Measurement of LEDs and Solid State Lighting

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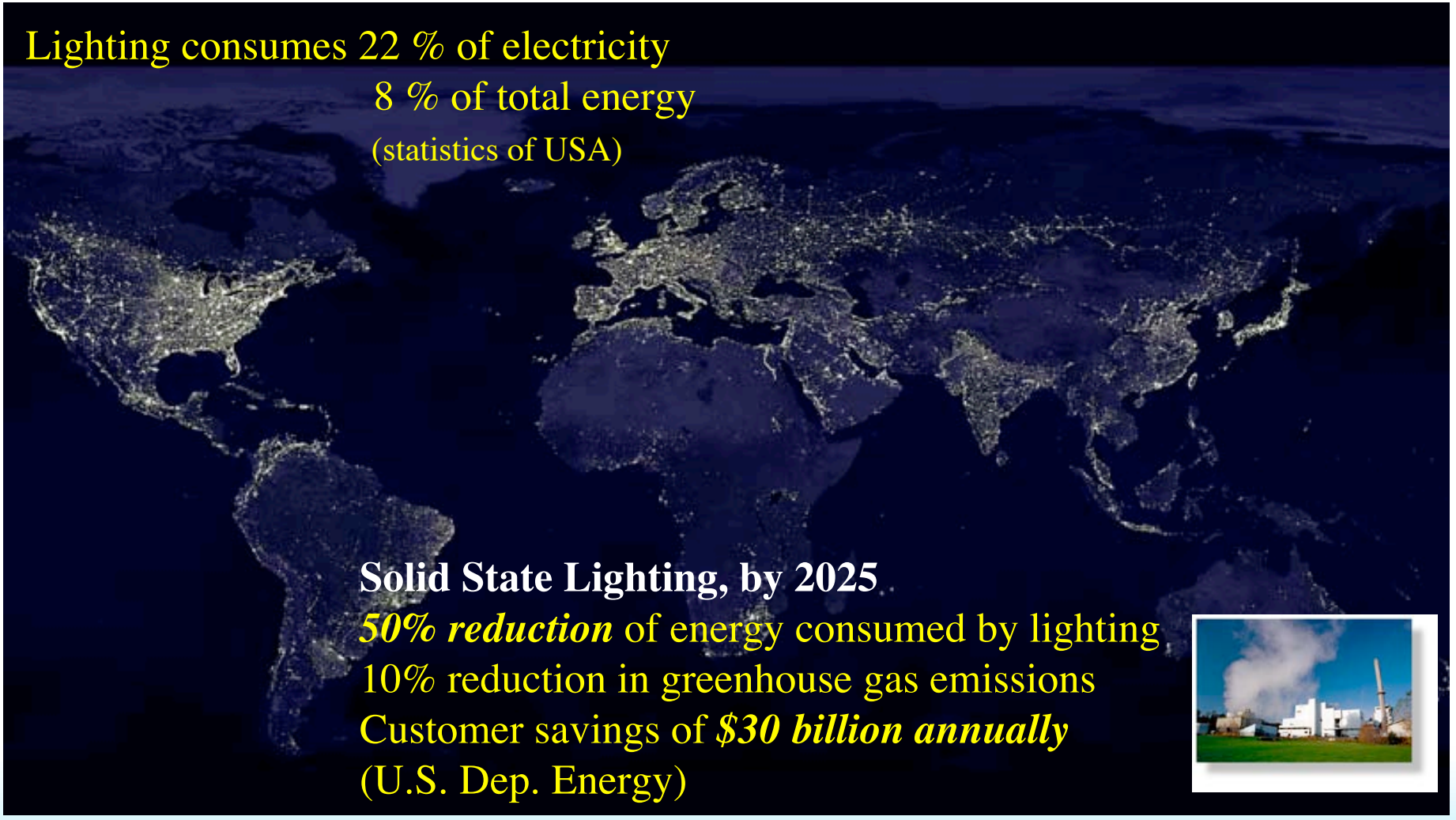
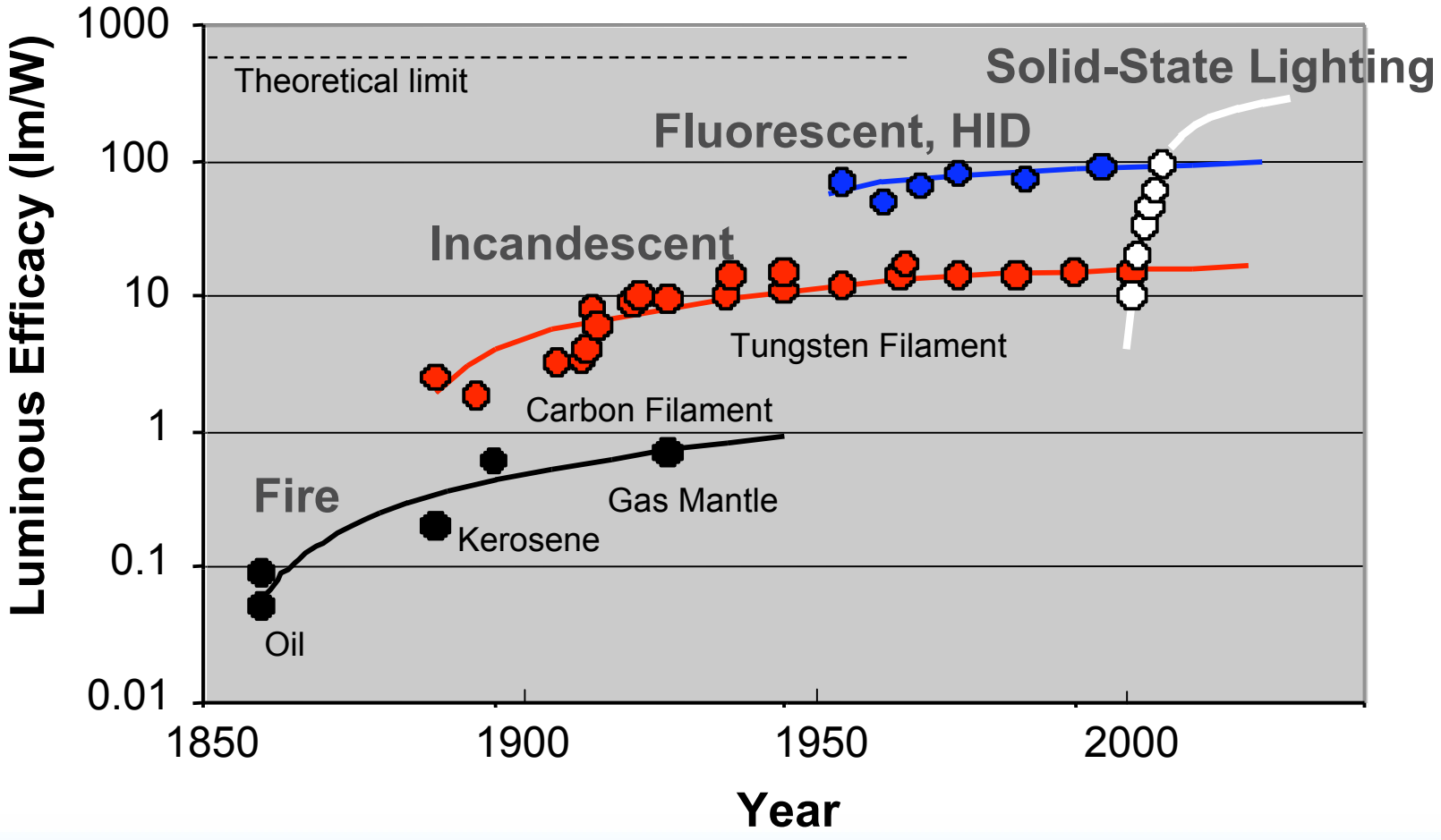
Outline

1. SSL products - commercialization support
2. Measurement standards for LED/SSL products
3. NIST facilities for LED/SSL measurements
4. Research on Color Quality of LED/SSL sources

Solid State Lighting – Driving Force

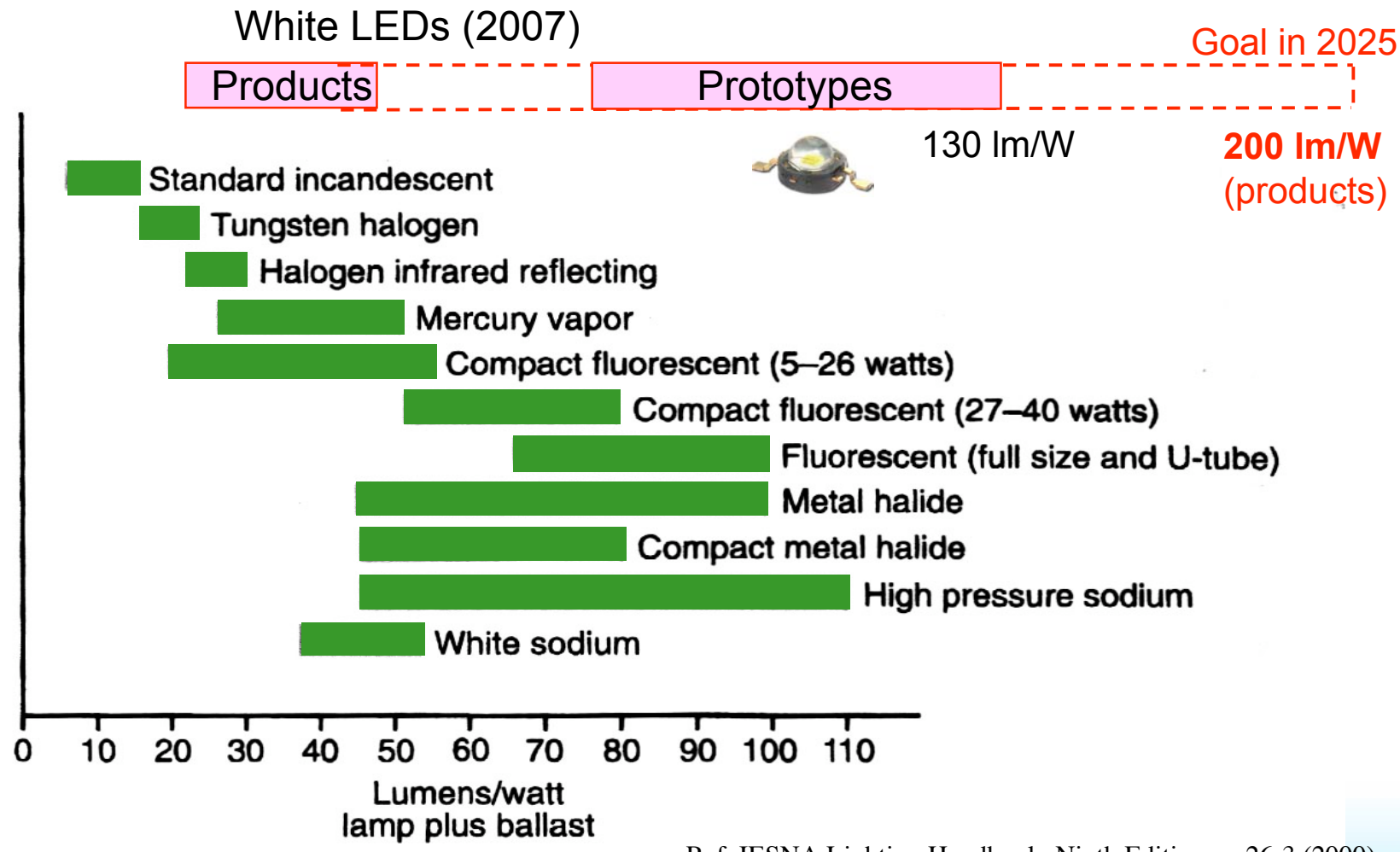


History of Light Sources



IEEE Circuits and Devices Vol 20, No 3, pp 28-37, May/June, 2004

Luminous Efficacy – Goal of SSL



Ref. IESNA Lighting Handbook, Ninth Edition, p. 26-3 (2000).

Rationale for 200 lm/W

Luminous Efficacy of a Source [lm/W] = **Luminous Efficacy of Radiation [lm/W]** X **Radiant efficiency**

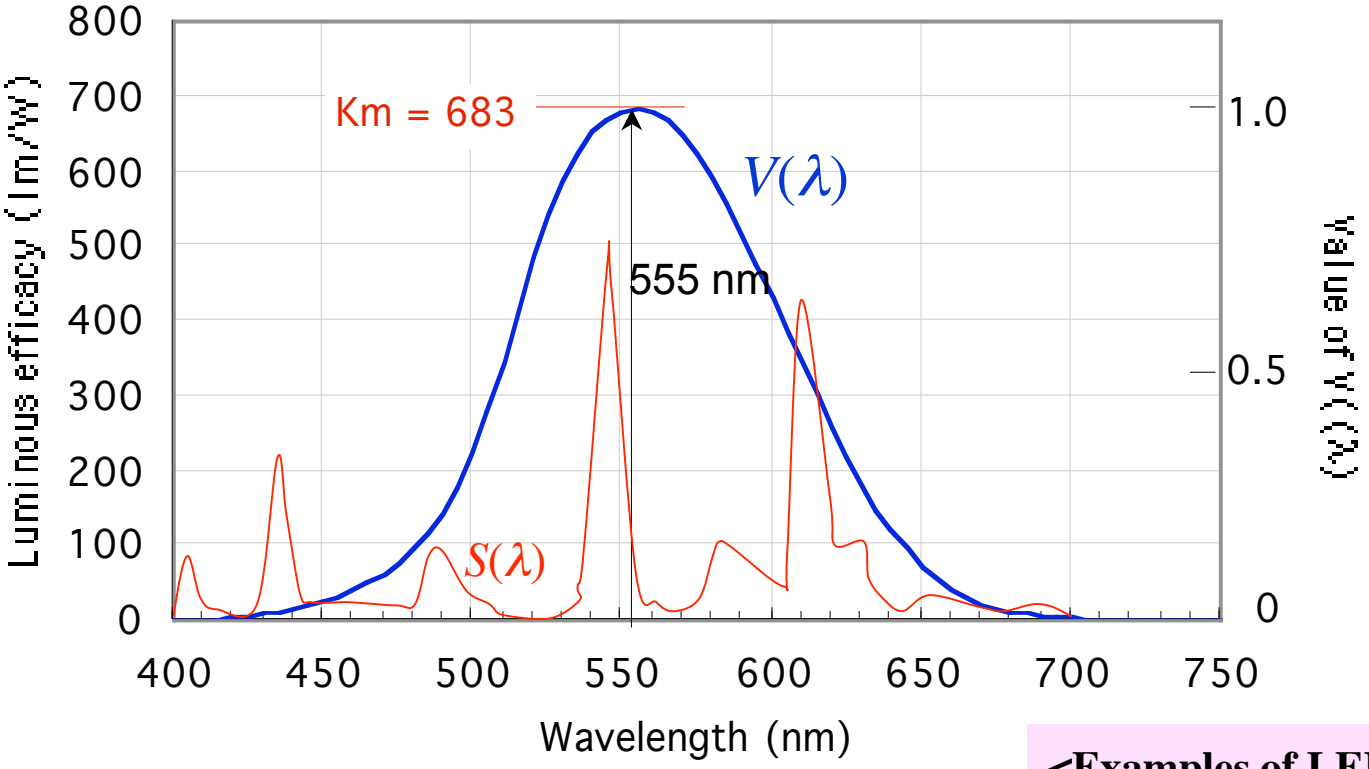
("Wall-plug efficiency") (Theoretical maximum lm/W) (External Q.E.)

