NBS MONOGRAPH 75

Colors of Signal Lights

Their Selection, Definition, Measurement, Production, and Use

U.S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

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Contents

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Foreword

The safety of the traveler, whether by rail, highway, air, or sea, depends on the reliability with which signal lights of various colors are seen and their meaning correctly interpreted. In August 1964, the United States Standard for the Colors of Signal Lights, developed under the auspices of the U.S. National Committee on Color for Signal Lights, was issued as National Bureau of Standards Handbook 95. The colors selected, the method of their specification, and the methods of testing signal ware for compliance with the specifications were all based upon technical information, much of it unpublished.

It is the purpose of this Monograph to make available a complete analysis of the problem of signaling by lights of various colors, combined with a detailed reproduction of the basic data used to derive the solution of this problem given in Handbook 95. An effort has been made to present the material in such a manner as to facilitate comparison between the technically established information and the requirements.

This Monograph is designed as a guide to the engineer who must implement the United States Standard, the psychophysicist who is concerned with the meaningful presentation of research in this field, and the administrator who is responsible for the use of signal lights. Those who seek, in years to come, to improve on the current signaling systems, should find their task simplified by the availability of this Monograph.

A. V. Astin, *Director.*

Preface

The work of many investigators, authors, and colleagues has provided the material from which this Monograph has been prepared so that it is not possible to call each by name, but the assistance derived from many discussions with Deane B. Judd have contributed so much to the analysis of the problem that the writer desires especially to acknowledge his indebtedness to him and to express his appreciation for his collaboration. Other highly valuable contributions to the work have come out of correspondence with J. G. Holmes of Great Britain and from Lorenzo Plaza, of the Institute of Optics, Madrid, Spain, who, before computer codes were available, very kindly carried out several of the more laborious tasks of transforming diagrams, which had been available only in the C.I.E. system, into the RUCS system. Other contributions have been acknowledged in connection with the figures and tables. Finally, I would like to thank Mrs. R. L. Meyers for assembling the references, Mr. R. E. Lee, Jr., for assistance with many of the computations and drawings, and especially Mrs. Ellen B. Way for her devotion to the task of completing the myriad of details that are essential to the final correction and completion of any manuscript.

F. C. Breckenridge.

Colors of Signal Lights: Their Selection, Definition, Measurement, Production, and Use

F. C. Breckenridge

This Monograph is intended to serve as a reference work for all those concerned with the selection, specifications, and use of signal-light colors. It discusses the nature of the problem, and the mathematical representation, recognition, production, control, and use of such colors. The characteristics of different types of chromaticity boundaries and the purpose and effect of the requirement for similarity of chromaticity characteristics are given special consideration. The treatment is varied according to the intended use. The discussion of the control of colors and the section on the use of colors are nontechnical, whereas the section on the production of signal colors is designed for the colorimetrist who is faced with the problem of selecting limit filters or drafting a specification.

1. Introduction

All forms of organized transportation depend to a very considerable extent upon signal lights of different colors for safe operation. Whether one travels by aircraft or railroad, automobile or ocean liner, his safety requires the correct interpretation of signal colors. Radio, radar, and other electronic aids have supplemented the signal lights in some forms of transportation, but in no form of transportation have the lights been abandoned. Other methods of identifying lights exist, such as flashing them and arranging them in distinctive shapes and configuration. These are also used by the transportation services, but they do not eliminate the need for color identification. On the other hand, the increasing density of traffic is constantly increasing the dependence upon signal lights. This situation seems to warrant additional attention to the specification and control of their colors.

This Monograph, which is an outgrowth of an informal publication,[1] has been prepared to furnish those interested in specifications for the colors of light signals with the technical information necessary for preparing and appraising such specifications. It is intended to provide a basis for interpreting the recommendations of the International Commission on Illumination (Commission Internationale de l'Eclairage, or C.I.E.) which were set forth in the Proceedings of the Thirteenth Session, held in Zürich in 1955 [CIE 1955][2] and later published as C.I.E. Publication No. 2 [1959], Colours of Light Signals. It also explains the background of the U.S. Standard [NBS 1964]. Most of the C.I.E. recommendations have been incorporated into this Monograph at appropriate places.

2. Outline of Problem

2.1. The Three Essential Steps

As one examines the specifications and recommendations for the colors of light signals, he finds a confusing assortment of requirements. Some of the specifications are lengthy with a diversity of provisions; some are relatively brief. Some depend entirely on numerical values, while others make reference to standard filters. Some of the provisions are directly related to what the observer sees. Other provisions refer only to items of equipment. All of these recommendations and specifications aim at similar final results, namely, the insurance that those who use the signal lights will be shown the most reliably distinctive colors practicable for their particular requirements.

To understand how the various requirements and provisions contribute to this end, it is necessary to recognize that the effective control of the colors of signal lights always involves three steps: the selection of the colors to be used, the selection of color standards,[3] and the application of those standards to control the colors of the signals. All three steps may not be immediately evident. The selection of the colors and the standards may, for example, be done at the same time. In other cases the controlling agency may define the acceptable

[1] NBS Letter Circular 484, no longer available.

[2] Brackets enclosing a date indicate a reference listed in Appendix 1.

[3] "standard(s)" with lower case "s" in this monograph refers to a filter in combination with a stipulated light source. When a publication is meant it will be called a "Standard" with capital "S".

colors and leave the selection of the standards and their application to the manufacturers who produce the equipment. In general the three steps are accomplished by basic chromaticity definitions, master specifications for color standards, and procurement specifications, although these may appear under other titles or may be combined into a single specification.

If instruments suitable for measuring the signal colors directly in colorimetric terms were available, it might be possible to eliminate the need for color standards selected for specific applications, but such instruments are not as yet available. The possible use of such instruments is discussed in sec. 9, Instrumentation.

2.2. Basic Chromaticity Definitions

Basic chromaticity definitions are statements of chromaticity limits within which a signal is acceptable for use in a system of signal colors. Such a system may be established by a government agency, an association of state or local authorities, or by a national or international technical body. For example, two very similar international systems have been adopted for signal-light colors, the recommendations of the International Commission on Illumination [1955, 1959] and the Standard of the International Civil Aviation Organization [1964].

Most specifications for signal-light colors in use in the United States contain statements of basic chromaticity requirements. The most complete systems are those contained in part I of the "U.S. Standard for the Colors of Signal Lights," the two government specifications for aeronautical lights, and the two specifications of the Association of American Railroads, Signal Section. These are all listed in Appendix 3 to this Monograph.

Other specifications used in the United States have paragraphs devoted to basic chromaticity requirements. Some of these, like the two railroad specifications mentioned above, are valid in Canada as well. These also are listed in Appendix 3.

For basic definitions, mathematically expressed chromaticity limits applicable to the emitted signal are used. Such limits are reproducible at any time and place if competent personnel and suitable instruments are available for their establishment. This makes them especially adaptable for international agreements and agreements between different agencies within a single country, since such agreements are expected to remain in force over long periods and may be used by many different laboratories. Basic definitions are also suitable for governmental regulations because such definitions apply to light signals as shown and allow the maximum freedom of means of accomplishment.

In principle the basic chromaticity definitions are the foundations upon which detailed specifications are built. For this reason it is desirable that these definitions be based entirely upon established principles of color recognition. The necessary researches, however, have turned out to be so laborious and expensive that thus far it has been necessary to base these definitions upon experience interpreted in the light of the research results. These will be discussed in section 4, Recognition of Signal Colors.

2.3. Master Specifications for Color Standards

To bridge the gap between the basic definitions and the purchase specifications, the U.S. Standard for the Colors of Signal Lights includes master specifications to control physical standards so that equipment purchased on the basis of such standards will provide signals in accordance with the basic definitions. These master specifications for standards for the colors of light signals are specifications giving chromaticity tolerances and other requirements for filters to be used in combination with specified light sources to constitute standards for the control of equipment, or the light-filtering components of equipment, to insure that such equipment will give a satisfactory color when placed in service.[4] If there are basic chromaticity definitions which are applicable to a type of signal lights, then the requirements for standards must be such as to insure that the colors of those lights will conform to those definitions. If there are no appropriate basic definitions, standards are chosen on the basis of experience with other types of signal lights.

Historically, the relationship of the standards and the basic chromaticity definitions has generally been the reverse of the ideal one described in the last section. In most cases the standards were chosen first by those responsible for the colors of the lights and the definitions were later devised to describe what was giving satisfactory service.

The master specifications are prepared for the use of laboratories, which may be presumed to have suitable spectrophotometric and colorimetric equipment as well as light sources calibrated for color temperature. They are applicable to flat filters, the spectral transmittances of which are readily measured. Such specifications, therefore, have generally been stated as mathematically expressed chromaticity limits for the filter-source combinations which are to serve as physical standards; but spectrophotometry of adequate accuracy is difficult and costly, whereas the required accuracy can be obtained with the expenditure of much less time by differential colorimetry. This makes it

[4] Another approach readily occurs to the spectrophotometrist. Two spectrophotometric curves may be drawn with the requirement that the filters used in lights have spectrophotometric transmissions that remain between these limits for all wavelengths between specified limits. For an example of this method see Otyřoký [1937]. This method presents a difficulty arising from the nature of the filters used in practical equipment. Very few signal light filters are in such a form that they can be spectrophotometered on American spectrophotometers. To sort acceptable from nonacceptable signal glasses by this method on a practical production scale would require an elaborate automatic spectrophotometer with an electronic evaluator which does not exist in this country. Furthermore, this approach unnecessarily restricts the contractor since a variety of spectrophotometric curves can produce the same chromaticity and all may be acceptable.

simpler in some instances to select primary[5] standards, and control duplicates by setting limits for the maximum colorimetric differences. No examples of specifications for limit standards issued apart from basic chromaticity definitions or procurement specifications are known. Part II of the U.S. Standard for Colors of Signal Lights is designed to be a separate master specification for physical standards to control the colors of light signals, but at present it is available only in the complete Standard, NBS Handbook 95 [1964]. The most complete provisions for such standards to be found in specifications previously in use are those in Federal Standard No. 3 [GSA 1951],[6] and those in the appendix of each of the two specifications for signal light colors issued by the Signal Section of the Association of American Railroads [1960, 1962]. These specifications contain chromaticity tolerances and transmittance requirements for filters to be used as limit standards, but they leave to the manufacturer the responsibility of seeing that the filters are satisfactory in other respects.

2.4. Procurement Specification

As the name implies, procurement specifications are specifications governing the purchase of equipment. Since they are to be used for distinguishing between satisfactory items, which are to be paid for, and unsatisfactory items, which constitute a loss to one of the parties to the contract, they should be as definite as it is practicable to make them. Most of those in use in the United States are based on standards. If such standards are not stipulated in the specification, whoever is responsible for compliance should provide himself with standards unless the item and available instruments are such that it is practicable to measure the chromaticity of *each* item to make certain that it is satisfactory. This could mean measuring the spectral transmittance of each item with a spectrophotometer, computing the corresponding chromaticity coordinates from the spectral transmittances, and checking these mathematically for compliance with the equations of basic chromaticity definitions. A possible compromise might be the measurement of a few representative items with a spectrophotometer and the acceptance or rejection of the remaining items by comparison with the measured items. In this case the measured items become standards for the purpose of checking the unmeasured ones.

If suitable colorimeters were available, it might be feasible to use mathematical limits for procurement purposes. Such a procedure, however, would involve the necessity for maintaining accurate calibrations, and the use of more elaborate and expensive equipment than is required when standard filters are used. Moreover, it is not clear that the use of mathematical limits would provide any economies or other advantages to offset the difficulties that would be involved in their use for practical inspection procedures.

Examples of procurement specifications are well known but it should be pointed out that only a part of such specification as the Military Specification for Colors of Aeronautical Lights and Lighting Equipment [MIL SPEC 1963] or one of the railroad specifications mentioned in sec. 2.3 [AAR–1960, 1962] is to be considered as a procurement specification in the sense in which the term is being used in this publication. Generally the supplier is responsible only for the production of signal-light equipment and not for the manner in which it is used. The manner of use, however, may affect the color of the signal, as when a wrong lamp is installed in signaling equipment or a wrong voltage is applied to a signal lamp. Procurement specifications, therefore, should apply to the equipment, and not the light signal, unless the procurement contract includes the maintenance and operation of the equipment.

2.5. Regulatory Requirements

The application of legal requirements such as safety regulations generally involves all of the three steps of controlling signal-light colors that have been discussed above. The initial laws or regulations are generally written in the form of chromaticity definitions applying to the light emitted as signals, but if the field inspectors check the colors they must carry out their work by testing the signal equipment in comparison with physical standards. This is generally most easily done at the plant of the equipment manufacturer. Between the law and the inspector comes the colorimetric laboratory, which provides the necessary physical standards, referees doubtful cases, and tests the signal equipment when unusual problems are involved.

3. Mathematical Representation of Colors

3.1. Three Attributes of Color

Several references have been made to the mathematical expression of chromaticity and as the discussion proceeds there will be occasion to represent chromaticities in diagrams. To understand the equations and diagrams, it is necessary to realize that the perception of color[7] is essentially three-dimensional, that is, three numbers are required to describe a color. The most familiar of these three attributes is hue. The gradual variation from red to violet from one side to the other of a

[5] The term "primary" is used here in a general sense to differentiate between two types of filters, each of which is composed of more than one class. For a general discussion of the naming of classes of standards see McNish [1958]. For a classification directly applying to signal lights see the "U.S. Standard for Colors of Signal Lights," NBS Handbook 95 [1964], Part I, Definitions 2.12 to 2.19 inclusive.

[6] Sec. 5.3.2. and table IV.

[7] In this Monograph the word *color* is used as a general word equally applicable to the stimulus and the perception.

rainbow is familiar to everyone. The same transition is even more clearly discernible in continuous spectra. This is the first attribute of color. When hues of all wavelengths are combined in the necessary proportions, the result is white light. The rainbow colors, while differing from each other in hue, differ from the more vivid colors which can be obtained in spectra because there is usually some white light shining through the rainbow and the resulting chromaticity is paler than the rainbow itself. This variation from pure colors to white constitutes the second attribute of color and is called saturation. The more the color departs from white or gray, the greater the saturation. The third attribute is the quantitative aspect to which one refers when he observes that one spectrum is brighter than another. While the most common name for this attribute is *brightness*, two other terms are also used, *lightness* and *brilliance*. Lightness refers to variations from black to white. It is perceived by comparing unknown objects or surfaces with each other in an environment that contains familiar elements. It is applicable to opaque surfaces and transparent volumes but not to signal lights, which are always seen either as self-luminous areas or as point sources. Brilliance is applicable only to point sources and is, therefore, used mostly for signal lights and stars.

Thus far we have described the attributes of color in psychological terms.[8] Such terms, however, cannot be numerically evaluated. The radiant energy by means of which the signal lights and surfaces are seen could, in theory at least, be described by giving its energy distribution with respect to wavelength in each case, but in practice this has turned out to be too cumbersome for use. To avoid this difficulty, psychophysical terms and relationships have been developed. These terms correlate with the physical terms on the one hand and with the psychological terms on the other. This correlation is shown in table 1. The correlation of the psychophysical with the physical is accomplished by deriving the psychophysical values from the physical quantities through the medium

[8] For a more extensive treatment of this aspect of the subject, the reader is referred to ASTM Special Technical Publication No. 297, Deane B. Judd [1961].

TABLE 1. *Correlation of terms*

The table below shows the relationship of photometric and colorimetric terms used in signal lighting (upper sections) to similar terms used in describing transmitted light (third section) and reflected light (lowest section). Each line shows the correlation between the terms of physics, psychophysics, and psychology.

Application	Physics	Psychophysics (color stimulus)		Psychology (color perception)	
		Quantitive	Qualitative	Magnitude	Quality
Point source, descriptive	Spectral intensity distribution $(P_\lambda/\omega)/P_{\lambda_0}/\omega)$				
Point source, quality			Chromaticity = Dominant wavelength and purity $\int (V_\lambda P_\lambda/\omega)d\lambda$*		Chromaticness = Hue and saturation
Point source, quantity	Radiant intensity $\int (P_\lambda/\omega)d\lambda$	Luminous intensity $\int (K_\lambda P_\lambda/\omega)d\lambda$			
Point source, visibility	Irradiance $\int (P_\lambda/A)d\lambda$	Illuminance $\int (K_\lambda P_\lambda/A)d\lambda$		Brillance or magnitude	
Self luminous source, descriptive	Spectral flux distribution P_λ/P_{λ_0}				
Self luminous, quality			Chromaticity = Dominant wavelength and purity $\int V_\lambda P_\lambda d\lambda$*		Chromaticness = Hue and saturation
Self luminous, quantity	Radiant flux $\int P_\lambda d\lambda$	Luminous flux $\int K_\lambda P_\lambda d\lambda$			
Self luminous, quantity/area	Radiance $\int (P_\lambda/\omega)d\lambda/A$	Luminance (Photometric brightness) $\int (K_\lambda P_\lambda/\omega)d\lambda/A$		Brightness	

TABLE 1. *Correlation of terms*—Continued

Application	Physics	Psychophysics (color stimulus)		Psychology (color perception)	
		Quantitive	Qualitative	Magnitude	Quality
Transparent volumes (Filters), descriptive	Spectral transmittance $(P_2/P_1)_\lambda$				
Filter and source, quality			Chromaticity = Dominant wavelength and purity $\int V_\lambda \tau_\lambda P_\lambda d\lambda$*		Chromaticness = Hue and saturation
Filter and source, quantity	Transmitted radiant flux $\int \tau_\lambda P_\lambda d\lambda$	Transmitted luminous flux $\int K_\lambda \tau_\lambda P_\lambda d\lambda$			
Filter and source, transmittance	Radiant transmittance $\int \tau_\lambda P_\lambda d\lambda \Big/ \int P_\lambda d_\lambda$	Luminous transmittance $\int K_\lambda \tau_\lambda P_\lambda d\lambda \Big/ \int K_\lambda P_\lambda d\lambda$		Clear to dense	
Reflecting surfaces, descriptive	Spectral reflectance $(P_2/P_1)_\lambda$				
Surface and source, quality			Chromaticity = Dominant wavelength and purity $\int V_\lambda R_\lambda P_\lambda d\lambda$*		Chromaticness = Hue and saturation
Surface and source, quantity	Reflected radiant flux $\int R_\lambda P_\lambda d\lambda$	Reflected luminous flux $\int K_\lambda R_\lambda P_\lambda d\lambda$			
Surface and source, reflectance	Radiant reflectance $\int R_\lambda P_\lambda d\lambda \Big/ \int P_\lambda d\lambda$	Luminous reflectance $\int K_\lambda R_\lambda P_\lambda d\lambda \Big/ \int K_\lambda P_\lambda d\lambda$		Lightness (black to white)	
Surface and source, quantity per unit area	Radiance $\int (R_\lambda P_\lambda/\omega) d\lambda/A$	Luminance $\int (K_\lambda R_\lambda P_\lambda/\omega) d\lambda/A$		Brightness (invisible to dazzling)	

*Symbolic formula, actual mathematical relationship is too complex for inclusion in table.

of the C.I.E. Standard Observer, which is numerically represented by three functions of wavelength known as the C.I.E. tristimulus distribution functions.

The symbols in table 1 have the following meanings:

P_λ radiant energy per second of wavelength λ,
ω solid angle,
K_λ luminosity function for relative effect of different wavelengths,
V_λ chromaticity function, a three component function relating radiant energy to visual quality,
τ_λ transmittance for wavelength λ,
R_λ reflectance for wavelength λ.

Table 1 is composed of four sections applying respectively to point-source signal lights, self-luminous sources, transparent volumes and opaque surfaces. "Self-luminous sources", for the purposes of this correlation, must be considered as including all lighting units containing optical systems or diffusing surfaces which cause the observer to see an appreciable bright area. This is the usual case with traffic signal lights and intervehicular signals. There is no sharp line of division between point sources and self-luminous sources. "Transparent volumes" are assumed to have nondiffusing surfaces and against black backgrounds they are seen by their surface reflections, some of which acquire color by being transmitted through the volume. Opaque surfaces are seen by light reflected from them.

The derivations of the psychophysical correlates from the corresponding physical quantities, by the inclusion of the luminosity function for quantitative

219-788 O-67—2

purposes and all three of the standard observer functions for qualitative purposes, are shown by the formulas following the terms. For qualitative purposes, that is, chromaticity computations, it is not necessary to know the actual energy distribution, but the relative energy distribution of the source must be known.

Although the psychophysical values are numerically derived from physical quantities, their definitions were constructed to correlate with the psychological terms. Thus the hues of the spectrum are naturally associated with the wavelengths of the radiations which give rise to them. Chromaticities which can be matched by a mixture of white light with monochromatic light of pure spectrum chromaticity are associated with the wavelengths of the spectral components, and these wavelengths are called the dominant wavelengths of the mixtures. All of the chromaticities now being used in signal lighting can be matched by such combinations of spectrum light and white light. Chromaticities exist, however, which can not be matched by any combination of monochromatic light and white light. In such cases it is possible to match white light by adding monochromatic light of suitable wavelength to the given sample. In this case the wavelength of the monochromatic light is called the complementary wavelength. In either case the ratio of the monochromatic light to the total light in the matching mixture is called the purity. As in the case of the saturation, the purity increases as the proportion of spectral light increases.

While the associations pointed out above are the basis for the correlations given in table 1, it must not be supposed that the hue of the response is determined solely by the qualitative aspects of the light from a source, or object, being viewed. In addition, the apparent size of a source, the illuminance received from a small source or the luminance of a larger one, and the characteristics of the environment in any case have important influences on the hue perceived. On the other hand, even when these factors remain the same, a change in the purity, that is, a change in the ratio of monochromatic to white light in the mixture received from a source, will also cause the observer to select a different monochromatic light as being the same in hue as the mixture.

Of the three psychological terms for the intensity attribute, *lightness*, *brightness*, and *brilliance*, only the latter two are applicable to signal lights. The choice of these is determined by the concentration of flux on the retina of the eye. If the light from the target is spread over an appreciable area of the retina, the signal is evaluated for brightness. If, however, the flux from the target appears to come from a point, its magnitude is evaluated for brilliance. As indicated in table 1, brightness correlates with luminance, which is sometimes called photometric brightness, while brilliance correlates with illuminance.

Colors may be defined by any three numbers which give their hue, saturation, and brightness or brilliance as, for example, the dominant wavelength, purity, and transmittance for the combination of a filter and a light source. These might be considered as cylindrical coordinates in which the dominant wavelength is plotted as the angle, the purity as a fraction of a fixed radius, and the transmittance as a distance perpendicular to the plane of the polar diagram. Experience has shown, however, that another form of diagram is more useful. This type of diagram results from the fact that it is possible to so arrange chromaticities that the chromaticity represented by any point on a line joining the points representing two given chromaticities can be produced by a certain mixture of lights having the given chromaticities. These diagrams are sometimes called color mixture diagrams because they are based upon this property. There are an infinite number of coordinate systems, derivable from each other by projective transformations, all of which give rise to diagrams having this characteristic. Two of these will be used in this circular, namely, the C.I.E. system and the RUCS system.

3.2. C.I.E. Coordinate System

The C.I.E. system of chromaticity coordinates was adopted as a device for the numerical description of chromaticities by the International Commission on Illumination at its meetings in 1931 [C.I.E., 1931; Judd, 1933]. Since that date it has been regularly used as the standard means of specifying chromaticities. This coordinate system rests on the C.I.E. Standard Observer of 1931 [Judd, 1933], which is a set of three functions of wavelength each expressed as a set of eighty-one values correlated with the 5 mμ intervals from 0.380 μ to 0.780 μ. One of these functions is the relative luminosity function for cone vision, that is, a set of values proportional to the relative contribution which light of different wavelengths makes to the brightness of a surface under daylight conditions. The other two functions which complete the standard observer express the results of color matching researches. An infinite number of coordinate systems are consistent with the standard observer, but any one of these can be derived from any other by a linear transformation, which in turn requires the assignment of eight coordinates to completely determine it. As defining coordinates, the C.I.E. selected values for the x and y coordinates for the spectrum colors of wavelengths 0.4358, 0.5461, and 0.7000 microns and C.I.E. standard light source B. The first two spectrum colors are to be found in the spectrum of mercury; the third can be produced by an incandescent lamp with a suitable red filter. Source B represents mean noon sunlight but it is defined in terms of a lamp and filter. By choosing the values in this way the calculation of the luminous transmittance or reflectance of a sample could be found incidental to the calculation of the chromaticity coordinates of the sample. The selection of the above cardinal stimuli also resulted in a set of primaries (X, Y, Z) which corresponds under usual conditions of observation to colors which may be considered as unitary red, green, and blue.

3.3. RUCS Coordinate System

The Rectangular-Uniform-Chromaticity-Scale Coordinate system was first proposed by Breckenridge and Schaub in 1937 [1939].[9] At the time when the C.I.E. coordinate system was adopted, little was known about the perceptibility of chromaticity differences. At that time it seemed reasonable to place the white point centrally with respect to the spectrum locus. It was believed that this would avoid the exaggerated extension or compression of any parts of the color field, that is, it would give approximately uniform chromaticity scales. Later research, however, showed that the spacing of the chromaticities in the C.I.E. system is far from uniform. The purpose of plotting chromaticities on a diagram is to assist in the visualization of the relationship between different chromaticities. The distortions of the C.I.E. diagram tend to defeat the purpose of such visual representations of chromaticity and a number of uniform chromaticity scale diagrams have been developed to reduce the distortions.

The limitations of the C.I.E. and RUCS systems are discussed in sec. 3.6. As compared with other available uniform chromaticity systems the RUCS has four advantages for the present use. Its derivation is based on sources of small angular size (2° or less), a transformation table is available for converting C.I.E. values into it, it has already been used in two international publications and there is a convenient relationship between arrangement of chromaticities and our ordinary conceptions of colors.

3.4. Chromaticity Diagrams

Each coordinate system gives rise to a characteristic chromaticity diagram in which every chromaticity is represented by a point. Figures 3–1 and 3–2 are C.I.E. and RUCS diagrams. In each of these the curved boundary represents colors such as those seen in spectra. It is called the spectrum locus and the numbers along the boundary are the wavelengths of the corresponding light. As already stated in sec. 3.1, to the observer with normal color vision these spectrum colors differ from each other in hue. If white light, which generally contains light of all the spectrum colors, is added to a single spectrum color, a new chromaticity results which does not match any color in the spectrum. Such chromaticities are represented by points inside the spectrum locus. The more white added, the further from the boundary will lie the point corresponding to the resulting chromaticity.

It is a basic property of both of these chromaticity diagrams that when two samples of light, which are represented by two points in the diagram, are mixed they produce a color which is represented by some point on the straight line joining the other two points. From this it follows that the points on the straight segment of the boundary connecting the ends of the spectrum locus represent mixtures of the extreme red and extreme violet. The usual purples lie close to this straight boundary at the short wave end, while near the other end will be found purplish-red chromaticities.

The curved line within the figure is called the Planckian locus. It represents the chromaticities of blackbodies at different temperatures. In practical applications, it is accepted as representing the chromaticities of incandescent bodies such as lamp filaments. The numbers along this curve on the C.I.E. diagram, and the corresponding numbers in the margin of the RUCS diagram, indicate the color temperature in degrees Kelvin, sometimes called degrees absolute, corresponding to the marked points.

3.5. The z Coordinate

The initial computation of the C.I.E. coordinates gives three values one of which is an intensity factor, usually in the case of signal-light filters the transmittance. Since only two independent values can be plotted in a plane diagram, it is customary to reduce the three values to three proportional numbers totaling 1. This eliminates the intensity attribute and results in three coordinates which represent a point in the plane through the three points on the axes at $x=1$, $y=1$, and $z=1$, respectively. As may be seen from figure 3–3, the C.I.E. diagram shown in figure 3–1 is the projection on the x,y plane of the true x,y,z diagram.

3.6. Relative Distortion of Diagrams

A system of numerical values derivable from physical measurements has great advantages over names as a means of specifying colors in that the values can be made independent of the observer. Even a colorblind individual can determine the correct color coordinates if he is provided with suitable instrumentation. Moreover, a color once measured can be reproduced at another time or place if its coordinates in any well-designed system are known. The C.I.E. coordinate system served this purpose quite well, and since it was the first system that appeared likely to be generally utilized, it rapidly came into general use. The only purpose served by plotting the coordinates of chromaticities, however, is to visualize the chromaticity relationships. For this purpose every distortion means a false visualization. The distortions of the C.I.E. system have already been mentioned in sec. 3.3. It

[9] The coordinates of the RUCS system may be computed directly from tables, derived by a linear transformation, or closely approximated from a transformation table. The constants for the first two methods are given in the referenced paper. For the tables see Breckenridge [1948] in the list of references. It is also possible to obtain the uniform spacing, but not the other advantages described in sec. 3.7 by plotting C.I.E. coordinates on a distorted C.I.E. diagram as proposed by Holmes [1940].

