

THE BLUE GLOW

BY

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Certain oxides when heated to incandescence emit light of a distinctly bluish cast at temperatures corresponding to the dull red heat of non-selective radiators.

To this effect, which is particularly well marked when the heating is done with a hydrogen flame sufficiently reinforced with oxygen to secure the desired temperature, we have given the name of the *blue glow*. It is a special case of the luminescence of incandescent solids, a topic upon which we are now engaged and which, in its broader aspects, will form the subject of a forthcoming paper. In our study of the blue glow it was desired to determine (1) the temperature of the glowing oxide; (2) the brightness of its temperature-radiation proper; and (3) the brightness of the *blue glow* itself which may be regarded as superimposed upon the temperature-radiation.

For this purpose we used an optical pyrometer of the type based upon the well known Morse gauge, in which the filament of an incandescent lamp in the eyepiece of the instrument is superimposed upon the image of the glowing surface the temperature of which is to be measured. To mount the oxide for observation an annular groove about 1 cm in outer diameter, 1 mm deep and 2 mm wide was ground in a bed of alundum. Fragments of thick walled alundum tubing of large diameter, of which an abundance chanced to be available, answered admirably for this purpose. The annular groove was pressed full of the black oxide of uranium, a substance which affords an excellent approximation to the ideal black body and which withstands the direct contact of the H-O flame better than any black powder which we have thus far found. The disk of alundum within this ring of uranium oxide was then covered with the oxide to be studied, the two surfaces of powder being carefully pressed down to the same level. Especial care was taken to have a sharp boundary line between the white oxide within and the ring of black powder surrounding it. Upon the surface thus prepared a flame of hydrogen from a blast lamp, with just

sufficient oxygen to give it direction and stability, played vertically and concentrically from above. It was found that when the two surfaces were at the same level, neither being sensibly elevated or depressed with reference to the other, and when the flame was large enough to cover them fully and was properly centered, they attained the same temperature.

TABLE I
The Blue Glow of Magnesium and Beryllium Oxides

Temp. C.	I_{bb}	$Mg\ O$				$Be\ O$			
		I_o		I_o/I_{bb}		I_o		I_o/I_{bb}	
		.65 μ	.45 μ	.65 μ	.45 μ	.65 μ	.45 μ	.65 μ	.45 μ
665°	.00013	.00000018	.0202	.00140	156.7	.000000025	.0563	.000195	437.
735°	.00123	.00000026	.0320	.00214	45.0	.00000016	.0795	.000867	65.8
837°	.0246	.00033	.423	.0135	17.2	.00067	.295	.0271	12.0
960°	.419	.0202	3.63	.0482	8.77	.038	1.44	.0832	3.14
1037°	1.95	.165	8.91	.0847	4.57	.213	1.95	.109	1.00
1097°	5.93	1.077	16.1	.182	2.72	1.00	3.31	.169	.561
1145°	13.2	.....	.....	.....	.....	2.46	6.37	.186	.511
1190°	26.6	9.77	26.4	.367	1.04	6.75	13.0	.252	.423
1228°	45.7	.....	.....	.....	.....	72.5	110.2	1.58	2.44
1263°	76.7	26.6	36.7	.347	.479	146.	179.9	1.91	2.35
1294°	156.	.....	.....	.....	.....	229.	230.	1.98	1.99
1328°	178.	55.6	72.0	.312	.404	295.	254.	1.66	1.43
1394°	389.	62.0	139.	.357	.356	513.	316.	1.32	.813
1429°	582.	182.	194.	.313	.333	.....	.....	.....	.....
1462°	828.	285.	277.	.344	.334	767.	513.	.927	.621
1488°	1097.	.....	.....	.....	.....	910.	600.	.830	.535
1527°	1602.	745.	525.	.460	.324	1181.	773.	.728	.477
1580°	2690.	1614.	1012.	.600	.375	1641.	1052.	.610	.391
1606°	3420.	2309.	1387.	.675	.406	1928.	1282.	.564	.375

Seen through the pyrometer, with the usual red screen in the eye-piece the field of view at about 700°C appeared as a red ring with dark center. Through a blue screen it consisted of a blue central patch, the blue and violet rays from the red hot uranium oxide not being of sufficient brightness to render the surrounding ring visible.

