COLOR TEMPERATURE CLASSIFICATION OF NATURAL AND ARTIFICIAL ILLUMINANTS*

BY NORMAN MACBETH**

SYNOPSIS: This paper discusses the need for a quality rating of artificial light sources on the basis of color temperature and presents on two scales a large number of color temperature values for sunlight and daylight, together with the measurements on over thirty glasses which with gas-filled tungsten filament lamps will result in a range in apparent color temperatures from 2100 degrees absolute to 30,000 degrees absolute. A new instrument is illustrated for color temperature determinations. Reference is made to the quality spread in natural daylight with the means for producing a corresponding range in artificial daylighting accessories, and the various color of light qualities for particular color work are discussed.

> *"Success in doing anything is always the result of discovering 'why' rather than 'how.' Nobody can tell how a thing should be done until he knows why it should be done at all and knowing why nearly always indicates how.*
>
> *The difference between why and how is the difference between principles and practice."*

Twenty years ago we were without the definite flux units and complete nomenclature in photometery that we have today. Our sources were rated in candlepower but rarely on a mean spherical or total flux basis—in general, electric incandescent lamps were rated in horizontal candlepower, which with a known distribution and reduction factor permitted a total flux value to be calculated. Other lamps were rated in mean lower hemispherical candlepower and frequently were credited with extraordinary ratings by quoting a maximum beam intensity due to a concentrating reflector, or the maximum at a certain angle as in the case of many electric arc lamps. Candlepower ratings just didn't mean anything in the manner they were frequently given, certainly our flux

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* A Paper presented before the Twenty-first Annual Convention of the Illuminating Engineering Society, Chicago, Ill., October 11-14, 1927.

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values were without the definite quantity possibilities of our present lumen ratings.

Illuminating engineering may be credited with that advance. Quantity ratings are recognized and in general use. Recently with sources of relatively higher efficiency and with lower costs for energy, the need has been felt for a quality rating.

While the ideal light source has invaribly been quoted "like daylight" I am convinced that if we had such a primary source much would be done to modify it for many of our needs for artificial illumination.

Flame-tint lamps, gas flames and the candle, for instance, have a large field of considerable usefulness in the home where an appreciable proportion of humanity is seriously interested in simulating "that school girl complexion."

About fifteen years ago the largest campaign in residence lighting that I recall, was put on in Chicago with this appeal.

The chemists of a large manufacturer of incandescent gas mantles had, in lectures before chemical and engineering audiences, frequently demonstrated the effect of ceria when added in small proportions to the pure thoria oxide used in the impregnation of mantle fabrics. This series of mantles, usually ten in number, ranged from a pale blue of low light output up to the point of maximum light quantity and then down the light scale to a low light output burnt-orange color on the end mantle, where 10 per cent ceria was used.

This heretofore pure science demonstration outfit was taken by the illuminating engineering department and set up for photometric comparison—mantle by mantle, with an open gas flame and that thoria-ceria content was selected which seemed to be the best compromise between effect and efficiency.

The campaign referred to resulted in the disposal of several hundred thousand new gas burners and many thousands of mantles in the Chicago territory alone.

The advertising behind this campaign was in my opinion the most effective ever run on residence lighting. A noted opera singer's endorsement was secured and the general text of the copy used was little from the gas or electric lighting points of view but much from the standpoint of the beauty specialist.

Now, that the gas formerly used for lighting, "to add a touch of tan to the cheek of the shut-in" is so largely used for fuel and heating purposes, these soft, mellow, warm effects can only be secured with candles, and millions of them are now used annually, or with the so-called flame-tint incandescent electric bulbs; standard crystal glass bulbs and colored glass, silk or paper also have a worthy place in contributing to this pleasant home atmosphere.

These warm appearing lights have their place in the home; merchandising and industrial aplications have other demands based also on effectiveness—eye efficiency is the measuring stick used here. In office work, mixed daylight and artificial light from incandescent lamps has frequently been complained of, particularly when the daylight is waning. Various explanations have been given to account for this effect, without any general agreement as to its cause and in some instances as to there being such an effect.

Among bathers we have "mermaids" and "polar bears" together with a large majority who stay near the shore in shallow water. At certain times when the sun may be shining and the air warm, the water may be cold—a wader in this water does not enjoy the sensation, and the advice proven by experience to be worth while is to "plunge in, get all the way under the surface"—it doesn't feel so uncomfortable then. The temperature of the water hasn't been changed, the plunge however has undoubtedly induced a more brisk blood circulation with the result that "the water's fine." So when a mixed daylight and artificial light is objectionable, the advice has been "pull down the window shades. Take a plunge into artificial light—let nature provide the remedy."

After many years study and observation, I am convinced that there is a quality difference readily appreciated by the eye, between artificial light from an incandescent filament below 3000°K and daylight of 8,000 to 10,000° K color temperature. Daylight is and always has been the ideal. The difficulty has been to find out just what quality in daylight was most effective in satisfying the eye's demand.

Daylight intensities are greater than is usual with artificial light. Is it intensity? Aside from the occasional discernment of minute detail there is no general complaint nor in fact recognition of a varying appreciation for a 10 foot-candle intensity as compared to that of several hundred foot-candles. Most of us will pull down the window shade or move to another location rather than read in direct sunlight under several thousand foot-candles. This aversion to high intensities is not general, however, as a daily rider on trains running south in the morning I have noticed many readers who select the sun-admitting-window seats and have been informed that they do not experience discomfort from the sunlit page of their paper. Intensity therefore is apparently not the deciding factor.

Daylight is highly diffused. Is it the diffusion quality? That also is questionable—we have had artificially illuminated interiors by indirect lighting systems for many years. The diffusion of light in these interiors is superior to that of daylight through windows, and studies have shown that intensity and diffusion of artificial light superior to window-admitted daylight is still lacking in that quality the eye most appreciates. There has even been some comment to the effect that this degree of diffusion is not wholly desirable.

Only color quality is left and while it is known that colored materials appear differently under artificial light than under daylight, the admission has not been at all general that a balanced white light is of any particular advantage excepting for "color matching"—and color matching touches upon but a small part of our human activities.