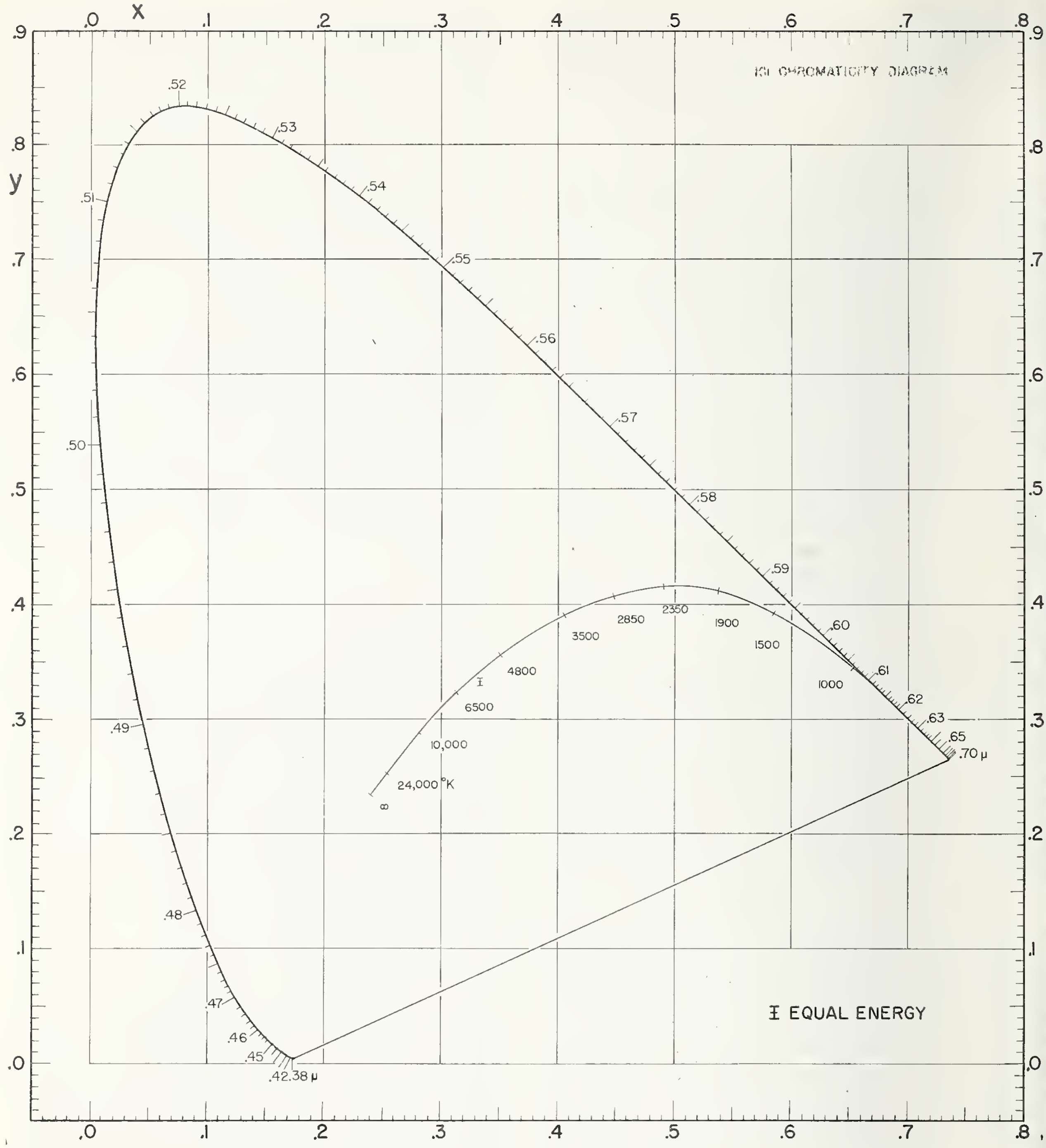

Figure 3–1. *C.I.E. chromaticity diagram.*

This diagram shows the spectrum locus and Planckian locus derived from the standard observer defined by the International Commission on Illumination in 1931 [C.I.E. 1931].

remains, however, to consider in this section the extent of those distortions.

The first attempt to estimate the extent of the distortions of the C.I.E. diagram was made by D. B. Judd in 1934 [1935]. Judd transformed the C.I.E. diagram into a system of trilinear coordinates designed to give uniformity of spacing in accordance with the best information then available. He then filled the area of real chromaticities on this Uniform Chromaticity Scale diagram with a group of equal tangent circles and transformed these back into the C.I.E. system. The result was the diagram of ellipses shown in figure 3–4 [Judd 1936].

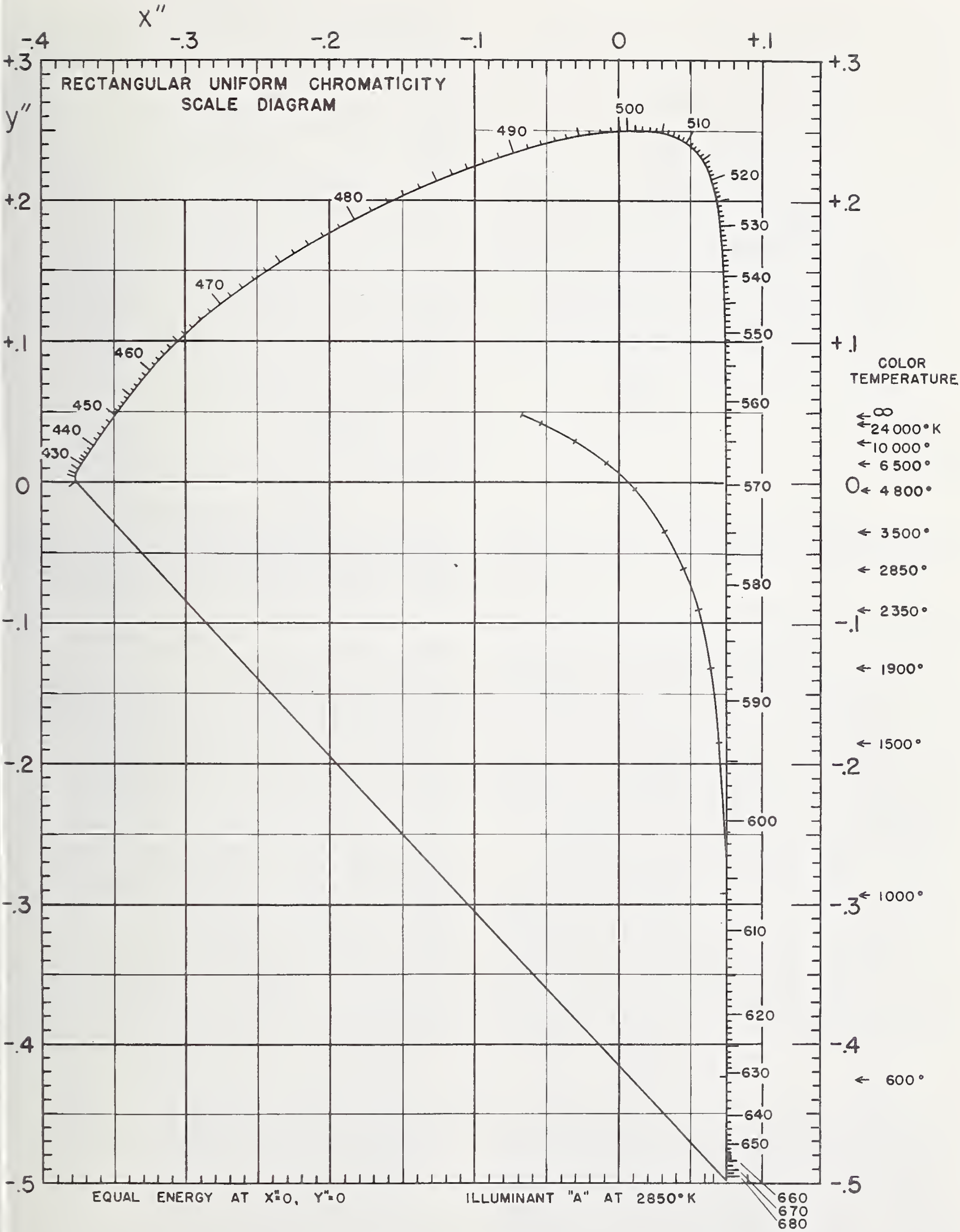

FIGURE 3–2. *RUCS chromaticity diagram.*

A transformation ot the C.I.E. diagram designed to space the chromaticities of small sources uniformly in rectangular coordinates.

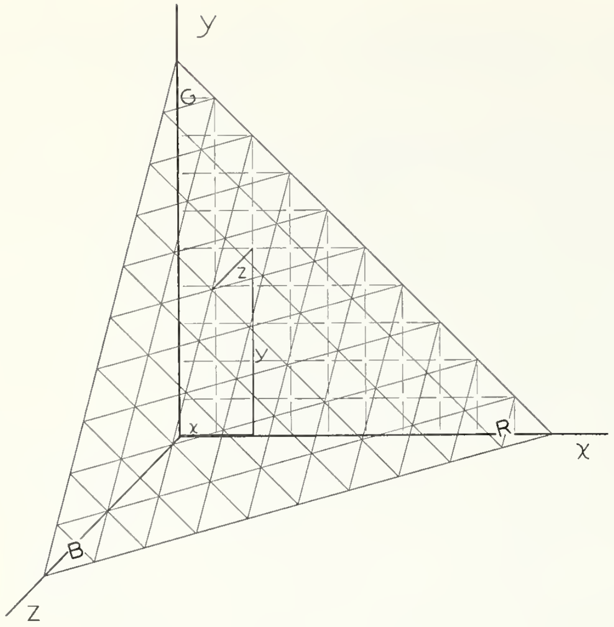

FIGURE 3–3. *The "z" coordinate.*
This diagram shows the relationship of the two-dimensional C.I.E. chromaticity diagram to the three-dimensional C.I.E. chromaticity coordinates. The coordinates plot in the sloping RGB plane. The C.I.E. diagram is the vertical plane at the back.

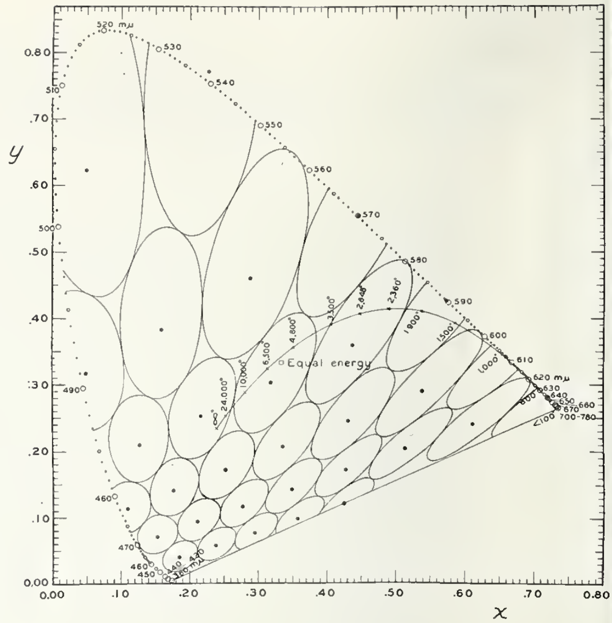

FIGURE 3–4. *The Judd ellipses.*
Circles drawn on the Judd Uniform Chromaticity Scale Diagram of 1934 [Judd 1935] presumably represent chromaticities that are equally different from the chromaticities at their centers. A group of such circles were transformed to the C.I.E. chromaticity diagram by Judd [1936]. The ratios of the diameters both within an ellipse and between ellipses presumably indicate the degree of nonuniformity throughout the C.I.E. diagram.

Numerous efforts have now been made to develop uniformly spaced diagrams, but most of these have been directed towards a diagram representative of the spacing for large color samples.[10] Two studies have been made, however, which are applicable to the signal lighting problem. The results of one of these researches are shown in figure 3–5 for the C.I.E. diagram, and corresponding results for the RUCS system are shown in figure 3–6. Both of these figures are taken from a paper by W. D. Wright [1941]. In each of them, the bars represent small changes in chromaticity that are equally perceptible at different locations on the diagram.[11]

Wright's study was made with a 2° field, that is, one with an angular diameter four times that of the full moon. Even this angular size is smaller than the apparent size of the samples preferred for accurate color matching of panels. On the other hand, it is a larger target than an ordinary 8" traffic light at a distance of 20 feet, a little more than a car length away. This is about the largest diameter at which a signal light ever has to be recognized, whereas in aviation and marine uses such lights frequently appear as "point" sources, lights often less than 1 minute in observed diameter.

Another study has been made by G. N. Rautian and M. K. Guryeva [1957]. In their study paths of least chromaticity difference were determined between chromaticities in different areas of the diagram and the number of distinguishable steps between these chromaticities was considered to be a measure of the chromaticity difference. The study was carried out with point sources[12] which adds to its significance as a test for the uniformity of a diagram intended for signal-light use. Figure 3–7 shows the results of the Rautian-Guryeva research on a C.I.E. diagram and figure 3–8 the same chromaticities on an RUCS diagram.

The results of the studies which have been shown in figures 3–4 to 3–8 can be expressed numerically by measuring the longest and shortest distances corresponding to equal perceptual differences and computing the ratios. These ratios are as follows:

Judd, C.I.E. in terms of U.C.S.	10/1
Judd, RUCS in terms of U.C.S.	1.1/1
Wright, C.I.E. for 2° field	20/1
Wright, RUCS for 2° field	4/1
Rautian and Guryeva, C.I.E. for point sources (5′)	11/1
Rautian and Guryeva, RUCS for point sources (5′)	6/1

These ratios indicate that the C.I.E. diagram is unsatisfactory and that the RUCS diagram, although

[10] In 1963 the International Commission on Illumination at its 15th Plenary Session adopted the CIE–UCS coordinate system to provide a generally acceptable system of representing surface colors with uniform spacing. This is applicable only to areas subtending at least 1° for the observer. See C.I.E. Proc 1963 or Judd [1963].

[11] Although most of the other researches are of little concern for signal light colors, three may be of interest to readers concerned with chromaticity diagrams. MacAdam [1943] made a study of the representation of small color differences and later [1959] he published the results of a comparison of small field and large field observations which show clearly that the diagrams most desirable for the representation of surface colors are not suitable for signal lights. The other study is that by Burnham and Newhall [1953]. Although this is a study of small fields, the criterion of uniformity used was the spacing of the Munsell diagram which has been carefully developed to approximate uniform spacing for large areas. The results shown are consequently quite misleading.

[12] Subtended diameter, 5′.

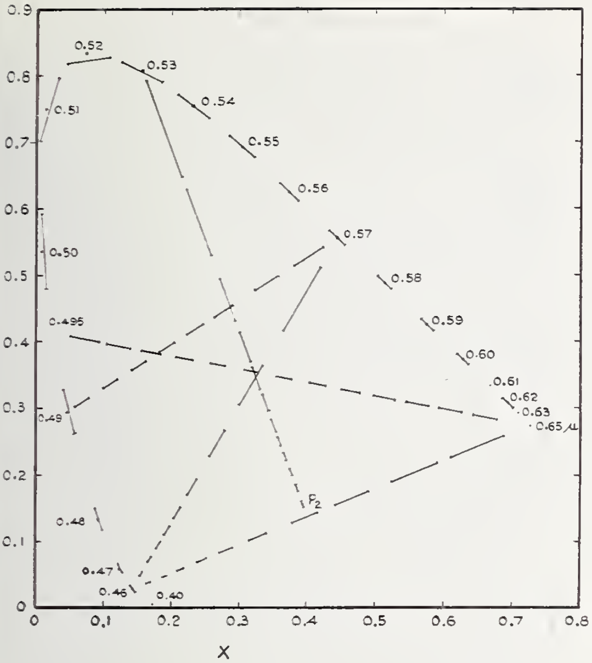

FIGURE 3–5. *Color steps for the mean of four observers plotted in the C.I.E. diagram.*

Each dash represents a chromaticity difference estimated to be the same as the others as determined by Wright [1941]. A comparison with figure 3–4 shows general agreement both as to the degree and the extent of the nonuniformity of the C.I.E. diagram.

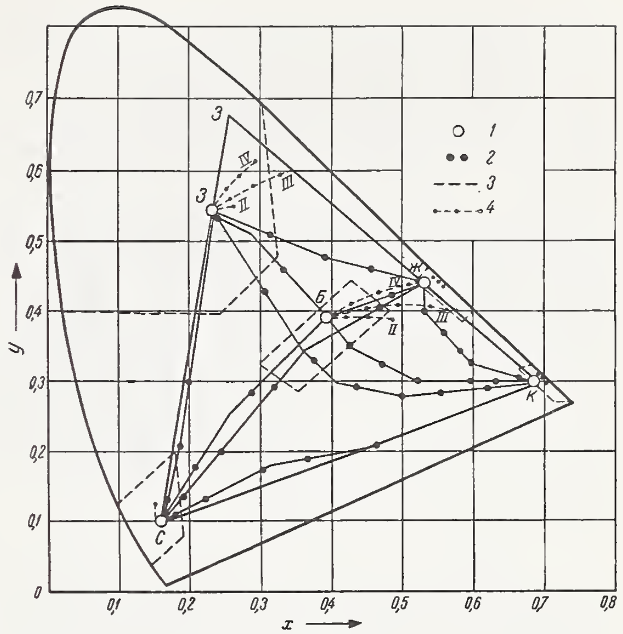

FIGURE 3–7. *Chromaticity differences for signal light colors in C.I.E.*

The dots indicate the distinguishable color steps for signal lights as determined by Rautian and Guryeva [1957]. Some similarities to the results shown in figure 3–5 are evident.

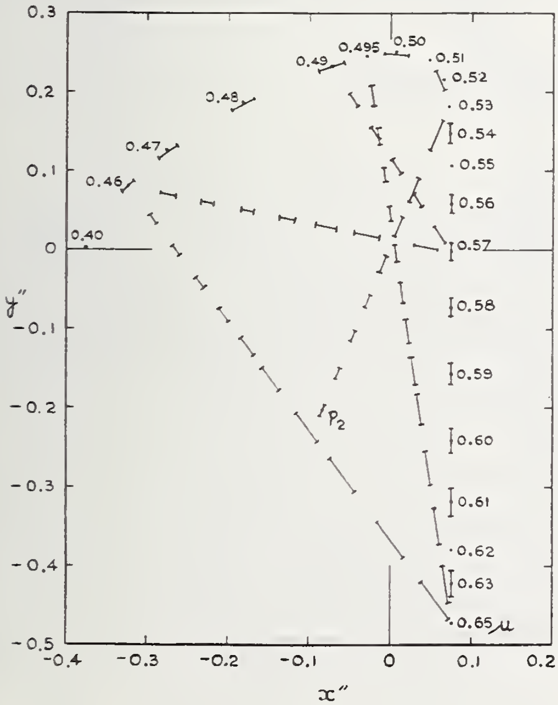

FIGURE 3–6. *Color steps for the mean of four observers plotted in the RUCS diagram.*

Each dash represents a chromaticity difference estimated equivalent to the others, as determined by Wright [1941]. A comparison of this diagram with figure 3–5 indicates that the RUCS is more uniform than the C.I.E. for small sources. It is also evident that the RUCS is not as uniform as would be desirable.

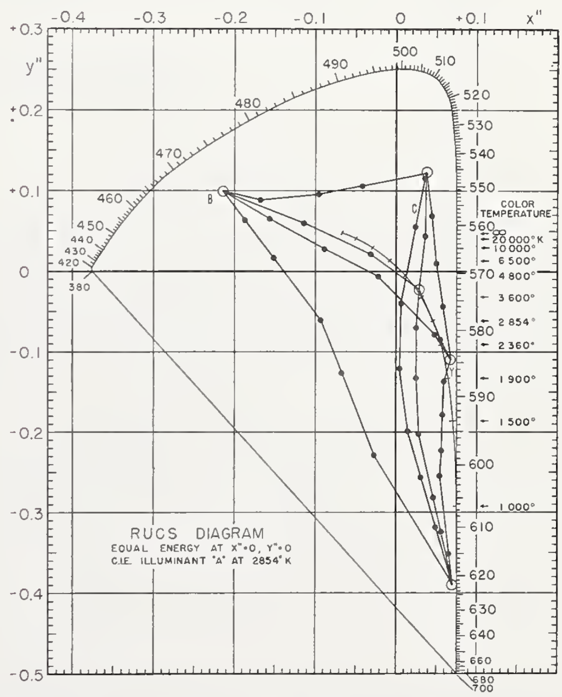

FIGURE 3–8. *Chromaticity differences for signal light colors in RUCS.*

The dots indicate the same points shown in figure 3–7 after transformation to the RUCS diagram. The comparison of figures 3–8 and 3–7 with figures 3–6 and 3–5 shows about the same degree of improvement. Both RUCS figures, 3–6 and 3–8, suggest that no linear transformation could make all the chromaticity differences shown equal. This is in agreement with MacAdam [1942].

leaving much to be desired, is not nearly as non-uniform as the C.I.E. While the close comformity of the RUCS to U.C.S. indicated by the ratio 1.1/1 merely reflects the derivation of the RUCS from the U.C.S., it is an indication of RUCS uniformity since the U.C.S. approximates uniformity by independent criteria.

The numerical values given above are not in themselves sufficient for estimating the distortions. It is also necessary to consider the degree to which the different results agree as to which areas of the diagrams are overextended and which too much compressed. All three agree in indicating the C.I.E. exaggerates the blue-green differences in the extreme green region. All three agree in indicating that the blue corner of the C.I.E. is the most compressed area, and that red-blue differences are exaggerated in the red corner.

An examination of the two RUCS diagrams indicates that the overextension of the green region has been corrected and the exaggeration of the red-blue differences at the red vertex has been reduced. The Wright data makes it appear that the blue vertex of the RUCS diagram should be further from the origin whereas the Rautian-Guryeva results indicate this vertex should be nearer the origin. This difference, however, should be expected to result from the difference between a 2° source and a point source as we shall see in the next section.[13]

3.7. Properties of RUCS Diagram

Although the chromaticity relationships in the Uniform Chromaticity Scale Diagram and the Rectangular Uniform Chromaticity Scale Diagrams are very nearly identical, in developing the RUCS diagram convenience of use was taken into consideration as well as uniformity of chromaticity spacing. From this standpoint it seemed desirable to use rectangular coordinates and to place a suitable white point, technically known as the achromatic point, at the origin of the coordinate system. If this is done, all radial lines from the origin become loci of approximately constant hue terminating in the corresponding dominant wavelength at the spectrum locus. Circles concentric with the origin approximate loci of constant saturation. By properly orienting the figure, it was found possible to make the y-axis correspond to red-green differences, while the x-axis corresponds, in a general way, to yellow-blue differences, although more specifically it connects violet to greenish yellow. As a result of this, the four quadrants represent green, yellow-orange-red, purple, and blue colors respectively, to a fairly satisfactory approximation.[14]

As will be seen in the next section, no one diagram can express chromaticity differences uniformly for all conditions of observation, but, so far as present knowledge makes it possible to judge, the deformation of the RUCS diagram to fit different conditions of observation is simpler than the corresponding deformation of the C.I.E. diagram.

4. Recognition of Signal Colors

4.1. General Principles

The first, and in some respects, the most important determinant for the limits of signal colors is the ability of the eye to recognize them. Unless there is a high degree of certainty that the signal will be recognized for the color it is intended to be, the signal may be a hazard instead of an aid to safety. The problem is a difficult one, however, because it is a statistical problem with nine parameters. The probability of correct recognition of a signal-light color depends upon: (1) the number of colors in the system, (2) the observer's familiarity with the system of colors, (3) the opportunity to compare colors if such is present, (4) the degree of concentration which the observer can devote to the recognition of the color, (5) the normality of the observer's vision, (6) the state of his visual adaptation, (7) the luminance of the background, (8) the solid angle subtended by the signal at the observer's eye, and (9) the illuminance, or the fixed-light equivalent illuminance at his eye.

[13] See fig. 4–12 and discussion in text

[14] Hues slightly on the blue side of the y'-axis are, however, classified as green by many observers and are used satisfactorily as green signals.

4.2. Results of Research

No one has found it possible to investigate the problem of signal color recognition with respect to all the variables listed in sec. 4.1, but H. J. McNicholas [1936], J. G. Holmes [1941 and 1949], N. E. G. Hill [1947], and R. M. Halsey [1959] have studied important segments of it.[15] A correlation of these four studies has been made and figures 4–1 to 4–12 and table 2 are from this correlation [Breckenridge, 1960]. The table gives most of the more important characteristics of these researches, but it should be added that only the observations of McNicholas Series II and Halsey Series III were properly recognition tests, that is, tests of signal colors separated by regions of unused chromaticities. All the other tests included in these four researches were naming tests to determine within what regions of chromaticity, and with what consistency, observers would

[15] Many other investigations furnish support to the results of the four studies mentioned. Of these, four are of especial interest: Guild [1928], Ornstein, Eymers, and Vermeulen [1934], Halsey and Chapanis [1954], and Bedford and Wyszecki [1958]. In the Halsey and Chapanis study, many chromaticities were visible at the same time. This may be particularly significant for signal lights seen against a background of other lights. Guild's work was confined to the selection of a range of yellows, but it is of especial interest for the unusual method used.

apply the typical signal color names to the members of well-distributed sets of chromaticities.

To understand the correlation of the different tests, it is necessary to take account of some additional observations on the appearance of point sources of light near the threshold of visibility.

When a light is just visible it is nearly colorless. Some observers state that red lights are recognizable as such even at threshold but not all observers have found this to be true. We must conclude that the recognition of red lights at threshold is too uncertain for signal purposes, and hence at threshold we have only one signal color. As the intensity of the light is increased, or the observer approaches closer to it, red lights may be distinguished from lights of other colors, but these continue to look alike. At still higher levels of illuminance at the eye of the observer, green lights become recognizable giving us the common three-color system composed of red, green, and an intermediate color which at still higher illuminances becomes differentiable into yellow, white, and blue. To get a sixth color reliably with point sources, it is necessary to use dichroic purple lights which usually appear as red lights surrounded by blue rays since the lenses of the eyes cannot focus for both colors at once. With sources of appreciable size, trained observers, and favorable conditions of observation, it is possible to insert additional colors.

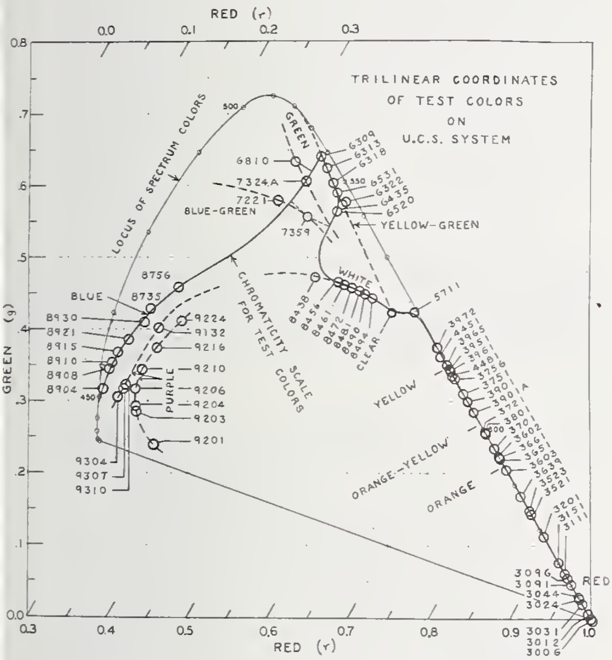

FIGURE 4–1. *McNicholas test colors.*
This diagram, reproduced from a paper by McNicholas [1936], shows how McNicholas undertook to arrange his test colors so as to correlate his results. The numbers identify the filters he used to obtain the test colors.

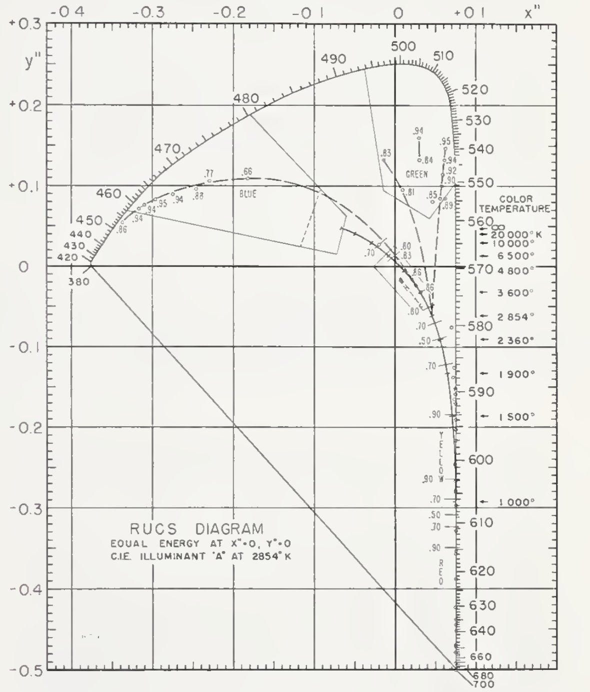

FIGURE 4–3. *McNicholas results plotted on RUCS diagram.*
This diagram was prepared to facilitate a comparison of the results obtained by McNicholas with those obtained in later researches. The numbers on the curves show the fraction of answers agreeing with the color shown.

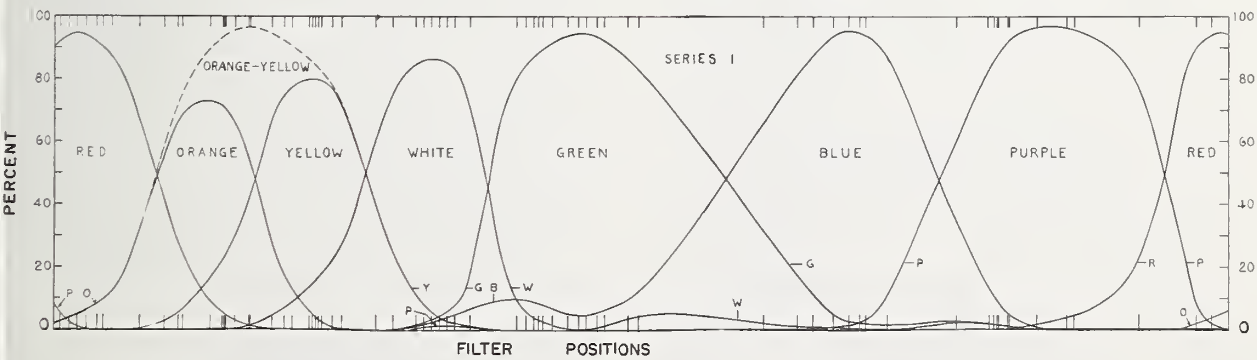

FIGURE 4–2. *Results of signal color recognition tests by McNicholas [1936].*
Colors are arranged in the order shown on the path drawn in figure 4–1. The ordinates are the percentage of answers indicated for the names shown under the curves. It would appear from this figure that none of McNicholas' colors were completely reliable under the conditions of observation, but these were relatively severe.

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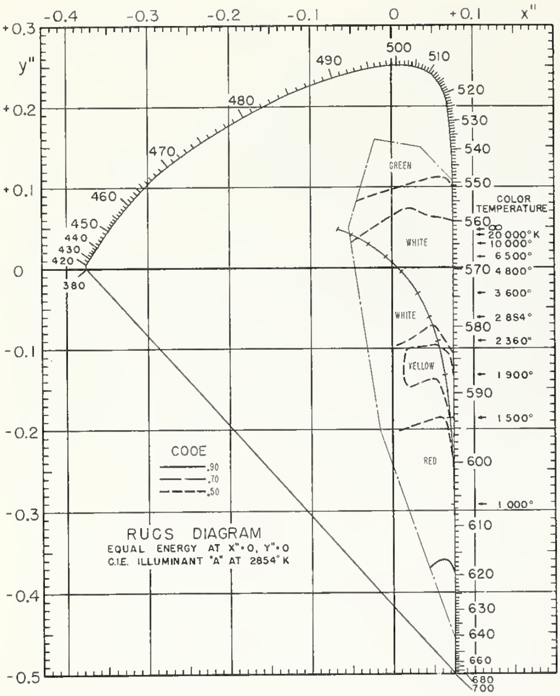

FIGURE 4–4. *Signal color identification with 1 sea mile candle illuminance.*

Determination from report by Holmes [1941]. Note that only red signal colors reach as high as 90 percent reliability under the conditions of observation.

