
ASSIST *recommends...*

Recommendations for Specifying Color Properties of Light Sources for Retail Merchandising

Volume 8, Issue 2
March 2010

A publication of the Alliance for Solid-State Illumination Systems and Technologies

Lighting
Research Center



Copyright © 2010 by the Alliance for Solid-State Illumination Systems and Technologies (ASSIST).

Published by the Lighting Research Center, Rensselaer Polytechnic Institute, 21 Union St., Troy, NY 12180 USA. Online at <http://www.lrc.rpi.edu>.

All rights reserved. No part of this publication may be reproduced in any form, print, electronic, or otherwise, without the express permission of the Lighting Research Center.

This *ASSIST recommends* was prepared by the Lighting Research Center at the request of the Alliance for Solid-State Illumination Systems and Technologies (ASSIST). The recommendations set forth here are developed by consensus of ASSIST sponsors and the Lighting Research Center. ASSIST and the Lighting Research Center may update these recommendations as new research, technologies, and methods become available.

Check for new and updated *ASSIST recommends* documents at:

<http://www.lrc.rpi.edu/programs/solidstate/assist/recommends.asp>

ASSIST Sponsors

Acuity Brands Lighting
Bridgelux
China Solid State Lighting Alliance
Cree
Everlight Electronics Co., Ltd.
Federal Aviation Administration
GE Lumination
ITRI, Industrial Technology Research Institute
LG Innotek
Lighting Science Group
Lite-On
NeoPac Lighting
New York State Energy Research and Development Authority
OSRAM SYLVANIA / OSRAM Opto Semiconductors
Perilight
Philips Color Kinetics
Seoul Semiconductor
Sharp Laboratories of America
United States Environmental Protection Agency
WAC Lighting

Lighting Research Center Technical Staff

Mark S. Rea, Jean Paul Freyssinier

Contents

Introduction	4
Proposed Systems.....	4
Correlated Color Temperature.....	4
Color Rendering.....	5
Step 1	6
Step 2	6
Step 3	7
Step 4	8
References.....	9
Acknowledgments	9
About ASSIST.....	9
Appendix A: Calculating Chromaticity	10
Appendix B: Calculating Color Rendering Index.....	12
Appendix C: Calculating Gamut Area Index.....	18
Appendix D: Spectral Data Used in the Examples	21

Introduction

This document offers specific guidance on how to specify light sources for retail applications using a two-metric approach for both CCT and CRI. The approaches detailed here are applicable to all light source technologies.

A companion publication, *ASSIST recommends...Guide to Light and Color in Retail Merchandising* (Vol. 8, Iss. 1), discusses the importance of color appearance in retail merchandising for achieving two goals: setting the atmosphere in the store and helping customers evaluate products for sale. That document presents the background and rationale behind the recommendations proposed here for achieving each of the two retail goals:

- a two-metric system for light source color appearance, correlated color temperature (CCT) plus proposed tolerance zones, for the first goal; and
- a two-metric system for color rendering, color rendering index (CRI)* and gamut area index (GAI), for the second goal.

Proposed Systems

Correlated Color Temperature

Proposed here is a two-metric approach for achieving satisfactory and consistent results in selecting the color appearance of light sources for retail merchandising applications.

As discussed in detail in *ASSIST recommends...Guide to Light and Color in Retail Merchandising* (Vol. 8, Iss. 1), it is necessary to have tolerance zones associated with a CCT to overcome the limitations of providing a CCT value by itself. As described in that document, ANSI/NEMA have specified CCT tolerance zones for solid-state light sources, but it remains to be seen whether the large number of CCTs available and their tolerance zones can provide acceptable color appearance consistency in retail merchandising applications. The recommendation proposed here simplifies the number of CCTs to the four most commonly used in practice—3000 K, 3500 K, 4000/4100 K, and 5000 K—and proposes more restrictive tolerance zones than those specified by ANSI/NEMA² to maximize consistency among products. The tolerance zone size proposed here for each CCT is approximately equal to 8 just-noticeable differences (jnds) or 4-step MacAdam ellipses (Figure 1; the chromaticity values of the corners that define each CCTr are given in Table 1). The combination of a target CCT and its associated tolerance zone is termed here as *correlated color temperature trapezoid*, or CCTr.

To use the two-metric lamp color appearance system, it is necessary to derive the CIE 1976 (u'v') chromaticity coordinates of the light source and determine whether they fall inside the target CCTr (Appendix A). Lighting specifiers may ask the manufacturer to determine the chromaticity coordinates of a light source of interest, or ask manufacturers to recommend light sources that fall within the proposed tolerance area.

* For the purpose of this document, CRI is used synonymously with general CRI, also denoted as R_a .¹

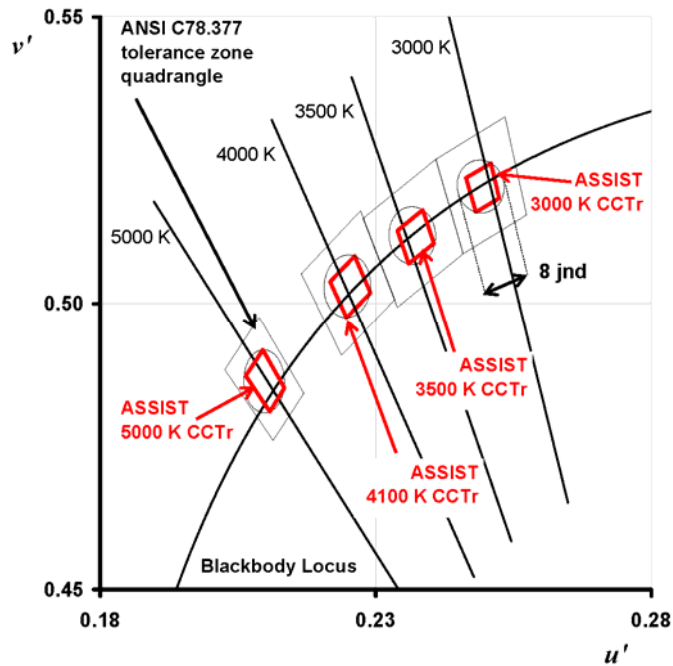


Figure 1. Correlated color temperature trapezoids for the four recommended CCTs for retail applications. Also shown in the figure for reference are the ANSI/NEMA tolerance zone quadrangles² and the 8 jnd-wide tolerance zones on which each CCTr is based.

