Artificial Daylight—I*

Light Sources Suitable for Color-Matching

By Herbert E. Ives

In the fourteenth century the Glovers' Company of London decreed that "no one shall sell his goods by candle light." When Tyrian purple was the staple cargo of the galleys of Phœnicia, it is safe to say that the buyers of that day early learned by experience to make no purchases by torchlight. Certainly it has long been known among those whose business it is to work with colors that daylight and "yellow candle light" are wide apart, not only in appearance, but also in their effect upon colors. It comes, nevertheless, as a surprise

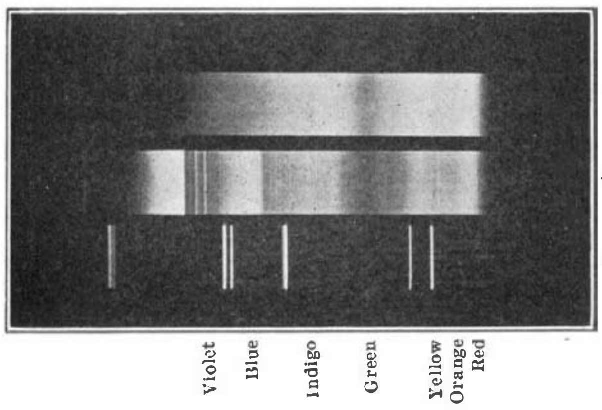

Fig. 1.—Spectra of representative light sources.

a, Continuous spectrum of the Welsbach mantle; b, continuous spectrum with superposed bands, carbon arc; c, line spectrum of the mercury arc.

to many to learn how numerous are the industries whose working hours depend upon daylight. Color printing and lithography, dyeing, the painting and viewing of pictures, tobacco sorting, the grading of sugar and flour, the sorting of precious stones, the matching of colored fabrics, the inspection of meats and delicate chemical analysis—these are a few having need for daylight at all hours, to say nothing of the surgeon and the dentist.

Among women a knowledge of the defects and pitfalls of artificial light is more general than among men, doubtless because the prevailing fashions call for color

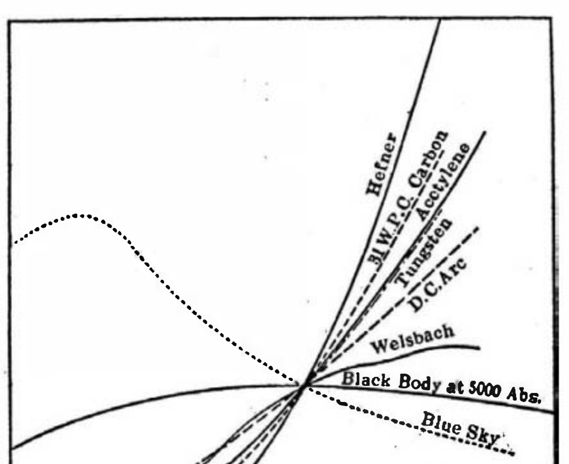

Fig. 2.—Relative intensities through the spectrum of certain representative illuminants.

in feminine attire. In a big store any day, almost any minute, one may see prospective purchasers of dress goods carrying pieces of goods, or having them carried, to the more or less distant windows to learn their true daylight appearance. For a dress must not look well merely by the artificial light over the counter, but out of doors as well, and frequently is good by one and inharmonious or ugly by the other.

The fact that, as a rule, artificial light is greatly different in appearance from daylight need be merely noted at this point. Most artificial lights are more or less yellow as compared with the light of the sun or sky. The difference is usually very great, as anyone can convince himself by comparing the two side by side under conditions of approximate equality of brightness for the two. For instance, if two shadows of a pencil are formed side by side by the two kinds of light, such as a tungsten lamp and the sky, the shadow illuminated by artificial light appears orange yellow; that by the sky, deep blue by contrast. Ordinarily we do not appreciate this difference because we do not see the two lights together, and because, if the artificial light is not too strongly colored, the eye by the process of adaptation will in large measure adjust itself to the new distorted color scale—just as a man in walking against the wind unconsciously leans forward. There is a large and interesting problem here for the physiologist and the psychologist to answer: in what way and how much the use of artificial light so different in quality from the light under which the race has been developed may affect the eye and the mind. Certain it is that artificial light is not an unmixed blessing. To its increased use is popularly ascribed many eye troubles. Then, too, many of our habits as social animals seem intimately connected with the use of artificial light. Whether it be the glitter and heat of our ballroom lights, or the odor and dimness of our midnight oil, that work their characteristic stimulation, benefits, depression, or ocular injury, or whether these are to be ascribed to their color, is a problem of interest, but here we shall concern ourselves almost entirely with the severely practical question of producing artificial daylight for industrial purposes.