To express these conditions and their changes with rising temperature in quantitative form the following cycle of readings

was made at intervals of about fifty degrees between 600°C and 1600° C, or up to the point of fusion of the oxide under observation:—

(a) A setting on the outer ring through the red screen (equivalent wave-length $.65\mu$). This gave the *actual black body temperature* of the black surface which was the same as that of the oxide of the central disk.

(b) A setting on the central disk through the red screen. This gave the black body temperature corresponding to the red radiation from the oxide of the central disk.

TABLE 2
The Blue Glow of Calcium and Aluminum Oxides

Temp. C.	I_{bb}	CaO				Al_2O_3			
		I_o		I_o/I_{bb}		I_o		I_o/I_{bb}	
		$.65\mu$	$.45\mu$	$.65\mu$	$.45\mu$	$.65\mu$	$.45\mu$	$.65\mu$	$.45\mu$
665°	.00013	.00000055	.0276	.00432	216.	.000000051	.0794	.00039	617.
735°	.00123	.0000159	.0632	.0128	52.2	.0000036	.144	.00287	117.
837°	.0246	.00292	.336	.114	13.7	.000209	.422	.00851	17.2
960°	.419	.100	1.46	.240	3.49	.0121	.733	.0287	1.74
1037°	1.95	.802	7.31	.411	3.75	.159	1.66	.0813	.852
1097°	5.93	2.62	25.0	.453	4.19	.912	3.76	.154	.634
1145°	13.2	6.92	41.7	.522	3.11	2.72	7.41	.206	.573
1190°	26.6	17.5	58.2	.656	2.18	7.76	24.5	.292	.923
1228°	45.7	33.1	87.5	.725	1.91	.....	.....	.....	.....
1263°	76.7	40.7	151.	.531	1.97	32.2	103.5	.420	1.35
1294°	156.	61.7	254.	.535	2.20	64.6	155.	.595	1.34
1328°	178.	120.	351.	.671	1.97	133.4	195.	.748	1.09
1362°	266.	264.	310.	.994	1.17	251.0	298.	.944	1.12
1394°	389.	345.	226.	.887	.582	408.	582.	1.048	1.49
1429°	528.	422.	190.	.725	.326	.....	.....	.....	.....
1462°	828.	507.	226.	.613	.274	1000.	1084.	1.21	1.31
1488°	1097.	624.	126.	.570	.115	.....	.....	.....	.....
1527°	1602.	871.	327.	.536	.202	2370.	1863.	1.46	1.15
1580°	2690.	1225.	578.	.455	.215	.....	.....	.....	.....
1606°	3420.	1429.	794.	.381	.232	.....	.....	.....	.....

Since, as has already been mentioned, the oxides in question are exceedingly feeble temperature radiators and since the blue glow is of too short wave-lengths to pass the red screen, these measurements, for the lower portion of our range

of temperature, i.e., below 1000°C, gave black body temperatures far below the actual temperature of the surface.

(c) A setting upon the central disk seen through a solution of ammonio-sulphate of copper which cut out all red and yellow rays and practically all of the green of the spectrum. The equivalent wave-length for this screen was about $.45\mu$. It transmitted the greater part of the radiation constituting the "blue glow" and since for the lower range, from 800° downwards, the temperature-radiation of these wave-lengths was almost too small to measure, this setting, with a very close approximation, gave the *blue glow alone*. At higher temperatures where the ordinary temperature-radiation became appreciable, this setting gave the sum of temperature-radiation and blue glow.