Table 1. CIE 1976 ($u'v'$) chromaticities of the corners that define each CCTr.

3000 K		3500 K		4000 K		5000 K	
u'	v'	u'	v'	u'	v'	u'	v'
0.2509	0.5245	0.2385	0.5163	0.2262	0.5083	0.2095	0.4918
0.2524	0.5184	0.2405	0.5105	0.2290	0.5019	0.2134	0.4852
0.2482	0.5160	0.2360	0.5070	0.2247	0.4975	0.2108	0.4810
0.2464	0.5219	0.2339	0.5127	0.2217	0.5038	0.2064	0.4873

Color Rendering

Proposed here is a two-metric system that tries to optimize stability and enhancement while, from a practical perspective, continuing the use of CRI, the traditional measure of color rendering, and minimizing the burden of making additional, complicated color-rendering calculations.

The proposed two-metric system is quite simple to use and is a simplification of the multiple-metric color rendering proposal introduced by Figueiro et al. for illumination of neonatal care intensive units.³ The first color rendering metric in the proposed system, CRI, is determined in exactly the same way as it has been for nearly 50 years. Importantly, CRI is the most widely recognized color rendering metric used today and is based upon the shift in the chromaticity of eight standard chips, or test-color samples (TCS), relative to a reference source of the same correlated color temperature (CCT).¹

The second color rendering metric is also based upon the chromaticity of the eight standard chips. Gamut area index (GAI), introduced by Rea et al., is based upon the area of the polygon formed by the eight TCS in the CIE 1976 uniform color space under the light source of interest, relative to the polygon formed by the TCS illuminated by an equal energy spectrum (EES).^{1,4} The ratio of these two values is determined and multiplied by 100. Thus, GAI is equal to 100 for an equal energy spectrum and all other light sources are scaled from 0 to more than 100.

Experimental results have shown consistently that light sources with both high CRI and GAI are generally preferred over light sources with only high CRI or only high GAI.^{5,6} Rea and Freyssonier^{5,6} have shown experimentally that observers rate light sources meeting the criteria for both high CRI ($80 \leq \text{CRI}$) and high (but not too high) GAI ($80 \leq \text{GAI} \leq 100$) as better in terms of apparent naturalness, apparent vividness, and overall preference when used to illuminate a multicolored display. The results are applicable to warm and cool correlated color temperatures (CCT~3000 K and CCT~5000 K).

The following steps show the use of the two-metric lamp color rendering system with an example.

Step 1

Determine the CRI of the light source. If the CRI value is not available from the manufacturer, it can be calculated from the spectral power distribution following the methodology outlined in Appendix B. The example below is given for an EES (Figure 2). An EES is a mathematically defined illuminant that is used as the reference for GAI. It has a CRI of 95 and a CCT of 5455 K.

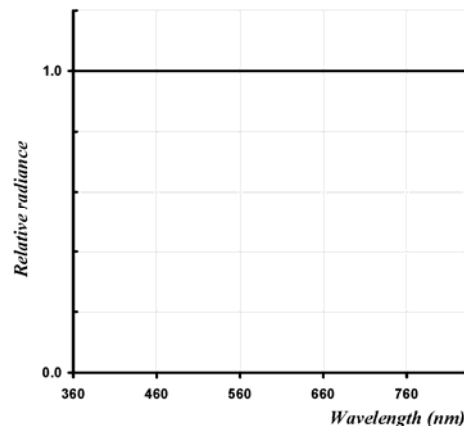


Figure 2. Equal energy spectrum normalized to unity.

Step 2

Determine the GAI of the light source. If the GAI value is not available from the manufacturer, it can be calculated from the spectral power distribution following the methodology outlined in Appendix C. Because an EES is used as the reference to scale the GAI of other light sources, it has a GAI of 100.³⁻⁵

Step 3

Determine if the CRI and GAI of the source are in the recommended range: $80 \leq \text{CRI}$ and $80 \leq \text{GAI} \leq 100$. Table 2 contains examples of commercial light sources that meet the two-metric criterion ($80 \leq \text{CRI}$ and $80 \leq \text{GAI} \leq 100$). This table is not intended to be a comprehensive compilation but includes sample light sources in all families (i.e., incandescent, fluorescent, high-intensity discharge, and SSL). *(The inclusion or mention of any specific brand or product in this document is for illustrative purposes only and does not constitute an endorsement by ASSIST or the Lighting Research Center.)*

Figure 3 shows graphically the ideal zone where light sources should plot so that the two-metric criterion for both high CRI and high (but not too high) GAI are met.

Table 2. Examples of light sources that meet the criteria for CRI (≥ 80) and GAI (≥ 80 and ≤ 100). (The inclusion or mention of any specific brand or product in this table is for illustrative purposes only and does not constitute an endorsement by ASSIST or the Lighting Research Center.)

	Light source	Manufacturer	Product Model	CCT (K)	CRI	GAI
1	Xenon	OSRAM SYLVANIA	1000W	5853	97	91
2	PC-LED	Cree	XRE lamp	4154	84	82
3	PC-LED	Sharp	Zenigata	5097	95	99
4	RGB-LED	Various	Peak wavelengths of 465 nm, 545 nm, and 614 nm	4000	89	82
5	T8	General Electric	F32T8SPX50	4751	87	86
6	T8	Lumiram	Lumichrome 1XX	5960	93	95
7	T8	Verilux	F32T8VLX	6369	85	96
8	T12	OSRAM SYLVANIA	Design50, 40W	4861	90	84
9	T12	General Electric	Sunshine F40C50	4944	92	87
10	T12	Duro-Test	Vita-Lite 5500	5159	88	90
11	T12	Lumiram	Lumichrome 1XC	5207	92	93
12	T12	Philips	Colortone 75	6217	90	85
13	T12	Duro-Test	DAYLITE 65, 40W	6588	93	95
14	MH	Philips	CDM100W/4K	4075	93	80
15	MH	Philips	CDM150W/4K	4197	92	83
16	Daylight		CIE D50	5000	100	88
17	Daylight		CIE D65	6500	100	98

PC-LED: phosphor-converted white light-emitting diode
 RGB-LED: red, green and blue LEDs mixed to create white light
 T8: linear fluorescent, 25 mm diameter
 T12: linear fluorescent, 38 mm diameter
 MH: metal halide