What is daylight? is the inevitable question, for it is at once evident that the setting sun, a clear blue sky, and a "white" cloud are markedly different. So, too, the light reflected into our buildings from snow, grass, foliage, from earth, brick pavements, or gray asphalt is far from being a uniform thing. Daylight is, in fact, quite variable in color, a fact which has led professional color matchers to search for the most constant kind of daylight. This they have decided to be the light from a clear north sky. To the eye this is unmistakably blue in color, hence the problem of producing daylight is not necessarily the same as that of producing "white" light.

In order to answer the question, "What is daylight?" it becomes necessary to measure color. We shall, therefore, first pay some heed to the scientific measurement of color. We shall then apply the methods of color measurement to our present illuminants, natural and artificial, and so learn how they differ from each other.

Various ways of producing artificial daylight will present themselves as a result of this study and will be discussed. Next we shall investigate the problem of why and how colors change in appearance in going from one kind of light to another. From this we shall be led to formulate the necessary characteristics of a color-matching artificial daylight. Some account of the practical achievement of artificial daylight, its various forms, and its characteristics, will follow. Then a little space will be devoted to a study of the distribution of natural daylight out of doors and in rooms, and the possibility of our ultimately copying, at a not prohibitive expense, both the color and the distribution of natural daylight.

COLOR MEASUREMENT.

There are two distinct methods of color measurement. The first is by analysis of the light radiations into their elements and then quantitative measurement of these elements. The second is by analysis according to the effects on the visual apparatus. Properly speaking, the first method is not color measurement at all, since, as will be seen, a color-blind observer or a thermometer, if sensitive enough, may be used to make the measurements. Nevertheless, our problem is an indeterminate one without such measurements, so that they must be treated in detail.

As everyone knows, light may be analyzed or dispersed by means of a prism or grating. Sunlight, when so dispersed, gives the rainbow or solar spectrum with its numerous colors, of which the principal ones are red, orange, yellow, green, indigo, blue, and violet. Any complete study of color must be a study of colored light, since it is only by seeing colored light that we appreciate objects as being colored. The color of an object is, in fact, determined by the completeness with which it reflects or transmits the light which falls upon it. It owes its color to the existence of that color in the light illuminating it. A red glass is red because it transmits the red of the spectrum. For this reason the whole story of an illuminant's behavior as a revealer of color is laid bare when once the light of the illuminant is analyzed completely. These analyses may be considered in two parts—qualitative and quantitative. Qualitatively we note important differences in the spectra of different light sources. Sunlight, for instance, gives a continuous spectrum with no noticeable breaks from red to violet. A candle gives a similar spectrum, but one which will give us some difficulty in seeing the blue and violet portions, unless we arrange our prism device (spectroscope) in a way favorable to bring considerable

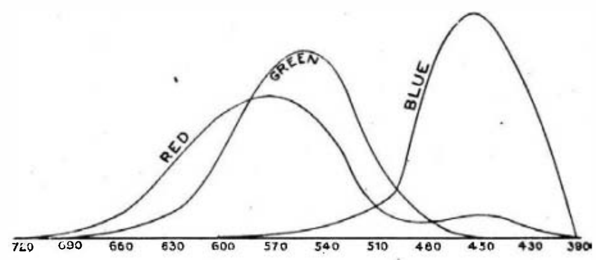

Fig. 3a.—Color sensations in white light.

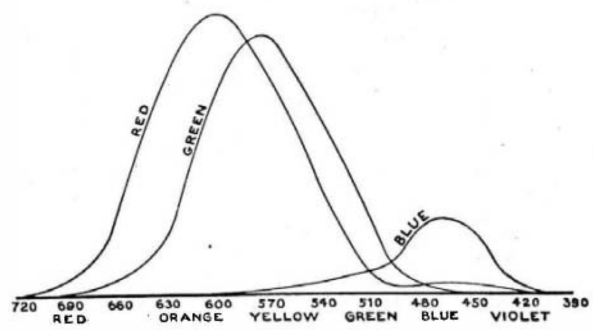

Fig. 3b.—Color sensations in incandescent carbon lamp light.

light to the eye. A carbon arc light shows a continuous spectrum, but one on which are superposed bright violet lines or bands. A nitrogen vacuum tube exhibits several isolated broad bands of colored light. A carbon dioxide vacuum tube shows numerous fine lines and bands nearly filling the entire spectrum. A mercury arc, representing the extreme from the continuous spectrum, exhibits merely isolated bright lines of light. In short, in the incandescent mercury vapor only comparatively few vibrations are represented, which when communicated to the ether produce light waves of those few wave-lengths only (Fig. 1).