From the standpoint of color to be "like daylight" infers a source under which colored materials will reflect light of the same quality and appear the same to the eye of the observer as when seen in daylight. This color quality apparently is appreciated by the eye on a quality basis alone, regardless of duplicating natural light either in intensity or diffusion.

All daylight lamps or equipment should be checked against good natural daylight and with a variety of known colors by a trained observer with normal color vision. Many of the so-called "daylight" lamps on the market today would require but a few minutes observation and fail to pass such a test even with a partially color blind individual, but the purchasing agent who listens, finds the price satisfactorily low and buys, usually buys a necessary experience. Thousands of orphan daylight lamps have been purchased with just that result. A satisfactory light for color work should be purchased through the eye—not the ear.

To say that a light has the color qualities of daylight and then hedge behind the conception of the wide color range of natural daylight from sunrise to sunset and of various exposures, and because one daylight exposure, or at one time of the day or season, may differ from another with highly selective colors in an exact color response, that this apparently wide but actually well defined range may be extended to include any tungsten filament lamp associated with a piece of blue glass, is taking unwarranted liberties with something capable of exact physical analysis and measurement.[1, 2, 3]

Brady stated,[4] "that the ultimate criterion of any daylight glass is not the spectrophotometric curve, but the color identification quality of the light, using colors extremely susceptible to change in appearance under artificial light. These colors viewed under an artificial daylight must appear the same as under natural daylight of good quality." To which should be added as a result of our later experience "and of a similar color temperature."

COLOR TEMPERATURE GRADING

The National Bureau of Standards has developed a method of grading daylight and artificial light sources. This it seems, in view of the past chaotic rating situation, is an important step forward.

This method is on the basis of color temperature. "The color temperature of a source is the temperature at which a Planckian radiator would emit radiant energy competent to evoke a color of the same quality as that evoked by the radiant energy from the source in question." All that is involved in giving the color temperature of any illuminant is the affirmation that the color of the illuminant is of the same quality as the color of a Planckian radiator at the given temperature.[1]

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[1] The Grading of Illuminants with Reference to Quality of Color. Irwin G. Priest, *J. Opt. Soc. Am.*, Dec. 1923, pg. 1179.

[2] Artificial Daylight Filters, K. S. Gibson, *J. Opt. Soc. Am.*, Nov. 1925, page 473.

[3] Artificial Daylight for Merchandising and Industry, Bulletin LD104, Edison Lamp Works of General Electric Company.

[4] TRANS., I. E. S., 1914, page 952.

If a piece of iron is heated to a temperature where it will appear dull red, it will radiate light or energy in the visible spectrum. Heat it to 1000° C. and the light is more intense, a blacksmith would say it was "white hot". At 1500° C., just below its melting point, it will radiate a still whiter light. The color of this light compared to the sun, is however, quite red or orange-yellow, while the sun is white, that is if certain stars relative to the sun may be designated as blue.

This temperature color, or as it has been called color temperature, for the measurement of which special instruments have been developed, applied to a theoretical complete radiator (black body) is proposed by the Bureau as a basis for classifying our artificial illuminants, sunlight and daylight.[6, 7, 8]

TEMPERATURE OF THE SUN AND ARTIFICIAL SOURCES

At sunrise or sunset, direct sunlight corresponds to quite a low color temperature. For example, on a certain day[5] Priest found an apparent color temperature of about 1900°K seventeen minutes after sunrise and before sunset.[6] This is well beyond the point where it was assumed that iron becomes "white hot" but actually was more orange or yellow than the light from the candle, kerosene or gas flames.

In the following half-hour the temperature color changes of the sun corresponds to the colors of the following sources: the flame sources at 1900°K to 2000°K, carbon filament electric lamps 2150°K, vacuum tungsten filament or Mazda B lamps 2500°K, gas-filled tungsten or Mazda C lamps at 2750°K,[9] as shown on diagrams Figs. 1 and 2. The sun at the corresponding apparent color temperature is now forty minutes after sunrise. At slightly above 3600°K tungsten melts and the maximum temperature of the unmodified light from our artificial

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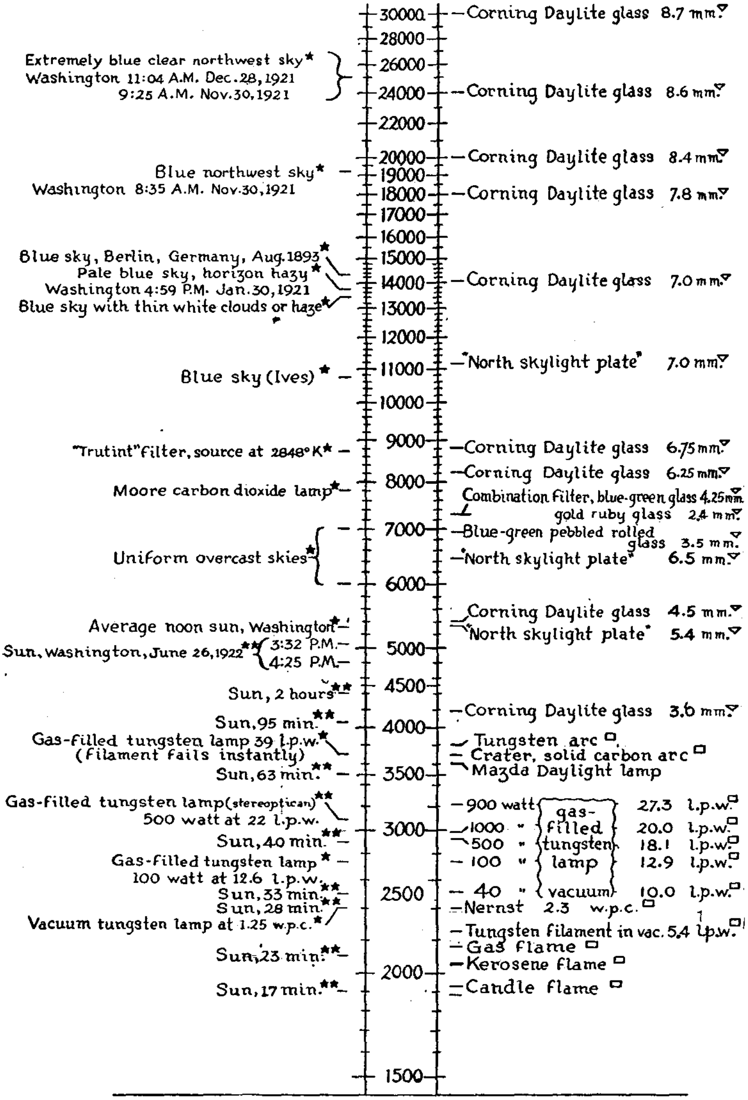
[5] Washington, D. C., Feb. 20, 1920.