$$\frac{\text{Luminous flux [lm]}}{\text{Electrical power [W]}} = \frac{\text{Luminous flux [lm]}}{\text{Optical power [W]}} \times \frac{\text{Optical power [W]}}{\text{Electrical power [W]}}$$

Goal:

200 lm/W **400 lm/W** **50 %**

Luminous Efficacy of Radiation



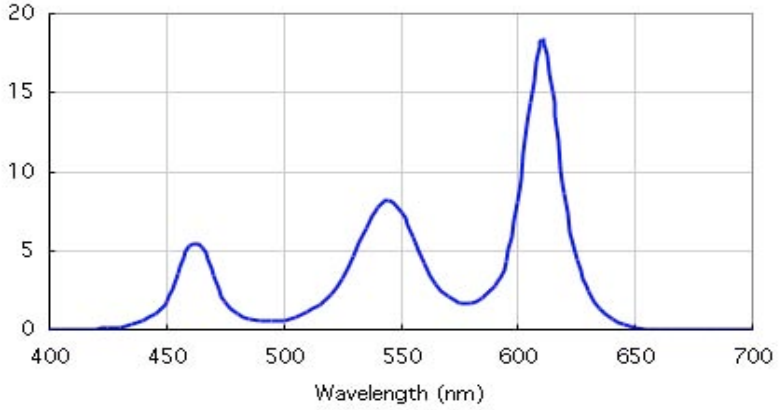
$$K = \frac{K_{\mathrm{m}} \int_{\lambda} S(\lambda) V(\lambda) \mathrm{d}\lambda}{\int_{\lambda} S(\lambda) \mathrm{d}\lambda} \quad [\mathrm{lm/W}]$$

$$(K_{\mathrm{m}} = 683 \ \mathrm{lm/W})$$

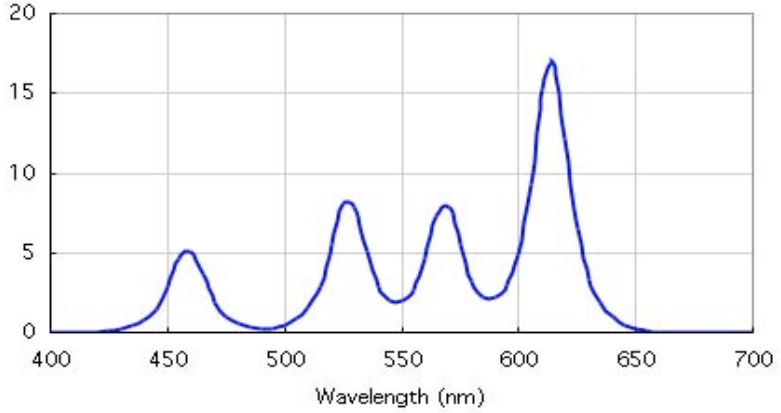
<Examples of LER>

Tri-p FL (3300 K)	~350 lm/W
CW FL (4300 K)	~340 lm/W
MH (4300 K)	~300 lm/W

RGB(Y) white LED Simulation

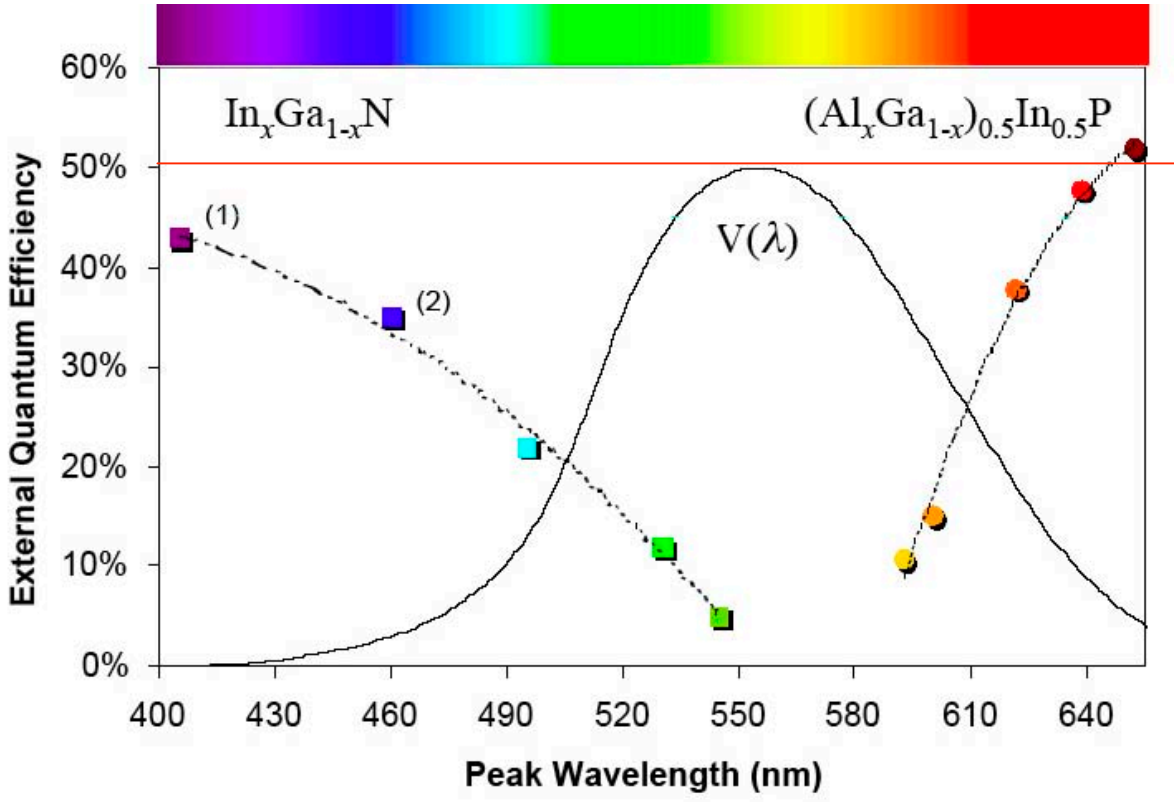


x	0.4369	
y	0.4041	
CCT	3000	K
Duv	0.000	
CRI (Ra)	86	
LER	401	lm/W



x	0.4369	
y	0.4041	
CCT	3000	K
Duv	0.0000	
CRI (Ra)	90	
LER	395	lm/W

External Quantum Efficiency of LEDs



White LED efficacy 200 lm/W

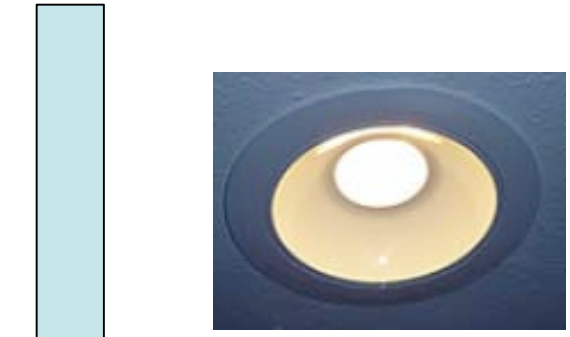
T_j=25°C

[1] Mitsubishi Cable: *III-Vs Review*, Vol. 16, No. 4, p.34 (May, 2003).
[2] Nichia Chemical Co.: Yamada et. al., *Jpn. J. Appl. Phys.* Vol. 41 (2002) pp. L 1431–L 1433.

Source: Mike Krames (Lumileds)

SSL products are coming out

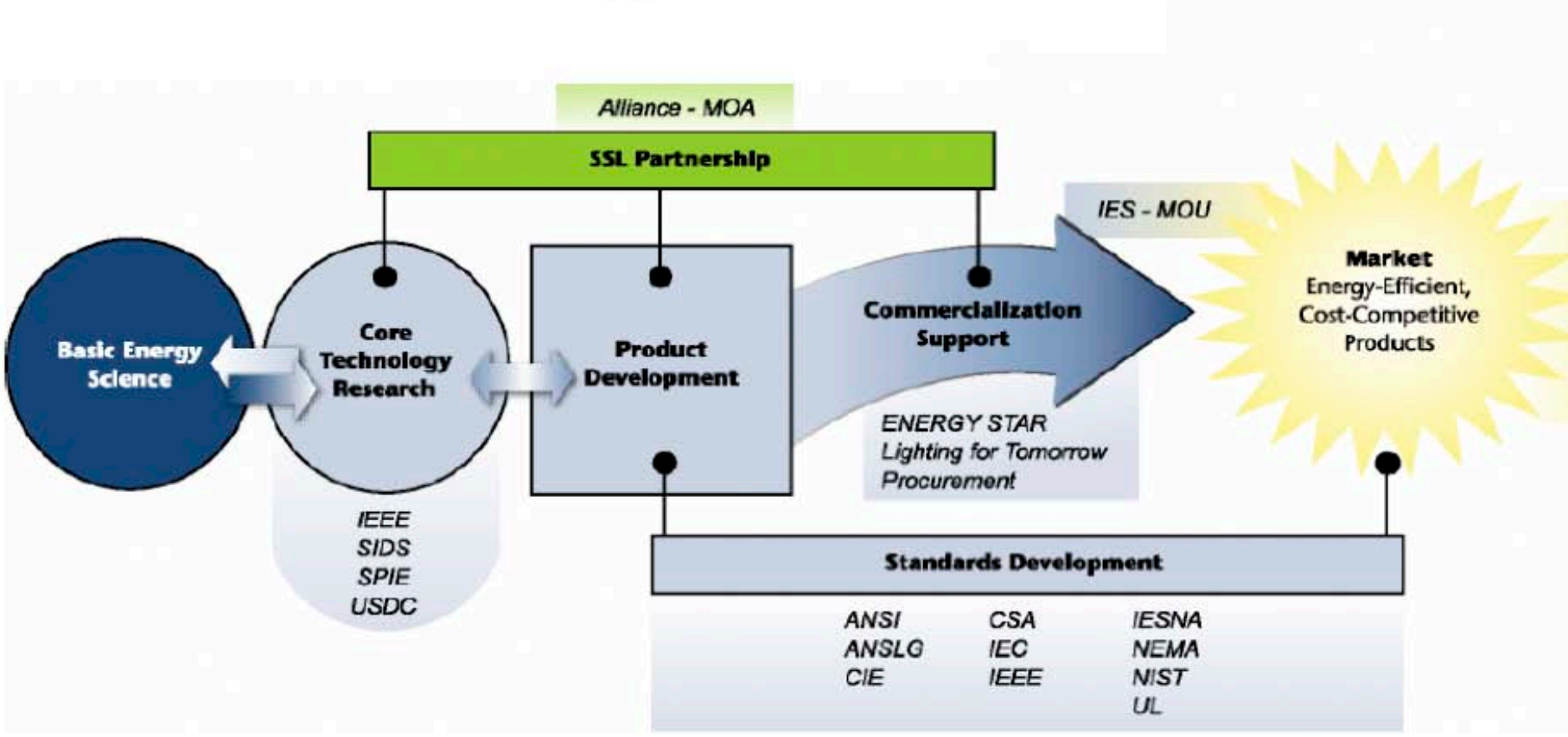
Niche applications



General lighting applications

DOE's SSL Commercialization Support

DOE's Lab-to-Market strategy



http://www.netl.doe.gov/ssl/materials_2007.html

DOE Energy Star program for SSL products

Final version 9/12/2007

- SSL products for general illumination (residential and commercial applications)
- Category A (niche applications), Category B (general lighting)
- Requirements for luminaire efficacy, chromaticity, and CRI (*R*a >75 for indoor applications).
- Ensure quality as well as energy efficiency
- Requires **standards for test methods**.
- Requires **laboratory accreditation**.

	Min. lm/W
Under cabinet kitchen	24
Portable desk/Task	29
Recessed downlights	35
Outdoor porch lights	24
Outdoor step lights	20
Outdoor pathway lights	25
Category B	70

http://www.netl.doe.gov/ssl/energy_star.html

DOE SSL Commercial Product Testing Program (CALiPER - formerly, CPTP)

- Workshop held Oct. 27, 2006
  http://www.netl.doe.gov/ssl/workshopHighlights-CPTP.htm
- Objective:
  - Provide high quality performance information, discourage low quality products.
  - Support R & D planning
  - Support ENERGY STAR
  - Inform industry test procedures and standards
- Key actors:
  - DOE, PNNL
  - Independent testing labs
- Tests may include
  total luminous flux, luminous Efficacy, color characteristics stability, life testing, and more.

■ Publication of CPTP Reports

- Via website:
  www.netl.doe.gov/ssl/comm_testing.htm
  - Summary reports (de-identified)
  - Detailed reports
    - Must be requested via web form

NIST Role

- Provide calibration services for LED and SSL products.
- Research on color quality.