Considerable information bearing on our special problem is furnished by this merely qualitative survey. It

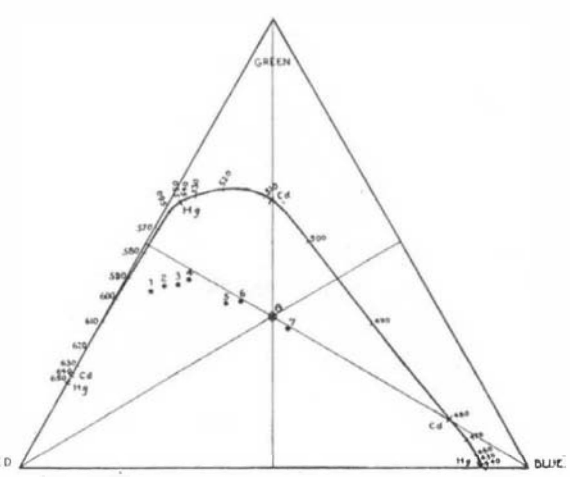

Fig. 4.—Color triangle, showing positions of spectrum colors and representative illuminants.

1, Hefner; 2, carbon; 3, tungsten; 4, Welsbach; 5, D. C. arc; 6, afternoon sun; 7, CO_2 tube; 8, whole light.

is at once evident that a light totally lacking in any color of the spectrum, such as the mercury arc, which is lacking in red, is not capable of showing that particular color in an object. But this qualitative knowledge must be supplemented by quantitative measurements before it has any real use. Such measurements are usually made by the spectrophotometer, which is, in brief, a spectroscope so arranged that each color may be compared in intensity with the same colored light from a chosen standard light. In place of a standard light it is much preferable to reduce the results to an absolute standard, i. e., to obtain the intensity of the radiation at each wave-length as indicated by the heating effect. The values which are given here have been so reduced as to show these energy values, as though they had been obtained by the use of a bolometer or thermocouple at the observing slit of the spectrometer.

Fig. 2 plots in the form of curves the relative inten-

*Paper read before the Franklin Institute and published in its *Journal*.

sities throughout the spectrum of certain representative illuminants, including sunlight and blue sky, these latter being the mean of a number of observations by different people. The curves as drawn equal 0.59μ, which is merely a matter of convention, since the actual relative intensities of the lights are not involved. As a matter of fact, this convention practically means that the lights compared are at nearly the same luminosity.

An examination of these curves yields interesting information. Practically all the common artificial illuminants differ from daylight in having an excess of red, orange, and yellow radiations, with a corresponding deficiency in blue and violet. They lie together in an entirely different family from the varieties of daylight. The latter differ in the blue on this scale by less than the factor two, whereas the ratio between day and the artificial lights is from six to twelve. The physical explanation of this lies in the fact that the common illuminants are incandescent solids at comparatively low temperatures, such as 1,500 to 2,500 deg. K., while sunlight approximates in color an incandescent solid or black body at 5,000 deg. K. The practical effects of this characteristic of the common illuminants, such as the incandescent electric lamp, the Welsbach mantle, the gas flame, etc., are two: First, their general yellow color, and, second, their different effects on colored objects. This latter peculiarity will be treated presently.

The second method of color measurement must now be considered. This is derived through color-mixture experiments. It owes its significance to the important fact that colors may look exactly alike which are, nevertheless, composed of quite different radiations, as indicated by the spectroscope. For instance, a mixture of red light and green light produces a yellow which is indistinguishable in hue from a true spectroscopic yellow, i. e., a color showing nothing but a small region of the spectrum around the yellow. Similarly a mixture of yellow light and blue light produces a white indistinguishable from one in which all the spectrum colors are present. Red and bluish green constitute another part of these "complementaries," as they are called. The most interesting set of mixture colors, however, are red, green, and blue, for it has been found that from these three may be made not only white, but all the colors of the spectrum, and hence all the colors formed by the addition and subtraction of these; that is, all the colors of Nature. It must be clearly understood, however, that these color matches are subjective; that is, they look the same, but of course on analysis with the spectroscope they at once show their composite character.