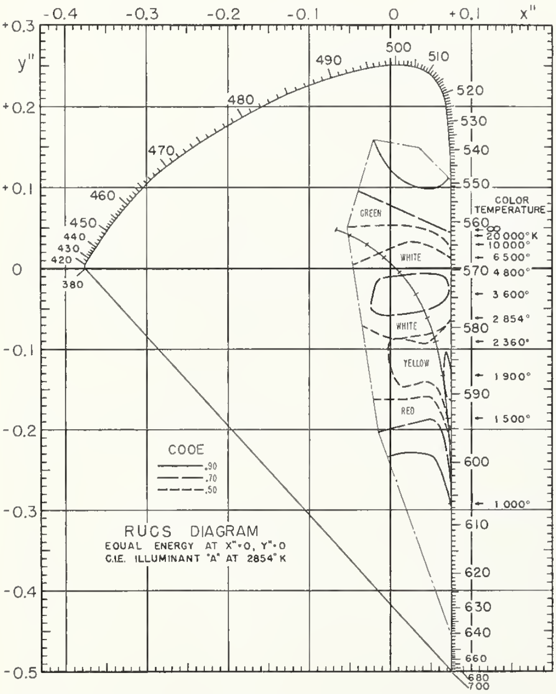

FIGURE 4–5. *Signal color identification with 10 sea mile candles illuminance.*

From report by Holmes [1941]. The increase in certainty of color identification as compared with figure 4–4 is quite evident.

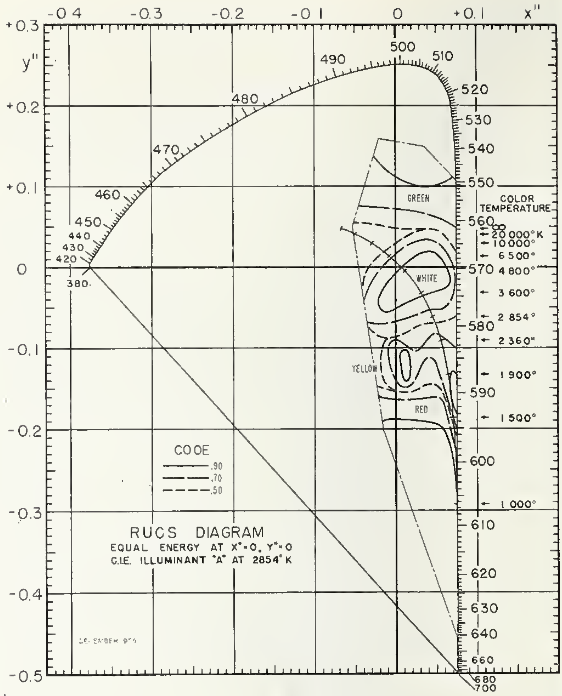

FIGURE 4–6. *The effect of increasing the number of observers.*

From report by Holmes [1941]. This figure represents results obtained under the same conditions as figure 4–5, but with 50 observers instead of 6 "average" observers. It was the author's conclusion that reliable results were being obtained with the smaller number of selected observers.

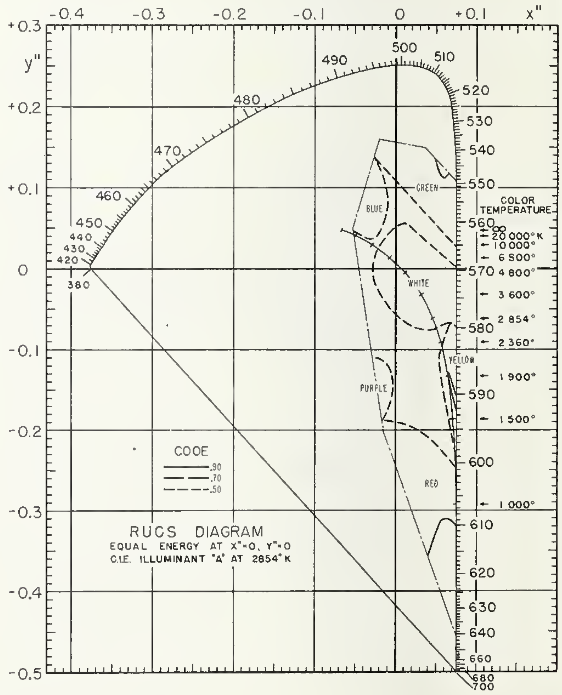

FIGURE 4–7. *Identification of signal colors with 100 sea mile candles illuminance.*

These results from Holmes' report show no further improvement in the reliability of red and green signals, but indicate for the first time the distinguishability of blue signals.

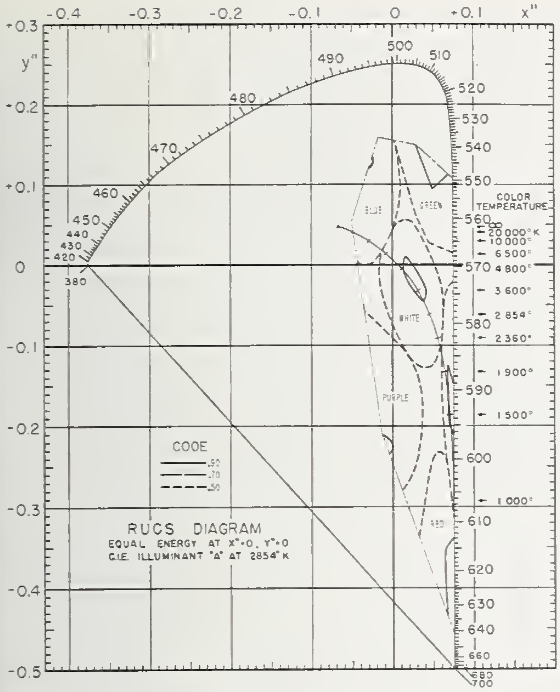

FIGURE 4–8. *Identification of signal light colors with 3400 sea mile candles of illuminance.*

This figure, the last from Holmes' report, shows a further increase in the distinguishability of blue signal lights and also in purple signals.

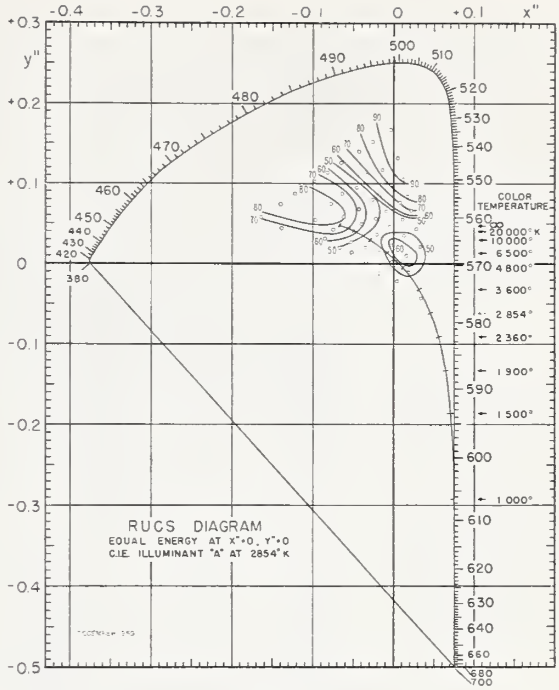

FIGURE 4–10. *Distinguishability of blue, green, and white signals.*

These results taken from a paper by Halsey [1959] were made with a relatively uniform distribution of target chromaticities throughout the test region as indicated by the small circles. For illuminance levels see text.

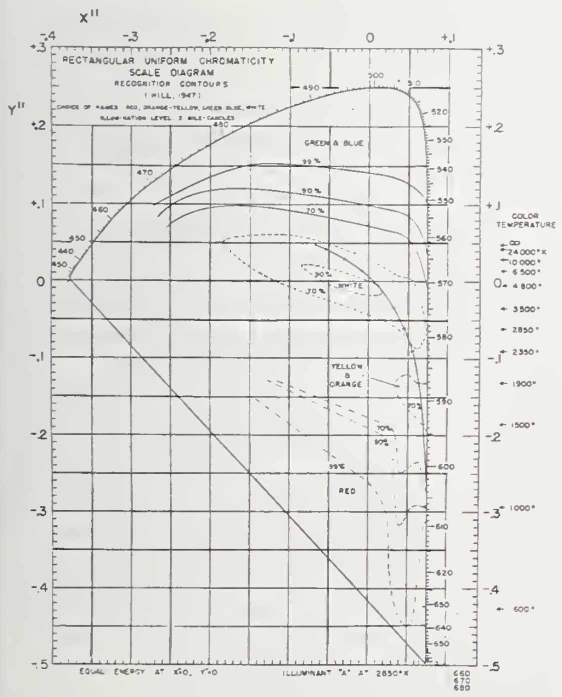

FIGURE 4–9. *Signal color identification at 2 mile candles illuminance.*

These results were obtained by Hill in 1947. An attempt to distinguish blue from green signals at this illuminance proved impracticable. Apparently the distinction of blue from green fades at a higher illuminance than the other distinctions which are represented in this figure. (See also figure 4–12 and discussion in sec. 4.2.)

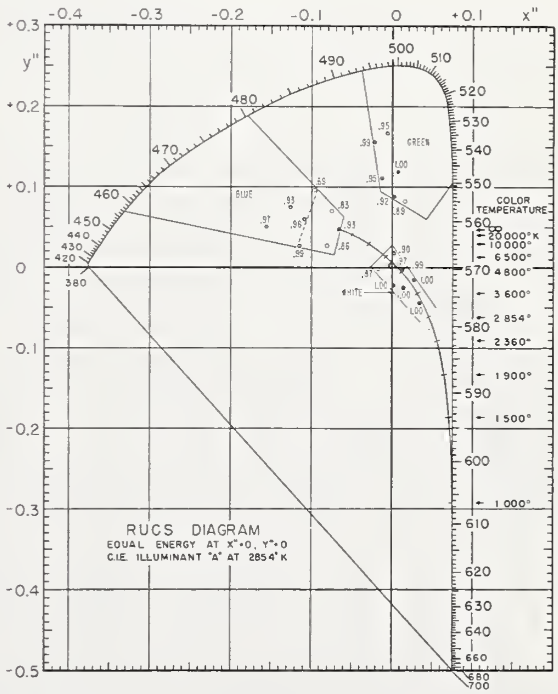

FIGURE 4–11. *Effect of confining target colors to normally acceptable chromaticities.*

This test, also by Halsey [1959] (not published), discloses the effect of omitting target chromaticities which were considered unreliable so that one might hope that the remaining chromaticities would be identified correctly 100 percent of the time. It also indicates the effect of giving observers some training.

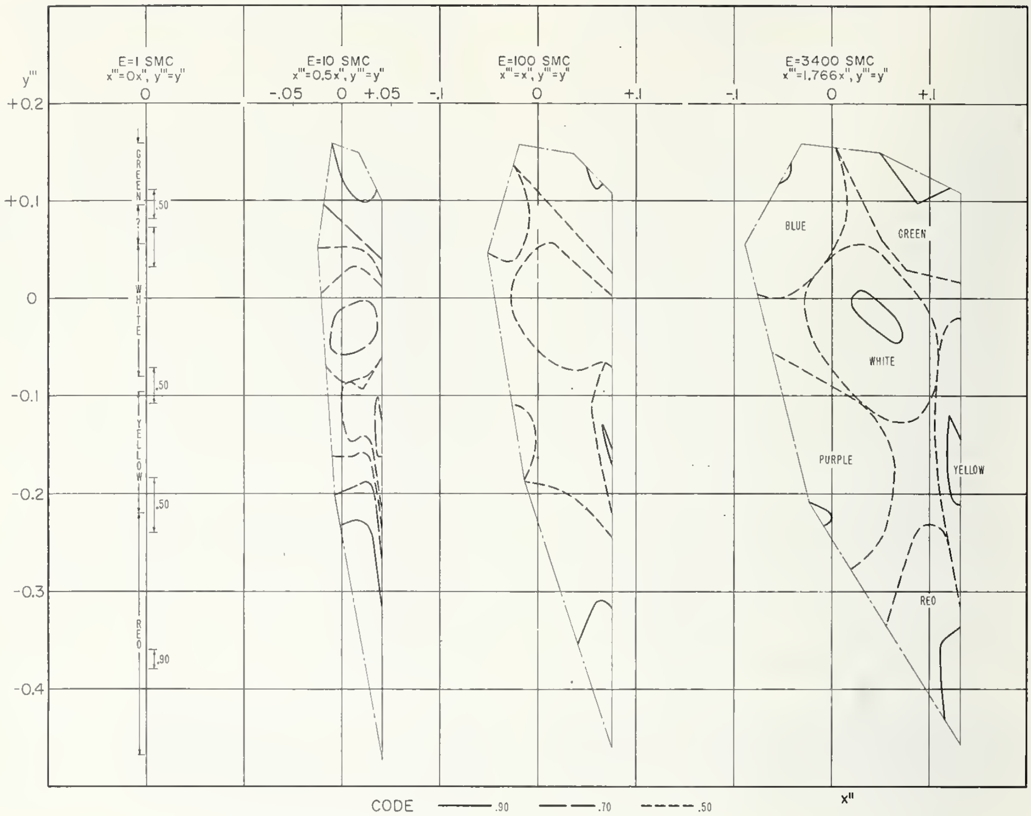

FIGURE 4–12. *Correlation of Holmes' results.*

The results shown in figures 4–4, 4–5, 4–7, and 4–8 have been compressed or expanded along the x'' axis to compensate for the effects of low-illuminance tritanopia. It should be noted that in the case of all except the leftmost figure, the white contours are approximately circular around a point near the origin. The leftmost figure has shrunk to a vertical line, signifying that the yellow-blue discrimination has been lost because of the tritanopic effect of low illuminance.

From the above discussion it becomes clear that if we were to represent signal colors in diagrams prepared to correspond to different levels of illuminance at the observer's eyes, we should make the one for threshold illuminance consist of a single point. At the next level of illuminance we shall need a short line with red represented at one end and non-red at the other. As the illuminance increases the line must be made longer and finally the figure takes on width and develops into something approximating the RUCS diagram.

An attempt has been made to prepare a series of diagrams on this principle by using the contours of Holmes' extensive investigation as a guide to the factor for the yellow-blue contraction, or expansion, of the RUCS diagram required for each level of illuminance. The results of this study are shown in figure 4–12 [Breckenridge, 1960]. The diagrams of this figure are those of figures 4–4, 4–5, 4–7, and 4–8 with the x'' coordinate contracted, or expanded by the factor indicated for x'' above each figure. Only that portion of the RUCS diagram necessary to include Holmes' test chromaticities has been included in each case. If these transformations had resulted in diagrams entirely in accord with the RUCS intent, the inner white contours would have been circles around the origin in each case.

4.3. Results of Experience

While the contributions of experience to our knowledge of the recognition of signal colors are less definite than those of research, their influence upon the actual selection of limits for the signal colors in use has been greater. It is, of course, possible that a definition of a signal color might be used for many years without the realization that it permits certain chromaticities that could be mistaken under some conditions. Considerable areas of chromaticity which are within the definitions are not used in service. Chromaticities near the extremes of those represented by the standard limits presumably do not occur frequently and it may be much more rare to find such a borderline filter in a situation in which color recognition is particularly difficult. Finally, not every error in color identification causes results that reveal the mistake. Nevertheless the long and successful use of the same colors for marine and railroad signals is a strong indication that chromaticities within the limits of those used in these services are satis-

TABLE 2. *Summary of procedures for color identification researches**

Research by	Illuminance	Source target size	Exposure	Number	Colors: Coloration	Colors: Other lights	Grouping of colors	Observers: Number × runs	Observers: Ages	Observations: Total number	Observations: Names allowed	Adaptation
	smc	*Minutes*	*Seconds*						*Years*			
McNicbolas Series I	0.5/8.2	0.4/0.04	5	69	Glass	Street	Partly Grouped	38*	20*/60	5800*	R Y O G B P W*	Below horizon on dark background of woodland and southern sky
Series II	1.0/2800	"	"	"	Filters	Lights	Grouped				R Y G B P W or R Y O G B W*	
Holmes	1	0.7	1 on/1 off *	256	Synthesized	None	Continuous	6 × 3	22/42	4608	R Y G B P W	5 minutes before test
	6	1.7	"	"	from	"	"	13 × 1	"	3328	do.	
	10	2.2	"	"	11 glass	"	"	6 × 1	"	1536	do.	
	10	2.2	"	"	filter	"	"	50 × 1	18/63	12800	do.	
	10	2.2	"	"	primaries	"	"	5 × 3	22/42	3840	R Y G W	
	10	2.2	"	"	do.	"	"	5 × 3	"	3840	R Y G N	
	10	2.2	"	"	do.	"	"	5 × 3	"	3840	R G W	
	10	2.2	"	"	do.	Desk lamp*	"	4 × 3	"	3072	R Y G B P W	Reading by desk lamp between observations
	100	7.0	"	"	do.	None	"	6 × 3	"	4608	do.	
	3400	40.0	"	"	do.	"	"	4 × 3	"	3072	do.	
Hill	1.3	0.6	1.5	73	17 Wratten filters	Dim reddish	Continuous	9 × 20#	20–40#	30420	R(YO)(G+B)W#	10 Minutes before testing General .0001 c/ft.² with 15′ disc illuminated to .0005 c/ft. for 1.5″ before signal
	2.6	0.6	1.5	73	+ white	glow	" 9 × 20#		20–40#		do.	
Halsey I_H	6.2/280	4.1/7.2	2	50	4 Wratten	Red &	Continuous	100 × 1	17–35	5000	R Y G B P W	.001 ftL on data pads for 15 minutes before test and during it
I_L	1.8/83	"	"	"	filter	yellow	"	100 × 1	"	5000	do.	
II_H	6.2/280	"	"	"	primaries	fixation	"	100 × 1	17–28	5000	R Y G B W	
II_L	1.8/83	"	"	"	do.	lights	"	100 × 1	"	5000	do.	do.
III_A	2.3/104	"	"	22	do.	do.	3	100 × 1	approx.	2200	R Y G B P W	Dimly illuminated room
III_B	"	"	"	"	do.	do.	Groups	100 × 1	as	2200	R Y G B W	do.
III_C	"	"	"	"	do.	do.	do.	100 × 1	above	2200	G B W	do.
III_D	"	"	"	"	do.	do.	do.	100 × 1	do.	2200	G B W	do.
Notes			*Flashed as long as desired			*Between observations		*In two series #Some 30 times	*3 < 20 #17 > 40	*In the two series	*Note orange included in one test #orange recorded as yellow	

*[Breckenridge, 1960]
Reproduced from report by author to Sixth International Lighthous Conference, Washington, 1960.

factory for their purposes. It does not follow that chromaticities outside of those limits are unsafe.

While the limits for the red and green signals used in marine and railroad practice were selected before the researches mentioned in the last section were carried out, their selection was not casual. The earlier limits used for railroad signal colors were not satisfactory and at its second meeting the newly organized Railway Signal Club appointed a committee in April 1895 [AAR, p. 74, 1953] to investigate the question of colors for night signaling. At first the problem was which colors should mean clear, go ahead, and which danger, stop. At that time the usual colors for railroad signals were white for safety, red for danger, and green for caution. This was the practice in most countries in accordance with an agreement reached at a congress of railroad men in Birmingham, England in 1841. The system had been developed in France and it is interesting to note that the originators had reached the conclusion in the course of their experimenting that "the visibility of a red light was but one-third that of a white light of the same intensity; that of a green light one-fifth; and that of a blue light one-seventh" [AAR, p. 73, 1953]. A comparison of these values with present information evidences the progress which has been made by the glass manufacturers in producing signal filters of higher transmittance.[16]

The 1841 standard proved defective because a signal with a broken glass frequently appeared white, converting a danger or caution signal into a safety signal. The same mistake occurred if an engineer mistook an ordinary white light for a signal. On this account English practice was changed to use green for the safety signal with no caution signal. The first use of the present red-yellow-green system in this country was by the New York, New Haven, and Hartford Railroad in 1899.

Starting about this time interest began to develop in the scientific aspects of signal-light recognition. Laboratory work was started at Yale University and later continued at the Corning Glass Works by Dr. William Churchill to select the most effective colors for signal lights [Churchill, 1914]. Between 1914 and 1930 several committees appointed by the Signal Section of the Association of American Railroads made field tests with the cooperation of the Corning Glass Works to determine the most favorable limits for the colors. These tests had the advantage that they were made by the men who used the lights in service and they were made under conditions approximating somewhat the conditions under which such lights are normally used.

[16] This assumes that the "same intensity" refers to the lamps without their filters and that the relative visibilities were measured by the distances at which the lights became visible.

The original selection of colors was made at a time when all railroad signal lights used kerosene wick lamps. The selection of glasses for use with electric lamp sources was carried out under the technical leadership of Dr. H. P. Gage at the Corning Glass Works. Dr. Gage [1928] reviewed the entire problem systematically. He found that in addition to meeting the requirements of recognizability, the railroad representatives considered it desirable that lights of the primary signal colors (red, yellow, and green) should be about equally visible. Since the green glass was thought to give the least conspicuous signal, the limits for green were determined first. Yellow and red glasses were then selected to obtain signals that were regarded as comparable in conspicuity as well as safely recognizable.

The ranges of acceptable color variation were identified by filters representing the palest acceptable ware and the minimum acceptable transmittances. These filters were called limits. The selection of limits for marine, aviation, and highway signal lights in the United States has been based to a considerable degree on the limits selected for railroad signals and such consistency as exists between these different systems results largely from the influence of Dr. Gage in the selection of all of these limits.

5. Production of Signal Colors

5.1. Source and Filter

The second determinant which controls the selection of limits for signal colors is the practicability of producing initially, and maintaining in service, signals that will be within the proposed limits. This is a problem with many aspects, as indicated by the subdivisions of this section.

The color of the signal seen by the user depends upon the chromatic qualities of the source of light and those of the filtering elements interposed between it and the observer.[17] Some signal colors can be obtained from autochromatic sources that require no filters, but most signaling is done with units that derive their light from incandescent lamps which for signal purposes are regarded as white and require glass, or plastic, filters when other colors are required. In some installations lamps have been used which contribute a weak coloration that is strengthened by a filtering element. In the following section, we will consider first, and chiefly, signals produced by filtered incandescent light, with a brief discussion of gaseous discharge lamps in the last subsection.

5.2. Effect of Colorants

If a desired signal color is to be obtained by filtering light from an incandescent lamp, the first question is whether suitable glass, plastic, or other material of the necessary spectral transmittance is available. The curves of figure 5–1 show chromaticities that are obtainable with different types of glass. In many cases slight changes in the composition of the colorant would move the corresponding curve to one side or the other of the path shown. It is evident from the distribution of these curves over the green and most of the blue quadrants that a considerable variety of chromaticities is available for these colors. In the yellow-red quadrant any desired degree of redness is available with high purity but this may not be apparent from the diagram since for wavelengths greater than $\lambda = 0.585\mu$ the curve for chromaticities obtainable from the practically available selenium glasses virtually coincides with the spectrum locus and is not represented by a separate line. In the purple quadrant only one type of glass is shown, but the

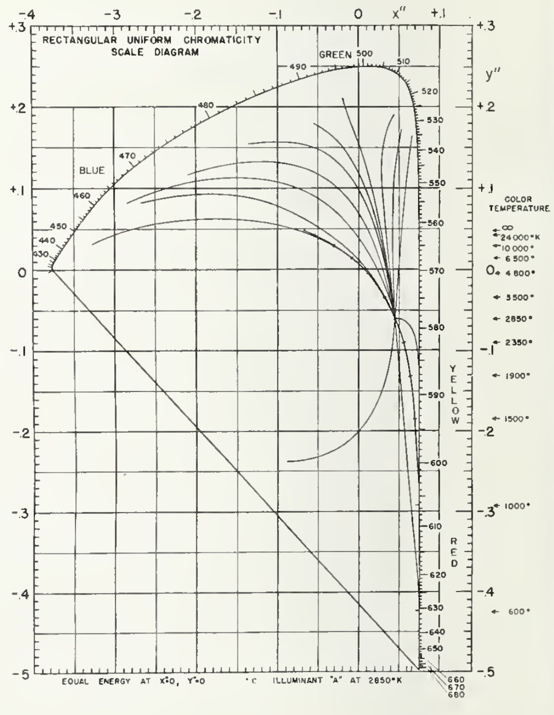

FIGURE 5–1. *The effect of colorant selection.*

With the exception of the Planckian locus, which is distinguished by the cross bars indicating the different color temperatures, each of these curves is the locus of chromaticities which result from changing the density of the colorant. In three cases, two types of glass have been combined in fixed proportions to obtain curves in the regions not commonly used for signal light purposes, but all the other loci correspond to actual filters.

[17] For a somewhat parallel discussion of this aspect of the problem from a different point of view, see "Coloured Glasses for Lighthouse Purposes," Holmes [1937]. There is also some parallel information in Holmes' "Colorimetry in the Glass Industry" [1947].

chromaticities in this quadrant are not generally used for signal lighting purposes.

Unfortunately no data for plastic filters comparable to that shown in figure 5–1 for glass filters are available to the author, but red and yellow plastics with spectral transmittances very similar to those of the red and yellow glass have been measured at the National Bureau of Standards as well as green plastics of suitable chromaticity for signal purposes.

The fundamental difference between filters of different colors derives from the different degrees with which light of different wavelengths is transmitted. Figures 5–2 and 5–3 have been included to show typical differences in spectral transmittances for filters of different colors.[18] The curves have been labeled to assist in correlating the curves of these figures with those of figure 5–1. For each color, two curves are shown with the same label, the lower curve representing a thicker filter than the upper curve. The filters represented by the curves of spectral transmittance are not the same as those of figure 5–1 but they are similar to some of them and would give chromaticity loci in the regions indicated.

5.3. Effect of Filter Thicknes

One of the means of controlling the color of a signal light is to vary the thickness of filter used, or if this is not feasible, to change the concentration of the colorant in the filter. In figure 5–1 it will be seen that all the curves for the filter chromaticities converge to a single point. This point corresponds to filters of zero thickness which do not change the color of the incident light at all and consequently transmit light that is the color of the source. Theoretically any filter that is not neutral can be increased in thickness or concentration until its transmittance becomes virtually monochromatic. In the figure this would be represented by prolonging each curve until it reached the spectrum locus. There are practical reasons why this is not feasible. Even at the outer ends of most of the curves shown in figure 5–1 the transmittance is below the minimum practicable for signal filters. In production there may also be chemical difficulties. There may be reactions between the colorant and the body material that will change the spectral transmittance characteristics of the colorant; or such a reaction may have a deleterious effect on the physical qualities of the glass.

In the practical production of colored glassware there is always a variation of thickness from piece to piece, and from lot to lot there may be variations of the composition and concentration of the colorant

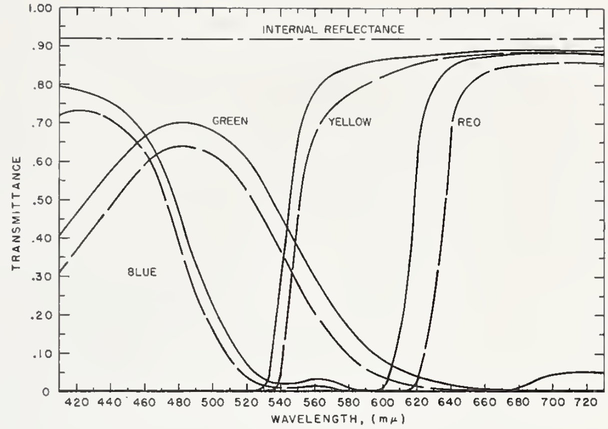

FIGURE 5–2. *Spectral transmittance curves for National Standard filters.*

Two filters of each of four colors are included. The upper full line line curves represent pale limits. A lower broken curve in each case represents a denser filter of similar type.

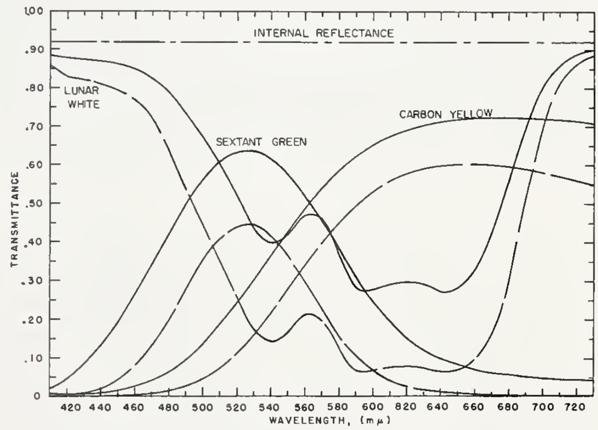

FIGURE 5–3. *Spectral transmittance curves for three types of glass available for signal ware.*

Lunar-white and carbon-yellow glasses have been used for railroad signal-light ware. Sextent green glass could be used if a yellow green signal were desirable. Broken curves are for thicker filters than those represented by the full line curves.

which cause corresponding variations in the chromaticity of the signal. In the case of green and blue ware, the possible variation is considerable. It is, in fact, so considerable that it is difficult to set up chromaticity limits for some ware that will keep within the limits regarded as safe for the recognition of the signal and at the same time allow enough variation to permit reasonably priced production. In the case of red and yellow selenium ware, the variation of chromaticity with thickness is much less and is mainly parallel to the spectrum locus. Similar, but larger, changes are produced by heat treating selenium glass. Since these sharp cutoff selenium red and yellow filters, excepting some too pale for signal purposes, produce colors close to the spectrum locus, there is a negligible change of

[18] The spectrophotometric transmittance of the national standard filters are given in the U.S. Standard for the Colors of Signal Lights [NBS 1964] and also in Gibson, Haupt, and Keegan [1945] and [1946].