NIST is funded by DOE for

- Developing NVLAP program for SSL - Handbook 150-A, Round-robin proficiency testing.
- Measurement support
  - verification of measurements in CALiPER program
  - test of prototypes from DOE projects
- Standards development

NIST leads

  - ANSI C78.377 chromaticity of SSL products
  - IESNA LM-79 photometric measurement of SSL products
  - CIE standard on color rendering (TC1-69)
  - participating in other standards development

1. SSL products - commercialization support

2. Measurement standards for LED/SSL products

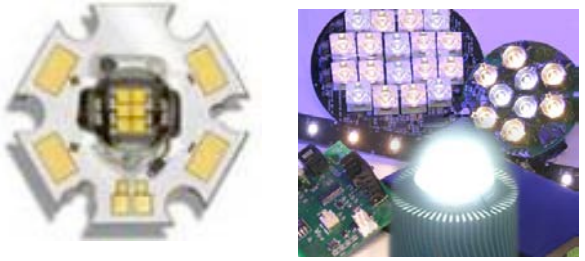
3. NIST facilities for LED/SSL measurements

4. Research on Color Quality of LED/SSL sources

Measurement of LED/ SSL Products

LED chips / packages

LED modules / clusters



SSL products

Measurement quantities

- Total luminous flux (lm)
- Luminous efficacy (lm/W)
- Luminous intensity (CIE Averaged Intensity)
- Chromaticity, CCT, Duv, CRI
- Angular intensity distribution
- Luminaire efficacy (lm/W)

Standards for measurement of LED/ SSL products

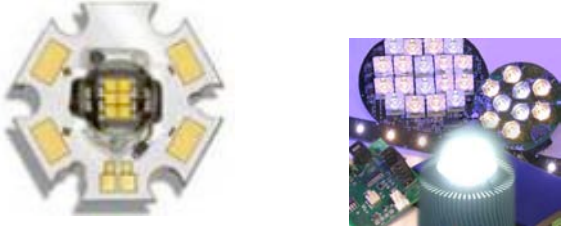
LED chips / packages

CIE 127:2007

does not address issues on high power LEDs

CIE TC2-46, TC2-58
CIE R2-36

LED modules / clusters



No standards / recommendation

CIE TC2-50

SSL products

No CIE publications, no TCs

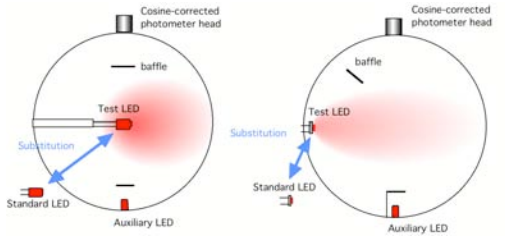
IESNA LM-79 Photometric Meas. (draft)
IESNA LM-80 Life time (draft)
ANSI C78.377 Chromaticity (draft)

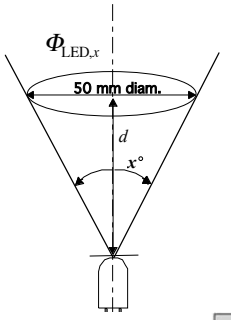
CIE 127:2007 Measurement of LED (2nd ed.)

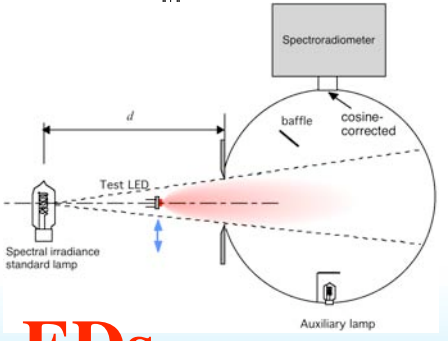
Major changes from last version (1997)

- New section on total luminous flux measurement.
  - Improved sphere geometries recommended
  - Partial LED flux defined.

- New section on spectral measurement (for colorimetric as well as photometric quantities)
  - Input geometries (irradiance mode, total flux mode, partial flux mode)
  - New recommendation on bandwidth and scanning interval (5 nm, for color)







Still does not address high power LEDs.

A big issue in High Power LED measurement

<LED data example>

Flux Characteristics at 700mA, Junction Temperature, T_J = 25°C

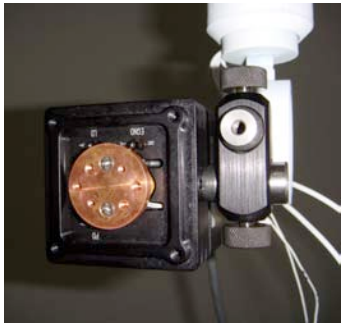
Table 1.

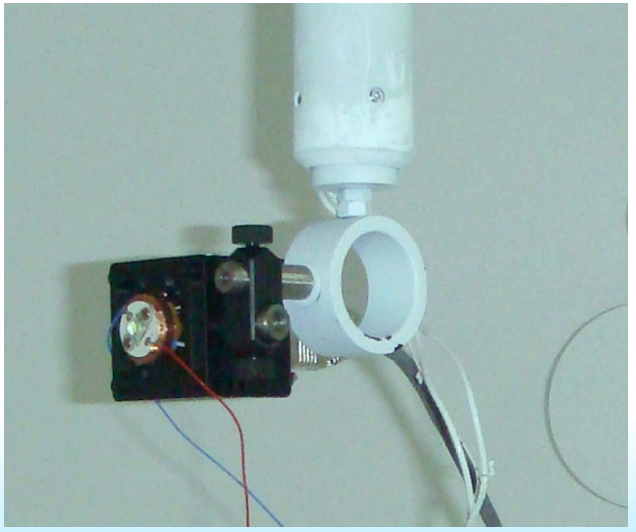
Color	LUXEON Emitter	Minimum Luminous Flux (lm) or Radiometric Power (mW) Φ_V [1,2]	Typical Luminous Flux (lm) or Radiometric Power (mW) Φ_V [2]	Radiation Pattern
White	LXHL-PW09	60.0	65	
Green	LXHL-PM09	51.7	64	Lambertian
Cyan	LXHL-PE09	51.7	64	
Blue[3]	LXHL-PB09	13.9	23	
Royal Blue[4]	LXHL-PR09	275 mW	340 mW	

- LEDs in SSL products are operating at much higher temperature. lm/W drops to 1/2 (in some cases) in luminaires.
- Large gap between published LED chip performance (lm/W) and SSL products performance (lm/W).
- A standard for high power LED specifications under realistic conditions (as used in luminaires) is urgently needed.

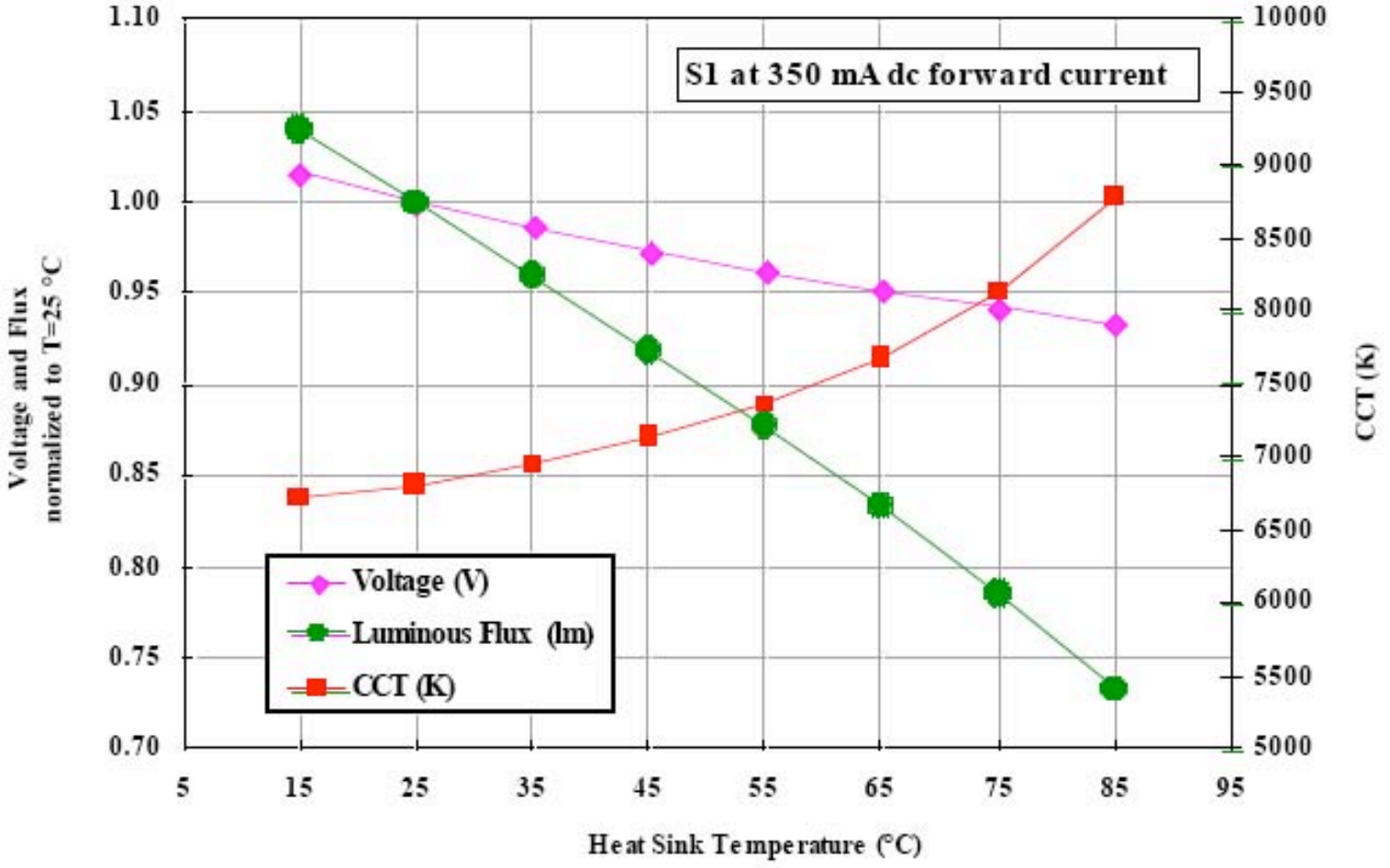
Approach at NIST

- Measure high power LEDs at a full DC current at thermal equilibrium.
  (A heat sink is needed; results vary depending on size of heat sink, ambient temp. and how LED is mounted)
- Use a temperature-controlled heat sink. Set heat sink temperature at 50°C, 60°C, ….
  (need to be standardized)
- Use a metal-core PC board to mount the LED to the heat sink.





Data example



Measurement of SSL products

SSL products: mostly in a form of luminaire

Traditional luminaire photometry (Relative Photometry)

- Luminaires are measured for relative luminous intensity distribution and total luminous flux, normalized by measured lamp total luminous fux, e.g., per 1000 lm.
- Absolute scale is given by published lamp lumen values.

This method does not work for SSL products.

- Lamp and fixture cannot be separated.
- Published LED luminous flux values are not reliable.

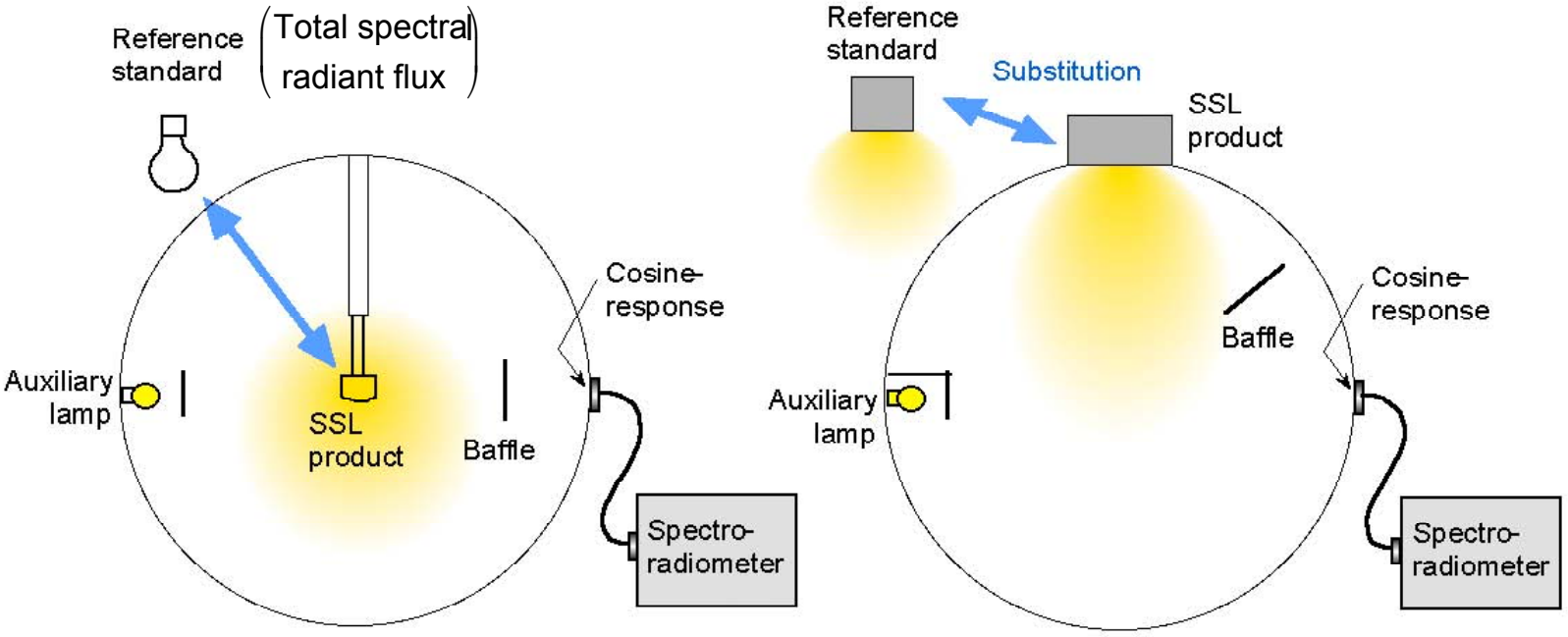
Existing standards do not fulfill the needs for SSL.

