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PHYSICAL METALLURGY DIVISION

TECHNICAL MEMORANDUM

DIVISIONAL NO. 19065

COLOUR MEASUREMENT

by

R.F. VISSER

Director of Division : Dr P.T. Wedepohl

Investigator/s : RF Visser (Student)

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1. THE CIE SYSTEM[1]

1.1. INTRODUCTION

The judgement ofcolor and its faithful reproduction are of the utmost importance in the commercial and industrial world. The quality of numerous products is judged by the color they display or fail to display. In all phases of life we are continually making judgments based on the color of materials that we encounter.

1.2. THE CIE SYSTEM

In 1931 the Commission International de ℓ'Eclairage (the CIE-International Commission on Illumination) developed a new colorimetric[2] system. The CIE system analyses the spectrum of light reflected from a surface and assigns a set of tristimulus values that specify the color. With this kind of system, any two surfaces that reflect spectra having the same tristimulus values will also appear the same color. Thus specification of the tristimulus values uniquely describes the color appearance of a surface. In understanding the CIE system, it is necessary to know the laws of color matching.

1.3. THE LAWS OF COLOR MATCHING

The laws of color matching are derived from careful experiments that use a set of three monochromatic lights as additive primaries. An attempt is made to match some combination of these three primaries with a standard intensity of each wavelength of the pure spectrum. It should be pointed out that the actual choice of the wavelengths used for the three primaries is completely arbitrary. The final CIE-XYZ system, which is the system we are working toward, is identical regardless of the choice of primaries.

Suppose we choose three monochromatic primaries of wavelength λR, λG and λB (R,G, and B refer to red, green and blue) and try to use these primaries to match some other monochromatic light of wavelength λ. For convenience let us define the following quantities:

IR = intensity of red primary (λR)
IG = intensity of green primary (λG)
IB = intensity of blue primary (λB)
$U\lambda$ = unit intensity of monochromatic light of wavelength λ.

Now if you try to match any $U\lambda$ from the visible spectrum with some combination of our three primaries, you will not find it possible to get any direct combination of IR, IG and IB that will exactly match $U\lambda$ in hue, saturation and brightness. However, further experimentation shows us that it is possible to achieve a condition where a match occurs. Depending on the value of λ, one of the following three matches will always prove possible:

$$U\lambda + IR \equiv IG + IB \quad \ldots\ldots\ldots \quad (1)$$
$$U\lambda + IG \equiv IR + IB \quad \ldots\ldots\ldots \quad (2)$$
$$U\lambda + IB \equiv IR + IG \quad \ldots\ldots\ldots \quad (3)$$

These three equations should be read as follows:

Equation (1) states that:

A UNIT INTENSITY OF LIGHT OF WAVELENGTH λ PLUS LIGHT OF WAVELENGTH λR AND INTENSITY IR	exactly matches	LIGHT OF WAVELENGTH λ AND INTENSITY IG PLUS LIGHT OF WAVELENGTH λB AND INTENSITY IB

Equations (2) and (3) should be read similarly. All the quantities in (1), (2) and (3) are intrinsically positive. That is they all represent the direct physical addition of real lights. We now can summarize the information in (1), (2) and (3) by the single equation

$$U\lambda = IR + IG + IB \quad \ldots\ldots\ldots\ldots \quad (4)$$

Notice the intentional change in sign in equation (4) - in comparison to equation (1) - (3). That is because one of the quantities IR, IG, IB is in fact negative and should be on the other side of the equation. Exactly which one depends on the value of λ. For every wavelength, λ, in the visible spectrum the triplet of numbers IR, IG, IB will take on a unique set of values. These values can be displayed graphically by plotting the relative intensity of each primary necessary to match a unit intensity of the pure colors of the visible spectrum. Such a plot is shown in Figure 1.1. The actual shape of these curves depends on the choice of wavelengths λR, λG and λB.However, when the information contained in such curves is further analysed to produce the CIE-XYZ system, the same result is obtained regardless of the original choice of λR, λG and λB.

The data of Figure 1.1 tells us how to match a unit intensity of any monochromatic light in the visible spectrum.

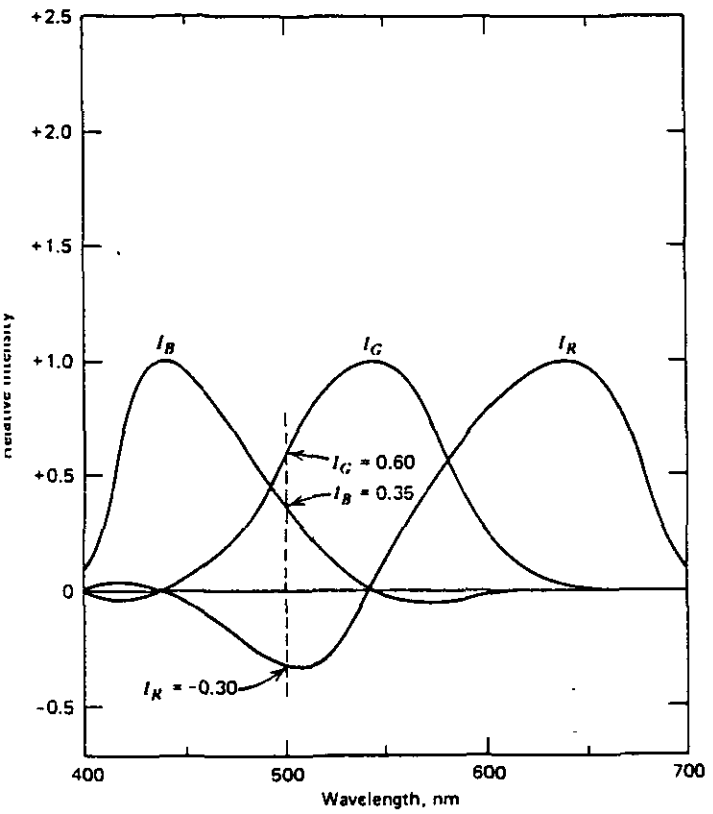

FIGURE 1.1

For example, let us use Figure 1.1 to determine the intensities IR, IG and IB necessary to match a unit intensity of 500 nm light. The dashed vertical line on Figure 1.1 is drawn at 500 nm. Where this line crosses the three curves on the figure indicates the intensities of IR, IG and IB needed to match a unit intensity of 500 nm light. From the figure we see that the required values of IR, IG and IB are:

IR = -0,30 units

IG = 0,60 units

IB = 0,35 units

We note in passing that in this case it happens to be IR that is negative, therefore the match must algebraically be written as follows:

1 UNIT OF 500 NM	=	0,30 UNITS OF λR	+	0,60 UNITS OF λG	+	0,35 UNITS OF λB

Light of other wavelengths is matched in a similar fashion.

This information can also be used to match any complex spectrum as well. That is, any complex spectrum can be reduced to an equivalent combination of some set of values IR, IG and IB.

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1.4. THE XYZ SYSTEM

Systems such as that of the previous paragraph are not usually used for colorimetric calculations for two reasons: (i) for many spectra. one of the intensities IR, IG, IB is often algebraically negative; (ii) no choice of primaries is really any more basic than any other set that might have been chosen. For these reasons the CIE created the XYZ system that can be derived from any system of real primaries, but that has some distinct advantages:

a) The XYZ primaries are "imaginary" primaries that can be algebraically derived from the color matching data representing any system of real primaries (such as the data of Figure 1.1). But these new primaries are derived in such a way that the color matches they express never require negative numbers.

b) The "green" primary is arbitrarily given a matching curve that is identical to the visual sensitivity curve of the human eye. That is, this curve represents how sensitive the human eye is to light of different wavelengths. Multiplying the green curve times the spectrum to be analysed automatically gives the apparent brightness of the spectrum.

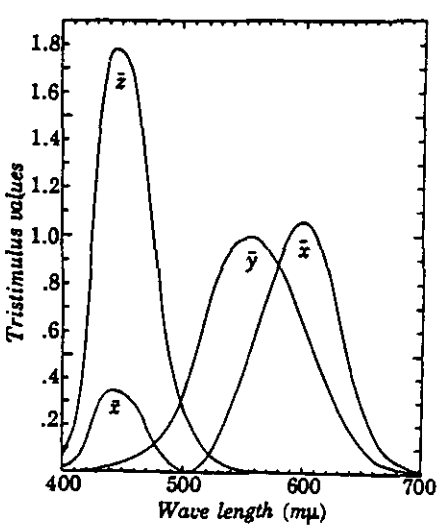

FIGURE 1.2

The color matching curves for the primaries of the XYZ system are shown in Figure 1.2. For convenience in computation, the ordinates are expressed in arbitrary units so that the areas under all three curves are equal. The symbols $\bar{x}$,$\bar{y}$ and $\bar{z}$ are used for the ordinates of the respective curves, and the values of x,y and z, at any wavelength, are called the tristimulus values of a spectrum color of that wavelength. Table 39, Appendix B, contains a list of the tristimulus values for most of the wavelengths of the visible spectrum. To use the XYZ system to analyze a particular spectrum we proceed just as we did in the previous section with the λR, λG, λB primaries. Appendix A[1.1] contains a detailed description on how to do this.

1.5 CHROMATICITY COORDINATES

Although the tristimulus values X,Y and Z do indeed specify the color of a given spectrum, many people still find it difficult to form a mental image of the actual color in question. Therefore a new set of numbers, called the color or chromaticity coordinates, were invented. They are calculated as follows:

$$x = \frac{X}{X+Y+Z} \qquad \text{.....(5a)}$$

$$y = \frac{Y}{X+Y+Z} \qquad \text{.....(5b)}$$

$$z = \frac{Z}{X+Y+Z} \qquad \text{.....(5c)}$$

In effect, x,y,and z represent the relative amounts of three imaginary primaries required to match a particular spectrum. From equations (5a) to (5c) it is apparent that x+y+z = 1. Thus once two of the three numbers x,y,z are given, the third is automatically determined, which means there are two independant numbers.As we shall see shortly, the chromaticity coordinates specify only the hue and saturation of a color, but not its brightness. In order to specify the brightness, we continue to use the value of Y. As a matter of convention, the two independant color coordinates that are used to describe the color of a spectrum are x and y. Thus the complete description of the color of a spectrum is given by the values of x,y and Y. These three numbers provide an alternative to using the values of X,Y and Z.