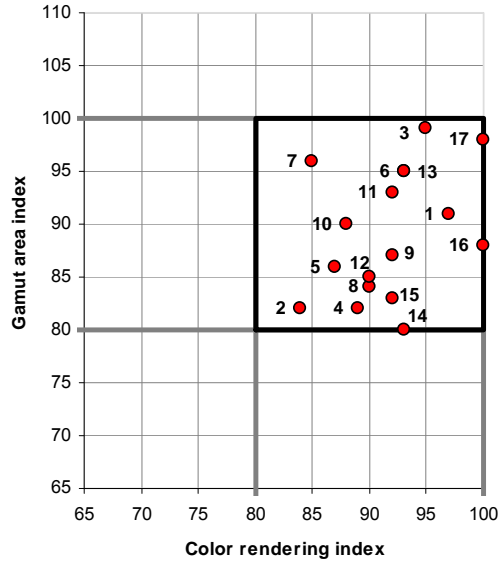


Figure 3. CRI and GAI of the light sources listed in Table 1. The black square shows the target zone for light sources that have both high CRI and high GAI.

Step 4

Select a light source in the recommended range: $80 \leq \text{CRI}$ and $80 \leq \text{GAI} \leq 100$. Selecting sources with both high CRI and high (but not too high) GAI values increases the chances that the light source will make objects appear vivid, natural and acceptable in most architectural applications, including retail settings. However, it is worth emphasizing that in certain applications where particular colors are of interest, other color metrics may still be needed to quantify a light source’s ability to render those specific colors.

References

1. Commission Internationale de l'Éclairage (CIE). 1995. *Technical report: Method of measuring and specifying colour rendering properties of light sources*. Vienna, Austria: Commission Internationale de l'Éclairage; CIE No. 13.3-1995. 16 p.
2. American National Standards Institute. 2008. *American National Standard for Electric Lamps: Specifications for the Chromaticity of Solid State Lighting Products*, ANSI C78.377. Rosslyn, VA: National Electrical Manufacturers Association.
3. Figueiro, M.G., K. Appleman, J.D. Bullough, and M.S. Rea. 2006. A discussion of recommended standards for lighting in the NICU. *J Perinatol* 26: S19–S26.
4. Rea M., L. Deng, and R. Wolsey. 2004. *NLPIP Lighting Answers: Light Sources and Color*. Troy, N.Y.: Rensselaer Polytechnic Institute; National Lighting Product Information Program.
5. Rea M.S., and J.P. Freyssinier-Nova. 2008. Color rendering: A tale of two metrics. *Color Res Appl* 33: 192–203.
6. Rea M.S., J.P. Freyssinier. In press. Color rendering: Beyond pride and prejudice. *Color Res Appl*.
7. Selected colorimetric tables, online: <http://www.cie.co.at/main/freepubs.html>; accessed October 31, 2009.
8. Commission Internationale de l'Éclairage (CIE). 2004. *Colorimetry*, 3rd edition. Vienna, Austria: Commission Internationale de l'Éclairage; CIE Publication No. 15:2004.
9. Wyszecki, G., and W.S. Stiles. 1982. *Color science: Concepts and methods, quantitative data and formulae*, 2nd ed. New York: John Wiley & Sons.
10. Boyce, P. 2003. *Human Factors in Lighting*. 2nd ed. London and New York, Taylor & Francis.
11. Commission Internationale de l'Éclairage (CIE). 1986. *Colorimetry*. Vienna, Austria: Commission Internationale de l'Éclairage; CIE Publication No. 15.2.
12. Rea, M.S. (ed). 2000. *IESNA lighting handbook: Reference & application*. New York: Illuminating Engineering Society of North America.

Acknowledgments

ASSIST and the Lighting Research Center would like to thank the following for their review and feedback during the development of this publication: John Bullough and Patricia Rizzo.

About ASSIST

ASSIST was established in 2002 by the Lighting Research Center at Rensselaer Polytechnic Institute to advance the effective use of energy-efficient solid-state lighting and speed its market acceptance. ASSIST's goal is to identify and reduce major technical hurdles and help LED technology gain widespread use in lighting applications that can benefit from this rapidly advancing light source.

Appendix A: Calculating Chromaticity

The CIE chromaticity of a light source is determined from the spectral power distribution and the CIE 1931 2° Standard Observer color matching functions (see Appendix D).^{7,8} The example below shows the steps needed to derive the CIE u'v' chromaticity values of any light source, using as an example an equal energy spectrum (EES; Figure A1).

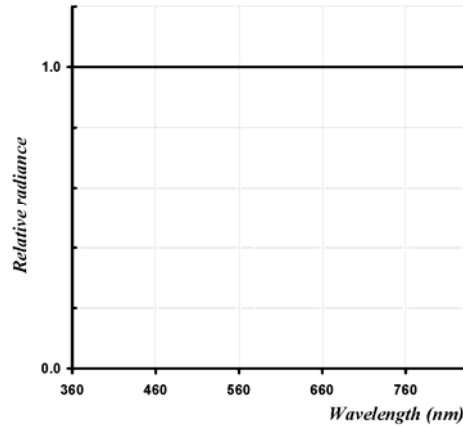


Figure A1. Equal energy spectrum normalized to unity (data in tabulated form can be found in Appendix D).

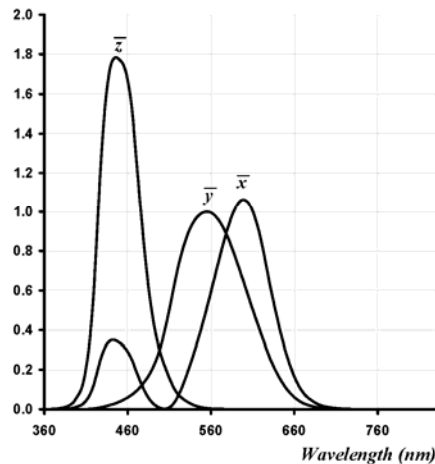


Figure A2. The three CIE 2° Standard Observer color matching functions used to derive chromaticity (data in tabulated form can be found in Appendix D).⁸

Step 1. Derive the CIE chromaticity coordinates in the CIE 1931 (xy) space.