IESNA LM-79 Approved Method for Electrical and Photometric Measurement of SSL Products (Draft)

- Covers SSL products **complete with electronics and heat sinks**. --- therefore, no temperature issues (SSL product operated at 25°C ambient).
- Does not cover LED modules, LED packages, nor individual LEDs.
- Addresses both aspects of lamp photometry and luminaire photometry
  - Total luminous flux (lumen), electrical input, luminous efficacy (lm/W)
  - Chromaticity, CCT, CRI (4 π integrated)
  - Goniophotometry (angular intensity distribution)

IESNA LM-79

One of the methods recommended (for small SSL products)

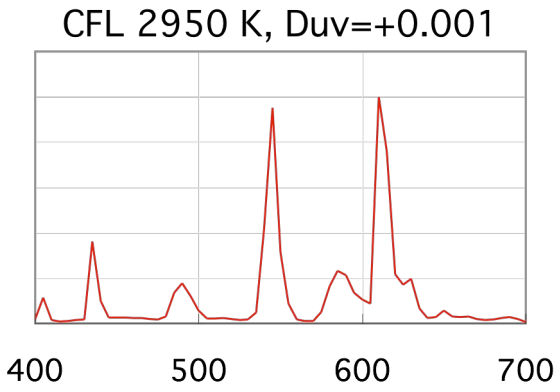


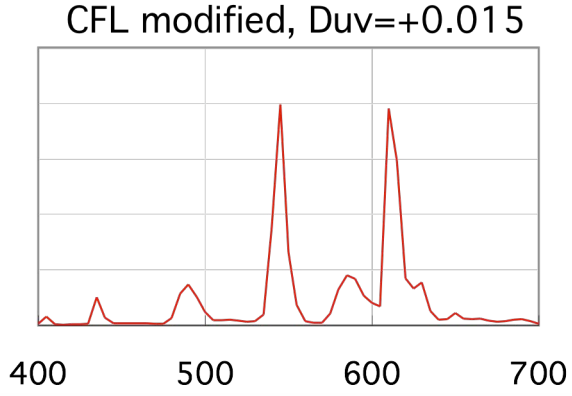
- Total luminous flux and color quantities measured at the same time.
- No spectral mismatch correction needed for luminous flux.
- Color quantities measured as spatially (4π) averaged values.
- Total spectral radiant flux standards available from NIST.

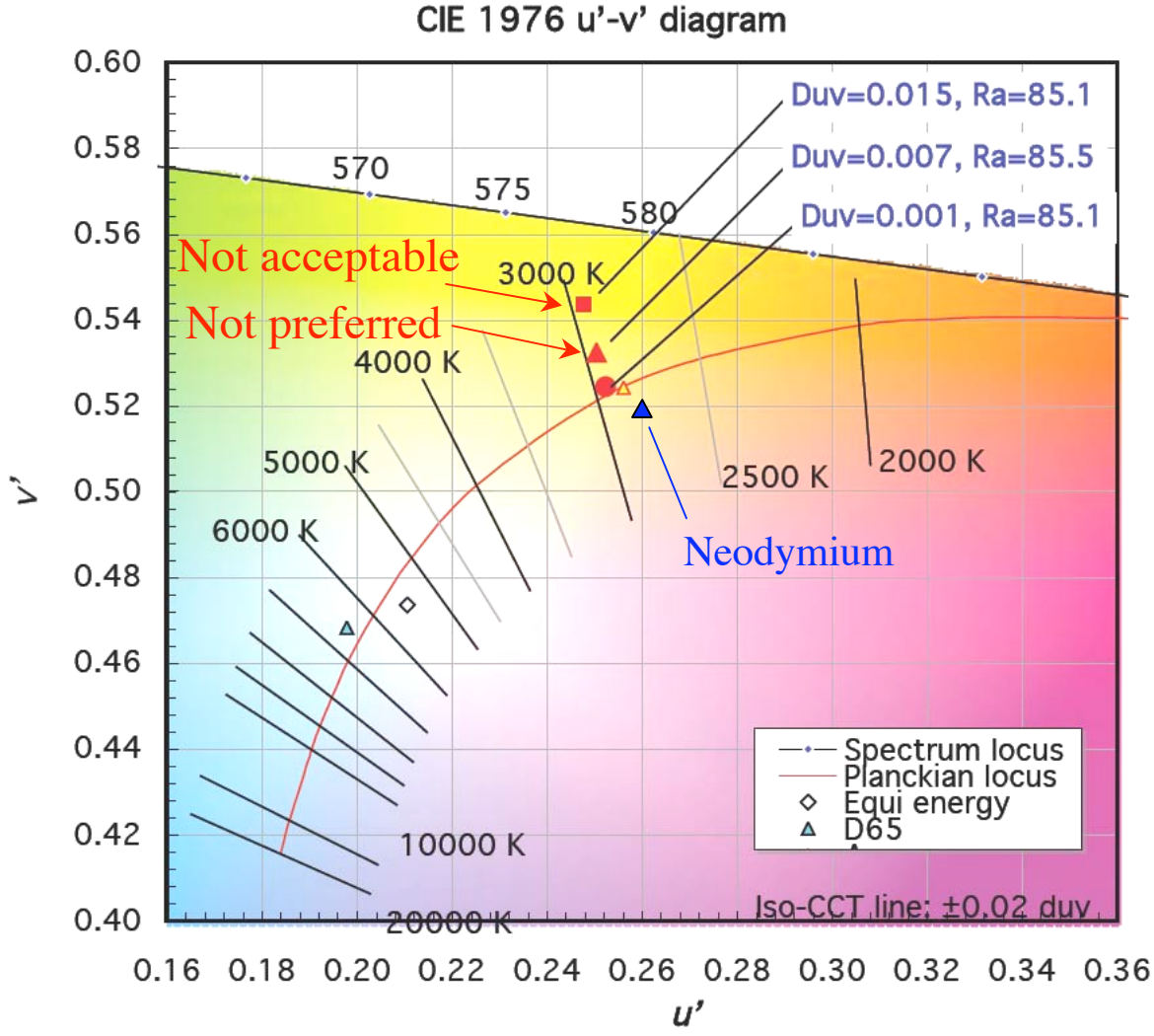
A goniphotometer is needed for large-size SSL products)

Chromaticity issues

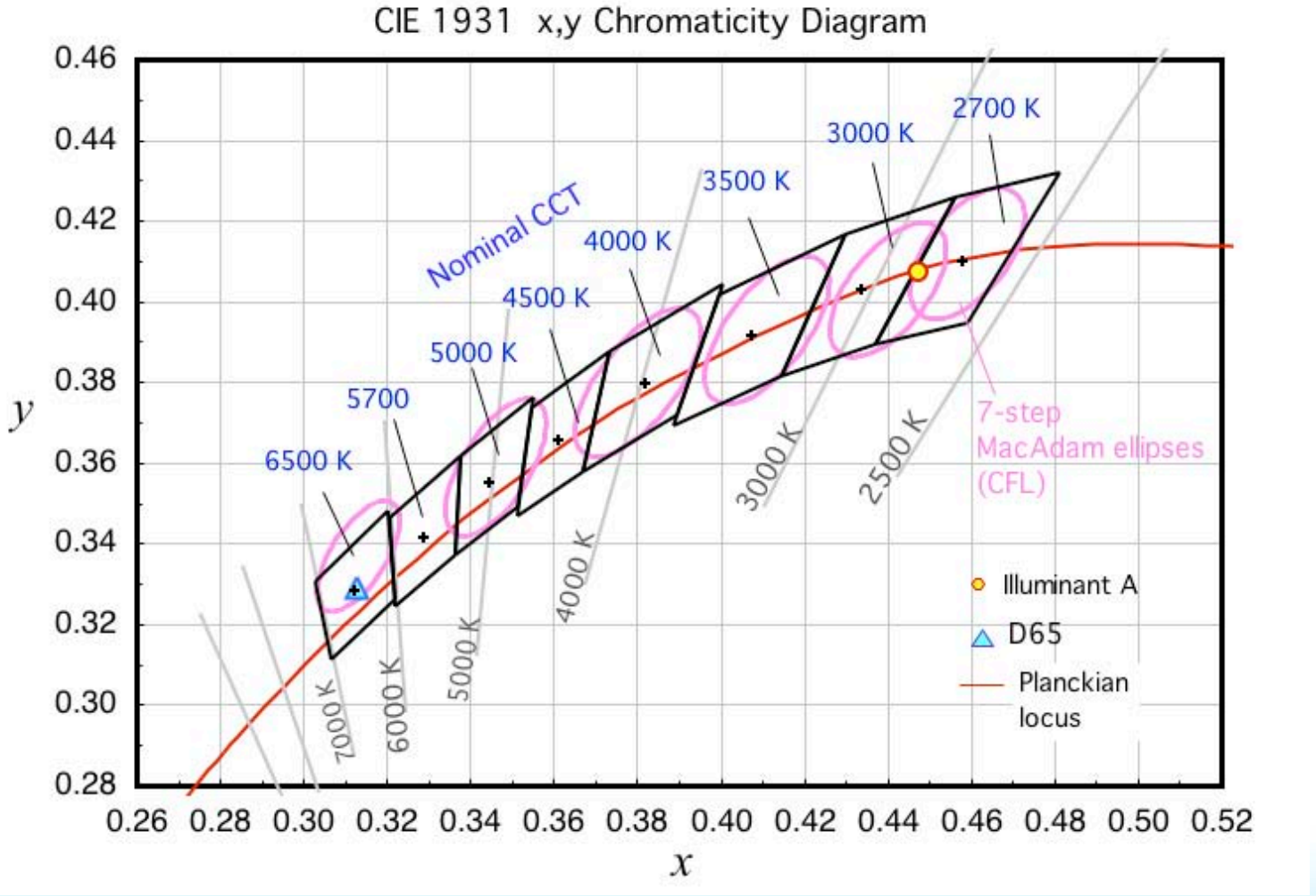
CCT and CRI do not tell the whole story.



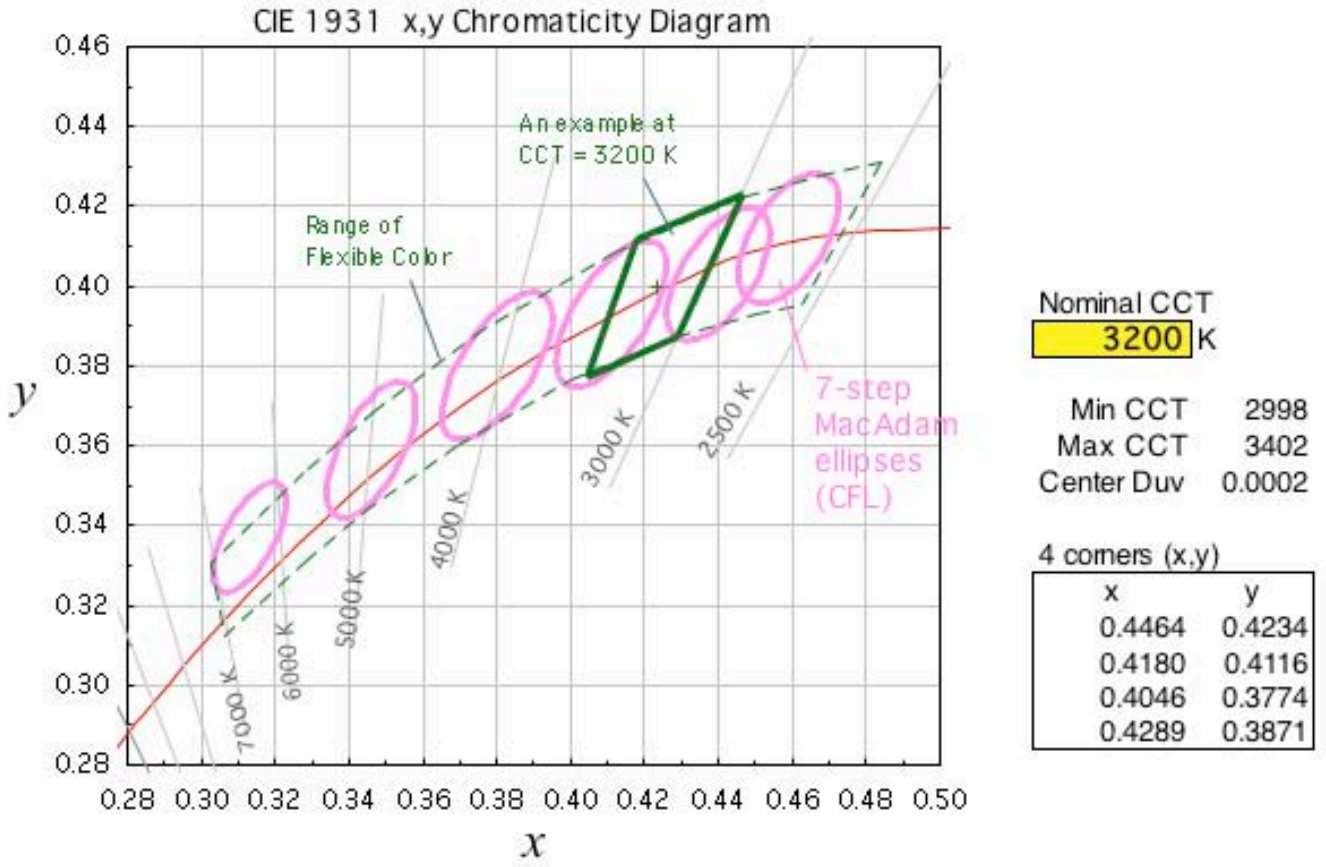




ANSI C78.377 Specifications for the Chromaticity of SSL products (Draft)



Flexible Color



2) T is chosen to be at 100 K steps (2800, 2900, …., 6400 K), excluding those eight nominal CCTs listed in Table 1.

3) ΔT is given by $\Delta T = 0.0000108 \times T^2 + 0.0262 \times T + 8$.

4) D_{uv} is given by $D_{uv} = 57700 \times (1/T)^2 - 44.6 \times (1/T) + 0.0085$.