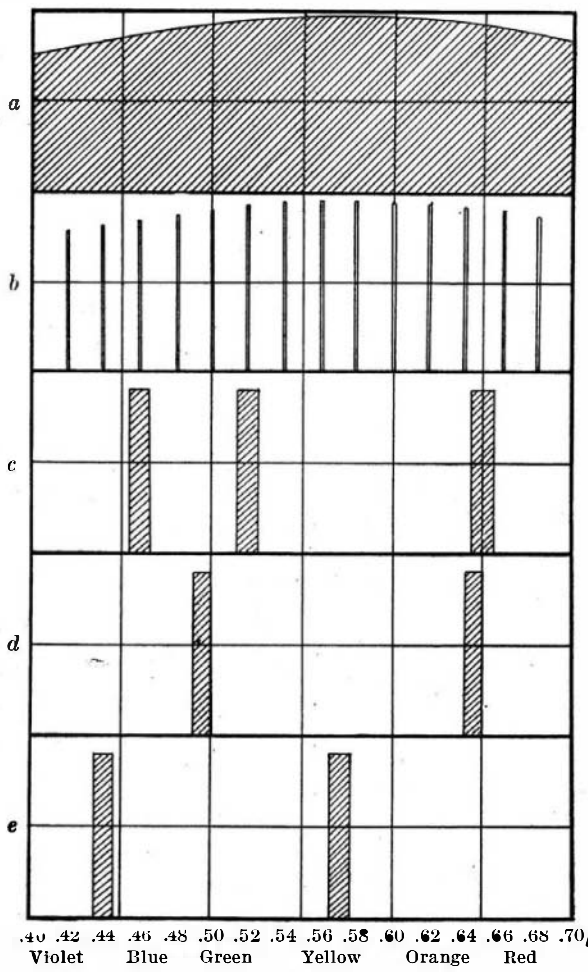

Fig. 5.—Various ways of making white light.

a, Continuous spectrum; *b*, a large number of lines or bands; *c*, a mixture of red, green, and blue; *d*, a mixture of red and blue-green; *e*, a mixture of yellow and blue.

Now this characteristic of red, green, and blue light has led to these colors being called "primaries." They constitute the smallest number of colors out of which all the others may be produced. As such they have had a notable part in making color photography possible. Here we are more interested in the fact that these phenomena of color mixture furnish a method of measuring and representing colors as they appear to the eye, irrespective of their composition.

Taking the spectrum of white light as our standard, it is possible by a series of experiments to determine the quantities of red, green, and blue necessary to match each of the other spectrum colors. Curves may thus be plotted representing these facts, and are called color-mixture curves of the spectrum. This has been done, and it has been found that the true primaries are a certain red, green, and blue a little purer and more saturated than any ordinarily found in the spectrum. These experimentally indicated true primaries are called the primary or fundamental sensations. Fig. 3*a* shows their distribution in the spectrum, where the units are chosen such that equal quantities of the three sensations give white.

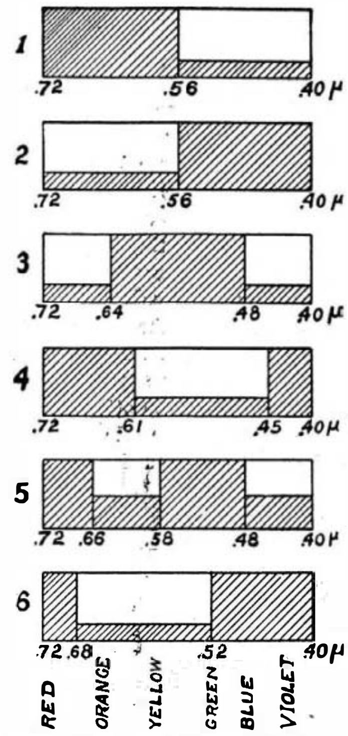

Fig. 6.—Spectral composition of certain arbitrary colors; reflecting power of surfaces or transmissions of absorbing media.

