Swedish Energy Agency

International Lighting Seminar:
Perspectives on Sustainability,
Performance, Health & Smart Lighting

Monday, 27 March 2023, Stockholm

New colour metrics to consider in the Ecodesign Regulation Revision

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Outline

1. Introduction - Ecodesign lighting regulation revision
2. Chromaticity specifications for Ecodesign
3. Color rendering metrics for Ecodesign

   - Review and pros/cons discussion of existing metrics – CRI, CIE R_f IES TM-30, others….

4. Ideas for a potential way forward

1. Introduction – Ecodesign regulation review

COMMISSION REGULATION (EU) 2019/2020 of 1 October 2019

Directive 2009/125/EC of the European Parliament and of the Council and repealing Commission Regulations (EC) No 244/2009, (EC) No 245/2009 and (EU) No 1194/2012 (Text with EEA relevance) (OJ L 315 5.12.2019, p. 209)

The EU Ecodesign Regulation will start its review later this year / early 2024 with a view to have a new draft proposal to stakeholders in December 2024.

Related to color, there are specifications on

1. Chromaticity of products
2. Color rendering of products

2. Consideration on chromaticity specifications

Ecodesign lighting regulation (2019) – Chromaticity range

Article 2

Definitions

For the purpose of this Regulation, the following definitions shall apply:

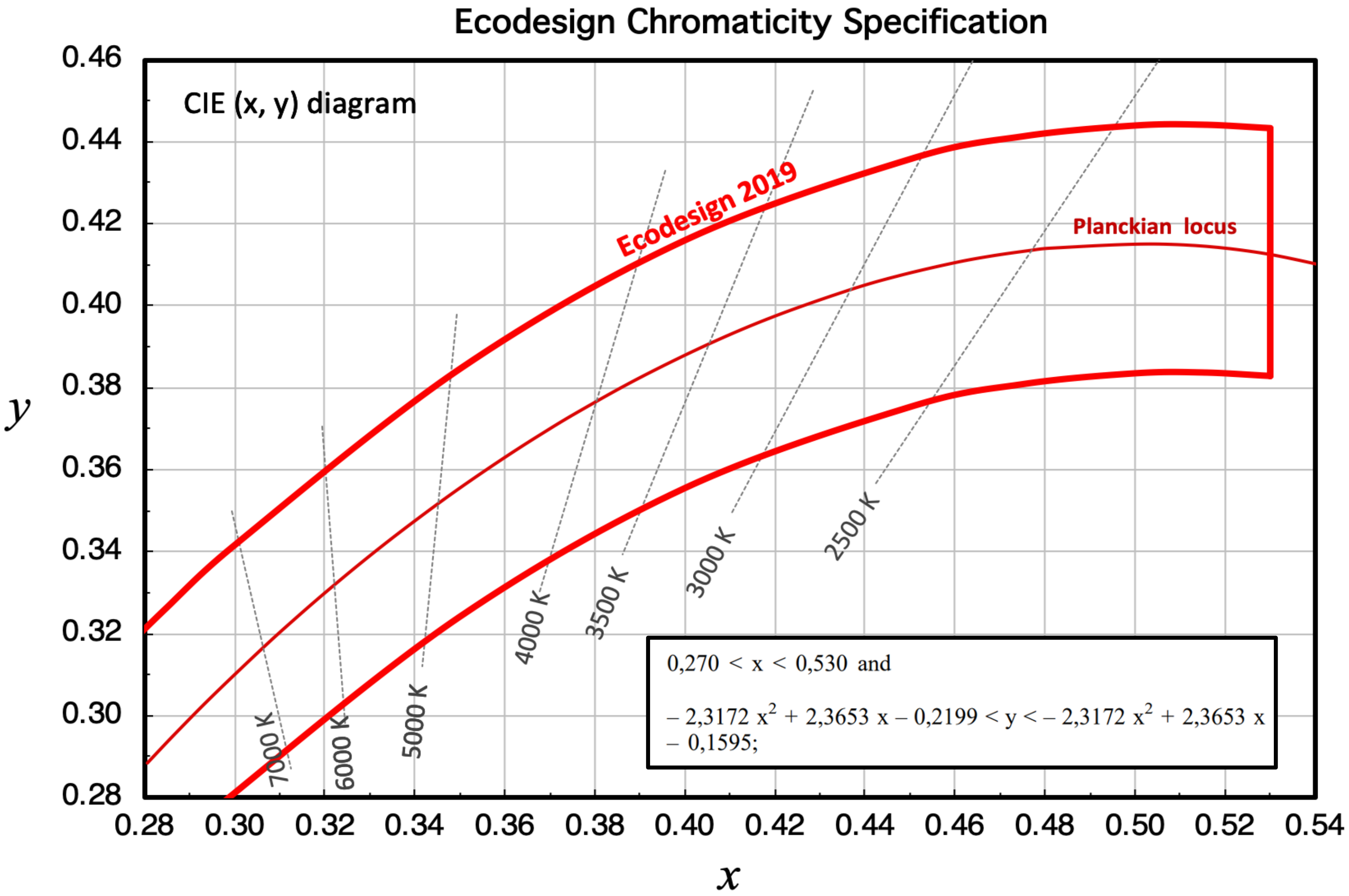
(1) 'light source' means an electrically operated product intended to emit, or, in the case of a non-incandescent light source, intended to be possibly tuned to emit, light, or both, with all of the following optical characteristics:

(a) chromaticity coordinates x and y in the range

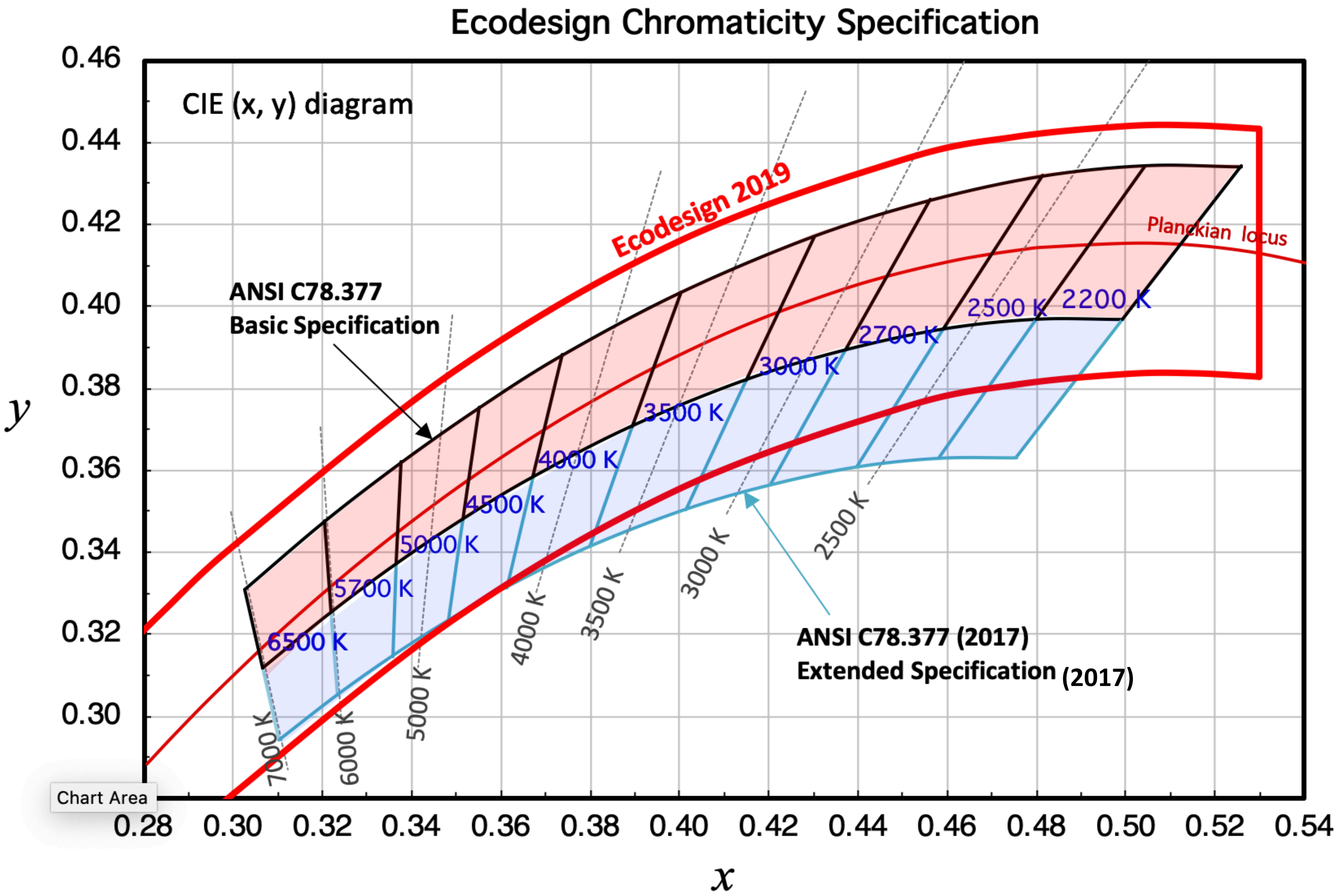
$0{,}270 < x < 0{,}530$ and

$-2{,}3172\,x^2 + 2{,}3653\,x - 0{,}2199 < y < -2{,}3172\,x^2 + 2{,}3653\,x - 0{,}1595$;