[6] A New Study of the Leucoscope and Its Application to Pyrometry. Irwin G. Priest, *J. Opt. Soc. Am.* Nov. 1920, page 448.

[7] The Colorimetry and Photometry of Daylight and Incandescent Illuminants by the Method of Rotary Dispersion, Irwin G. Priest, TRANSACTIONS, I. E. S., 1923, Page 681.

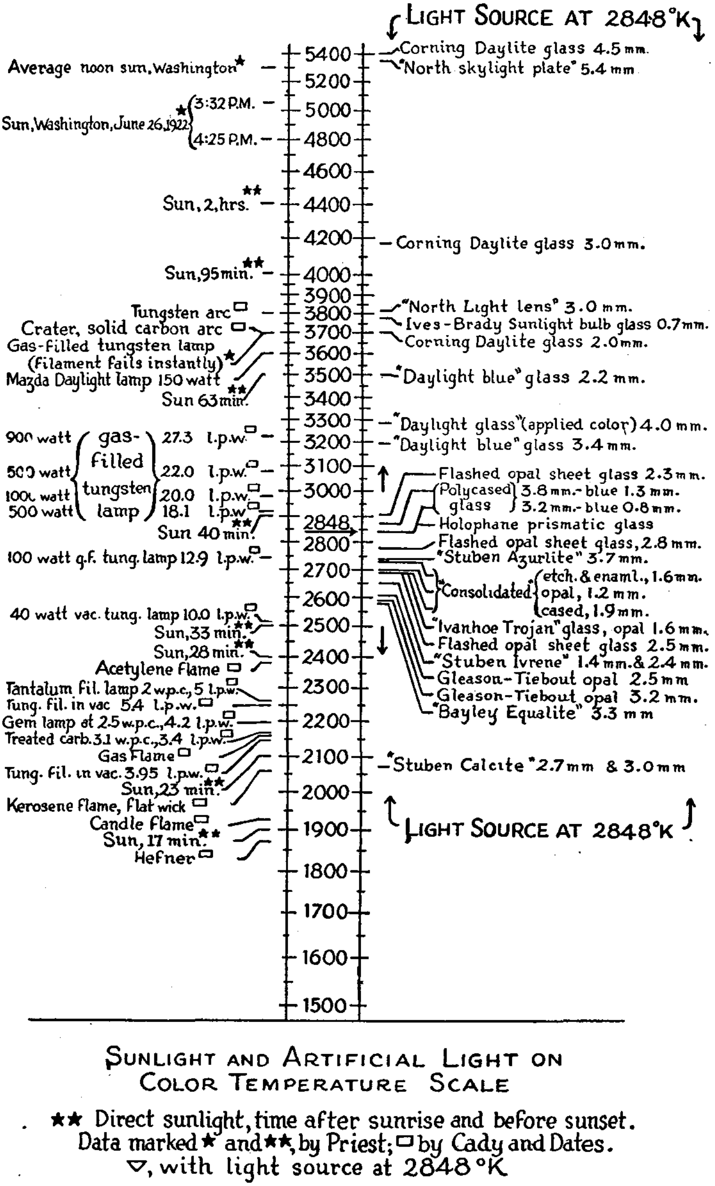
[8] The Colorimetry and Photometry of Daylight and Incandescent Illuminants by the Method of Rotatory Dispersion. Irwin G. Priest, *J. Opt. Soc. Am.* Dec. 1923, page 1175.

[9] Cady & Dates, *"Illuminating Engineering,"* pages 38 and 96.



DAYLIGHT AND ARTIFICIAL LIGHT ON COLOR TEMPERATURE SCALE

FIG. 1.—Color temperature scale of Daylight and Sunlight from 1900°K to 24,000°K and of Artificial Light Sources below 4000°K and as modified by filter glasses to 30,000°K with a light source at 2848°K.



SUNLIGHT AND ARTIFICIAL LIGHT ON COLOR TEMPERATURE SCALE

★★ Direct sunlight, time after sunrise and before sunset.
Data marked ★ and ★★, by Priest; □ by Cady and Dates.
▽, with light source at 2848 °K

FIG. 2.—Natural and Artificial Illuminants in the Sunlight range below 5400°K, indicating the effect of color modifying glasses in raising or lowering the apparent color temperature of a light source at 2848°K.

sources is reached in the crater of the tungsten arc at 3800°K. One and a half hours after sunrise the sun's color temperature is 4000°K and at noon the maximum 5000° to 5400°K is reached. From this maximum the scale is reversed to sunset.

DAYLIGHT COLOR TEMPERATURES

Certain daylight exposures may have a proportion of sunlight present, either direct or reflected from light clouds. The resulting color temperature will then approximate 6000° to 7000°K. Excluding the direct sunlight, the light from the sky at the same time will be from about 8000° to 10,000°K.

Blue sky has been noted by several observers as between 12,000° and 15,000°K and extremely blue clear north-west sky before noon in Washington, D. C., by Priest as equivalent to 24,000°K. The new Rotatory Dispersion Colorimetric Photometer[8] permitted tests to be made which showed that glass filters of a certain color mixture possessed the property of raising the apparent color temperature of one black body to that of another.[1, 2, 10] Which means that various thicknesses or densities of this glass when used with a gas-filled tungsten filament lamp may be used to color match any color temperature and likewise produce any daylight equivalent above 2848°K, with a 500-watt lamp and a minimum thickness of glass, to the extreme of the clear blue north-west sky, 24,000°K or even beyond if desired.

A more portable instrument, Figs. 3 and 4, has recently been developed at the Bureau for color temperature measurements embodying a pair of daylight glass wedges similar to those originally calibrated by the Bureau,[2] shown on diagram Fig. 5.

