for carbon and tungsten (vacuum and gas-filled) are also discussed.

Section 4 deals with the colour of the radiation from molten platinum in relation to the practical usefulness of the Violle standard of light.

### 1. *Electric Sub-standards of Colour for the Determination of Temperature.*

In spite of the fact that the device of colour comparison by means of a Lummer Brodhun photometer has been used for many years by various observers for obtaining equality of efficiency of glow lamps of the same type, it is not generally realised how easily and with what precision such colour com-

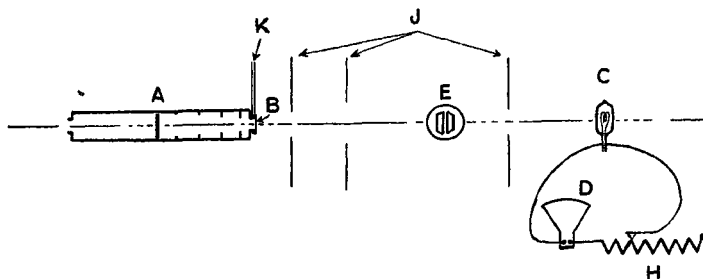


FIG. 1.—DIAGRAM SHOWING ARRANGEMENT OF APPARATUS USED TO OBTAIN THE RELATION BETWEEN THE CURRENT IN CARBON AND TUNGSTEN FILAMENT LAMPS, AND THE TEMPERATURE OF A BLACK BODY AT EQUALITY OF HUE OF THEIR RADIATIONS.

parisons can be made. Morris,\* Stroud and Ellis employed this method in 1907, and extensive use has been made of it for investigating selectivity and other properties of radiating substances by E. P. Hyde,† with whom Cady and Middlekauff have sometimes collaborated. Hyde,‡ in discussing the question of colour identity and temperature (p. 40, *loc. cit.*), showed that a colour match with a black body might be regarded as indicating that the temperature of the black body was at

\* Morris, Stroud and Ellis, "The Electrician," Vol. LIX., p. 584.

† Hyde, Cady and Middlekauff, "Selective Emission of Incandescent Lamps," Ill. Eng. Soc., New York, Vol. IV., 1909, p. 334. Hyde, "Physical Characteristics of Luminous Sources," Lectures, John Hopkins University, 1910. Hyde, "Radiation Laws for Metals," "Astrophys. Journ.," Vol. XXXVI., 1912, p. 89.

‡ Hyde, "The Physical Production of Light," "Journ." Franklin Inst., Vol. CLXX., 1910.

least as high or higher than that of the body compared against it, but he expressed the opinion (p. 39) that under the condition of colour identity two different radiators although with continuous spectra would not be at the same temperature.

A black body furnace electrically heated and capable of being raised to a temperature of  $2,200^{\circ}\text{C}.$ , with a clear internal atmosphere, was kindly put at the disposal of the authors by Dr. J. A. Harker, F.R.S. The very excellent arrangements of this furnace need not be explained in detail here. The apparatus is shown diagrammatically in Fig. 1. A is a black body kept clear of fumes by a stream of nitrogen admitted at K.

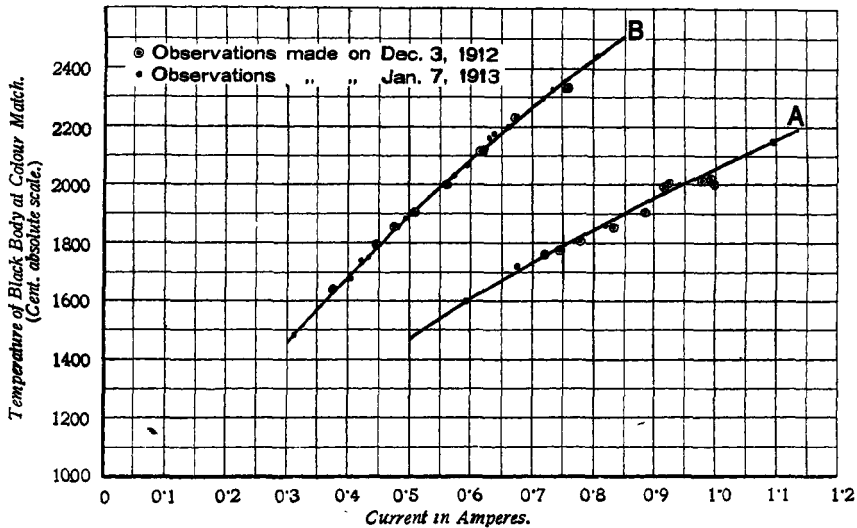


FIG. 2.—CARBON (A) AND TUNGSTEN (B) COLOUR STANDARDS.

Curves connecting the current in the lamps with the temperature of the black body whose radiation is identical in colour with that of the lamps.

B is a diaphragm with glass window, which permits only light from the centre of the incandescent surface to pass down the photometer bench, and J are screens to cut off extraneous light. C is a carefully seasoned electric lamp, the current through whose filament can be accurately measured by means of ammeter D. Between the two at E is a Lummer Brodhun photometer head. This photometer is not used to compare the *intensities* of the two sources of light A and C, but to determine when the hue of their radiations is identical. Two optical pyrometers were used of the Siemens and F  ry types, by means

of which the temperature of the black body was determined before and after each colour determination by the photometer. Complete determinations were made on two separate occasions and the mean result taken—every photometer and pyrometer setting being made on each occasion by two observers. The furnace was first run at a relatively low temperature, and the electric heating adjusted so that it would remain at a constant temperature sufficiently long for both photometric and pyrometric readings to be taken. The hue of the light from the electric lamp C was varied by means of rheostat H until there was exact identity of colour in the photometer. In doing this it is, of course, necessary to place the photometer so that there is also equality of brightness.

Two or three settings were made by each observer before and after which the pyrometers were read. The same process was followed in a series of increasing temperatures up to about 2,200°C.—the maximum temperature to which the furnace was carried in these experiments. Two electric lamps were calibrated in this way, one having a carbon and the other a tungsten filament. These two lamps calibrated in the above manner form intermediate standards of colour against which any glow lamp can be matched, and the temperature of the black body fixed to which the colour of its light corresponds. The temperatures so determined are on the optical scale, using pyrometers for which the dominant wave length is  $\lambda=0.650\mu$ .

Fig. 1 shows the curve connecting current in the lamps and the temperature of the black body for colour identity in the case of each of these lamps. It was found that the sensitivity of the process of colour matching is more than equal to that of temperature measurement by optical pyrometers.

Duplicates of these two lamps were then made for use in experiments where their continued employment at the higher efficiencies might affect their constancy.

## 2. “Colour Identity” Temperatures Corresponding with Different Efficiencies.

It is common for the specific consumption of glow lamps to be stated in terms of the watts per mean horizontal candle. The only rigorous way, however, is to state it in terms of watts per mean spherical candle or in lumens per watt. Throughout this Paper the latter designation is used, representing as it does the true measure of the ratio of the total light emitted to the



power supplied. In the table of results the approximate watts per mean horizontal candle of the glow lamps is also given, since this is the more familiar designation, but it is not rigorous on account of the varying ratios of mean horizontal to mean spherical candle-power to be found in different lamps. It is to be noted that in the determination of the total light emitted from the glow lamps the light which is obscured by the cap of the lamp is counted as being radiated and not absorbed, but in any case this light is less than 1 per cent. of the total for filaments of ordinary form.

The objects of the measurements are :—

(a) to find the relation between the various values of lumens per watt for tungsten and carbon filament lamps and the corresponding temperatures of a black body on the basis of colour identity ;

(b) to ascertain to what extent the temperature so measured represents those of the principal parts of the glowing filaments, having regard to the cooling effect of the filament supports ;

(c) to find laws connecting lumens per watt and corresponding "colour identity" temperature for tungsten and carbon filaments.

Evidence is given later in the Paper to show that there seems to be justification for the assumption that the colour identity method at any rate in certain cases gives within narrow limits a measure of the true filament temperature. This assumption is, therefore, made in what immediately follows here, and it will be seen that the results which follow from this assumption whilst not proving its validity, are in agreement with those of Forsythe, who determined temperatures by more orthodox methods.

(a) A number of carbon and tungsten filament lamps were selected for the measurements. The carbon lamps had both flashed and unflashed filaments. The tungsten lamps had squirted and drawn filaments of different diameters and lengths, so that the effect of the cooling of the ends by the leading-in wires if appreciable might be observed.

All the lamps were measured for lumens per watt at different voltages up to the highest they were capable of standing without deterioration. They were then compared for identity of colour against the colour standards, and in this way the temperatures of a black body were determined which corresponded with the various values of lumens per watt. The results are given in Table I., and plotted in Fig. 3.

TABLE I.

(Reduction factor=Mean spherical candle-power divided by mean horizontal candle-power.)

