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ARTIFICIAL DAYLIGHT.*

BY

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In the fourteenth century the Glover's 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 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

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the prevailing fashions call for color 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 any one 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.

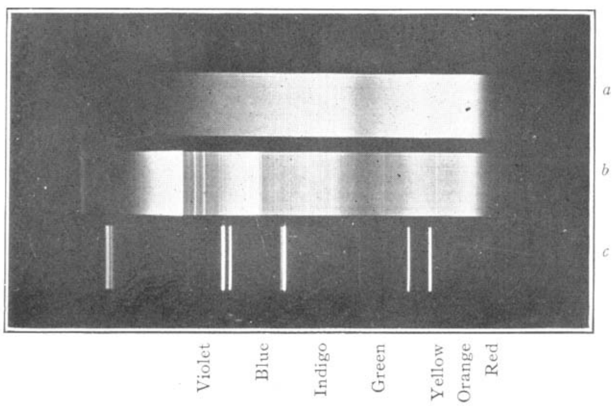
There are two distinct methods of color measurement. The first is by analysis of the light radiations into their elements and then quantitative measurement of these elements. The second is by analysis according to the effects on the visual apparatus. Properly speaking, the first method is not color measurement 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 every one 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 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 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 intensities 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 .59μ, which is merely a matter of convention, since the

FIG. 1.



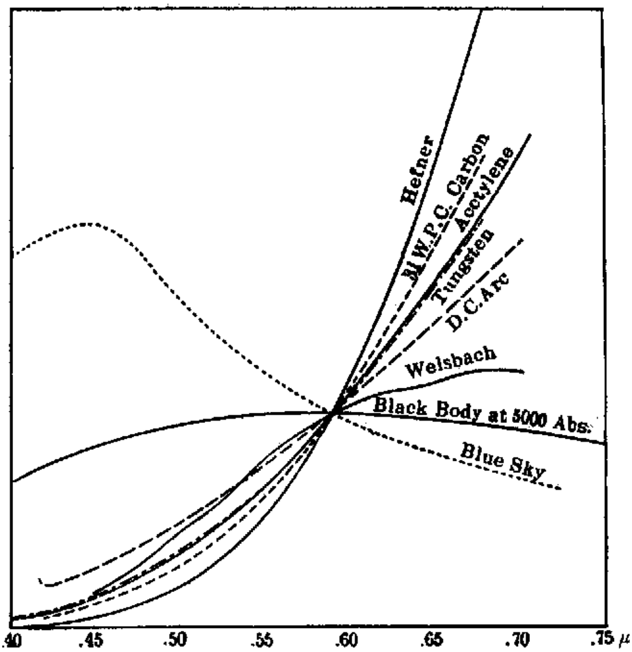
Spectra of representative light sources. (*a*) Continuous spectrum of the Welsbach mantle; (*b*) continuous spectrum with superposed bands, carbon arc; (*c*) line spectrum of the mercury arc.

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 1500–2500° K., while sunlight approximates in color an incandescent solid or black body at 5000° 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

FIG. 2.

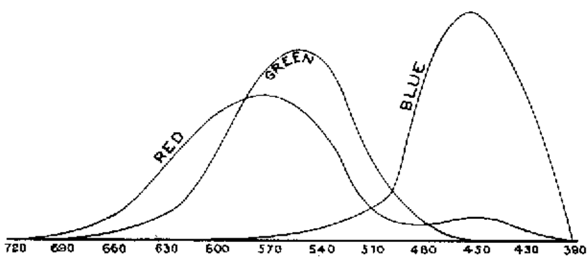


Relative intensities through the spectrum of certain representative illuminants.

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.

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

FIG. 3*a*.



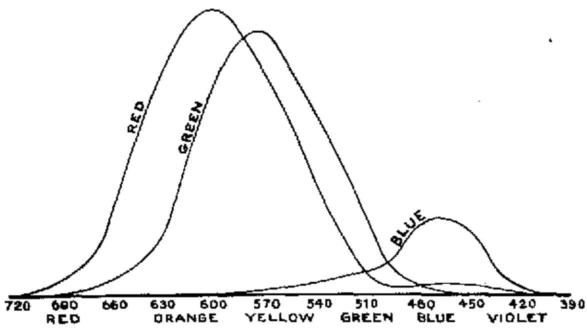
Color sensations in white light.

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.

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.

FIG. 3*b*.

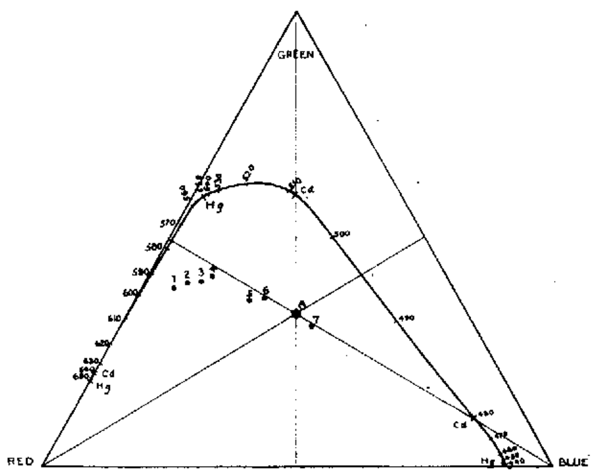


Color sensations in incandescent carbon lamp light.