Step 1a. Determine the CIE 1931 XYZ tristimulus values of the light source

$$X = K \int_{\lambda=380}^{780} \text{SPD}(\lambda) \bar{x}(\lambda) d\lambda$$

$$Y = K \sum_{\lambda=380}^{780} \text{SPD}(\lambda) \bar{y}(\lambda) d\lambda$$

$$Z = K \sum_{\lambda=380}^{780} \text{SPD}(\lambda) \bar{z}(\lambda) d\lambda$$

where:

- K is a constant to normalize Y to 100
- SPD (λ) is the relative spectral power distribution of the light source
- $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ are the color matching functions for the CIE 1931 2° Standard Observer (see Appendix D)
- $d\lambda$ is the wavelength increment of the SPD

It is worth emphasizing that in order to multiply the SPD and the color matching functions, both sets of data should be tabulated for the same range of wavelengths and with the same wavelength increments.

For an EES, the XYZ values are X=106.85, Y=106.86 and Z=106.84 before normalizing Y to 100 using a constant K=0.9358.

Step 1b. Determine the CIE 1931 (x,y) values of the light source

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

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

For an EES, x= 0.3333 and y=0.3333.

Step 2. Determine the CIE 1976 (u',v') values of the light source

$$u' = \frac{4x}{-2x + 12y + 3z}$$

$$v' = \frac{9x}{-2x + 12y + 3z}$$

For an EES, u'= 0.2105 and v'=0.4737.

Appendix B: Calculating Color Rendering Index

The general color rendering index (CRI) of a light source is determined from the spectral power distribution and other standard conditions. The example below follows the method outlined in publication *CIE Technical Report No. 13.3-1995 Method of Measuring and Specifying Colour Rendering Properties of Light Sources*, where the method is described in detail and standard colorimetric data needed for the calculations are available.¹ Selected spectral and colorimetric data is also available from other sources.⁷

The steps below detail the CRI calculation process using a given light source's SPD; for example, an equal energy spectrum (EES) as depicted in Figure B1 (data in tabulated form can be found in Appendix D).

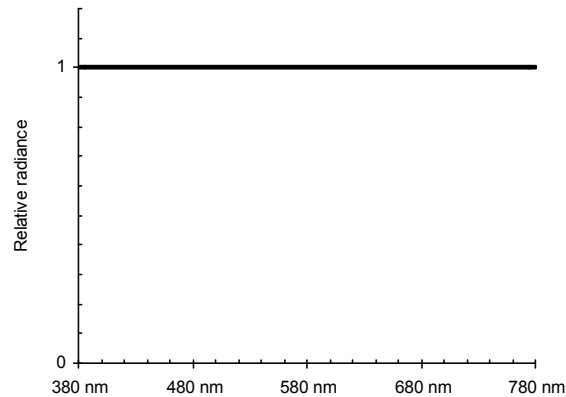


Figure B1. Equal energy spectrum normalized to unity (data in tabulated form can be found in Appendix D).

Step 1. Derive the correlated color temperature (CCT) of the light source from its chromaticity coordinates in the CIE 1960 (u,v) uniform color space.

Step 1a. Determine the CIE 1931 XYZ tristimulus values of the light source

$$X = K \int_{\lambda=380}^{780} \text{SPD}(\lambda) \bar{x}(\lambda) d\lambda$$

$$Y = K \int_{\lambda=380}^{780} \text{SPD}(\lambda) \bar{y}(\lambda) d\lambda$$

$$Z = K \int_{\lambda=380}^{780} \text{SPD}(\lambda) \bar{z}(\lambda) d\lambda$$

where:

- K is a constant to normalize Y to 100
- SPD (λ) is the relative spectral power distribution of the light source
- $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ are the color matching functions for the CIE 1931 2° Standard Observer (see Appendix D)
- $d\lambda$ is the wavelength increment of the SPD

For an EES, the XYZ values are X=106.85, Y=106.86 and Z=106.84 before normalizing Y to 100 using a constant K=0.9358.

Step 1b. Determine the CIE 1960 (u,v) values of the light source

$$u = \frac{4 X}{X + 15Y + 3Z}$$

$$v = \frac{6 X}{X + 15Y + 3Z}$$

For an EES, u= 0.2105 and v=0.3158.

Step 1c. Determine the CCT of the light source.

For an EES, CCT=5455 K.

Step 2. Determine the reference illuminant based on the CCT of the light source. The reference illuminant is mathematically defined and has the same CCT as the light source of interest. The reference illuminant is calculated in one of the following two ways:

Step 2a. If the CCT of the light source is less than 5000 K, the reference illuminant is a Planckian radiator of the same CCT and can be calculated as

$$SPD_{Ref}(\lambda) = 2 \times \pi \times h \times c^2 \times (1 \times 10^{-9} \times \lambda)^{-5} \div (e^{[(h \times c \times k) + (Tc \times 1 \times 10^{-9} \times \lambda)]} - 1)$$

where:

- c = 299792458
- h = 6.6260693 × 10⁻³⁴
- k = 1.3806505 × 10⁻²³
- λ = each wavelength in the range of interest, for example, 380 nm, 382 nm, 384 nm...780 nm
- Tc = the CCT of interest in kelvin

Step 2b. If the CCT of the light source is greater than or equal to 5000 K, the reference illuminant is a mathematically defined phase of daylight of the same CCT and can be calculated as⁹

$$SPD_{Ref}(\lambda) = S_0(\lambda) + [M_1 \times S_1(\lambda)] + [M_2 \times S_2(\lambda)]$$

where:

- S₀(λ), S₁(λ), and S₂(λ) are daylight distribution vectors (see Appendix D)
- $M_1 = \frac{-1.3515 - 1.7703x_D + 5.9114y_D}{0.0241 + 0.2562x_D - 0.7341y_D}$
- $M_2 = \frac{0.0300 - 31.4424x_D + 30.0717y_D}{0.0241 + 0.2562x_D - 0.7341y_D}$
- $x_D = \frac{-4.6070 \times 10^9}{T_C^3} + \frac{2.9678 \times 10^6}{T_C^2} + \frac{0.09911 \times 10^3}{T_C} + 0.244063$, if CCT ≤ 7000 K

- $x_D = \frac{-2.0064 \times 10^9}{T_C^3} + \frac{1.9018 \times 10^6}{T_C^2} + \frac{0.24748 \times 10^3}{T_C} + 0.237040$,
if $7000 \text{ K} < \text{CCT} \leq 25000 \text{ K}$
- $y_D = -3.000(x_D)^2 + 2.870x_D - .0275$
- T_C = the CCT of interest in kelvin

For an EES, the reference illuminant is shown in Figure B2 and the spectral data is tabulated in Appendix C.