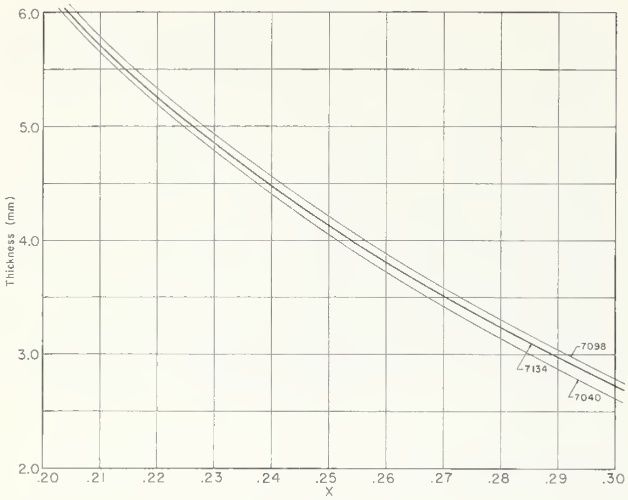

FIGURE 5–4. *Variation of chromaticity with thickness.*

The center curve shows the variation in the x coordinate for the chromaticity of a green filter transmitting light from a source 2854 °K as the thickness of the filter is varied thru a range of approximately 1 to 2. This type of curve is useful in estimating the change of thickness necessary to produce a required change in chromaticity when filters are being ground to come within a given tolerance. The central curve is for a national standard filter and the upper and lower curves are for other filters of similar types of glass. It is to be noted that the tangents for all three curves are nearly the same for any given value of x. In adjusting chromaticities by grinding, it is the rate of change that is important. This enables us to use a standard curve even though the particular piece of glass to be adjusted may have a slightly displaced curve.

x'' (or z) not only with changes of thickness but with changes in any of the other parameters we shall consider. For this reason the changes of chromaticity of the red and yellow selenium glasses may be represented diagrammatically by using y'' or y as an index of redness.

Variations in the chromaticity of plastic ware are less than those for glass but similar in character because the methods of production permit more rigid controls of thickness and composition. There is, on the other hand, greater risk of change of chromaticity through fading with age in the case of plastics. Some plastic colorants, however, are resistant to fading.

Curves showing the variation of chromaticity as represented by one of the coordinates as a function of the filter thickness are useful in the duplication of standard filters. Figure 5–4 shows this variation for three similar green glasses. To prepare the curve it is necessary to know the spectral transmittance of the filter, but after the curve is drawn all other chromaticity measurements may be made with a differential colorimeter (see sec. 9.1). An ordinary spectral transmittance curve does not give values that enable one to compute chromaticity coordinates with the accuracy suggested by the curves of figure 5–4, and for this reason the first grinding of the blank should be to a thickness that

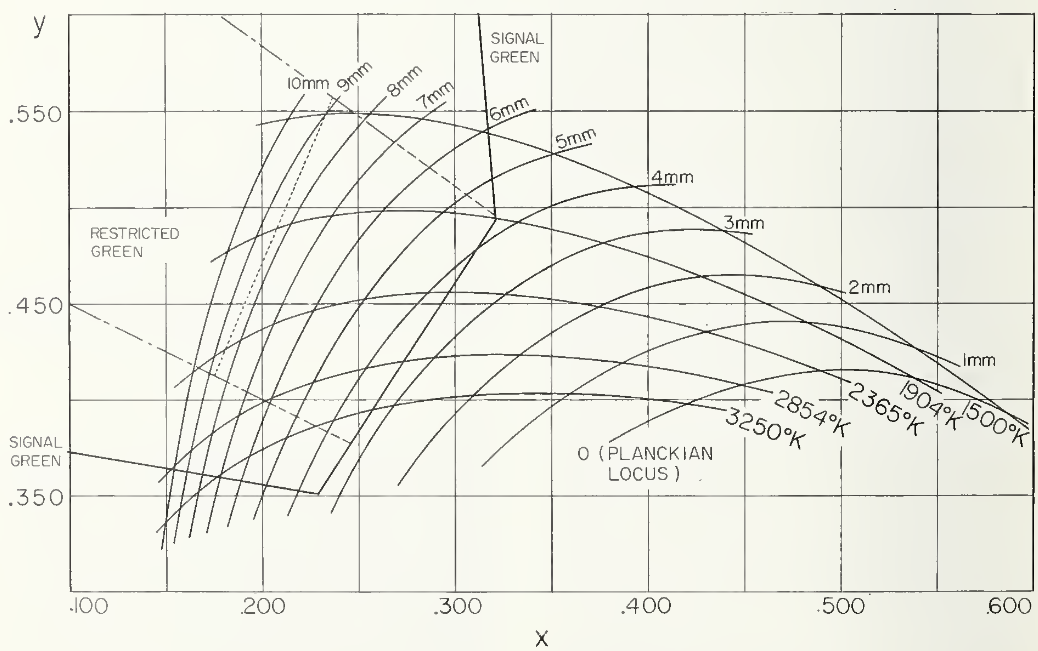

FIGURE 5–5. *Variation (C.I.E.) of chromaticity in service for green glass filters.*

This is the type of diagram which must be prepared to show that the signal color will remain within the basic chromaticity definitions in service. The curves in this figure are based on U.S. Standard Filter 7.134. Those labeled with color temperatures show the variation with thickness using light sources of the labeled color temperatures. Curves labeled with thicknesses show the variation with light-source color temperature for filters of the labeled thicknesses. The straight lines show the boundaries of the basic chromaticity definitions for signal green, intermediate green, and restricted green. To be acceptable, the chromaticities for the proposed colorant must remain inside the applicable basic chromaticity definitions for all points within the area bounded by the minimum and maximum light source color temperatures to be expected in service and by the curves for two thicknesses representative of the minimum and maximum thickness to be expected in the filter ware.

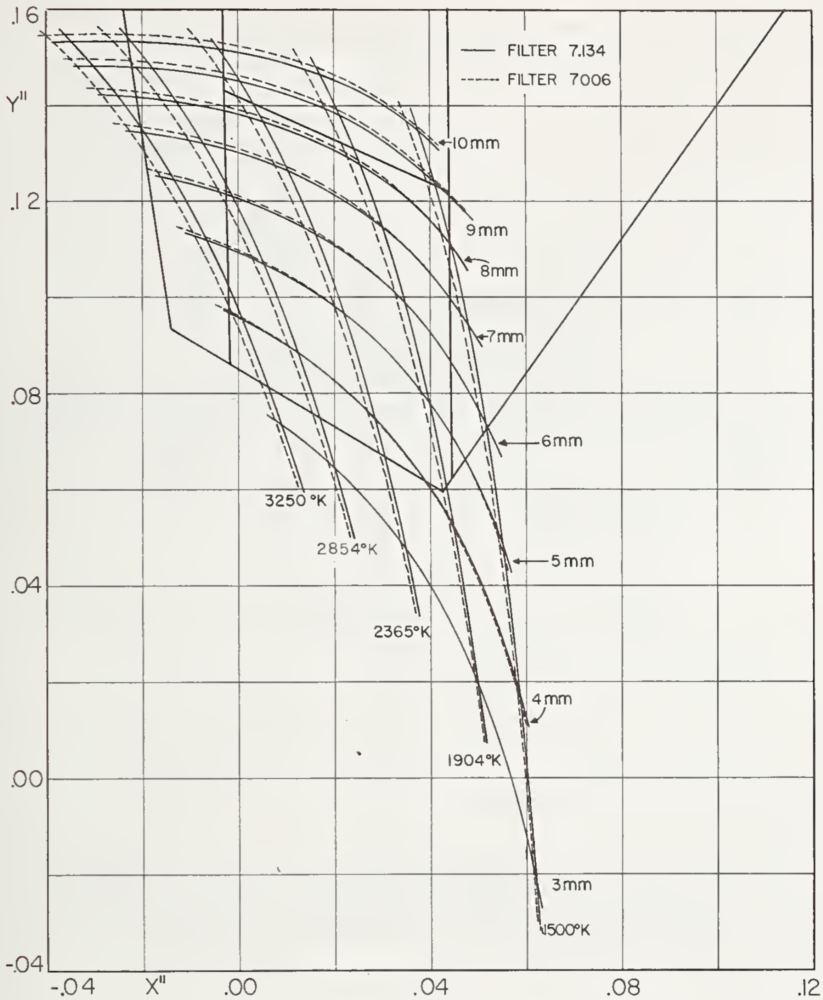

FIGURE 5–6. *Variation (RUCS) of chromaticity in service for green filters.*

The full line curves here represent the same variations as in figure 5–5. The dotted line curves represent the chromaticities to be expected on the basis of a green filter manufactured by a different company.

allows for a possible error of at least the estimated uncertainty. The differential measurement provides a more accurate value of the chromaticity, and if this were plotted on a diagram corresponding to figure 5–4 it would probably not fall on the curve. However, we now know how much change in x or y we desire, and we know the slope of the curve for the chromaticity as a function of thickness with sufficient accuracy so that we can compute the reduction in thickness required to bring the filter within the tolerances.

5.4. Effect of Color Temperature of Source

It has been stated in sec. 5.1 that not only the characteristics of the filtering element but also the color of the source affects the color of the signal. Most signal lights today operate with incandescent lamps, but signal lights using kerosene wick flames, acetylene flames, and mantle burners may still be in use, and each of these has its characteristic spectral energy distribution. The incandescent lamps also differ in spectral energy distribution because of differences in the operating temperatures of the filaments. It is customary to specify the energy distribution of an incandescent lamp by giving its color temperature. This is not the physical temperature of the filament but the temperature of the blackbody or complete radiator which would most nearly match the filament in chromaticity.

The differences in filament temperature result in part from differences in lamp design and in part from variations in operating voltage and the latter may be either incidental or intentional. Lamps for

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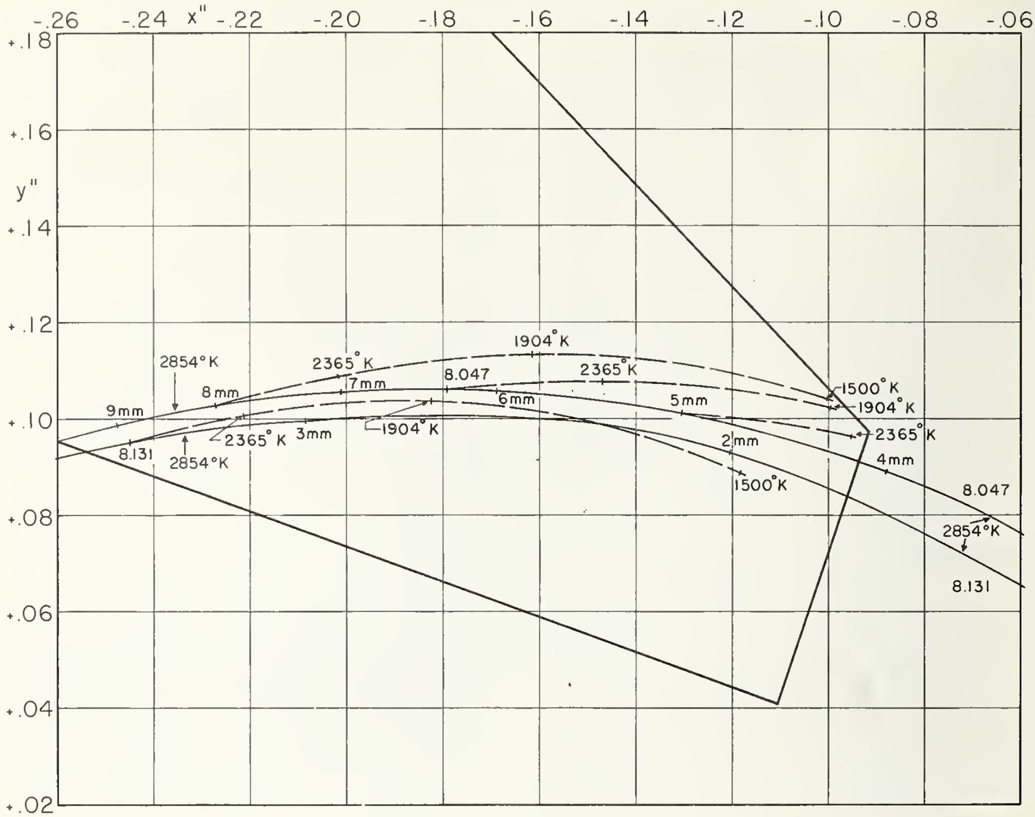


FIGURE 5–7. *Variations (RUCS) of chromaticity in service for blue filters.*

This figure is analogous to figure 5–6. In the case of blue signal filter ware, the variations caused by change of light source color temperature and those caused by change in the thickness of the filter tend in nearly the same direction, with the result that the entire range of colors actually used is compressed within a relatively narrow belt across the region defined by the basic chromaticity definitions. For this reason it is not practicable to show as many lines as in the case of green.

different applications are designed for different periods of life and this means different filament temperatures. Lamps now in use for signal lighting vary from about 2300 °K to about 3100 °K in color temperature at designed voltage. This variation should be compensated by a proper selection of colorant density in the filtering element, and in selecting the limit standards it is necessary to take account of the color temperature of the lamps to be used with the ware to be controlled.

It is difficult to estimate the variations in supply voltage for signal light installations in general but one survey of traffic signal lights showed that the lamps in the installations studied were operating at a minimum of 100 volts and a maximum of 130 volts. This could cause color temperatures varying through an interval of 200 °K. The largest color temperature variations are those caused by variations in lamp current which are made intentionally in order to adapt the intensity of the signal to prevailing conditions. Approach and runway lights designed for use at airports under conditions varying from daytime fog to clear night darkness are designed to have their lamp filaments vary from 3100 °K at maximum intensity to 1500 °K at minimum intensity.

While it is not feasible in most signal-light applications to make provision for varying the intensity of the lights to compensate for the difference between fog and clear air, it would be feasible in some cases to make allowance for the variation between night and day requirements. With the increasing intensities required for traffic signals on high-speed roads, such compensation may soon be imperative for traffic signals. The increasing intensities used for vehicular signals make them glaring at night and it has been proposed to cut these intensities when headlights are used. Tests made in connection with the development of approach and runway lighting for airports have shown that approximately 1000 times the intensity is needed in the daytime to obtain the conspicuity equivalent to that considered necessary at night with the same atmospheric transmissivity.

Figures 5–5 to 5–9 show the effect of light-source color temperature on the chromaticity of the signal

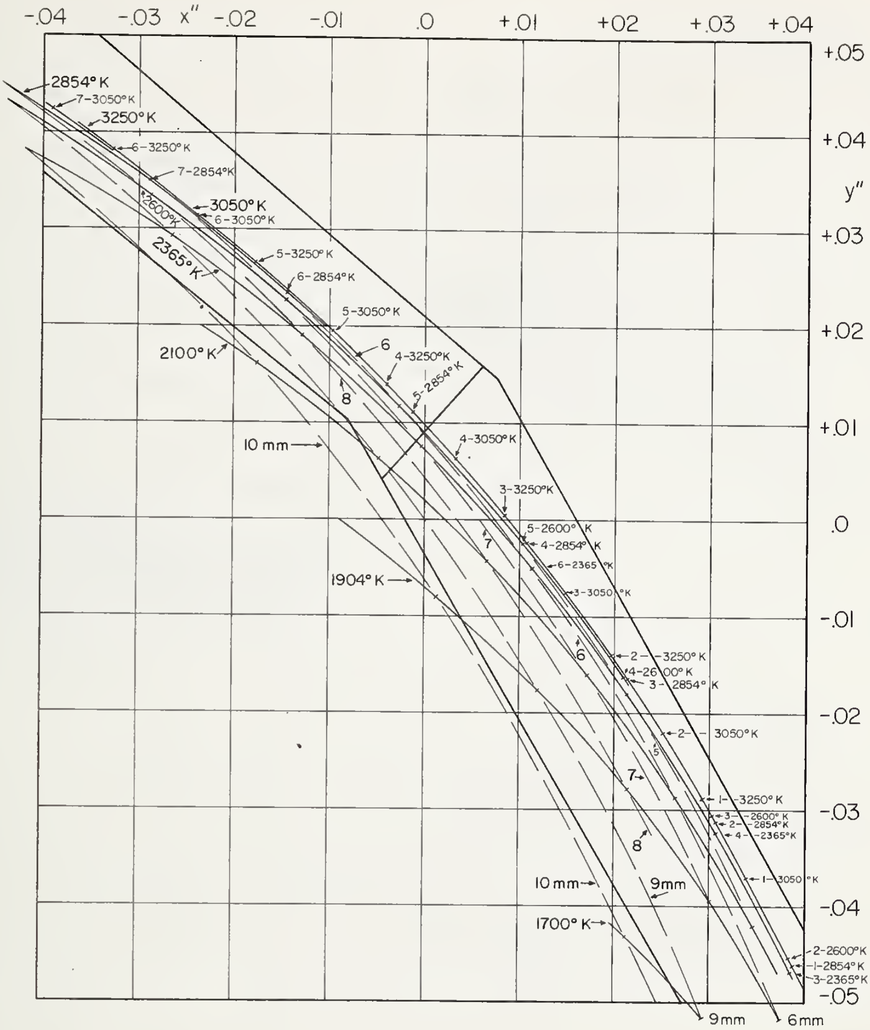


FIGURE 5–8. *Variations (RUCS) of chromaticity in service for lunar-white and blue-white filters.*

This figure corresponds to the preceding figures for green and blue filters. It shows how similar the changes of chromaticity caused by variations of thickness are to those resulting from changes of light-source color temperature in the case of lunar-white filters. The straight lines are boundaries for U.S. Standard Lunar White and Blue White.

for glasses of different colorant "densities." For green glasses, figures 5–5 and 5–6 also show the loci of constant colorant "densities." These curves and those for constant color temperature follow quite different paths so that it is feasible to show both sets on the same diagram as functions of x'' and y''. Similar curves are shown for blue glasses in figure 5–7, but these may be found somewhat confusing because in this case the two types of loci lie much closer to each other, the change of chromaticity with source color temperature and with colorant density being similar. This similarity of variation is shown even more clearly in figure 5–8 which shows the corresponding variations of chromaticity for lunar white and blue white filters. In figure 5–9, however, we have plotted the change of the y'' coordinate as a function of the color temperature of the source since the chromaticity of red and yellow filters can be represented to a good approximation by a single parameter.

To simplify the discussion the term "density" has been given a generalized meaning above. In the case of blue glass the change of "density" can be made either by changing the concentration of the colorant or by changing the thickness. In the case of green glass the change in concentration is liable to have undesirable chemical effects and the change of "density" must be considered as referring to changes of thickness primarily. With red and yellow glass of the selenium, sharp cutoff type a change of thickness has little effect upon the chromaticity. For these glasses the chromaticity is largely determined by the wavelength at which the cutoff occurs. This is to a considerable extent determined by the heat treatment given the glass. In the case of the blue and green glasses we have

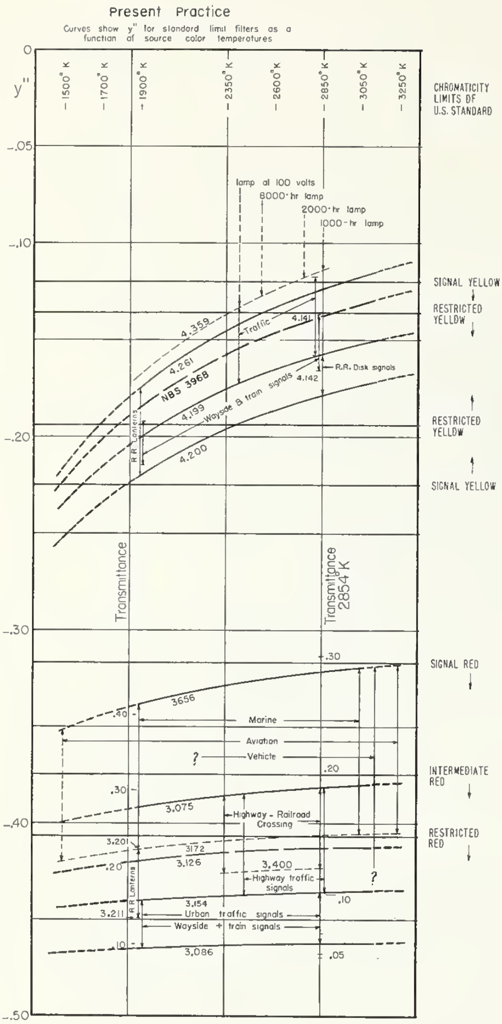


FIGURE 5–9. *Variation (RUCS) of chromaticity in service for red and yellow filters.*

In this figure the value of y'' has been used as an index of redness and yellowness. Since all these chromaticities lie so close to the spectrum locus that the distance between them and the spectrum locus is not significant, it is feasible to represent the chromaticities by a value for y'' alone. Limits shown by vertical arrows are for specifications in use prior to the adoption of the U.S. Standard. The chromaticity limits of the Standard are shown by horizontal lines as labeled.

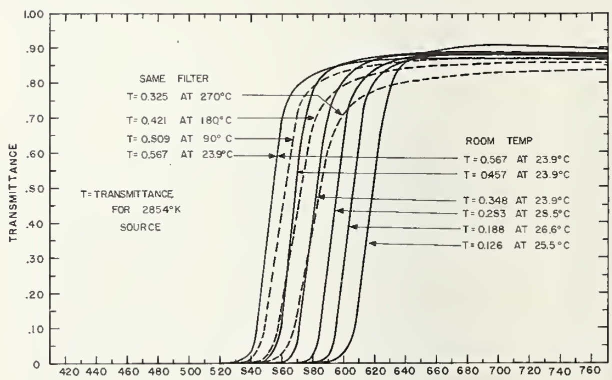


FIGURE 5–10. *Effect of physical temperature on spectral transmittance.*

Spectral transmittances of six red and yellow selenium glass filters as measured by Leberknight and Stone [1955] compared with the spectral transmittance of one of them at four different physical temperatures. The filters are identified by giving their approximate transmittances at the temperature nearest room temperature.

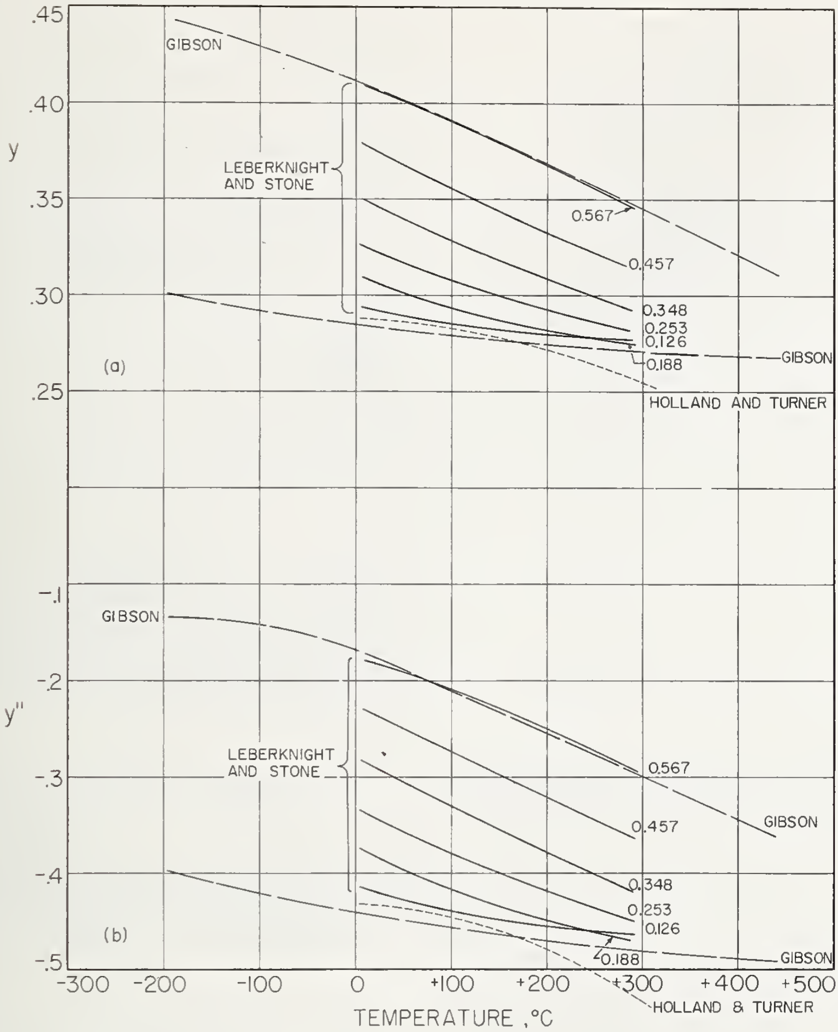


FIGURE 5–11. *Effect of physical temperature on the chromaticity for selenium filters.*

(a) These curves show how the chromaticity of the transmitted light, as measured by the y coordinate, varies with the physical temperature. Six of the curves are for the same filters shown in figure 5–10 and are identified by their transmittances at room temperature as shown in that figure; two are from measurements made by K. S. Gibson [1916]; and one is from the researches of Holland and Turner [1941].

(b) These curves are based on the same red and yellow filters shown in the upper curves (a), but y'' (RUCS) is used in place of y (C.I.E.) as the index of redness.

used thickness as a parameter of colorant "density" and in the case of the red and yellow glasses we have selected filters of different cutoff as the equivalent of different "densities" in the other cases.

From figures 5–5, 5–7 and 5–9, it is evident that there must be a correlation between the variations of colorant "density" required for a practical manufacturing tolerance, the changes of source color temperature required by the conditions of service, and the variation of chromaticity allowed by the basic chromaticity definitions. Especially in the green and the yellow it is necessary to consider the manufacturing and service limitations in adopting the definitions and in all cases it is necessary to consider them in adopting limits for the control of production.

5.5. Effect of Filter Temperature

Another source of variation which must be considered is the change in the chromaticity of the signal resulting from changes in the temperature of the filtering element. This effect is most marked in the case of selenium glassware. To understand the nature of the change in transmittance with the temperature of the glass, it is well to compare the curves of spectral transmittance for different glasses at different temperatures shown in figure 5–10. These curves, which are due to Leberknight and Stone [1955], show six glasses at room temperature and one of these glasses at three additional temperatures. There is a considerable similarity between the changes from glass to glass and those from

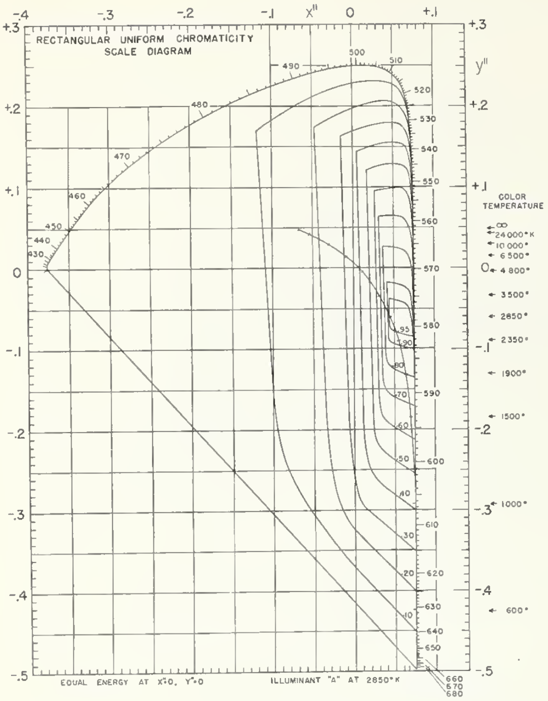


FIGURE 5–12. *Contours of maximum transmittance.*

The curves are contours of maximum possible transmittance for assumed source as computed by D. L. MacAdam [1935]. Source is at 2850 °K. These curves were computed by assuming 100 percent transmittance throughout one or two sections of the spectrum and zero transmittance for all other wavelengths. The original diagram in C.I.E. coordinates has been transformed to RUCS coordinates by Plaza.

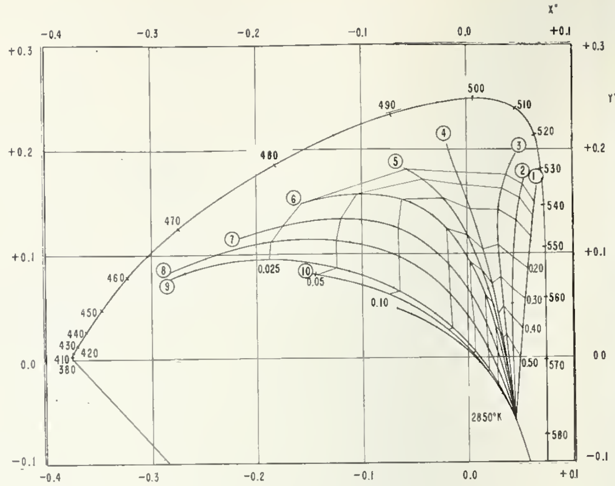


FIGURE 5–13. *Transmittance obtainable with blue and green glasses.*

The smooth curves which fan out from the point 2850 °K are the loci resulting from changing the thickness with the same type of filter. The irregular lines are contours of equal transmittance for the filters included. The diagram gives some indication of the maximum transmittance it is reasonable to expect for different chromaticities, but service glassware will have somewhat lower transmittances for the same chromaticities because of losses incidental to the designs. Types of glasses are shown in the following table by designation in use at the time the glasses were received at the Bureau.

Types of Glasses
Corning Glass Works Designations

1	G 401 CZ	7	Combination 2/3 thickness G 403 ED 1/3 thickness 552 PY
2	G 408 N		
3	G 408 F	8	Combination 1/3 thickness G 403 ED 2/3 thickness 552 PY
4	G 406 AY		
5	G 40 D	9	552 PY
6	G 403 ED	10	557

temperature to temperature. In both cases the curves differ from others of the same set in the wavelength region in which the cutoff occurs, and the effect of increasing the temperature of the filter is much the same as that of substituting a somewhat redder filter except that heating reduces the transmittance as well as moves the cutoff.

Figures 5–11a and 5–11b show the change in redness as measured by the y (C.I.E.) and y'' (RUCS) coordinates for the chromaticities of the six filters of figure 5–10 as a function of physical temperature. The light source is at 2854 °K. These figures include, in addition to the filters measured by Leberknight and Stone, two measured by K. S. Gibson [1916] and one measured by Holland and Turner [1941]. The filters are all selenium red glasses, which indicates that they are all sharp cutoff filters. Although some of the measurements used for these curves were published as early as 1916 and some as late as 1955, although some were made in this country and some in Great Britain, and although the glass of three different glassmakers was measured, the results are in substantial agreement. Glass of other colors changes slightly with temperature but not sufficiently to constitute a problem.