TABLE 3
The Blue Glow of Silicon and Zirconium Oxides

Temp. C.	I_{bb}	SiO_2				ZrO_2			
		I_o		I_o/I_{bb}		I_o		I_o/I_{bb}	
		$.65\mu$	$.45\mu$	$.65\mu$	$.45\mu$	$.65\mu$	$.45\mu$	$.65\mu$	$.45\mu$
665°	.00013	.000000076	.0382	.00059	195	.0000026	.0068	.0204	53.1
735°	.00123	.0000026	.0708	.00210	57.3	.000077	.0382	.0621	30.9
837°	.0246	.00059	.341	.0239	13.9	.0039	.403	1.61	16.4
960°	.419	.0275	1.65	.0600	3.59	.121	3.41	.288	8.15
1037°	1.95	.191	4.42	.0977	2.26	1.20	69.1	.617	3.50
1097°	5.93	1.10	11.0	.186	1.86	6.34	19.2	1.07	3.25
1190°	26.6	8.51	35.3	.316	1.33	24.5	87.5	.923	3.29
1263°	76.7	41.2	89.1	.537	1.16	59.0	146.	.770	1.91
1294°	156.	100.0	167.	.865	1.44	.....	.....	.....	.....
1328°	178.	233.	316.	1.31	1.77	155.	233.	.870	1.31
1362°	266.	.....	.....	.....	.....	254.	317.	.979	1.19
1394°	389.	614.	631.	1.58	3.09	419.	397.	1.07	1.00
1429°	528.	.....	.....	.....	.....	769.	610.	1.32	1.04
1462°	828.	1390.	1902.	1.68	2.30	1150.	798.	1.38	.990
1527°	1602.	2500.	2566.	1.54	1.55	1950.	1102.	1.20	.679
1580°	2690.	.....	.....	.....	.....	2620.	1500.	.973	.427

By measurements of this sort on the oxides of calcium, magnesium, zirconium, beryllium, silicon, aluminum, etc., some of the results of which are given in the following tables and figures, we are able to describe the *blue glow* in fairly definite terms.

The blue glow is essentially a phenomenon of the lower stages of incandescence. Its upper limit cannot be given definitely in degrees since it depends upon the state of activity of the oxide, but it lies between 1000° and 1200° in the cases thus far studied. If, as in Fig. 1, we plot the brightness of the blue of the spectrum ($.45\mu$) of one of these oxides (MgO) between 900° and 1200° and for comparison the brightness curve (B.B.) for the corresponding region of the spectrum of a black body we see that the oxide remains *brighter than the black body* until a temperature of about 1200° is reached. It is this excess of radiation above what even a perfect radiator such as the ideal black body is capable of producing by virtue of its temperature alone which constitutes the effect in question.

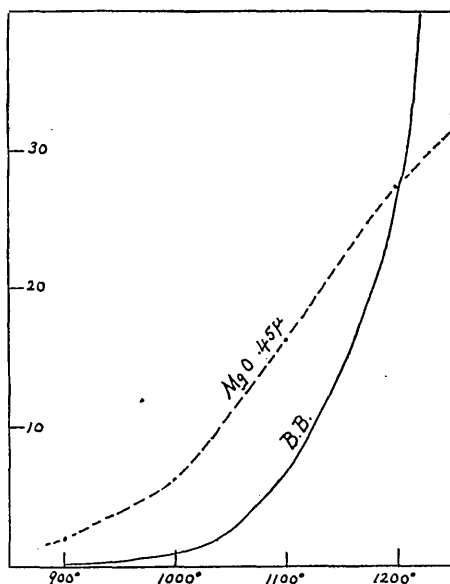


Fig. 1. Blue glow of magnesium oxide, 900° to 1200° C

The lower limit of the blue glow is the temperature threshold of visibility. For the lowest temperature at which we can observe we get the *maximum value* of the ratio between the brightness of the glow and that of a black body of the same temperature. This ratio may be denoted as I_o/I_{bb} .