1. SSL products - commercialization support

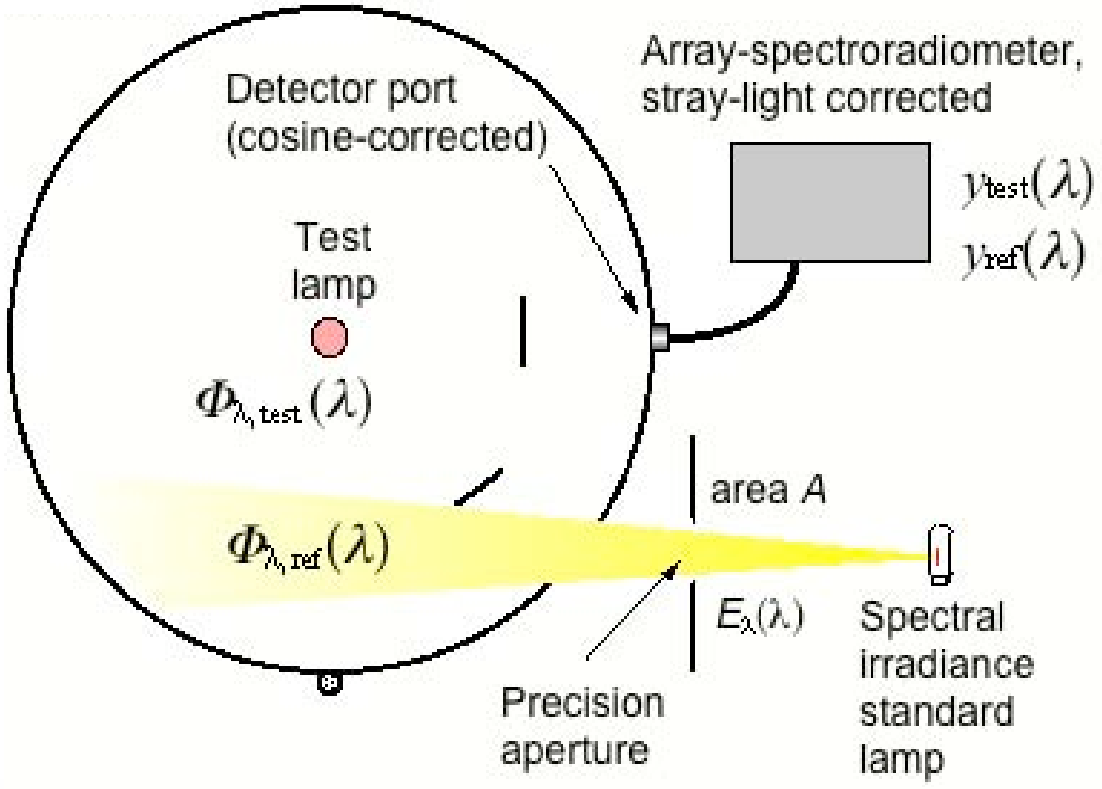
2. Standardization for LED/SSL products

3. NIST facilities for LED/SSL measurements

4. Research on Color Quality of LED/SSL sources

NIST Facilities for LED/SSL measurements

2.5 m absolute integrating sphere



External reference flux:

$$\Phi_{\lambda,\mathrm{ref}}(\lambda) = A \cdot E_\lambda(\lambda)$$

Spectral radiant flux of the test lamp:

$$\Phi_{\lambda,\mathrm{test}}(\lambda) = \frac{y_{\mathrm{test}}(\lambda)}{y_{\mathrm{ref}}(\lambda)} \cdot k_{\mathrm{cor}}(\lambda) \cdot \Phi_{\lambda,\mathrm{ref}}(\lambda)$$

$k_{\mathrm{corr}}(\lambda)$: correction factor

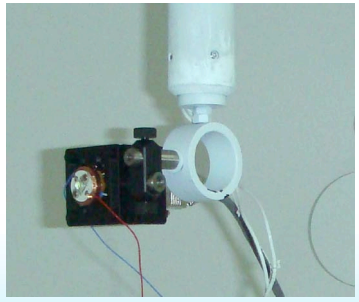
* Absolute scale of radiant flux is based on the NIST lumen.

2.5 m absolute integrating sphere

Measuring a refrigerator LED luminaire

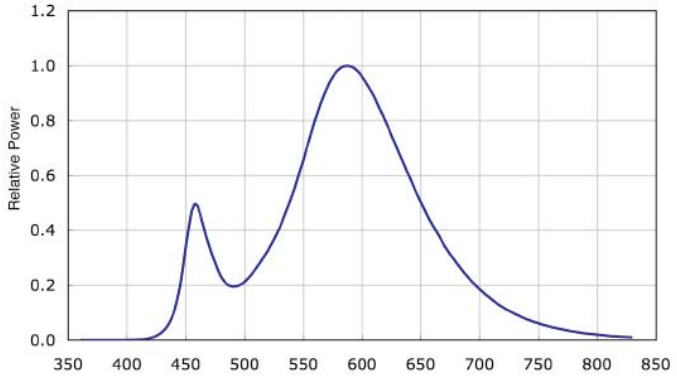
For SSL products

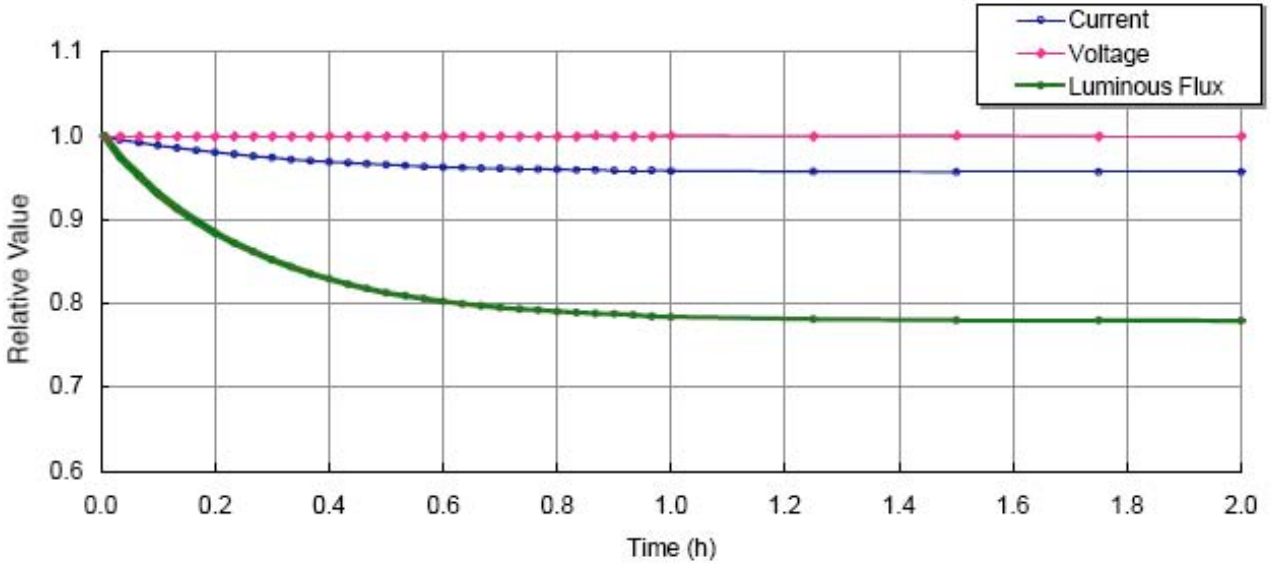
- Total luminous flux (lm)
- Total spectral radiant flux (350 nm to 830 nm)
- Chromaticity, CCT, Duv, CRI (4 π averaged)
- 25°C ambient temp.
- SSL products up to ~30 cm diameter or linear ~1.5 m long.
- Individual LEDs also measured.



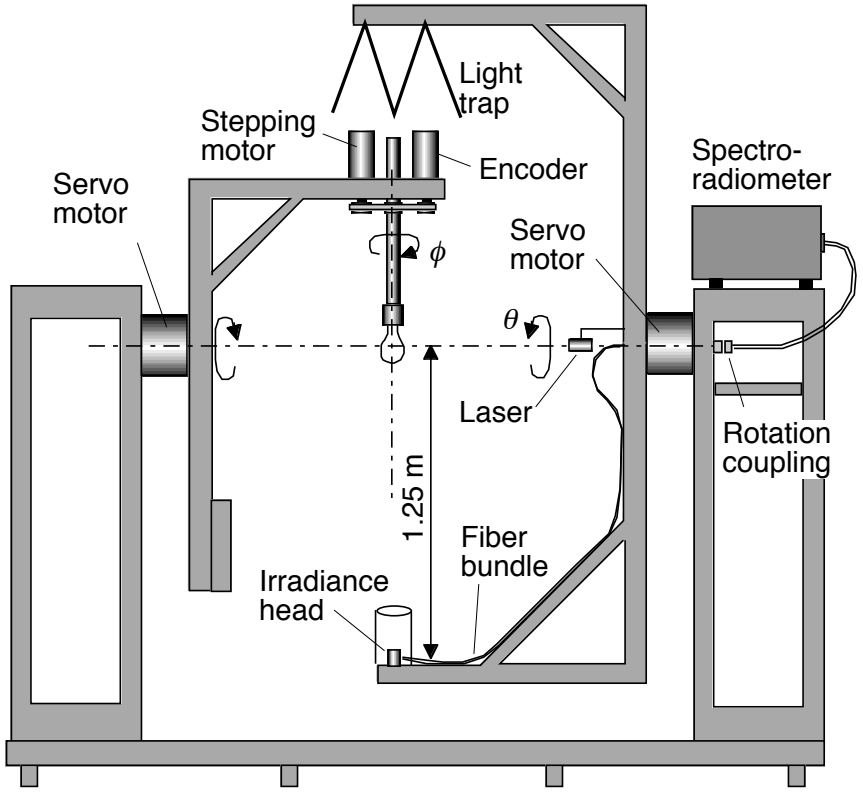
2.5 m absolute integrating sphere

Data example (LED down light)

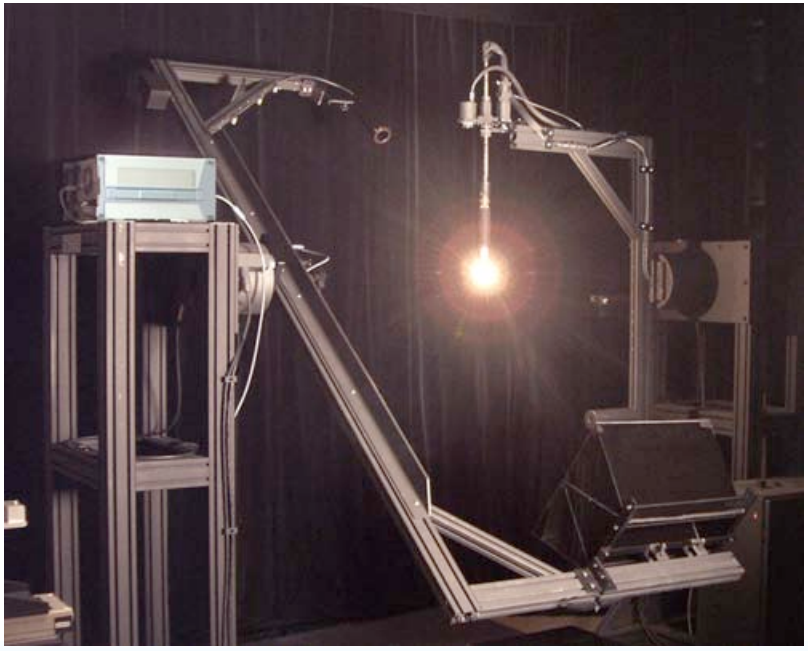




Gonio-spectroradiometer



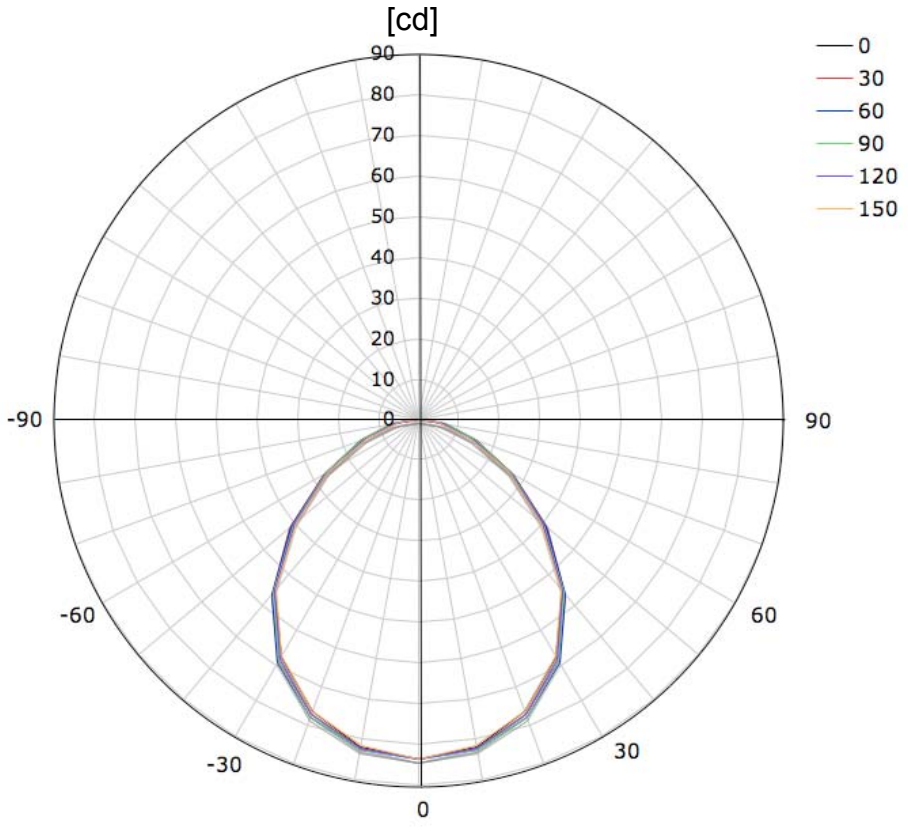
- Total spectral radiant flux scale
- **Measurement of small SSL products**
  - Angular luminous intensity distribution
  - Color uniformity