Volts.	Watts per mean horizontal candle.	Lumens per watt.	Temperature of black body at identity of colour (Cent. absolute).	Volts.	Watts per mean horizontal candle.	Lumens per watt.	Temperature of black body at identity of colour (Cent. absolute).
<i>Carbon Filament Lamp (flashed) No. 1.</i> 100 volts, 16 candles.				<i>Carbon Filament Lamp (flashed) No. 2.</i> 100 volts, 16 candles.			
Reduction Factor=0.85 <sub>5</sub> .				Reduction Factor=0.89.			
49.2 <sub>5</sub>	111.0	0.09 <sub>7</sub>	1,515	65	20.2	0.55 <sub>5</sub>	1,715
59.5 <sub>0</sub>	38.0	0.28 <sub>1</sub>	1,640	70	14.1	0.80	1,775
72.7 <sub>0</sub>	13.9	0.77 <sub>5</sub>	1,755	75	10.3	1.09	1,835
82.7 <sub>0</sub>	7.9 <sub>5</sub>	1.35	1,865	80	7.7 <sub>0</sub>	1.45	1,890
92.5 <sub>0</sub>	5.0 <sub>3</sub>	2.14	1,960	85	6.1 <sub>8</sub>	1.84	1,935
103.0	3.7 <sub>7</sub>	2.85	2,055	90	4.8 <sub>2</sub>	2.33	1,980
110.0	2.5 <sub>9</sub>	4.14	2,120	100	3.2 <sub>1</sub>	3.43	2,075
130.0	1.5 <sub>6</sub>	6.85	2,250	105	2.6 <sub>9</sub>	4.17	2,120
135.0	1.3 <sub>7</sub>	7.7 <sub>7</sub>	2,300	107	2.5 <sub>2</sub>	4.44	2,135
140.0	1.2 <sub>1</sub>	8.8 <sub>5</sub>	2,325				
<i>Carbon Filament Lamp (flashed) No. 3.</i> 100 volts, 16 candles.				<i>Carbon Filament Lamp (flashed) No. 4.</i> 200 volts, 16 candles.			
Reduction factor=0.85.				Reduction factor=0.86 <sub>5</sub> .			
65	19.5	0.55	1,720	140	18.2	0.60	1,710
70	13.9	0.77 <sub>5</sub>	1,775	150	12.7	0.85	1,770
75	10.0	1.06 <sub>5</sub>	1,835	160	9.0 <sub>0</sub>	1.18	1,835
80	7.6 <sub>4</sub>	1.40 <sub>5</sub>	1,890	180	5.2 <sub>0</sub>	2.09	1,955
85	6.0 <sub>4</sub>	1.77 <sub>5</sub>	1,935	200	3.2 <sub>7</sub>	3.41	2,070
90	4.8 <sub>6</sub>	2.20	1,985	210	2.6 <sub>8</sub>	4.05	2,120
100	3.3 <sub>4</sub>	3.21	2,070	220	2.2 <sub>0</sub>	4.95	2,165
105	2.7 <sub>9</sub>	3.83	2,115				
107	2.6 <sub>3</sub>	4.07	2,130				
115	2.0 <sub>4</sub>	5.25	2,200				
120	1.8 <sub>1</sub>	5.91	2,240				
130	1.4 <sub>3</sub>	7.50	2,310				
135	1.2 <sub>5</sub>	8.58	2,345				
<i>Tungsten Filament Lamp (Drawn) No. 6.</i> 115 volts, 30 watts.				<i>Carbon Filament Lamp (unflashed) No. 5.</i> 200 volts, 16 candles.			
Reduction factor=0.79.				Reduction factor=0.82 <sub>5</sub> .			
38.2	21.7	0.46	1,640	140	22.2	0.47	1,710
47.4	11.1	0.90	1,755	150	15.2	0.68	1,775
57.8	6.3 <sub>2</sub>	1.57	1,865	160	10.9	0.95	1,835
68.7	4.0 <sub>2</sub>	2.47	1,960	180	6.1 <sub>4</sub>	1.68	1,940
93.2	1.9 <sub>2</sub>	5.17	2,145	200	3.7 <sub>8</sub>	2.74	2,050
120.5	1.1	9.00	2,325	210	3.0 <sub>8</sub>	3.36	2,095
				220	2.5 <sub>4</sub>	4.08	2,140
<i>Tungsten Filament Lamp (Squirted) No. 7.</i> 105 volts, 32 watts.				<i>Tungsten Filament Lamp (Squirted) No. 8.</i> 105 volts, 30 watts.			
Reduction factor=0.79.				Reduction factor=0.78 <sub>5</sub> .			
38.8	15.6	0.63	1,640	37	14.7	0.72	1,710
48.2	9.3 <sub>4</sub>	1.06	1,755	40	11.6	0.85	1,745
57.2	5.4 <sub>1</sub>	1.84	1,865	45	7.8 <sub>5</sub>	1.26	1,800
67.0	3.5 <sub>8</sub>	2.78	1,960	50	6.1 <sub>6</sub>	1.62	1,860
90.5	1.7 <sub>6</sub>	5.66	2,145	55	4.7 <sub>8</sub>	2.10	1,900
117.0	1.0 <sub>5</sub>	9.54	2,325	60	3.7 <sub>8</sub>	2.61	1,960
				65	3.0 <sub>6</sub>	3.28	2,010
				70	2.6 <sub>0</sub>	3.81	2,055
				75	2.2 <sub>2</sub>	4.47	2,095
				80	1.9 <sub>1</sub>	5.21	2,135
				90	1.4 <sub>3</sub>	6.65	2,215
				100	1.2 <sub>0</sub>	8.19	2,285
				105	1.0 <sub>9</sub>	9.06	2,320

TABLE I.—*Continued.*

Volts.	Watts per mean horizontal candle.	Lumens per watt.	Temperature of black body at identity of colour (Cent. absolute).	Volts.	Watts per mean horizontal candle.	Lumens per watt.	Temperature of black body at identity of colour (Cent. absolute).
<i>Tungsten Filament Lamp (Squirted) No. 9.</i> 105 volts, 60 watts. <i>Reduction factor=0.78<sub>5</sub>.</i>				<i>Tungsten Filament Lamp (Drawn) No. 10.</i> 100 volts, 15 watts. <i>Reduction factor=0.78<sub>5</sub>.</i>			
40	12 <sub>8</sub>	0.77 <sub>5</sub>	1,710	45	8.6 <sub>0</sub>	1.17	1,800
45	9.8 <sub>2</sub>	1.01	1,775	50	6.1 <sub>5</sub>	1.59	1,860
50	7.3 <sub>4</sub>	1.35	1,835	55	4.8 <sub>0</sub>	2.05	1,915
55	5.7 <sub>0</sub>	1.74	1,880	60	3.8 <sub>8</sub>	2.55	1,960
60	4.5 <sub>3</sub>	2.18	1,920	65	3.2 <sub>0</sub>	3.09	2,015
65	3.7 <sub>1</sub>	2.67	1,970	70	2.6 <sub>6</sub>	3.71	2,055
70	3.1 <sub>2</sub>	3.17	2,015	75	2.2 <sub>6</sub>	4.36	2,105
75	2.6 <sub>5</sub>	3.73	2,055	80	1.9 <sub>5</sub>	5.10	2,140
80	2.2 <sub>6</sub>	4.37	2,100	90	1.5 <sub>0</sub>	6.75	2,225
90	1.7 <sub>4</sub>	5.70	2,175	100	1.2 <sub>1</sub>	8.13	2,290
100	1.3 <sub>9</sub>	7.12	2,245	105	1.1 <sub>1</sub>	9.02	2,325
105	1.2 <sub>5</sub>	8.06	2,280	110	1.0 <sub>0</sub>	9.88	2,360
110	1.1 <sub>4</sub>	8.66	2,315	115	0.91 <sub>5</sub>	10.8 <sub>2</sub>	2,400
115	1.0 <sub>4</sub>	9.51	2,340	120	0.83 <sub>5</sub>	11.8 <sub>3</sub>	2,430
120	0.94 <sub>5</sub>	10.4	2,375	125	0.77 <sub>5</sub>	12.7 <sub>6</sub>	2,455
125	0.88 <sub>5</sub>	11.2	2,395	130	0.72 <sub>0</sub>	13.7 <sub>3</sub>	2,485
130	0.82 <sub>0</sub>	12.1	2,435	135	0.66 <sub>5</sub>	14.8 <sub>5</sub>	2,505
135	0.76 <sub>0</sub>	13.0	2,460				
<i>Tungsten Filament Lamp (Drawn) No. 11.</i> 200 volts, 20 watts. <i>Reduction factor=0.78<sub>5</sub>.</i>				<i>Tungsten Filament Lamp (Drawn) No. 12.</i> 230 volts, 60 watts. <i>Reduction factor=0.78<sub>5</sub>.</i>			
80	13.5	0.73	1,720	100	9.5 <sub>0</sub>	1.04	1,770
90	9.7 <sub>0</sub>	1.02	1,770	110	7.3 <sub>5</sub>	1.34	1,825
100	7.2 <sub>5</sub>	1.36	1,835	120	5.7 <sub>0</sub>	1.74	1,870
110	5.5 <sub>0</sub>	1.80	1,885	130	4.5 <sub>1</sub>	2.17	1,915
120	4.4 <sub>2</sub>	2.23	1,935	140	3.8 <sub>0</sub>	2.60	1,960
130	3.5 <sub>8</sub>	2.75	1,970	150	3.1 <sub>9</sub>	3.10	2,000
140	3.0 <sub>1</sub>	3.28	2,020	160	2.7 <sub>4</sub>	3.60	2,040
150	2.5 <sub>5</sub>	3.87	2,060	170	2.3 <sub>5</sub>	4.1 <sub>9</sub>	2,080
160	2.1 <sub>8</sub>	4.4 <sub>8</sub>	2,105	180	2.0 <sub>5</sub>	4.8 <sub>1</sub>	2,110
180	1.7 <sub>1</sub>	5.8 <sub>5</sub>	2,170	190	1.8 <sub>1</sub>	5.4 <sub>8</sub>	2,145
200	1.3 <sub>8</sub>	7.2 <sub>5</sub>	2,245	210	1.4 <sub>8</sub>	6.7 <sub>8</sub>	2,210
210	1.2 <sub>5</sub>	7.9 <sub>0</sub>	2,270	230	1.2 <sub>2</sub>	8.0 <sub>8</sub>	2,270
220	1.1 <sub>4</sub>	8.0 <sub>6</sub>	2,320	240	1.1 <sub>3</sub>	8.7 <sub>2</sub>	2,305
				260	0.96 <sub>5</sub>	10.2	2,360