In Fig. 2 are plotted curves for this ratio for several oxides. Such a diagram, to this scale, indicates nothing of the phenomena occurring above 1000° where the values approach and often fall

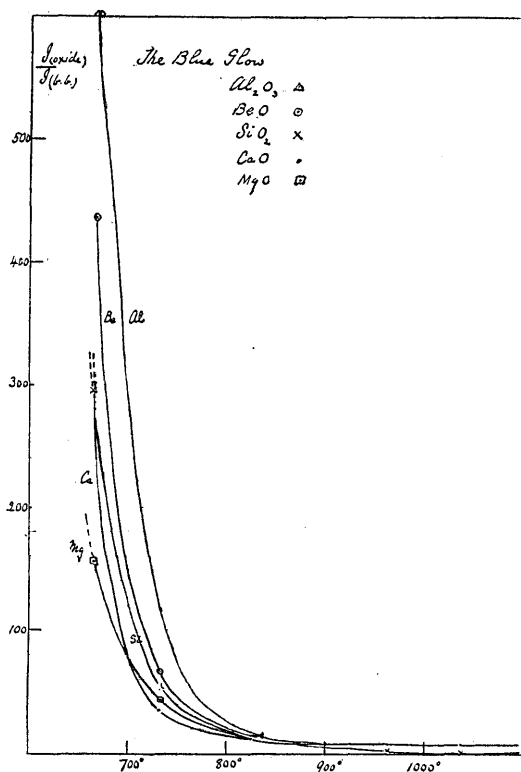


Fig. 2. Ratios of luminescence to black body radiation for several oxides below 1000° C

below unity. Still less can the ratio for the red of the spectrum be thus depicted. The figure shows, however, that:—

- (1) The curves for the various oxides are similar as to type.
- (2) In no case is there an indication of an approaching maximum in the direction of lower temperatures.
- (3) The temperature range within which the brightness of the blue end of the spectrum, to which these curves apply, falls to values of the same order as the corresponding intensity of black body radiation is nearly the same for all these oxides.

With logarithms of the intensity ratios as ordinates, we can bring the entire range of temperatures over which measurements were made into one plot and compare the changes occurring in the intensity of the red end of the spectrum with those in the blue.

Figure 3 contains such curves for magnesium oxide and these are quite typical of all the substances thus far investigated.

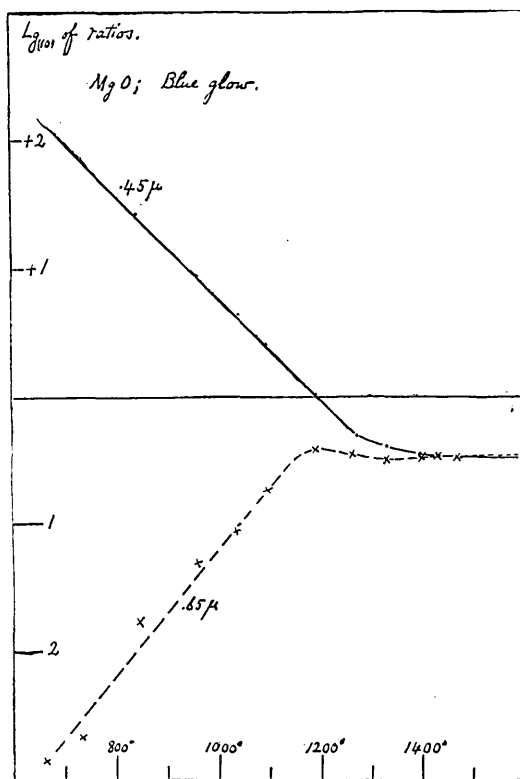


Fig. 3. Logarithmic curves for blue glow (.45 μ) and temperature-radiation (.65 μ) of Mg O

The characteristics common to all are as follows:—

- (1) The luminescent outburst, with certain exceptions to be considered later, does not involve the longer wave lengths.
- (2) The radiation in the red which, at the lower temperatures, is probably all temperature-radiation, rises from very small intensities and approaches the falling values for the radiation in the

blue. Thus the oxide in passing from 600° to 1200° goes over from a body exhibiting blue luminescence and almost no temperature-radiation (for MgO less than a thousandth of that of a black body) to a body radiating almost nonselectively by temperature alone with a radiating power of the same order as that of the black body.

(3) The logarithmic curve is approximately linear up to the point where temperature-radiation supplants luminescence (1000° to 1200°). The curves for the ratio $\frac{I_o}{I_{bb}}$ in Fig. 2 are, then, exponential curves, warped sometimes by changes due to fatigue during the run and rendered more or less irregular by failures to completely control the conditions.