QUALITY OF LIGHT VARIABLES

The physicist accepts light of a color temperature of 5000°K, practically noon sunlight, as a neutral white, and higher temperatures as blue-white. The working colorist has not at any time taken observations in direct sunlight. A sunlight standard, without a reliable artificial light substitute, would mean a short

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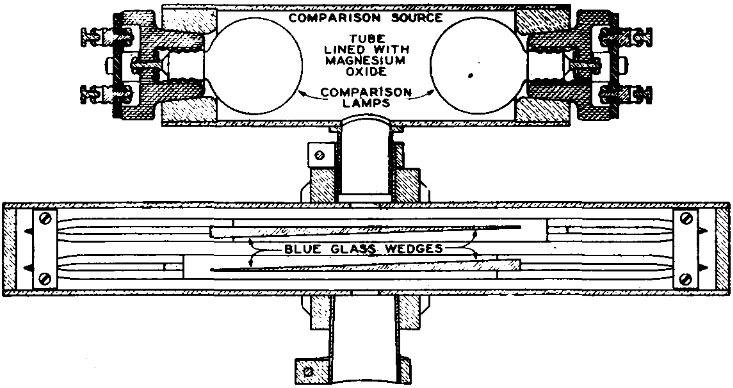
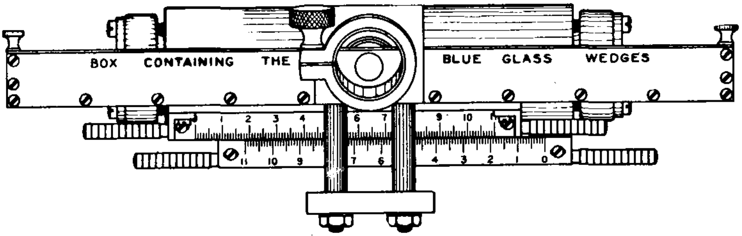
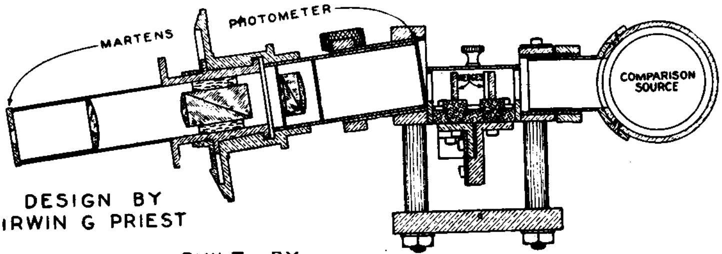
[10] TRANS., I. E. S., 1923, page 865.



HORIZONTAL MEDIAN SECTION



FRONT ELEVATION
WITH
MARTENS PHOTOMETER REMOVED



DESIGN BY
IRWIN G PRIEST

BUILT BY
THE NATIONAL BUREAU OF STANDARDS
IN COOPERATION WITH
THE MUNSELL RESEARCH LABORATORY

VERTICAL MEDIAN SECTION

FIG. 3.—Detailed arrangement of parts in Blue Wedge Colorimetric Photometer.

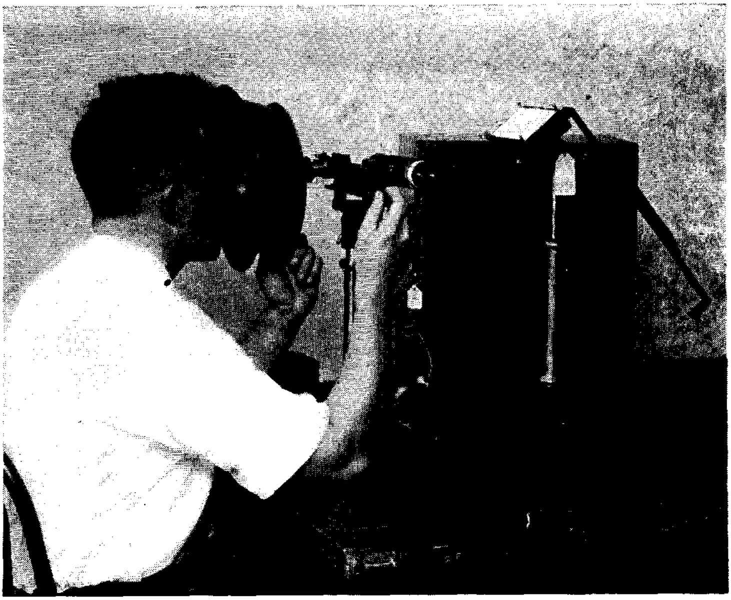


FIG. 4.—Priest's Blue Wedge Colorimetric Photometer set up for determining apparent color temperature of light source incident on magnesium block test surface.

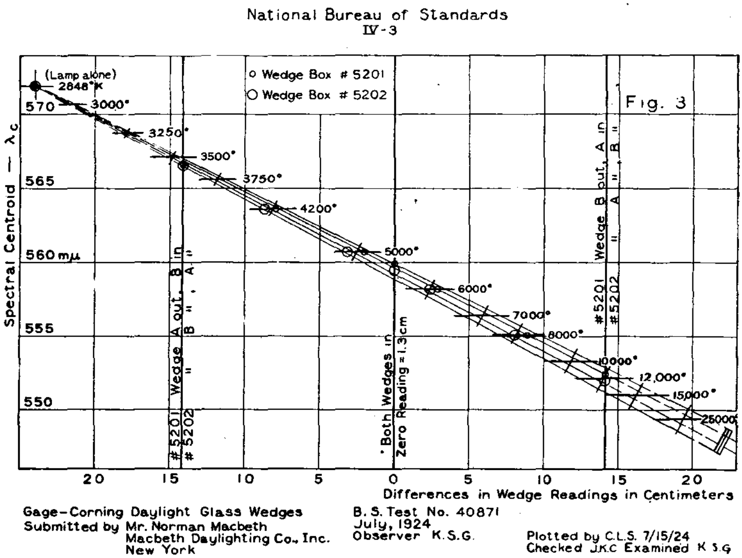


FIG. 5.—Values of Color Temperature and Spectral Centroid of Light from a standard source of 2848°K as modified by transmission through increased densities of daylight glass wedges and plates.

summer day production period and many idle hours and days throughout the year.