For the reference illuminant, $X=96.72$, $Y=101.03$, $Z=92.21$, $K=0.9898$, $u=0.2048$ and $v=0.3209$.

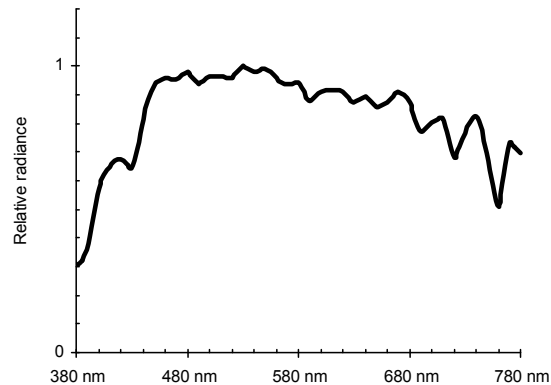


Figure B2. Phase of daylight at 5455 K that serves as reference illuminant for an EES.

Step 3. Determine the CIE 1960 (u,v) values for each of the eight test color samples (TCS¹) for both the light source of interest and the reference illuminant.

Step 3a. Derive the tristimulus values (X, Y and Z) for each one of the 8 TCS.

For $i=1$ to 8

$$X_i = K \int_{380}^{780} \text{SPD}(\lambda) \bar{x}(\lambda) \text{TCS}_i(\lambda) d\lambda$$

$$Y_i = K \int_{380}^{780} \text{SPD}(\lambda) \bar{y}(\lambda) \text{TCS}_i(\lambda) d\lambda$$

$$Z_i = K \int_{380}^{780} \text{SPD}(\lambda) \bar{z}(\lambda) \text{TCS}_i(\lambda) d\lambda$$

where:

- K is a constant to normalize Y to 100 (from Step 1)
- $\text{SPD}(\lambda)$ is the relative spectral power distribution of the light source or the reference illuminant
- $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ are the color matching functions for the CIE 1931 2° Standard Observer (see Appendix D)

- $TCS_i(\lambda)$ is the spectral reflectance of the TCS denoted by number i (see Appendix D; for tabulated values see reference 1)
- $d\lambda$ is the wavelength increment of the SPD

Table B1 shows the results of the calculations for Step 3a.

Table B1. CIE 1931 tristimulus values of the 8 TCS when illuminated by an equal energy spectrum and the reference illuminant of the same CCT.

	EES			Reference illuminant		
	X	Y	Z	X	Y	Z
TCS₁	37.95	32.56	24.14	34.30	30.50	20.72
TCS₂	31.48	31.26	14.57	28.68	29.46	12.74
TCS₃	27.05	32.46	9.67	24.87	30.85	8.54
TCS₄	22.59	30.87	20.54	20.77	29.48	18.32
TCS₅	27.39	32.30	39.36	24.85	30.77	34.31
TCS₆	30.88	31.23	56.60	27.68	29.66	48.90
TCS₇	37.42	31.51	52.49	33.43	29.67	44.68
TCS₈	43.09	34.11	44.80	38.57	31.96	38.17

Step 3b. Derive the CIE 1960 (u,v) values for each TCS using the equations

$$u = \frac{4X}{X + 15Y + 3Z}$$

$$v = \frac{6X}{X + 15Y + 3Z}$$

Table B2 shows the results of the calculations for Step 3b.

Table B2. CIE 1960 (u,v) chromaticities of the TCS when illuminated by an EES and a reference illuminant of the same CCT.

	EES		Reference illuminant	
	u	v	U	V
TCS₁	0.2535	0.3263	0.2477	0.3303
TCS₂	0.2314	0.3447	0.2255	0.3474
TCS₃	0.1993	0.3587	0.1939	0.3607
TCS₄	0.1651	0.3384	0.1604	0.3415
TCS₅	0.1739	0.3076	0.1687	0.3133
TCS₆	0.1846	0.2800	0.1788	0.2874
TCS₇	0.2242	0.2832	0.2183	0.2906
TCS₈	0.2501	0.2970	0.2439	0.3032

Step 4. Apply the von Kries adaptive color shift to account for the differences in chromatic adaptation states between the light source of interest and the reference illuminant.¹

Step 4a. Derive constants c and d for both the light source (sub index k) and the reference illuminant (sub index ref) using the following equations:

$$c = \frac{1}{v}(4 - u - 10v)$$

$$d = \frac{1}{v}(1.708v + 0.404 - 1.481u)$$

For the EES, $c_k=1.9997$, $d_k=2.0000$ and for the reference illuminant $c_{ref}=1.8255$ and $d_{ref}=0.3209$.

Step 4b. Apply the adaptive color shift to each TCS under the light source using the following equations¹:

$$u_{k,i} = \frac{10.872 + 0.404 \frac{c_{ref}}{c_k} c_{k,i} - 4 \frac{d_{ref}}{d_{k,i}} d_{k,i}}{16.518 + 1.481 \frac{c_{ref}}{c_k} c_{k,i} - \frac{d_{ref}}{d_{k,i}} d_{k,i}}$$

$$v_{k,i} = \frac{5.520}{16.518 + 1.481 \frac{c_{ref}}{c_k} c_{k,i} - \frac{d_{ref}}{d_{k,i}} d_{k,i}}$$

Table B3 shows the results of the calculations for Step 4b.

Table B3. CIE 1960 (u,v) chromaticities of the eight TCS after applying the adaptive color shift.

	EES	
	U _{k,i}	V _{k,i}
TCS₁	0.2490	0.3304
TCS₂	0.2263	0.3478
TCS₃	0.1935	0.3610
TCS₄	0.1584	0.3425
TCS₅	0.1670	0.3135
TCS₆	0.1778	0.2872
TCS₇	0.2189	0.2899
TCS₈	0.2456	0.3028

Step 5. Determine the CIE 1964 $W^*U^*V_i^*$ values for each TCS when illuminated by the light source (sub index k) and the reference illuminant (sub index ref).