In obtaining the higher temperature values for plotting on Fig. 3, it is very useful to make use of a "watt-temperature" curve. The carbon lamp, for instance, cannot with safety be run for long periods at temperatures in the region of 2,000°C. If the watts be plotted against temperatures obtained by the identity of colour method the resulting curve will be found to be a logarithmic, and no deviation whatever can be detected

from such logarithmic over the range between the highest and the lowest observed values. This is illustrated in Fig. 4, in which the logs of temperature and watts have been plotted for both carbon and tungsten lamps Nos. 3, 5, 6, 8 and 12. It is

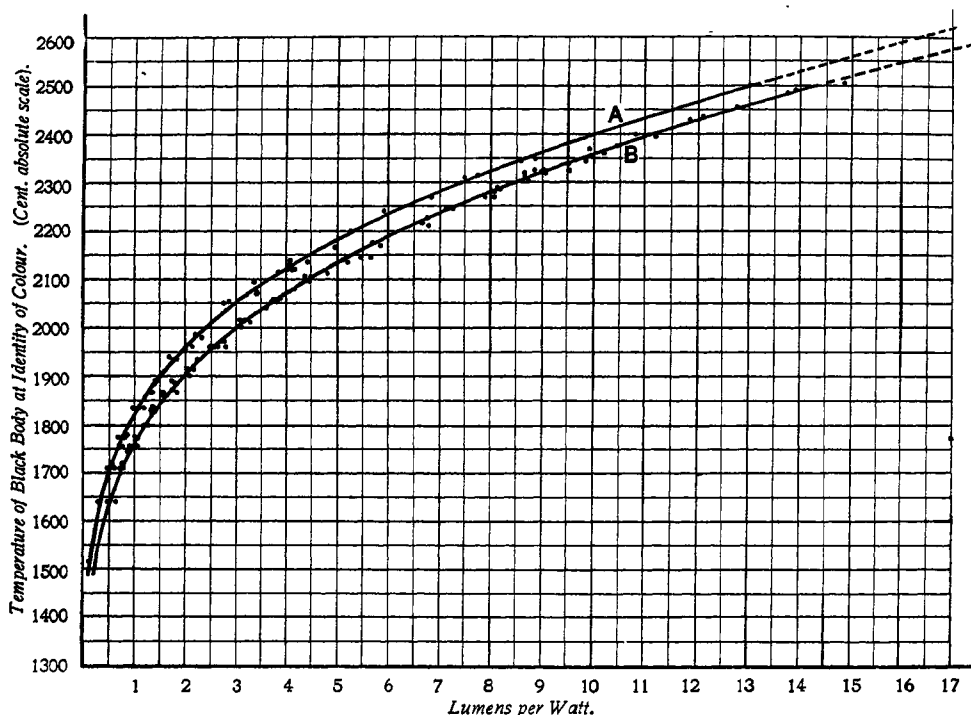


FIG. 3.—ORDINARY 100 AND 200-VOLT CARBON (CURVE A) AND TUNGSTEN (CURVE B) FILAMENT VACUUM LAMPS.

Curves connecting lumens per watt of the lamps with the temperature of a black body whose radiation is identical in colour with that of the lamps.

safe from a knowledge of the watts in any lamp to deduce intermediate temperature values from such a curve, so that the actual number of colour comparisons may be a minimum, and the burning period of the colour standard reduced.

The watt-temperature relation is given, for carbon filament lamps, by

$$W \propto T^{4.58},$$

and for tungsten filament lamps by

$$W \propto T^{5.1}.$$

Considering again Fig. 3, the first point to notice is that no difference can be detected between the various carbon lamps tested or between the different tungsten lamps. Whether the carbon filaments are flashed or unflashed, and the tungsten filaments squirted or drawn, appears to leave unaffected the relation between lumens per watt and the corresponding "colour identity" temperature of a black body for either of these types.

It will, therefore, be seen that all the results may be taken as

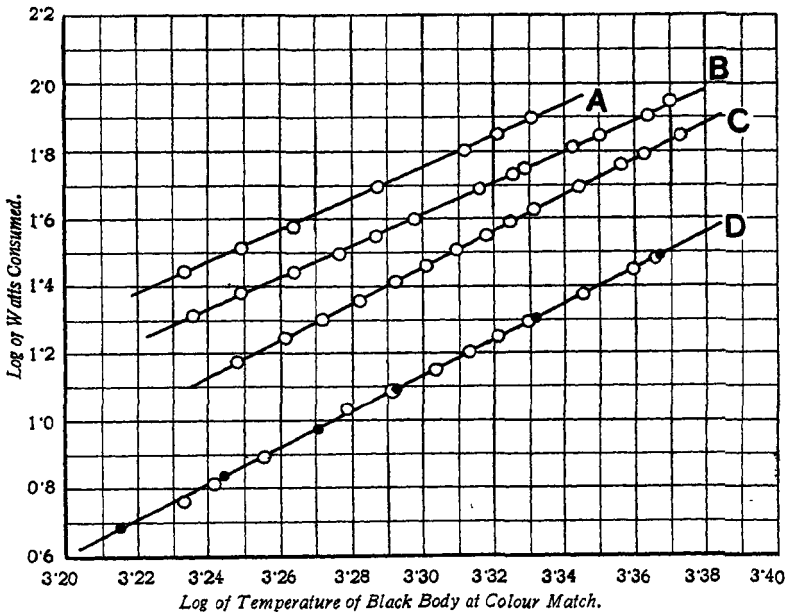


FIG. 4.

Curves connecting watts consumed by carbon and tungsten filament lamps, and the temperature of the black body whose radiation matches in colour that of the lamps.

A	is for Lamp No. 5.	(Carbon filament.)
B	" " No. 3.	( " " )
C	" " No. 12.	(Tungsten " )
D	" " Nos. 6 and 8.	( " " )

lying on two curves, one representing the carbon group and the other the tungsten group, and so closely do the points keep to the curves that very few observations lie more than 1 per cent. in temperature from the mean curve.

This implies that in all ordinary lamps of the same character (vacuum tungsten or carbon) the colour of the radiation from the whole filament, including the cooled ends, is the same for the same value of lumens per watt. Therefore, to considerable

accuracy it may be said, that a knowledge of the lumens per watt of a lamp implies a knowledge of the temperature of a black body whose radiation is the same in hue as that of the lamp.

(b) The following considerations show to what extent a temperature, determined as above, may be regarded as the temperatures of the main glowing part of the filament. If there were no cooling at the ends of a filament it would be equally bright for the whole of its length. The cooling, however, as shown by Hyde, Cady and Worthing\* is appreciable, but it must be remembered that the colour of the light is governed by the part of the filament giving off most light. The ends of the filament give off actually very little light because the amount emitted falls off according to a very high power of the temperature ( $T^{12}$  to  $T^{20}$ ). Hence the effect of the dulled ends of the filament on the colour of the total light from it, is exceedingly small. In an actual case† the total light emitted below the point where the filament began to become measurably dull was only 5 per cent. of the whole, and a large percentage of this amount differs only very slightly in colour from the light emitted by the remainder of the filament.

The following measurements, Table II., were made of the total effect on the measured temperature due to end cooling by determining the "colour identity" temperature of the central portion of the filament only and comparing it against that of the whole filament, including the cooled ends.

TABLE II.

Lamp.	Volts.	Temperature of black body for colour identity.	
		Whole filament.	Centre of filament.
No. 11 .....	200	2,245	2,255
	110	1,885	1,898
	54	1,556	1,570
No. 9 .....	105	2,280	2,290
	60	1,920	1,930
	40	1,710	1,722
Motor headlight. 16 volts, 50 watts	...	1,486	1,508
	...	2,014	2,043
	...	2,240	2,285

\* Amer. Ill. Eng. Soc. "Trans." 6, pp. 238-257.

† See Hyde, Cady and Worthing. *Loc. cit.*

Lamp No. 11 was an ordinary 200 volt, 20 watt tungsten lamp, and No. 9 was rated for 100 volts, 55 watts; the difference of filament diameter and distance between supports were, therefore, as large as is usually met with in practice. The motor headlight filament was for 16 volts and 50 watts, and, therefore, represented an extreme case.

It will be seen from this that unless a very thick, short filament be taken with abnormal end cooling, the measured colour identity temperature will be that of the central bright portion of the filament, within about 1 per cent. Whilst in the extreme case of the headlight lamp it is of the order of 2 per cent. It is obvious that the cooling effect for carbon filament lamps is considerably less than for tungsten, and is, in fact, quite inappreciable.

It is thus clear that the colour identity method gives results which depend very closely on the temperature of the central portion of the filament. If it may be assumed that the method also gives the *true* temperature of lamp filaments, the figures in Table I. and Fig. 3 indicate the appreciable difference of efficiency existing between the carbon and tungsten lamps for the same temperature, and, therefore, establish the selectivity of the tungsten filament in favour of the shorter wave-lengths, a subject upon which much has been written, and which has been thoroughly investigated by Dr. E. P. Hyde.\* This difference in efficiency would, if anything, be very slightly increased by taking into account the end cooling of the filaments, the tendency of which is to act in favour of the carbon lamp. Also, if the carbon filament is "greyer" than the tungsten filament in the visible region the apparent difference of efficiency will be increased.