Ecodesign lighting regulation – Chromaticity range



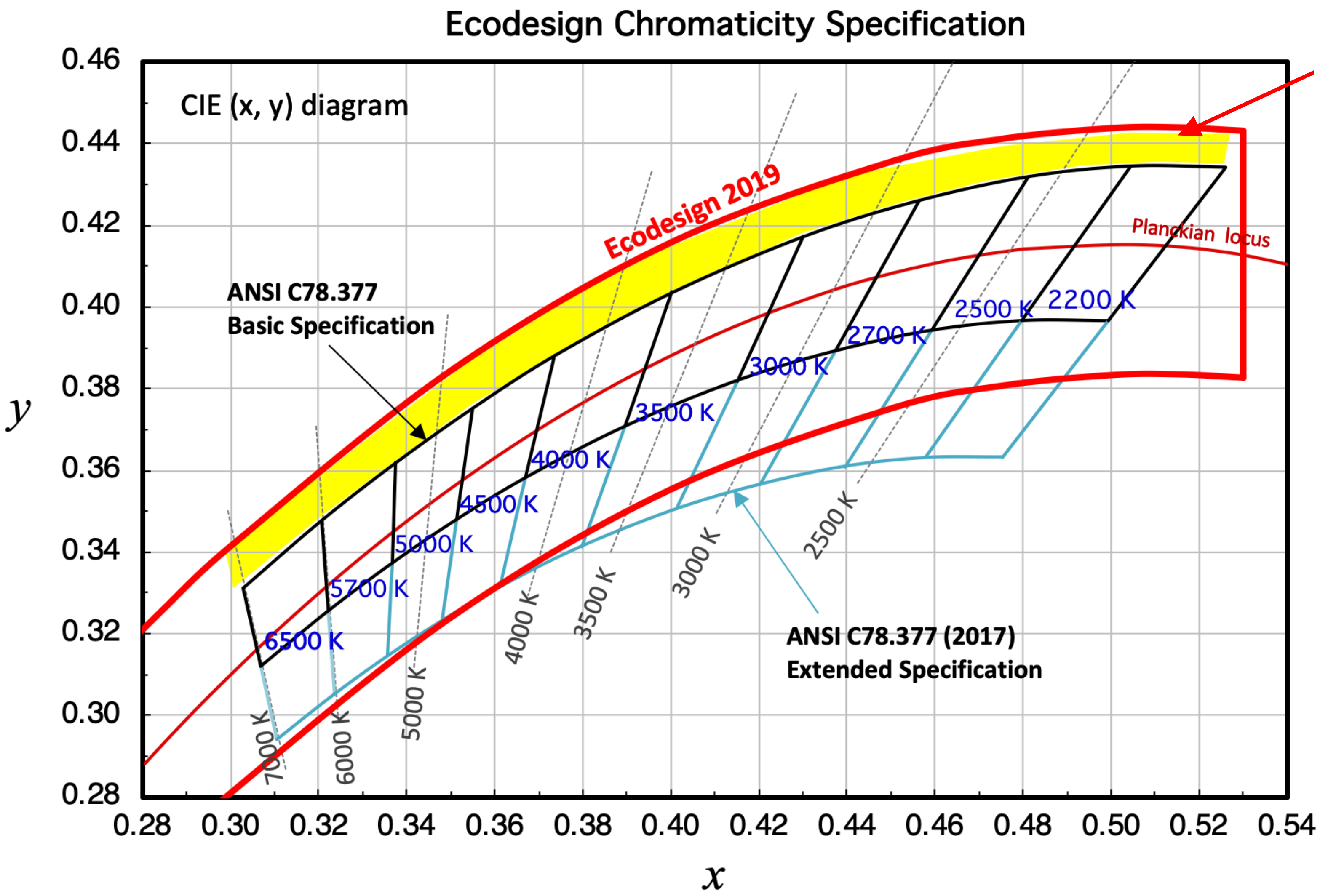
Ecodesign lighting regulation + ANSI C78.377



ANSI C78.377 Chromaticity Specifications for Solid State Lighting Products.

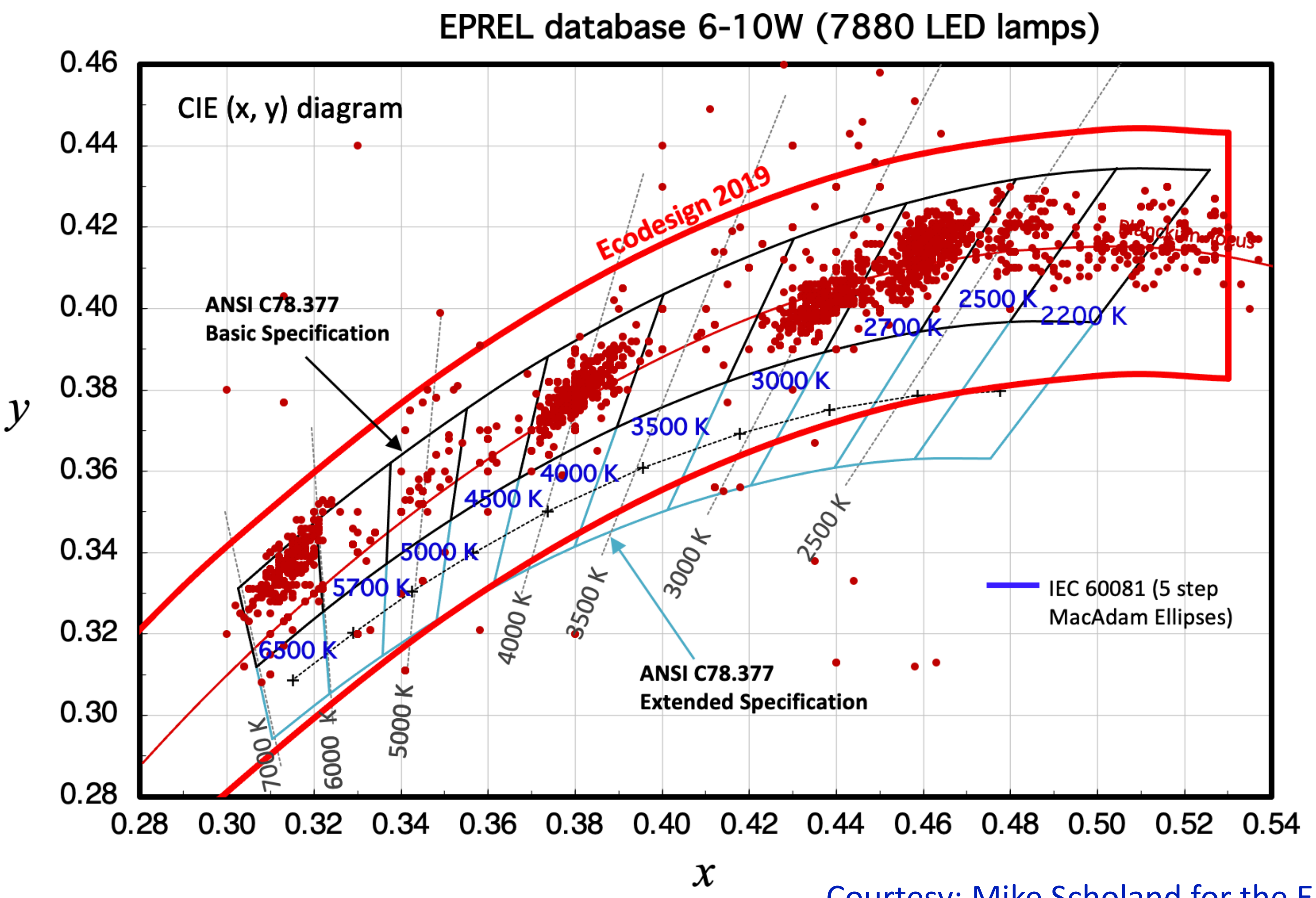
- widely used in the U.S. and worldwide (for indoor applications).
- many outdoor products also use this specification.
- The quadrangle ranges determined based on experimental studies.