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.

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 centre 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 centre.

FIG. 4.



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

1. Hefner. 4. Welsbach. 7. CO_2 tube.
2. Carbon. 5. D. C. arc. 8. Whole light.
3. Tungsten. 6. Afternoon sun.

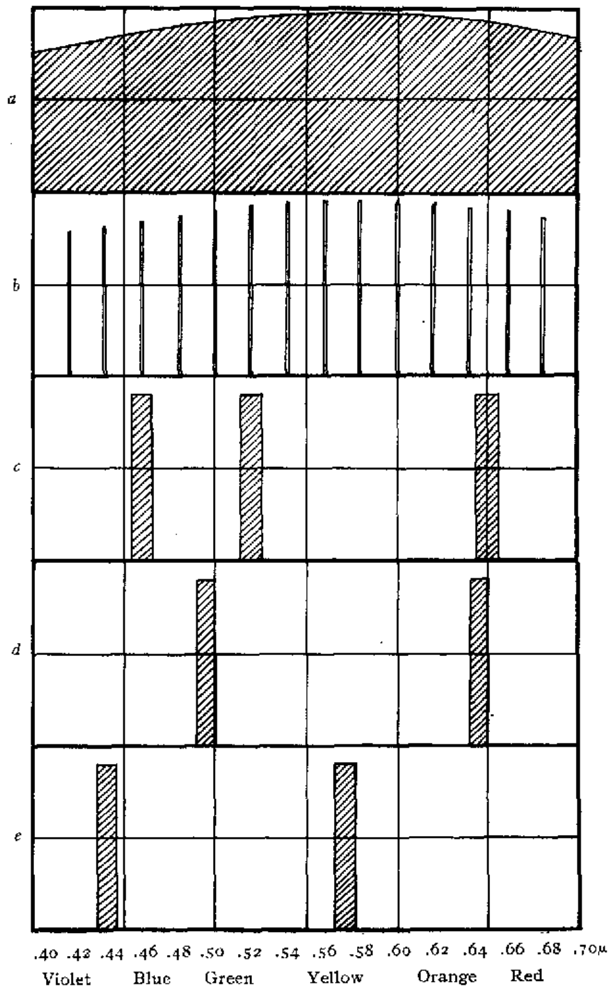
An interesting and valuable property of the triangle is that mixtures of two colors lie on the line joining them. Thus the yellow lies on the line joining red and green. White lies on the line joining a large number of pairs of colors, the "complementaries" met with above. We can then read off from this 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 centre.

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

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.

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 5000° C. 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.

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.

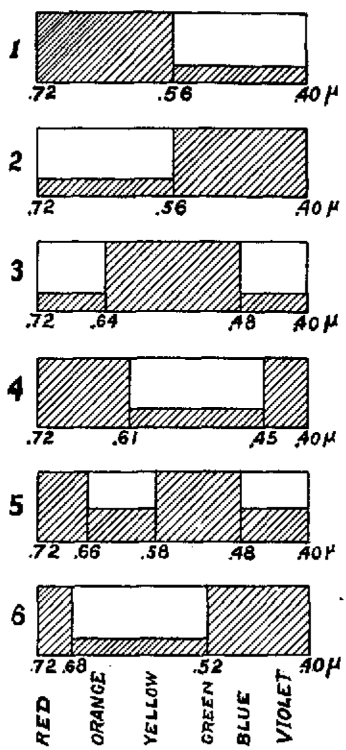
A third method of producing white light is indicated by the color-mixture experiments; namely, by the mixing of two or three colors respectively complimentary. Fig. 5 shows an illustration of how white light might be made up of (*a*) a continuous spectrum, (*b*) a large number of lines or bands, (*c*) 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 their 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,

FIG. 6.

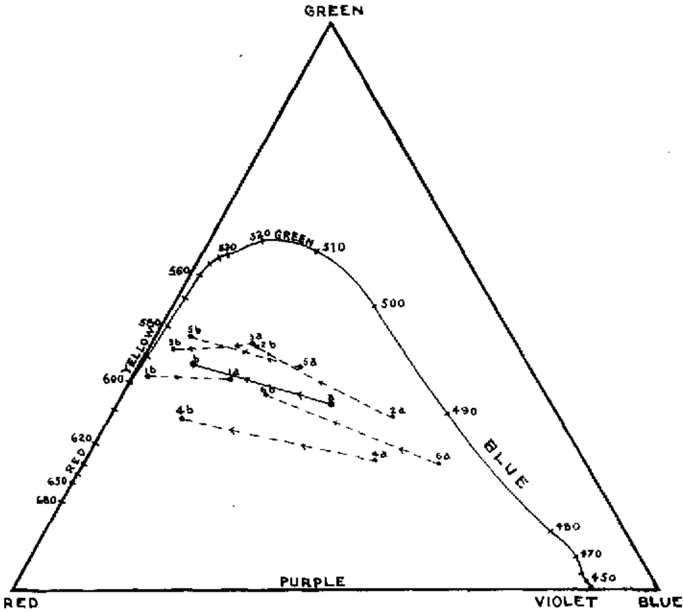


Spectral composition of certain arbitrary colors; reflecting power of surfaces or transmissions of absorbing media.