The advantage of using the color coordinates x and y is that they can be displayed graphically - Figure 1.3.

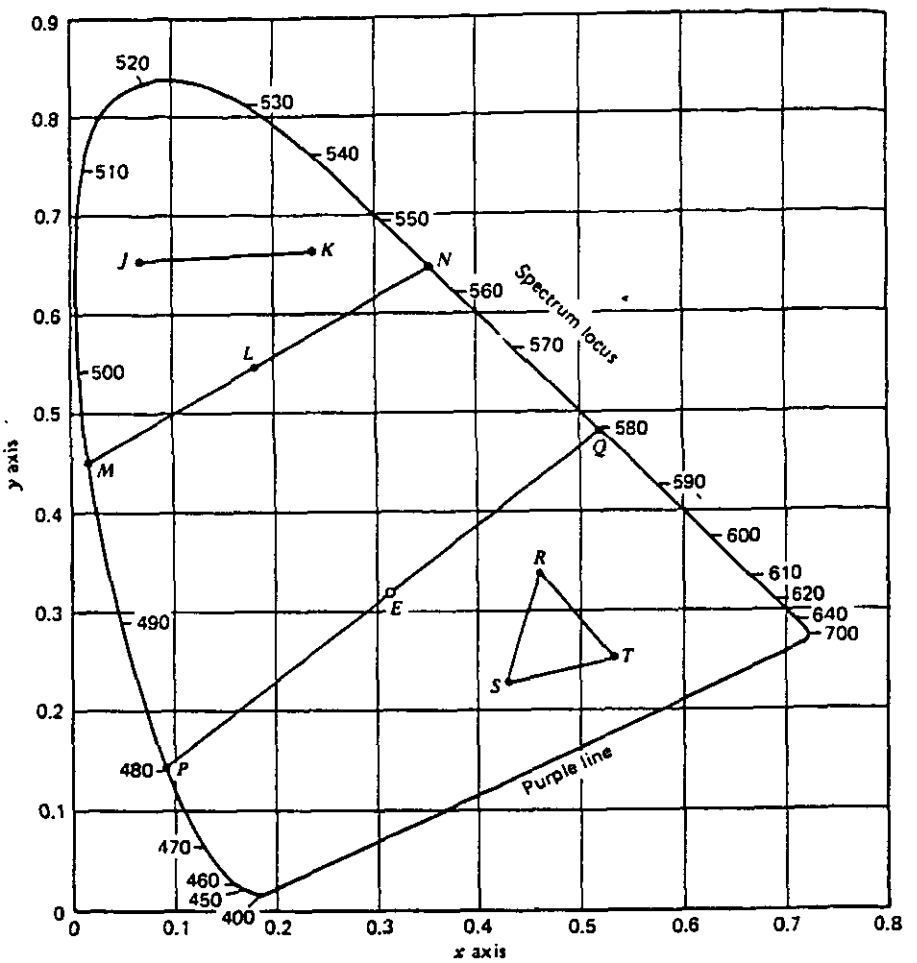

FIGURE 1.3

Such a graph is called a chromaticity diagram and every point (x,y) represents a unique color or chromaticity. Table 38, Appendix B, contains a list of the chromaticity coordinates for most of the wavelengths of the visible spectrum. It turns out that all the chromaticitie are found inside the horse-shoe shaped graph. This region is called the color locus.

The outer boundary (straight line excluded) of the color locus represents the chromaticities of all the pure colors of the visible spectrum. The corresponding wavelengths-innm-are labelled around the periphery of this curve, which is known as the spectrum locus. The straight-line is called the purple line, which is composed of a mixture of red and blue light.

Points along the spectrum locus and purple line represent colors of the maximum possible saturation or purity. As you move toward the center of the color locus the saturation diminishes until, at the point x=0,33 and y=0,33 the saturation becomes zero. This central point, labelled E in Figure 1.3, represents equal energy[3] white.

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1.6. USE OF THE CHROMATICITY DIAGRAM

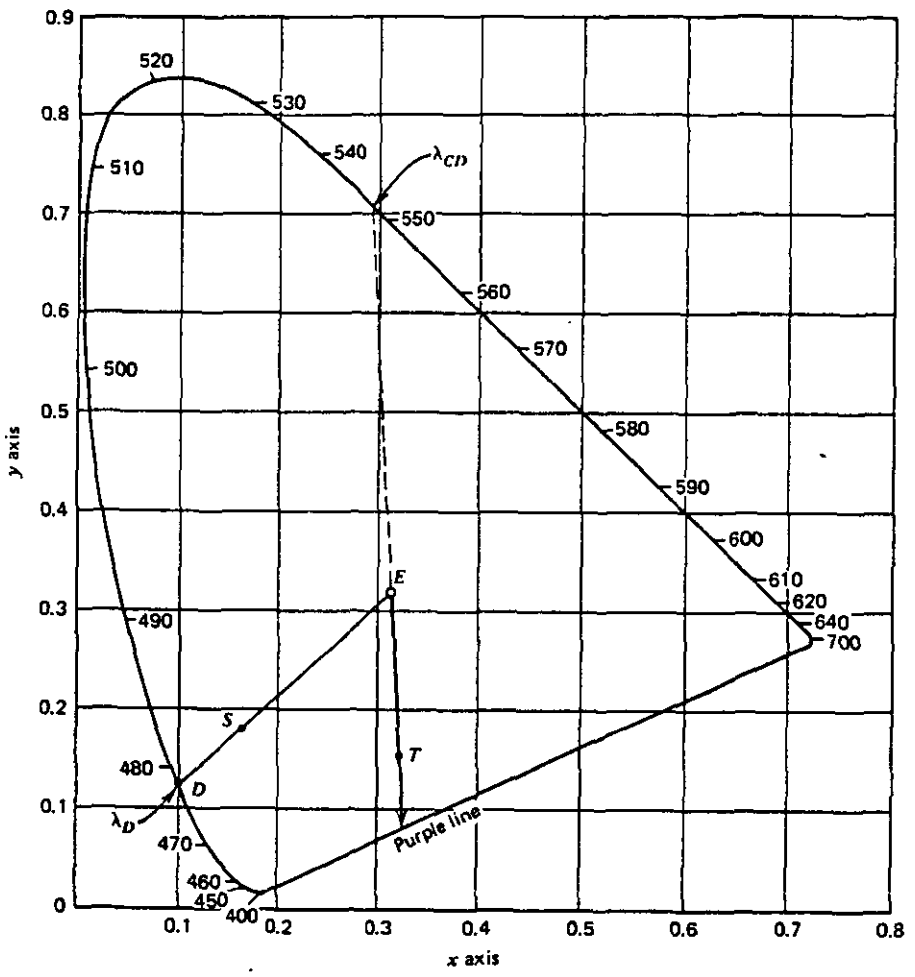
The CIE chromaticity diagram can be used to analyze color mixtures and other features of color. Look again at figure 1.3. Points M and N represent two colors on the spectrum locus. All the chromaticities along the line joining M and N can be achieved by mixing various combinations of the pure color M and the pure color N. For example, point L represents an equal mixture of M and N. Now consider points J and K, which represent the color of light coming through two filters, for example. Again, any chromaticity along the line joining J and K can be achieved by mixing lights J and K.

Of particular interest in Figure 1.3 are points P and Q. Notice that these points both represent pure spectrum colors, and they are joined by a line passing through point E. Pure colors such as P and Q, which lie at opposite ends of a straight line passing through the white point, are called complementary[4] colors.

Finally, let us examine the small triangular region labelled RST. The three spectra represented by R,S and T can be combined to produce any chromaticity inside this triangle. All the points in the whole area outside the triangle (that is to say the rest of the color locus) cannot be matched by combining R,S and T.

1.7 DOMINANT WAVELENGTH AND PURITY

Let us turn to Figure 1.4. On this figure point S represents the chromaticity of some spectrum of light. Draw a line from point E through point S until the line strikes the spectrum locus at point D. Point D will be located at a particular wavelength on the spectrum locus. This wavelength is called the dominant wavelength λD of the spectrum represented by point S. The basic hue of this dominant wavelength is the hue of color S. Thus knowing λD gives us an immediate idea of what kind of color S really is. Now we can also define a purity -p- for the color. White (point E) is considered to have zero purity, while a pure color such as D is considered to be 100% pure.



Thus the purity of point S, expressed as a percent is given by

$$p = \frac{\text{length of SE}}{\text{length of DE}} \times 10$$

Purity is a measure of the saturation of the color, or how far it is remov from white toward the full color of t spectrum locus. Th the color of a part icular spectrum of light can be comple ly specified by giving λD, p and Y.

FIGURE 1.4

NB. For some spectra, the chromaticity may lie at a point such as T in Figure 1.4. The purity is still calculated as before, but for the dominant wavelength you extend the line backwards (dash line in fig.1.4) until it hits the spectrum locus. The wavelength at which this occurs is called the complementary dominant wavelength λCD, of the color T.

1.8. THE ANALYSIS OF SURFACES

When using CIE method of analysis, you will have to keep two things in mind: (a) the CIE system analyzes the spectrum of light coming from a given object; (b) the spectrum of light coming from a given surface depends on the spectrum of light that illuminates the surface. Thus it would seem that a particular surface could have a whole variety of chromaticities under different circumstances. In order to reduce this problem to manageable proportions, the CIE has adopted three standard light sources, which are used in most

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practical colorimetry. The spectra of these sources, which are described below, are shown in Figure 1.5.