Ecodesign lighting regulation + ANSI C78.377



This region unacceptably yellowish for indoor applications (experimental studies)

Lighting products data in European Market

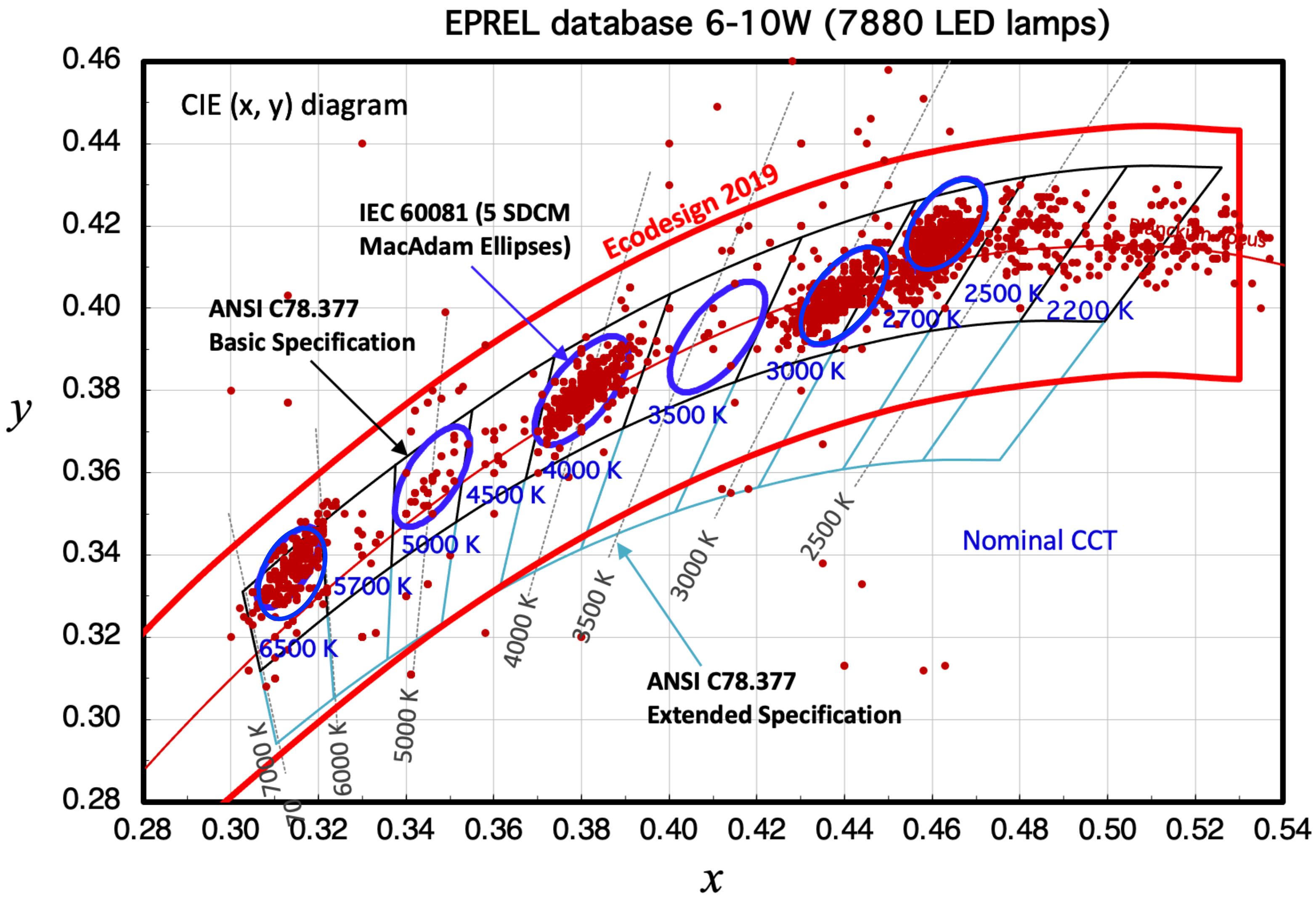


EPREL: European Product Registry for Energy Labelling

- More than 99% of the lamps are within the ANSI bins (below 2200 K excluded)

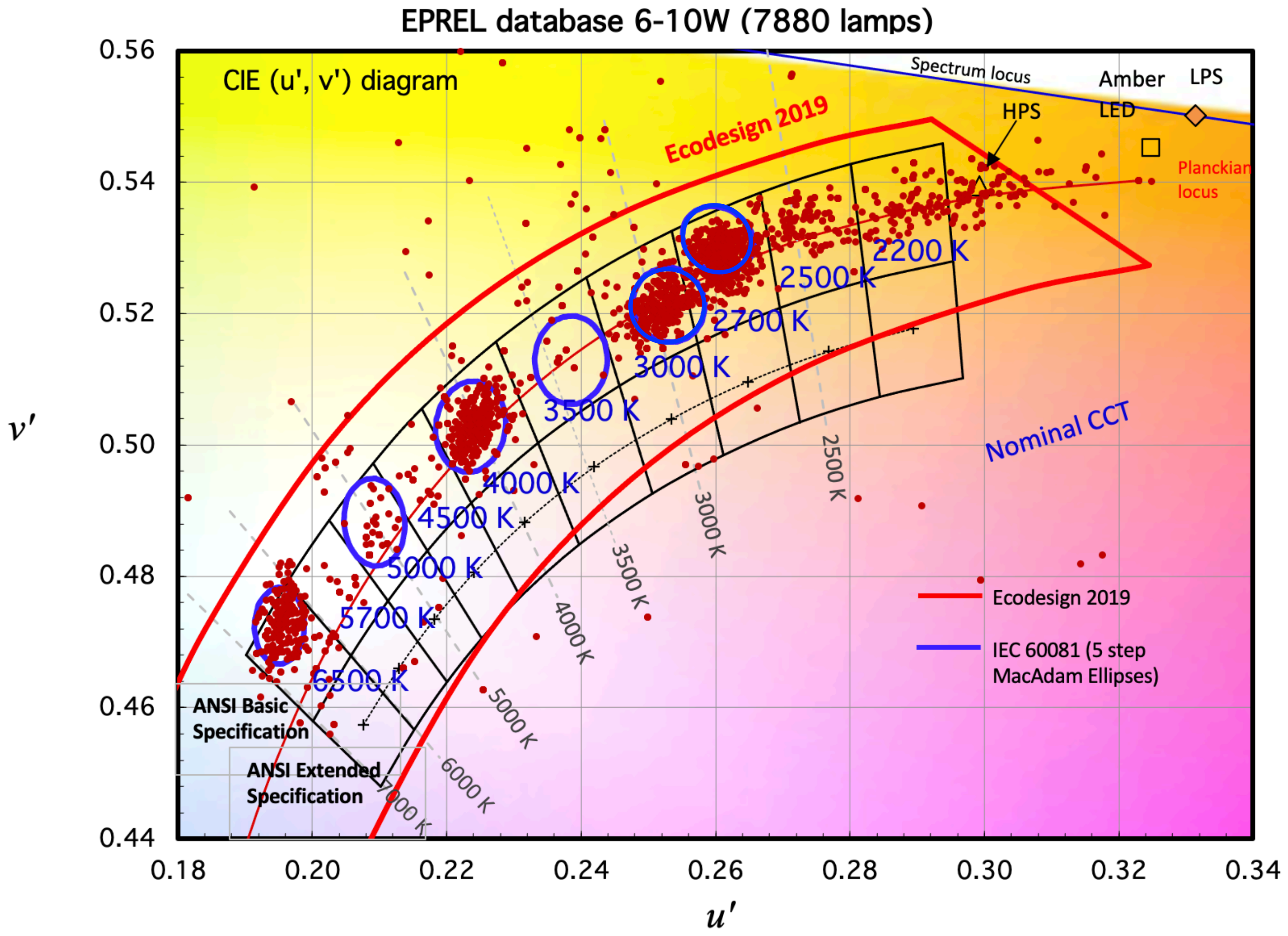
Courtesy: Mike Scholand for the EPREL database.

Ecodesign lighting regulation – Chromaticity range



IEC 60081 uses 5-SDCM MacAdam ellipses.