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

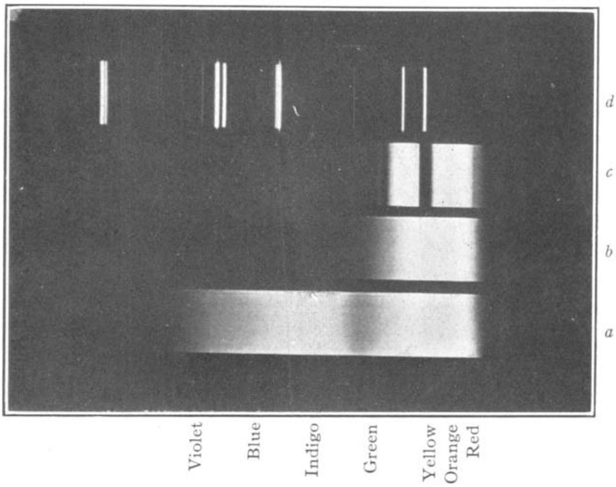
FIG. 7.



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

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 ele-

FIG. 8.



Cause of change of appearance of colors of different composition 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*).

ment 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.

THE PRACTICAL ACHIEVEMENT OF ARTIFICIAL DAYLIGHT.

Before proceeding to an account of various artificial daylights let us here review briefly the pertinent facts about daylight and color. We have seen that daylight is variable, but that it always lies in a class apart from the usual artificial light sources, which latter are in general of a yellow color. We have seen how color may be exactly measured, and have learned that the same color appearance may be produced in several ways. Several theoretical ways of producing artificial daylight have been described. Finally, by investigating the changes in the apparent color of objects under different colors of light, we have been led to formulate the essential characteristic of artificial daylight; namely, it must not only look like daylight, but also be like it, as shown by an analysis of the spectrum.

In approaching the practical side of the problem it becomes necessary to choose a standard for daylight, and it becomes necessary to know what degree of approximation to the last-named criterion is sufficient for practical purposes. It is also necessary to pay attention to the matter of efficiency—the artificial daylight must not be prohibitive in cost.

The standard of white light adopted by the writer is derived from the mean of a large number of spectrophotometric determinations of sunlight quoted above, into which an additional factor has been introduced. It is always desirable to connect any standard with other standards; to depend not on a set of numerical values, but on some simple mathematical expression which may be developed by the introduction of a few constants. It appears, for instance, that the white light standard mentioned has to within the limits of accuracy of its determination the distribution of intensity through the spectrum of a perfect incandescent solid or black body at 5000° C. absolute; a distribution immediately calculable from the laws of black body radiation. So much for a scientific standpoint. In commercial practice another fact has had to be given weight; namely, professional color matchers have chosen as their standard light the blue north sky. It is difficult to change the customs of experts, and so it became practically necessary to supply a blue sky standard. For this the spectrophotometer values given in Fig. 2 serve as a basis.

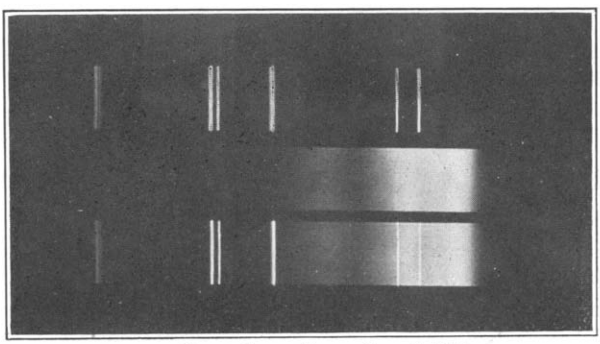
How closely is it necessary in practice to approximate the exact spectrum distribution of daylight? Very closely indeed, but not so exactly as to be prohibitively difficult, for this reason: that all ordinary colored objects and coloring materials have rather long diffuse spectra; they are not isolated, sharply defined spectrum colors. Consequently, if such gaps and irregularities of the artificial daylight spectrum are bridged over by the reflection spectrum of the color illuminated, they will not be noted. For instance, an illuminant whose spectrum consisted of twenty-five or thirty equally spaced lines would probably behave excellently as a color-matching light, provided, of course, their intensity was closely that of the daylight spectrum at each point. An expert with a knowledge of the spectrum and of the kind of coloring media used in the arts can make up critical colors having several maxima of reflecting power in the spectrum, colors which match under one light but not under another, and from the accumulated experience of the practical dyer other colors may be found of similar difficult character. The behavior of these colors under an artificial daylight in its experimental stages provides valuable information and guidance.