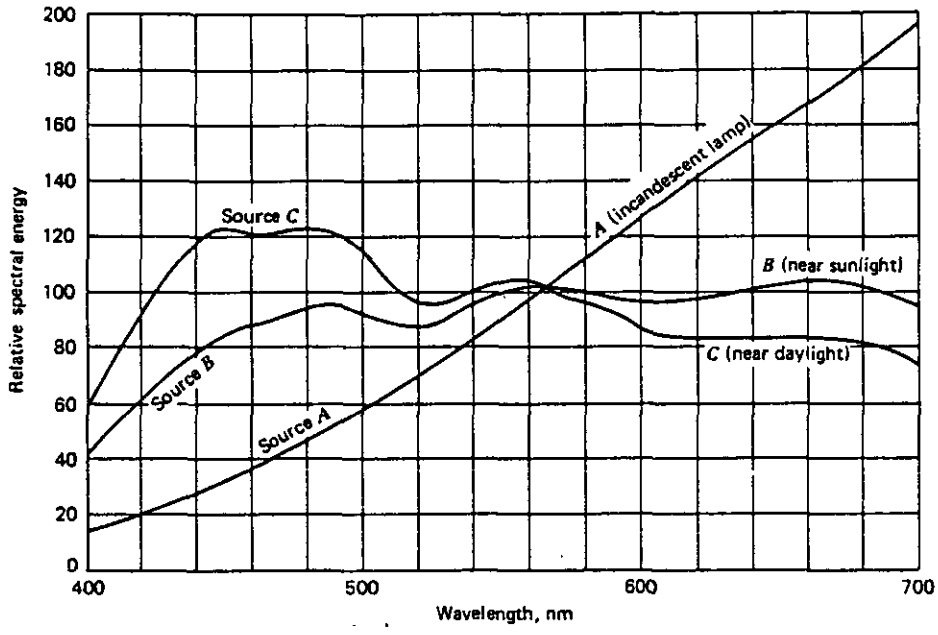

FIGURE 1.5

SOURCE A

Representative of a gas-filled incandescent lamp.

SOURCE B

Representative of noon sunlight. Thi source is produced bg using source A in combination with a special liquid filter.

SOURCE C

This source is similar to an overcast sky or average daylight. Like source B, it can be produced by the use of source A with proper liquid filters.

As an example of how these sources are used in the analysis of color let us begin with Source B. When this source is analyzed, it is found to have chromaticity coordinates of x=0,35 and y=0,35. Notice they are different from the equal energy spectrum. Figure 1.6 shows the chromaticity of illuminant B plotted on a chromaticity diagram.

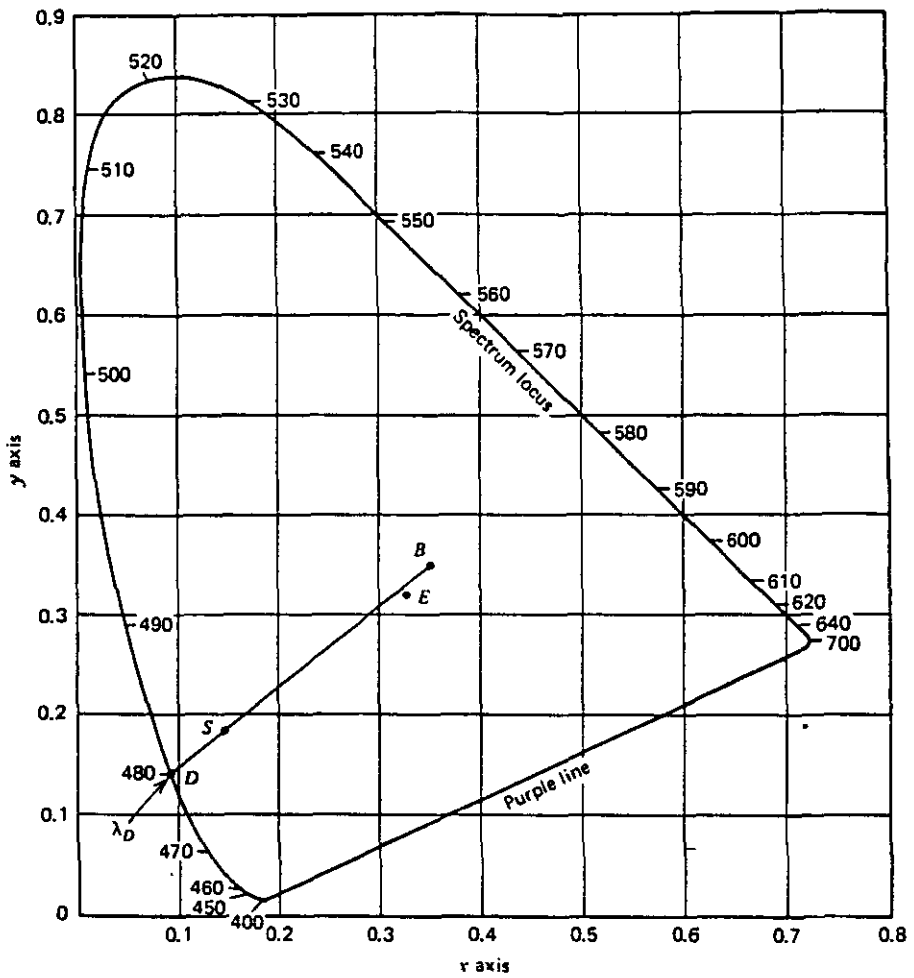

FIGURE 1.6

Point S represents the chromaticity of a surface when illuminated by sourc B. If a different source were used, the location of point S would probably shift somewhat.

In order to compute the dominant wavelength and purity of S we must use point B as the white point, not point E. The reason for this is simple. If sourc B illuminates a perfectly white surface the reflecte light will have the same spectral content as source B. The chromaticity of this reflected light will thus be given by point B. Thus point B is taken as the white point under these circumstances. We now proceed as before to compute the dominant wavelength and purity of point S.

In analyzing a surface we must also consider the value of Y. Frequently this is done in terms of a percent. We begin by imagining that our illuminant (for example source B) illuminates a perfectly white surface. We compute the value of Y for this situation and call this value YO. Next we compute the value of Y for the actual surface of interest, and call this value YR. The value of Y expressed as a percent is then given by

$$Y = \frac{YR}{YO} X\ 100.$$

This means that a perfectly white surface would have a value of Y of 100%, while a perfectly black surface would be characterized by 0%. It is entirely possible for two different surfaces to have the same chromaticity

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coordinates (and therefore the samd λD and p), but have different values of Y. An example of two such colors might be pink and a dark unsaturated red.

1.9. THE COLOUR OF ALLOYS

Of the few fundamental colorimetric studies of alloys Gardam[6] measured the spectral reflectivity curves of gold, gold alloys, sterling silver, platinum, nickel silver, stainless steel and other alloys. Positions on the colour triangle were calculated. Copper, gold and their alloys gave red or yellow colours with low saturation values. The remainder were very near to the white point being white or grey with zinc, chromium and aluminium tinged slightly blue. The reflectivity curves for copper and gold alloys were stepped while for the basically white or grey metals they were fairly flat. He also demonstrated the important facts that metals are:

1) Highly desarurated, (2) Of a limited range of dominant wavelengths,
3) Of very high luminance - Refer to Table 111.

Furthermore, the variation of CIE coordinates with composition (Table 111) emphasizes that optical phenomena are atomic effects and hence designated in weight percentages will tend to show non-linear variations of 'colour' with composition. During alloying, only relative changes in spectral intensities, depending upon the proportion of phases present in the alloy, are distinguishable.

Table III

CIE (Illuminant C 1931) Colour Co-Ordinates of Binary and Ternary Alloys in the Gold-Silver-Copper System

Alloy No.	Co-ordinates x	Co-ordinates y	Saturation %	Dominant wavelength nm	Luminance %
1R	0.3583	0.3376	18.68	588.9	71.09
2	0.3559	0.3366	17.77	588.8	70.47
3	0.3539	0.3358	17.02	588.8	69.26
4	0.3533	0.3355	16.78	588.8	69.37
5	0.3517	0.3346	16.13	589.0	70.16
6	0.3506	0.3348	15.87	588.5	68.07
7	0.3501	0.3360	16.04	587.5	69.94
8	0.3508	0.3369	16.47	587.1	69.05
9R	0.3598	0.3464	21.45	584.6	68.87
10R	0.3620	0.3483	22.57	584.3	69.34
11R	0.3779	0.3770	34.53	579.1	65.01
12	0.3154	0.3220	3.00	576.4	95.33
13	0.3196	0.3245	4.79	579.7	91.28
14	0.3253	0.3264	6.83	583.3	86.77
15	0.3307	0.3316	9.67	581.8	86.90
16	0.3385	0.3372	13.28	581.9	84.45
17	0.3434	0.3383	14.88	583.4	83.81
18	0.3490	0.3408	17.06	584.1	80.22
19	0.3505	0.3399	17.21	585.1	79.68
20	0.3579	0.3407	19.41	587.0	74.12
21	0.3679	0.3873	34.59	574.8	80.81
22	0.3558	0.3783	28.96	573.5	81.56
23	0.3420	0.3635	21.27	572.3	85.43
24	0.3278	0.3451	12.54	571.1	85.51
25	0.3211	0.3332	7.54	571.9	90.06
26	0.3177	0.3268	4.91	573.2	90.53
27	0.3157	0.3235	3.50	574.3	90.46
28	0.3129	0.3197	1.70	575.0	87.29
29R	0.3128	0.3193	1.58	576.5	93.71
30R	0.3110	0.3173	0.57	577.1	95.86
31	0.3602	0.3595	25.08	579.6	72.56
32	0.3545	0.3495	20.87	581.7	75.37
33	0.3538	0.3619	24.01	577.0	78.24
34	0.3464	0.3591	21.27	575.3	80.95
35	0.3506	0.3528	20.72	579.0	76.21
36	0.3537	0.3451	19.46	583.4	71.51
37	0.3392	0.3529	17.70	574.5	82.63
38	0.3430	0.3495	17.77	577.5	80.47
39	0.3478	0.3462	18.21	580.8	76.89
40	0.3515	0.3418	18.00	584.4	72.14
41	0.3312	0.3432	12.94	574.3	85.16
42	0.3348	0.3410	13.28	577.6	83.53
43	0.3401	0.3406	14.61	580.5	79.34
44	0.3447	0.3402	15.74	582.8	76.72
45	0.3500	0.3418	17.58	583.9	74.46
45R	0.3519	0.3411	17.89	584.9	72.33
46	0.3310	0.3356	10.82	578.7	81.22
46R	0.3276	0.3401	11.12	573.5	90.34
47	0.3293	0.3352	10.28	577.8	84.81
48	0.3334	0.3353	11.42	580.4	82.91
49	0.3404	0.3378	13.94	582.4	77.99
50	0.3466	0.3381	15.68	584.8	74.49
51	0.3497	0.3378	16.30	586.5	73.13
52	0.3224	0.3310	7.29	575.2	86.83
53	0.3265	0.3327	8.85	577.6	85.49
54	0.3306	0.3331	10.05	580.4	83.64
55	0.3336	0.3338	11.04	581.7	82.46
56	0.3419	0.3375	14.25	583.3	76.01
57	0.3452	0.3364	14.86	585.4	76.09
58	0.3511	0.3374	16.70	586.9	72.60
59	0.3184	0.3254	4.72	576.4	87.76
60	0.3231	0.3268	6.35	580.5	86.66
61	0.3271	0.3290	8.02	581.6	85.20
62	0.3325	0.3311	10.02	583.4	81.08
63	0.3488	0.3376	16.14	585.9	72.13
64	0.3437	0.3366	14.51	584.6	74.95
65	0.3360	0.3349	11.98	582.3	79.76
66	0.3536	0.3376	17.42	587.5	71.76

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1.10 IN CONCLUSION

The whole point of colorimetry is to provide an accurate way of describing a color that can be faithfully reproduced anywhere at anytime. The CIE system provides a way of reducing the spectrum of light coming from any object to a set of three numbers - X,Y,Z or x,y,Y or λD,p,Y. Very important is that the tristimulus values do tell us how to match the visual stimulus presented by the spectrum in question, but under a given set of conditions.