(4) When temperature radiation has supplanted luminescence (at from 1000° to 1200°) the logarithmic curve tends to become horizontal; indicating that the effect of temperature is now that expressed by the usual equation for black-body radiation.

(5) The knee of the logarithmic curve affords a criterion for the change to temperature-radiation and thus serves to locate the upper limit of the blue glow. Comparing Figs. 1 and 3 we should conclude that luminescence did not altogether cease at the crossing of the curves at 1200° but continued slightly beyond to a point at which the normal radiating power by temperature had been reached. (Say at 1260° for MgO in the experiment which these curves illustrate.)

The foregoing paragraphs describe the blue glow as though it were the only form of luminescence occurring above the red heat. More frequently than not there are, however, other manifestations of luminescence within the range covered by our experiments. These either modify or supplant the blue glow at temperatures below 1200° or succeed it when the oxide is still further heated.

Outbursts of luminescence at higher temperatures characterize several of the oxides already described notably, CaO, BeO and SiO₂. In silica, as may be seen from Fig. 4, in which the ratio curves for $.45\mu$ and $.65\mu$ between 1000° and 1600° are plotted, we have such an outburst. In this cut ordinates are magnified one hundred times as compared with those in Fig. 2. The hori-

zontal line, of intensity equal to unity, represents the brightness of the black body at the wave length and temperatures in question.

This luminescence, expressed in terms of ratios, appears quite insignificant when compared with the blue glow of silica which at 600° is represented by a value for I_o/I_{bb} of over 400 as against

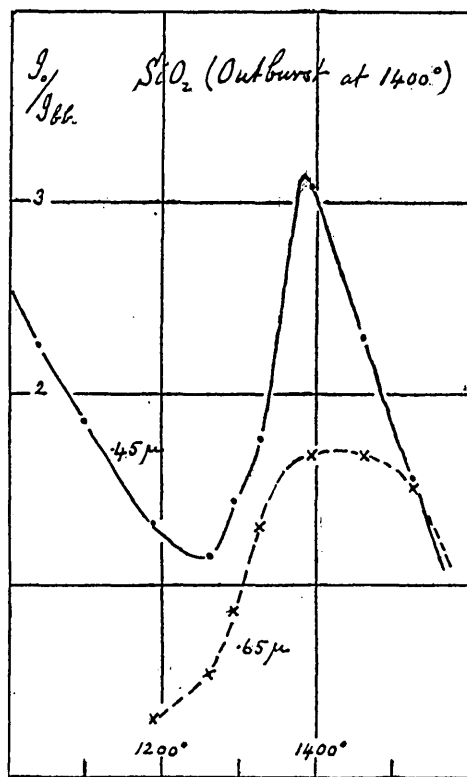


Fig. 4. Luminescence of SiO₂ at 1400° C

3.1 for the outburst at 1400°. Since, however, the intensity of the black body radiation which forms the denominator of this ratio increases according to the usual radiation law, we find the luminescence at 1400 degrees to be about 300,000 times as bright as the blue glow at 600 degrees and nearly 40,000 as great as the latter at 700 degrees. This high temperature outburst differs

from the blue glow also in that a greater portion of the spectrum is involved. That the red end at $.65\mu$ is considerably affected is evident from the curve for that wave length.

Modifications of the blue glow itself occur in several of the substances which we have examined. When cerium oxide for example is heated and its spectrum studied, we find excess radiation at