North light has been universally preferred in the Northern hemisphere because of the freedom of this exposure from direct sunlight, although this exposure is not different in its color effect from that of any blue sky, *i. e.*, a western sky in the morning, an eastern sky in the afternoon or a southern sky in midsummer.

In a recent article in an engineering publication,[11] the point was made that north skylight was no longer necessary for colorists as a neutral white artificial light was now available. That the northern exposure daylight "colored" colors instead of merely revealing them. "North light from a clear sky is decidedly bluish. It very much favors the violet, blue and green components of colors. It makes the purples much more bluish.....it dulls the orange and red components." This apparent inspiration of a white light producer would require a new generation of colorists. The experienced colorist trained as today under a "too blue" daylight would undoubtedly select under a "neutral white light" purples even more blue and oranges and reds still more dull, which if exposed to daylight free from direct sunlight would certainly not be satisfactory to the colorist trained under blue sky daylight. He knows his skylight daylight and names his colors according to their selectivity in this light.

The quality of light demanded by workers in color varies over a comparatively wide range from that of the physicist, the neutral white of the noon-day sun, to the extreme clear blue sky of the expert colorist.

The gas-filled tungsten filament lamps used in artificial daylighting equipment also differ in color of light, the smaller size lamps compared with the larger sizes generating a greater quantity of red, orange and yellow light in proportion to the violet-blue end of the spectrum. Further color differences are due to the design of the filament structure. The greater number of filament anchors for instance in the stereoptican or flood-lighting types of lamp will result in conducting heat from the fila-

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[11] *Electrical World*, July 2, 1927, page 3.

ment thereby causing the light to be less blue and more red than a similar size or wattage of lamp with fewer filament anchors.

Then finally the correctly compounded daylight glass will vary in color density and thickness. These combined variables in view of the range of daylight qualities demanded are fortunate, otherwise the user of artificial daylighting equipment would invariably have to accept a substitute which would probably be other than of the desired quality. Users would probably complain that the light was either "too red" or "too blue" depending upon the individual opinion of what constituted a satisfactory white light. Meeting the individual demand for daylighting over a comparatively wide range is therefore economically possible and fits in with manufacturing processes.

By accepting these incandescent lamp and glass variations, rather than a standard that could possibly be agreed upon, results in appreciably lower production costs of equipment. To secure the same color of light from a 100-watt lamp at 13.2 lumens per watt, as from a 500-watt with 19.2 lumens per watt, would necessitate running the smaller lamp at a higher than normal efficiency, practically at 145 per cent of normal voltage, thus appreciably shortening its life to probably 20 per cent of normal.

VARIATION IN GLASS

If only one standard color concentration of filter could be used, probably 900 of each 1000 made would have to be scrapped. In the early work of Ives and Brady a 5000°K standard was adopted and it was stated that with a glass of 5.4 mm. (0.213 in., approx. 7/32 in.) thickness a tolerance of 5 per cent only was allowed, practically a plus or minus of one one-hundredth inch.[12]

To accept 10 per cent of a manufactured product would result in a ten times normal cost. This 10 per cent would have to carry the total cost of production. These variations in glass thicknesses are due to the human element—the judgment of the glass worker in determinig the amount of glass that will just fill the mold. The mold is not set to press a pre-determined thickness of glass, but presses whatever amount of glass may be

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[12] TRANSACTIONS, I. E. S., 1914, page 947.

dropped into it. This results in a spread of various thicknesses. It may be decided to press from a center of 6 mm. (0.236 in., approx. 15/64 in.) thickness and that glass from 5 mm. to 7 mm. (0.197 in. to 0.275 in., approx. 13/64 to 17/64 in.) thickness will be acceptable. The annealed, mechanically perfect glass is then photometered using pre-determined standard pieces which are exceedingly valuable because of the extent of the numerous tests to which they have been subjected. These standards are used as a basis from which this density grading is done.

These color steps result in a spread totalling approximately 40 divisions, Fig. 6. These are small steps, each closer than could possibly be observed by any user of a lamp. Each per cent difference being due to an increase or decrease in glass thickness of approximately two one-thousandths of an inch.

After photometering, all glass of either light or heavy density outside the acceptable limits of the minimum equivalent correction, the 5000°K point of the physicist colorist, to the maximum acceptable to the blue sky daylight worker of 15,000°K., is broken up into cullet to be used in a new melt. This selection reduces the acceptable range to eight separate and distinct divisions.

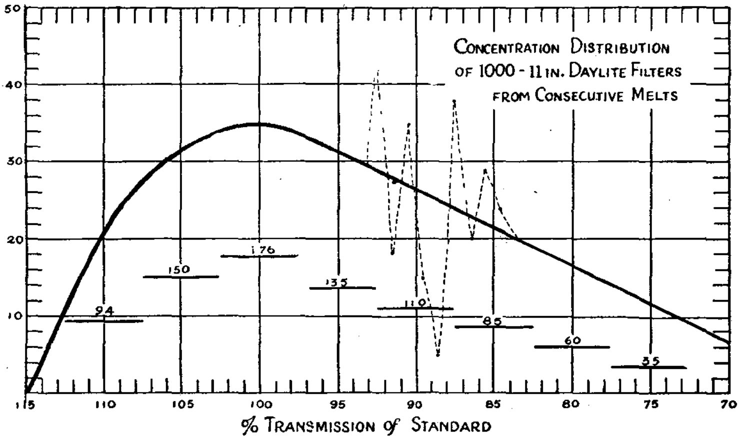

FIG. 6.—Variation in color concentration of Gage-Corning Daylite filters of pressed convex roundel type. Each 1 per cent represents a difference in thickness of approximately two one-thousandths of an inch.

SELECTION BY INDUSTRY

At the beginning when little was known as to the acceptability of these various concetrations and the present more complete color temperature information on daylight was not available, every opportunity was sought with silk dyers, silk examiners and others trained in close color discrimination to determine the desirable concentrations to meet each demand.

Six or eight filters of known percentage color concentration were sent out with a lamp with instructions to experiment with a wide range of highly selective known colors and decide just which filter was acceptable. The dye customers decided that satisfactory results were secured with a certain narrow band. This procedure was followed with color printers, silk buyers in department stores, clothing salesmen in men's wear stores and generally throughout all industries served.