A color may now be specified in terms of but three quantities, instead of a dozen or more, as is necessary with the spectrophotometer. White is equal quantities red, green, and blue sensation; yellow is so much red sensation and so much green, as may be read off the curves. A complex color such as that of an illuminant may be evaluated by multiplying its spectrophotometric value at each wave-length (as compared with white light) by the values of the three sensations at the corresponding wave-lengths and then integrating the curves. Thus the values derived by the use of the spectrophotometer may be translated into sensation values. This transformation process is indicated by the curves of Fig. 3*b*, in the case of a carbon incandescent lamp.

Still another way to obtain the sensation values is by actually making mixtures of red, green, and blue light to match the color under measurement. If one knows the sensation values of the red, green, and blue lights mixed, the results may be at once translated into terms of the fundamental sensations. Some results of transformations to color sensations from both kinds of measurements of color are shown in the color triangle, Fig. 4.

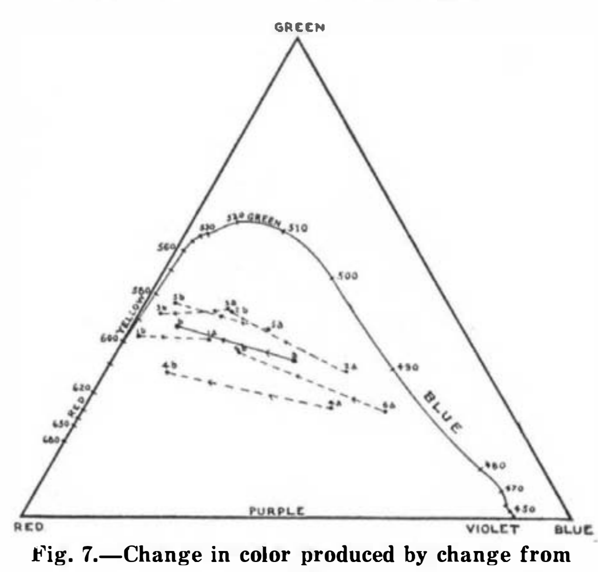

Fig. 7.—Change in color produced by change from daylight (a) to carbon incandescent lamp illumination (b).

The results of measurements in terms of color sensations lend themselves to an elegant and useful diagrammatic representation in what is called the Maxwell color triangle, which we shall have occasion to use later. This triangle is shown in Fig. 4, where the three fundamental sensations are indicated at the three vertices, white at the center and the various spectrum colors in their appropriate positions around the triangle. A certain property of an equilateral triangle is here utilized; namely, that the sum of the vertical distances of any point from the three sides is equal to the altitude. If, then, the three sensations which constitute a color be represented in such units that their sum is the altitude of the triangle, every color finds a place in it. White, being equal parts of the three sensations, lies at the center.

An interesting and valuable property of the triangle is that mixtures of two colors lie on the line joining them. Thus the yellow lies on the line joining red and green. White lies on the line joining a large number of pairs of colors, the "complementaries" met with above. We can then read off from this triangle what colors are to be mixed to produce any others, among them white.

The various sensation values for different illuminants are plotted in the triangle of Fig. 4. This plot again shows how most artificial illuminants differ from white toward yellow, as they are much nearer the yellow of the spectrum than the white center.

METHODS OF MAKING WHITE LIGHT.

As a result of the study of color measurement several methods of artificially making white light present themselves. First and most obvious, theoretically, is the production of an illuminant that has the same distribution of intensity throughout the spectrum as a chosen daylight standard. For instance, if the standard be taken as the color of an incandescent solid at 5,000 deg. Cent. absolute, the direct way to make artificial daylight would be to heat a solid to such a temperature. This, of course, we know is impossible with our present facilities for high temperatures and our known refractory substances. Some form of selective radiation, as from certain oxides as yet unstudied, or from gases under electrical discharge, must then be looked to as a possible means of securing directly, without prohibitive temperature, the desired energy distribution in the spectrum.

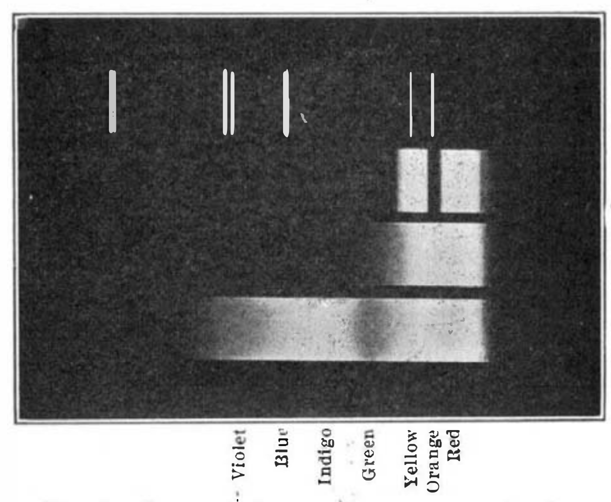

Fig. 8.—Cause of change of appearance of colors of different compositions when viewed under different illuminants.

a, Continuous spectrum light source; *b* and *c*, two yellow solutions which appear exactly alike when illuminated by light source *a*; *d*, line spectrum. Solution *c* absorbs one of the principal lines of this spectrum and consequently appears different in color from *b*.