(c) Referring to the curves shown in Fig. 3 and bearing in mind what has been said in the foregoing remarks, it becomes of interest to know if a relation connecting lumens per watt and temperature can be deduced from our knowledge of the phenomena involved, and especially to ascertain how nearly the experimental observations conform to such a relation deduced from theoretical considerations.

We have to consider, therefore, how the rate of dissipation of energy by a lamp filament, *i.e.*, the watts,† increases with a

\* See Hyde. *Loc. cit.*

† The rate at which energy is radiated is power and is spoken of hereafter as radiant power.

rise in temperature, and also how the eye estimates the rate at which this energy is radiated.

The eye is only sensitive to a small portion of this energy, *i.e.*, that emitted in wave-lengths lying approximately between  $0.3\mu$  and  $0.8\mu$ . Further, the eye does not appreciate the intensity of the energy radiation in any wave-length over this limited range in direct proportion to the amount radiated, but weights it according to its own peculiar sensitivity to energy of that wave-length. This appreciation of power by the eye is expressed in lumens which may be defined as the measure of the appreciation of the eye for radiant power.

An expression must, therefore, be found connecting lumens and the temperature of the radiating body both in terms of the power distribution throughout the visible spectrum and of the sensitivity characteristics of the eye.

The theoretical investigation of the problem thus subdivides itself naturally into three distinct parts:—

(a) The rate of energy dissipation of the radiator at any temperature.

(b) The quantitative distribution of this radiant power throughout the spectrum at any temperature, with special reference to that range of the spectrum over which the energy stimulates the sense of vision.

(c) The relative capacity of equal amounts of radiant-power in different wave-lengths for stimulating vision, this being necessarily referred to the average or normal human eye.

(a) *Relation Between Watts and Temperature.*—Attention has been already drawn to curves showing the relation between the rate of dissipation of energy by a lamp and its temperature as measured by the colour identity method. Many lamps of ordinary dimensions have been examined, and in all cases the results can be expressed by an equation of the form

$$\text{watts} \propto T^m \text{ or } (\log W = \log D + m \log T), \quad . \quad . \quad . \quad (1)$$

$m$  being  $4.5$  to  $4.6$  for carbon lamps and  $5.0_5$  to  $5.2$  for tungsten lamps.

In no case has any appreciable deviation been observed from this logarithmic relationship for temperatures ranging from  $1,700$  deg. to  $2,300$  deg. abs.

This relationship is at once recognised as being identical in form with that ascribed to Stefan and Boltzman connecting the temperature and radiant watts of the ideal black body,  $m$  in the latter case being  $4.0$ .



(b) *Distribution of Radiant Power throughout the Visible Spectrum.*—In the case of the ideal black body, the radiant power in any wave-length of the visible spectrum at any temperature below 3,000°C. can be expressed according to the well-known law of Wien

$$E = C_1 \lambda^{-n} e^{-\frac{C_2}{\lambda T}} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

$E$  being the radiant power of wave-length  $\lambda$  at temperature  $T$ ,  $C_1$  and  $C_2$  being constants,  $n=5$  (for a black body).

Seeing that in the experiments described in the following section (3), in which the colour of the radiation of melting platinum was found to be identical with that of a black body operating at the same temperature, it is reasonable to assume that the power distribution, at least *over the range of the visible spectrum*, can be expressed by a formula of the above form. Lummer and Pringsheim found this condition to be closely fulfilled by radiators having the characteristics of platinum.

When the visible spectrum only is under consideration the values of  $C_1$ ,  $C_2$  and  $n$  can vary considerably without affecting the shape of the curve by an amount corresponding to a difference of temperature of 10°C. in the region of 2,000°C.

(c) *Sensitivity of the Eye to Energy of Different Wave-lengths.* By examining a large number of persons, Nutting\* has obtained data connecting the wave-lengths of radiant energy and the luminous sensation produced per unit of power in that wave-length.

He expresses his results in the form

$$V_\lambda = V_m \left( \frac{\lambda_m}{\lambda} \right)^a e^{a \left( 1 - \frac{\lambda_m}{\lambda} \right)} \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where  $V_m$  is the photometric value of a unit of power in the wave-length of maximum sensitivity  $\lambda_m$ ,  $a$  is a constant,  $e$  is the base of Napierian logarithms.

For the luminous intensities ordinarily employed in photometry he gives  $a=181$  and  $\lambda_m=0.55\mu$ .

Combining the expression for power distribution and the sensitivity curve for the eye (equations 2 and 3), we obtain for the photometric value of radiant power of wave-length  $\lambda$ ,  $E_\lambda V$ , and for the photometric value of the whole of the radiant power

$$\int_0^\infty E_\lambda V_\lambda d\lambda \quad . \quad . \quad . \quad . \quad . \quad (4)$$

\* "Bulletin" of the Bureau of Standards, Vol. V., p. 261, and Vol. VI., p. 337.

If the power distribution can be represented by

$$E_{\lambda} = P \lambda^{-n} e^{-\frac{Q}{\lambda T}} \quad . \quad . \quad . \quad . \quad . \quad (5)$$

Nutting\* shows that the above expression for the photometric value of radiant power reduces to

$$L = A \left( 1 + \frac{B}{T} \right)^{-\rho} \quad . \quad . \quad . \quad . \quad . \quad (6)$$

where the photometric value of the total radiant power in lumens at a given temperature,  $T$ , is represented by  $L$ ,

$$A = P V_m \lambda_m^a e^a (a \lambda_m)^{-\rho} \Gamma \rho, \quad .$$

$$B = \frac{Q}{a \lambda_m},$$

$$\rho = n + a - 1.$$

It follows from what has been said above that the lumens radiated by carbon or tungsten filaments should be capable of being represented by an expression of the form of equation (6). Combining with this expression that for the watt-temperature relationship for the filament under consideration (equation 1), we get for the equation connecting lumens per watt and temperature

$$\frac{L}{W} = A_1 \left( 1 + \frac{B}{T} \right)^{-\rho} T^{-m},$$

or expressed for convenience in the logarithmic form

$$\text{Log } \frac{L}{W} = C - m \log T - \rho \log \left( 1 + \frac{B}{T} \right) \quad . \quad . \quad . \quad . \quad (7)$$

From the measured values of lumens/watt and temperature, which are plotted in Fig. 3, the following values of the constants in the foregoing equation are found.

For carbon filaments

$$\text{Log}_{10} \frac{L}{W} = 21.51 - 4.58 \log_{10} T - 185 \log_{10} \left( 1 + \frac{155}{T} \right) \quad (8)$$

and for tungsten filaments \*

$$\text{Log}_{10} \frac{L}{W} = 23.31_2 - 5.1 \log_{10} T - 185 \log_{10} \left( 1 + \frac{155}{T} \right) \quad (9)$$

\* *Loc. cit.*

The curves drawn in Fig. 3 are those derived from these equations, and it will be seen at once how nearly the observations fall on the curves; in fact, it would hardly be possible to find a form of curve which would fit the observations better. The error in temperature rarely exceeds 2 per cent. and in most cases is considerably less than 1 per cent.—*i.e.*, within the possible error of the experiments. Further, it is shown later that a very large extrapolation of the tungsten curve by this formula indicates a value for the melting point of tungsten which is not inconsistent with that found by other observers. The formulæ indicate that the maximum attainable efficiency would occur in the region of 6,000°C., which is quite in accord with accepted theories.

The origin of the constants in equations 7, 8 and 9 should be particularly noted. The watts-temperature relationship for a lamp has been found to be of the form  $W \propto T^m$  (equation 1),  $m$  being a constant which appears in equation (7). The constant  $\rho$  of equation (7) is equal to  $n+a-1$ , where “ $-n$ ” is the index of  $\lambda$  in equation (2) of the “Wien” form, which is assumed to give the power distribution curve for the filament throughout the visible part of the spectrum, and where “ $a$ ” is derived from Nutting’s equation for the sensitivity of the

eye and has the value of 181.  $B = \frac{Q}{a\lambda_m}$  (see equation 6), where

$Q$  is the other constant in the assumed Wien equation for power distribution, “ $a$ ” has the value as before of 181, and  $\lambda_m$  is the wave-length of the energy to which the eye is most

sensitive, *i.e.*,  $0.55\mu$ . Hence  $B = \frac{Q}{99.55}$ . For a true black or grey body  $m=4$ ,  $n=5$ ,  $\rho=185=14,500$ , and  $B=145.0$  approximately.

Before leaving the consideration of these equations connecting lumens per watt and temperature, it is desirable to discuss one or two points which at first sight may appear to have an important bearing on the deductions that can be made from the foregoing results.

Firstly as regards “ $n$ ” in equation (5) and “ $m$ ” in equation (7). For a black body the value of “ $n$ ” in equation (5) is 5, and it will also be 5 for a true grey body whose radiation in all wave-lengths bears a definite proportion to that of a black body. It will not necessarily be 5, however, for selective bodies, although, as in the selective bodies under consideration,

they appear to radiate very much like grey bodies over *the visible spectrum*.

In equation (7) the constant " $m$ ," which is derived directly from equation (1), can only be regarded as connected with " $n$ " ( $n=m+1$ ) in equation (5) if the latter represents the distribution of power throughout the *whole* spectrum, and not merely in the visible spectrum. This latter is the assumption made in using equation (5) in this investigation, and the extent of the work described here does not justify the wider application of equation (5) to the whole spectrum for substances which do not behave as true black or grey bodies.