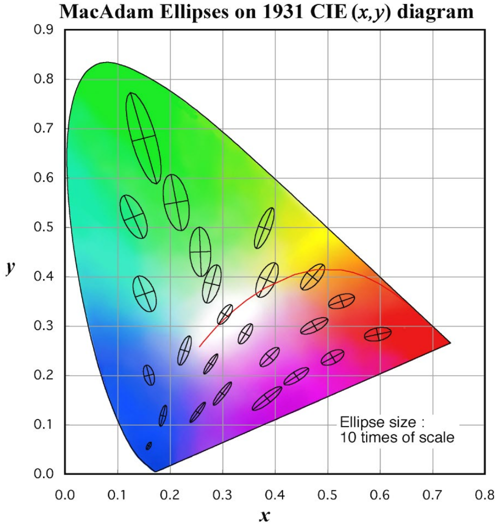
The graph converted to CIE 1976 (u’, v’) Uniform Chromaticity Scale Diagram

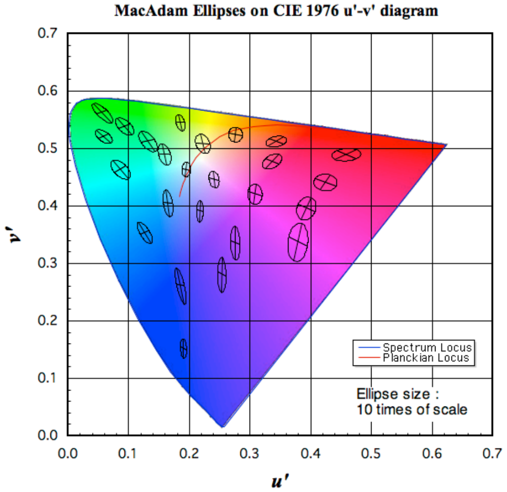


MacAdam ellipses are near circular on (u’, v’) diagram.

(u’, v’) space is much more uniform than (x, y).

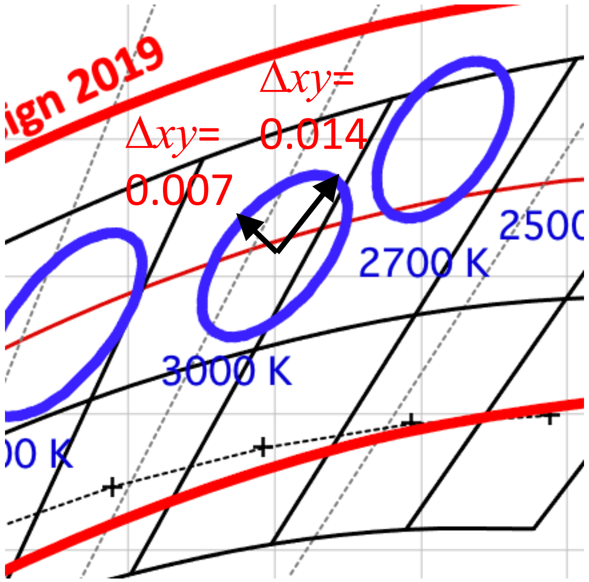
Comparing (*x, y*) space and (*u', v'*) space



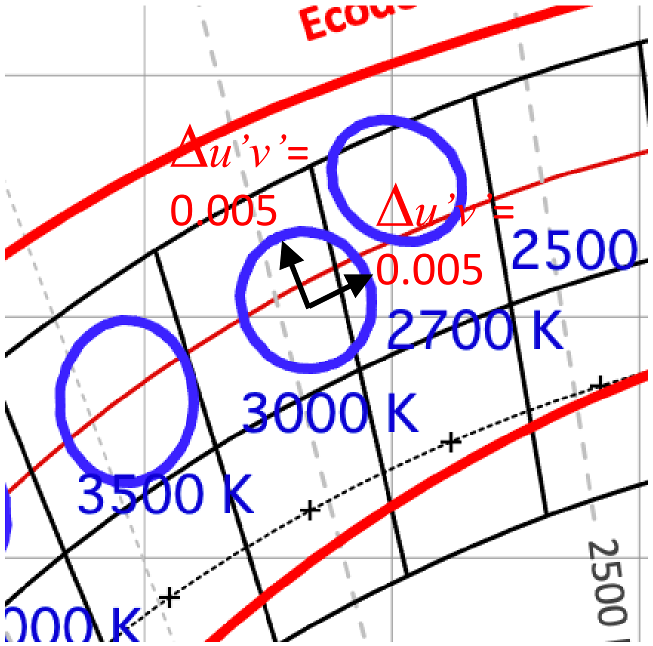


(x, y) space

For the same visual color difference:



(u',v') space



(x,y) space is non-uniform, problematic in specifying color tolerance and color shifts, requiring MacAdam ellipses to specify tolerances.

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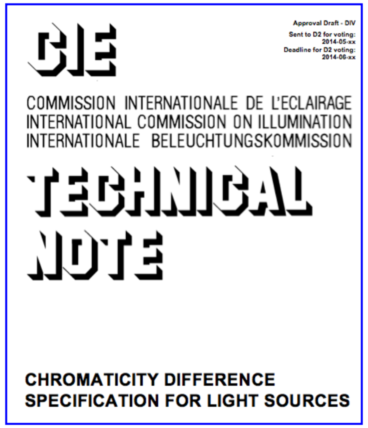
National Institute of Standards and Technology U.S. Department of Commerce

CIE TN 001 (2014) Chromaticity Difference Specification for Light Sources

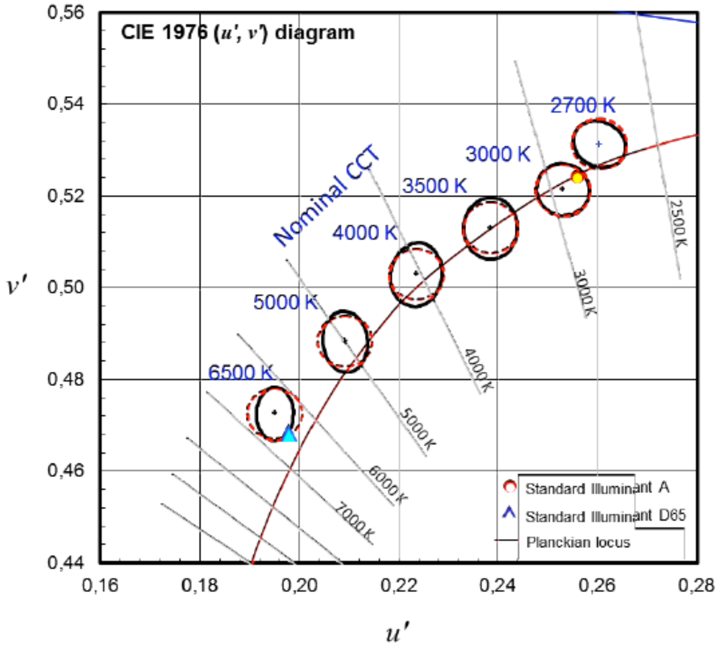

Approval Draft - DIV
Sent to D2 for voting: 2014-05-xx
Deadline for D2 voting: 2014-06-xx

CIE

COMMISSION INTERNATIONALE DE L'ECLAIRAGE
INTERNATIONAL COMMISSION ON ILLUMINATION
INTERNATIONALE BELEUCHTUNGSKOMMISSION

TECHNICAL NOTE

CHROMATICITY DIFFERENCE SPECIFICATION FOR LIGHT SOURCES



3 Alternative to MacAdam Ellipses

3.1 *u'v'* Circle

The *u'v' circle* is specified with a centre point (u'_c, v'_c) and radius *r* on the (*u'*,*v'*) diagram, expressed by,

$$(u' - u'_c)^2 + (v' - v'_c)^2 = r^2$$

3.2 *n*-step *u'v'* circle

$$(u' - u'_c)^2 + (v' - v'_c)^2 = (0{,}0011 \cdot n)^2$$

This can replace *n*-step (or *n*-SDCM) MacAdam ellipses

4. Color difference

$$\Delta_{u',v'} = \sqrt{(u'_2 - u'_1)^2 + (v'_2 - v'_1)^2} \; .$$

Used for color tolerance, color maintenance, angular color uniformity, etc.

https://files.cie.co.at/738_CIE_TN_001-2014.pdf

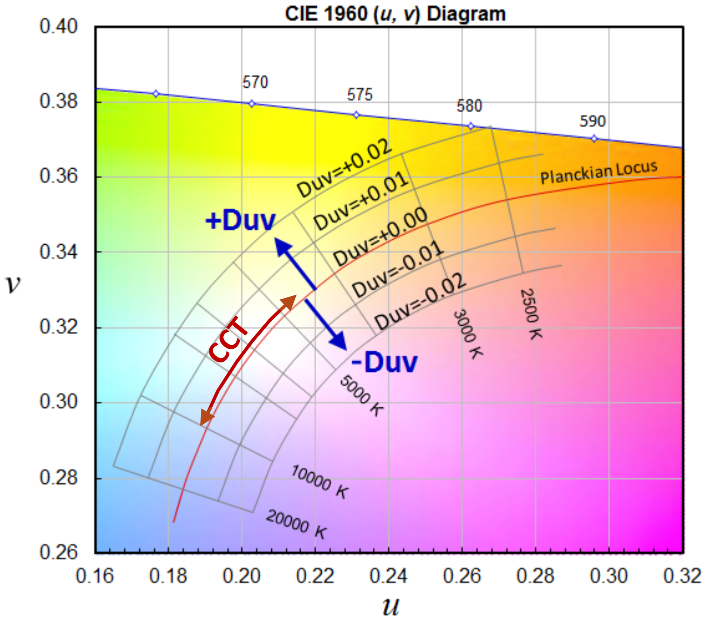
Chromaticity expression for lighting – CCT and Duv