5.6. Relation of Transmittance to Chromaticity

All those variations which affect the chromaticity of a signal light also affect the transmittance of the filtering element and so increase or decrease the intensity of the signal.[19, 20] There are, moreover, limits to the transmittance which it is possible to obtain for any given degree of saturation in a selected hue. This is evident from the fact that the selective coloration of the light transmitted by the filtering element is obtained by absorbing the undesirable wavelengths. These limits have been computed by D. L. MacAdam [1935].[21] One of his fig-

[19] For similar information on glass made by a different manufacturer, see Holmes, [1937] and [1946].

[20] It has now been found, as was long suspected, that the luminous intensity of a colored signal light computed from the transmittance of the filter is not an accurate measure of the relative brilliance of the light as seen at long range. (See Middleton [1957] and Dressler [1953].)

[21] Later MacAdam [1950] extended his investigation of this problem to the case of the maximum attainable luminous efficiencies with any possible sources. He found these to be monochromatic sources or pairs of such sources in every case.

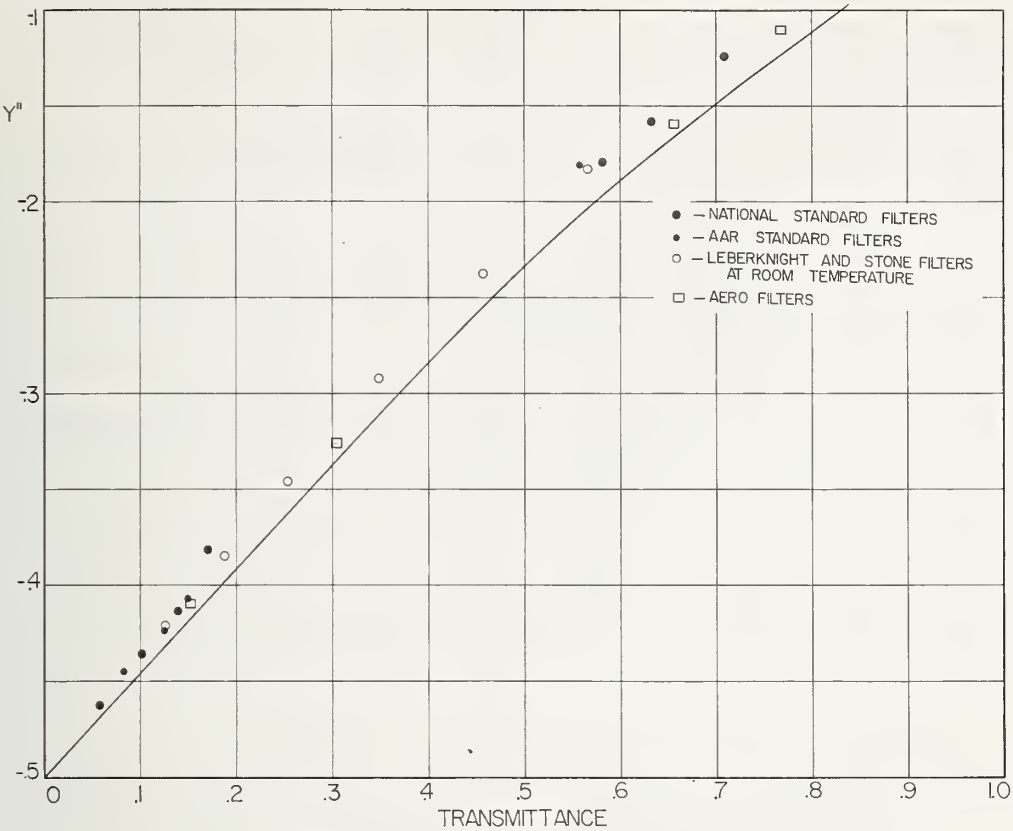


FIGURE 5–14. *Maximum and practical transmittance for red and yellow filters.*
The continuous line represents the theoretical limit of transmittance (T) as a function of redness as indicated by y''. Allowance has been made for surface losses of 0.08. The points marked by the several symbols represent actual filters of selenium glass.

ures, transformed into the RUCS system by Plaza,[22] is shown in figure 5–12. In practice the available transmittance is always somewhat lower than the theoretical maximum. Figure 5–13 shows the transmittances obtainable in different parts of the green and blue areas through the use of different types of glass in different thicknesses. These curves were computed for some of the same filters selected for figure 5–1.[23]

Figure 5–14 shows the relation of the transmittance to the y'' coordinate, representing redness, for typical selenium glass filters transmitting light from sources at 2854 °K color temperature. The closer y'' approaches -0.5, the redder the chromaticity represented. The theoretical limit for the maximum transmittance possible for each value of y'' with a light source at this color temperature is also shown on this diagram. The values for the typical filters are shown by open and solid circles. The reader can readily draw a curve to represent the maximum transmittances obtainable in practice for any desired redness. In using this curve as a basis for estimating the characteristics of glassware, a further allowance must be made for the differences between polished filters and practical filter ware, that is, for losses due to scattered light and additional internal reflections. This allowance may be more closely estimated when the transmittances of similar glassware of a somewhat different color are known, in which case it is only necessary to multiply the transmittance for the known ware by the ratio of the transmittances given by the curve for the desired and the known chromaticities. The ratios obtainable from this curve can be very useful in revising transmittance requirements to allow for changes in chromaticity requirements.

Figure 5–15 shows the variation of transmittance with the color temperature of the light source for typical filters of the more commonly used signal colors.

[22] Lorenzo Plaza, of the Institute of Optics of Madrid, assisting as a guest associate at the National Bureau of Standards.

[23] It is customary to consider that the transmittance determined spectrophotometrically can be used to determine range and apparent brightness (brilliance) of a signal light, notwithstanding the experience of signal-light engineers that red lights often appeared brighter than this assumption warranted. Middleton and Gottfried [1957] have made tests confirming the qualitative observations. A corresponding effect with large sources has been found by several investigators. For a review see Dressler [1953]. Another practical consideration is the differential transmittance of smoke and haze. See Breckenridge [1931].

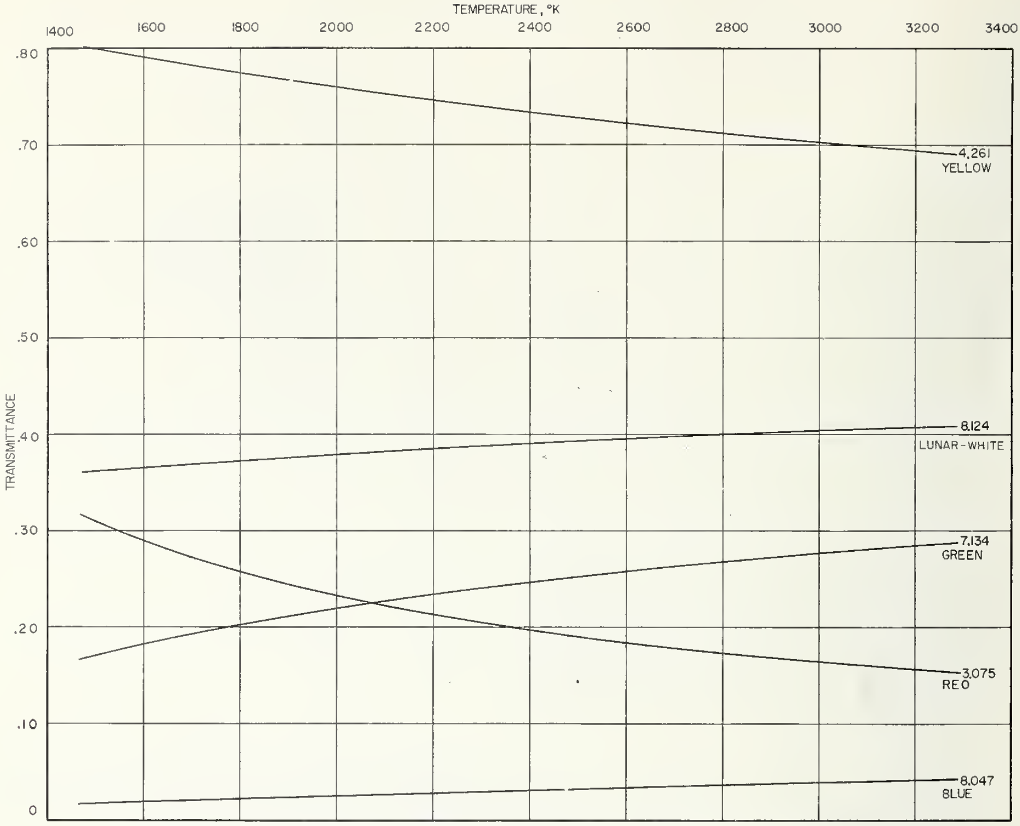
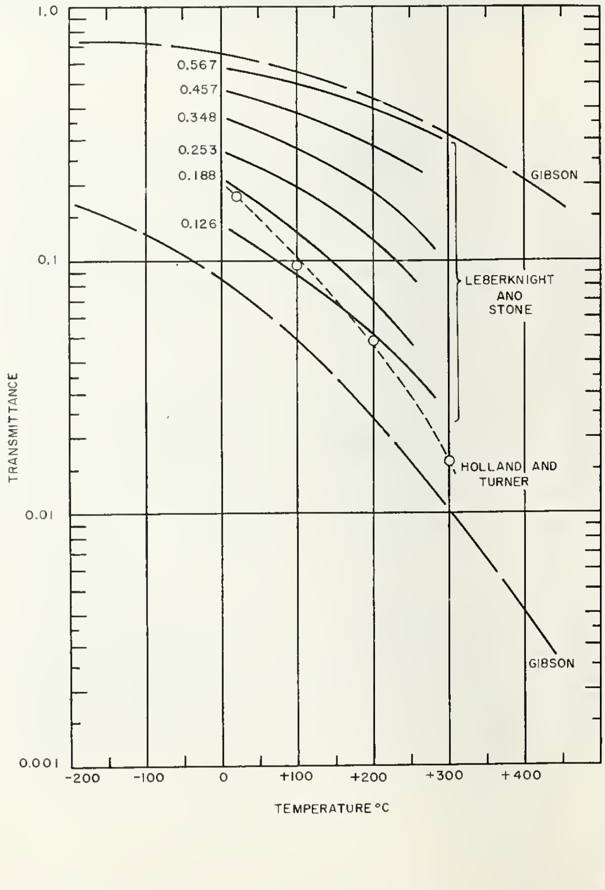


FIGURE 5–15. *Variation of transmittance with color temperature of light source.*

The figure shows the relationship between the transmittance (T) and the color temperature of the light source for five of the standard filters included in the U.S. Standard N.B.S. [1964]. It should be noted that while the blue, green, and lunar-white filters increase in transmittance with the increase in color temperature of the source, the red and yellow filters decrease.

FIGURE 5–16. *Effect of physical temperature on transmittance of selenium filters.*

The curves show the decrease in transmittance as the physical temperature of the filter increases. Three different researches are included. They are distinguished by the names of the investigators: Gibson [1916]; Holland and Turner [1941]; and Leberknight and Stone [1955]. The numbering of the curves is the same as in figures 5–10 and 5–11. The two sets of measurements made in the United States appear consistent, notwithstanding that Gibson made his measurements on Corning glass filters and Leberknight and Stone made theirs on Kopp glass filters. The results by Holland and Turner indicate a more rapid change of transmittance with temperature than was found by either of the other researches.



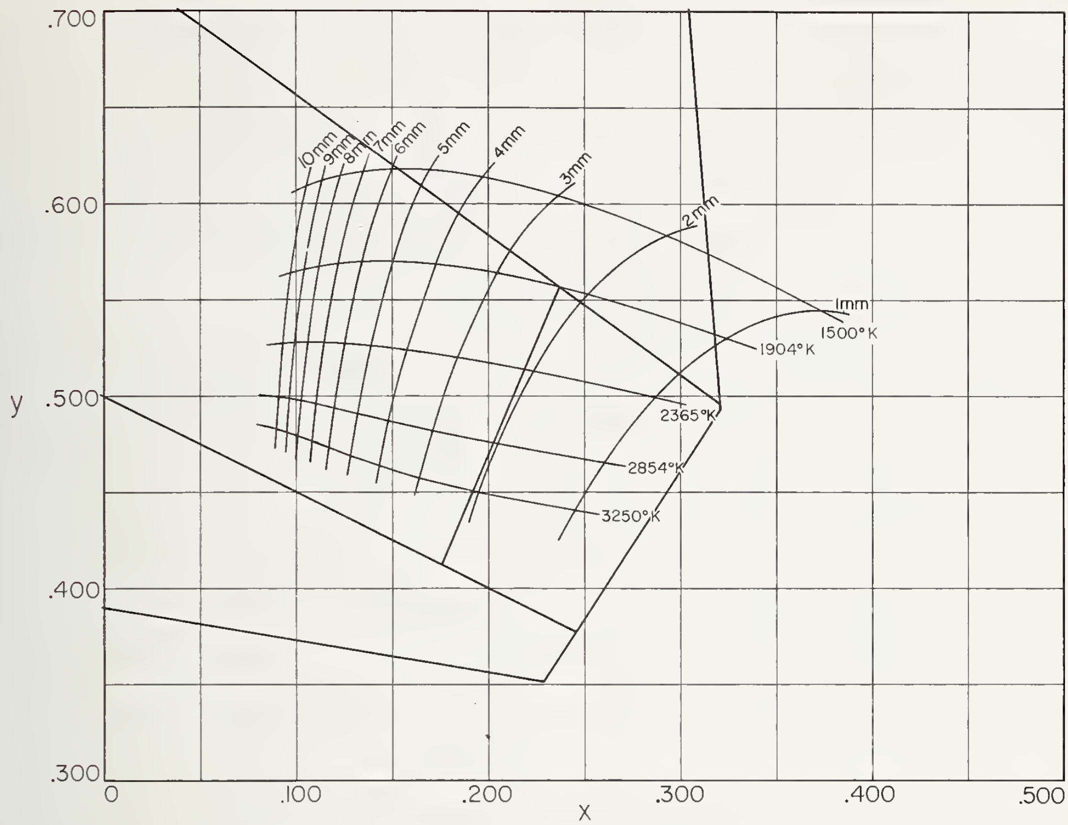


FIGURE 5–17. *Chromaticities of green plastic filters (C.I.E.).*

These curves correspond to those shown in figure 5–5. The more nearly horizontal curves (labeled with color temperatures) show the variations of chromaticity with change of thickness for the filter used with a light source of the color temperature indicated for each curve. The more nearly vertical curves (labeled with the thickness of the filter) show variations of chromaticity for changes of light source color temperature. The straight lines are chromaticity boundaries from the U.S. Standard, N.B.S. [1964].

5.7. Effect of Filter Temperature on Transmittance

The changes in the chromaticity of selenium filters with the temperature of the glass are accompanied by changes in their transmittances as shown in figure 5–16. The glasses for which values are given in these curves are the same filters for which the chromaticity characteristics are given in figures 5–11a and 5–11b. Some other types of filters show changes in transmittance with change of filter temperature but such changes are important only if the change of temperature amounts to several hundred degrees and the requirements are exacting.

5.8. Plastic Filters

Filters of any color required for signal lighting can be made of plastic material and spectral transmittance data are available for a few red, yellow, and green plastic filters. Unless care is taken to choose color-fast dyes, however, blue and green filters are liable to fade in service. Figures 5–17 and 5–18 show the chromaticities for light sources of color temperatures ranging from 1500 to 3250 °K for a plastic filter which has been found to have a resistance to fading that was adjudged satisfactory for use in a beacon cover. This same figure also shows the variation in chromaticity with thickness for this filter for all these light sources.

Red and yellow plastic filters are available with sharp cutoffs that give as high purity of color as is available in glass. Yellow filters are also available which have chromaticities very similar to those of carbon-yellow glass although the spectral transmittance characteristics are somewhat different. Some of these red and yellow filters are fluorescent which interferes with making reliable spectrophotometric measurements for them on some of the common types of spectrophotometers.

5.9. Gaseous Discharge and Fluorescent Lamps

Gaseous discharge lamps offer the possibility of obtaining signal-light colors without the use of filters although such lamps may also be used with filters to improve their chromaticity. Such lamps

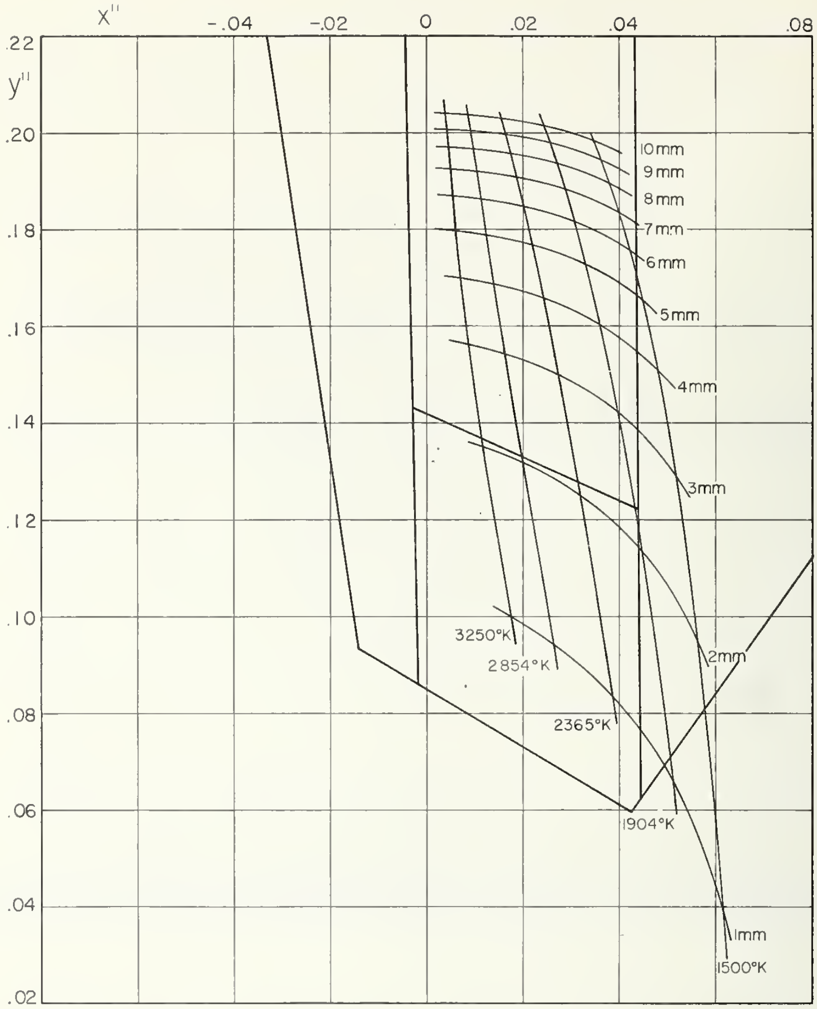


FIGURE 5–18. *Chromaticities of green plastic filters (RUCS).*
This figure is a transformation into RUCS coordinates of the curves shown in figure 5–17.

are sometimes assumed to have characteristic colors that are dependable. This is not an entirely safe assumption. The chromaticity of neon lamps varies with the pressure as indicated in figures 5–19a and 5–19b. When the lamps are new the pressures used in them are not normally low enough to give chromaticities paler than the limit allowed in the U.S. Standard [NBS 1964] and C.I.E. Recommendations [1955]. In use, however, the neon lamps decrease in pressure and this may cause the chromaticity to become paler than the specified limit.

In the case of discharge lamps which contain mercury, there may be a large change of chromaticity as the ambient temperature varies. At lower temperatures the vapor pressure of the mercury is reduced with consequent decrease in the intensity of the mercury spectrum while the spectral distribution of the light from any rare gases in the lamp is little affected by the change in temperature.

Similar difficulties have been experienced with sodium lamps which contain neon. At low temperatures the sodium is not volatilized and the neon gas which is used to start the discharge contributes most of the light. At such temperatures, the light is nearly red enough to meet the definition of aviation red. When the lamp is fully heated the color is slightly redder than the sodium *D* lines. One lamp measured at the National Bureau of Standards was found to have a chromaticity approximating $x=0.578$, $y=0.422$ ($x''=+0.075$, $y''=-0.160$) which would make it an acceptable yellow under any of the signal-color specifications in common use in the United States.

Fluorescent lamps are seldom used as signal lamps because of their low luminance. Figure 5–20, however, shows the chromaticities for a number of common types of fluorescent lamps. To distinguish those lamps which lie within the boundaries of the U.S. Standard [NBS 1964] the boundaries for the signal colors are also shown.

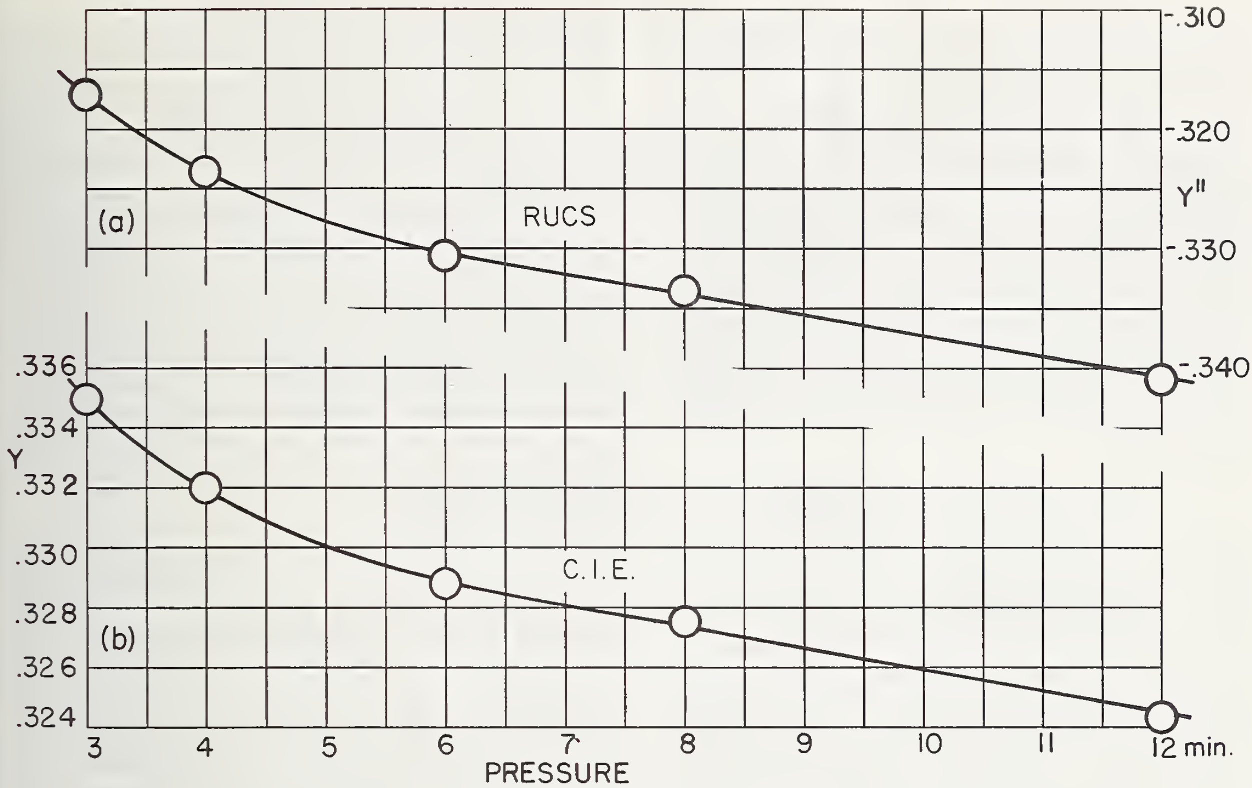
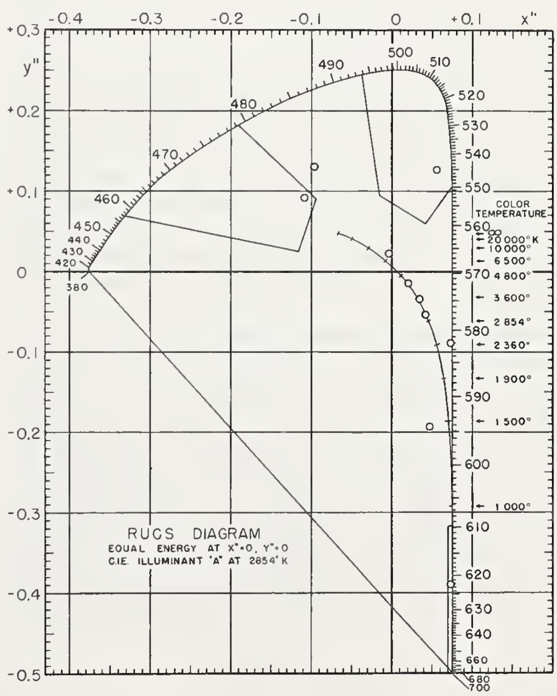


FIGURE 5–19. *Chromaticity of neon lamps.*

The curve shows the variation in the chromaticity in a group of neon lamps which had been filled with different pressures by the manufacturer. There was no way to determine how accurately the pressures had been measured. Inaccuracies in adjusting the pressures to the nominal values indicated may account for the irregularities in the values plotted. The pressure is expressed in mm of Hg. (a) Redness indicated by y'' (RUCS). (b) Redness indicated by y (C.I.E.).

FIGURE 5–20. *Chromaticities of fluorescent lamps (RUCS).*

The circles show chromaticities obtainable with the use of commercially available fluorescent lamps, plotted in RUCS coordinates. Additional chromaticities are obtainable with mercury, neon, and the sign-lighting type of lamps. Those shown in the figure along the Planckian locus are known as daylight, cool-white, white, and warm-white. Those with more saturated colors are blue, deep-blue (it is nearer the spectrum locus), green, gold, pink, and red.



6. Control of Signal Colors

6.1. Selection of Standards

In addition to making sure that specifications and regulations controlling signal-light colors describe colors which are recognizable and which may be produced in service with practicable means, it is also essential to be certain that the requirements be such that they may be applied most effectively in the various situations for which they are intended. Usually the control of signal-light colors involves the use of chromaticity standards which are represented by filters in combination with stipulated light sources.

6.2. Types of Color Standards

Most of the signal-light applications have so much in common that it is possible to have a single set of filters which, with a light source of 2854 °K, can be used as national standards for most purposes. A set of 18 such national standards is now in process of adoption. Fourteen suitable glasses are available among the thirty filters which the Signal Section of the Association of American Railroads adopted between 1931 and 1935.[24] The chromaticity characteristics for the other four have been approximately defined, but glasses have not yet been selected. All of the national standards have been checked in relation to the basic chromaticity definitions and found satisfactory.

The national standards [25] have been selected to provide for the colors that are at present required by more than one organization. There are a few other applications such as those for which the railroads use lunar white, and perhaps the walk signals used at pedestrian crossings, which did not appear to be sufficiently general to warrant the establishment of national standards. Provision is made in the U.S. Standard for the Colors of Signal Lights [1964] for organization standards to meet these needs. Organization standards must be checked against the basic chromaticity definitions to make sure that the signals will remain within these definitions under all the conditions of use.

Neither the national standard filters nor the filters of organization standards are available for inspection purposes. Duplicates are required for such purposes and the U.S. Standard provides for such duplicates by establishing tolerances for them.

Even the duplicates are likely to be considered too valuable for routine operations, and manufacturers and laboratories will generally make their own duplicates for use as working standards. No standard tolerances have been provided for these since they are solely the responsibility of the manufacturers.

[24] See Association of American Railroads [1953].

[25] For the status of national standards see McNish 1958.

6.3. Inspection Testing

The final step required to assure that the signal colors conform to the selected standards is the inspection testing of the equipment. This inspection may be made on completely assembled equipment, but more often it is made on the filtering element, for example, on a piece of glassware or a plastic cover. In either case the problem is to compare the light from the unit, or the light transmitted by its filter, with light from a source of known color transmitted through a duplicate standard and to decide from that comparison that the light from the unit is, or is not, within the specified chromaticity limits.

Several researches have been carried out to develop a photoelectric colorimeter for this purpose. The objective was to build an instrument which would give a direct reading of the chromaticity coordinates for the light intercepted by the meter. Few, if any, colorimetric laboratories have such equipment today. At this time, we know of no manufacturer who has an instrument of this type that is suitable for use on routine inspections. It would appear practicable to design photoelectric equipment that could be adjusted to distinguish between acceptable and unacceptable ware made with a predetermined colorant, but such equipment is not yet available.

An instrument has recently become available which measures small color differences photoelectrically and which is proving useful for some inspection purposes. Unless such instrumentation is available, visual comparisons must still be relied upon.

Since visual comparisons must be used for carrying out inspection tests, it is important to take into consideration the types of comparison which can be made by the usual inspector. These comparisons are limited to discriminations of hue, saturation, and brightness. In view of this, it is essential to draft specifications so that only direct comparisons of hue and saturation are required in testing equipment for conformity with the chromaticity requirements. Specifications worded in this manner are most easily correlated with basic chromaticity definitions if the boundaries of these definitions are lines of constant hue and saturation.

The practical problem of inspection is greatly simplified if there is a requirement in the specification that the chromaticity characteristics be similar to those of a standard filter. This type of requirement is discussed in sec. 8.

6.4. Laws and Regulations

A somewhat distinct problem in the control of signal-light colors arises in connection with laws and regulations. These are usually written in terms of color designations that are defined in technical Standards. To be suitable for such legal citation the Standard must define the signal as observed by the user, in order to be impartial, and this definition must be stated with sufficient precision to avoid any significant uncertainty of interpretation.

As has been mentioned in sec. 2.5, the application of laws and regulations to the performance of signal-light units involves the same procedures as the inspection of ware on procurement. Whether the enforcement is by an inspector on the staff of the regulatory authorities, or by an inspector in the employ of the manufacturer, his basis for acceptance or rejection will be similar to that in a procurement transaction, that is, it will be a comparison of light from a test piece with light of known chromaticity. For this reason the same principles apply to the choice of boundaries for chromaticity definitions underlying laws and regulations as in setting up procurement specifications. In this case, however, there is more likelihood that no standard having chromaticity characteristics [26] similar with respect to the test item will be available, and the visual comparison may have to be made with a greater chromaticity difference than is commonly encountered in the inspection of purchased filter ware. This makes it even more necessary that the type of judgment required be one of hue or saturation.