Lummer and Pringsheim\*, investigating platinum, state that the distribution of power throughout the whole spectrum for platinum is given by the following equation:—

$$E_{\lambda} = a\lambda^{-6} e^{-\frac{15,600}{\lambda T}} \quad . \quad . \quad . \quad . \quad . \quad (10)$$

corresponding to the form for an ideal black body of

$$E_{\lambda} = C_1 \lambda^{-5} e^{-\frac{14,500}{\lambda T}} \quad . \quad . \quad . \quad . \quad . \quad (11)$$

If this assumption were justifiable, the authors values for tungsten work out very nearly the same as those given by Lummer and Pringsheim for platinum; but, for the reasons just stated, too much significance must not be attached to this agreement.

Coblentz† expresses the opinion, based on an investigation of several metals, that " $n$ " in equation (5) is not a constant, but is a function of wave-length and temperature.

There is nothing in the results discussed above which is inconsistent with either Lummer and Pringsheim's or Coblentz's suggestions.

Throughout this work the practical case has been dealt with of filaments mounted in exhausted globes in which there is undoubtedly some loss of watts and efficiency due to the cooling effect of the leading-in wires. If conclusions of a fundamental nature are to be drawn from the results obtained, it is necessary to know to what extent this cooling is likely to affect the constants given in equations (8) and (9).

In the work already referred to by Hyde and Cady, figures are given for the loss of watts by conduction at the ends of

\* Lummer and Pringsheim, "Verhandlungen der Deutschen Phys. Gesell.," pp. 23-25, 1899.

† "Bulletin" B.S., Vol. V., pp. 338-379, 1908-1909.

filaments, and columns I. to IV. of the following Table are from this Paper.

TABLE III.

I. Lamp.	II. Watts	III. Watt loss.	IV. Effi- ciency loss.	V. Lumens Watt.	VI. Temp. ° Abs.
	mean horizontal candles.				
Carbon 115 volts ...	3.1	2%	4%	3.4 <sub>5</sub>	2,085
„ „ „ ...	18.0	3%	5%	0.5 <sub>9</sub>	1,730
Tungsten 115 volts, 60 watts	1.25	4%	7%	8.0	2,280
„ „	11.0	8%	16%	0.9 <sub>1</sub>	1,745

These losses are calculated for different efficiencies as a percentage of the watts which would be required to maintain the filament throughout its whole length at the temperature of its midpoint, assuming no loss by conduction.

In columns V. and VI. are tabulated the values of lumens per watt calculated from Column II. using average values for the reduction factors of the types of lamp under consideration, and the corresponding temperatures taken from the curves in Fig. 3.

The difference between the temperature corresponding to the colour of the light radiated from the *centre* of the filament of any lamp of the above types, and that radiated from the *whole* filament are given in Table II. The following results are obtained by using the values in Tables II. and III. for ascertaining what would be the behaviour of the filaments used in this investigation had there been no cooling.

#### *Carbon Lamps.*

In ordinary lamps the watts and temperature are connected by the relation

$$\text{Log}_{10} W = C_1 + 4.58 \log_{10} T. \quad . \quad . \quad . \quad (12)$$

Allowing for the watt loss as per column III., Table III., due to conduction, the watt-temperature relation for a filament kept at uniform temperature throughout its length and having no conduction losses is :

$$\text{Log}_{10} W_1 = C_1 - 0.191 + 4.63_5 \log_{10} T. \quad . \quad . \quad (13)$$

Likewise for ordinary lamps the relation between lumens per watt and temperature is expressed by

$$\text{Log}_{10} \frac{L}{W} = C_2 - 4.58 \log_{10} T - 185 \log_{10} \left( 1 + \frac{155}{T} \right). \quad . \quad (14)$$

Allowing in a similar manner for the efficiency losses (column IV., Table III.), the lumens per watt and temperature relation for the ideal filament is given by

$$\text{Log } \frac{L}{W} = C_2 + 0.199 - 4.63_5 \log T - 185 \log \left(1 + \frac{155}{T}\right). \quad (15)$$

#### *Tungsten Lamps.*

Similarly the equations for tungsten filaments are changed when cooling is allowed for, from

$$\text{and } \text{Log } W = C_3 + 5.1 \log T, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (23)$$

$$\text{Log } \frac{L}{W} = C_4 - 5.1 \log T - 185 \log \left(1 + \frac{155}{T}\right) \quad . \quad . \quad (24)$$

to

$$\text{and } \text{Log } W = C_3 - 0.700 + 5.3 \log T, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (25)$$

$$\text{Log } \frac{L}{W} = C_4 + 0.703 - 5.3 \log T - 185 \log \left(1 + \frac{155.4}{T}\right) \quad (26)$$

and the same phenomenon is observable as for the carbon filament lamps.

By comparing equations (13) and (15) and (25) and (26) respectively and remembering that (13) and (25) deal only with the *watt* relationship, omitting lumens altogether, it will be seen that practically all the change produced by cooling is in the watts. That means that the loss of lumens at the ends of a filament is virtually equal to the gain in lumens due to the centre of the filament (as shown in Table II.) being at a slightly higher temperature than that ascribed by the colour identity method to the filament as a whole.

The fact that temperatures based on the colour identity method and covering so wide a range are thus found to fit in so well with fundamental theory seems to afford presumptive evidence that the colour identity method gives values of temperature which are accurate at least from the relative point of view, and affords further experimental support for the conclusions which are arrived at on page 233 as a result of a general consideration of the phenomena underlying colour identity.

### *3. Temperature of Lamp Filaments and of Melting Platinum.*

The foregoing experiments assume that a temperature ascribed to a filament by comparing the hue of its total radiation with that of a black body of known temperature approxi-

mates to the true temperature of the filament although the latter is glowing under open radiation conditions. If this approximation can be shown to be a very close one, the method might be of considerable use in certain branches of practical pyrometry. In what follows enough evidence is given of the correctness of the temperatures determined by the colour identity method, to justify the assumption for certain substances and to warrant a more complete investigation of the subject.

As regards the determination of filament temperature by previous observers, only three sets of determinations, those of Forsythe,\* Von Pirani and Meyer† and Langmuir‡ are given in comparable form.

In some other determinations no mention is made of the watts per candle or lumens per watt of the lamps tested. In others "black body" temperatures and not true temperatures are given of the filaments radiating in the open.§

In Table IV. the results obtained by the authors are compared with those of the above-mentioned observers. Both Forsythe and Von Pirani only measured the mean horizontal candle-power of their lamps, and a reduction factor of 0.85 for carbon and 0.79 for tungsten has been assumed in both cases for the ratio  $\frac{\text{M.S.C.P.}}{\text{M.H.C.P.}}$ . It will be seen that the authors' results

agree very closely with those of Forsythe, and it should further be noted that whilst agreeing with Forsythe, who used the usual optical methods, in the case of comparatively non-selective carbon filaments, they also virtually agree with his results for tungsten, although the latter is admittedly selective.

Von Pirani and Meyer found values of true temperature which are appreciably higher than Forsythe's and, therefore, also higher than by the colour identity method given here. They are given in column IV. of Table IV., the values being taken off a curve through Von Pirani and Meyer's values and

\* "Phys. Rev." Vol. XXXIV., May, 1912.

† "E.T.Z.," 1912, May 2, p. 457 and July 11, p. 725.

‡ "Proc." of Amer. Inst. of Elect. Engineers. Vol. XXXII., p. 1895.

§ Dr. H. Lux, "E.T.Z.," May 28, 1914, gives tables connecting temperature and watts per mean spherical candle of tungsten lamps. The values given in the table would appear to approximate to true temperatures, but the method described for determining the temperatures is that ordinarily used for obtaining black body temperature. Without further information of the methods used by Dr. Lux for the determination of true temperature, a useful comparison with readings of other observers is difficult to make.

reduced to the same basis of lumens per watt. A considerable amount of this difference appears to be accounted for by the use by Von Pirani of a temperature scale which gives the melting point of platinum at 1,790°C.\*

TABLE IV.

Type of lamp.	Lumens per watt.	True Temperature of Filament °C.		
		Forsythe.	Pirani and Meyer.	The Authors.
Tungsten .....	8.0 <sub>5</sub>	1,980	2,069	2,010
" .....	8.1 <sub>5</sub>	1,982	2,072	2,014
" .....	8.4	2,008	2,084	2,027
" .....	8.8 <sub>4</sub>	2,020	2,100	2,041
" .....	9.0 <sub>6</sub>	2,025	2,109	2,051
" .....	8.8 <sub>8</sub>	2,035	2,101	2,044
" .....	9.3 <sub>6</sub>	2,040	2,121	2,063
Carbon .....	3.5 <sub>2</sub>	1,820	1,935	1,818
" .....	3.9 <sub>6</sub>	1,847	1,966	1,846
" .....	3.9 <sub>4</sub>	1,843	1,965	1,845

The lumens per watt are obtained from the values given by the authors of watts per candle, by assuming ratios of 0.79 and 0.85 respectively for the reduction factors  $\left(\frac{\text{M.S.C.P.}}{\text{M.H.C.P.}}\right)$  for tungsten and carbon lamps.

The value of 0.9 is taken for the ratio of the Hefner to the British units of candle-power.