Certain grades proved more acceptable in certain lines, the silk dyer and handlers of silk generally, wholesale and retail, demanding daylight reproductions within a narrow color temperature range. This range was so narrow that only a comparatively few filters were produced in every thousand made. With the varied demands of wholesale and retail stores, artists, color printers, lithographers, process inspectors, proof readers and eye workers on black and white; the dermatologist and the medical specialist, the hospital operating room and many others, a practical color of light spread can now be absorbed with satisfaction to the user and appreciation by the glass manufacturer.

Priest's Rotatory Dispersion Colorimetric Photometer and his later Blue Wedge Colorimetric Photometer for high color temperature measurements open up an entirely new field in furnishing another necessary dimensional notation.

If a given illumination results in sustained acuity of vision over a greater than usual period; to intensity, brightness and contrast determinations may also be added a color quality measurement.

A reconciliation of certain nomenclature will be necessary. Just the correct warmth of color of light desired by the artist or the decorator will, of course, be at a lower color temperature than is indicated for a "cold light" which may be and is probably due to a color temperature several times higher than the "warm" light.

The effect of wall and ceiling finishes in contributing to the ultimate resultant color of light may now be readily determined. The tests of the typical opal and opalescent glasses shown on the diagram Fig. 2, is suggestive for a new line of research. If it is a fact that the higher filament temperatures of Mazda C lamps have a quality appeal, then it may not be generally desirable to enclose them in glassware which will result in a color match for the carbon filament lamp of forty years ago. Likewise to produce the "flame-tint" for residence lighting may result in an appreciation for certain glassware or fabrics which today are not being used to the best advantage.

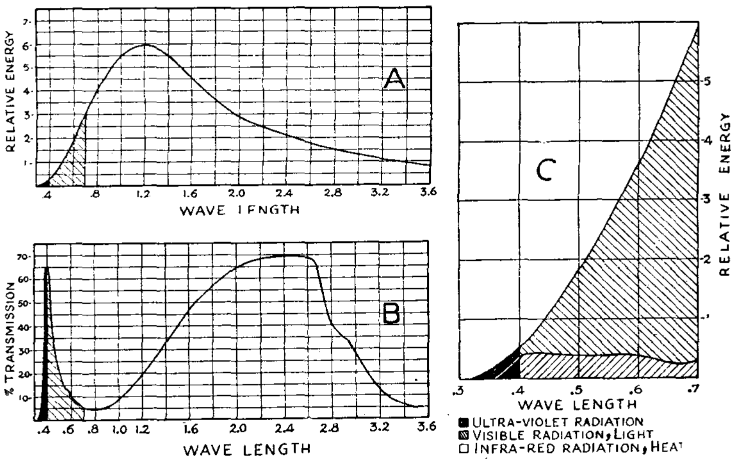

FIG. 7.—"A" The proportional distribution of energy from a typical large size Mazda C lamp.

(Edison Lamp Works of G. E. Co., Bulletin LD121A, page 37).

"B" Spectral transmission in Ultraviolet, Visible and Infra-red of Gage-Corning Daylite glass No. "D".

(Tests by Bureau of Standards 2/24, 4/28, 7/24, 1922).

"C" Enlarged section of ultraviolet and visible energy distribution "A," with energy transmitted through "B".

Proportion of total energy transmitted: Violet 59 per cent, Blue 34 per cent, Green 16 per cent, Yellow 13 per cent, Orange 10 per cent, Red 5 per cent. Total transmission 12 per cent; Total absorption 88 per cent.

This approximate result was predicted by Luckiesh and Cady* thirteen years ago. They stated that the transmission of the ideal screen used with a gas-filled tungsten lamp at 22 lumens per watt would be 13 per cent, about 2.9 lumens per watt. It should be noted that if this transmission resulted in a satisfactory white light that the absorption cost must be charged not against the screen, but the light source, owing to the considerable proportion of excess radiation to be absorbed.

*TRANS. I. E. S. 1914, page 847.

COLOR DISCRIMINATION

Electrical engineering specialists in lighting apparently have little or no appreciation of the extent of the discrimination of an expert colorist. To have a light that will enable yellow to be distinguished on a white background or not to confuse blues and blacks is not sufficient. The chemist interested in bleaching compounds has to deal exclusively with a large variety of whites—all different—and it takes a highly trained eye with the purest quality daylight to distinguish and identify these differences. The number of blacks in dress goods for instance, is probably as great as the average engineer assumes is sufficient to cover the entire color range of visual sensation. A book is now in the publication stage which will illustrate and name 6000 colors. We find workers in this field who can identify and name one to two thousand colors. It is fair to say that the number of colors that can be declared different probably lies between several hundred thousand and a few million.

Even the same colored yarns cannot be used to produce fabrics of the same color when the constructions are different. Furthermore, the products and color combinations from various dyers in wool, cotton, silk, rayon and mixed materials as combined in the average costume, will undoubtedly be seen under all qualities of daylight and sunlight extremes, and consequently while the important decision observations should preferably be made under a daylight free from direct or reflected sunlight, the fact should not be overlooked that it is a false and somewhat insecure standard as the results will also be judged under sunlight—largely during the mid-day hours and through to sunset. Sunrise may be omitted as even with "daylight saving," it is not so frequent a human experience.

The deciding series of color observations, if dependence is placed on natural light alone, should therefore extend throughout the day, at all sky exposures and include also direct sunlight up to noon or during the afternoon to sunset.

The application of this theory would unduly prolong manufacturing processes and slow production tremendously. With the unknown selectivity and reflection characteristics of dye combinations, nothing short of such a series of observations would ensure reliable color decisions or matching certainties. Single observations in daylight at ten o'clack or at any given hour may result in a match which has drifted later in the day or at another location to a mis-match or even a contrast combination, owing to color temperature changes in the light. Dyers have long been aware of this condition but were helpless to correct it when depending upon natural light.

The idea has long persisted throughout artificial lighting articles that "an accurate reproduction of daylight is necessary for color matching."

This entire subject is a complicated one however, and a "color matching unit" regardless of its quality of light will afford but slight assistance in solving the problem.