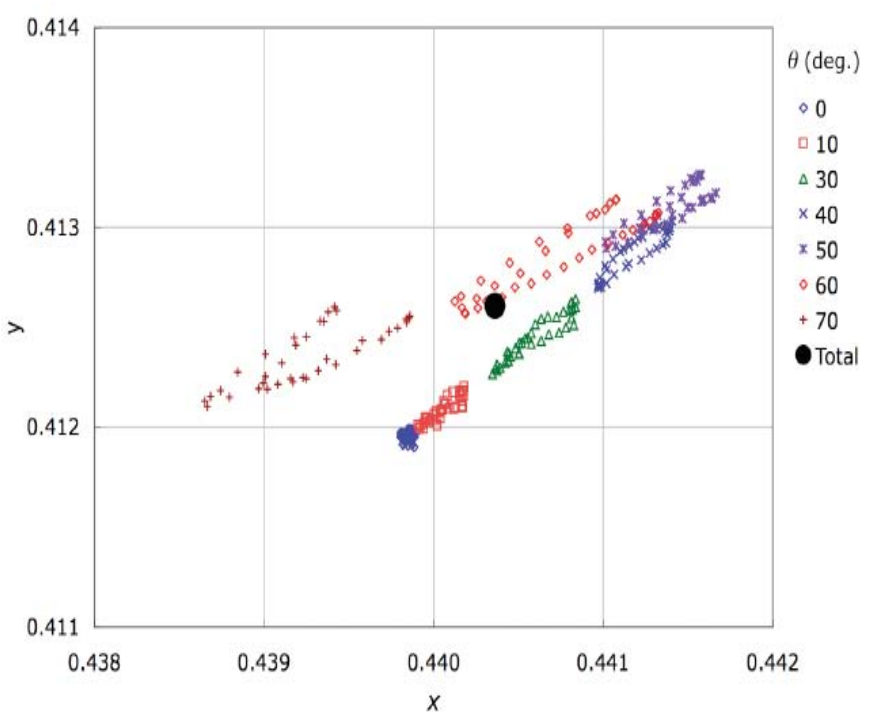
Gonio-spectroradiometer

Data example (LED down light)

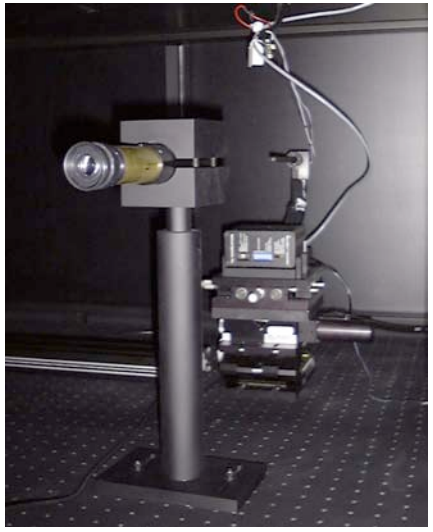
Luminous intensity distribution

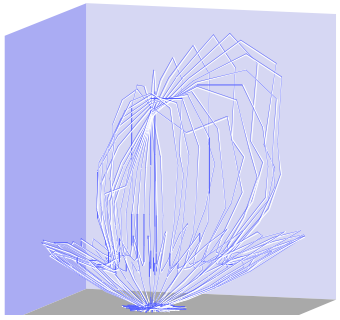


Color uniformity

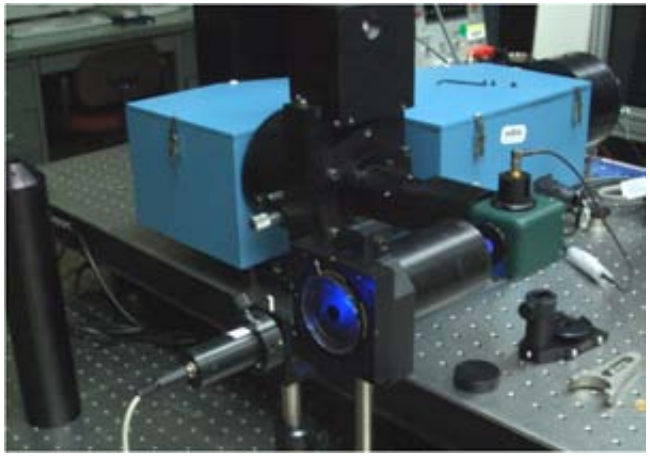


Other NIST instruments for LEDs





Goniophotometer for luminous intensity distribution



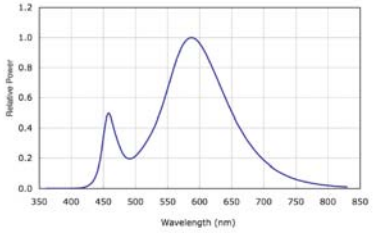
Reference spectroradiometer (double-monochromator) for LED color measurement

Variable temperature chamber (~10°C to 35°C)

NIST Calibration Services for LED/SSL Products

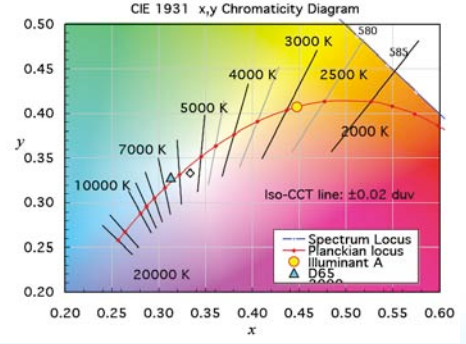
Photometric and radiometric quantities

- Total luminous flux (lm), luminous efficacy (lm/W)
- Total radiant flux (W) … (350 - 830 nm)
- Luminous Intensity
  CIE Averaged LED Intensity A/B
- Luminous intensity distribution (small sources)



Color quantities

- Chromaticity coordinates (*x,y), (u', v')*
- Correlated color temperature
- Color Rendering Index (CRI R_a)
- Dominant wavelength λ_d
- Spectral distribution (total spectral radiant flux)



1. SSL products - commercialization support

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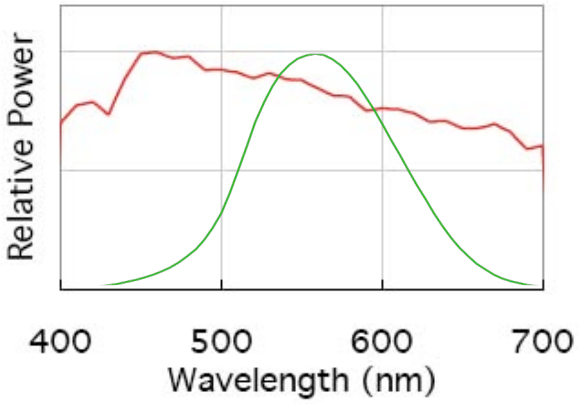
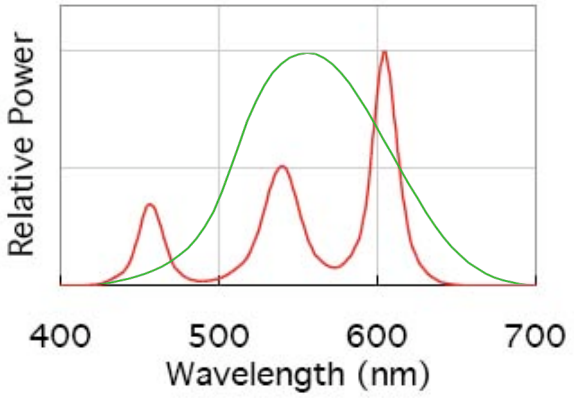
4. Research on Color Quality of LED/SSL sources (update)

Color Quality vs. Energy Efficiency

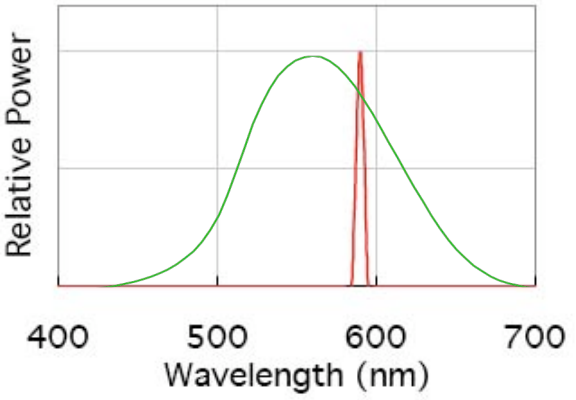
Daylight



White LED



Low pressure sodium lamp



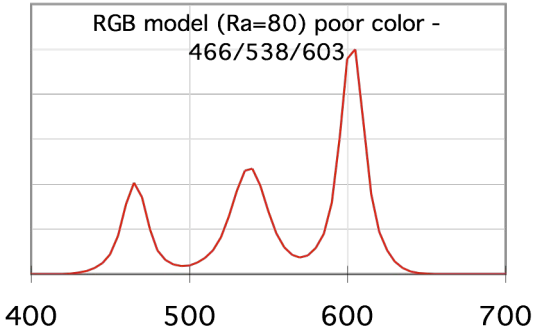
Theoretical maximum

~250 lm/W ~ 400 lm/W 520 lm/W

Excellent color rendering ?? color rendering No color rendering

Problems of CRI (1)

Good scores do not guarantee good saturated colors

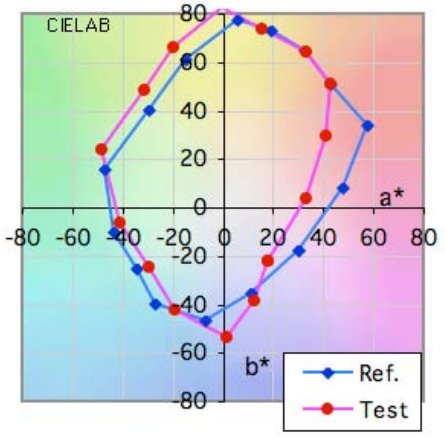


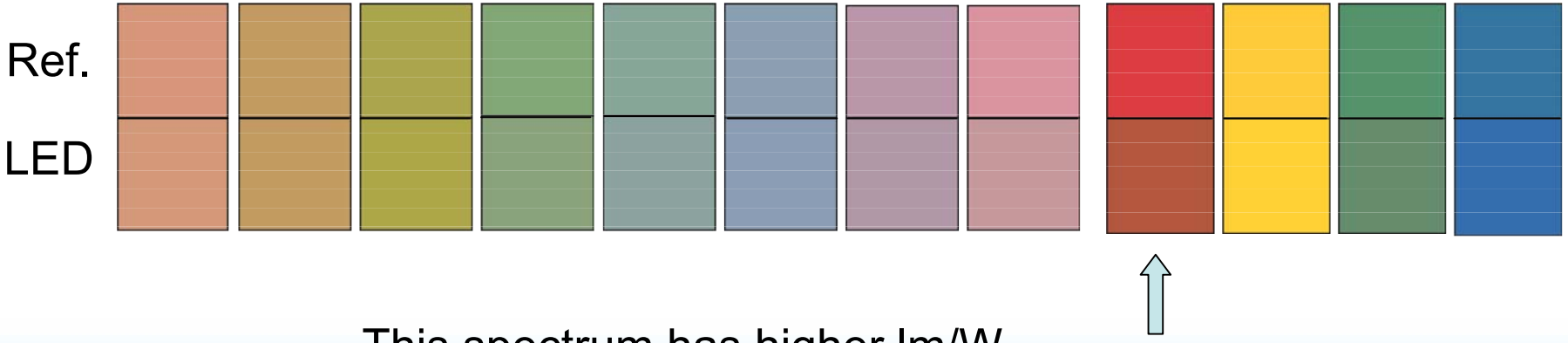
3-LED Model

Peaks at:

457, 540, & 605 nm

CRI *Ra* =80

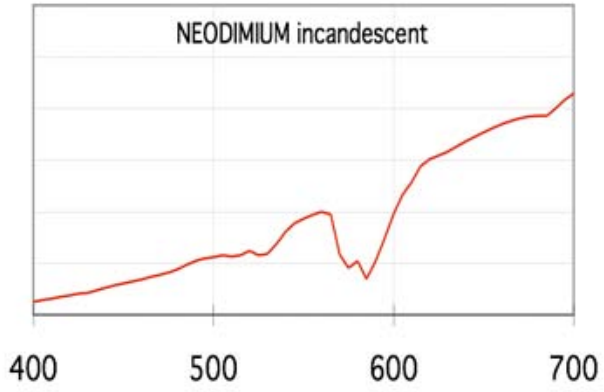




This spectrum has higher lm/W.

Problems of CRI (2)

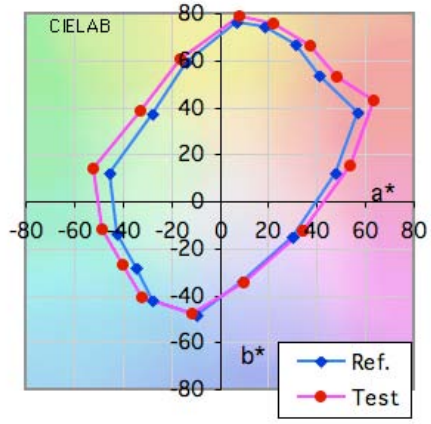
CRI penalizes light sources having enhanced color contrast.