A second method is to subtract, as by a process of absorption, those radiations in an illuminant which are present in excess over daylight. The manner of accomplishing this theoretically is indicated by Fig. 11, where an ordinary artificial illuminant (excess in red, orange, and yellow) is to be made to match daylight. Starting with a point on the extreme blue of the spectrum, progressively greater portions of the illuminant's radiations are to be absorbed, as indicated by the area of the curve above the cross-hatched portion. Assuming the absorption performed, there remains a spectrum identical in every respect to the standard white light.

A third method of producing white light is indicated by the color-mixture experiments; namely, by the mixing of two or three colors respectively complimentary. Fig. 5 shows an illustration of how white light might be made up of (*a*) a continuous spectrum, (*b*) a large number of lines or bands, (*c*) a mixture of red and blue green, (*d*) a mixture of yellow and blue, and (*e*) a mixture of red, green, and blue, the proper quantities of each being taken so that the total of each fundamental sensation is in every case the same.

With these various means at our disposal it becomes necessary to establish criteria upon which the relative merits may be decided. Among such criteria are efficiency and suitability for color matching. The latter requirement is the most important one here, and will next be considered.

THE REQUIREMENTS OF A COLOR-MATCHING ILLUMINANT.

What is the relationship between the color of an illuminant and the color of the illuminated object? An answer in one simple case is straightway evident. If the illuminant lacks the spectrum rays which by reflection from a surface constitute the color of the surface, then the illuminant obviously is useless for revealing whether two such non-reflecting surfaces are the same color or not under other and more usual illuminants. But if all the spectrum colors are present, though with varying intensity, it is not so easy to answer the question at issue. We must have recourse to the methods of measurement above outlined.

Let us take a representative color, such as is to be found in a dyed fabric. With a spectrophotometer determine its reflecting power at each wave-length of the spectrum. If we multiply the values obtained by the values of the sensation curves in two illuminants under study, we arrive at the resultant sensations as excited by the light reflected from the fabric under the two different lights. These values may then be tabulated or plotted in a color triangle showing the change in the color of the surface under the different illuminants. On carrying through this operation for the set of arbitrary colors shown in Fig. 6, under daylight and under carbon lamp light, the color triangle data of Fig. 7 were obtained. It is to be seen that, while pure spectrum colors change not at all (since they have no various spectral components to be altered in relative intensity), the colors nearer white are bodily shifted in hue. Purples become reds, greens turn to yellows, and so on. This illustrates the change of color appearance, which is very marked, for the kind of illuminants compared, with purples and lavenders (which become ruddy), blues (which become black), yellows (which appear less strongly colored). But the question of color matching is the paramount one. If two colors match under one illuminant, will they match under another? The answer is evident if we consider the two possible kinds of matches. If we have two yellows, identical as to reflecting power through the spectrum, obviously they will continue to match under any illuminant, since both will be affected alike. But suppose one of them is a mixture of red and green, the other a spectrum yellow. Under white light they are identical in appearance. But when they are placed under a light different in composition, such as a carbon incandescent lamp, the red element of the composite color is unduly accentuated, the green element insufficiently brought out, and the resultant appearance is not the same as that of the simple yellow. This difference may be shown numerically by the use of the color sensation curves and the color triangles. It is illustrated for an extreme case by the spectrograms of Fig. 8. Here are shown (*a*) a continuous spectrum light (Welsbach mantle), (*b*) and (*c*) the spectra of two yellow solutions which match perfectly under this light, and (*d*) a discontinuous spectrum (mercury arc). Note that the absorption band in the second yellow falls exactly over the yellow mercury line; the mercury arc light viewed through this solution is bright green; through the other solution it is yellow. The two solutions look exactly alike by one light, totally different by the other.