7. Chromaticity Boundaries

7.1. Selection of Boundaries for Chromaticity Definitions

Chromaticity boundaries are involved in two ways in the control of signal-light colors, in the basic chromaticity definitions and in the tolerances for the duplication of standard filters. The problems are essentially different in these two applications. The basic definitions will be considered first.

As in the case of signal color specifications as a whole, it is essential that the chromaticity definitions in particular be so designed that they not only describe chromaticities that can be dependably recognized and can be practicably produced, but also that the boundaries differentiate between acceptable and unacceptable chromaticities in ways that afford the most prospect of positive differentiation in practice. These definitions are used mainly for three purposes, namely: (1) the control of color standards; (2) the inspection of filter ware; and (3) the application of regulations.

For the selection of standards, any positively defined lines in a coordinate system that can be computed from spectral transmittances will suffice because standard filters are regularly tested either by spectrophotometry or differential colorimetry, both of which methods of measurement provide the chromaticity coordinates of the filter source combination.

The inspection of ware and the enforcement of regulations, on the other hand, usually involve visual comparisons and the only such chromaticity judgments that can be directly made are those of hue and saturation. It follows that reliable judgments with reference to whether a difference indicates a chromaticity inside, or outside, of the chromaticity definitions can only be made if the definition boundary is a line of constant hue or constant saturation.

7.2. Constant Hue Boundaries

It was stated in sec. 3.4 that the C.I.E. and RUCS diagrams are color-mixture diagrams with pure spectrum colors situated along the curved outside boundary and white located somewhere in the center. The selection of the white point, which is technically known as the heterogeneous stimulus, should properly be determined by the conditions of observation. In developing the RUCS diagram, the equal-energy point, that is, the point representing a mixture of all visible wavelengths in equal parts, was selected as the white point because it is centrally located among the points usually advocated as desirable white points and also because it is easily defined. For signal-lighting purposes it might be preferable to use a point corresponding more closely to the color temperature of the lights which are most commonly seen at night, but the difference between the equal energy point and the point representing 2854 °K, for example, produces no difficulties that are serious so far as present requirements are concerned.

It was pointed out in sec. 3.4 that in any mixture diagram all the points lying between two points on a straight line through them represent chromaticities that may be produced by adding light of the chromaticities represented by the two selected points. It follows, therefore, that all the points on a line from the origin in the RUCS diagram through any point on the spectrum locus represent chromaticities which may be produced by adding white light to the spectrum color represented by the point on the spectrum locus. Such a line is a line of constant dominant wavelength and one would expect it to be a line of constant hue. This is approximately true.

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[26] See NBS Hanhbook 95, p. 2, sec. 2.11 [1964] and chapter 8 of this Monograph.

Newhall, Nickerson, and Judd [1943] have determined lines of constant hue from the spacing of elements in the Munsell uniform color space and D. L. MacAdam [1950, 51] has made a direct determination. While both of these determinations show some curvature, the departure from straight lines is not greater than the uncertainty of applying determinations made with surface colors to the case of signal lights. In view of this and the lack of standard definitions for constant-hue lines, there would seem to be little advantage in complicating a specification to allow for the difference between the straight and the curved lines.

7.3. Constant Saturation Boundaries

On a uniform chromaticity diagram which faithfully represented chromaticity differences for given conditions of observation, the loci of constant saturation would be circles having the white point, or heterogeneous stimulus, as center. If circular arcs on the RUCS diagram were adopted as saturation boundaries for the basic chromaticity definitions, the corresponding boundaries on the C.I.E. system would be ellipses. Since the C.I.E. system is the only one recognized as standard at the present time, and ellipses are too difficult to apply as criteria in practical problems, it is necessary to use the chords of elliptical arcs to express boundaries that approximate boundaries of constant saturation on the C.I.E. diagram. Transformed to the RUCS, these lines become chords of circular arcs concentric with the origin.

7.4. Comparison of Rational and Adopted Boundaries

Figure 7–1 shows a comparison of the boundaries of signal-light colors as defined in the C.I.E. Recommendations [1955] and the U.S. Standard [NBS 1964] with a system of radial and chord boundaries on the RUCS diagram. The radii and chords of this figure may be considered as lines approximating constant hue and constant saturation, as described in the discussions of secs. 7.2 and 7.3. In addition, four of these radii have been evenly spaced, since it is plausible to assume that optimum boundaries for signal colors can be constructed from such lines if the RUCS diagram is uniform in its chromaticity spacing. To construct this diagram, line (A, A') was drawn from the red terminus of the spectrum locus at $x''=+0.075$, $y''=-0.500$ through the origin and prolonged to intersect the spectrum locus in the upper left quadrant. This is a significant line on the RUCS diagram because it is both a line of constant dominant wavelength and close to a locus of confusion for the protanopic type of colorblindness. The angle between (AA') and the $-X''$-axis has been bisected to obtain (BB'), and this line has been reflected about AA' to obtain

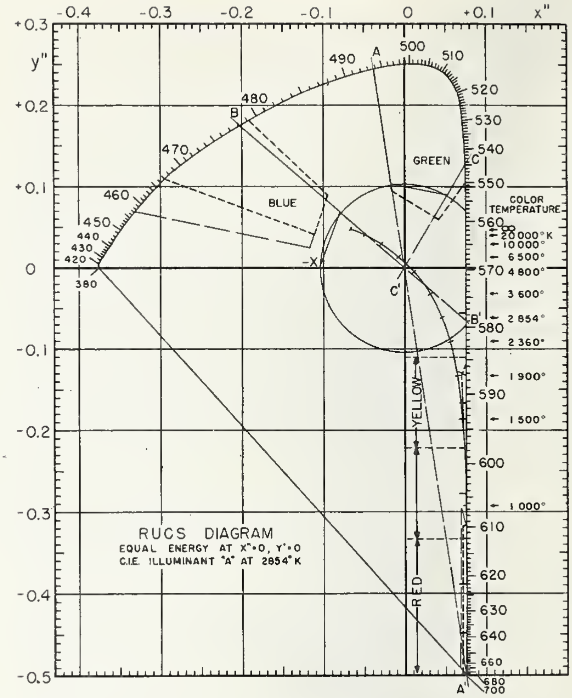

FIGURE 7–1. *Comparison of rational boundaries with those of the U.S. Standard.*

Figure 7–1 shows a comparison of boundaries for signal light colors as defined in the C.I.E. Recommendations [1955] and the U.S. Standard, N.B.S. [1964] with a system of radial and chord boundaries on the RUCS diagram. The construction of the diagram is explained in the text. It is intended to show that there is a general approximation between the spacing of chromaticities in the RUCS diagram and that to be expected if the limits of the C.I.E. Recommendations and U.S. Standard are accepted as representing optimal signal colors. The absence of signal colors in the lower left hand quadrant is explained by the lack of filters giving such chromaticities.

(CC'). Designating the origin as O, this makes $\angle X''OB=\angle BOA=\angle AOC$. The chords were drawn through the points in which an arc centered at the origin intersected the hue boundaries ($-X''O$, BO, AO, and CO). The radius of this arc was made equal to the mean distance from the origin to the four inner corners of the C.I.E. blue and green regions.

7.5. Boundaries for Blue and Green

A comparison of these rationally constructed boundaries (sec. 7.4 and figure 7–1) with those which have been adopted on the basis of research and experience shows that in the blue and green regions there is a considerable degree of correspondence between the rational and the recommended boundaries. The coincidence of the blue boundary recommended for green with the line through the red terminus may be accidental. The blue boundary of green was, however, intentionally displaced towards the blue to make it possible to use green signals that can be differentiated from red and yellow signals by red-green colorblind observers. The similarity of the rational divisions to the chromaticity boundaries of the C.I.E. Recommendations and the U.S. standard in the blue and green regions favors the use of a uniform-chromaticity-scale diagram, such as the RUCS diagram, for studying the chromaticities of such signals.

7.6. Boundaries for Red and Yellow

Returning to figure 7–1, it is seen that the boundaries for yellow are displaced clockwise and the boundaries for red counterclockwise from the sectors opposite the blue and green. This places both the red and yellow in the sector opposite the gap between blue and green. The displacement of the yellow is reasonable in view of the fact that the spectrum locus in the region opposite the blue, which should have been selected on the basis of equal arcs, is too close to the white point to be acceptable as a color distinct from white. The sector opposite the green, on the other hand, is characterized by much lower transmittances and saturations than are obtainable in the long wavelength region.

From the fact that both recommended red and recommended yellow lie in the same sector, it appears that the discrimination is not made on the basis of hue angle alone, and that the linear distance of separation on the RUCS diagram rather than the angle may be the basis for the recognition of these colors. Since the acceptable regions here lie so close to the spectrum locus, we may take distance along the line $x''=+0.075$ as a possible basis for assigning boundaries to red and yellow. In figure 7–1 the rational boundaries in the yellow-red quadrant have been drawn by dividing the spectrum locus in this quadrant into nine equal parts. Two-ninths have been allotted to yellow and two-ninths to each of the unused sectors on both sides of yellow, leaving three-ninths for red. This extra allotment to red may be, to some extent, justified by the fact that the longest wavelength portion of the red allotment is not serviceable for some red signals because it cannot be produced wth a transmittance sufficient for use where long-range visibility is important. As in the blue and green regions, the similarity of the rational divisions of the RUCS diagram to the chromaticity boundaries of the C.I.E. 1955 Recommendations is sufficient to indicate that the RUCS diagram is an advantageous one for studying the chromaticities of light signals.

The unused sector along the spectrum locus from the yellow limit of green to the X''-axis is approximately equal to the unused sector between the X''-axis and the green limit of yellow. This makes the total gap between green and yellow twice that between yellow and red. As we have just observed, however, this long gap is required because the spectrum locus in this region is so close to the Planckian locus that both can not be used to represent distinct colors, and the chromaticities of the Planckian locus are those of the lights regularly used as white signals.

Having considered the hue limits of red and yellow on the basis of their extent along the spectrum locus, it remains to complete the boundaries of these colors. To extend the paler hue limits towards the white point is to include chromaticities that are paler than some chromaticities these limits exclude at the spectrum locus. It seems desirable, therefore, that the boundaries from these points should follow loci of constant saturation. A possible way of completing each of these areas in a manner somewhat analogous in form to that of the green and blue areas would be to follow arcs having their centers at the origin until these arcs intersect radii from the origin through the second hue limits. This would cause the yellow area to include the chromaticities of lamps incandescing at low voltage. From the standpoint of producibility there is no need to include these chromaticities in the yellow region. For any system which includes a white signal, it is advantageous to limit the yellow to a narrow band along the spectrum locus. In the case of red lights, an area defined by an arc of minimum saturation through the pale hue limit and a radius through the reddest chromaticity visible would include chromaticities which, according to Hill's results shown in figure 4–9, are much less dependable than those closer to the spectrum locus. On the other hand, it is quite practical to close the red and yellow areas with boundaries approximately parallel to the spectrum locus which is the direction of the natural chromaticity variations of the glasses used. The C.I.E. green boundary of yellow and yellow boundary of red do extend somewhat inward on lines directed towards the white area but since this is not necessary to secure adequate transmittances, the U.S. Standard uses lines approximating constant saturation for these boundaries.

7.7. Boundaries for White

White lights are commonly lights without filters, so that the chromaticity definitions for white lights usually follow the Planckian, or blackbody, locus. This suggests a definition for white in the form of a maximum permissible departure from the blackbody locus. It appears feasible to accomplish this in the C.I.E. system by a tolerance in y alone. When such a tolerance is transformed into RUCS coordinates, however, it is evident that the boundaries are far from uniform tolerances. The U.S. Standard [NBS 1964] has tolerances expressed as functions of x and y, and it is a region of fairly uniform width in RUCS which does not actually overlap the yellow region.

There is another type of white light which requires pale blue filters if the source is an incandescent lamp. These are called "lunar white" or "blue white" lights. Since they require filters, it is frequently desired to compute their chromaticities from spectrophotometric data. Curved boundaries are unsatisfactory in this case because of the undue amount of computing which may be required to find out whether the chromaticity is inside or outside the chromaticity definition. In this region, also, the Planckian locus is much less curved than in the region of the unfiltered white lights. For these reasons, it is both desirable and feasible in this region to use a narrow quadrilateral as a boundary.

The U.S. Standard for the Colors of Signal Lights [NBS 1964] uses straight boundaries for lunar white and blue white since these require filters and curved boundaries based upon the blackbody locus for beacon white and variable white. The International Commission on Illumination [1955] and the International Civil Aviation Organization [1964] solve the problem by using complex straight-sided figures allowing rather large departures from blackbody chromaticities in some regions in order not to limit the departure too severely in other regions. The problems encountered in distinguishing yellow from white will be discussed in sec. 10, "Use of Signal Light Colors."

7.8. Mathematical Simplicity

In the past, specification writers have shown a preference for limits that were easily expressed in the C.I.E. system, as for example, $x=$constant. This is quite reasonable as long as no reason for prefering other limits is known, but the consideration of mathematical simplicity seems entitled to little weight in comparison with the importance of having the limits follow lines representing sequences of colors which an inspector can recognize; that is, the chromaticities on one side of the boundary should differ from those on the other in some common, recognizable respect.

In another sense mathematical simplicity is a sound principle. The direction and location of a boundary having been determined in accordance with the general principles discussed above, the equation used to define the boundary should not be expressed with more significant figures than are warranted by the precision with which the facts are known. On the other hand the use of equations that are not reduced to mathematically simplest terms may be warranted if by their use it is possible to make it clear that the equation passes through a particular point of interest.

7.9. Relation of Chromaticity Boundaries to Primary Limit Standards

In approving primary standards, the laboratory concerned must consider the use to be made of these standards. If they are to be used to test duplicates by direct colorimetric comparison with a visual instrument, the primary standards should be far enough within the boundaries as to insure that the duplicates in turn can be used by direct comparison to keep the ware within those boundaries. Color standards may, of course, be located even further inside the basic chromaticity definitions if it is deemed advisable to restrict the chromaticity of the signals controlled by these standards to something less than the entire range permitted by the definition.

7.10. Boundaries for Duplicates

Boundaries for tolerances are quite a different problem from those for basic chromaticity definitions. Although duplicate filters are frequently tested visually, this testing is done with colorimeters designed to give precise values for the color differences between the filters being compared. For this reason, it is not important that the boundaries of these tolerances follow lines of constant hue and saturation.

It would be logical and quite simple to assign tolerances for duplicate filters by requiring that the chromaticity coordinates for the duplicates, expressed in the RUCS system, fall within a fixed radius of the point representing the chromaticity of the primary standard. It is not at present practicable to do this, however. The calibration of the existing colorimeters used for this work is in terms of C.I.E. coordinates and their immediate recalibration in RUCS would be a considerable task. More than this, the duplicates must sometimes be ground a number of times to bring them within the tolerances, and the increase in the complexity of the calculations involved in checking glasses for compliance with circular tolerance areas would not be offset by any advantage to be gained from excluding the corners of rectangular tolerance areas.

A. J. Werner[27] has developed a rational method of constructing tolerances for duplicates. When the glass for duplicates is ground to meet a tolerance, the chromaticities of all the ground filters will be found to lie on a curve which is approximately parallel to that generated by the chromaticity of the primary calculated for various thicknesses (see fig. 5–4). Werner proposed to make the slope of two sides of the tolerance parallelogram parallel to the tangent to the locus for the primary filter at the point representing the primary itself. The spread between the curves for glasses from different melts, all of which represent good practice in the reproduction of the original melt, determines the separation of the long sides of the tolerance. If the tolerance area lies close to a boundary for a basic chromaticity definition, its other two sides may be made parallel to that boundary. Making these sides parallel to the boundary may facilitate the inclusion of the necessary area within the tolerance without encroaching too close to the boundary.

[27] Unpublished memorandum prepared in connection with the revision of Specification 59–39 (now 59–61), Signal Section, Association of American Railroads. For further information consult Mr. A. J. Werner, Corning Glass Works, Corning, New York.

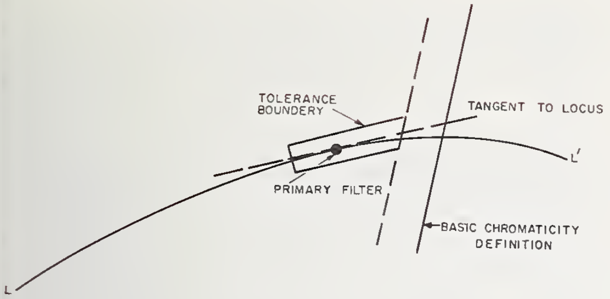

FIGURE 7–2. *Illustration of filter tolerance.*
The diagram shows the relationship of tolerance boundaries to the chromaticity of the primary filter and the locus of chromaticities for filters made from the same type of material but differing in thickness, *LL′*.

Such a tolerance area is illustrated in figure 7–2. In this figure *LL′* represents the locus of a primary standard filter. The straight lines represent a tolerance area constructed in accordance with Werner's proposal as used for specifications of the Association of American Railroads and subsequently adopted for tolerances in the U.S. National Standard [NBS 1964].

Another construction, preferred by the author, is to make the slope of the ends approximately perpendicular to the sides when this is feasible. This construction gives the most compact area practicable. The distance between the ends of the parallelogram is determined by the accuracy within which the optimum thickness may be approximated, which, in turn, is determined by the difficulties of computing and grinding. The size of the tolerance required varies from primary to primary according to the closeness with which melts can be duplicated and the precision with which thickness may be adjusted.

Since chromaticity differences are more easily measured to the accuracy required in duplicating tolerances than chromaticity coordinates are, it is preferable that the tolerances be expressed in terms of the differences between the chromaticity of the primary and that of the duplicate rather than as equations in the coordinates themselves. This, however, need not prevent the use of tolerances in accordance with the principles outlined above.

8. Requirement for Chromaticity Characteristics Similar to Standard

8.1. Purpose of Requirement

It is evident from the purpose of standard filters that their selection is primarily controlled by the basic chromaticity definitions, but since it has been pointed out in sec. 5 that both the chromaticity and the intensity of a light depend not only on the colorant in its filter but also on the filter's thickness, the color temperature of a light source and, in some cases, the physical temperature of the filter, the variation of these factors must also be taken into account. In the case of green filters especially, and to a lesser extent in the case of blue filters, the chromaticity variations caused by changes in the source are at substantial angles on the diagram with those caused by changes in thickness, or in colorant concentration, with the result that the total variation caused by both covers an area on a chromaticity diagram. This was illustrated in figures 5–5 to 5–8.

If a change is made in the colorant, the area of utilized chromaticities will be changed, and even though the original standards had been carefully checked to make certain that ware of the same colorant would stay within the basic chromaticity definitions for all the anticipated conditions of use, the ware with the changed colorant might produce signals outside of these definitions. A requirement to prevent the acceptance of improperly colored ware is an essential part of a dependable specification.

A change of colorant may also make a satisfactory inspection impossible. So long as the chromaticity differences in ware are such as can result from changes in the thickness of the ware, the variations in chromaticity will be such that they may be represented on a chromaticity diagram by a smooth curve such as the broken curves in figures 8–1 and 8–2. It is a simple task for an inspector with normal eyesight to compare the chromaticities produced by the members of a group of filters which vary in this manner with a pair of standard chromaticities located on the same curve and determine that the tested chromaticities are within, or outside of, the acceptable segment of chromaticities. If the colorant used in the inspected ware is identical with that used for the standard filters, or if it is a satisfactory equivalent, the curve of chromaticity variation will pass through the points which represent the chromaticities of the color standard. If the colorant used in the inspected ware gives rise to a curve of chromaticity variation slightly displaced but parallel to the curve for the color standard, the inspector is still able to make satisfactory judgment and this material should be considered a satisfactory equivalent for that used in the standard filter. If, on the other hand, the curve of chromaticity variation is considerably displaced from that of the standard filter, for some thicknesses of the ware, it may be impossible for the inspector to arrive at any satisfactory judgment. A requirement to assure that the material submitted can be inspected with the standard is therefore an essential part of a dependable specification.

In addition to these two reasons for restricting the chromaticities more strictly than the basic chromaticity definitions alone would restrict them, a third reason arises from the fact that these defini-

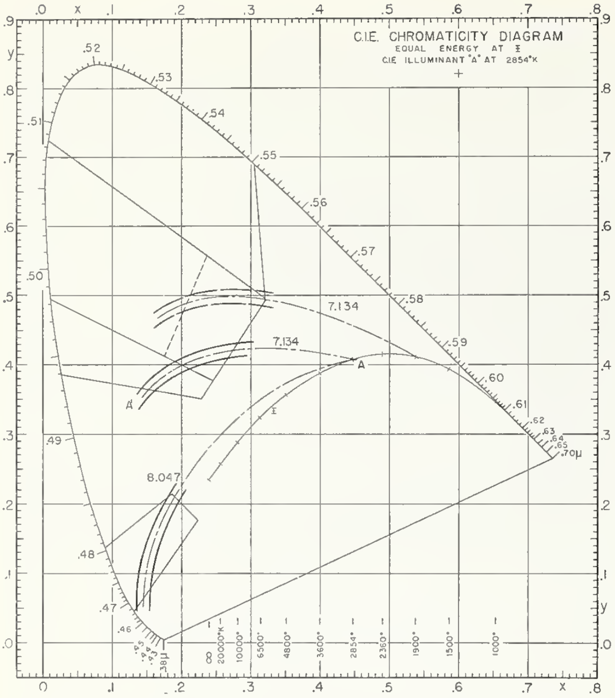

FIGURE 8–1. *Similar chromaticity characteristics (C.I.E.).*
The figure shows the limits allowed in the U.S. Standard, N.B.S. [1964] for similar chromaticity characteristics in the case of national green standard No. 7.134 and national blue standard No. 8.047. The green standard is shown for light sources of two color temperatures, 1900 °K and 2854 °K, but in the case of the blue only the limits for 2854 °K are shown because the curves would overlap each other so much as to produce a confused pattern.

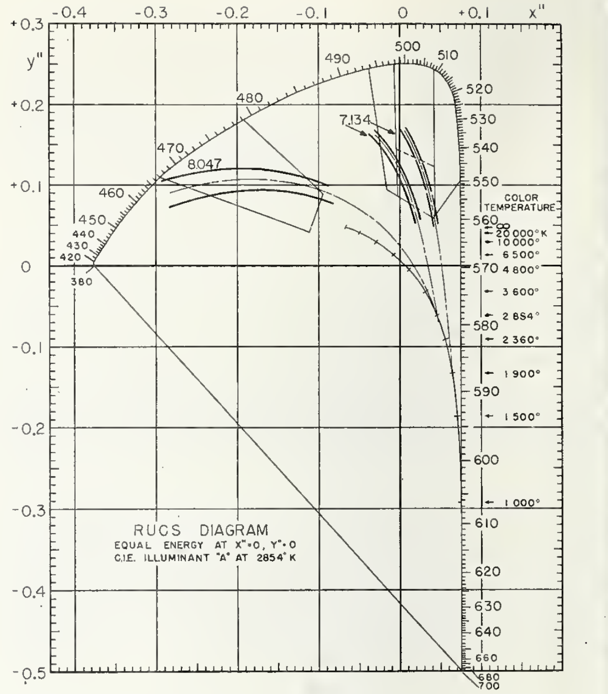

FIGURE 8–2. *Similar chromaticity characteristics (RUCS).*
This diagram shows the same data as figure 8–1, transformed into the RUCS system. It is evident from this figure that the blue is less closely controlled than the green notwithstanding that in the C.I.E. diagram the blue and green tolerances appear about equal.

tions which are intended only to restrict the colors used to those that may be relied upon under usual circumstances, necessarily accept a considerable range of chromaticities. A purchaser who has been accustomed to receive material of one type might well feel he has been provided with an inadequate specification if, upon receiving filters of a noticeably different type, he finds he has no grounds for rejecting the new material. If a producer is able to improve his product, or finds that efficient production requires a change in his colorant, he should inform his customers and arrange for the change of product upon the basis of new standard filters.

The requirement that ware have similar chromaticity characteristics to those of the standard filter cited in the specification was developed for the three reasons outlined above. It is designed to limit the chromaticity characteristics of the product furnished without introducing unnecessary restrictions on the physical characteristics, or chemical constitution, that might add to the cost by restricting competition or that might retard improvements which did not change the color characteristics.

8.2. Statement of Requirement

In the U.S. Standard for the Colors of Signal Lights [NBS 1964] the similarity requirement is stated as follows:

Similar Chromaticity Characteristics

A light-transmitting material has chromaticity characteristics similar to a standard material for a given light source over a stated chromaticity range if the chromaticity coordinates, within that range, of the light from the given source transmitted by any thickness of the standard material can be duplicated within stated tolerances by the chromaticity coordinates of the light from the same source transmitted by some thickness of the subject material. As used in this Standard and in specifications based upon it, the phrase "similar chromaticity characteristics" will be understood to include the range of illuminants to be used with the light-transmitting material in service, and the chromaticity range extends from the chromaticity of the applicable pale limit to that of the second hue limit, or to the chromaticity of such thickness of the subject material as has the minimum acceptable transmittance, whichever gives the lesser range. In this Standard the range of illuminants is that specified in Part II, Table II–1; the minimum transmittance is that stated in Table II–2; and the tolerance is that given in Table II–3.

8.3. Effect of Requirement

Figures 8–1 and 8–2 illustrate this requirement by showing the area within which the chromaticity must remain to qualify green signal ware as conforming to the definition for similar chromaticity characteristics with respect to the pale limits indicated. The figures show the application of the definition with respect to a green pale limit for illuminants at 1900 °K and 2854 °K and for a blue pale limit for the illuminant at 2854 °K. As stated in the definition, the test is applied only for the range of illuminants and chromaticities which may be involved in the use of the ware to be delivered in fulfilling the order or orders which are being inspected.

As already pointed out, the advantages of this requirement are so considerable from the standpoint of both inspection and service as to warrant the drafting of purchase specifications for signal ware to require ware having chromaticity characteristics similar to those of the pale-limit and transmittance-standard filters adopted to control the purchases. If a purchasing agency finds that such a restriction limits the competition unnecessarily, then it is possible to adopt two or more alternative sets of standard filters. Experience to date suggests that this will rarely, if ever, be necessary. The additional standard filters, if required, should be obtained from prospective bidders who are not satisfied with the existing standards. The requirement for similar chromaticity characteristics places no burden on manufacturers who have produced acceptable material so long as such manufacturers do not change the chromaticity characteristics of their ware. When they do desire to make such a change, and when a new bidder offers ware, an analysis of the chromaticity characteristics of the new colorant is necessary to allow the effects of the change to be evaluated. Moreover, since the manufacturers who have established the characteristics of their ware have presumably already furnished standard filters to customers who regularly purchase from them, or to inspection agencies which inspect the ware for them, it is equitable to require new bidders to furnish at least a pair of filters for each color. Preferably a bidder should submit duplicate filters, one of which would be returned for his guidance and the other held by the purchaser for inspection purposes. That no more difficulty has been experienced in the past in checking the chromaticities of glassware must be attributed to the fact that manufacturers have adhered quite closely to material that was similar in its chromaticity characteristics to existing pale-limit standards or to samples submitted to customers.

8.4. Application to Plasticware

Plasticware should be required to meet the same specifications for similarity of chromaticity characteristics as glassware although the requirements may be based upon different standards. Thickness in this case is likely to offer little difficulty because it usually varies much less than in the case of glassware. Changing the color temperature of the source can cause the chromaticity of a sample to depart from that of the standard by more than the allowable amount, but since the variation in thickness is likely to be less than with glass, variations from changes in source color temperature should be easier to keep within the basic chromaticity definition. This is because the chromaticity limits can be more favorably located within the area allowed by the chromaticity definitions. Information on the variability of dyes from mix to mix is unfortunately not available. It would be of considerable interest.

9. Instrumentation

9.1. Chromaticity Measurements

The measurement of signal-light chromaticities is carried out, for the most part, on the same principles as other color measurements. When spectrophotometric measurements are to be made, the measurements are made with photoelectric spectrophotometers and the results are evaluated with the use of accepted mathematical functions. Such measurements are regarded as free from subjective estimates. On the other hand, nearly all direct colorimetry of signal lights is carried out with visual instruments which depend upon visual estimations. In general, the photoelectric colorimeters which have been developed for the measurement of surface colors are not satisfactory for use in measuring the colors of the light transmitted by signal ware. The lack of suitable photoelectric instrumentation is partly due to the difficulties inherent in the problem of making such an instrument and partly the result of the small number of laboratories which would be justified in purchasing such instruments. A new approach to the problem of objective instrumentation is discussed in sec. 9.3, Photoelectric Measurements.

Whenever new standards are to be adopted, the spectral transmittances of the filters must be measured. This is essential because it is necessary to compute the chromaticities to be obtained with the type of colorant represented in different densities (thicknesses or concentrations) and also with sources of different color temperatures. The procedures of spectrophotometry have been described in NBS Circular 484 [Gibson, 1949] to which reference may be made for details of procedure and the probable accuracy to be expected.[28, 29]

[28] The fact that chromaticity differences are more easily and more accurately measured than the chromaticity itself suggests the desirability of standardizing a set of precision standards judiciously spaced over the regions of interest and making all other chromaticity measurements by chromaticity difference. Even if it is important to know the spectral characteristics of a filter the results of the spectrophotometry should be checked against the chromaticity as determined by difference with respect to the precision standards. W. D. Wright [1959] has advocated this procedure for surface color measurements and it seems even more advantageous in the case of filters.

[29] To assist in keeping the errors of spectrophotometry to a minimum, the National Bureau of Standards has made sets of standard filters designed for this purpose available. See Keegan, Schleter, and Judd [1962].

In sec. 6.2 it was stated that the U.S. Standard makes provision for duplicates of the national and organization standard filters by requiring that they conform to definite chromaticity tolerances. Such duplicates are polished squares and may be measured with a spectrophotometer. More frequently, however, they are tested by visual methods with colorimeters which measure the chromaticity differences between the duplicates and the originals. This method is generally preferable when there are satisfactory reasons for assuming that the duplicates are similar in chromaticity characteristics to the standard filters they represent. The chromaticity-difference measurements are more accurate than the ordinary spectrophotometric measurements and take less time. The instruments and procedures used for these chromaticity-difference measurements are described in NBS Circular 478 [Judd, 1950].