Step 5a. Derive the CIE 1964 chromaticity values for each TCS using the following equations¹

$$W_i^* = 25(Y_i)^{1/3} - 17$$

$$U_i^* = 13(W_i^*) (u_i - u)$$

$$V_i^* = 13(W_i^*) (v_i - v)$$

Table B4 shows the results of the calculations for Step 5a.

Table B4. CIE 1964 U*V* chromaticities of each TCS when illuminated by an EES and the reference illuminant of the same CCT.

	EES		Reference illuminant	
	U*	V*	U*	V*
TCS₁	61.1	35.0	60.8	33.9
TCS₂	60.0	16.7	59.9	16.1
TCS₃	61.0	-9.0	61.1	-8.7
TCS₄	59.7	-36.1	60.0	-34.6
TCS₅	60.9	-29.9	61.1	-28.7
TCS₆	60.0	-21.1	60.1	-20.3
TCS₇	60.2	11.0	60.1	10.5
TCS₈	62.3	33.0	62.1	31.6

Step 6. Determine the individual color rendering indices for each TCS.

Step 6a. Determine the color shift ΔE for each TCS using the equation¹

For $i=1$ to 8

$$\Delta E_i = \sqrt{(U_{ref,i}^* - U_{k,i}^*)^2 + (V_{ref,i}^* - V_{k,i}^*)^2 + (W_{ref,i}^* - W_{k,i}^*)^2}$$

Step 6a. Determine the individual color rendering index using the equation

For $i=1$ to 8

$$R_i = 100 - 4.6 \Delta E$$

Table B5 shows the results of Step 6a.

Table B5. Color shift and individual color rendering index for each TCS when illuminated by an EES.

	ΔE	R_i
TCS₁	1.17	94.6
TCS₂	0.69	96.8
TCS₃	0.39	98.2
TCS₄	1.61	92.6
TCS₅	1.27	94.2
TCS₆	0.77	96.4
TCS₇	0.77	96.5
TCS₈	1.52	93.0

Step 7. Determine the general color rendering index

Step 7a. Derive the arithmetic mean of the eight individual color rendering indices R_1 to R_8 .

$$R_a = \frac{1}{8} \sum_{i=1}^8 R_i$$

For an EES, $R_a = 95$.

Appendix C: Calculating Gamut Area Index

Gamut area of a light source is commonly calculated as the area of the polygon defined by the chromaticities in CIE 1976 $u'v'$ color space of the eight CIE test color samples specified in *CIE Technical Report No. 13.3-1995* when illuminated by a test light source.^{1,10} For this study, the gamut area of the equal energy spectrum (EES) is scaled to 100 and defined as gamut area index (GAI).³⁻⁶ The gamut area of any other light sources is scaled accordingly. GAI is a convenient metric to supplement color rendering index (CRI) because, like CRI, it is derived from the spectral power distribution of a light source and the resulting chromaticities of the same eight CIE standard color samples.

The following steps show how to derive the gamut area for an equal energy spectrum (Figure C1) but the process is the same for a light source of any SPD and can be completed while calculating the CRI of the light source (Appendix B).

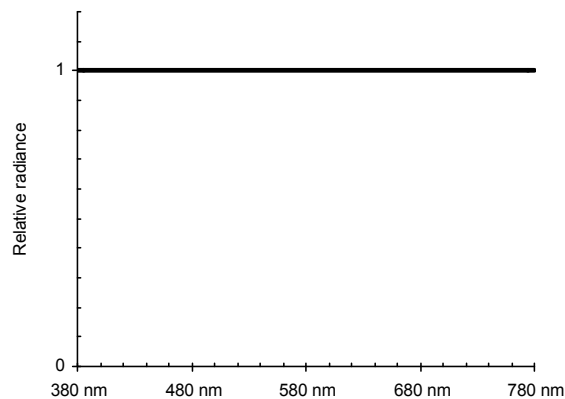


Figure C1. Equal energy spectrum normalized to unity (data in tabulated form can be found in Appendix D).

Step 1. Determine the CIE 1976 (u',v') values for each of the eight test color samples (TCS¹) when illuminated by the light source (also see Step 2 in Appendix A).

Step 1a. Derive the CIE 1931 tristimulus values (X, Y and Z) for each TCS

For $i=1$ to 8

$$X_i = K \int_{380}^{780} \text{SPD}(\lambda) \bar{x}(\lambda) \text{TCS}_i(\lambda) d\lambda$$

$$Y_i = K \int_{380}^{780} \text{SPD}(\lambda) \bar{y}(\lambda) \text{TCS}_i(\lambda) d\lambda$$

$$Z_i = K \int_{380}^{780} \text{SPD}(\lambda) \bar{z}(\lambda) \text{TCS}_i(\lambda) d\lambda$$

where:

- K is a constant to normalize Y to 100

- SPD (λ) is the relative spectral power distribution of the light source or the reference illuminant
- $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ are the color matching functions for the CIE 1931 2° Standard Observer (see Appendix D)
- $TCS_i(\lambda)$ is the spectral reflectance of the test color sample denoted by number i (see Appendix D; for tabulated values see reference 1)
- $d\lambda$ is the wavelength increment of the SPD

Table C1 shows the results of the calculations for step 1a.

Table C1. CIE 1931 tristimulus values of the eight TCS when illuminated by an equal energy spectrum.

	EES		
	X	Y	Z
TCS₁	37.95	32.56	24.14
TCS₂	31.48	31.26	14.57
TCS₃	27.05	32.46	9.67
TCS₄	22.59	30.87	20.54
TCS₅	27.39	32.30	39.36
TCS₆	30.88	31.23	56.60
TCS₇	37.42	31.51	52.49
TCS₈	43.09	34.11	44.80

Step 1b. Derive the CIE 1976 (u', v') values for each TCS using the equations

$$u' = \frac{4X}{X + 15Y + 3Z}$$

$$v' = \frac{9X}{X + 15Y + 3Z}$$

Table B2 shows the results of the calculations for Step 1b. Figure B1 shows the data in graphic form.

Table C2. CIE 1976 (u', v') chromaticities of each TCS when illuminated by an EES.