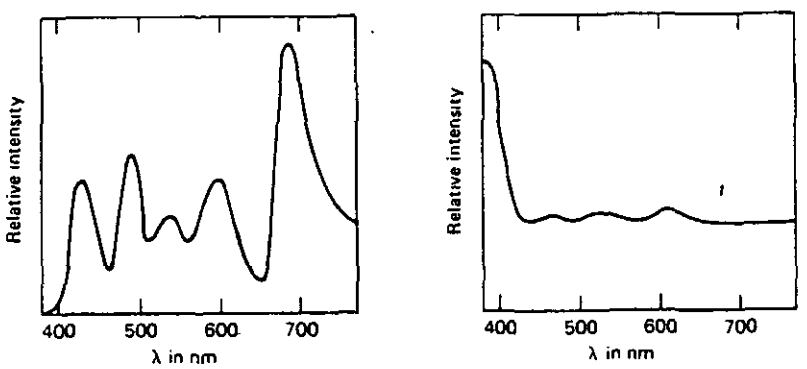

FIGURE 1.7.

Thus two entirely different spectra which have identical tristimulus values will appear identical- Figure 1.7. If the viewing conditions are changed, the actual color produced by the two spectra may change, but the match will remain intact provided the tristimulus values are still equal.

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REFERENCES AND NOTES FOR SECTION 1

1. From "Light and Color" by R. Daniel Overheim and David L. Wagner, 1982, p.63-78; 1.1 p. 246-252.

NB. Compare with p 350-356 and p.360-363 from "Optics" by Sears, 3rd edition, 1958.

2. Colorimetry - the science dealing with the description of color.

3. An "equal energy" source is only theoretical and is a perfectly white source which contains equal intensities of all wavelengths.

4. When two colors can be combined in the proper proportion to produce pure white, they are complementary.

5. Refer to p.356 and p.359 from "Optics" by F.W. Sears, 3rd edition, 1958.

6. G.E. Gardam, Trans. Inst. Met. Finish, 1964, 41, p. 190-199.
G.E. Gardam, Trans. Inst. Met. Finish, 1966, 44, p. 186-188.

NOTE:

The explanation of the CIE system for the description of colour in this T.M., is very much simplified, and the graphs supplied are not suitable for accurate calculations. The methods described in Appendix A are not necessarily the best or the most accurate, but they were given just to give an idea of how to use the system. With some practice, you will be able to develop much quicker and more accurate methods, for example when using some of the other tables provided in Appendix B.

For more detailed descriptions of the CIE system and other colour aspects, refer to ref.1 mentioned above, as well as the following publications.

i. "An Introduction to Color" by Ralph, M. Evans, John Wiley and Sons, Inc, New York, 1959.

ii. "The CIE International Colour System Explained" by G.J. Chamberlin, Tintometer Ltd, Salisbury, 2nd ed. 1955.

2. THE SPECTROPHOTOMETER

2.1. INTRODUCTION

Spectrophotometry is the measurement of light emitted, transmitted or reflected as a function of wavelength. The spectrophotometer is an instrument to do this measurement. In the spectrophotometer white light is split into its constituent wavelengths and monochromatic light impinges on the unknown surface. The intensity of the reflected light is measured by photocells and colour is characterised by plotting absorbence versus wavelength.. The CIE system is then used to desribe the colour of the surface.

2.2. THE PRINCIPLE OF A MONOCHROMATIC SPECTROPHOTOMETER[1]

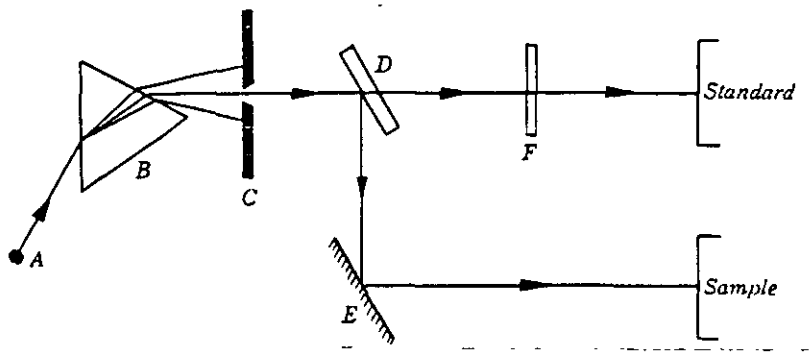

FIGURE 2.1

Refer to Figure 2.1. Light from source A is dispersed by prism B, and a narrow range of wavelengths is isolated by slit C- in other words the light beam has been made monochromatic[2]. The beam passing through the slit is divided at D into two beams of equal intensity by a half-silvered mirror or its equivalent. The transmitted beam strikes a standard white surface, usually magnesium oxide, while the reflected beam, after reflection from mirror E, strikes the surface of the sample. The latter, in general, has a lower reflectance than the standard, so it appears less bright than the standard. The quantity of light striking the standard may be reduced by a device shown schematically at F, until sample and standard appear equally bright. If, for example, the light incident on the standard must be reduced to 70% to secure a brightness match, the reflectance of the sample at this wavelength is 70%. By repeating the measurement at other wavelengths, the complete reflectance curve of the sample may be obtained. Usually this reflectance curve is plotted automatically on a sheet of coordinate paper by a device on the spectrophotometer. Such a spectrophotometer is called an automatic recording spectrophotometer. Figure 2.2 contains reflectance curves and chromaticities of a few colour samples.

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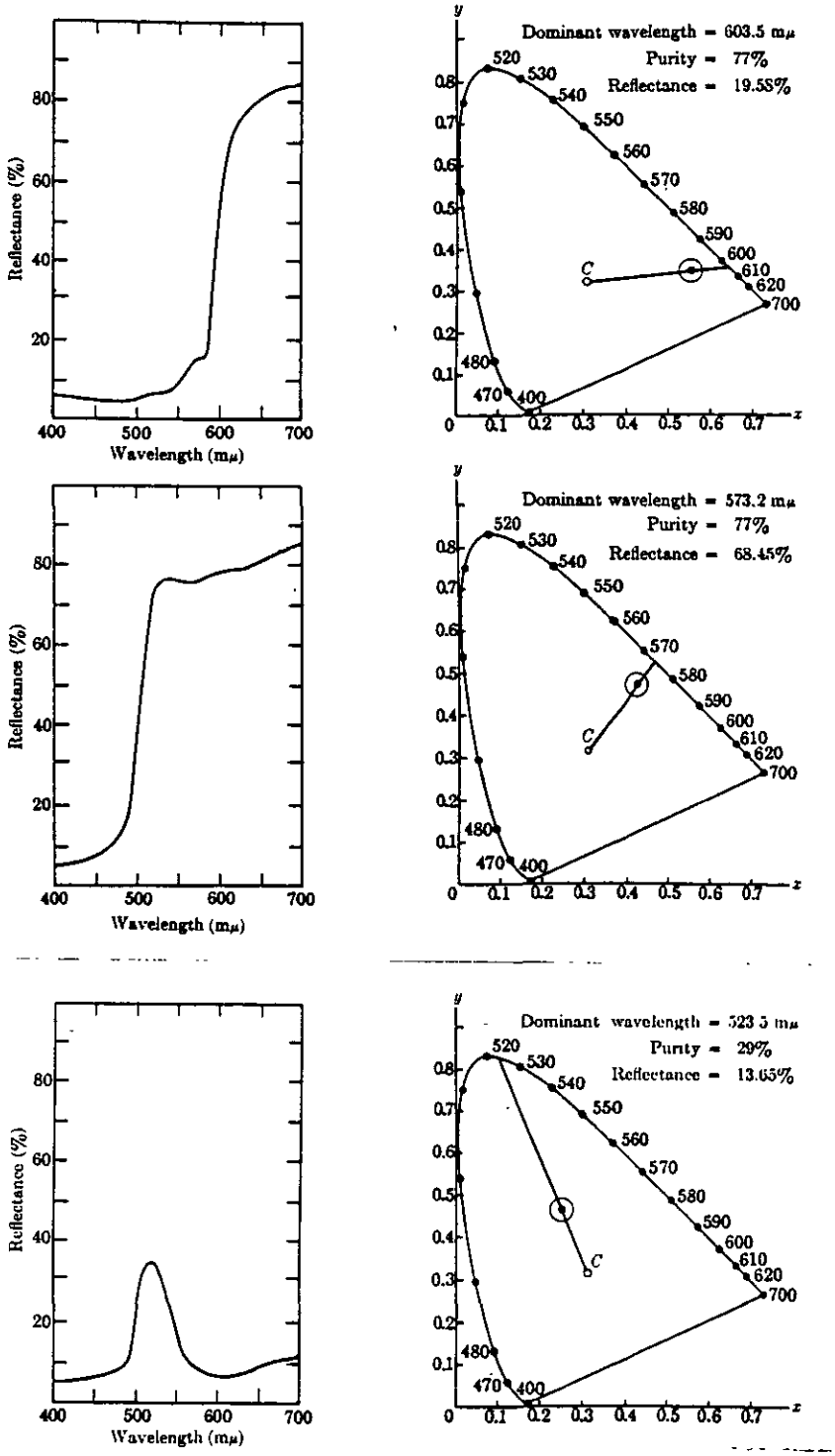
The curves were replotted on a smaller scale from the curves drawn by a recording spectrophotometer. Notice carefully that each sample reflects to some extent throughout the spectrum. That is, it is not true that the yellow sample reflects only yellow, the green sample only green, and so on.