In principle the procedures for inspecting ware are those of colorimetry, and from the colorimetric standpoint they are relatively simple. They are, however, unusual in having to be made on ware that has optical properties which make it desirable that the chromaticity measurements be made at some distance from the test specimen in order that the measurements represent an average chromaticity such as is seen in service. For this reason the instrumentation is likely to resemble that used for the visual photometry of signal units rather than the usual colorimeters. The instrument may, in fact, be an ordinary Lummer-Brodhun photometer with one side illuminated with light of a known chromaticity.

The variations of chromaticity which have to be checked in an inspection of signal ware will usually constitute a one-dimensional system, that is, they all lie on a smooth curve. The problem is to discriminate between ware which transmits light falling within an acceptable interval from ware which transmits light of a chromaticity outside of that interval. If the similarity of chromaticity requirement has been met, all differences of chromaticity are of a clearly recognizable nature although small differences may require more careful observations than large ones. If such a requirement is applicable and the inspector experiences difficulty in determining whether units are inside or outside of the hue limits, he should refer samples to a colorimetric laboratory equipped to determine whether or not the similarity requirement has been met. If there is no similarity requirement, the inspector should likewise feel free to seek the assistance of a well-equipped colorimetric laboratory since the discriminations required may be such that they can not be made by comparison with one or two hue limits.

9.2. Transmittance Measurements

Most specifications for signal colors contain requirements with reference to the transmittance [30] or transmittance ratio [31] of the ware since this is closely associated with the chromaticity in that both result from the nature of the colorant and the amount of it in the path of the light. The transmittance of signal ware is usually determined as the ratio of two intensity measurements, one with test ware in the optical path and one with a standard filter in the path. If the test ware has no optical effect on the beam, that is, if there is no designed convergence or divergence of the light, nor any appreciable scattering at the surface, the simple interchange of the test ware and standard filter suffices to give the ratio of the transmittances from which we may compute true transmittance values. But most signal ware does not meet these conditions and it is necessary to insert a piece of colorless ware of the same optical characteristics into the path with the standard filter when the light transmitted by the filter is being measured. This results in a nonsymmetrical comparison with two extra glass-air surfaces in the light path when the standard is being measured. The symmetry may be restored by inserting a colorless (neutral) filter into the path when the test ware is being measured. Numerically, the same result is obtained by introducing the equivalent of the colorless filter mathematically.

The formulae for transmittance and transmittance ratio, with and without the colorless flat filter, may be derived as follows: Let us assume that a seasoned lamp (figure 9–1), standardized for the color temperature for which the measurements are to be made, is mounted at a fixed distance from an illuminometer (I) which gives readings in proportion to the illuminance at the instrument. Between the lamp and illuminometer, two lenses are placed successively, the first a standard lens (L_s) which is colorless but of the same design as the lenses to be tested and the second a test lens (L_t). The lenses must be properly focused with respect to the lamp and the illuminometer must be far enough from the lens so that the inverse-square law holds [Waldran, 1951, 1952]. When the colorless standard lens is in place, a standard filter (F_s) of the color of the test lens is placed between it and the illuminometer. When the test lens is in place a colorless filter (F_c) may be substituted for the standard filter, or may be omitted as indicated by the instructions.

[30] The transmittance values of all filters are ultimately derived from the spectrophotometric measurements on the filter or some other filter of similar spectral transmittance. In signal lighting most transmittance values can be traced back to the work of Gibson, Haupt and Keegan [1945] and [1946].

[31] See p. 41, eq (4) for the definition and discussion following.

Let the pertinent quantities be represented as follows:

E = illuminance at illuminometer from standard lamp, without lens or filter.
L_s = optical effect of standard lens, including transmittance.
L_t = optical effect of test lens, including transmittance.
T_s = transmittance of standard filter.
T_c = transmittance of colorless filter, assumed to be 0.92.
R_s = illuminometer reading for standard lens with standard filter in place.
R_t = illuminometer reading for test lens with colorless filter in place.
R_t' = illuminometer reading for test lens without colorless filter in place.
K = calibration constant of illuminometer which is assumed to give a linear response and to approximate the spectral response of the C.I.E. luminosity function.

From which:

$$R_sK = EL_sT_s \qquad (1)$$

$$R_tK = EL_tT_c \qquad (2)$$

$$R_t'K = EL_t \qquad (3)$$

(2)/(1) gives $L_t/L_s = (R_t/R_s)(T_s/T_c)$

= transmittance ratio of test lens. (4)

or $(L_t/L_s)T_c = (R_t/R_s)T_s$

= "transmittance" of test lens. (5)

(3)/(1) gives $L_t/L_s = (R_t'/R_s)T_s$

= transmittance ratio of test lens. (6)

or $(L_t/L_s)T_c = (R_t'/R_s)(T_s \times 0.92)$

= "transmittance" of test lens. (7)

Quotation marks are used around the word "transmittance" in eqs (5) and (7) because the ratio obtained in this measurement does not, in general, conform to the usually accepted definition of "transmittance", namely: "The ratio of the luminous flux transmitted by the body to that which it received" [CIE 1957]. The purpose of the measurement in this case is to obtain an index of the loss of light due to the colorant in the specimen. There may be much light wasted by a lens or diffusing cover which does not in principle affect the determined ratio, it being the purpose of the standard lens to cancel this out of the measurement. In actual practice the measured ratio may be influenced in either direction by this wasted light according to the relative amount of light lost by the test and standard pieces. The factor T_c, or 0.92, allows only for the surface reflection which may be small as compared with the other wasted light. It is for this reason that the term "transmittance ratio" was introduced as a term referring to the relative efficiency of a lens. It matters little to the user of a light signal whether the light was lost in a poor colorant, or a poorly molded surface, or an optical design that is less efficient than that of the standard lens.

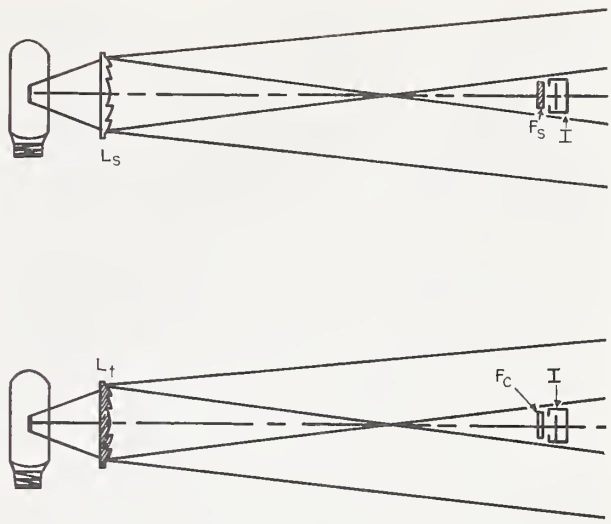

FIGURE 9–1. *Arrangement of parts for transmittance measarements.*
L_s = Standard lens (colorless) L_t = Test lens (colored)
F_s = Standard filter (colored) F_c = Colorless filter
I = Receptor of measuring instrument. See text for procedure.

Another procedure may be used which makes it unnecessary to measure either the "transmittance" or transmittance ratio. The specification writer may multiply the candlepower distribution expected for a clear lens by the desired minimum transmittance ratio and specify a performance curve in the colored light. This requires a candlepower distribution curve to be made on enough pieces to insure that all those accepted meet the specification.

9.3. Photoelectric Measurements

There has been, over a period of years, an increasing interest in the use of photoelectric instruments for the measurement of the chromaticity and transmittance of signal ware. Efforts to produce a suitable instrument seem thus far to have been directed to the development of an instrument that will read chromaticity coordinates and the transmittance of the test specimen directly. This is a difficult objective. A much more simple approach would be to develop instruments that could be substituted for the human eye in the operations which are performed by an inspector. The simplest approach might be a combination of photoelectric cell, filter, and meter, which would give readings that are a simple, single-value function of the position of a test chromaticity with respect to that of a standard chromaticity when both lie on the path of the normal variation of chromaticity with thickness for the specimen being measured. A change of photocell, filter, or instrument scale in changing from one color to another would not be a prohibitive complication.

The difficulty in applying this simple approach lies in the variation in optical efficiency from piece to piece. Suppose, for example, some small areas of the test piece are blanked out so that they contribute nothing to the illuminance on the photocell but do not change the chromaticity at all. This sort of effect has to be distinguished from those changes that result from changes in colorant density which do affect the chromaticity. This can probably be done by means of a preliminary filter which transmits only a narrow band of wavelengths in a region that is relatively well transmitted by the colorant. This should enable one to interpret the readings taken with the chromaticity filter and determine whether or not the chromaticity is paler than is allowed by the specifications. If there is a second hue limit it might be necessary to have a second chromaticity filter to check the test piece for this possible deficiency.

To inspect ware for compliance with transmittance requirements, a photocell corrected to the spectral luminous efficiency of the C.I.E. standard observer [CIE 1924] can be used and the measurements interpreted in accordance with the appropriate formula of sec. 9.2.

9.4. Sampling

Measurements are of no value unless the things measured represent something significant. This requires a comment on sampling. The variability of color in most glass filterware is so great that it is not practicable to apply to its inspection the ordinary principles for sampling material. Instead of random samples, samples deliberately chosen to contain the palest and densest specimens in the lot are required to assure a satisfactory product. This selection can be based upon a visual intercomparison of the items submitted. An instrument test is then made on the few specimens so chosen. If all of these specimens are satisfactory, that is good evidence that the whole lot is within the limits. If some of these are not satisfactory, that does not show that the lot is all unacceptable but rather that the lot has not had an adequate inspection by the contractor. When the inspector is satisfied that the contractor has reinspected the lot and replaced those pieces found outside of the limits, there need be no bar to another inspection.

In the case of plastic filters and perhaps some types of glass filters, it is possible to keep the production well inside of the limits. In such cases it is possible to use such statistical sampling procedures as are approved for other materials that are normally well within safe limits.

10. Use of Signal Light Colors

10.1. General Principles

In considering the recognition of signal light colors in sec. 4, it was pointed out that such recognitions depend upon the conditions under which the light is seen, and nine elements which affect the certainty of recognition were listed. In designing or redesigning a system of light signals, it is important to take these elements into consideration and determine how they will affect the certainty of recognition under the conditions of service. Unfortunately, there are almost no research results available for correlating these conditions with service applications. For this reason it is possible to give only a general discussion of this problem. The following simple principles indicate ways in which the most common sources of signal-color confusion can be reduced to a minimum.

10.2. Number of Colors

The first condition affecting the recognition of signal-light colors is the number of colors in the signal system. The number of colors should be kept to the minimum that will serve the needs of the signaling since every color that is added increases the risk of mistaken identification.

10.3 The Primary Signal Colors

The most elementary signal-light system is a one color system. Its use in the form of a beacon fire on a tower serving as a landfall light can be traced to archeological times and there is no reason to doubt that signal fires were used by primitive tribes long before the towers were built. From the standpoint of color, it might be thought that such a system would be completely safe since it does not lose its identity at the limit of range, or even when it is used by a colorblind person. There may be, however, the possibility that some stray light may be mistaken for the signal.

If more colors are required, the next step is a two-color system. If it is required that a single signal color be distinguishable from the general aggregate of ordinary lights, then such a system must be regarded as a two-color system since the ordinary lights are in effect being given a negative significance. It might be thought that for maximum dependability the colors of a two-color signal-light system should be as far apart on the mixture diagram as is practicable. According to the RUCS diagram these would be the longest wavelength red and the most saturated bluish green available. This theoretical solution, however, has to be modified in practice since these highly saturated colors are available only with extremely low luminance.

With a fixed amount of light available from the lamp, the distance at which the signal color may be recognized is at first increased by the greater illuminance that may be obtained by transmitting more light even though the resultant signal is less saturated.[32] After an optimum mixture has been reached, further additions of less saturated light reduce the recognition distance as the saturation becomes too low for long range recognition. In practice a two-color system is likely to consist of a red signal and a yellow-white signal, that is, a signal of whatever color the light source may be. Such a system should have dependable color recognition almost to the threshold of the red, for just above threshold all lights except red ones appear white or bluish white, but red lights retain some reddishness almost, if not quite, to their threshold. If a two-color system is to be used by red-green confusers, a bluish white light should be substituted for the yellow-white light.

The next step is a three-color system in which red, green, and yellow-white or yellow, lights are all used. This is the most common of signal systems. It is used for the long-range lights of aviation, for the navigation lights of ships and for aids for marine navigation with nominally white lights. With yellow lights it is used for highway traffic signals, and for the primary signaling system of most railroads. It is doubtful if any signal system should contain colors other than these three unless the additional colors are to be used solely under conditions that are favorable to color recognition. These will be discussed in connection with the four-, five-, and six-color signal systems.

It has already been pointed out in connection with the two-color system that there is an optimum color density for a color filter to be used on a light intended for recognition at maximum range, and this, of course, is equally applicable to a three-color system.

J. G. Holmes included a determination of the optimum color density for two green filters in the report of his investigation of "The Recognition of Coloured Light Signals" [1941]. For signal green glass he found that 70 percent correct recognition was obtained at maximum range with the following transmittances: [33]

Light source at 1904 °K, optimum transmittance 0.125
Light source at 2365 °K, optimum transmittance 0.16
Light source at 2854 °K, optimum transmittance 0.12

For 80 and 90 percent correct recognition, the transmittances of the optimum densities for light of color temperature 1904 °K were the same within the accuracy of the determination, the greater reliability corresponding to a decreased range. Since both increasing and decreasing the density of the filter tend to reduce its effectiveness as a signal, the transmittances given above presumably should apply to the middle of the range of transmittances to be furnished under the specification. The values given above may not be strictly applicable to a three-color signal-light system since they are based upon tests in which the observers were allowed six color names, but the location of signal green on the chromaticity diagram is such as to indicate much more probability that unsaturated signals would be called white than that they would be called blue. It is also probable that the green glass made by Messrs. Chance Brothers and Co. Ltd., of England is somewhat different from the corresponding green glass made in the United States, but a comparison of the above values for signal green glass with those Holmes found for emerald green glass indicates that the presumably smaller difference between glasses of the same color made in the two countries is likely to have less effect than that resulting from the changes of light source color temperature shown above (see footnote [33]).

The practice in the United States is to use green glass of higher transmittance than the optimum found by Holmes. This may be justified on the ground that the additional range or conspicuity is of more value than the greater certainty. A light must be noticed before it can be identified, and in the short interval between discovery and identification the range is usually reduced, which increases the certainty of identification. On the other hand green signals are also easily confused with white at excessive luminances.

10.4. Systems with Yellow and White Signals

For aviation, both yellow and white signals are used for beacons and for runway-lighting systems. In accordance with the principles set forth in the last section these are questionable practices. So far as they are permissible, it is because of the circumstances of their use, for in both cases the two colors are associated in the same application in such a way that they are subject to intercomparisons which enable the observer to distinguish them. Seadrome beacons flash yellow and white alternately at intervals of 2 to 5 seconds, and this permits comparison of a present

[32] The thresholds of visibility and color recognition have been investigated by Hill [1947]. More recently, Middleton and Wyszecki have determined peripheral thresholds for red, green and white lights [1951].

[33] These values are from table 20 of the Holmes report. Holmes notes a risk of confusion with blue if the Chance Bros. signal green glass is used with a light source at 2850 °K and recommends against the practice. The signal green glasses used in this country with sources at 2850 °K are designed for this use and have given no difficulty, although it should be noted that the blue lights in this case are secondary signals for short range identification.

flash with the memory image of its predecessor. In the case of some runway-light systems, yellow lights have been used to differentiate the last section of a runway from the rest. In this case the intercomparison is of two groups of lights in the same field of view. Both cases therefore involve only the distinguishing of chromaticity differences rather than the recognition of two chromaticities independently. A much smaller chromaticity difference is sufficient for such distinctions than is required to assure the correct recognition of two chromaticities independently.

The justification of the use of both yellow and white lights on runways has to be qualified. In clear weather when the whole length of the runway lighting system is visible at once, the contrast between the two segments is easily detected and a pilot can keep the transition point in view until he is on the ground and nearly abreast of the point where the color changes. In fog, however, the interval during which both types of lights are visible may be limited to 2 or 3 seconds and under the circumstances this is not long enough to insure that the distinction will be observed. This method of marking the last segment of a runway has never been universally used in this country and it has been used very little, if at all, in any other country. The requirements for use of yellow both in seadrome beacons and on runways are still in effect but seadrome beacons are becoming less common and there is a growing recognition that the runway use is not dependable. These uses, therefore, do not constitute safe precedents for any similar usage in any other application.

The importance of exercising caution in the use of both yellow and white as primary signal colors in the same system was appreciated by the International Civil Aviation Organization at the time when it approved its Standards and Recommended Practices for "Aeronautical Ground Light and Surface Marking Colours" [ICAO 1964]. This is shown by the following quotation from Annex 14 to the Convention on International Civil Aviation (p. 52). These paragraphs are quoted as being the best summary available of the precautions which should be exercised if circumstances seem to make it unavoidable to use both yellow and white lights as primary signal colors.

2.2—Discrimination Between Yellow and White Lights

2.2.1 Recommendation.—If yellow and white are to be discriminated from each other, they should be displayed in close proximity of time or space as, for example, by being flashed successively from the same beacon.

Note.—The limits of yellow and white have been based on the assumption that they will be used in situations in which the characteristics (colour temperature) of the light source will be substantially constant.

2.2.2 Recommendation.—The colours variable-yellow and variable-white are intended to be used only for lights that are to be varied in intensity, e.g., to avoid dazzling. If these colours are to be discriminated from each other, the lights should be so designed and operated that:

a) the chromaticity of the yellow lights will be represented by coordinates such that y is not greater than $x-0.160$ at any time when the chromaticity of the white lights is represented by coordinates of which x is greater than 0.470; and

b) the disposition of the lights will be such that the yellow lights are displayed simultaneously and in close proximity to the white lights.

Highway traffic signal systems do not include white lights, but the assumption that the yellow traffic lights are recognizably different from ordinary lights commonly seen along streets and highways involves the same difficulties as using yellow and white in the same system. The warning light of the traffic signal system is generally recognizable for reasons other than color. In some installations it does not appear except in association with the green light and in this use any color could serve the purpose. In other installations where this is not true, the warning light is seen following a green one or preceding a red one, and this change of colors, if seen, is an indication that both signals are traffic lights. In still other installations the yellow light is flashed and this differentiates it from street lights and miscellaneous lights which may be within the view of the driver. At short range it is possible for drivers to recognize that the warning light is coming from a traffic light fixture. All of these considerations contribute to making the use of yellow traffic signals possible notwithstanding that many other yellowish lights are frequently visible to drivers.

The realization that the circumstances associated with the use of yellow as a traffic signal have been important to the satisfactory experience with this color makes it clear that it is not safe to conclude that such yellow lights may be used as independent signals. In particular, it is not safe to depend upon the exposure of a fixed yellow light as a warning signal to automobile drivers unless the situation has been examined to make certain that drivers cannot mistake such a light for a stray light. This becomes an increasingly important consideration with the growing use of traffic lights on open highways where the higher speeds of traffic, and the longer distances from which lights must be observed, make it more difficult for drivers to distinguish between traffic lights and stray lights than is the case in city driving.

Another use for yellow light signals on highways is in turn signals on vehicles. In this use yellow and white have been used somewhat interchangeably on the front end of vehicles without difficulty. This would seem to be primarily because the location of the signals on the vehicles has indicated their purpose and the location has been recognizable from the outline of the car in the day time and from its relation to headlights or tail-lights at night. The Society of Automotive Engineers has now adopted a standard which requires all turn signals to be yellow signals and this should in time simplify the situation constructively.

10.5. The Secondary Signal Colors

In some signaling systems one set of colors is needed for operations at long range and additional colors are needed for purposes which permit observing the lights at shorter range and with more deliberation. For these secondary applications it must be possible to design the fixtures so that by the time a decision must be made the lights will either be observed as small surfaces, rather than as point sources, or they will be seen at luminances which are neither very high nor very low. Under these conditions it is possible to use as many as three additional colors. The colors usually adopted for such purposes are lunar white (which could equally well be called lunar), blue, and purple. The general policy in such systems should be to define the primaries for optimum recognition as if the secondaries were not used because the primaries perform the more important functions and do it under the more severe conditions. The blue and lunar secondaries are then fitted in to give the best differentiation possible with the green and yellow. The transmittances obtainable for the lunar glasses are about the same as those for the green glasses, but the transmittances of the blue glasses are about one tenth of those feasible in the green. Blue signal ware should be required to be free from an excessive transmission of red light.

Purple signals have been used in the United States to differentiate certain fixed signals from blue hand lanterns used in railroad yards, but the present trend is away from their use for this purpose. Purple signals fall into a class by themselves in that they are recognized by their dichroic character. The red and blue components of the light transmitted by purple glasses are separated by the chromatic aberration of the eye and are seen separately, usually as a reddish signal surrounded by a blue halo. For this reason the specifications for purple signal ware must contain a requirement to insure that the proportion of red light transmitted is not too low. Otherwise the signal is liable to be mistaken for a blue signal. On the other hand, too high a proportion of red in the transmitted light may cause a risk that the signal will be mistaken for a red signal. If the system uses both blue and purple signals, the limitations for the transmittance of red by the purple ware have to be held within narrow limits and the complementary requirement that the blue ware not transmit too much red light becomes essential.

Requirements relating to the proportion of red light transmitted by a blue or purple filter are represented as minimum or maximum limits for T_r/T_w. T_w, the transmittance for "white" light, is the total transmittance for light of the specified color temperature, and T_r is the transmittance of red light which has been defined for this purpose as light of wavelengths longer than 0.650μ. T_r and T_w are not difficult to compute from spectrophotometric measurements in cases where spectrophotometric measurements are available, but the inspection of signal ware has to be carried out without spectrophotometry. As a practical equivalent, the blue or purple light may be measured through a deep red, sharp-cutoff filter, but it is important that the use of this procedure be clearly defined in the specification in order to avoid possible misunderstanding and litigations based upon the difference between the actual cutoff of the filter and the abrupt cut implied by the reference to a wavelength.

Table 3 shows the defining red filters, color temperatures for testing, and the limits prescribed for blue ware in the specifications and standards named.

TABLE 3—*Maximum transmittance of red light allowed for blue ware*

Specification	Test filter	Color temperature	Maximum T_r/T_w
Federal Standard No. 3 Colors Aeronautical Lighting	3113A	2854 °K	0.015
Military Specification, MIL–C–25050 Colors Aeronautical Lights and Lighting Equipment (p. 9)	3055A	2854 °K	0.015
A.A.R. Specification 59–61 Glasses for Kerosene Hand Lanterns (p. 4, 8)	A.A.R.* 211	1900 °K	0.029
A.A.R. Specification 69–59 Signal Glasses (p. 11)	A.A.R. 86	2854 °K	0.006

*Expressed as light of wavelength greater than 0.650μ but tested with filter.

10.6. Signals for Colorblind Observers

Signal light systems are generally planned for persons having normal color vision. As pointed out in section 3.1, for such persons the world of color is three dimensional. In looking at surface colors, luminances are relative and are governed by the reflectances of the surfaces. Such differences are recognized as true color differences and in normal surroundings a baby blue ribbon is easily distinguished from one of navy blue by any person with normal color vision even though the hue and saturation may be the same. In signal lighting the transmittance of the signal ware, which is the analog of reflectance, merely affects the intensity, and while this is technically part of the color, it is not available for distinguishing signals since the apparent intensity is dependent upon the distance to the signal and the state of the intervening atmosphere. In the interpretation of signal lights, even the normal observer, or trichromat, is limited to chromaticity differences which constitute a two dimensional space.

In contrast to the normal trichromats, the completely colorblind monochromats appraise what they see with reference to a single primary. These persons have no chromatic world and no signal light colors can be of any use to them for they see only differences in brightness or brilliance. Intermediate between these groups are the partially colorblind dichromats who live in one dimensional chromaticity worlds.[34]

Since very few persons are totally colorblind, whereas a substantial fraction are dichromats, it seems reasonable to consider the possibility of designing a system of signal colors that can be used by at least a part of the dichromats. A dichromat, however, may lack any one of the three normal processes and hence there are three kinds of dichromats, known as protanopes, deuteranopes, and tritanopes. The differences between these three groups can be appreciated from figures 10–1, 10–2, and 10–3. In each of these figures there is a family of lines radiating from a focus outside the spectrum locus, that is, outside the region of visible colors. These are chromaticity confusion lines and each set corresponds to the vision of one of the three types of dichromats. All the chromaticities along any one line seem the same to a colorblind observer of the type to which the locus applies.

D. B. Judd has designed a three-color specification for use in control panels for electronic equipment which should be satisfactory for protanopes and deuteranopes as well as for normal observers. This system consists of aviation red, aviation blue, and aviation green with its yellow boundary moved to the line

$$y = 0.667(1 - x).$$

These areas have been indicated in figures 10–1, 10–2, and 10–3 by the boundaries of the aviation colors, the allowable portion of the green area being distinguished by shading. It appears from figures 10–1 and 10–2 that the system should be useful to protanopes and deuteranopes but figure 10–3 indicates that tritanopes will easily confuse the blues and greens. The Judd proposals have been tested by Sloan and Habel [1955] in a research with 22 deuteranopes and 18 protanopes using signals subtending 1° at the observer's eye. Normal observers, all the deuteranopes, and 13 protanopes recognized the colors correctly. Five protanopes experienced difficulty with some of the test colors, making 16 errors out of 120 identifications. The results confirm the principle but indicate that further study is desirable before depending upon such a system in any situation involving appreciable risks. The test must also be considered inconclusive for the more common applications of signal light colors in which the subtended angle is a few minutes more or less.

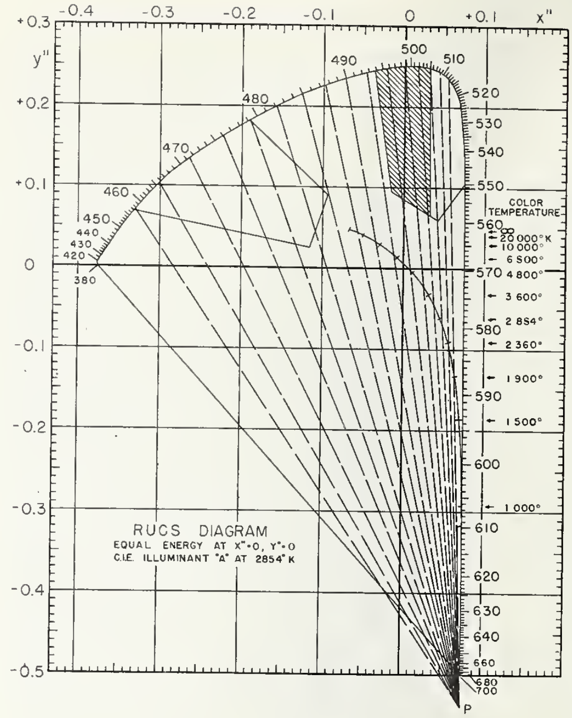

FIGURE 10–1. *Confusion loci for protanopes.*

All points lying on any one of the radii through P will appear to a person having partial color blindness of the type called protanopic as having the same chromaticness. This diagram is a transformation into RUCS coordinates of the diagram given in the original paper by Pitt [1935].

The boundaries for signal red, green and blue and intermediate green (shaded) as defined in the U.S. Standard have been added showing that protanopes may be expected to have difficulty distinguishing between signal green and red.

The possibility of a system designed to be recognizable by all three types of dichromats deserves consideration. Three small areas have been crosshatched on figure 10–3 to make a modification of the Judd system for this purpose. This proposal has not been tested because the most important application for such a system would seem to be in connection with the control of traffic. For this use, however, the proposal has a serious handicap in the very low transmittance (1 or 2 percent) which must be accepted in order to obtain sufficiently saturated green and blue signals.

10.7. Backgrounds

The background of a signal light can have a considerable effect on its conspicuity and its recognition. The conspicuity of a signal is greatly reduced if it must be seen among a number of other lights from which the observer receives an equal or greater illuminance. A yellow traffic light, for example, hanging in the center of a number of highway lights installed to illuminate a crossing may be difficult to find even though it is known to be there. A driver who has noticed a green light must transfer his attention to the roadway surface to check his alinement and make sure his path is still clear, and he may see only a cluster of yellowish lights when he looks back to check the traffic signal. If

[34] For discussions of the response functions of protanopes and deuteranopes see Judd [1944] and [1949].

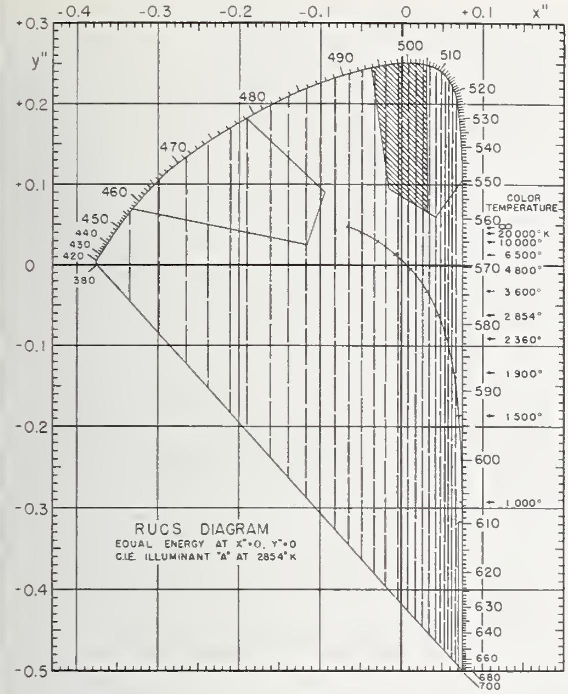

FIGURE 10–2. *Confusion loci for deuteranopes.*

All points lying on any one of the broken vertical lines will appear to have the same chromaticity to a person of deuteranopic vision. The spacing of the lines near the spectrum locus is based upon the results obtained by Pitt [1935]. The lines are drawn vertical because different investigators disagree as to the location of the conversion point in the case of deuteranopes. The conversion point found by some researches would lie at a fairly large negative value, whereas another research would place the conversion point at a positive value. In view of this uncertainty, it is felt that the vertical lines represent the facts as far as known adequately. The other lines have the same significance as in figure 10–1.