	EES	
	u'	v'
TCS₁	0.2535	0.4894
TCS₂	0.2314	0.5171
TCS₃	0.1993	0.5380
TCS₄	0.1652	0.5076
TCS₅	0.1739	0.4614
TCS₆	0.1846	0.4201
TCS₇	0.2242	0.4249
TCS₈	0.2500	0.4456

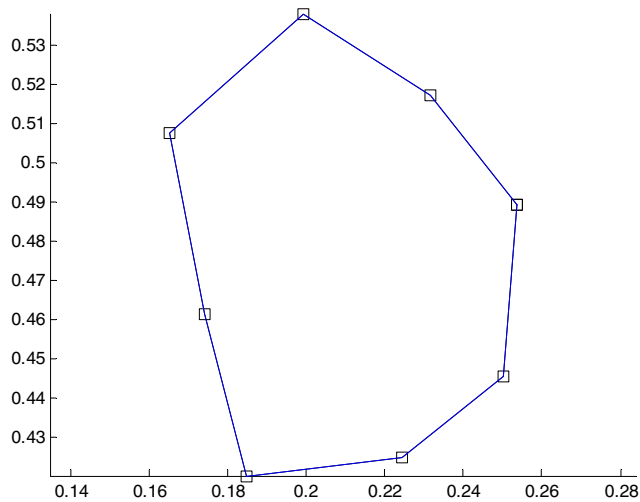


Figure C1. Chromaticity values of the eight TCS (from Table C2) in the CIE 1976 CIE (u',v') color space.

Step 1c. Derive the gamut area of the polygon created by the CIE 1976 (u',v') values of each TCS.

From Figure C1, the gamut area of an EES can be calculated as 0.007354.

Step 1d. Derive the gamut area index (GAI) of the light source.

Because this gamut area is a very small number, GAI was developed to normalize to 100 the gamut area of an EES.³⁻⁶ The gamut area of any light source is scaled accordingly but is not limited in value to that of an EES. Thus, GAI is a number that could be as small as 0 or greater than 100. To derive the GAI of any light source, simply divide its gamut area by 0.007354 and multiply the result by 100.

$$\text{GAI} = (\text{Gamut area} \div 0.007354) \times 100$$

For the EES example:

$$\text{GAI}_{\text{EES}} = (0.007354 \div 0.007354) \times 100 = 100$$

Appendix D: Spectral Data Used in the Examples

Table D1. CIE 2° Standard Observer color matching functions.^{7,8}

λ	$\bar{x}(\lambda)$	$\bar{y}(\lambda)$	$\bar{z}(\lambda)$	λ	$\bar{x}(\lambda)$	$\bar{y}(\lambda)$	$\bar{z}(\lambda)$
380	0.001368	0.000039	0.006450	585	0.978600	0.816300	0.001400
385	0.002236	0.000064	0.010550	590	1.026300	0.757000	0.001100
390	0.004243	0.000120	0.020050	595	1.056700	0.694900	0.001000
395	0.007650	0.000217	0.036210	600	1.062200	0.631000	0.000800
400	0.014310	0.000396	0.067850	605	1.045600	0.566800	0.000600
405	0.023190	0.000640	0.110200	610	1.002600	0.503000	0.000340
410	0.043510	0.001210	0.207400	615	0.938400	0.441200	0.000240
415	0.077630	0.002180	0.371300	620	0.854450	0.381000	0.000190
420	0.134380	0.004000	0.645600	625	0.751400	0.321000	0.000100
425	0.214770	0.007300	1.039050	630	0.642400	0.265000	0.000050
430	0.283900	0.011600	1.385600	635	0.541900	0.217000	0.000030
435	0.328500	0.016840	1.622960	640	0.447900	0.175000	0.000020
440	0.348280	0.023000	1.747060	645	0.360800	0.138200	0.000010
445	0.348060	0.029800	1.782600	650	0.283500	0.107000	0.000000
450	0.336200	0.038000	1.772110	655	0.218700	0.081600	0.000000
455	0.318700	0.048000	1.744100	660	0.164900	0.061000	0.000000
460	0.290800	0.060000	1.669200	665	0.121200	0.044580	0.000000
465	0.251100	0.073900	1.528100	670	0.087400	0.032000	0.000000
470	0.195360	0.090980	1.287640	675	0.063600	0.023200	0.000000
475	0.142100	0.112600	1.041900	680	0.046770	0.017000	0.000000
480	0.095640	0.139020	0.812950	685	0.032900	0.011920	0.000000
485	0.057950	0.169300	0.616200	690	0.022700	0.008210	0.000000
490	0.032010	0.208020	0.465180	695	0.015840	0.005723	0.000000
495	0.014700	0.258600	0.353300	700	0.011359	0.004102	0.000000
500	0.004900	0.323000	0.272000	705	0.008111	0.002929	0.000000
505	0.002400	0.407300	0.212300	710	0.005790	0.002091	0.000000
510	0.009300	0.503000	0.158200	715	0.004109	0.001484	0.000000
515	0.029100	0.608200	0.111700	720	0.002899	0.001047	0.000000
520	0.063270	0.710000	0.078250	725	0.002049	0.000740	0.000000
525	0.109600	0.793200	0.057250	730	0.001440	0.000520	0.000000
530	0.165500	0.862000	0.042160	735	0.001000	0.000361	0.000000
535	0.225750	0.914850	0.029840	740	0.000690	0.000249	0.000000
540	0.290400	0.954000	0.020300	745	0.000476	0.000172	0.000000
545	0.359700	0.980300	0.013400	750	0.000332	0.000120	0.000000
550	0.433450	0.994950	0.008750	755	0.000235	0.000085	0.000000
555	0.512050	1.000000	0.005750	760	0.000166	0.000060	0.000000
560	0.594500	0.995000	0.003900	765	0.000117	0.000042	0.000000
565	0.678400	0.978600	0.002750	770	0.000083	0.000030	0.000000
570	0.762100	0.952000	0.002100	775	0.000059	0.000021	0.000000
575	0.842500	0.915400	0.001800	780	0.000042	0.000015	0.000000
580	0.916300	0.870000	0.001650				

Table D2. Relative spectral radiance of an equal energy spectrum (EES) and the 5455 K phase of daylight that serves as the reference illuminant, both normalized to unity.