Both Von Pirani and Forsythe determined black body temperatures and added an amount depending on certain assumptions in order to get true temperatures. It is not possible to correct Von Pirani and Meyer's figures to make them comparable with those based on a temperature scale which gives the more usually accepted melting point for platinum, but it is clear that if this could be done Von Pirani and Meyer's figures would agree much more closely with Forsythe's. Langmuir does not give details of how he obtained his temperature values, since his Paper was not directly concerned with the measurement of temperature. His results differ by about 2 per cent. from the authors' values obtained by extrapolating the curves shown in Fig. 3 of this Paper, using the formula given on page 246.

In order to ascertain if the colour identity method is correct for substances other than carbon it is necessary to know the true temperature of some glowing filament. The melting point of platinum is now very generally accepted as  $(1750 \pm 20)^\circ\text{C}.$ \* If a filament of platinum could be gradually raised to the melting point by an electric current and compared at its

\* Burgess-Le Chatelier. "Measurement of High Temperatures," p. 492.



melting point against one of the colour standards, the "colour identity" temperature of the platinum could be fixed at the melting point and compared with the known melting point of platinum. Platinum is admittedly a selective body. In addition, when radiating in the open its black body temperature determined by the ordinary optical methods ( $\lambda=0.650\mu$ ) is some  $200^{\circ}\text{C.}$  lower than the true temperature, and as the colour comparison would be made under open radiation conditions, the experiment should be a crucial one for proving if the colour identity method gives true temperatures.

The only precaution necessary is to take a fair length of platinum wire and use only the central portion so that the cooling of the ends of the wire by the leading-in terminals shall not influence the determination. Lengths of No. 25 gauge wire were used, 13 cm. long, of which all but the centre 5 cm. was screened off. Simultaneous comparisons were made with both carbon and tungsten colour standards. The current in the platinum wire was slowly raised and that in the colour standards increased so that identity of colour was always maintained in the photometer up to the melting point of the platinum. The colour standards were arranged each with a photometer head on either side of the platinum wire, and no difficulty was found in maintaining colour identity to the point at which the platinum melted.

Table V. gives the results of all the 15 determinations.

TABLE V.

Experiment.	Temperature of platinum at melting point by colour identity method $^{\circ}\text{C.}$	
	With carbon filament colour standard.	With tungsten filament colour standard.
1	1,752 $^{\circ}\text{C.}$	1,765 $^{\circ}\text{C.}$
2	1,746 $^{\circ}\text{C.}$	1,770 $^{\circ}\text{C.}$
3	1,727 $^{\circ}\text{C.}$	1,751 $^{\circ}\text{C.}$
4	1,737 $^{\circ}\text{C.}$	1,765 $^{\circ}\text{C.}$
5	—	1,747 $^{\circ}\text{C.}$
6	1,761 $^{\circ}\text{C.}$	1,784 $^{\circ}\text{C.}$
7	1,769 $^{\circ}\text{C.}$	1,779 $^{\circ}\text{C.}$
8	1,755 $^{\circ}\text{C.}$	1,784 $^{\circ}\text{C.}$
9	1,763 $^{\circ}\text{C.}$	1,782 $^{\circ}\text{C.}$
10	1,759 $^{\circ}\text{C.}$	1,782 $^{\circ}\text{C.}$
11	1,727 $^{\circ}\text{C.}$	1,765 $^{\circ}\text{C.}$
12	1,737 $^{\circ}\text{C.}$	1,769 $^{\circ}\text{C.}$
13	1,747 $^{\circ}\text{C.}$	1,782 $^{\circ}\text{C.}$
14	1,764 $^{\circ}\text{C.}$	1,789 $^{\circ}\text{C.}$
15	1,757 $^{\circ}\text{C.}$	1,789 $^{\circ}\text{C.}$
	Mean 1,750 $^{\circ}\text{C.}$	1,773 $^{\circ}\text{C.}$

The mean result gives the melting point of platinum as  $1,750^{\circ}\text{C.}$  by the carbon filament lamp and  $1,770^{\circ}\text{C.}$  by the Tungsten lamp, a result so near to the accepted value of  $1,750^{\circ}\text{C.}^*$  as to afford strong evidence of the reliability of the colour identity method. It is intended later to repeat this experiment with other metals such as nickel, iridium or rhodium, using a neutral atmosphere to surround the incandescent wires. The difference of 1 per cent. in the temperatures given respectively by the carbon and the tungsten colour standards must not be assigned too much weight. Although the method is capable of a greater accuracy than this, it is not claimed that the determinations described here are correct to 1 per cent.

Comparing again the usual optical methods and the colour identity method of estimating temperature, it is worth while to see what is the explanation of the phenomenon which has been described in this Paper. The factor of chief interest is, that if a black body at  $1,750^{\circ}\text{C.}$  radiates towards one side of a photometer and platinum at the melting point ( $1,750^{\circ}\text{C.}$ ) towards the other, there will be identity of hue on the two sides of the photometer, even though the platinum is operating under open radiation conditions. The hue of the total radiation of the platinum is, therefore, a measure of its true temperature.

If, on the other hand, a pyrometer be used to measure the temperature, first, of the black body and then of the melting platinum, it will give a value of  $1,750^{\circ}\text{C.}$  for the black body and about  $1,550^{\circ}\text{C.}$  for the platinum. The latter temperature will depend on the wave-length in which the measurements are made, but whatever the wave-length used the temperature given will be very much lower than the true temperature of the platinum.

Waidner and Burgess have given the melting point temperatures of platinum (black body) determined in three wave-lengths as follows :—

TABLE VI.			
Colour.	Wave-length.		Melting point.
Red .....	0.666 $\mu$	.....	1,534 $^{\circ}\text{C.}$
Green .....	0.547 $\mu$	.....	1,578 $^{\circ}\text{C.}$
Blue .....	0.462 $\mu$	.....	1,610 $^{\circ}\text{C.}$

Examining the cases of a grey body and then of platinum, for which most data are available, it is possible to see from what

\* Burgess-Le Chatelier, "Measurement of High Temperature," p. 492.

follows how closely the colour identity method will tend in practice to give the true temperature.

Curve A (Fig. 5\*) shows the power distribution of a black body at  $1,750^{\circ}\text{C}.$  over the visible spectrum calculated from the Wien equation. Curve C is a curve for a grey body with a certain emissivity at the same *true* temperature. If the temperature of this grey body be measured with an optical pyro-

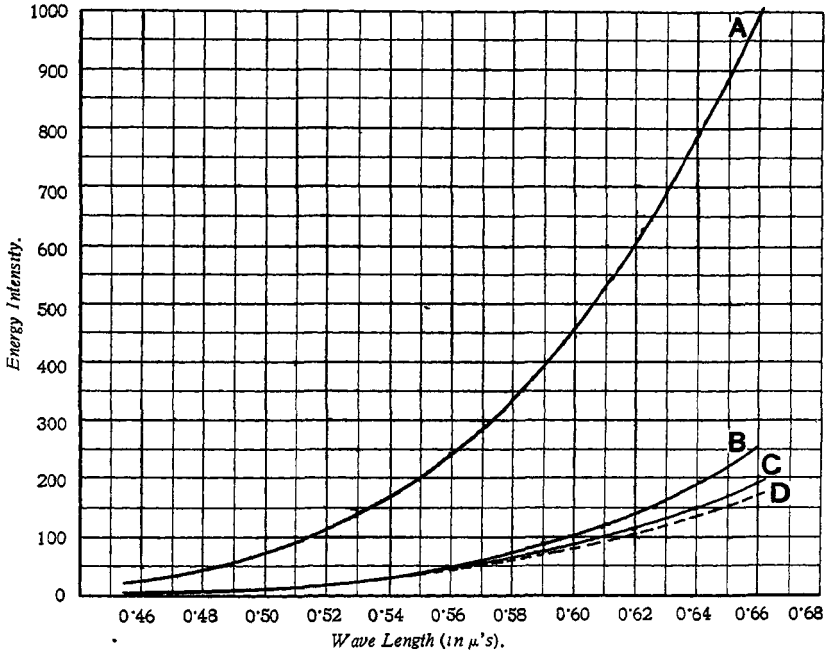


FIG. 5.

Energy intensity curves in the visible spectrum for :—

- A. Black body at  $1,750^{\circ}\text{C}.$
- B. " " at  $1,578^{\circ}\text{C}.$
- C. A grey " at  $1,750^{\circ}\text{C}.$
- D. Platinum under open radiation conditions plotted from values given by Waidner and Burgess.

meter, in the green ( $\lambda=0.547\mu$ ) it will be given a value of  $1,578^{\circ}\text{C}.$  This particular grey body curve has been taken in order that it may be comparable with Waidner and Burgess's platinum curve, in which the black body temperature of the platinum melting point at  $\lambda=0.547\mu$ , is given as  $1,578^{\circ}\text{C}.$  Curve B is the true black body curve for a temperature of

\* Hyde, " Journ." Franklin Inst., *loc. cit.*, shows curves very similar to these to illustrate points connected with his investigations on selectivity.

1,578°C., and has been drawn in order to show the difference between the black body and grey body power curves referred to the same intensity of radiation in the green.

The ordinates are relatively so small at the shorter wave-lengths that the crossing of curves B and C at  $\lambda=0.547\mu$  cannot be distinguished. They do, however, actually cross. It is well to notice from curves B and C what a difference in light distribution at different wave lengths exists between the black body and grey body at the same apparent temperature (measured optically). It is this difference of relative distribution which results, by the colour identity method, in the grey body (curve C) being given a temperature of 1,750°C. and the black body (curve B) a temperature of 1,578°C.

