



DOE's SSL Commercialization Support

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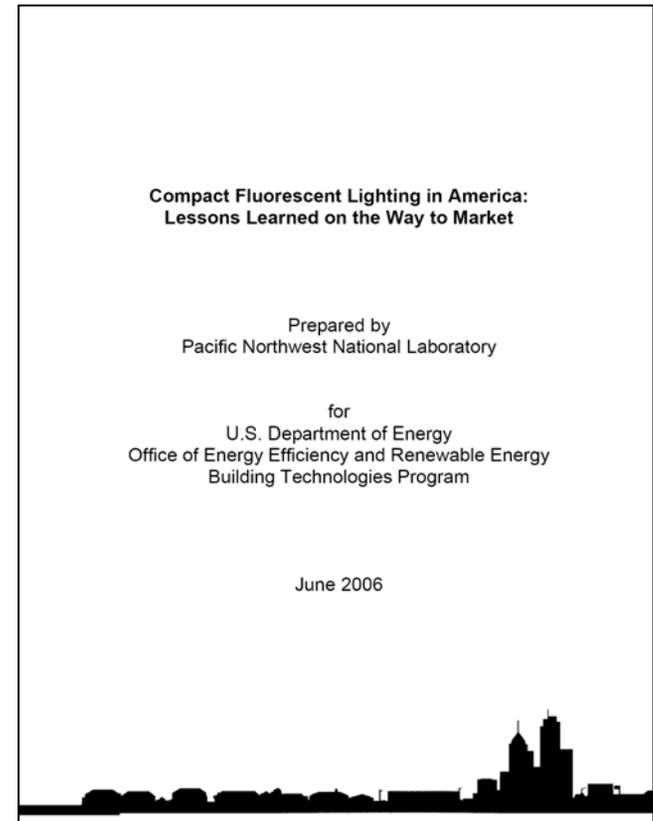
2007 DOE SSL Workshop

Phoenix



SSL Lessons from CFL Market Introduction?

- Compact Fluorescent Lighting in America: Lessons Learned on the Way to Market
 - Prepared for U.S. DOE by PNNL
 - LJ Sandahl, et al.
 - June 2006
 - <http://www.netl.doe.gov/ssl/publications.html>





Early fluorescent lamp days (Pre-CFL)

- Green tint due to use of halophosphors
- Harsh, unattractive
- Reputation persists
- Carried over to CFLs



“Harsh fluorescent lighting, linoleum floors and regular plaster walls are not ideal surroundings for neonatal intensive care units.” – Google Search.



Early CFLs

- Too big
- Too heavy
- Buzz and flicker
- Poor cold weather performance
- Poor color quality (high CCT, low CRI)
- High prices (\$25 - \$35 in 1980s)





CFL Marketing Mistakes

- Exaggerated life claims
- Inconsistent incandescent equivalency claims
- Consumer awareness hindered by lack of common name (CFL, CFB, SL-lamps, etc.)
- Weren't available where people buy bulbs
- Retailers didn't understand the product



Lessons Learned (Examples from Report)

- Know and admit technology limitations
 - Life
 - Incandescent equivalency
 - Inappropriate lighting applications



Lessons Learned (Examples from Report)

- Manufacturers and energy-efficiency groups should coordinate to establish minimum performance requirements
 - Wide disparity of program specifications caused confusion & complication



Lessons Learned (Examples from Report)

- Work toward consistent, industry-wide terminology. Identify and avoid terms with negative connotations
 - “Fluorescent” was probably a mistake
 - “Compact Fluorescent Lamp” was complicated



Key Take Away from CFL Experience

- Early consumer experience with fluorescent lamps and CFLs still defines attitudes towards CFLs, even though the technology has greatly improved since its introduction





DOE SSL Commercialization Support Program Elements

- Technical Information
- Commercial Product Testing Program
- Technology Demonstrations
- Standards and Test Procedures Support
- Buyer/User Guidance
- Coordination/Leadership
- Design Competitions

All activities aimed at SSL general illumination applications.