The question of efficiency will be considered in connection with each of the three kinds of artificial daylight described below.

The first kind of artificial daylight postulated as possible is a light source that has naturally the same spectrum distribution of intensity as daylight. An incandescent black body at 5000° C. absolute would have this distribution, but such a temperature is entirely beyond our present means. The same distribution could be obtained at much lower temperatures if we had available a selectively radiating substance which would give out a comparatively small amount of invisible heat radiation and have a much greater emissivity at the blue end of the spectrum than at the red. Such a substance is not yet known, but the materials used in the

Welsbach mantle approximate the characteristics to a degree which incites us to further study of these oxides. Another possible way of achieving this spectrum distribution is through non-temperature radiations, as, for instance, by the passage of a current of electricity through a rarefied gas which would radiate at a sufficient number of wave-lengths in the right proportion. Such an artificial daylight has been found in the radiation from the carbon dioxide vacuum tube, which under the name of the Moore tube has been developed commercially and has deservedly been used to considerable extent for color-matching

FIG. 9.



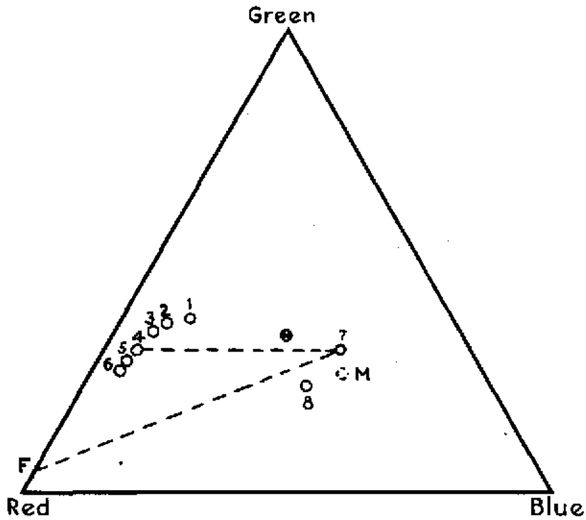
Additive production of artificial daylight. (a) Mercury arc spectrum; (b) tungsten lamp spectrum; (c) combination of mercury arc and tungsten lamp light to make a white light.

work. Its spectrum consists of many fine lines and bands, together giving the color of a light blue sky and of reasonable uniform intensity. The Moore tube is, however, comparatively inefficient and demands an expensive installation of alternating current and transformer to produce high potential—drawbacks which have prevented its extensive use.

The second kind of artificial daylight I wish to treat of here is one of interest from the standpoint of color measurement and theory. So far as concerns the question of color matching, this particular daylight,—namely, the one made by matching pairs of colors to look like daylight,—is chiefly of importance as illustrating the pitfalls to be avoided.

A property of the color triangle above referred to is that colors lying on opposite sides of a line passing through the centre of the triangle (white) mix to produce all colors lying on that line, among them white. Consequently, if two happen to lie thus on opposite ends of a line through the centre of the color triangle, it should be possible to make a white-appearing mixture. Examination of the color triangle, Fig. 10, shows that the mercury vapor arc lies opposite the tungsten lamp. Consequently, if

FIG. 10.



Illustrating white-appearing lights made by combining the mercury arc with other illuminants; 1, 2 and 3, Welsbach mantles; 4, tungsten lamp; 5 and 6, tantalum and carbon lamps; 7, mercury arc; *F*, color of fluorescent reflector; 8, mixture of mercury light from lamp and reflector (*M*) with *F*.

these two illuminants act together the appearance should be that of white light. Such is, in fact, the case. White-appearing light can be so produced at an efficiency somewhere between that of the two constituents, and white light of this constitution is to be found in several places. The term "additive" production of artificial daylight may be applied to this process to distinguish it from the other process presently to be described as "subtractive." This particular "additive" daylight, and others which are apt to be produced experimentally in efforts to make a true artificial daylight, are characterized by their failure to show up colors in their true daylight appearance. The reason for the failure of this particular combination is easily seen from the spectrograms of Fig. 9, where the tungsten lamp spectrum is shown, with its deficiency in blue; the mercury arc spectrum, deficient in red, and the combination of the two. The latter is characterized by long gaps and irregularities. The mercury arc-tungsten combination is not, therefore, suited for one use to which it has been mistakenly put; namely, the illumination of picture galleries.