It is obvious, from these considerations, that if an artificial daylight is to behave toward all kinds of colors exactly as does real daylight, it must not only look like daylight, but must be identical with it, wave-length by wave-length through the spectrum.

(*To be continued.*)

The Safe Use of Electricity in Coal Mining*

Conditions Under Which Explosions of Gases and Dust May Result from Sparks

By W. M. Thornton, D.Sc., D.Eng.

At present there are 3,500,000 workers in coal mines throughout the world, and there are few mines in which electricity is not used for signaling, lighting or power. On a conservative estimate, the value of the electrical machinery now being installed every year in coal mines approaches $50,000,000, and with the development of the Chinese coalfields this may be expected to increase; but the possible danger from electric ignition of firedamp or coal dust has only been at all fully considered in the last few years. Within five years there have been three great colliery explosions which have had a possible electrical origin. At West Stanley, in Durham, direct electrical ignition of coal dust by a flash from a faulty fuse box was suggested; at Hulton, in Lancashire, ignition of gas at a faulty switch; at Senghenydd, in South Wales, ignition of gas by the spark on a signaling bell circuit. These disasters have directed public attention to the subject with increasing force, and the present notes, compiled at the suggestion of H.M. Electrical Inspector of Mines, give the more important conclusions which have been reached by recent research. It must be said, however, that there is no class of work in which electricity can be used with more advantage than in coal mining; but to insure safety it is necessary to take precautions which are not necessary above ground. For some years competition lowered the quality of electrical mining gear below that on the surface. This is now less usual, and the quality of mining work is in many cases better than surface work, and I am told is especially good in the latest installations in Manchuria. With regard to danger from electric shock, there is nothing peculiar to coal mining, and the risk is not here discussed.

Lower limit of ignition of gas.—The initial ignition in most colliery explosions is of firedamp alone. For this to occur sufficient gas must be present to form a lower limit mixture. If the combustible gas is pure methane (CH_4), the lower limit of inflammability is at 5.6 per cent of gas in air by volume at atmospheric temperature and pressure.[1] If, however, there is ethane or other higher hydrocarbon present, the limit is lowered in inverse ratio to the heat of combustion of the mixture. The calorific value of methane is 189.1 and of ethane 336.6 kilogramme-calories per gramme-molecule. Thus, a mixture in which ethane formed 30 per cent and methane 70 per cent of the combustible gas would have a lower limit of inflammability at 4.5 per cent of gas in air. Such large fractions of ethane are unusual in most large coalfields.

Influence of Temperature.—The most recent work on the influence of temperature on limits of inflammability is that of M. Taffanel, of the French Coal Dust Research Station at Lievin, and M. Le Floch. They have shown[2] that as the temperature is raised the lower limit of inflammability falls. In the case of methane values are given in Table I.

These are of interest in the case of heat from gob fires, but electric arcs from breaks are transient and local, and we may, in the absence of coal dust, take 5.6 as the lower limit in electrical coal mining practice. It will be shown later that even one half per cent of gas with sufficient dust present helps to forward an explosion.

TABLE I.

Initial temp., Cent...	20°	175°	237°	312°	555°	690°
Lower limit........	5.8	5.25	4.75	4.3	3.4	3.0

The Most Inflammable Mixtures.—The usual measure of inflammability of a mixture between the limits has been by the velocity of an explosion wave in it, but the measurements are difficult to make. For the purpose of safeguarding the use of electricity in mines a more convenient test is to find the electric current which, when broken in the mixture, causes ignition by its break spark. The results, using non-inductive circuits—that is, with power factors not less than 0.95 when the current is alternating—are as follows for methane and ethane:[3]

Table II.—*Methane.*

Percentage of gas in air by volume.	Least igniting current. Continuous at 100 volts.	Least igniting current. Alternating at 40 ∾ 200 volts.
5·6	Lower limit	
5·0	1·9	12·5
7·0	1·20	7·5
8·0	1·0	4·9
9·0	1·07	3·2
10·0	1·20	2·7
12·0	1·50	4·9
13·0	1·65	7·5
14·0	2·10	12·0
14·8	Upper limit	
Most inflammable mixtures.........	8 per cent.	10·2 per cent.

Table III.—*Ethane.*

Percentage of gas in air.	Least igniting current. Continuous at 100 volts.	Least igniting current. Alternating at 40 ∾ 200 volts.
3·1	Lower limit	
3·5	1·6	12·0
4·5	1·0	7·0
5·0	0·98	6·0
6·0	1·08	4·5
7·0	1·25	4·0
8·0	1·45	4·5
10·0	1·82	10·2
10·7	Upper limit	
Most inflammable mixtures..........	5·0 per cent.	7·0 per cent.