Market Needs Addressed by DOE SSL Commercialization Support

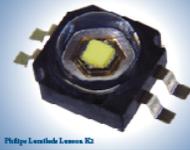
- Objective, widely available technical information
- Independent performance test results
- High-profile examples of model applications of SSL
- Industry standards and test procedures
- Guidance for purchasing and proper application
- Coordination of local and regional commercialization activities
- High visibility for state of the art products and designs



Building Technologies Program

Thermal Management of White LEDs

LEDs won't burn your hand like some light sources, but they do produce heat. In fact, thermal management is arguably the most important aspect of successful LED system design. This fact sheet reviews the role of heat in LED performance and methods for managing it.



Terms
Conduction – transfer of heat through matter by communication of kinetic energy from particle to particle. An example is the use of a conductive metal such as copper to transfer heat.
Convection – heat transfer through the circulatory motion in a fluid (liquid or gas) at a non-uniform temperature. Liquid or gas surrounding a heat source provides cooling by convection, such as at a flow over a heat sink.

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All light sources convert electric power into radiant energy and heat in various proportions. Incandescent lamps emit primarily infrared (IR), with a small amount of visible light. Fluorescent and metal halide sources convert a higher proportion of the energy into visible light, but also emit IR, ultraviolet (UV), and heat. LEDs generate little or no IR or UV, but convert only 15%-25% of the power into visible light; the remainder is converted to heat that must be conducted from the LED die to the underlying circuit board and heat sinks, bondings, or luminaire frame elements. The table below shows the proportions in which each watt of input power is converted to heat and radiant energy (including visible light) for various white light sources.

Power Conversion for "White" Light Sources				
	Incandescent ¹ (60W)	Fluorescent ² (typical 40W)	Metal Halide ³	LED ⁴
Visible Light	7.5%	21%	27%	15-25%
IR	73.3%	37%	17%	0%
UV	0%	0%	1%	0%
Total Radiant Energy	80.8%	58%	65%	10-15%
Heat (Infrared + Ultraviolet)	19.2%	42%	33%	75-85%
Total	100	100	100	100

¹IESNA Handbook ²OSRAM Syline ³OSRAM Syline
⁴Varies depending on LED efficacy. This is based on DOE's 161-Mile Year Program

Why does thermal management matter? Excess heat directly affects both reversible effects or color shift and lumen depreciation and color shift.

The light output of different colored LEDs responds differently to temperature changes, with amber and red the most sensitive, and blue the least. (See graph at right.) These unique temperature response rates can result in noticeable color shifts in RGB-based white light manufacturers use and sort (or "millisecond power pulse, at a fine temperature and with engineers. Therefore white LEDs will provide reduction in light output for per

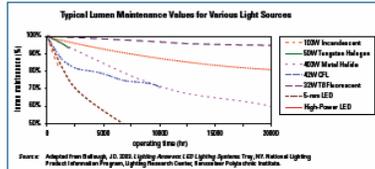
Lifetime of White LEDs

One of the main "selling points" of LEDs is their potentially very long life. Do they really last 50,000 hours or even 100,000 hours? This fact sheet discusses lumen depreciation, measurement of LED useful life, and the features to look for in evaluating LED products.

Lumen Depreciation

All electric light sources experience a decrease in the amount of light they emit over time, a process known as lumen depreciation. Incandescent filaments evaporate over time and the tungsten particles collect on the bulb wall. This typically results in 10-15% depreciation compared to initial lumen output over the 1,000 hour life of an incandescent lamp.

In fluorescent lamps, photochemical degradation of the phosphor coating and accumulation of light-absorbing deposits cause lumen depreciation. Compact fluorescent lamps (CFLs) generally lose no more than 20% of initial lumens over their 10,000 hour life. High-quality linear fluorescent lamps (T8 and T5) using rare earth phosphors will lose only about 5% of initial lumens at 20,000 hours of operation.



The primary cause of LED lumen depreciation is heat generated at the LED junction. LEDs do not emit heat as infrared radiation (IR), so the heat must be removed from the device by conduction or convection. Without adequate heat sinking or ventilation, the device temperature will rise, resulting in lower light output. While the effects of short-term exposure to high temperatures can be reversed, continuous high temperature operation will cause permanent reduction in light output. LEDs continue to operate even after their light output has decreased to very low levels. This becomes the important factor in determining the effective useful life of the LED.