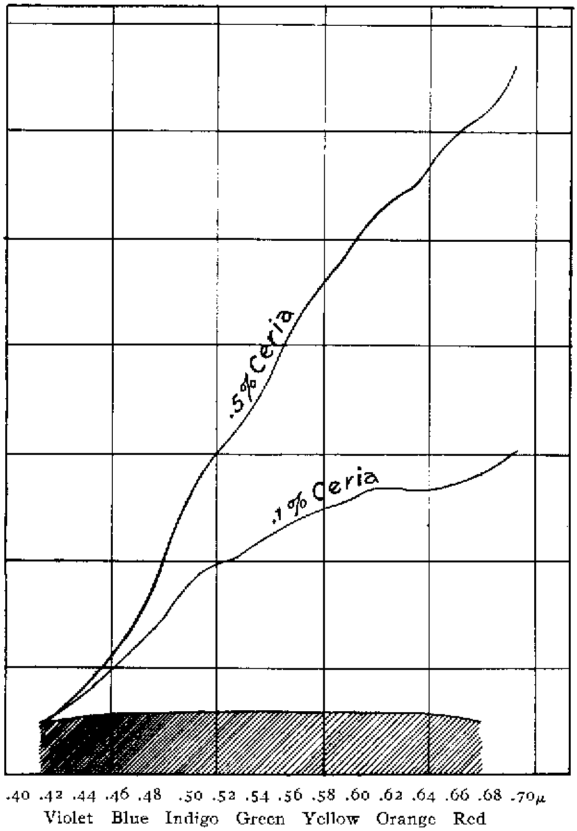
Another example of this additive method of producing white light is furnished by the Cooper-Hewitt lamp with fluorescent reflector. The fluorescent substance—rhodamine—is of a color approximately complementary to the hue of the mercury arc, as is shown in the color triangle of Fig. 10, where the fluorescent light is shown at F, the mercury arc at 7, and the "white" light at 8. This is not exactly on the line joining 7 and F, because the mercury arc light reflected from the rhodamine reflector is deficient in green. The real mixture is between F and M. It will be seen that the resultant color is a purplish-white (below centre of the triangle). This light is, unfortunately, not suited for delicate color matching, because its spectrum is merely the mercury lines with an orange-red band added. Large portions of the spectrum are missing.

The next, and on the whole the most important, method of producing artificial daylight is the subtractive one; that is, the subtraction by absorption of those radiations which an illuminant emits in excess over daylight.

By way of detailed explanation let us now carry through the various steps in the practical production of such an artificial daylight. Let us take as our illuminant to be transformed to daylight the Welsbach mantle, which, because of its nearer approach to whiteness than the usual incandescent solids, especially recommends itself for the purpose. The first step is to determine its distribution of intensity throughout the spectrum and compare it to that of daylight. At once cognizance must be taken of the fact that the color (intensity distribution) of a mantle depends upon the composition. A pure thoria mantle is much whiter than a mantle of pure ceria, the light of the latter being, in fact, deep orange-yellow. Fig. 11 shows the energy distribution of two typical mantles, containing .25 per cent. and

.50 per cent. ceria respectively, each compared with daylight under such conditions that the intensity at the extreme blue end of the spectrum is equal. When these data are so plotted the space between the mantle curves and the daylight curve represents light which must be absorbed. It is obvious that the whiter

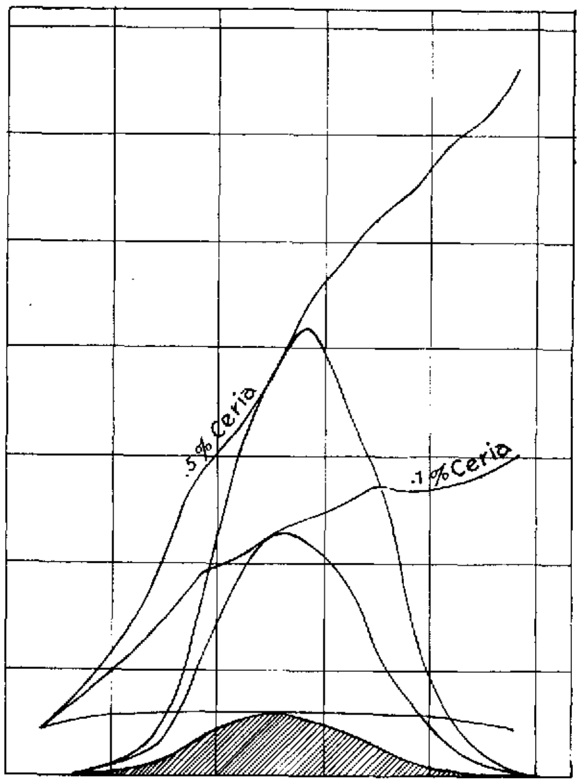
FIG. 11.



Typical Welsbach mantles compared spectrophotometrically with daylight.

the mantle (*i.e.*, the smaller the percentage of ceria) the less light must be absorbed in order to leave daylight. As yet, however, the amount of this absorption is not expressible in useful comparative units. It is necessary to express this in terms of luminosity. This is done by replotting the data of Fig. 11, multiplying the value at each wave-length by the relative brightness of that kind of radiation as is done in Fig. 12. Now the area of the "white" luminosity curve, compared to the area of the mantle curve, gives us at once the relative amount of light left after the subtraction process. This ratio I have called the "daylight efficiency." Its value for mantles of various percentages of ceria

FIG. 12.