2.3. ABRIDGED SPECTROPHOTOMETRY[3]

For approximate determination of spectral reflection and transmission curves, simple types of spectrophotometer are used in which narrow bands throughout the spectrum are produced by means of coloured filters sometimes again by mechanical screening of a spectrum. This method is known as abridged spectrophotometry. For a sample that has a very gradual change of reflectance with wavelength, the abridged approach may be entirely satisfactory. The widespread use of abridged spectrophotometry is due to the dual situation that most colours show gradual selective absorption and that such instruments are relatively inexpensive.



BRIGHT RED

YELLOW

GREEN

FIGURE 2.2

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2.4. ACCURACY OF RESULTS[4]

Let us now discuss some aspects, as well as a few components of the spectrophotometer, that may have an influence on the accuracy of results obtained.

a) Surface of sample

When determining whether two samples will match when viewed together, it is essential that the viewing and measuring situations give the same results. It is entirely possible, for example, to have a glossy and dull sample which have exactly the same colour to the eye but which measure quite differently on a particular instrument. Colours with these two surfaces if they measured alike on the instrument would look different.

When working with metal surfaces, you must be extra careful, for reasons that will soon become clear. When light strikes the surface of a metal it is selectively reflected. That is, some wavelengths are reflected more efficiently than others. This selective reflection is different for each type of metal, thus gold appears different from silver, which appears different from copper, and so on.

If the surface is somewhat rough, the tiny imperfections in the metal surface produce a certain amount of diffuse reflection, and the effective specular reflection is thus reduced. However, the spectral composition of the reflected light will be the same regardless of the nature of the surface (provided it is clean).

Whenever a glossy surface of the ordinary type-varnished wood or the like - is illuminated by sunlight, there is a relatively high percentage of light falling on the surface which is specularly reflected without selective absorption. When such a sample is seen by an observer who wants to look at the wood he turns it at such an angle that he does not see this specular beam. Most, but not all, spectrophotometers are designed to imitate this kind of viewing. The usual technique is to block out the beam which reflects from the front surface and measure only the light diffusely reflected from the material below. This works satisfactorily for samples in which the colour to be measured is produced diffusely. A case of particular importance is that of the metals. As noted earlier it is the specular beam that is selectively reflected,and the energy distribution of its colour determines the

appearance. If a highly polished sample of copper or brass is placed in an instrument which blocks out the specularly reflected beam, it will give either no reading at all or so little as not to be significant, even though the true reflectances may run from 60 to 100 percent. Obviously, in this case it is the specular component that should be picked up and measured.

In conclusion, be aware of the following: how the instrument will respond to the way the surface has been prepared; the angle at which the sample is placed with reference to the light source and the receptor.

b) Illuminance

As mentioned in the previous section, it is always important to give the source of illumination when giving the colour coordinates of a specific surface. Standard Illuminants A,B and C have been described in paragraph 8 of the previous section. The CIE Committee on colorimetry proposed in 1965 to define new standard illuminants called D which are intended to represent mean daylight of various colour temperatures[5]; the standard one is D6500 (or D65).

It must be emphasised that the illumination and the viewing conditions in a spectrophotometer must be made uniform if comparable sets of readings are to be obtained. Although this necessity is entirely correct as a generalization and holds for all samples of all types, its importance varies from one sample to another. For a few types of measurement uniformity of illumination and viewing conditions is so extremely important that a specially constructed instrument may be necessary, particularly when measurements are made on metallic surfaces or on those which fluoresce under ordinary illumination.

c) Photoelectric Receptors

It is a fact that two different persons will not observe a colour, or change in colour, in exactly the same way. This problem was greatly overcome by the development of the photocell. There are distinct advantages in using it rather than the eye. For instance, observations are independent of the observer and are made more quickly and with less fatigue. But there are two things about photoelectric receptors that must always be kept in mind:

i) the wavelength sensitivity of the receptor, and
ii) the absolute sensitivity of the receptor.

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i) In monochromatic spectrophotometry the wavelength sensitivity of the receptor, whether it is the eye, a photocell or any other photosensitive device, does not affect the result obtained. The fact that the light used is restricted to a narrow wavelength region means that only this range of the sensitivity is used for any one measurement. If this region is quite narrow, there will be no appreciable change in the sensitivity over such range, and the results will not change. If the range is larger, however, as it is in most of the abridged spectrophotometers, the change in sensitivity with wavelength will affect each reading differently and the result will no longer be independent of the receptor used. If a given sample is completely unknown, it follows that only an instrument with narrowest possible range can be used for the first measurement. If many samples known to be similar to it are to be measured, a suitable abridged type may then be used. This restriction is not severe in many applications, and abridged instruments, because of their lower cost and high operating speed, have many valuable applications. To avoid serious error, however, they should be used in conjunction with a monochromatic type.

ii) In general the lower the light intensity to which the receptor will respond measurably the lower is the minimum percent reflectance that may be determined with the instrument, although the minimum also depends on the intensity of the light falling on the sample and the way in which the reflected light is picked up from the sample. The ordinary spectrophotometer is not capable of reading less than one percent of reflectance in any part of the spectrum. Whereas this limitation is suitable for a good many samples, there are a great many cases for which it is entirely insufficient, especially in the blue end of the spectrum. Instruments for doing these measurements are too expensive for most practical purposes.

If a spectrophotometer is to give readings on the CIE system[6], it means that three filters of some kind must be provided which will give to the photocell spectral sensitivities similar to the $\bar{x}$, $\bar{y}$, and $\bar{z}$ distribution curves. Then if the output of the cell is proportional to the amount of light falling on it, and adjustments can be made so that the readings, using the three filters are equal for an equal energy source (or proportional to the tristimulus values for any other standard source used for calibration), observations on any colour sample will give readings proportional to the tristimulus values (or distribution coefficients), X, Y and Z of the sample.

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Two different methods have been adopted for producing the required spectral responses of the cell. In the first, optical and mechanical filters in the form of masks are used, while the second employs special glass or gelatine colour filters.

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REFERENCES AND NOTES FOR SECTION 2

1. From "Optics" by F.W. Sears, p 357, 359, 3rd ed. 1958.
2. A device that transmits a particular wavelength from a achromatic spectrum, is called a monochromator. Unfortunately a certain amount of stray white light is always present; it arises from the presence of small dust particles on the various optical components and from any multiple reflections which may occur in them. To remove this unwanted light the light from the monochromator is passed through a second monochromator which readily transmits the selected monochromatic beam and disperses the unwanted white light. The whole system is known as a double monochromator.
3. From "Optics" by C.J. Smith, p 436; 1960 and "An Introduction to Color" by R.M. Evans, p 190; 1959.
4. From "An Introduction to Color" by R.M. Evans, p 191-192 and "Optics" by C.J. Smith, p455-456.
5. For more information on colour temperatures, refer to "Light and Color" by R.D. Overheim and D.L. Wagner, p28-30, 1982.
6. This is an alternative method to those described in Appendix A, which assume a spectrophotometer only gives a reflectance versus wavelength curve.

NOTE:

Most of the references used for this section are more than 20 years old. Thus there could have been new developments and inventions since then, but the aim of this section was really to briefly outline the working principles of spectrophotometers and points which should be borne in mind when using them.

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APPENDIX A[1.1]

Here then is the procedure for the calculation of the tristimulus value X,Y and Z. Figure A-1 shows the three CIE color matching functions for the imaginary primaries $\bar{x},\bar{y},\bar{z}$.

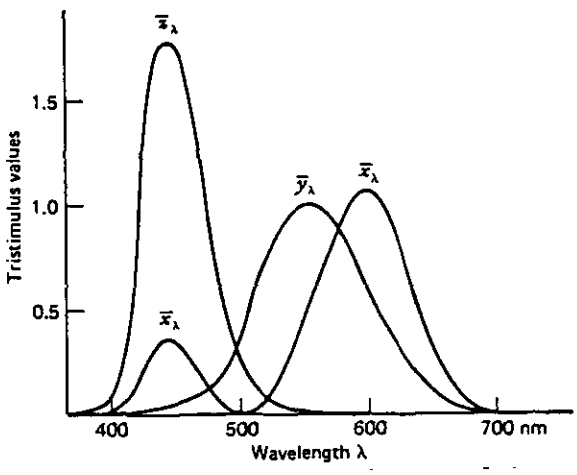

Figure A-1

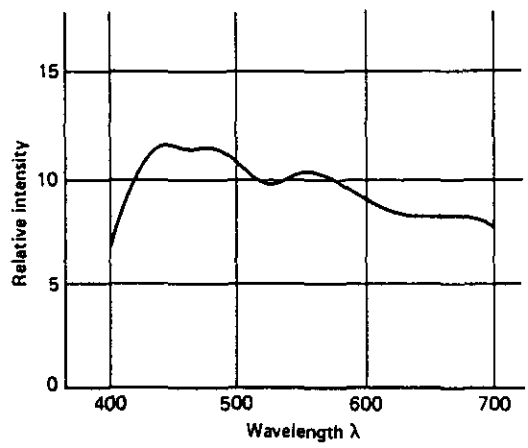

Figure A-3

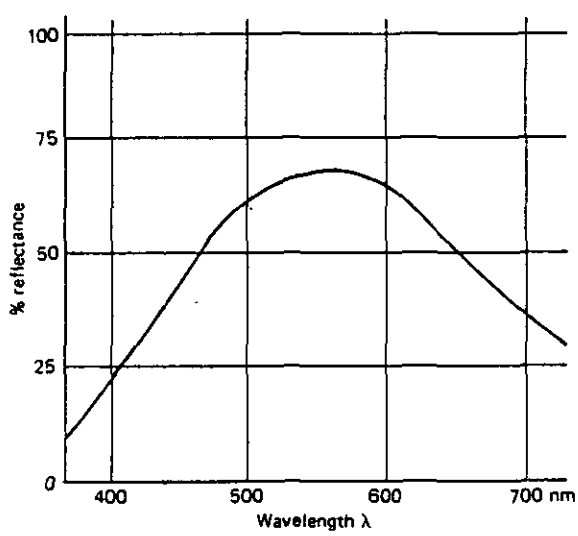

Figure A-2

Figure A-2 shows the reflectance curve of some hypothetical surface. Figure A-3 shows the spectral content of CIE Standard Illuminant C, which is supposed to represent light from the sky. To compute the tristimulus values of the surface of Figure A-2 when illuminated by Standard Source C, we recommend one of three methods:

Method 1

1) Divide the visible spectrum (400 nm-700 nm) into equal segments, say 10 with each 30 nm wide. The more segments that are used, the more accurate will be the calculation.