Defining LED Useful Life

To provide an appropriate measure of useful life of an LED, a level of acceptable lumen depreciation must be chosen. As what point is the light level no longer meeting the needs of the application? The answer may differ depending on the application of the product. For a common application such as general lighting in an office environment, research has shown that the majority of occupants in a space will accept high level reductions of up to 30% with little notice, particularly if the reduction is gradual.¹ Therefore a level of 70% of initial light level could be considered an appropriate threshold of useful life for general lighting. Based on this research, the Alliance for Solid State Illumination Systems and Technologies (ASSIST), a group led by the Lighting Research Center (LRC),

¹See M93 (M3) 2008, LEDVANCE Lighting Handbook Reference and Application, Feb. 10, 2008. ²See "How Valid Thermal Modeling Engineering Research of Thermal Analysis, March 16, 2010. ³Available for downloading under Creative Commons Attribution License (CC BY) for AIAA 1370-1382-1387.

Building Technologies Program



Terms
Lumen depreciation – the decrease in lumen output that occurs as a lamp is operated.

Rated lamp life – the life value assigned to a particular type lamp. This is commonly a statistically determined estimate of average or median operational life. For certain lamp types other criteria than failure to light can be used; for example, the life can be based on the average time until the lamp type produces a given fraction of initial luminous flux.

Life performance curve – a curve that presents the variation of a particular characteristic of a light source (such as luminous flux, intensity, etc.) throughout the life of the source. Also called lumen maintenance curve.

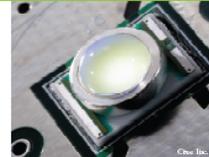
Checklist

- What features should you look for in evaluating the projected lifetime of LED products?
- Does the LED manufacturer publish thermal design guidance?
- Does the lamp design have any special features for heat sinking/thermal management?
- Does the fixture manufacturer have test data supporting life claims?
- What life rating methodology was used?
- What warranty is offered by the manufacturer?

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Energy Efficiency of White LEDs

The energy efficiency of light-emitting diodes (LEDs) is expected to rival the most efficient white light sources by 2010. But how energy efficient are LEDs right now? This fact sheet discusses various aspects of lighting energy efficiency and the rapidly evolving status of white LEDs.



Luminous Efficacy
Energy efficiency of light sources is typically measured in lumens per watt (lm/W), meaning the amount of light produced for each watt of electricity consumed. This is known as luminous efficacy. DOE's long-term research and development goal called for white-light LEDs producing 160 lm/W in cost-effective, market-ready systems by 2025. In the meantime, how does the luminous efficacy of today's white LEDs compare to traditional light sources? Currently, the best white LEDs approach the efficacy of compact fluorescent lamps (CFLs). However, there are several important caveats, as explained below.

Color Quality
To date, LED luminous efficacy similar to that of CFLs has been achievable only with higher color temperature products, which produce a "cool" or bluish-toned light and relatively low color rendering index (CRI) in the 70s. LEDs with warmer color appearance and higher CRI are only marginally more efficacious than incandescent sources. However, this is changing rapidly, with new performance improvements being announced regularly by the industry. For more detail, see DOE fact sheet "Color Quality of White LEDs."

Driver Losses
Fluorescent and high-intensity discharge (HID) light sources cannot function without a ballast, which provides a starting voltage and limits electrical supplementary electronics, usually called drivers. The voltage (typically between 2 and 4 volts DC for high-1000 millamps or mA), and may also include dimming.

Currently available LED drivers are typically about 85% efficient. To account for the driver, a 100% efficiency for traditional and LED sources, including ballast losses.

Light Source	Type
Incandescent	
Compact incandescent	
Halogen incandescent (CFL)	
Linear fluorescent	
Metal halide	
Cool white LED 5000K	
Warm white LED 3000K	

Thermal Effects
The luminous flux figures cited by LED manufacturers (7) of 20°C/68°F. LEDs are tested during manufacture, which provides a starting voltage and limits electrical supplementary electronics, usually called drivers. The voltage (typically between 2 and 4 volts DC for high-1000 millamps or mA), and may also include dimming.



Terms
Lumen – the SI unit of luminous flux. The total amount of light emitted by a light source, without regard to directionality is given in lumens.
Luminous efficacy – the total lumens flux emitted by the light source divided by the lamp wattage expressed in lumens per watt (lm/W).
Luminance efficacy – the total lumens flux emitted by the light source divided by the lamp wattage expressed in lumens per watt (lm/W).