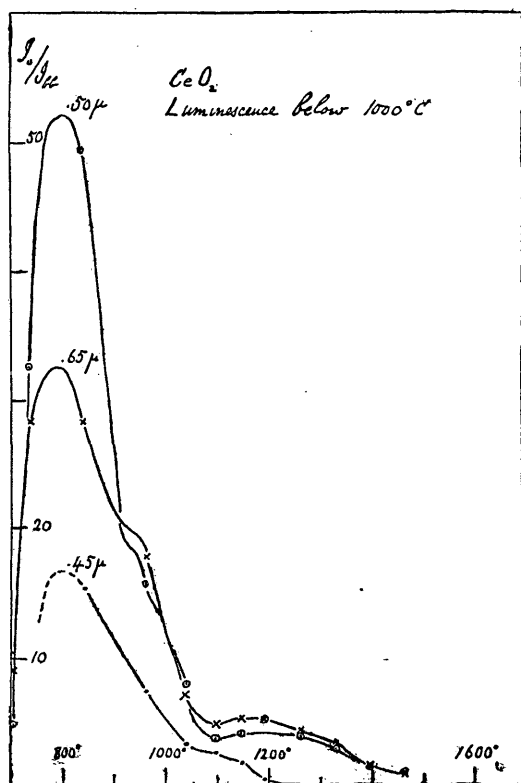


Fig. 5. Luminescence of cerium oxide below 1000° C

the lowest stages of incandescence. The phenomenon differs from the blue glow in that the red and green become visible before the blue and in that the ratio I_0/I_{bb} rises in value to a maximum, at about 800 degrees. (See Table 4 and Fig. 5.) The blue is less strongly involved than either red or green and the brightness of the red instead of starting with almost infinitesimal values is

nearly nine times great at 700 degrees as the corresponding region in the spectrum of the black body.

TABLE 4
Modified Blue Glow in Cerium Oxide

Temp. C	I_{bb}	Brightness at Various Temperatures					
		I_o			I_o/I_{bb}		
		.65 μ	.50 μ	.45 μ	.65 μ	.50 μ	.45 μ
702°	.00045	.0040	.0017	.....	8.95	4.72	.....
735°	.00123	.0349	.0403	.....	28.3	32.6	.....
837°	.0246	.692	1.21	.370	28.2	49.5	15.2
960°	.419	4.92	6.53	3.02	17.7	15.6	7.21
1037°	1.95	13.9	15.3	13.7	7.12	7.85	3.09
1097°	5.93	28.3	21.4	15.2	4.78	3.63	2.55
1145°	13.2	69.5	53.2	25.4	5.25	4.02	1.91
1190°	26.6	133.	133.	11.7	5.02	5.02	0.44
1263°	76.7	334.	304.	11.1	4.34	3.95	.144
1328°	178.	596.	519.	25.4	3.34	2.91	.142
1394°	389.	653.	695.	87.9	1.58	1.69	.227
1462°	828.	783.	887.	113.	0.95	1.07	.136
1527°	1602.	1319.	1109.	423.	.813	0.684	.260
1580°	2690.	3304.	1514.	656.	1.23	0.562	.244

Here then is a luminescent glow which at 800 degrees is composed approximately of one part blue, two parts red and three parts green, not in energy units but relatively to a nonselective radiator of the like temperature.

Without going further into details in the present paper it may be stated that the blue glow and other similar instances of luminescence at high temperatures occur in bodies which have the following characteristics.

- (1) They are inactive under excitation by light or by the X-rays.
- (2) They are, however, in general, excited to luminescence in the cathode tube.
- (3) In many cases they are sensitive to flame excitation.
- (4) Like other luminescent substances they are white, or nearly so, i.e. transparent to most portions of the visible spectrum.
- (5) They are of necessity highly refractory.

The luminescence of incandescent bodies is subject to fatigue. It is in the highest degree affected by previous heat treatment of the material; it is in some cases destroyed by fusion of the oxide; it is dependent on the mode of heating, being much more intense where an excess of oxygen is present than where there is a deficiency.

Finally it appears to be a phenomenon of instability associated with and perhaps dependent upon changes of the conditions of equilibrium. Thus all the oxides which exhibit the blue glow are in transition, within the temperature range in question from a condition of almost infinite electric resistance to one of semi-metallic conductivity and this change is accompanied by the well known profound modifications in optical properties, radiating power etc. Again the outburst of luminescence in silica at 1400 degrees occurs at the transformation point of quartz and is presumably intimately related to that change.

The most promising view at the present moment would seem to be that this form of luminescence like many well known forms at lower temperatures is the result of oxidation.

During these transitional conditions it would appear that a partial reduction takes place through the agency of the hydrogen of the flame and that this is immediately followed by oxidation, the two opposing processes going on in rapid alternation.

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