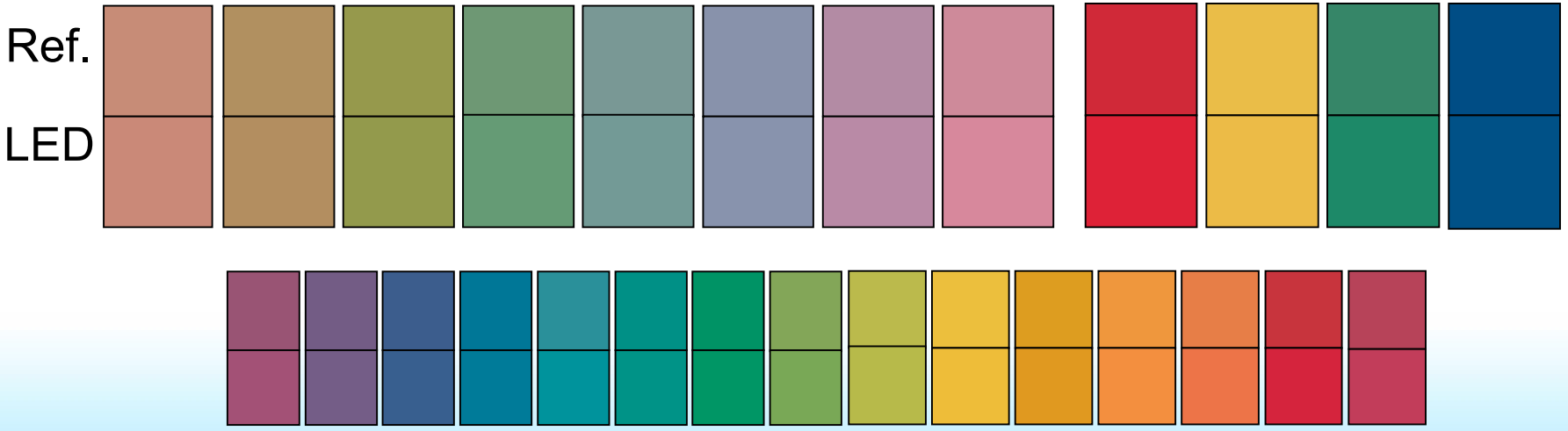


Neodymium incandescent lamp

CRI *Ra* = 77

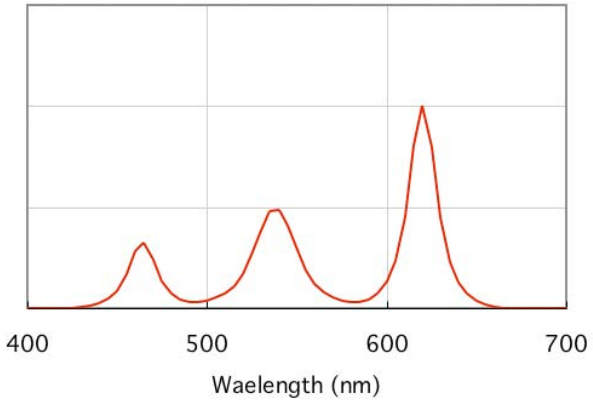
(Normal incandescent lamp Ra =100)





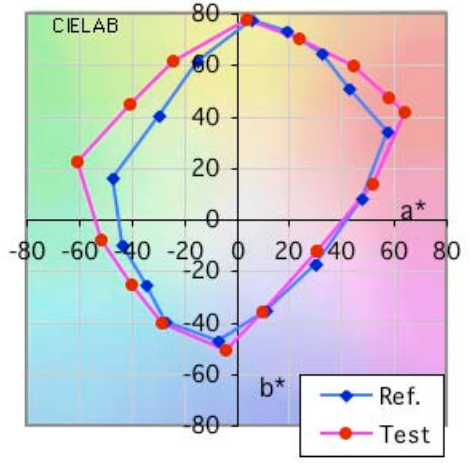
Problems of CRI (2)

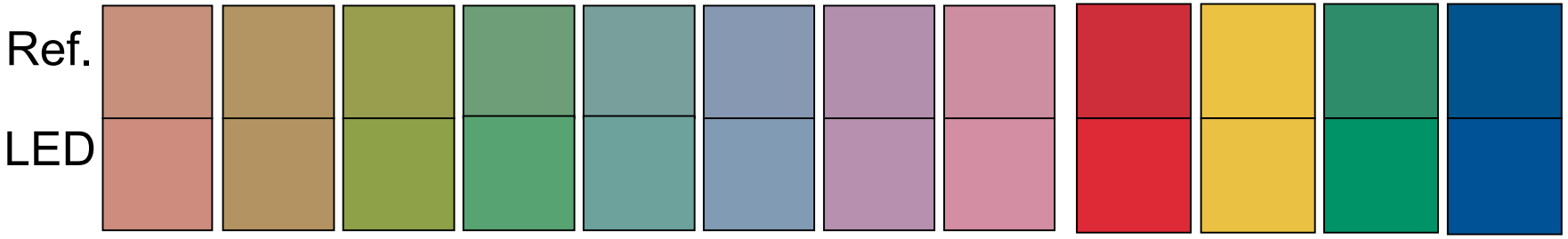
RGB white light can have the same effects



3-LED Model
Peaks at:
464, 538, 620 nm

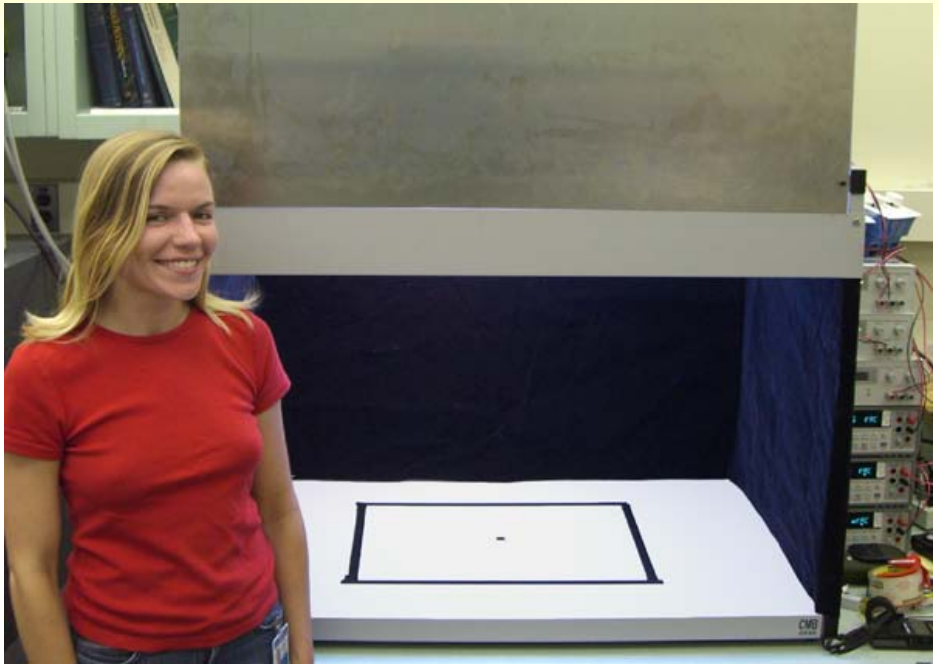
CRI *Ra* = 63

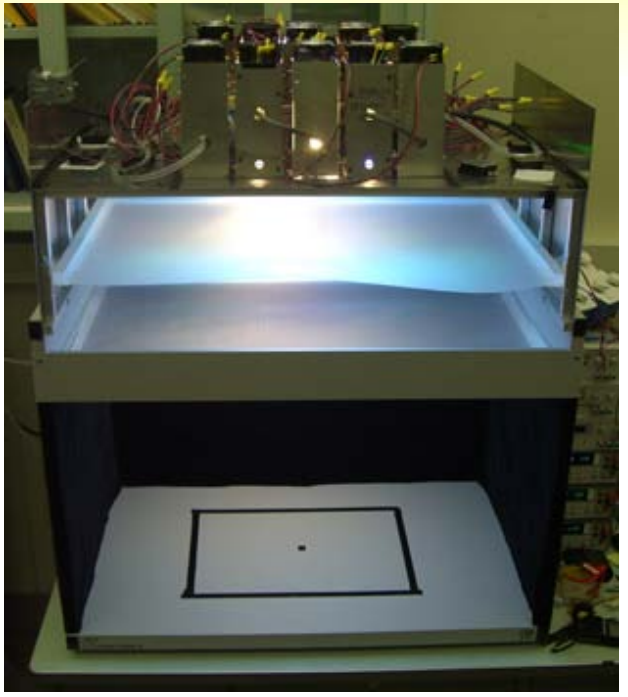


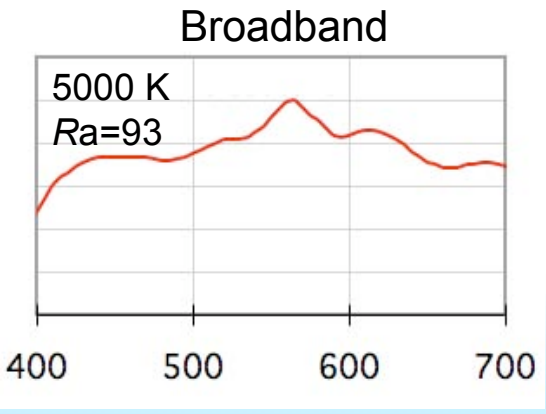


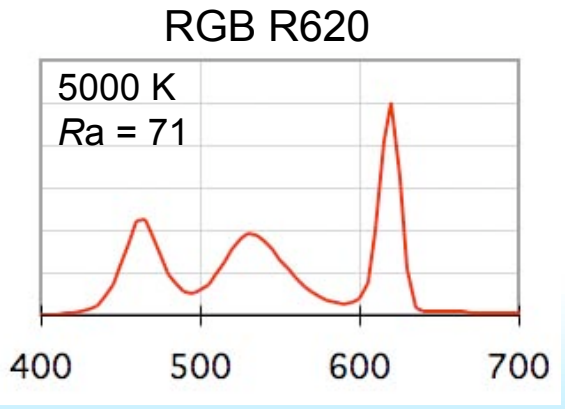
Products are optimized for metric.
Outdated metric impedes development of new technologies.

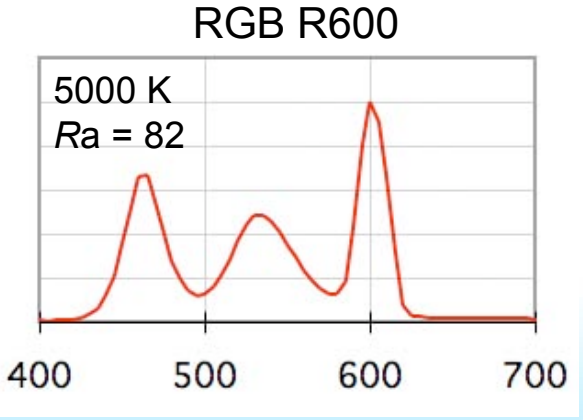
Experimental RGB Source developed at NIST



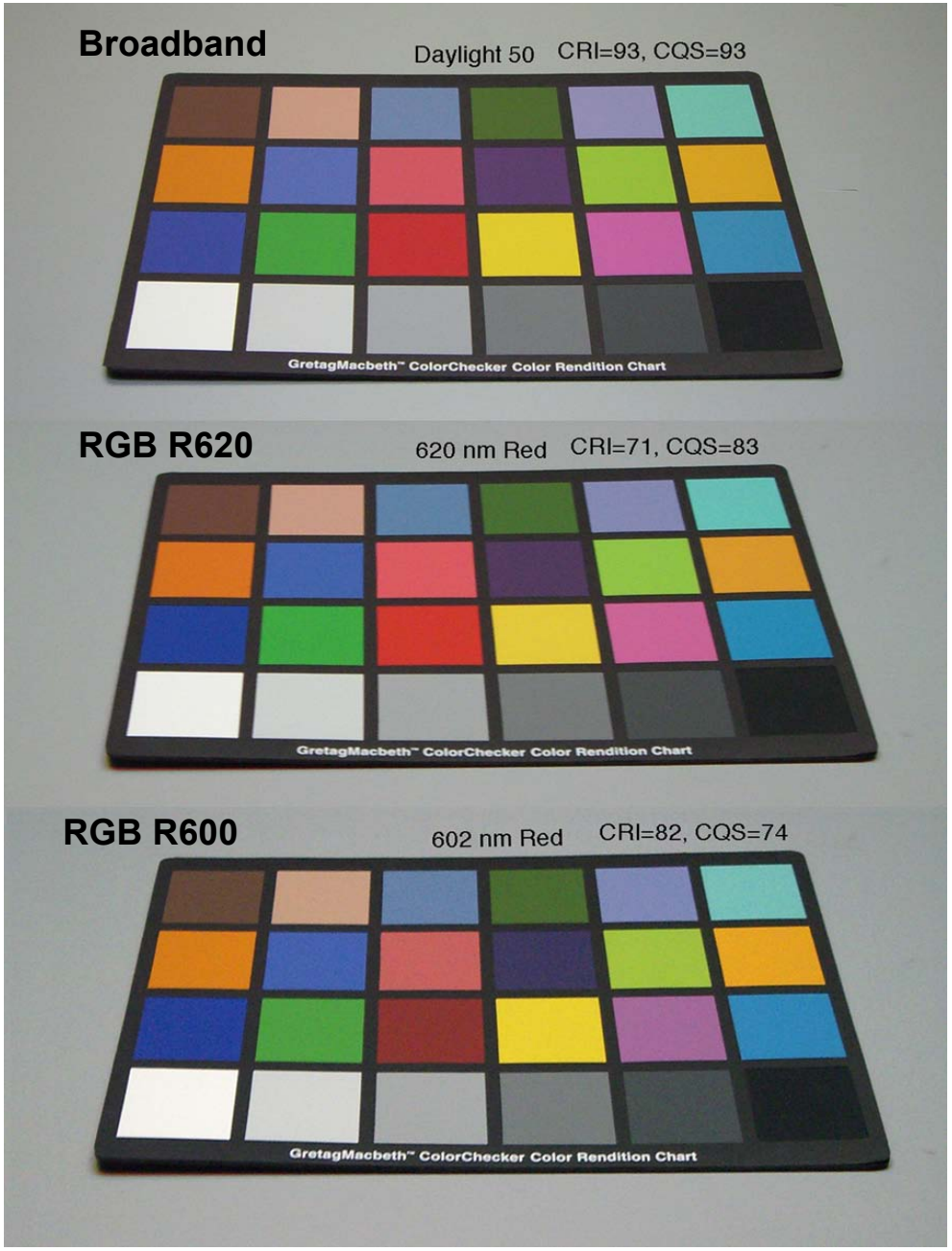


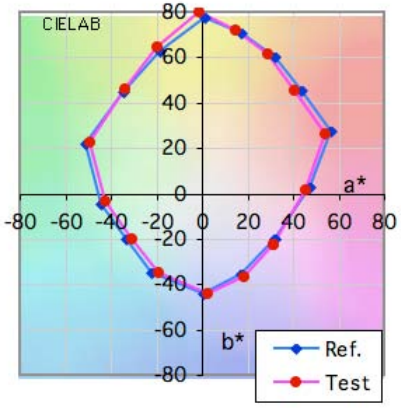


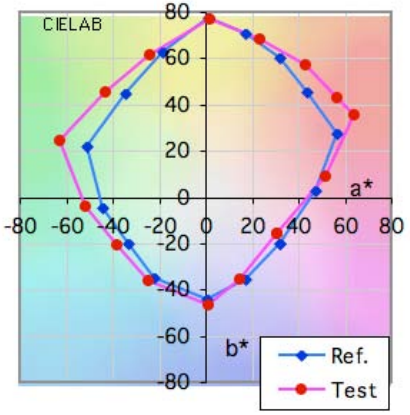


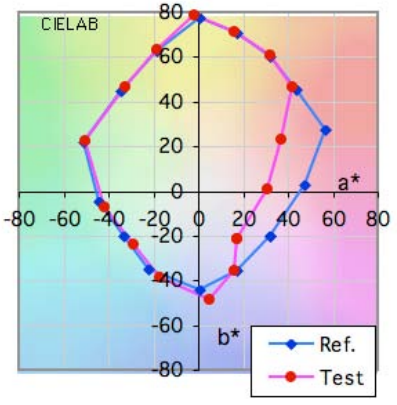


Viewed under real sources







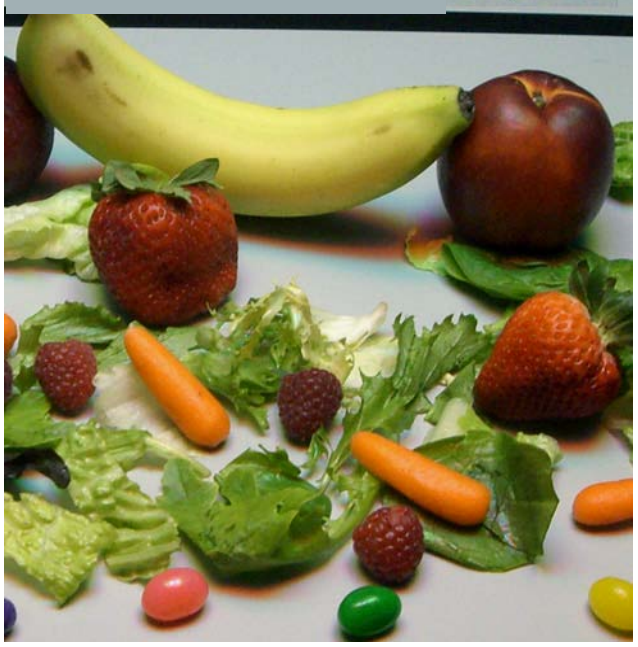


Booth (300 lx)