Building Technologies Program

Color Quality of White LEDs

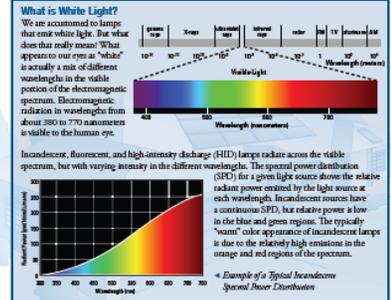
Color quality is one of the key challenges facing light-emitting diodes (LEDs) as a general light source. This fact sheet reviews the basics regarding light color and summarizes the most important color issues related to white light LEDs.

Unlike incandescent and fluorescent lamps, LEDs are not inherently white light sources. Instead, LEDs emit light in a very narrow range of wavelengths in the visible spectrum, resulting in nearly monochromatic light. This is why LEDs are so efficient for colored light applications such as traffic lights and exit signs. However, to be used as a general light source, white light is needed. The potential of LED technology to produce high-quality white light with unprecedented energy efficiency is the impetus for the intense level of research and development currently being supported by the U.S. Department of Energy.

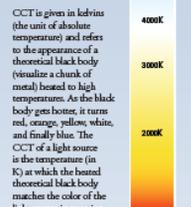
White Light from LEDs
White light can be achieved with LEDs in two main ways: 1) phosphor conversion, in which a blue or ultraviolet (UV) chip is coated with phosphor to emit white light; and 2) RGB system, in which light from multiple monochromatic LEDs (red, green, and blue) is mixed, resulting in white light.

The phosphor conversion approach is most commonly based on a blue LED. When combined with a yellow phosphor (usually cerium-doped yttrium aluminum garnet or YAG:Ce), the light will appear white to the human eye. A more recently developed approach uses an LED emitting in the near-UV region of the spectrum to excite multi-chromatic phosphors to generate white light.

The RGB approach produces white light by mixing the three primary colors red, green, and blue. Color quality of the resulting light can be enhanced by the addition of amber to "fill in" the yellow region of the spectrum. Status, benefits and trade-offs of each approach are explored on page 2.



Correlated Color Temperature (CCT)
CCT describes the relative color appearance of a white light source, indicating whether it appears more yellow/gold or more blue, in terms of the range of available shades of white.



CCT is given in kelvins (the unit of absolute temperature) and refers to the appearance of a theoretical black body (visualize a chunk of metal) heated to high temperatures. As the black body gets hotter, it turns red, orange, yellow, white, and finally blue. The CCT of a light source is the temperature (in K) at which the heated theoretical black body matches the color of the light source in question. Incandescent light sources with a higher CCT are said to be "cool" in appearance, while those with lower CCT are characterized as "warm."

Color Rendering Index (CRI)
CRI indicates how well a light source renders colors, on a scale of 0-100, compared to a reference light source. The test procedure established by the International Commission on Illumination (CIE) involves measuring the extent to which a series of eight standardized color samples differ in appearance when illuminated under a given light source, relative to the reference source. The average "shift" in those eight color samples is reported as R_a or CRI.

In addition to the eight color samples used by convention, some lighting manufacturers report an "R_s" score, which indicates how well the light source renders a saturated deep red color.



Building Technologies Program

LED Application Series:

Recessed Downlights

Recessed downlights are very common in both residential and commercial buildings. Is this a good application for LEDs? This fact sheet explores issues unique to this type of luminaire, and the potential for use of LEDs in downlights.

Recessed downlights are the most common installed luminaire type in residential new construction. Downlights are used for general ambient lighting in kitchens, hallways, bathrooms, and other areas of the home. Downlights with small apertures and more directional lensing and baffling are also used for wall-washing and accent lighting. In commercial settings, a wide variety of downlight types, sizes, and finishes are used in lobbies, perimeter areas, hallways, and restrooms.

The light output of a recessed downlight is a function of the lumens produced by the lamp and the luminaire efficiency. Reflector-style lamps are specially shaped and coated to emit light in a defined cone, while "A" style incandescent lamps and CFLs emit light in all directions, leading to significant light loss within the luminaire. Downlights using non-reflector lamps are typically only 50% efficient, meaning about half the light produced by the lamp is wasted inside the fixture. LEDs are more directional, but can they provide enough light? For comparison, the table below shows typical light output and efficiency of residential-style fluorescent and incandescent recessed downlights and an LED downlight.