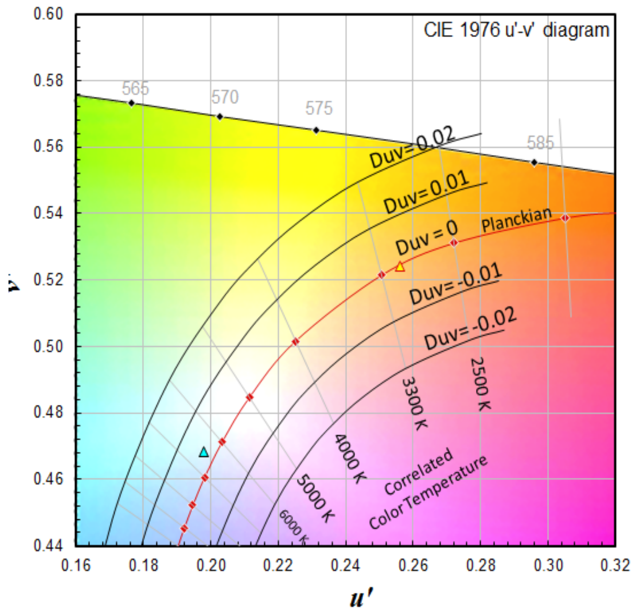
Two numbers of (x, y) or (u', v') are not intuitive to communicate color.

Intuitive way of communicating color of white light for lighting:

CCT (Correlated Color Temperature) and

Duv (Distance from Planckian locus with ±sign), symbol D_{uv},
- defined and used in ANSI C78.377. (D_{uv} defined in CIE 15:2018).





How to calculate CCT and Duv:

(CCT, Duv) ⟷ (x, y) (u', v')

Practical Use and Calculation of CCT and Duv

Yoshi Ohno
National Institute of Standards and Technology, Gaithersburg, Maryland, USA

ABSTRACT Correlated color temperature (CCT) is often used to represent chromaticity of white light sources, but chromaticity is two-dimensional, and another dimension, the distance from the Planckian locus, is often missing. Duv is defined in ANSI C78.377 for this purpose but is not yet widely used. In this article, the use of a combination of CCT and Duv is proposed as an intuitive expression of chromaticity of white light sources for general lighting. In addition, this article presents practical calculation methods to calculate CCT and Duv, having sufficient accuracy, within an error of 1 K, in a wide range of chromaticity, from 1000 to 20,000 K in CCT and −0.03 to 0.03 in Duv.

KEYWORDS chromaticity, correlated color temperature, Duv, light source, Planckian locus

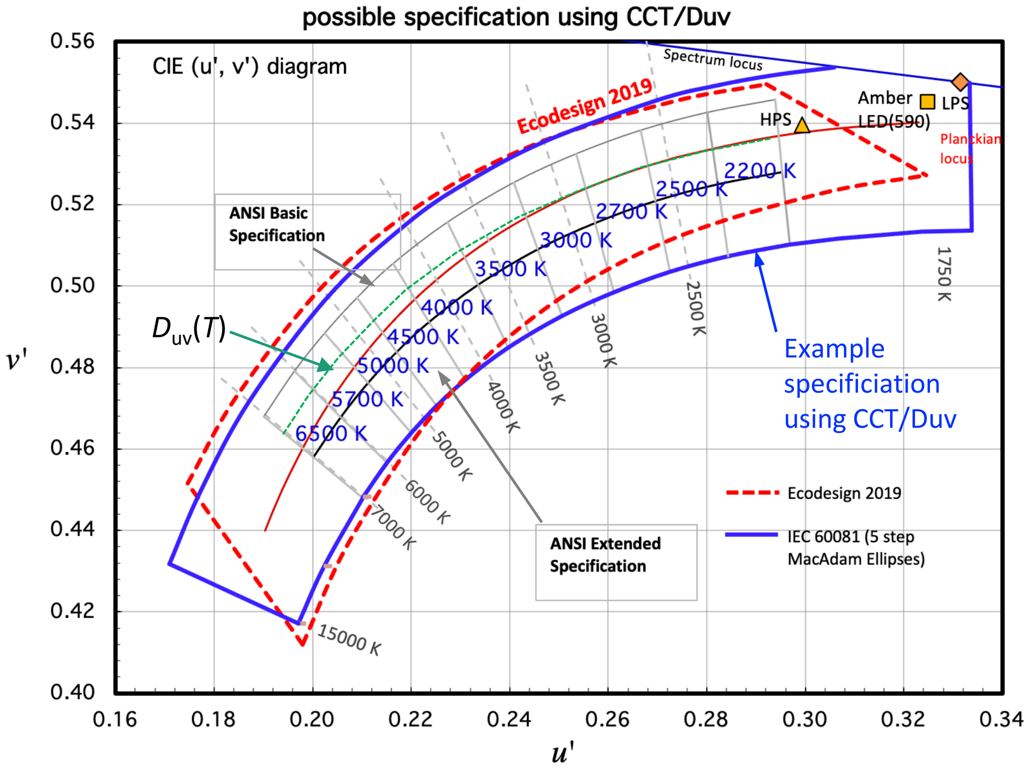
LEUKOS 10:1, 47-55, 2014 (DOI: 10.1080/15502724.2014.839020)

Use of (CCT, Duv) for chromaticity specifications

A chromaticity range can be easily defined by the range of CCT and the range of Duv.
For Ecodesign, **an example** could be:

1700 K ≤ CCT ≤ 15000 K
D_{uv} +0.01 to -0.018 from target $D_{uv}(T)$

$D_{uv}(T) = 0$ for T<2870K, $D_{uv}(T) = 57700 \times (1/T)^2 - 44.6 \times (1/T) + 0.00854$ for T≥2870K.



- Made similar to the current 2019 specification
- Extended to low CCT region to cover chromaticities of HPS, LPS, and amber LEDs, used for outdoor applications
- An additional smaller range (CCT, Duv) for performance requirements for indoor applications would be desirable.

Summary for chromaticity specification

It is suggested that Ecodesign revision may consider:

1. Use of CIE 1976 (u’, v’) coordinates rather than 1931 (x, y) coordinates, for evaluation /specification of color differences (CIE TN 001).
2. Use of (CCT, Duv) to define chromaticity range, which will be more intuitive and easy to handle.
3. Extension to lower CCT regions (to 1700 K) to cover amber LED products for outdoor applications.
4. An additional chromaticity range for indoor applications (similar to the ANSI spec.) to ensure good color quality for indoor.

15

3. Consideration on color rendering metrics for lighting products

Ecodesign lighting regulation (2019) – Color rendering

2. Functional requirements

From 1 September 2021, the functional requirements specified in Table 4 shall apply for light sources:

Table 4

Functional requirements for light sources

Colour rendering	CRI ≥ 80 (except for HID with Φ_{use} > 4 klm and for light sources intended for use in outdoor applications, industrial applications or other applications where lighting standards allow a CRI< 80, when a clear indication to this effect is shown on the light source packaging and in all relevant printed and electronic documentation)

CRI used for maximum power requirement

1. Energy efficiency requirements:

(a) From 1 September 2021, the declared power consumption of a light source P_{on} shall not exceed the maximum allowed power P_{onmax} (in *W*), defined as a function of the declared useful luminous flux Φ_{use} (in *lm*) and the declared colour rendering index CRI (-) as follows:

$$P_{onmax} = C \times (L + \Phi_{use}/(F \times \eta)) \times R;$$

where:

— The values for threshold efficacy (η in *lm/W*) and end loss factor (L in *W*) are specified in Table 1, depending on the light source type. They are constants used for computations and do not reflect true parameters of light sources. The threshold efficacy is not the minimum required efficacy; the latter can be computed by dividing the useful luminous flux by the computed maximum allowed power.

— Basic values for correction factor (C) depending on light source type, and additions to C for special light source features are specified in Table 2.

— Efficacy factor (F) is:

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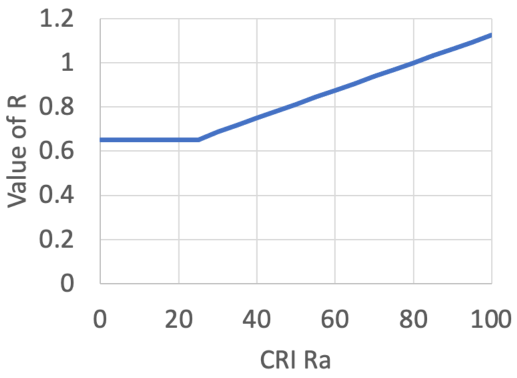
1,00 for non-directional light sources (NDLS, using total flux)

0,85 for directional light sources (DLS, using flux in a cone)

— CRI factor (R) is:

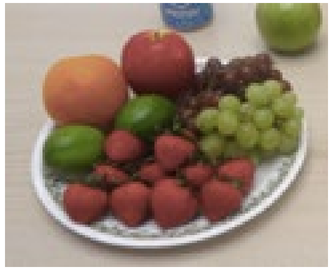
0,65 for CRI ≤ 25;

(CRI+80)/160 for CRI > 25, rounded to two decimals.