.40 .42 .44 .46 .48 .50 .52 .54 .56 .58 .60 .62 .64 .66 .68 .70μ

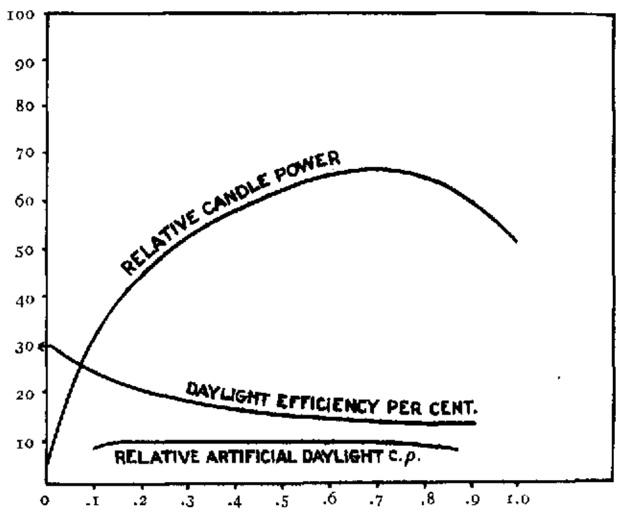
Violet Blue Indigo Green Yellow Orange Red

Calculation of daylight efficiencies of different mantles.

is plotted in curve *a*, Fig. 13. Other things being equal, it is clear that the mantle with no ceria should be chosen. But other things are not equal, for with varying percentages of ceria the candle-power of a mantle changes, rising from a minimum for the pure ceria one to a maximum for a mixture of 99 per cent.

ceria and 1 per cent. of thoria, then again decreasing as the ceria content is increased. This curve of relative candle-power is also shown in Fig. 13. It is obvious that the product of curves *a* and *b* will give the total daylight efficiency of all mantles when screened to make artificial daylight. This product is shown in curve *c*, interesting as showing that mantles through quite a range of composition—from .25 per cent. to .7 per cent. ceria—can yield the same efficiency of artificial daylight. Above .7 per cent. ceria the efficiency drops off rapidly. This efficiency is only

FIG. 13.

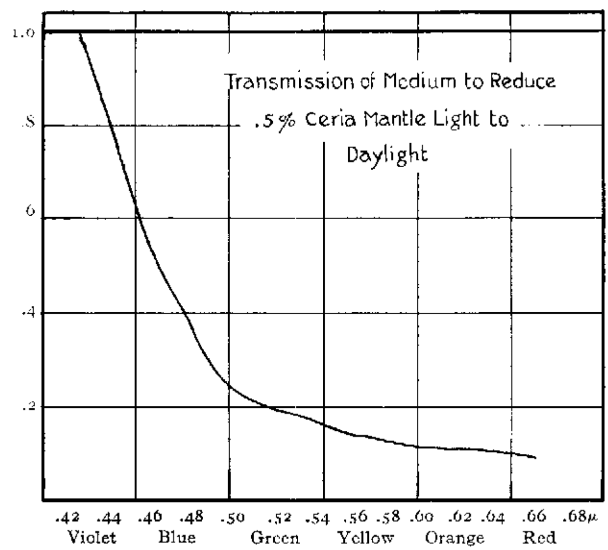


Total efficiency calculations for mantles of various compositions.

about 15 per cent., showing that artificial daylight is necessarily an expensive product when thus secured.

Having chosen a mantle to be screened, the next question is that of absorbing media. What is the absorption needed? Putting it in terms of transmission it is this: The transmission at each wave-length must be the ratio of the daylight intensity to the artificial light intensity when so represented that the value is unity for the extreme end of the spectrum. The transmission required to transform the light of the Welsbach mantle of .5 per cent. ceria to "white" (black body at 5000° C. absolute) is shown in Fig. 14. It appears that the absorbing medium indicated is of general blue color. The next step is to study the various available absorbing media. These are practically reduced to two: first, colored glass, and, second, dyes which may be incorporated in gelatine or some similar transparent carrier. No single glass or combination of glasses at present on the market possesses the absorption called for. Cobalt blue glass, which is the first thought of every one, has several irregular bands, not a uniformly increasing transmission toward the blue end of the spectrum. Copper

FIG. 14.