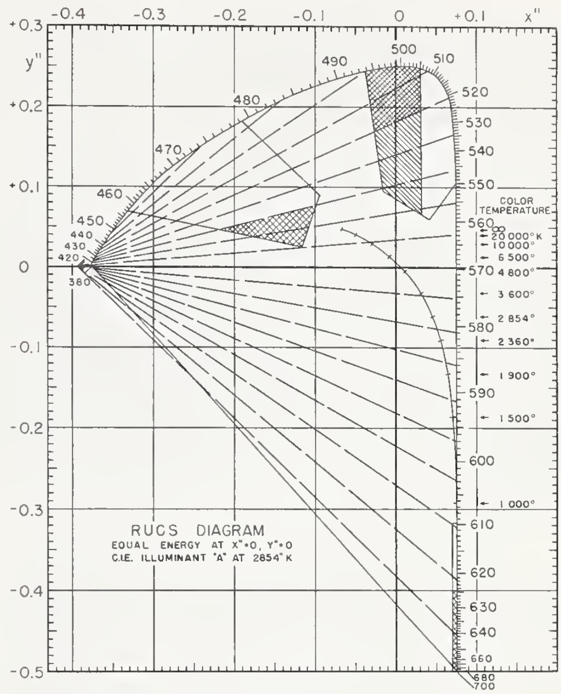

FIGURE 10–3. *Confusion loci for tritanopes.*

In this case all of the points on any one of the converging lines will have the same chromaticity for a tritanope. The conversion point represents a mean of the locations found by Thomson and Wright [1953], Judd [1944], and one computed from the Muller theory [Judd, 1949]. The other lines have the same significance as in figure 10–1.

the driver is traveling at a good speed, he cannot devote much attention to playing hide and seek with lights, and so he reverts to his relation to the roadway surface. When he has reassured himself that all is well here, he looks again at the lights to find a red one among them. Unless he has reduced his speed as a response to a realization that he is dealing with a situation that he may not completely understand, he must now make an emergency stop, if he can, before he reaches the crossing.

Green lights given a high intensity to insure their visibility by daylight look quite pale to the dark-adapted eye at night. This may cause a green traffic light to become lost among highway lights with mercury lamps, which are frequently quite greenish as seen from a few hundred yards away. The obscuration of red traffic lights by neon signs is a common source of concern.

The loss of conspicuity because of competing lights is not as serious a problem with city traffic lights as it would otherwise be because drivers become accustomed to the exact location of traffic lights with reference to the driving lane in their own city and city driving speeds allow more attention to be given to lights. A study, however, of the whole problem of conspicuity is needed. The mere increasing of the intensities may increase the problem of recognition and do little to solve the problem of conspicuity.

Closely related to the problem of conspicuity is the problem of visibility. At night the presence of many bright lights will destroy the dark adaptation and make it impossible for observers to see distant signals if they are faint. This is a situation which has to be avoided in marine and aeronautical navigation, and it has received some attention in these fields, but it has not been thought a serious problem in land transportation where signals are closer to the observer. The increasing use of highway lights and the higher intensities used for headlamps and brakelights is making it a problem on the highway.

Both visibility and conspicuity may be reduced by too high a background brightness. This is particularly true of traffic lights hung over the center of an intersection which by day are seen against the sky. This problem has long been recognized in railroad signaling, and high intensity railroad signals used in the daytime are regularly provided with artificial backgrounds by surrounding the light with a black shield.

A promising field for the improvement of the color recognition of traffic lights is the possibility of improving their backgrounds. While it is probably impracticable to use as large background shields as are used for some of the railroad signals, it should be possible to redesign the traffic light fixtures so as to present the largest practicable black cross section surrounding the signals. An effort might be made to have special lighting units designed for use in locations near traffic signals in order to eliminate the competition between street and highway lights and traffic lights. The location of traffic signals should be considered with reference to competing lights and means sought to eliminate lights from the background if they are interfering with the conspicuity of a needed trafffic light. A first approach might be to seek the cooperation of landowners in order to educate the public with reference to the problem. If this proves inadequate legal means should be considered.[35]

These are only the obvious ways in which the situation might be improved. It is quite probable that a thorough study of the problem would develop other and possibly more important steps that could be taken to improve the recognition of traffic signals. The same principles apply to other types of signal lights when such lights are used in close proximity to stray lights.

10.8. Naming of Signal Colors

The naming of signal colors might not be expected to have much importance but one problem has arisen that merits some attention. It is common practice to think of an ordinary incandescent lamp seen through colorless signal ware as white. This has been the accepted practice in connection with lighthouses and aviation beacons and it is probable that people in general seldom ascribe any color to the lights used for illumination. If such a color, at moderate brightness, is shown an observer whose eyes are adapted to ordinary daylight, he will generally classify it as yellow. In the case of airport approach and runway lights the situation is aggravated by the necessity of dimming the lights to a color temperature close to 1500 °K which is redder than candlelight and almost at the red limit of some signal yellow lights although not as saturated. At full intensity these lamps may operate at more than twice this color temperature. It is necessary to have a single name for this entire range of colors. The International Civil Aviation Organization selected the term "aviation variable white." The Recommendations of the International Commission on Illumination for colors of signal lights refer to these lights as "white/yellow lights." The U.S. Standard for the Colors of Signal Lights calls it "variable-source white," and this may be a satisfactory name provided all concerned can be made to realize the scope of the term. The limitations which should be placed on the use of both yellow and white in the same system have already been discussed in sec. 10.4.

A minor difficulty encountered in the effort to bring the several specifications for signal-light colors used in the United States into a more consistent relationship has arisen from the practice of naming signal colors with the names of the services in which they are used. It may seem quite inappropriate to railroad signal engineerings, for example, to use an aviation green. For this reason the names used in the U.S. Standard [NBS 1964] have been designed to avoid reference to any applications.

[35] From an engineering point of view the projection of hazardous photons would not seem to be essentially different from the projection of hazardous pebbles.

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American Standards Association, Adjustable Face Traffic Control Signal Head Standards, ASA D10.1–1958, UDC–656.057 (1958). Address: American Standard Association, 70 East 45th Street, New York, N.Y.

Society of Automotive Engineers, Inc., SAE Standards, TR–34, Lighting Equipment and Photometric Tests. Address: Society of Automotive Engineers, Inc., 485 Lexington Ave., New York 17, N.Y.

Other Countries

Australia

Standard in preparation.

Germany

DIN 6163 Blatt 1: Farben und Farbgrenzen für Signallichter, Allgemeines

DIN 6163 sheet 1: Colors and color limits for signal lights; General.

DIN 6163 Blatt 2: Farben und Farbgrenzen für Signallichter, Ortsfeste Signallichter an See-und Binnenschiffahrtstrassen

DIN 6163 sheet 2: Colors and color limits for signal lights; Fixed signal lights at maritime and inland waterways.

DIN 6163 Blatt 3: Farben und Farbgrenzen für Signallichter, Signallichter an Strassenfahrzeugen und Strassenbahn

DIN 6163 sheet 3: Colors and color limits for signal lights: Signal lights on road vehicles and tramways.

DIN 6163 Blatt 4: Farben und Farbgrenzen für Signallichter, Signallichter der Eisenbahn

DIN 6163 sheet 4: Colors and color limits for signal lights; Signal lights of the railways.

DIN 6163 Blatt 5: Farben und Farbgrenzen für Signallichter, Ortsfeste Signallichter im Strassen-und Strassenbahnverkehr

DIN 6163 sheet 5: Colors and color limits for signal lights: Fixed signal lights in road and tramway traffic.

DIN 6163 Blatt 6: Farben und Farbgrenzen für Signallichter, Signallichter an Wasserfahrzeugen

DIN 6163 sheet 6: Colors and color limits for signal lights; Signal lights on vessels.

DIN 6163 Blatt 7: Farben und Farbgrenzen für Signallichter, Luftfahrtfeuer und Signallichter zur Luftverkehrsregelung

DIN 6163 sheet 7: Colors and color limits for signal lights: Air navigation lights and signal lights for air traffic regulation.

DIN 6163 Blatt 8: Farben und Farbgrenzen für Signallichter, Signallichter an Luftfahrzeugen

DIN 6163 sheet 8: Colors and color limits for signal lights; Signal lights on aircraft.

DIN 6171: Aufsichtfarben für Verkehrszeichen, Farben und Farbgrenzen

DIN 6171: Control colors for traffic signals; Colors and color limits.

Deutschen Normenausechusses, Berlin W 15.

United Kingdom

British Standards Institution, British Standard 1376:1953, Colours of Light Signals (1953). Address: British Standards Institution, British Standards House, 2 Park Street, London W1, England.

Appendixes 4 and 5

The tables of 4 and 5 show the equations used as boundaries for the signal-light colors in the U.S. Standard [N.B.S. 1964], together with the corresponding equations used in the Standards of the International Civil Aviation Organization [1964] and the Recommendations of the International Commission on Illumination [1955]. All of the equations of App. 4 are expressed in the coordinates of the C.I.E. system, which is the system used in all the specifications, but since the RUCS equivalents of the C.I.E. recommendations are more significant for color differentiation, App. 5 has been added to give these also. For the titles of the Standards and the addresses of the issuing authorities, see App. 3.

Appendix 4. Corresponding Boundary Equations CIE Coordinates

Colors and Boundaries[1]	International Commission on Illumination[2]	International Civil Aviation Organization[3]	U.S. Standard for the Colors of Signal Lights[4]
Signal Red			
Purple boundary	$x=0.980-y$	$y=0.980-x$	$x+y=0.992$
Yellow boundary	$y=0.335$	$y=0.335$	$x-y=0.330$
Intermediate Signal Red			
Purple boundary	No equivalent	No equivalent	$x+y=0.992$
Yellow boundary			$x-y=0.380$

Appendix 4. Corresponding Boundary Equations CIE Coordinates—Continued

Colors and Boundaries [1]	International Commission on Illumination [2]	International Civil Aviation Organization [3]	U.S. Standard for the Colors of Signal Lights [4]
Restricted Signal Red			
Purple boundary	$y=0.985-x$	No equivalent	$x+y=0.997$
Yellow boundary	$y=0.300$		$x-y=0.405$
Signal Yellow			
Red boundary	$y=0.382$	$y=0.382$	$y=0.383$
White boundary	$y=0.790-0.667x$	$y=0.790-0.667x$	$x+y=0.872+0.200x$
Green boundary	$y=x-0.120$	$x=0.550$	$x=0.550$
Intermediate Signal Yellow			
Red boundary	No equivalent	No equivalent	$y=0.383$
White boundary			$x+y=0.872+0.200x$
Green boundary			$x-y=0.124$
Restricted Signal Yellow			
Red boundary	No equivalent	$y=0.400$	$y=0.400$
White boundary		$y=0.790-0.667x$	$x\pm y=0.872+0.200x$
Green boundary		$x=0.560$	$x-y=0.124$
Signal Green			
Yellow boundary	$x=0.360-0.080y$	$x=0.333$	$x=0.360-0.080y$
White boundary	$x=0.650y$	$x=0.650y$	$x=0.650y$
Blue boundary	$y=0.390-0.171x$	$y=0.390-0.171x$	$y=0.390-0.171x$
Intermediate Signal Green			
Yellow boundary	No equivalent	No equivalent	$y=0.730\ (1-x)$
White boundary			$x=0.650y$
Blue boundary			$y=0.500-0.500x$
Restricted Signal Green			
Yellow boundary	No equivalent	$y=0.850-x$	$y=0.730\ (1-x)$
White boundary		$x=0.650y-0.030$	$x=0.425y$
Blue boundary		$y=0.390-0.171x$	$y=0.500-0.500x$
Signal Blue			
Green boundary	$y=0.065+0.805x$	$y=0.805x+0.065$	$y=0.065+0.805x$
White boundary	$x=0.400-y$	$y=0.480-x$	$y=0.400-x$
Purple boundary	$x=0.133+0.600y$	$x=0.600y+0.133$	$x=0.100+0.700y$
Signal White	Variable source white is nearest equivalent	Variable source white is nearest equivalent	Signal white includes all chromaticities which qualify as one of the following four.
Variable Source White			
Green boundary	$y=0.150+0.640x$ $y=0.440$	$y=0.640-0.400x$ $y=0.150+0.640x$	$y-y_0=0.003$
Purple boundary	$y=0.382$ $y=0.050+0.750x$	$y=0.050+0.750x$ $y=0.390$	$y_0-y=0.003$
Yellow boundary	$x=0.255+0.750y$ $y=0.790-0.667x$	$x=0.560$	$x=0.555+0.750(y-0.405)$
Blue boundary	$x=0.310$	$x=0.310$	$x=0.325$
Beacon White			
Green boundary	$y=0.150+0.640x$ $y=0.440$	$y=0.640+0.400x$ $y=0.150+0.640x$	$y-y_0=0.003$
Purple boundary	$y=0.382$ $y=0.050+0.750x$	$y=0.050+0.750x$ $y=0.390$	$y_0-y=0.003$
Yellow boundary	$x=0.500$	$x=0.500$	$x=0.490+0.500(y-0.410)$
Blue boundary	$x=0.310$	$x=0.310$	$x=0.325$
Lunar White			
Green boundary	$y=0.150+0.640x$	No equivalent	$y=0.195+0.500x$
Purple boundary	$y=0.050+0.750x$		$y=0.170+0.500x$
Yellow boundary	$x=0.440$		$x=0.445+0.333(y-0.405)$
Blue boundary	$x=0.310$		$x=0.325$

Appendix 4. Corresponding Boundary Equations CIE Coordinates—Continued

Colors and Boundaries [1]	International Commission on Illumination [2]	International Civil Aviation Organization [3]	U.S. Standard for the Colors of Signal Lights [4]
Blue White			
Green boundary			
For $x < 0.330$	No equivalent	No equivalent	$y = 0.030 + x$ and
For $x > 0.330$			$y = 0.195 + 0.500x$
Purple boundary			
For $x < 0.330$			$y = 0.005 + x$ or
For $x > 0.330$			$y = 0.170 + 0.500x$
Yellow boundary			$x = 0.445 + 0.333(y - 0.405)$
Blue boundary			$x = 0.265 - 0.250(y - 0.280)$

1 Boundary names are from the U.S. Standard. In the case of the I.C.A.O. the correspondence is readily evident with these possible exceptions: "variable yellow" is classified as signal yellow because it is the most inclusive; restricted green is an I.C.A.O. recommended practice; the use of the C.I.E. white boundary for blue is recommended in I.C.A.O. The correspondence in the case of the C.I.E. is clear except for white lights. In this case the correspondence has been determined from the uses indicated in the two documents.
2 Recommendations, Publication No. 2.
3 International Standards and Recommended Practices, Aerodromes, Annex 14.
4 NBS Handbook 95.

Appendix 5. Corresponding Boundary Equations RUCS Coordinates

Colors and Boundaries [1]	International Commission on Illumination [2]	International Civil Aviation Organization [3]	U.S. Standard for the Colors of Signal Lights [4]
Signal Red	$\Delta x'' = x'' - 0.075$	$\Delta x'' = x'' - 0.075$	$\Delta x'' = x'' - 0.075$
Purple boundary	$x'' = +0.070$	$x'' = +0.070$	$x'' = +0.0725$
Yellow boundary	$y'' = -0.317 - 4\Delta x''$	$y'' = -0.317 - 4\Delta x''$	$y'' = -0.317 + 0.16\Delta x''$
Intermediate Signal Red			
Purple boundary	No equivalent	No equivalent	$x'' = +0.0725$
Yellow boundary			$y'' = -0.375 + 0.4\Delta x''$
Restricted Signal Red			
Purple boundary	$x'' = +0.071$	No equivalent	$x'' = +0.0741$
Yellow boundary	$y'' = -0.400 - 4\Delta x''$		$y'' = -0.407 + 0.5\Delta x''$
Signal Yellow			
Red boundary	$y'' = -0.225 - 4\Delta x''$	$y'' = -0.225 - 4\Delta x''$	$y'' = -0.225 - 4\Delta x''$
White boundary	$x'' = +0.063 - 0.050y''$	$x'' = +0.063 - 0.050y''$	$x'' = +0.068 - 0.026y''$
Green boundary	$y'' = -0.134 - 0.50\Delta x''$	$y'' = -0.120 + 3\Delta x''$	$y'' = -0.120 + 3\Delta x''$
Intermediate Signal Yellow			
Red boundary			$y'' = -0.225 - 4\Delta x''$
White boundary	No equivalent	No equivalent	$x'' = +0.068 - 0.026y''$
Green boundary			$y'' = -0.136 + 0.5\Delta x''$
Restricted Signal Yellow			
Red boundary		$y'' = -0.194 - 4\Delta x''$	$y'' = -0.194 - 4\Delta x''$
White boundary	No equivalent	$x'' = +0.063 - 0.050y''$	$x'' = +0.068 - 026y''$
Green boundary		$y'' = -0.134 + 3\Delta x''$	$y'' = -0.136 + 0.5\Delta x''$
Signal Green			
Yellow boundary	$x'' = +0.715y''$	$x'' = +0.875y''$	$x'' = +0.715y''$
White boundary	$y'' = +0.085 - 0.600x''$	$y'' = +0.085 - 0.600x''$	$y'' = +0.085 - 0.600x''$
Blue boundary	$x'' = -0.150y''$	$x'' = -0.150y''$	$x'' = -0.150y''$
Intermediate Signal Green			
Yellow boundary			$x'' = +0.045 - 0.0075y''$
White boundary	No equivalent	No equivalent	$y'' = +0.085 - 0.600x''$
Blue boundary			$x'' = -0.020y''$
Restricted Signal Green			
Yellow boundary		$x'' = +0.047 + 0.050y''$	$x'' = +0.045 - 0.0075y''$
White boundary	No equivalent	$y'' = +0.104 - 0.650x''$	$y'' = +0.142 - 0.450x''$
Blue boundary		$x'' = -0.150y''$	$x'' = -0.020y''$

Appendix 5. Corresponding Boundary Equations RUCS Coordinates — Continued

Colors and Boundaries [1]	International Commission on Illumination [2]	International Civil Aviation Organization [3]	U.S. Standard for the Colors of Signal Lights [4]
Signal Blue			
Green boundary	$x''=-0.950y''$	$x''=-0.950y''$	$x''=-0.950y''$
White boundary	$x''=-0.125+0.350y''$	$x''=-0.075+0.250y''$	$x''=-0.125+0.350y''$
Purple boundary	$y''=-0.205x''$	$y''=-0.205x''$	$y''=-0.370x''$
Signal White	Variable source white is nearest equivalent	Variable source white is nearest equivalent	Signal White includes all chromaticities which qualify as one of the following four
Variable Source White			
Green boundary	$x''=+0.020-0.700y''$ $x''=+0.042-0.247y''$	$x''=+0.055-0.100y''$ $x''=+0.020-0.700y''$	Curved boundaries, no simple transformation
Purple boundary	$x''=+0.021-0.240y''$ $x''=-0.026-0.900y''$	$x''=-0.026-0.900y''$ $x''=+0.024-0.240y''$	
Yellow boundary	$y''=-0.161+0.086x''$ $x''=+0.063-0.050y''$	$x''=+0.115+0.300y''$	$y''=-0.1515$
Blue boundary	$x''=-0.025+0.984y''$	$x''=-0.025+1.000y''$	$x''=-0.000+0.900(y''-0.009)$
Beacon White			
Green boundary	$x''=+0.020-0.700y''$ $x''=+0.042-0.247y''$	$x''=+0.055-0.100y''$ $x''=+0.020-0.700y''$	Curved boundaries, no simple transformation
Purple boundary	$x''=+0.021-0.240y''$ $x''=-0.026-0.900y''$	$x''=-0.026-0.900y''$ $x''=+0.024-0.240y''$	
Yellow boundary	$x''=+0.100+0.420y''$	$x''=+0.100+0.420y''$	$y''=-0.094+0.400(x''-0.056)$
Blue boundary	$x''=-0.025+0.984y''$	$x''=-0.025+1.000y''$	$x''=-0.000+0.900(y''-0.009)$
Lunar White		No equivalent	
Green boundary	$x''=+0.020-0.700y''$		$x''=+0.016-0.571y''$
Purple boundary	$x''=-0.026-0.900y''$		$x''=-0.002-0.586y''$
Yellow boundary	$x''=+0.074+0.536y''$		$y''=-0.060+0.700(x''-0.045)$
Blue boundary	$x''=-0.025+0.984y''$		$x''=+0.000+0.900(y''-0.009)$
Blue White	No equivalent	No equivalent	
Green boundary			
For $x<0.330$			$y''=+0.021-0.844x''$
For $x>0.330$			$x''=+0.016-0.571y''$
Purple boundary			
For $x<0.330$			$y''=+0.004-0.794x''$
For $x>0.330$			$x''=-0.002-0.586y''$
Yellow boundary			$y''=-0.060+0.700(x''-0.045)$
Blue boundary			$x''=-0.037+0.700(y''-0.040)$

[1,2,3,4] See corresponding notes to Appendix 4.

Appendix 6. Comparative Diagrams of Signal Color Boundaries

Figures A–1, A–1A, and A–1B, and figures A–2, A–2A and A–2B show a comparison of the chromaticity boundaries of the three standards for signal light colors listed in App. 3 of the Appendix: the U.S. Standard, the C.I.E. Recommendations, and the I.C.A.O. Standards and Recommended Practice. To avoid confusion, some boundary lines in the yellow-white region and one in the red region have been omitted from figure A–2. The RUCS boundaries for restricted red in the C.I.E. Recommendations may be fairly well located by noting the location of these boundaries on the C.I.E. diagram in comparison with other boundaries that are shown on both the C.I.E. and RUCS diagrams. Space limitations have also dictated the use of different types of lines to distinguish the boundaries of the three standards. When the same equation has been used as a boundary in more than one standard, a combination of the different types of lines has been used to represent the common boundary. The significances of the different types of lines have been shown in the figures. Labels have been used to distinguish boundaries of the same standard which are specified for different uses and again it has been found necessary to conserve space by abbreviating the terms. The following code has been used:

U.S. Standard:
- SIG = Signal Color (broadest category)
- INT = Intermediate Color
- RES = Restricted Color (highest certainty category)
- BW = Blue white (special category)
- LW = Lunar white (distinguishable from yellow)

C.I.E. Recommendations:
- RES = Restricted (red only)

I.C.A.O. Standard and Recommended Practices:
- VAR = Variable (color of signal varies with source as intensity is changed for different conditions)
- CON = Constant (signals not in previous category)
- REC = Recommended practice.

In the case of the C.I.E. white boundaries, the selection of the boundary depends upon the number of colors in the system and this seemed to make it impracticable to label the C.I.E. boundaries. Reference should be had to the Standard itself for the interpretation of the boundary lines.

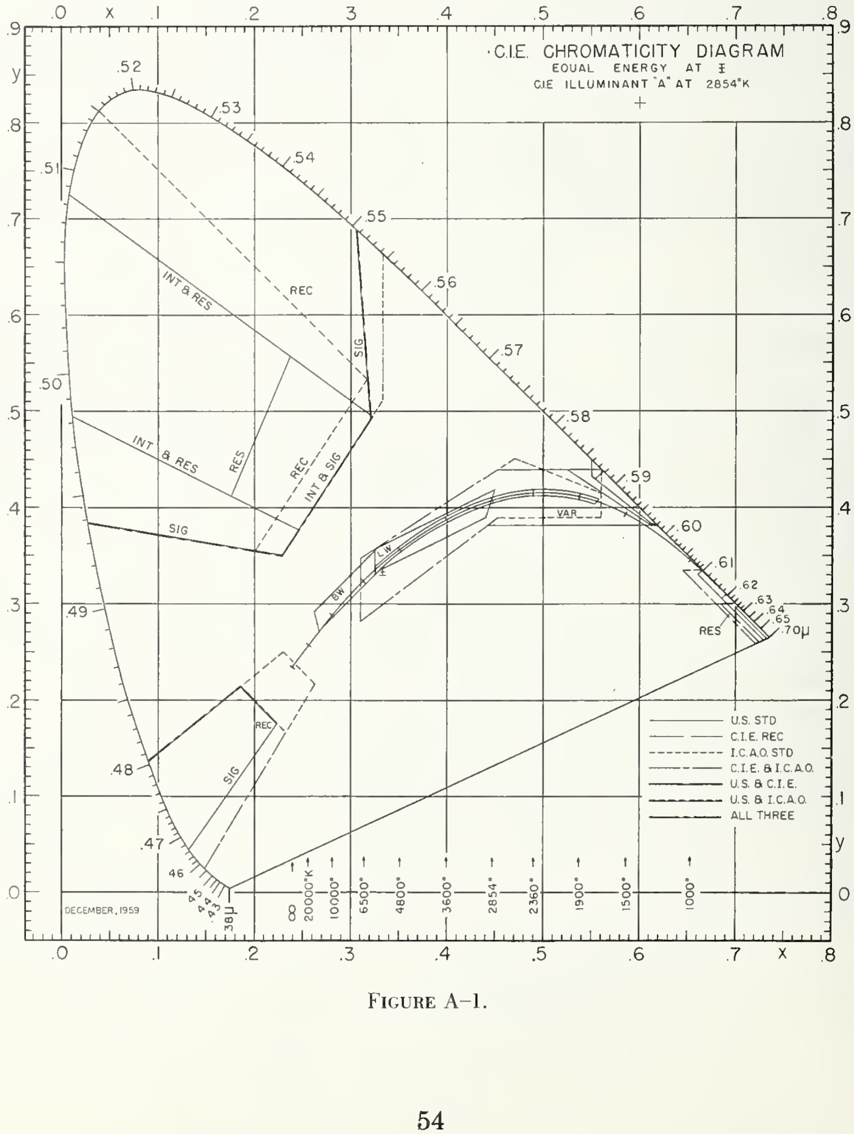
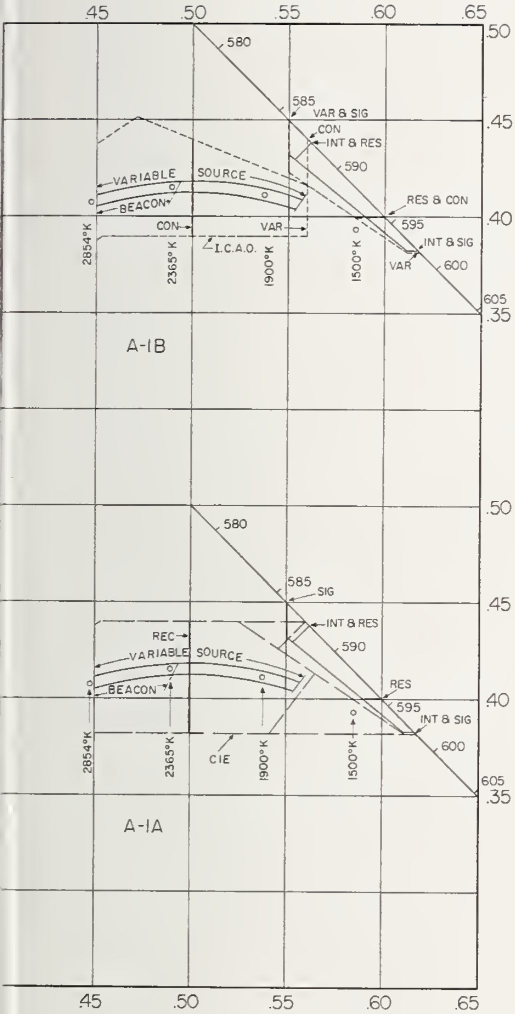


Figure A–1.



Figures A–1A and A–1B.

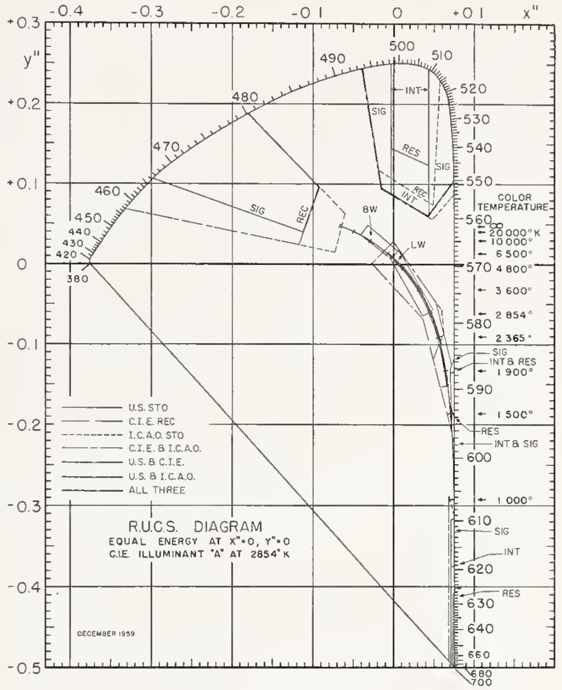
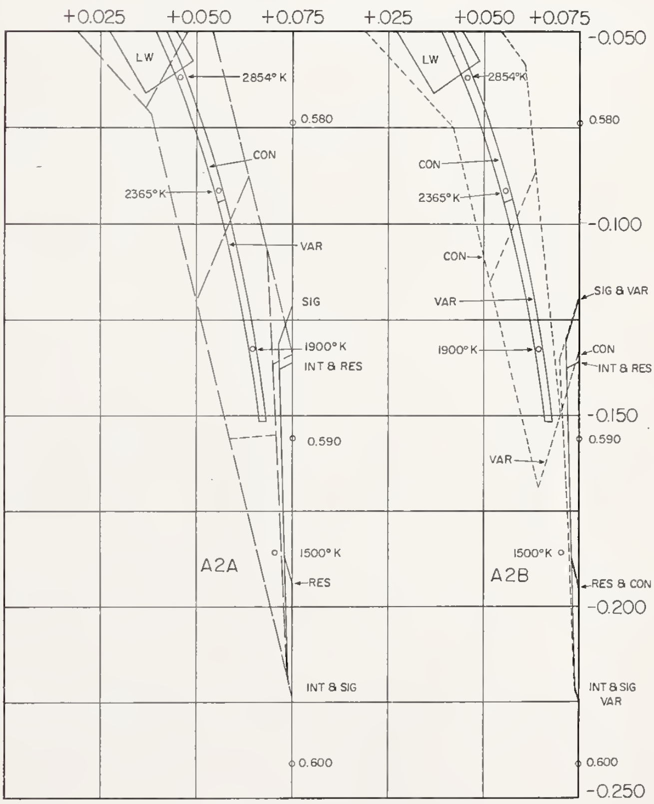


Figure A–2.



Figures A–2A and A–2B.

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