Color Rendering Index (CRI) – CIE13.3 (1995)

- CRI (R_a) is widely accepted for over 40 years, widely used in lighting product regulations.
- CRI has been serving well for traditional sources (with few exceptions) and phosphor-converted white LED products.
- CRI formula is a color fidelity metric but not accurate fidelity.
- R_9 (index for red) is occasionally used in addition to R_a in regulations

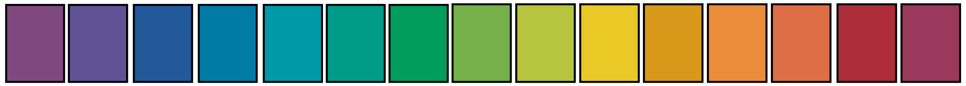


Problem

- Formulae are outdated (1974), too small number of test samples, and has several known scientific inaccuracies as fidelity metric.
- CRI penalizes some good preferred products and is **impeding developments of new LED light sources** utilizing narrow band spectra (hybrid, multi-color, quantum dots, etc.).

Outdated Object Color Space used in CRI

Plots of 15 saturated Munsell samples.

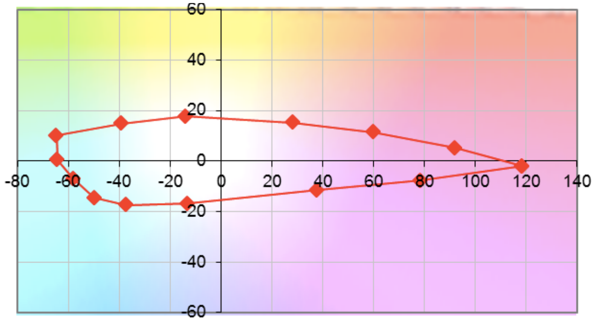


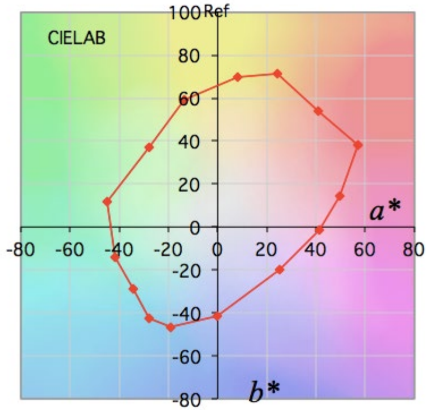
W*U*V*
used in CRI

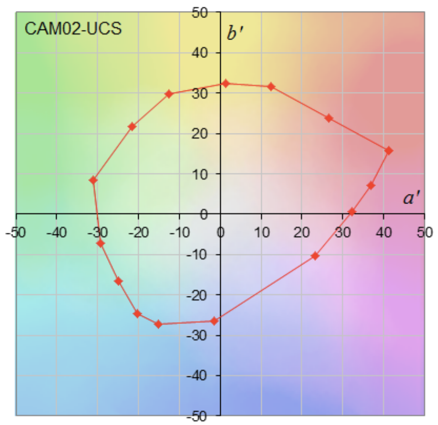
CIELAB
(Current CIE standard)

CAM02UCS
used in CIE 224 R_f

2700 K
Planck

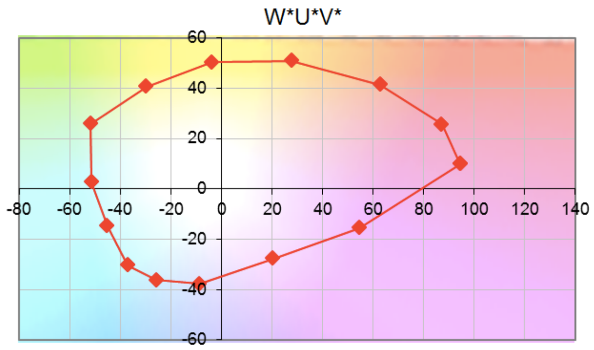


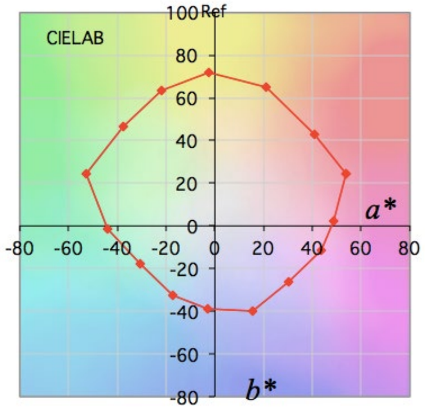


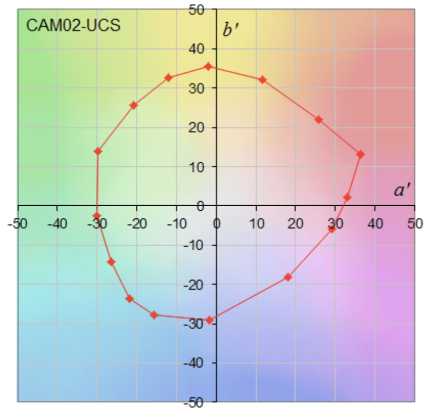


High weight in red, low weight for yellow/blue.

D65
(6500 K)

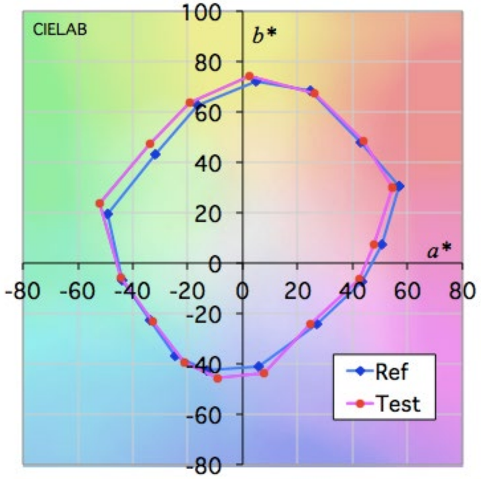






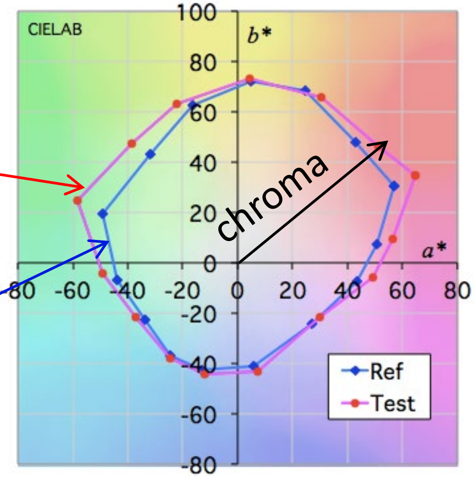
Example: the CRI score does not agree with perception

Looks better (for most people)



Test light (R_a=78)

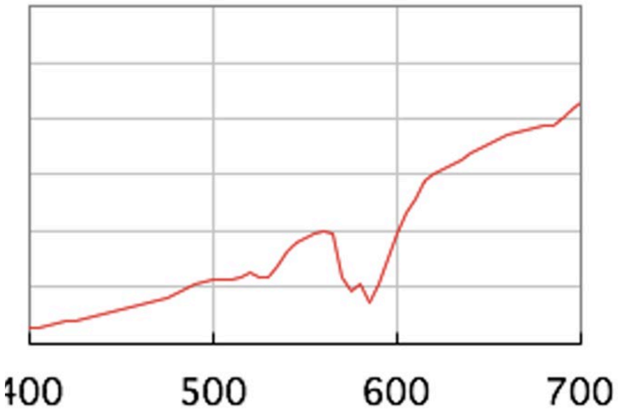
Reference (Planckian)



- Slightly increased color saturation is generally preferred
- CRI penalizes such preferred light sources.