Now, the curve for platinum at its melting point lies close to curve C for a grey body. Waidner and Burgess's platinum melting point determinations for the three wave-lengths given in Table VI. are plotted in curve D. If the figures published by Waidner and Burgess may be depended on to give the relative intensities in the three wave-lengths, curve D indicates that the colour identity method should have given a value for the melting point of platinum above 1,750°C., since, as compared with the grey body, Waidner and Burgess show relatively more radiation from platinum at the blue than at the red end of the spectrum. Before definite conclusions can be drawn it would be desirable to have measurements in other than the three wave-lengths considered and information as to the monochromatism of the light in each of the wave-lengths for which the intensities are plotted in curve D. The figures for the melting point of platinum, shown in Table V., indicate, it is true, a tendency to fall in the direction to be expected from Waidner and Burgess's values plotted in the diagram, but not, however, as much as line D indicates. The opinion, therefore, expressed by Hyde that the colour identity method will err in ascribing temperatures which are, if anything, slightly too high, is supported so long as the bodies in question are selective *in the visible spectrum* in favour of the shorter wave-lengths. If they are selective in favour of the red end, the temperature ascribed will tend to be low whilst if they are true grey bodies the method will be accurate.

It should, however, be recalled that compared with other substances platinum is regarded as a relatively selective body in the visible spectrum, and if this is so, the differences indicated in Fig. 6 are for a fairly extreme case,

Little is actually known as yet regarding the departure of metallic bodies from the characteristics of grey bodies in the *region of the visible spectrum*. Any deviation which there is would seem to be small in amount and insufficient to invalidate estimations of the temperature by the colour identity method, intelligently used. It is suggested that the method should be specially useful for assisting in the determination of temperatures and melting points of some of the more refractory substances whose true temperatures by the usual optical methods and assumptions are admittedly open to doubt.

It is of interest now to see what are the temperatures of filaments in gas-filled lamps determined by the colour identity method of measurement.\*

In estimating the temperature of the filament in a lamp bulb containing gas it must be remembered that the relation between lumens/watt and temperature cannot be the same as in the ordinary vacuum lamp because of the considerable number of watts carried away from the filament by convection in the gas. Further, the proportion of watts convected depends considerably on the diameter of the wire and on the density of the gas in the bulb.

Six gas-filled lamps have been compared against an ordinary vacuum tungsten lamp in order to determine the difference of efficiency expressed in watts per mean spherical candle or lumens per watt between the two types of lamps when the colour of their radiations is identical, and therefore, when, to a close approximation their temperatures are the same.

Comparisons were made up to an efficiency of about 0.75 watts/mean spherical candle for the vacuum lamp, or about 0.9 watts/mean spherical candle for the gas-filled lamp. The results are shown in Fig. 5, where watts/mean spherical candle for the vacuum lamp is plotted as ordinate and watts/mean spherical candle for the gas-filled lamp as abscissa. The considerable difference between these curves must be ascribed to differences in the amount of gas in the bulbs and to varying diameters of filaments and spirals.

The curves have been extrapolated to pass through the zero of the diagram, and it will be seen that all the points lie on a straight line which passes through the origin except at the comparatively low values of efficiency.

\* See Langmuir, "Proc." Amer. Inst. of Elect. Eng., Vol. XXXII., p. 1895.

The ordinary working efficiency of gas-filled lamps is at the present time about 0.7 watts/mean spherical candle, corresponding in identity of colour of radiation with the vacuum lamp at 0.5 watts/mean spherical candle—i.e., 25 lumens per watt approximately.

From the equation to the curve shown on Fig. 3 this gives a temperature of  $2,800^{\circ}\text{C. abs.}$  for the ordinary working temperature of tungsten in gas-filled lamps.

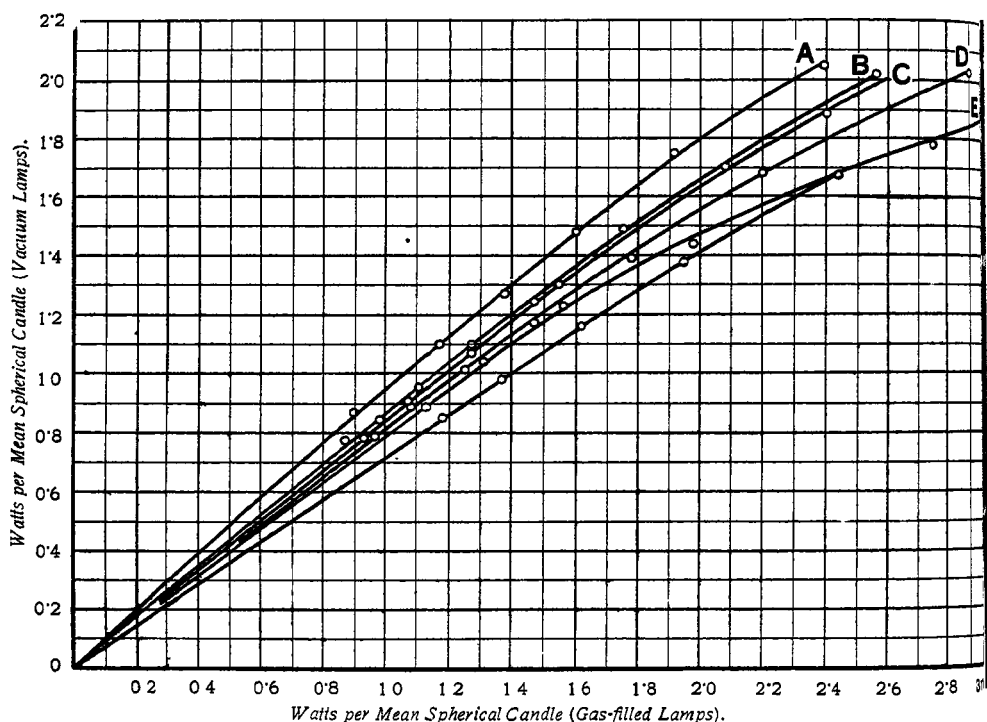


FIG. 6.—GAS-FILLED LAMPS.

Curves showing for various gas-filled tungsten filament lamps A to E, the relation between the actual watts per mean spherical candle and the watts per mean spherical candle of a vacuum lamp filament at the same temperature.

If the half-watt lamps are overrun they will be found to burn for a short time satisfactorily at 0.40 watts/mean spherical candle, corresponding to a vacuum lamp at 0.32 watts/mean spherical candle, or approximately 40 lumens/watt. Using the same formula this value of lumens/watt corresponds with a temperature of  $3,100^{\circ}\text{C. abs.}$  ( $2,830^{\circ}\text{C.}$ ). It is clear, then,

that the melting point of tungsten would be above this value, but it cannot be said with certainty how much higher. The comparison lamps used in the determination were of the vacuum type and themselves had tungsten filaments. At  $3,000^{\circ}\text{C}$ . abs. the blackening of the bulbs of such lamps is rapid and liable to lead to error if the temperature of the filament is pushed up to the melting point. The determination of the melting point of tungsten, therefore, by this method could only be undertaken if precautions were taken against errors due to blackening of the bulb. The experiment will be more successful when gas-filled colour standards are made by comparison direct against the black body. Burgess and Le Chatelier\* give the melting point of tungsten as  $(3,000 \pm 100)^{\circ}\text{C}$ ., a value with which the authors' observations by the colour identity method are not inconsistent at the highest temperature at which they could safely make measurements.

#### 4. *The Colour of Radiation from the Violle Standard.*

At the beginning of this Paper the importance was explained of giving proper consideration to the colour of the radiation from any proposed standard of light. The increasing efficiencies of modern sources of light owe these increases mainly to higher running temperatures, and hence the light emitted tends to consist of a relatively larger proportion of shorter waves. The light from the Hefner lamp has been found by the authors to correspond in colour with that from a black body at  $1,540^{\circ}\text{C}$ . That from the Pentane lamp to  $1,610^{\circ}\text{C}$ .

The Violle standard consisting as it does of platinum at the melting point ( $1,750^{\circ}\text{C}$ .) has a radiation which corresponds with the colour of a carbon filament glow lamp running at an efficiency of  $2.6\frac{1}{2}$  lumens per watt, or  $4.7\frac{1}{2}$  watts per mean spherical candle (see Fig. 3). Assuming a reduction factor of 0.85 this is equivalent to an ordinary carbon filament lamp with a specific consumption of 3.8 watts per mean horizontal candle.

The authors wish to express their acknowledgment in connection with this work to Dr. R. T. Glazebrook, C.B., F.R.S., Director of the National Physical Laboratory, and also to Dr. J. A. Harker, F.R.S., for facilities afforded in the use of the black body furnace referred to at the beginning of the Paper.

\* *Loc. cit.*, p. 492.

## DISCUSSION.

Prof. S. P. THOMPSON thought something must be wrong with the English language when "white" light had to be defined as that radiated by a "black" body. The term "grey" body seemed indefinite. There were many shades of grey, and it would be interesting to know how many bodies were really "grey" according to the precise definition of the authors. He thought that in plotting lumens per watt against temperature it would have accorded better with custom to have plotted temperatures as abscissæ instead of as ordinates.