Color work can be divided into three classes: color harmonizing, color identification, and last and least, color matching. The latter in the field of widest general application, retail stores, usually arises when an individual requires more of a certain material. A sample is supplied to be duplicated. A large proportion of this duplication can be done under any source of light affording sufficient intensity to enable the sample to be observed as to color, weave, structure and so forth. Many samples in this class can be proven even under a mercury vapor lamp. Quite a wide spread of color can also be satisfactorily matched under the light of any of our common sources. For this grade of color matching there is no apparent advantage of the tungsten filament gas-filled or vacuum lamps over the carbon filament bulbs. Some opal enclosing globes with gas-filled lamps will actually deliver a light of lower color temperature than a bare carbon filament lamp.

This store color matching arises where "Mother purchased material for Mary's dress—she has run short or desires to use similar material also for Jane." A sample is sent to the store, where the original purchase had been made, for "color matching;" which means—find the bolt from which this material was cut. The clerk who knows his stock can, with a single glance at the sample further confirmed by a movement of his thumb and finger, noting the "feel" of each side of the sample, be more certain of the fabric, its weave and structure. As this material, in this weave has only been stocked in five widely separated shades, the color matching is not difficult, and Jane's dress is just like Mary's.

Another grade of color matching comes in the paint, printing and lithographic trades where pigments or dyes are used in paint or ink compounds. The original mixture has been used up, an additional quantity has to be prepared. If a record is available of the colors and proportions used in compounding the original batch it will not be difficult to repeat the dose, nor is the demand here for a particular quality of light at all exacting. If the pigment, dye or color combination is not known then the problem is indeed a complicated one—it may even be impossible. An accurate reproduction of daylight, of north sky light or any other one quality alone may afford only a false assurance. A group of light sources would be nearer the ideal. This group to be composed of a variety of qualities not alone of independent color temperature values but should include an ultraviolet source to catch those dyes or materials that fluoresce. The photo-engraving artist has learned that in extending a white background on white bristol that there is a difference due to the use of either Chinese white or French white. One will absorb ultraviolet radiation and the other will reflect it. Both whites appear to the eye to be like the paper background, but the added white in one case will photograph as though a yellow pigment had been used. If the illustration is for half-tone reproduction then this condition is a serious one.

For difficult color work—to produce more of the same color or a similar color when a sample is furnished and the color chemicals are unknown—a combination of at least four separate qualities of light would be most helpful, a spectrally pure red, green, blue and an ultraviolet. The latter could be produced with a mercury arc in quartz with a screen to transmit the ultraviolet and absorb the visible radiation. The known and unknown colored surfaces to then be compared under each of these sources.

Color identification is likewise not satisfactory under any one light source. In wearing apparel a purple or a brown under artificial light, of 2000° to 3000°K equivalent, may be a blue or green under a daylight of 7000°K and upwards. A yellow under the physicists' white light may under the white light of the textile colorist be quite "muddy" and much dulled. A point therefore to determine is the color education and light source standard of the individual selecting the color, also the purpose for which it is required. Two white silks were selected after matching in daylight—a wedding dress was to be made. Artificial light would be used in the church and in the home. It just happened that the dressmaker saw these two materials under artificial light. "These materials are not satisfactory, I couldn't possibly use them in one dress—don't you see, one piece is pink while the other is cream!" Both had been carefully compared under natural daylight—southern sky exposure. And $80.00 worth of silk went back to two stores, cut into odd lengths to later appear at a reduced price on the remnant counter. For color identification, therefore, ordinary artificial light—even from candles—is just as important and necessary as a good quality daylight.

Satisfactory equipment for this demand should permit alternate observations with simultaneous contrast under the light from the two common visual sensation extremes of below 2500°K and above 8000°K color temperature.

Color harmonizing cannot be done under any one light source regardless of its quality. Colored materials, whether with pigments or dyes when associated with other colored materials if selected under a north-sky daylight could only be displayed satisfactorily under a similar north-sky daylight. Colors in harmony in daylight may be in contrast under artificial light, or if not worn indoors, then under late afternoon direct sunlight. This application therefore may call for all of our ordinary light sources from 2000°K color temperature to 20,000°K. In its practical application, however, a combination equipment for alternating between two light sources of 2500°K and 8000 to 10,000°K has been found to be satisfactory.

A colorimetric notation by an individual with normal color vision rarely corresponds with that of another operator, hence color notations have been of little practical value. And largely because colorimeters have not been associated generally with light sources of a known standard color temperature. A white card or surface which will reflect equally all wave-lengths of light incident on it would be classed as yellow, under direct sunlight with the sun near the horizon and would be a pale blue under skylight. If however, it is "white" under skylight, then under noon sunlight it becomes yellow and with the sun just above the horizon—probably orange. It all depends upon individual nomenclature with normal eyes. Complicated by the individual whose color sensation is abnormal in red, green or blue, there may be no end to the difficulty.

The layman may be excused for ignorance of these color of light responses. That this situation is practically unknown to the specialist in store and industrial plant illumination is difficult to understand without the conclusion that more attention has been given to "how"rather than "why."

DISCUSSION

J. C. FISHER: I just wanted to ask Mr. Macbeth if there is any noticeable change in the color temperature of the radiation transmitted by the different glasses due to ageing or to exposure to heat of the incandescent lamp.

NORMAN MACBETH: On Mr. Fisher's question as regards the change in color. We have treated this subject practically. During the ten years this equipment has been put out we have guaranteed "no change of color." I am frank to say we did not know whether we would have a change or not. But with a guarantee we knew that if a change was suspected they would tell us about it.

We had one case about six months ago where the purchasing agent of a large dyer called up and asked for a price on fifteen filters. This dyer had been using more than seventy of these lamps throughout the plant. We asked him, "What is the trouble, are you going to make an outfit of your own, or did you have a wreck or something of that kind?"

He replied, "We have had these lamps for eight years and I think that they have changed in color."

Our reply was that if the lamps were not exactly as they were within the first thirty days, we would supply replacements without charge.

We examined the equipment and found that the filters were almost completely covered with accumulated dust and also that a lamp of about half the proper size was being used. They were instructed to wash the glass, put in the proper size of lamp bulb and make all the tests that were possible with all kinds of colors, and if the glass in their opinion was not exactly as when purchased eight years ago, they could have a complete replacement free of charge. The tests were made and they found no change —just a matter of cleaning up.