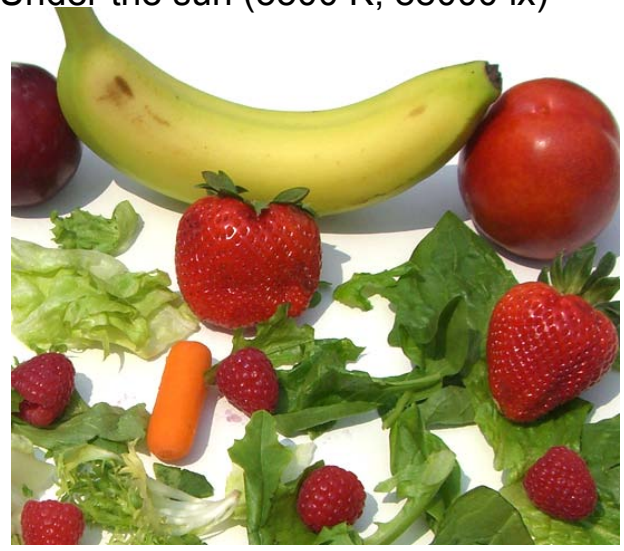
Broadband Ra = 93 CQS=93

RGB R620 Ra = 71 CQS=83

RGB R600 Ra = 82 CQS=74



Under the sun (5500 K, 88000 lx)



SSL Energy Star minimum requirements

	lm/W	CRI Ra
Under cabinet kitchen	24	75
Portable desk/Task	29	75
Recessed downlights	35	75
Outdoor porch lights	24	
Outdoor step lights	20	
Outdoor pathway lights	25	
Category B	70	75

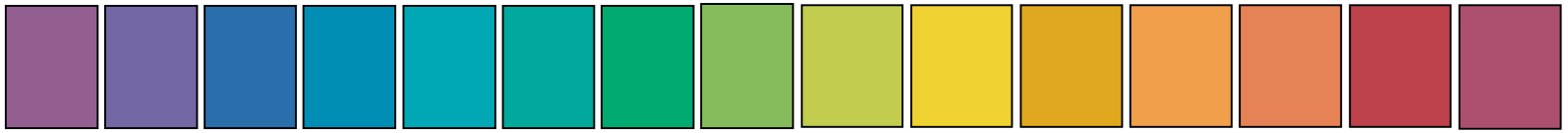
ENERGY STAR

Developing "Color Quality Scale"

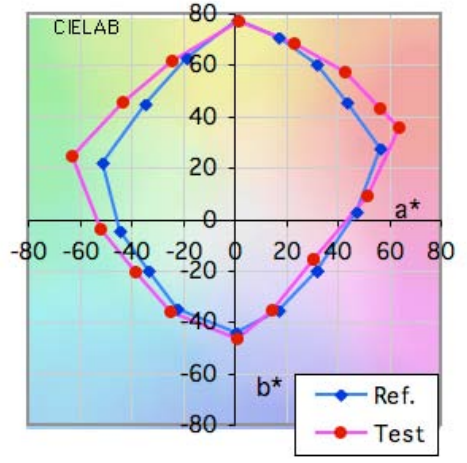
Proposed by NIST

- Fix the problems of CRI (based on color fidelity)

  1) use 15 saturated reference color samples



  2) use the latest color space (CIE LAB)
  3) use the latest chromatic adaptation formula (CMCCAT2000)
  4) 0 to 100 scale (CRI can have negative score.)
  5) CCT factor based on gamut area of ref. Illuminant
  6) RMS combining of color differences
  7) Scale normalized for consistency with CRI for fluorescent lamps

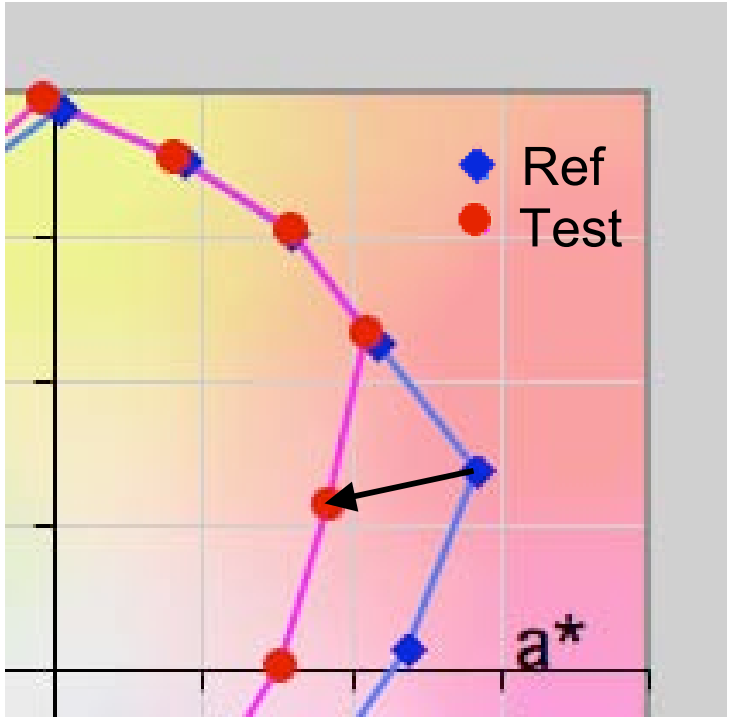


- Address color quality Issue – Saturation factor

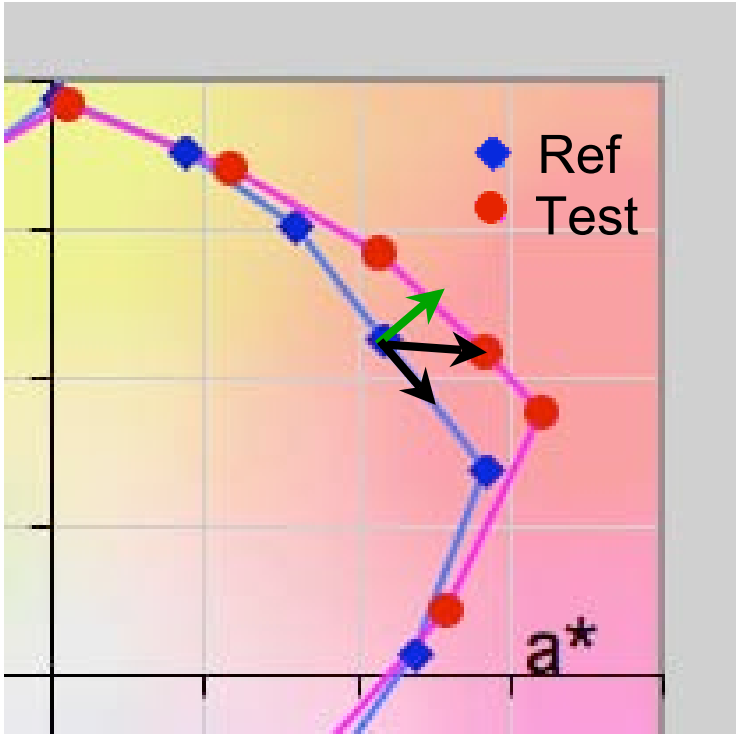
"Color Quality Scale"

Proposed by NIST

Saturation factor

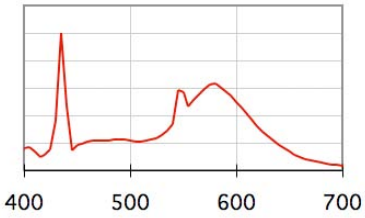
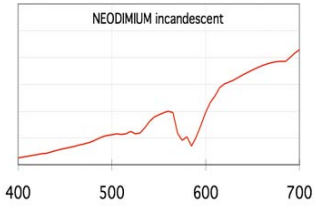
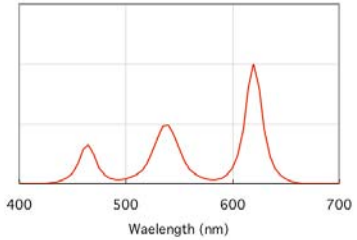
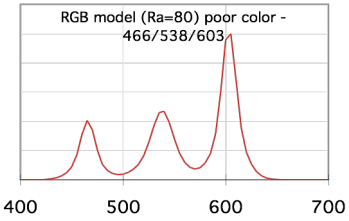
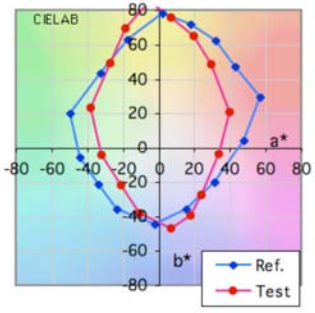
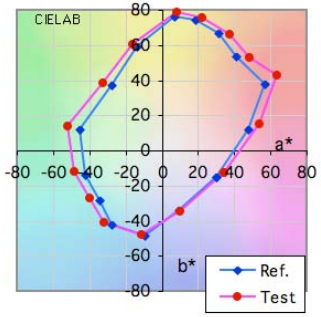
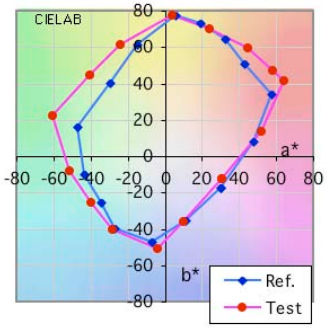
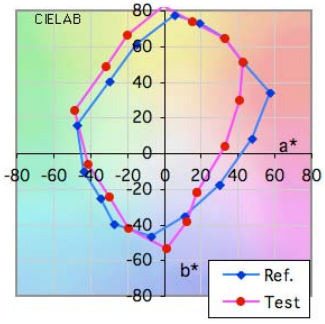


Score is decreased for the full color difference



Score is not penalized for increase of chroma.
(Score is decreased for hue and lightness shifts)

Some Results of CQS

Cool White fluorescent	Neodymium inc. lamp	RGB (enhanced) (464/538/620 nm)	RGB (poor red) (457/540/605 nm)
			
			
CRI =63 CQS=64	CRI =77 CQS=88	CRI =63 CQS=80	CRI =80 CQS=74

Consistency of scores is maintained for fluorescent lamps

CIE TC 1-69

CIE TC1-69 Colour Rendition by White Light Sources
Established in May 2006

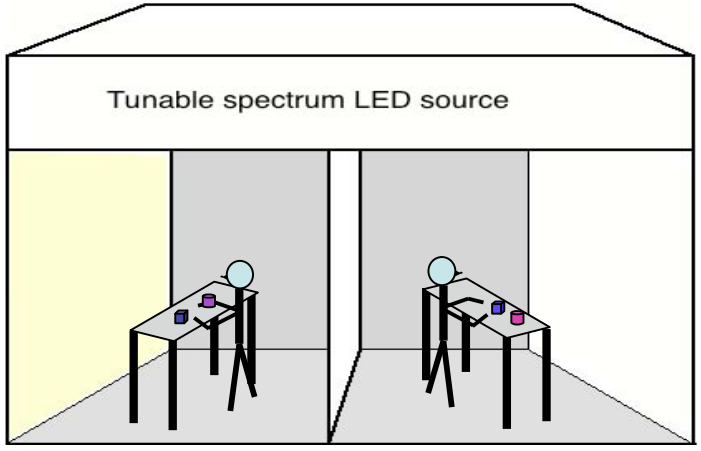
Chair: Wendy Davis (NIST)

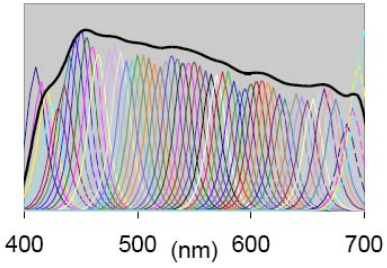
TR:
To investigate new methods for assessing the colour rendition properties of white-light sources used for illumination, including solid-state light sources, with the goal of recommending new assessment procedures.

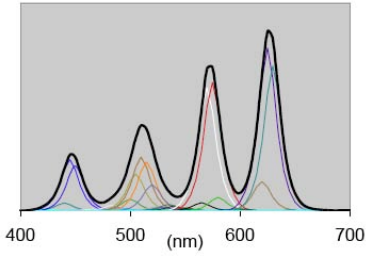
Vision experiments planned by several members.

Spectrally Tunable Lighting Facility

Under development at NIST







Specification goal

- 48 channels of high- power LEDs, 400 - 650 nm.
- Spectrally tunable to simulate white LEDs and traditional light sources.
- Uniform illumination for the whole cubicle (500 lx).
- Contract awarded.
- First phase system (16 ch) to be delivered in May 2008.

Thank you for your attention.

Contact: ohno@nist.gov

Ref. http://physics.nist.gov/OTD
(Optical Sensor Group)