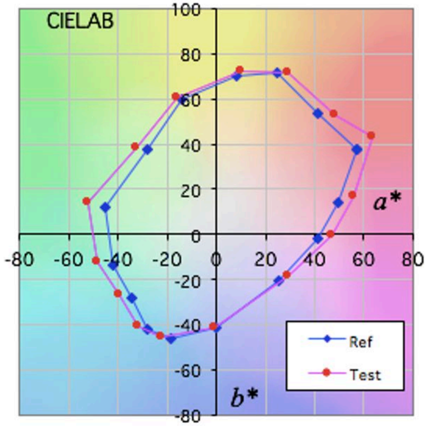
An example of well-known lamp product

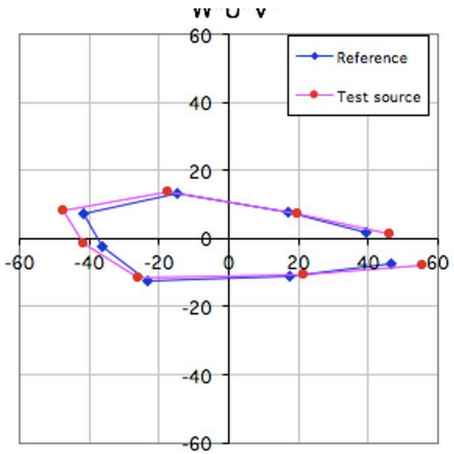
Neodymium lamp



CCT = 2757 K
Duv = - 0.005
CRI R_a = 77
CIE R_f = 87
TM30 R_g=105
CQS Q_a = 90

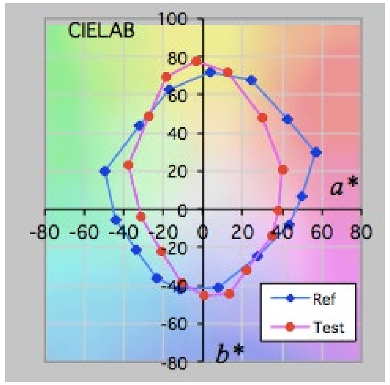
This lamp is often preferred to normal incandescent lamps which have CRI score of 100.



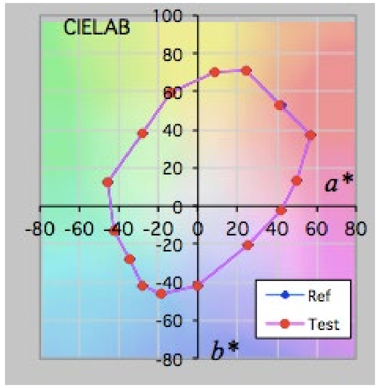


Color Gamut and Perception

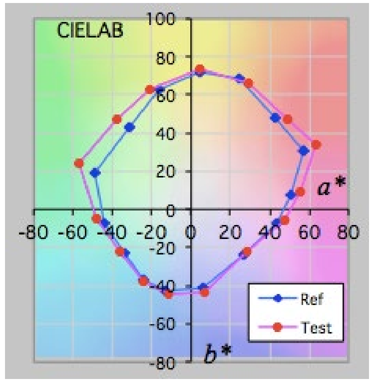
De-saturated
Looks poor



Neutral
Good



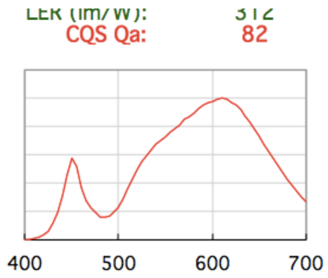
Over-saturated
Looks better
(to some extent)



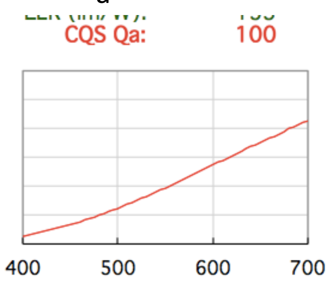
CRI R_a and perception agree well

CRI R_a and perception do not agree

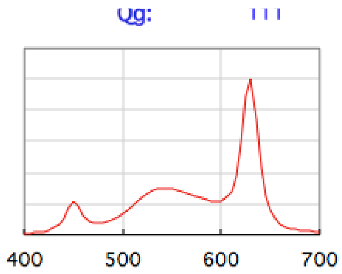
R_a=82



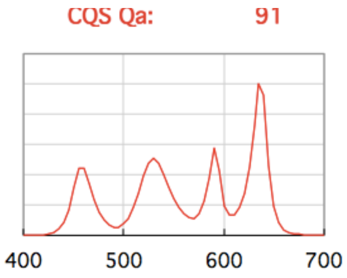
R_a=100



R_a=85



R_a=82



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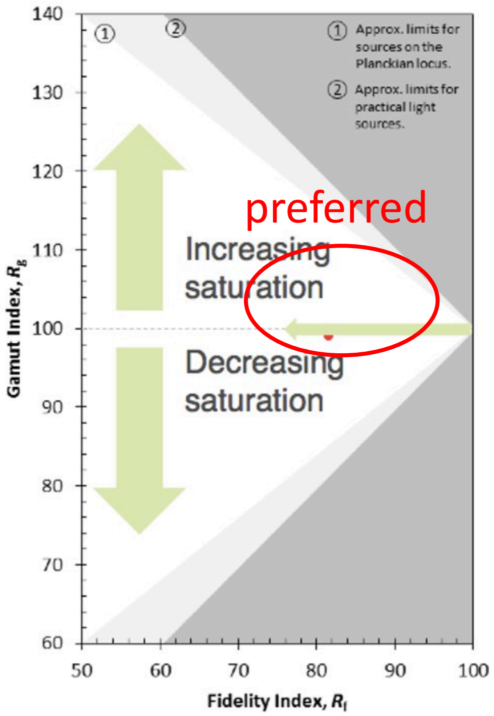
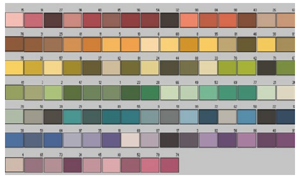
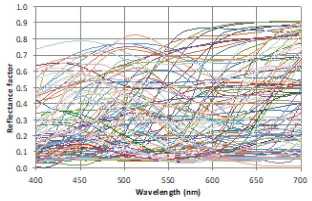
IES TM-30 (2015) IES Method for Evaluating Light Source Color Rendition



Concept of a Two-Metric System

- ❑ Fidelity index R_f
  - Latest color space
  - 99 test color samples



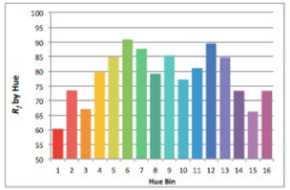


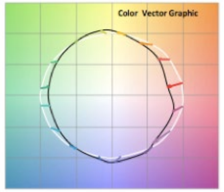
- ❑ Gamut index R_g

Accurate color fidelity (improvement of CRI R_a as a color fidelity metric)

For evaluation of preference

- ❑ Color shift graphics

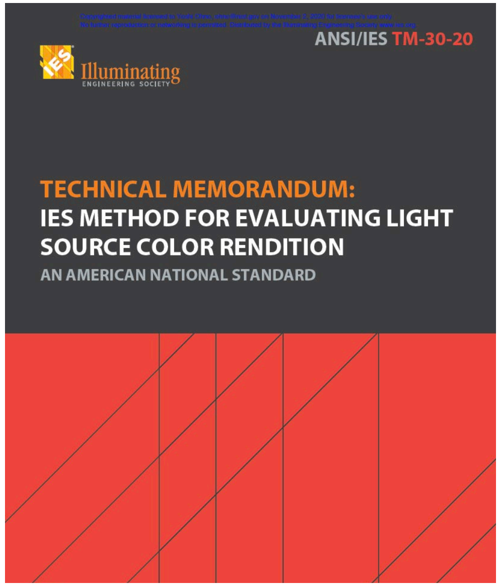




Details beyond R_f and R_g.

IES TM-30-2018, 2020 version

Annex E – Recommendations for Specifying Light Source Color Rendition



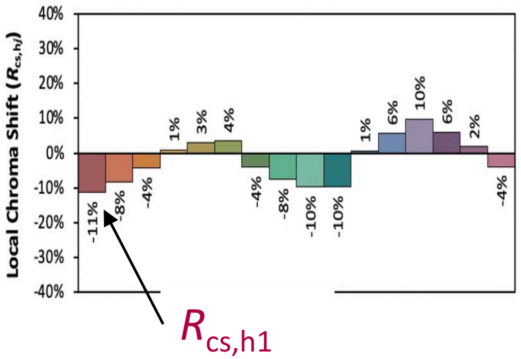


Table E-2. Recommended Specification Criteria.