M. LUCKIESH (Communicated): The color-temperature method of rating daylight and artificial illuminants has many advantages—but it has serious limitations. In the first place it is not scientifically sound for general application outside the realm of the theoretical black-body and of illuminants whose spectral distributions of energy approximate those of so-called pure "temperature radiation." Mr. Priest and Mr. Macbeth know these limitations, as scientific men have known them for years. However, this warning is for those who do not know. To make the point clear we can produce illuminants which appear white but which are wholly unfit for color-identification. (See Color and Its Applications, by M. Luckiesh, page 235). The color-temperature method does not give any measure of the spectral characteristics of an illuminant excepting in the cases mentioned. This method appraises the light from a quartz mercury-arc as being not far from white, but even the most enthusiastic salesman of mercury-arcs would not recommend them for general color-discrimination.

There is still another warning. Two illuminants may be separated widely on the scale in Figs. 1 and 2 without differing much in value for color-identification. On other parts of the scale the converse is true. A scale of spectral centroid values or of dominant hues presents a different picture.

Mr. Macbeth advocates a variety of artificial-daylight units whose color-temperatures cover an appreciable range on this scale—I believe, from white (noon sunlight) upward to blue skylight. Fortunately, as Mr. Macbeth points out, this dovetails nicely with manufacturing and economic expediency. Leaving out of account the whims, experiences, and habits of the relatively few color-experts, there is only one illuminant which can be scientifically recommended for revealing colors. *That illuminant is white light.* Such an illuminant favors no colors. Blue skylight favors violets, blues and greens and dulls the colors at the other end of the spectrum. It makes the colors of the great family of purples appear more bluish than under white light. In other words, it distorts a great many colors as compared with their appearance under white light. It distorts colors just as certainly as a yellowish light does.

To produce artificial north-skylight with tungsten-filament lamps it is necessary to absorb about 85 per cent of the light. However, to produce white light corresponding to noon sunlight on a clear day in summer, an absorption of only 60 per cent is necessary. In other words, white light—the only illuminant which is scientifically sound for color-discrimination—can be produced with tungsten-filament lamps at nearly three times the efficiency of artificial north-skylight.

Colorists have acquired the north-skylight habit for very good reasons which are no longer as potent as they were. They were driven to use the least variable daylight. Now, constant artificial light is available. They should be educated to use artificial white light but those who want artificial skylight of course may have it. These relatively few colorists should not dictate what a color-identification illuminant for general use shall be. The field for artificial daylight outside that confined to the expert colorists is by far the larger field. In these places white light is the proper illuminant—because it is fair to all colors—and there is a great field for units which are not very accurate. In a factory where 1000 machinists are at work how many need, or are capable of using to capacity, a set of the finest calipers made? So it is with color-sensibility. Few persons can use to the utmost a highly accurate white light. There is room for various grades of artificial daylight on the yellow side of white light as well as on the blue side. We have some data and many experiences (Light and Work, by M. Luckiesh) which indicate that a light whiter than ordinary artificial light has some advantages even in cases where color-discrimination is not involved. Sometimes the advantage is marked. But this does not mean that an accurate artificial daylight must necessarily be used. It is not a case of using either this or ordinary artificial light. A step toward white light may result in a certain advantage. The length of the step toward white light which is economically justifiable is not always easy to determine. And then, finally, there is no reason why for many purposes we cannot improve upon daylight. In fact, this is already accomplished in many ways.

NORMAN MACBETH (Communicated): Replying to Dr. Luckiesh, I had no intention of advancing the color temperature method as an indication of the color identification value of a light source. That point is, I believe, clearly covered on the fourth and fifth pages of my paper. Nor had I any idea of advocating the sole use of the range from noon sunlight to blue skylight. References confirming this statement, on the third page are to sources of value down to 2000° K color temperature. Nor did I believe that color temperature would be used with spectral distributions of energy having other than black body radiation characteristics.

A scale of spectral centroid may also be abused as may be noted when you locate a signal green in the midst of a color-identification family.

A color temperature rating of an illuminant is not in my opinion comparable to a measurement by a machinist with the "finest calipers made." Your machinist, however, will use an accurate steel rule with divisions in at least sixty-fourths of an inch, and a surprising number of micrometers are also in use.

What I have attempted to protest against and hoped to offer a substitute for was our present designations of "flame tint" for sources around 1500° K with our common flames at 2000° K to 2100° K; "approximate noon sunlight" and "average daylight quality" for sources actually 3300° to 3600° K and "approximate north skylight" for equipment ranging in color quality from 5300° K to 11,000° K. These designations have been in use for many years.* I believe that they have been unsatisfactory technically although quite successful in certain quarters commercially. Considered as statements of illuminant qualities they are as unsatisfactory as would be the result if Dr. Luckiesh's 1000 machinists had access only to "furniture-store" yard sticks.

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* The Lighting Art: M. Luckiesh, 1917.

My experience is in accord with his statement that we can improve upon daylight. We have hundreds of instances where that has been done; many where an investment of a few hundred dollars has resulted in stopping waste which had previously amounted to thousands of dollars a year.

Our experience has also shown that all steps towards an apparent white light are not equally beneficial. A plain light cobalt colored glass will appreciably whiten the light of a tungsten filament lamp. The red transmission band with this glass, however, results in a somewhat marked lessened ability of the eye to stand up to its work; an excess of green has a similar effect.

We do know that a daylight of overcast sky quality—6000° K to 7000° K is satisfactory and it may be also true that a properly balanced spectral quality ranging between 4000° K and 5000° K may furnish all that the eye desires.

Dr. Luckiesh's recommendation that the one satisfactory illuminant for color is that white light corresponding to noon sunlight on a clear day in summer is also discussed on page 311. On these points I was dealing with today's practical applications. Dr. Luckiesh on this point is in agreement with other physicists, in advocating tomorrow's ideal. I do not know that we have had any very extended experiences with this ideal white light. It has not been favored for close continued eye work, largely perhaps, because of its relatively high intensity, and I am without information as to its general use or availability in intensities below several thousand foot-candles.

"The length of the step toward white light which is economically justifiable" has not presented any difficulty when we deal with an individual problem. I can understand from the standpoint of an arbiter that this step may not be easy of determination for an industry. I had no idea, however, of accepting any such responsibility in presenting this paper.