The curves drawn from the continuous and alternating-current values are quite different in type; the former is chisel-pointed, the latter U-shaped and parabolic at the lowest values. In neither case is the most sensitive mixture that for complete combustion. For continuous currents it is below it, for alternating current above it. The least igniting continuous current is very nearly the same for all the paraffin gases.[4] The influence of ethane is, therefore, not to increase the sensitiveness of the mixture to electrical ignition other than by lowering the limit of inflammability. For alternating circuits ethane actually requires greater currents than methane,[5] and the very great increase in the magnitude of alternating as compared with continuous current is the first and strongest argument in favor of the use of alternating current from the point of view of risks from break sparks.

Influence of Inert Gases.—A small excess percentage of nitrogen appears to have a marked effect on the magnitude of the igniting currents. Pit gas containing from 6 to 12 per cent of nitrogen, diluted with an air to form mixtures having measured percentage of combustible gas, required the igniting currents to be from one and a half to twice as great as with methane when direct currents was used, and to as much as four times greater when alternating currents, at a frequency of 40, were used for ignition[6]. This point requires fuller examination.

Influence of Circuit Voltage.—The change of igniting currents with voltage is not the same in continuous and alternating circuit. In the former the product of voltage and current is approximately constant over part of the working range; in the latter the current does not always diminish as the voltage is raised, but remains constant over a considerable range of it. An alternating pressure of about 500 is the safest in the sense that, at this pressure, a greater power can be broken without ignition than at any other.

Table IV.—*Igniting Currents for a 9·5 per cent. Mixture of Methane and Air.*

Voltage.	Continuous current at 100 volts.	Alternating at different frequencies. 40.	60.	80.	100.
50	2·5	16·0	...	...	...
100	1·0	7·0	16·0	20·0	29·0
200	0·4	3·8	12·2	14·2	19·0
300	0·25	3·5	7·0	12·5	17·0
500	0·2	3·5	6·0	11·0	13·0
700	...	3·0	4·5	10·0	10·7
1,000	...	0·75	1·5	5·5	8·0

Thus, at 1,000 volts alternating current at 40 frequency the igniting current is a little less than at 100 continuous volts.

It can be shown that at a frequency of about 100 a break spark ignites gas with more difficulty than at any other frequency. For all circuits other than large power circuits this frequency is to be recommended from the point of view of safety from ignition by break of cable.

Influence of Self-induction in a Circuit.—Inductance in a circuit, either continuous or alternating, increases the igniting action of a break spark. The energy of the circuit which just causes ignition is the same at all inductances from 0.02 to 0.6 henry[7]—that is, the igniting current is inversely proportional to the square root of the inductance in a circuit. This is most important in signaling circuits in which the inductance of a bell may reach 0.5 henry. The igniting current at this for a single break is 0.5 ampere. Bell circuits in which open sparking may occur, may, therefore, be regarded as dangerous unless otherwise protected.

Signaling by Electric Bells.—The voltage for this purpose in Great Britain is limited to 25, but there are no conditions specified as to its source. It is most usually 6 to 15, except on long haulage roads. The working current taken by an ordinary mining signaling

*Paper read before the British Association in Australia.

[1] "The Lower Limit of Inflammation of Mixtures of the Paraffin Hydrocarbons with Air," by R. V. Wheeler and M. J. Burgess, "Trans. Chem. Soc.," 1911, Vol. XCIX., p. 2,013.

[2] "Sur la Combustion des Melanges Gazeux," par. M. M. Taffanel et Le Floch, "Comptes Rendus," Tom. 157, No. 15, October 13th, 1913, 1.595.

[3] "The Ignition of Coal Gas and Methane by Momentary Arcs," by W. M. Thornton, "Trans." Inst. Min. Eng., 1912.

[4] "The Electrical Ignition of Gaseous Mixtures," Roy. Soc. "Proc.," VA., Fig. 2.

[5] *Loc. cit.*, Fig. 12.

[6] "The Comparative Inflammability of Mixtures of Pit Gases Ignited by Momentary Electric Arcs," "Trans." Inst. Min., Eng., Vol. XLVI., part 1, pp. 112-124, 1913.

[7] "The Ignition of Coal-gas and Methane." *Loc. cit.*, Fig. 5.