λ	EES	Daylight	λ	EES	Daylight
380	1	0.306	585	1	0.911
385	1	0.321	590	1	0.881
390	1	0.359	595	1	0.894
395	1	0.464	600	1	0.910
400	1	0.575	605	1	0.916
405	1	0.620	610	1	0.918
410	1	0.648	615	1	0.916
415	1	0.668	620	1	0.910
420	1	0.678	625	1	0.890
425	1	0.661	630	1	0.874
430	1	0.644	635	1	0.883
435	1	0.711	640	1	0.893
440	1	0.813	645	1	0.876
445	1	0.885	650	1	0.860
450	1	0.933	655	1	0.864
455	1	0.950	660	1	0.875
460	1	0.957	665	1	0.895
465	1	0.955	670	1	0.910
470	1	0.953	675	1	0.898
475	1	0.967	680	1	0.872
480	1	0.981	685	1	0.815
485	1	0.959	690	1	0.772
490	1	0.937	695	1	0.785
495	1	0.950	700	1	0.803
500	1	0.964	705	1	0.816
505	1	0.964	710	1	0.822
510	1	0.964	715	1	0.751
515	1	0.962	720	1	0.680
520	1	0.959	725	1	0.716
525	1	0.979	730	1	0.768
530	1	1	735	1	0.804
535	1	0.990	740	1	0.823
540	1	0.980	745	1	0.778
545	1	0.985	750	1	0.696
550	1	0.989	755	1	0.585
555	1	0.979	760	1	0.511
560	1	0.961	765	1	0.623
565	1	0.945	770	1	0.736
570	1	0.935	775	1	0.716
575	1	0.938	780	1	0.696
580	1	0.941			

Table D3. Daylight vectors used in the calculation of CIE Standard D illuminants.^{7,8,9,11}

	$S_0(\lambda)$	$S_1(\lambda)$	$S_2(\lambda)$	λ	$S_0(\lambda)$	$S_1(\lambda)$	$S_2(\lambda)$
380	63.40	38.50	3.00	585	92.10	-3.50	1.30
385	64.60	36.75	2.10	590	89.10	-3.50	2.10
390	65.80	35.00	1.20	595	89.80	-4.65	2.65
395	80.30	39.20	0.05	600	90.50	-5.80	3.20
400	94.80	43.40	-1.10	605	90.40	-6.50	3.65
405	99.80	44.85	-0.80	610	90.30	-7.20	4.10
410	104.80	46.30	-0.50	615	89.35	-7.90	4.40
415	105.35	45.10	-0.60	620	88.40	-8.60	4.70
420	105.90	43.90	-0.70	625	86.20	-9.05	4.90
425	101.35	40.50	-0.95	630	84.00	-9.50	5.10
430	96.80	37.10	-1.20	635	84.55	-10.20	5.90
435	105.35	36.90	-1.90	640	85.10	-10.90	6.70
440	113.90	36.70	-2.60	645	83.50	-10.80	7.00
445	119.75	36.30	-2.75	650	81.90	-10.70	7.30
450	125.60	35.90	-2.90	655	82.25	-11.35	7.95
455	125.55	34.25	-2.85	660	82.60	-12.00	8.60
460	125.50	32.60	-2.80	665	83.75	-13.00	9.20
465	123.40	30.25	-2.70	670	84.90	-14.00	9.80
470	121.30	27.90	-2.60	675	83.10	-13.80	10.00
475	121.30	26.10	-2.60	680	81.30	-13.60	10.20
480	121.30	24.30	-2.60	685	76.60	-12.80	9.25
485	117.40	22.20	-2.20	690	71.90	-12.00	8.30
490	113.50	20.10	-1.80	695	73.10	-12.65	8.95
495	113.30	18.15	-1.65	700	74.30	-13.30	9.60
500	113.10	16.20	-1.50	705	75.35	-13.10	9.05
505	111.95	14.70	-1.40	710	76.40	-12.90	8.50
510	110.80	13.20	-1.30	715	69.85	-11.75	7.75
515	108.65	10.90	-1.25	720	63.30	-10.60	7.00
520	106.50	8.60	-1.20	725	67.50	-11.10	7.30
525	107.65	7.35	-1.10	730	71.70	-11.60	7.60
530	108.80	6.10	-1.00	735	74.35	-11.90	7.80
535	107.05	5.15	-0.75	740	77.00	-12.20	8.00
540	105.30	4.20	-0.50	745	71.10	-11.20	7.35
545	104.85	3.05	-0.40	750	65.20	-10.20	6.70
550	104.40	1.90	-0.30	755	56.45	-9.00	5.95
555	102.20	0.95	-0.15	760	47.70	-7.80	5.20
560	100.00	0.00	0.00	765	58.15	-9.50	6.30
565	98.00	-0.80	0.10	770	68.60	-11.20	7.40
570	96.00	-1.60	0.20	775	66.80	-10.80	7.10
575	95.55	-2.55	0.35	780	65.00	-10.40	6.80
580	95.10	-3.50	0.50				

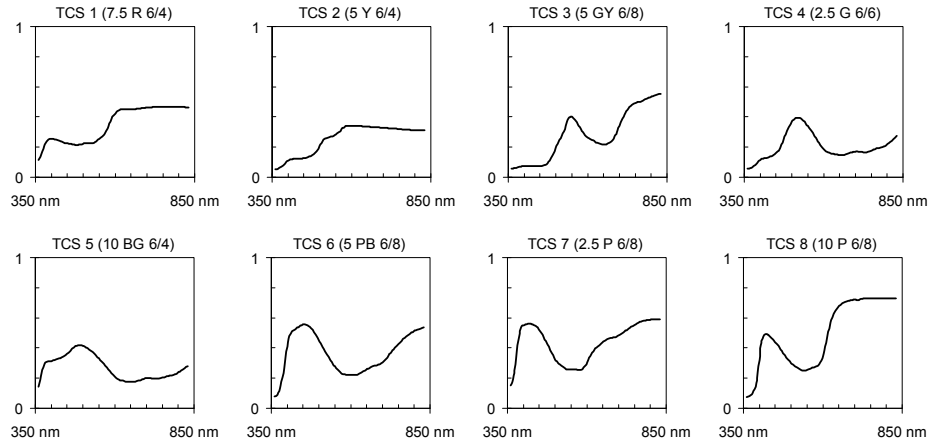


Figure D1. Relative spectral reflectance of the eight test color samples¹ (TCS) used in the calculation of CRI and GAI. The Munsell notation¹² of each TCS is shown in parentheses.