2) Use the wavelengths in the exact center of each segment. Thus you will use the following (in nm): 415, 445, 475, 505,535,565,595,625,655,685.

3) To compute the X tristimulus value we begin with the first of our 10 central wavelengths, 415 nm.

   i) On Figure A-1(or Table 39, Appendix B) we read the value of $\bar{x}$ at 415 nm.

   ii) On Figure A-3 we read the relative intensity of illuminant C at 415 nm. Multiply these two numbers.

   iii) Next, on Figure A-2 we read the value of the reflectance at 415 nm and multiply this number by the result of the previous multiplication.

   iv) Write this number down as the first of 10 numbers that will be needed to compute X.

   v) Now repeat the entire procedure for each of the remaining central wavelengths.

   vi) Add together all 10 the final answers to give X.

4) To compute the Y and Z tristimulus values use the same procedure as above, but on Figure A-1 (or Table 39) read values for $\bar{y}$ and $\bar{z}$ respectively.

5) Now compute the chromaticity coordinates as described in section 1.5.

Method 2

Computing forms such as these in Figure A-4a,b and c were developed to compute the tristimulus values X,Y and Z. Figure A-4a, was developed to compute the value of X. Notice on the figure that the 10 central wavelengths discussed above, are listed and that next to each wavelength is a double scale. The upper scale goes from zero to 100. The bottom scale goes from zero to some maximum value, different to each wavelength. To use the scale we proceed as follows:

1. i) From figure A-2 read the reflectance percentage at 415 nm.

   ii) Find the percentage on the top scale next to 415 nm of computing from Figure A-4a. Make a mark at this percentage.

   iii) This mark will fall at a definite place on the lower scale following 415 nm.

   iv) Read the number from the lower scale and write it in the blank space provided to the right of the scale.

   v) Repeat the procedure for each wavelength listed.

   vi) Add these 10 numbers to get X.

2. The computing forms shown in Figure A-4b and A-4c are used to find Y and Z in the same fashion.

3. The numbers X,Y and Z you have now, are the tristimulus values of the surface whose reflectance curve is given by figure A-2.

4. Further information on computing forms:

   i) These tristimulus values assume that the surface is illuminated by standard source C, and the computing forms were constructed with this source in mind.

   ii) If the illumination were changed to standard source A or B, then a new set of computing forms would be required.

   iii) Computing forms for Standard Illuminants A,B and C are available commercially.

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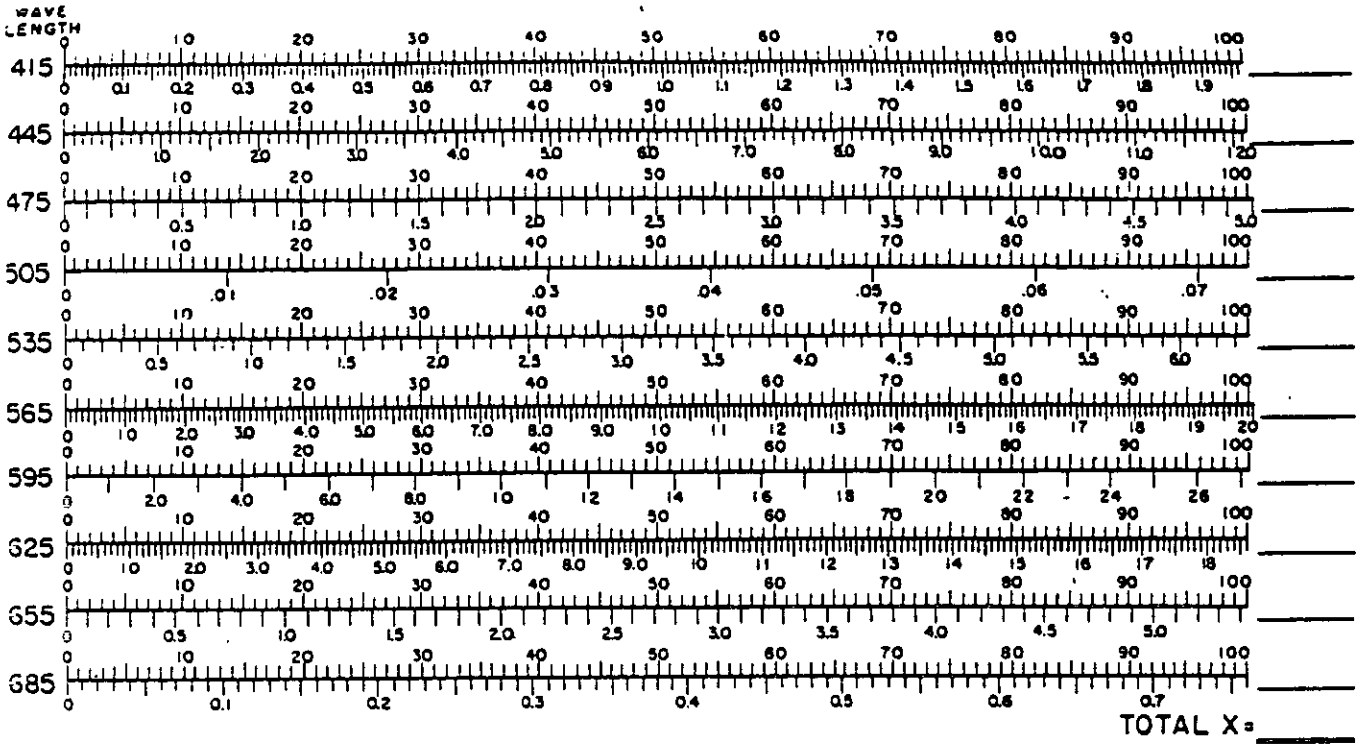
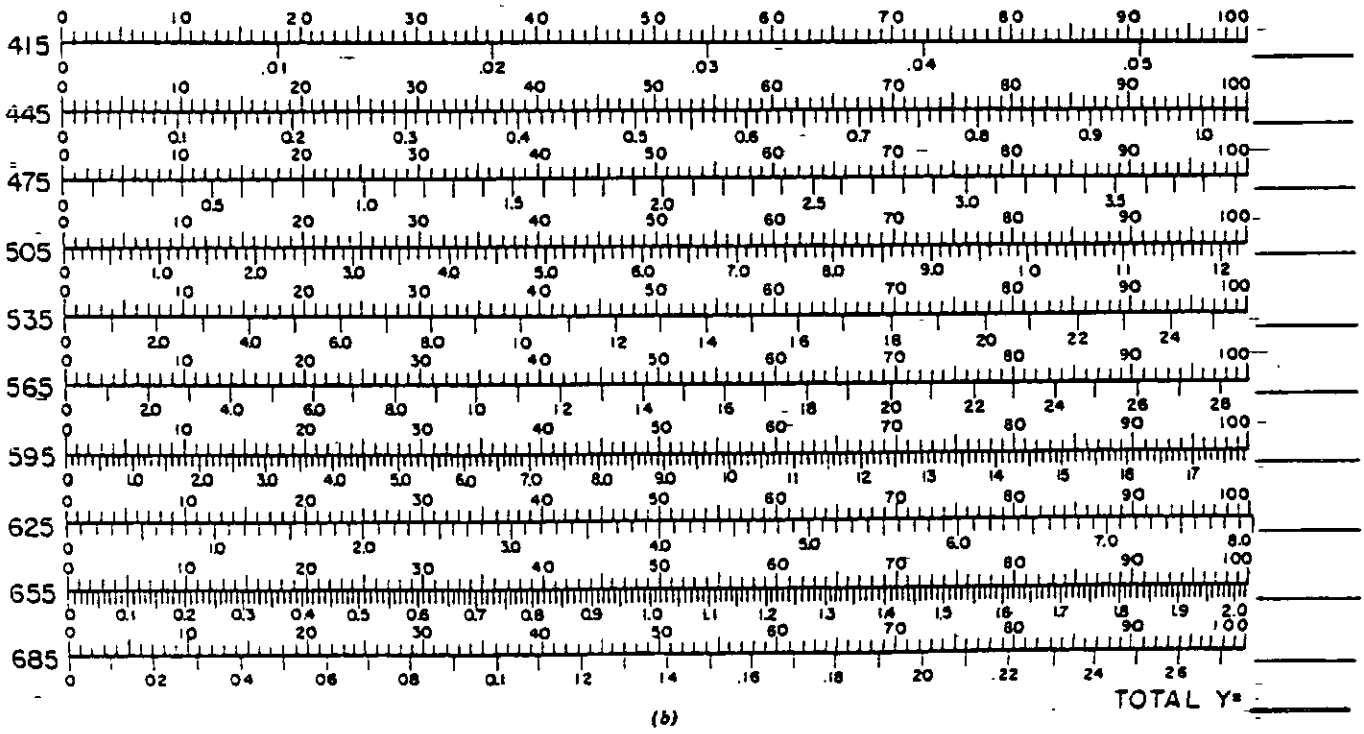


(a)

Figure A-4a Computing form for calculating X, assuming illumination by Standard Source C. (From Bausch and Lomb)



(b)

Figure A-4b Computing form for calculating Y, assuming illumination by Standard Source C. (From Bausch and Lomb)