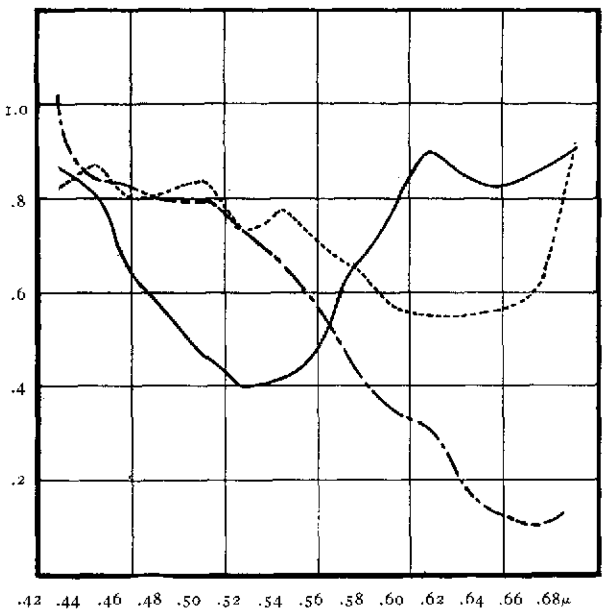


Transmission of medium to reduce light from .5 per cent. ceria mantle to daylight.

glass, which is blue-green in color, has a gradual absorption, but is too green. The great advantages of glass over dyed gelatine are its permanence and the possibility of working it into all shapes, from flat sheet to spherical enclosure. Still, dyes have the one advantage that they provide an enormous number of absorptions of both broad and narrow types. Some representative transmissions are shown in Fig. 15. The bands and deficiencies of glasses can almost always be filled in by properly chosen dyes, although many dyes are not at all permanent, which reduces very materially the number available.

It has been found possible to make a practical combination of copper glass in sheet form with a dyed gelatine layer on a separate sheet, which accomplishes the purpose admirably, using dyes of great permanence. The commercial device is shown in Fig. 16. It consists of a small booth, closed at back and sides, in order that stray light from other light sources may not enter and mix with the daylight. Samples of cloth, tobacco, etc., are held under

FIG. 15.

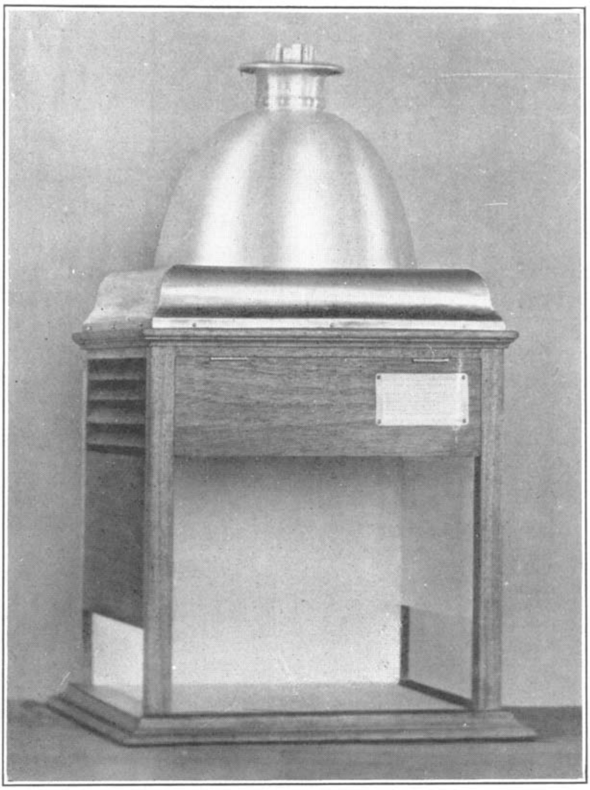


Transmission curves of representative glasses and dyes.

the glasses, and the result is identical with daylight. The spectrophotometer intensity curve is shown in Fig. 17, both for a .7 per cent. ceria mantle, which gives the sunlight color, and for a .25 per cent. ceria mantle, which gives the north light used by dyers and color matchers.

With the .25 per cent. upright mantle more than 20 ft. candles illumination is obtained on the working plane, while with a large inverted mantle the figure is multiplied by four—in either case sufficient for color-matching purposes. The absorption of light by the glasses is about 90 per cent. The device has been worked out in the booth form partly because the expense of lighting large areas would be excessive, were there not some good reason for so doing, which often there is not, and partly to educate the user to exclude stray light of other colors which

FIG. 16.

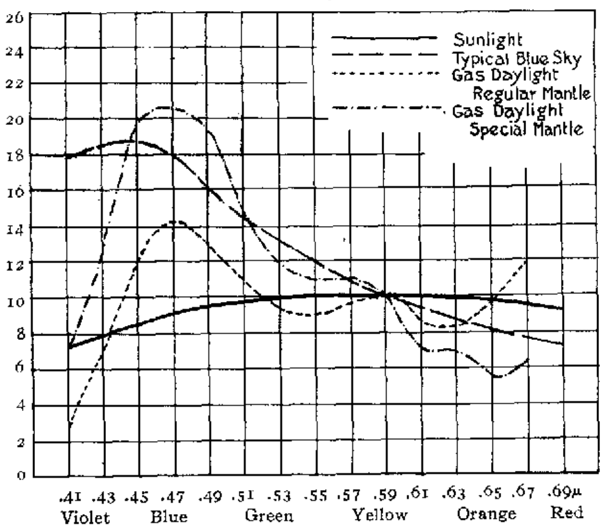


Color-matching booth.

would distort his color values. These devices are now being used extensively in silk mills, cigar factories, department stores, etc.