Design Intent (The desired effect of color rendition on the illuminated environment)

Priority Level (The balance between allowing for tradeoffs and increasing the likelihood of meeting the design intent)	**Preference (P)**		**Vividness (V)**		**Fidelity (F)**	
1	**P1**	$R_f \geq 78$ $R_g \geq 95$ $-1\% \leq R_{cs,h1} \leq 15\%$	**V1**	$R_g \geq 118$ $R_{cs,h1} \geq 15\%$	**F1**	$R_f \geq 95$
2	**P2**	$R_f \geq 75$ $R_g \geq 92$ $-7\% \leq R_{cs,h1} \leq 19\%$	**V2**	$R_g \geq 110$ $R_{cs,h1} \geq 6\%$	**F2**	$R_f \geq 90$ $R_{f,h1} \geq 90$
3	**P3**	$R_f \geq 70$ $R_g \geq 89$ $-12\% \leq R_{cs,h1} \leq 23\%$	**V3**	$R_g \geq 100$ $R_{cs,h1} \geq 0\%$	**F3**	$R_f \geq 85$ $R_{f,h1} \geq 85$

Table note: All criteria assume a polychromatic environment with average horizontal illuminance between 200 and 700 lux and uniform chromaticity.

TM-30-20 free download available. https://www.techstreet.com/standards/ies-tm-30-20?product_id=2207652

An example of use of TM-30 Annex E parameters in public specifications

DLC

P3

Custo
m

Color Rendition	*All Indoor products, except high bay:* **Option 1 - ANSI/IES TM-30-18** • IES $R_f \geq 70$ • IES $R_g \geq 89$ • $-12\% \leq$ IES $R_{cs,h1} \leq +23\%$ **Option 2 – CIE 13.3-1995:** • $R_a \geq 80$ • $R_g \geq 0$	All color rendition metrics for patent products from LM-79 test reports listed as Tested Data. All color rendition metrics for child products listed as Reported Data	ANSI/IES LM-79 *ANSI/IES TM-30-18* *CIE 13.3-1995*
	All Outdoor and high-bay products: **Option 1 - ANSI/IES TM-30-18** • IES $R_f \geq 70$ • IES $R_g \geq 89$ • $-18\% \leq$ IES $R_{cs,h1} \leq +23\%$ **Option 2 – CIE 13.3-1995:** • $R_a \geq 70$ • $R_g \geq -40$ (high bay only) • Outdoor must report R_g		

Courtesy – from Michael Royer's presentation at IES Seminar on March 17, 2023

CIE 2017 Colour Fidelity Index

for Accurate Scientific Use

Recent CIE work on CRI issue

CRI issue
- Color fidelity (TC1-90)
- Color rendition beyond fidelity (TC1-91)


cie
International Commission on Illumination
Commission Internationale de l'Eclairage
Internationale Beleuchtungskommission

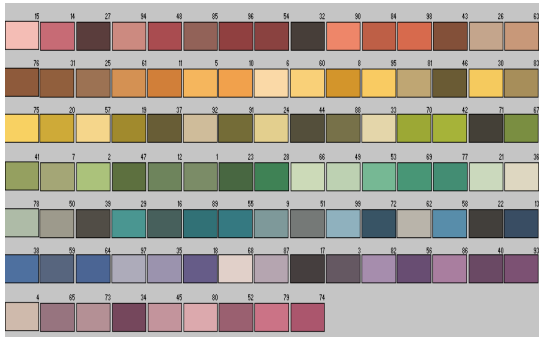
TECHNICAL REPORT

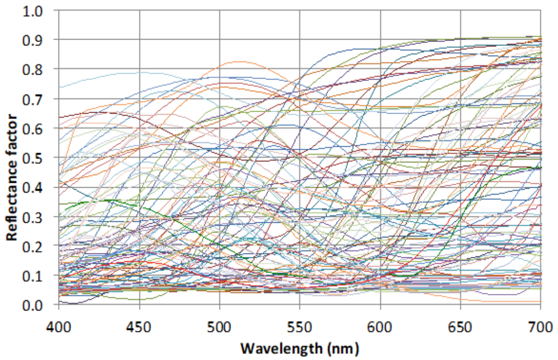
CIE 2017 Colour Fidelity Index for accurate scientific use

CIE 224:2017

UDC: 159.937.51
535.67
612.843.31
535.66

- CIE adopted **IES TM-30-15 Fidelity Index R_f** with small modifications. The 99 test samples and color space, calculation formulae are the same.

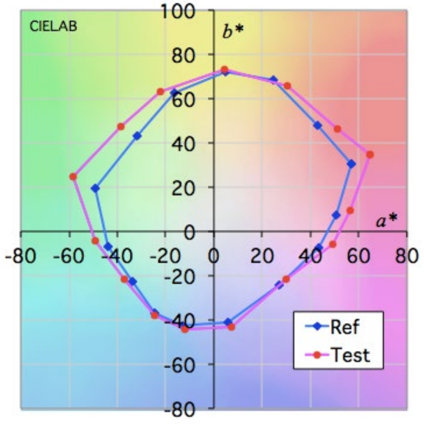




IES TM-30 was revised in 2018 to be consistent with the CIE R_f.

- The use of this index is limited. Its summary says "The general colour fidelity index R_f is not a replacement of the CRI (R_a) for the purpose of rating and specification of products nor for regulatory or other minimum performance requirements"

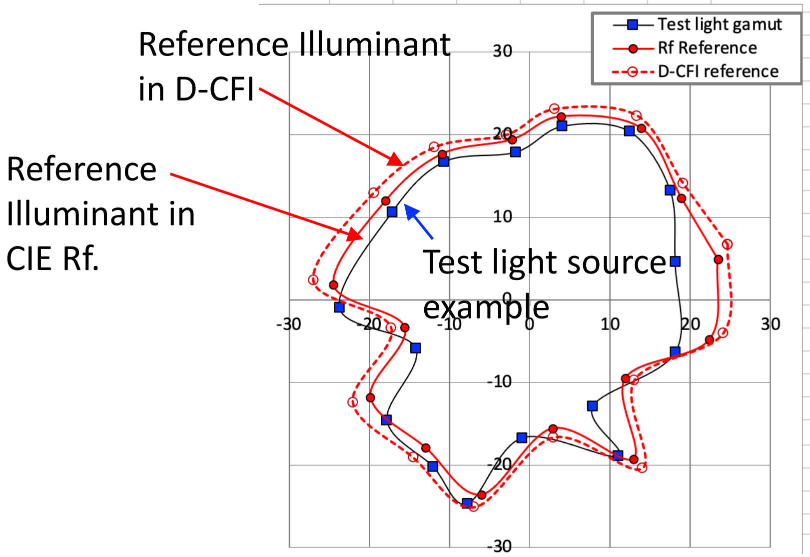
Fidelity Index based on Hunt Effect (NIST research)

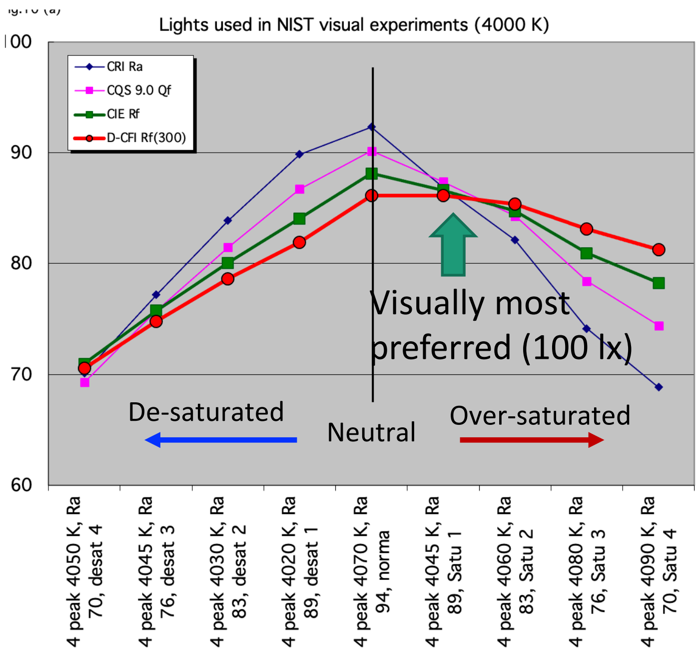


Will this create "fake" colors of objects?

Based on Hunt Effect, this will be **higher color fidelity** (close to appearance in outdoor daylight).

"Dynamic Color Fidelity Index (D-CFI) based on Hunt Effect" (to be published at CIE 2023, Slovenia)





Summary on color rendering specification

1. A new CIE publication "Overview of Methods for Evaluating Colour Rendition of White-Light Sources beyond Colour Fidelity" will come out soon.
2. The new fidelity index R_f (CIE 224 or IES TM-30) alone, nor the metrics in CIE 1-91 report, are not recommended to replace CRI. CIE plans to develop a set of new metrics that can replace CRI, which will take several years.
3. The three parameters in IES TM-30 Annex E (R_f, R_g, $R_{ch,h1}$) might be tentatively used combined with CRI R_a.
4. Research on Hunt Effect (effect of light level on perceived color saturation) is in progress at NIST and other places, which may lead to a new fidelity index that can solve this CRI problem.

Thank you for your attention

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