Mr. A. P. TROTTER (communicated remarks): If this Paper had preceded the introduction of the optical pyrometer, that instrument would not perhaps have gained such a footing. Notwithstanding the apparent advantage that the intensity of light for any given wave-length varied as the fifth power of the temperature, while that of the whole light varied as the fourth power, the principle of colour identity seemed clearly to be the right one for measuring high temperatures, and the use of an arbitrary coloured screen, the wrong one. The estimation of high temperatures by observing the colour of an incandescent body was perhaps practised by Tubal Cain in judging forging and welding heat. What the blacksmith calls "just red at the back of the forge" is about  $400^{\circ}\text{C.}$ , and "cherry red" is about  $1,650^{\circ}\text{C.}$ , but it has remained for the authors to convert it from a matter of judgment to one of accurate measurement. The method directs attention to small colour differences which in ordinary photometry are deliberately and sometimes with difficulty ignored. This difficulty drives some observers to the flicker photometer. The difficulty is reduced by experience. Possibly some eyes are more sensitive to differences of brilliance and others to differences of hue. The authors are justified in the use of the expression "grey body." The ideal black body which absorbs all radiations and reflects none, and for any temperature radiates more than any other body, is rather repulsive to some people, for it is inseparably connected in their minds with the complicated laws of Stefan, Planck and Wien. The opposite of this would be a body which absorbs no radiations, is a perfect reflector, does not emit any radiation when at a high temperature and entails no mathematics. No such body is known. Intermediate bodies are of two classes, and in their radiant properties they may be called selective and grey, just as bodies between the extreme hues of black and white are coloured and grey. There is an indefinitely large number, several thousands, of perceptibly different shades of grey, and the degree of greyness of a radiant body is merely the factor by which the ordinates of such a curve as C, Fig. 5, must be multiplied to fit curve A. If it does not fit, but cuts it, it is not grey but selective. The authors do not seem to be justified in stating that white light means light of any colour emitted by a black body. It is generally recognised that there can be no definite standard of white light, but there are many substances such as magnesia, snow, or even paper, which are white, and white light is best represented by sunlight reflected from such a substance. But the convention is that it must be our sun, not the hotter Sirius, or the cooler Antares. A grey body also reflects pure white light, but not so much as a white body. In colorimetric tests as made in chemical and physiological laboratories it is found that two tints may appear to one observer to be of identical hue, while to another they differ. This occurs when the two hues differ spectroscopically, and when the eyes of the observers differ in colour sensitivity. In the present method of colour identity, so long as the hues are in general of similar spectroscopic character this difficulty would not arise. When a piece of white porcelain with a dark pattern is heated red hot, the pattern becomes brighter than the background. An optical pyrometer would indicate that the dark pattern was at a higher temperature. But the author's method would reduce the brilliance of the pattern to that of the ground, would show that the hues are identical, and would indicate equality of temperature. The weak point of the ordinary optical pyrometer with a screen as monochromatic as is practicable is that it is applicable only to bodies which approxi-



mate to the conditions of the ideal black body. It is interesting that so useful a side issue should have arisen from the investigation of the Violle standard of light which seems less likely to become a practical one since the publication of Dr. Petavel's work than it did before.

Dr. J. A. HARKER said that to one accustomed to look at the physics of optical pyrometry in the ordinary way it is difficult at first sight to see why platinum at its melting point should emit the same colour of radiation as a black body at the same temperature. In fact one's predisposition would be to the opinion that this is quite unlikely. The accuracy with which the authors by their method determined the value for the melting point of platinum was very surprising, and the considerations the authors bring forward put a new complexion on one's conceptions. With regard to the "black body" used by the authors, it was extremely difficult to obtain a furnace at these high temperatures without a cloudy atmosphere, but after distilling the impurities out of the carbon—which was the only suitable substance to use—he had found it possible to obtain a high temperature furnace with a perfectly clear atmosphere. With the ordinary optical pyrometer it was impossible by means of the coloured glass supplied to get sufficiently perfect monochromatism to give great accuracy. If a strip of platinum be used instead of a wire it is possible to maintain it within a degree or two of its melting point for some time.

Mr. A. CAMPBELL asked how the optical pyrometer was calibrated at high temperatures. In the case of the Violle standard, was it essential actually to melt the standard strip? Would it not be more satisfactory to use a tungsten strip heated up until a small speck of (*e.g.*), quartz on it began to melt rather than to melt the strip which was under observation?

Mr. J. S. DOW doubted if metal filament lamps could be regarded as strictly grey through their visible spectrum. He recalled a series of articles by W. Coblentz in the "Illuminating Engineer," in 1910, showing how metals in general had a low emissivity in the infra-red, and this suggests irregularity in the emissivity of a polished metal surface, even in the visible spectrum. The methods the authors proposed seemed to require less manipulative skill than most pyrometers. For example, one observer had discovered an interference effect that might give rise to considerable errors in the case of instruments involving the inspection of a bright filament against a luminous background. Measurements with a photometer would be free from this source of error. The authors had found that half-watt lamps could be run for a short time at 0.4 watt per mean spherical candle. Could they, by extrapolation, state the approximate limiting theoretical efficiency of a tungsten filament? Dr. Lux had recently estimated that the melting point of tungsten would be approached at 0.3 watt per candle.

Mr. A. W. BEUTTELL suggested that any difference in the colour sensations of the observer from the normal would affect the results obtained by the method.

Dr. C. CHREE asked which of the values, 1,750°C. or 1,770°C., the authors considered most nearly correct.

Mr. E. H. RAYNER thought it might add to the sensitiveness of the method if, when the colour match had been obtained, coloured glasses—say, first a red and then a blue glass—were put in front of the eye. Any inexactness in the match might be increased and shown up in this way.

Mr. J. GUILD (communicated remarks): The auxiliary adjustment for equality of brightness mentioned by the authors on page 236 is an important one, inasmuch as, on account of the change in the sensitivity curve of the eye with change in brightness of the incident light, it is only when both sources produce the same illumination *at the eye* that identity in the colour perceived involves identity in their energy distribution curves over the visible spectrum. If, for example, one adjusted two sources to give identity of hue but neglected to equalise the brightness at the photometer the source producing the weaker light would require to be at a lower temperature, *i.e.*, to have more red in its spectrum than the other, since, for the weaker light,

the red-sensitivity of the eye bears a smaller ratio to the total sensitivity than for the stronger. In what way does the accuracy of the colour-identity method vary with temperature? To the casual observer the colour of a furnace appears to vary much more rapidly with temperature at low red and orange heats than at higher temperatures, and one would expect considerable precision at, say,  $700^{\circ}\text{C.}$  or  $800^{\circ}\text{C.}$ , and a progressive falling off of sensitiveness as the temperature is increased. This could be calculated from the radiation laws and the chromatic properties of the eye, but a series of test experiments over a wide temperature range would be more convincing.

Mr. PATERSON thanked the speakers for their remarks. In answer to Prof. Thompson, Mr. Trotter's contention regarding "grey" bodies seems to explain the matter clearly. The convention of restricting the term "grey" body to one which radiated in the way shown in curve C, Fig. 5, is a very usual one. There could be an indefinite number of such curves, but each had the property that some one multiplier would make all its ordinates coincide with a black body curve at the same true temperature as the grey bodies in question. A body whose curve would not conform with this requirement would be spoken of as a "selective" body rather than as a "grey" body. The question is mainly one of nomenclature and definition. In the American literature the above convention is generally accepted. According to Prof. Thompson and Mr. Trotter the authors may be wrong in suggesting that white light is the light emitted by a black body at any temperature. Mr. Trotter prefers to restrict it to light radiated by the sun. He was still of opinion that "white light" was a good term to use, since it conveys the impression of a mixture of all wave-lengths in definite proportions. If "white light" were to be regarded as the light emitted by the sun, it would be very indefinite owing to atmospheric absorption.\* In reply to Mr. Campbell, no effort has been made by the authors to use platinum strip as a standard of light, but experiments had been made by others on these lines without much success. In reply to Mr. Dow, several experimenters had come to the conclusion from the evidence at their disposal that these materials were mainly selective in favour of the visible spectrum as a whole. The authors had now shown experimentally that platinum had the same relative distribution of light as a black body at the same temperature, and this appears to the authors important evidence to justify the last statement, that is to say, that they approximate to "grey" bodies in the visible spectrum. The authors had compared a tungsten filament with a carbon filament over the visible spectrum with a spectrophotometer, and to the accuracy to which the instrument could be used no difference in selectivity could be detected. Over the infra-red portion of the spectrum it is well known that a large difference exists. An answer to the question regarding the limiting efficiency of half-watt lamps is given in the Paper. In reply to Mr. Beutell, a person with defective colour sight should only be less sensitive than one with normal vision, but on the average should not obtain different results. In reply to Dr. Chree, the melting point of platinum is usually given as  $1,750^{\circ}\text{C.} +$  or  $-20^{\circ}\text{C.}$  The present experiments were carried out not to determine the melting point of platinum but to show from the melting point values obtained the accuracy of the method of colour identity. Mr. Rayner's suggestion is certainly worth trying and ought to yield very interesting results. In reply to Mr. Guild, it is impossible to obtain identity of colour with accuracy unless illuminations at the two sides of the photometer are the same. There is a slight difference in sensitiveness of the colour identity method at different temperatures, for instance, a definite change of colour which is caused by 1 per cent. in temperature at  $2,000$  deg. abs. is caused by 1.6 per cent. at  $2,800$  deg. abs. Regarding Dr. Harker's remarks, the authors hope to take advantage of the offer made by him to use one of his black body furnaces up to higher temperatures. In doing so they would add to the obligation they are already under to Dr. Harker in connection with the furnaces used in the present work.

\* See "Modern Illuminants." Gaster and Dow. P. 181.