A limitation to this form is its lack of flexibility, caused by the necessity for using dyed gelatine, which can be laid down only on a flat plate. The extreme desirability of effecting the entire absorption through glass has long been apparent, and in the Research Laboratories of The United Gas Improvement Company a small experimental glass plant has been actively engaged in the problem of producing such glass. All known coloring oxides have been studied, and Mr. Edw. J. Brady, in charge of this particular research, has recently succeeded in producing a true daylight glass. This glass will shortly be available for gas and other illuminants, and will make artificial daylight as easy to produce as any other artificial light—necessarily at a larger cost, to be sure; but in many cases this larger cost will be an insignificant item compared with the twelve or more additional working hours furnished by artificial daylight.

FIG. 17.



Spectrophotometric curves of natural and artificial daylight.

Before leaving this subject of the production of light having a daylight color, one of the methods of using the absorbing medium claims attention. Colored objects, it must be remembered, owe their color to the effect on the light incident upon and reflected from them. Now, it is immaterial whether the light is subjected to the day-color producing absorption before or after its incidence on the colored object. Except for considerations of convenience, the absorbing glasses could just as well be placed vertically in front of the booth in Fig. 16, and the colored samples placed in the direct light of the illuminant. Advantage is taken of this alternative possibility in the construction of the daylight spectacles, shown in Fig. 18. Built with a perfectly light-excluding hood, these may be worn by the surgeon

FIG. 18.

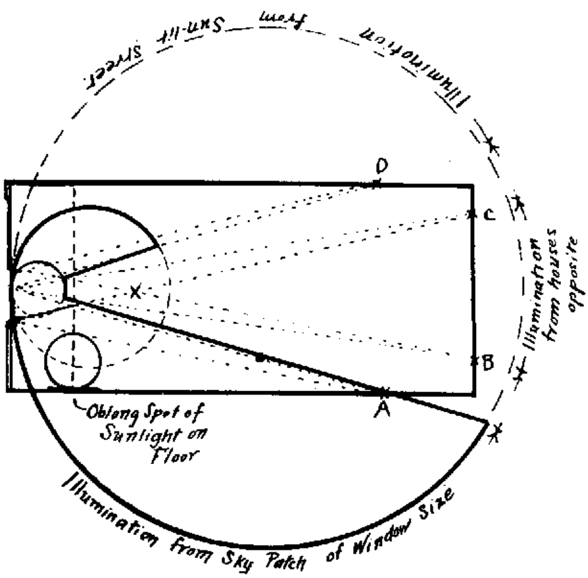
Manner of using daylight spectacles.

or the color matcher, and when used with the appropriate light source they produce daylight for him alone, thus obviating the necessity for a special booth or room in which to do his work. Further advantages of this form of color-matching device are the small amount of special glass needed and the entire freedom from questions of breakage through overheating.

THE COST OF A COMPLETE COPY OF DAYLIGHT.

The question always asked about artificial daylight is: How much does it cost to make a complete copy of daylight illumination in a room? Some figures which I have given elsewhere in connection with a study of the distribution of daylight may, therefore, be of interest here. Pleasant daylighting of the room taken for study, a room 16 feet x 10 feet, was produced when the light of the sky illuminated the whole floor of the room and

FIG. 19.



The distribution of daylight from a window.

when the ceiling was illuminated by the light reflected from the street below, while the opposite houses, which were in shadow, were the only outside objects visible to the occupants of the room. The bright sky, which does most of the lighting of the room, forms a concealed light source. The distribution of light from the window as a light source is shown in elevation in Fig. 19. It was found possible by a construction of mirrors to closely duplicate this distribution and to produce an illumination about one-tenth that of real daylight at an expenditure of about 260 watts. To secure daylight intensity would have taken 2000 watts.

whereas if the light had all been subjected to daylight-producing absorption it should have required 20,000 watts.

If, however, daylight could be produced directly in an illuminant without any waste heat radiation, it would not only be a much more efficient process than that indicated, but even more efficient than any present known artificial light source. Instead of 20,000 watts, 50 watts would suffice.

The ultimate goal of the student of artificial daylight, therefore, is the production of daylight whenever and wherever it is wanted, distributed in any desired manner, at no greater cost than our present yellow artificial light.

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Value of Explosives for Engineering. ANON. (*Amer. Mach.*, xxxix, No. 24, 996.)—The greatest engineering works of the present day are undoubtedly those connected with the removal of vast quantities of soil and rock. The Panama Canal, the Catskill Aqueduct and many other tunnels, excavations and mines are the feats which arouse popular enthusiasm. These would be quite impossible if it were not for the knowledge we have of powerful explosives and modern drilling methods. It is interesting to note that gunpowder as an explosive agent was not used in mines in Europe till a century and a half after the discovery of America, and was first used in Germany. It is only within the last fifty years that mine excavations have been revolutionized by the development of these fundamental requisities, dynamite, the air-compressor, and the power drill.