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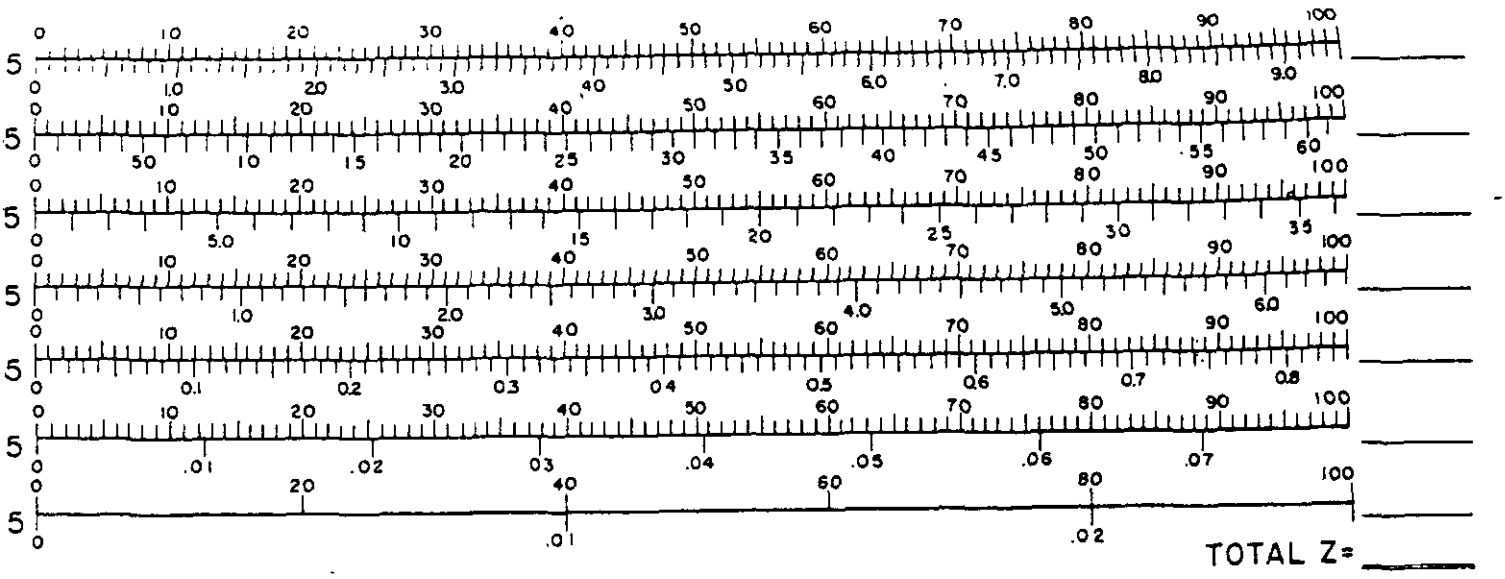

(c)

Figure A-4c Computing form for calculating Z assuming illumination by Standard Source C. (From Bausch and Lomb)

X = _____ Y = _____ Z = _____

$x = \frac{X}{X + Y + Z}$ $y = \frac{Y}{X + Y + Z}$

x = _____ y = _____

From Figure A-5:

λ_D = _____

ρ = _____

_____

Method 3

The tristimulus values X,Y and Z can also be computed by means of integration[5].

In Conclusion

The calculations above assume that you have a reflectance curve for the surface of interest. If such a curve has not been measured, then it will be necessary to make one yourself. However, measurements need only to be made at those wavelengths listed on the computing forms.

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APPENDIX B

Numerical Tables of the XYZ system

From: i) "Light, Colour and Vision" by Yves Le Grand, 2nd ed. 1968.

ii) Table 43 - "An Introduction to Color" by Ralph M. Evans, 1959 p 208.

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TABLE 38

Chromaticity co-ordinates

λ	x	y	z	λ	x	y	z
380	0·1741	0·0050	0·8209	545	0·2658	0·7243	0·0099
385	0·17398	0·00495	0·82107	550	0·3016	0·6923	0·0061
390	0·1738	0·0049	0·8213	555	0·3373	0·6589	0·0038
395	0·17358	0·00484	0·82158	560	0·3731	0·62448	0·00242
400	0·1733	0·0048	0·8219	565	0·4078	0·58968	0·00162
405	0·17299	0·00478	0·82223	570	0·4441	0·55470	0·00120
410	0·1726	0·0048	0·8226	575	0·4788	0·52022	0·00098
415	0·1721	0·0048	0·8231	580	0·5125	0·48664	0·00086
420	0·1714	0·0051	0·8235	585	0·5448	0·45445	0·00075
425	0·1703	0·0058	0·8239	590	0·5752	0·42415	0·00065
430	0·1689	0·0069	0·8242	595	0·6029	0·39655	0·00055
435	0·1669	0·0086	0·8245	600	0·6270	0·37255	0·00045
440	0·1644	0·0109	0·8247	605	0·6482	0·35145	0·00035
445	0·1611	0·0138	0·8251	610	0·6658	0·33395	0·00025
450	0·1566	0·0177	0·8257	615	0·6801	0·31970	0·00020
455	0·1510	0·0227	0·8263	620	0·6915	0·30834	0·00016
460	0·1440	0·0297	0·8263	625	0·7006	0·29927	0·00013
465	0·1355	0·0399	0·8246	630	0·7079	0·29200	0·00010
470	0·1241	0·0578	0·8181	635	0·7140	0·28593	0·00007
475	0·1096	0·0868	0·8306	640	0·7190	0·28095	0·00005
480	0·0913	0·1327	0·7760	645	0·7230	0·27697	0·00003
485	0·0687	0·2007	0·7306	650	0·7260	0·27399	0·00001
490	0·0454	0·2950	0·6596	655	0·7283	0·2717	
495	0·0235	0·4127	0·5638	660	0·7300	0·2700	
500	0·0082	0·5384	0·4534	665	0·7311	0·2689	
505	0·0039	0·6548	0·3413	670	0·7320	0·2680	
510	0·0139	0·7502	0·2359	675	0·7327	0·2673	
515	0·0389	0·8120	0·1491	680	0·7334	0·2666	
520	0·0743	0·8338	0·0919	685	0·73397	0·26603	
525	0·1142	0·8262	0·0596	690	0·7344	0·2656	
530	0·1547	0·8059	0·0394	695	0·73461	0·26539	
535	0·1929	0·7816	0·0255	700	0·73467	0·26533	
540	0·2296	0·7543	0·0161	780	0·73467	0·26533	

TABLE 39

Distribution coefficients (equal energy spectrum)

λ	$\bar{x}$	$\bar{y}$	$\bar{z}$	λ	$\bar{x}$	$\bar{y}$	$\bar{z}$
380	0·00139	0·00004	0·0066	580	0·9162	0·8700	0·00154
385	0·00226	0·00006	0·0107	585	0·9785	0·8163	0·00135
390	0·00426	0·00012	0·0201	590	1·0266	0·7570	0·00116
395	0·00771	0·00022	0·0365	595	1·0566	0·6949	0·00096
400	0·0144	0·00040	0·0685	600	1·0620	0·6310	0·00076
405	0·0233	0·00064	0·1105	605	1·0453	0·5668	0·00056
410	0·0432	0·00120	0·2056	610	1·0028	0·5030	0·00038
415	0·0780	0·00218	0·3730	615	0·9387	0·4412	0·00028
420	0·1344	0·00400	0·6459	620	0·8545	0·3810	0·00020
425	0·2132	0·0073	1·0317	625	0·7515	0·3210	0·00014
430	0·2839	0·0116	1·3856	630	0·6424	0·2650	0·00009
435	0·3268	0·0168	1·6142	635	0·5419	0·2170	0·00005
440	0·3469	0·0230	1·7402	640	0·4479	0·1750	0·00003
445	0·3483	0·0298	1·7840	645	0·3609	0·1382	0·00002
450	0·3362	0·0380	1·7727	650	0·2835	0·1070	
455	0·3193	0·0480	1·7472	655	0·2186	0·0816	
460	0·2909	0·0600	1·6693	660	0·1649	0·0610	
465	0·2509	0·0739	1·5268	665	0·1212	0·0446	
470	0·1954	0·0910	1·2880	670	0·0874	0·0320	
475	0·1422	0·1126	1·0427	675	0·0637	0·0232	
480	0·0956	0·1390	0·8128	680	0·0468	0·0170	
485	0·0580	0·1693	0·6163	685	0·0329	0·0119	
490	0·0320	0·2080	0·4651	690	0·0227	0·0082	
495	0·0147	0·2586	0·3532	695	0·0158	0·00572	
500	0·0049	0·3230	0·2720	700	0·01135	0·00410	
505	0·0024	0·4073	0·2123	705	0·00806	0·00291	
510	0·0093	0·5030	0·1582	710	0·00581	0·00210	
515	0·0291	0·6082	0·1117	715	0·00411	0·00148	
520	0·0633	0·7100	0·0783	720	0·00291	0·00105	
525	0·1096	0·7932	0·0572	725	0·00204	0·00074	
530	0·1655	0·8620	0·0421	730	0·00144	0·00052	
535	0·2258	0·9149	0·0299	735	0·00100	0·00036	
540	0·2904	0·9540	0·0204	740	0·00069	0·00025	
545	0·3597	0·9802	0·0134	745	0·00048	0·00017	
550	0·4335	0·9950	0·00877	750	0·00033	0·00012	
555	0·5120	1·0002	0·00577	755	0·00023	0·00008	
560	0·5945	0·9950	0·00386	760	0·00017	0·00006	
565	0·6783	0·9786	0·00269	765	0·00012	0·00004	
570	0·7622	0·9520	0·00206	770	0·00008	0·00003	
575	0·8425	0·9154	0·00172	sums	21·3683	21·3714	21·3531

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TABLE 40

Distribution coefficients for Standard Illuminant A

λ	$\bar{x}_A$	$\bar{y}_A$	$\bar{z}_A$	λ	$\bar{x}_A$	$\bar{y}_A$	$\bar{z}_A$
380	0·0006		0·0030	580	4·8590	4·6139	0·0082
385	0·0012		0·0054	585	5·3545	4·4665	0·0074
390	0·0024		0·0113	590	5·7910	4·2703	0·0065
395	0·0048	0·0001	0·0226	595	6·1393	4·0381	0·0056
400	0·0098	0·0003	0·0467	600	6·3504	3·7733	0·0045
405	0·0174	0·0005	0·0827	605	6·4280	3·4852	0·0035
410	0·0354	0·0010	0·1685	610	6·3361	3·1780	0·0024
415	0·0697	0·0020	0·3334	615	6·0894	2·8625	0·0018
420	0·1308	0·0039	0·6286	620	5·6868	2·5357	0·0013
425	0·2252	0·0077	1·0895	625	5·1271	2·1901	0·0010
430	0·3246	0·0133	1·5841	630	4·4904	1·8523	0·0006
435	0·4034	0·0208	1·9928	635	3·8776	1·5528	0·0004
440	0·4614	0·0306	2·3145	640	3·2787	1·2812	0·0002
445	0·4980	0·0426	2·5504	645	2·7011	1·0347	0·0001
450	0·5155	0·0583	2·7183	650	2·1683	0·8183	
455	0·5239	0·0788	2·8671	655	1·7072	0·6369	
460	0·5098	0·1052	2·9256	660	1·3143	0·4861	
465	0·4685	0·1380	2·8513	665	0·9847	0·3622	
470	0·3882	0·1808	2·5588	670	0·7241	0·2651	
475	0·3000	0·2376	2·1995	675	0·5376	0·1961	
480	0·2138	0·3108	1·8175	680	0·4019	0·1461	
485	0·1370	0·4005	1·4578	685	0·2875	0·1042	
490	0·0800	0·5196	1·1619	690	0·2017	0·0729	
495	0·0388	0·6812	0·9306	695	0·1433	0·0518	
500	0·0136	0·8960	0·7545	700	0·1043	0·0377	
505	0·0071	1·1876	0·6190	705	0·0752	0·0272	
510	0·0285	1·5398	0·4842	710	0·0551	0·0199	
515	0·0935	1·9519	0·3584	715	0·0395	0·0143	
520	0·2126	2·3854	0·2629	720	0·0284	0·0102	
525	0·3850	2·7858	0·2010	725	0·0202	0·0073	
530	0·6068	3·1609	0·1545	730	0·0144	0·0052	
535	0·8635	3·4988	0·1141	735	0·0101	0·0037	
540	1·1566	3·7998	0·0811	740	0·0071	0·0026	
545	1·4905	4·0616	0·0555	745	0·0050	0·0018	
550	1·8663	4·2840	0·0378	750	0·0035	0·0013	
555	2·2884	4·4702	0·0258	755	0·0025	0·0009	
560	2·7548	4·6109	0·0179	760	0·0018	0·0006	
565	3·2557	4·6974	0·0129	765	0·0013	0·0005	
570	3·7856	4·7284	0·0102	770	0·0009	0·0003	
575	4·3259	4·7001	0·0089	sums	109·8439	100·0000	35·5641

TABLE 41

Distribution coefficients for Standard Illuminant B

λ	$\bar{x}_B$	$\bar{y}_B$	$\bar{z}_B$	λ	$\bar{x}_B$	$\bar{y}_B$	$\bar{z}_B$
380	0·0015		0·0070	580	4·4214	4·1983	0·0074
385	0·0029	0·0001	0·0137	585	4·6786	3·9027	0·0065
390	0·0064	0·0002	0·0301	590	4·8657	3·5879	0·0055
395	0·0133	0·0004	0·0631	595	4·9694	3·2686	0·0045
400	0·0285	0·0008	0·1352	600	4·9725	2·9545	0·0036
405	0·0518	0·0014	0·2462	605	4·8984	2·6559	0·0026
410	0·1074	0·0030	0·5119	610	4·7195	2·3673	0·0018
415	0·2150	0·0060	1·0282	615	4·4427	2·0884	0·0013
420	0·4059	0·0121	1·9503	620	4·0702	1·8149	0·0010
425	0·6966	0·0237	3·3700	625	3·6034	1·5392	0·0007
430	0·9917	0·0405	4·8394	630	3·1002	1·2788	0·0004
435	1·2070	0·0622	5·9627	635	2·6294	1·0530	0·0002
440	1·3392	0·0888	6·7181	640	2·1869	0·8545	0·0001
445	1·3886	0·1190	7·1121	645	1·7768	0·6807	0·0001
450	1·3718	0·1550	7·2331	650	1·4075	0·5312	
455	1·3254	0·1992	7·2528	655	1·0925	0·4076	
460	1·2273	0·2531	7·0426	660	0·8274	0·3060	
465	1·0798	0·3180	6·5710	665	0·6083	0·2237	
470	0·8588	0·4000	5·6617	670	0·4381	0·1604	
475	0·6370	0·5045	4·6705	675	0·3182	0·1161	
480	0·4350	0·6323	3·6972	680	0·2322	0·0844	
485	0·2665	0·7785	2·8338	685	0·1616	0·0586	
490	0·1476	0·9590	2·1443	690	0·1101	0·0398	
495	0·0673	1·1824	1·6153	695	0·0761	0·0275	
500	0·0221	1·4538	1·2242	700	0·0538	0·0194	
505	0·0107	1·7973	0·9368	705	0·0376	0·0136	
510	0·0405	2·1798	0·6854	710	0·0267	0·0097	
515	0·1248	2·6054	0·4784	715	0·0185	0·0067	
520	0·2705	3·0361	0·3346	720	0·0129	0·0047	
525	0·4737	3·4271	0·2472	725	0·0089	0·0032	
530	0·7289	3·7973	0·1857	730	0·0062	0·0022	
535	1·0191	4·1293	0·1347	735	0·0042	0·0015	
540	1·3444	4·4168	0·0943	740	0·0029	0·0011	
545	1·7043	4·6442	0·0635	745	0·0020	0·0007	
550	2·0918	4·8015	0·0423	750	0·0013	0·0005	
555	2·5003	4·8842	0·0282	755	0·0010	0·0003	
560	2·9198	4·8871	0·0189	760	0·0007	0·0002	
565	3·3353	4·8123	0·0132	765	0·0005	0·0002	
570	3·7363	4·6668	0·0101	770	0·0004	0·0001	
575	4·1018	4·4567	0·0084	sums	99·0813	100·0000	85·2519

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TABLE 42

Distribution coefficients for Standard Illuminant C

λ	$\bar{x}_c$	$\bar{y}_c$	$\bar{z}_c$	λ	$\bar{x}_c$	$\bar{y}_c$	$\bar{z}_c$
380	0·0022		0·0101	580	4·2081	3·9958	0·0070
385	0·0042	0·0001	0·0200	585	4·3853	3·6580	0·0061
390	0·0095	0·0003	0·0448	590	4·4932	3·3132	0·0051
395	0·0200	0·0006	0·0945	595	4·5261	2·9770	0·0041
400	0·0429	0·0012	0·2036	600	4·4735	2·6580	0·0032
405	0·0784	0·0022	0·3727	605	4·3605	2·3643	0·0023
410	0·1633	0·0046	0·7784	610	4·1632	2·0881	0·0015
415	0·3279	0·0091	1·5681	615	3·8875	1·8275	0·0011
420	0·6193	0·0184	2·9755	620	3·5351	1·5763	0·0008
425	1·0595	0·0361	5·1258	625	3·1076	1·3275	0·0006
430	1·4989	0·0612	7·3138	630	2·6549	1·0952	0·0004
435	1·8070	0·0931	8·9263	635	2·2357	0·8954	0·0002
440	1·9794	0·1312	9·9292	640	1·8466	0·7216	0·0001
445	2·0194	0·1730	10·3424	645	1·4912	0·5713	
450	1·9578	0·2213	10·3227	650	1·1744	0·4432	
455	1·8534	0·2786	10·1418	655	0·9056	0·3378	
460	1·6818	0·3469	9·6501	660	0·6808	0·2518	
465	1·4527	0·4278	8·8404	665	0·4963	0·1825	
470	1·1359	0·5291	7·4882	670	0·3542	0·1297	
475	0·8287	0·6563	6·0761	675	0·2552	0·0931	
480	0·5565	0·8088	4·7295	680	0·1845	0·0671	
485	0·3346	0·9774	3·5578	685	0·1269	0·0460	
490	0·1815	1·1790	2·6361	690	0·0854	0·0309	
495	0·0808	1·4195	1·9391	695	0·0582	0·0210	
500	0·0259	1·7004	1·4320	700	0·0407	0·0147	
505	0·0122	2·0460	1·0665	705	0·0281	0·0101	
510	0·0448	2·4165	0·7599	710	0·0198	0·0071	
515	0·1352	2·8224	0·5183	715	0·0136	0·0049	
520	0·2879	3·2309	0·3561	720	0·0093	0·0034	
525	0·4983	3·6050	0·2601	725	0·0063	0·0023	
530	0·7615	3·9671	0·1940	730	0·0044	0·0016	
535	1·0598	4·2941	0·1401	735	0·0030	0·0011	
540	1·3923	4·5742	0·0976	740	0·0020	0·0007	
545	1·7561	4·7852	0·0654	745	0·0014	0·0005	
550	2·1414	4·9156	0·0433	750	0·0009	0·0003	
555	2·5409	4·9636	0·0286	755	0·0006	0·0002	
560	2·9397	4·9203	0·0191	760	0·0005	0·0001	
565	3·3161	4·7847	0·0131	765	0·0003	0·0001	
570	3·6616	4·5736	0·0099	770	0·0002	0·0001	
575	3·9624	4·3052	0·0081	sums	98·0535	100·0000	118·1305

TABLE 43

Tabulated spectral-distribution data of standard CIE illuminants A,B and C

Wavelength	E_A	E_B	E_C
380	9.79	22.40	33.00
390	12.09	31.30	47.40
400	14.71	41.30	63.30
410	17.68	52.10	80.60
420	21.00	63.20	98.10
430	24.67	73.10	112.40
440	28.70	80.80	121.50
450	33.09	85.40	124.00
460	37.82	88.30	123.10
470	42.87	92.00	123.80
480	48.25	95.20	123.90
490	53.91	96.50	120.70
500	59.86	94.20	112.10
510	66.06	90.70	102.30
520	72.50	89.50	96.90
530	79.13	92.20	98.00
540	85.95	96.90	102.10
550	92.91	101.00	105.20
560	100.00	102.80	105.30
570	107.18	102.60	102.30
580	114.44	101.00	97.80
590	121.73	99.20	93.20
600	129.04	98.00	89.70
610	136.34	98.50	88.40
620	143.62	99.70	88.10
630	150.83	101.00	88.00
640	157.98	102.20	87.80
650	165.03	103.90	88.20
660	171.96	105.00	87.90
670	178.77	104.90	86.30
680	185.43	103.90	84.00
690	191.93	101.60	80.20
700	198.26	99.10	76.30
710	204.41	96.20	72.40
720	210.36	92.90	68.30
730	216.12	89.40	64.40
740	221.66	86.00	61.50
750	227.00	85.20	59.20
760	232.11	84.70	58.10
770	237.01	85.40	58.20
780	241.67	87.00	59.10

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