Examples of Recessed Downlight Performance Using Different Light Sources

	Fluorescent*		Incandescent*		LED**
	26W pin-based CFL	15W R-30 CFL Edison base	65W R-30	100W A-19	LED 15W Downlight
LAMP					
Rated lamp lumens	1800	750	755	1700	unknown
Lamp wattage (nominal W)	26	15	65	100	9 x 1W LEDs
Lamp efficacy (lm/W)	70	50	12	17	45
LUMINAIRE					
Luminaire efficiency	50%	90%	90%	50%	unknown
Delivered light output (lumens), initial	900	675	680	850	300
Luminaire wattage (nominal W)	27	15	65	100	15
Luminaire efficacy (lm/W)	33	45	10	9	20

*Based on photometric data for commonly available products. Actual product performance depends on reflection, trim, lamp positioning, and other factors. Availability varies from PNSL.

**Based on one commercially available product tested. Other LED-based downlights may differ. Lamp efficacy for the LED pendant refers to the manufacturer listed "typical luminous flux" of the LEDs used. Luminous flux of the 9-LED array is not known.

Even though the 26W CFL is the most efficacious light source listed, the 15W reflector CFL provides higher luminaire efficacy, i.e., total lumens out of the fixture per watt consumed. The 15W LED downlight provides less than half the delivered light output of the 15W reflector CFL. As LED technology matures, this performance is expected to improve.



Terms

Luminaire – a complete lighting unit including lamp(s), ballast(s) (when applicable), and the parts designed to distribute the light, position and protect the lamps, and connect to the power supply.

Luminaire (fixture) efficiency – the ratio of luminous flux (lumens) emitted by a luminaire to that emitted by the lamp or lamps used therein; expressed as a percentage.

Luminaire efficacy – total lumens provided by the luminaire divided by the total wattage drawn by the fixture, expressed in lumens per watt (lm/W).

ICAT – stands for "insulated ceiling (or "insulation contact"), air tight" and refers to ratings on recessed downlight luminaires used in residential construction.

Downlights installed on the top floor of a house are immersed in insulation, creating a high-temperature operating environment that is difficult for CFLs and potentially similarly challenging for LEDs. Further, energy codes in most states require downlights installed in the building shell to be rated "air tight" to minimize loss of heating and cooling energy.



- Application series:
 - Recessed downlights
 - Undercabinet
 - Portable desk/task
- Other:
 - Compare/contrast LED and traditional light sources
 - Cost/economics
- Measurement series:
 - Luminaire efficacy



Technical Information Network

- Cooperative agreements to be awarded soon to selected partners
- Outreach to efficiency orgs, utilities, and their contractors
- Leverage existing programs & contacts
- Quarterly meetings
- Disseminate information to:
 - Retailers
 - Builders
 - Consumers
 - Others





Commercial Product Testing

- Testing of commercially-available LED products
- Early stages of program rollout
- Purposes
 - Input to DOE planning
 - Provide objective performance information to public
 - Input for test procedure development/refinement





Commercial Product Testing

- Arranging for multiple test labs (via solicitation)
- Completed pilot testing & public workshop
- Round 1 testing underway for 11 products
 - Undercabinet, portable task, outdoor area, step lights, etc.
- Summary and detailed test reports available via DOE SSL website
- "No commercial use" policy

Product Test Reference # CPTP 06-01 Downlight Page 5

Measured Photometric Quantities – Test Results: Light Output & Efficacy

Light Output & Efficacy Values

Test Identifier	Measured Energy Use (Watts)	Total Measured Light Output (lumens)	Calculated Luminance Efficacy (lumens/Watt)
CPTP 06-01-01 spectro	14.87 W	187.4	12.6
CPTP 06-01-02 gonio-ambient	14.89 W	201	13.4
CPTP 06-01-03 gonio-enclosure	14.38 W	170	11.8
CPTP 06-01-04 gonio-spectro	15.06 W	193.0	12.8

Light Output & Efficacy Uncertainties

Test Identifier	Measured Energy Use Uncertainty (k=2) %	Total Measured Light Output Uncertainty (k=2) %	Calculated Luminance Efficacy Uncertainty (k=2) %
CPTP 06-01-04 gonio-spectro	0.25	0.96	1.0

Intensity Distribution Plots

Polar candela distribution curve
CPTP 06-01-04 gonio-spectro

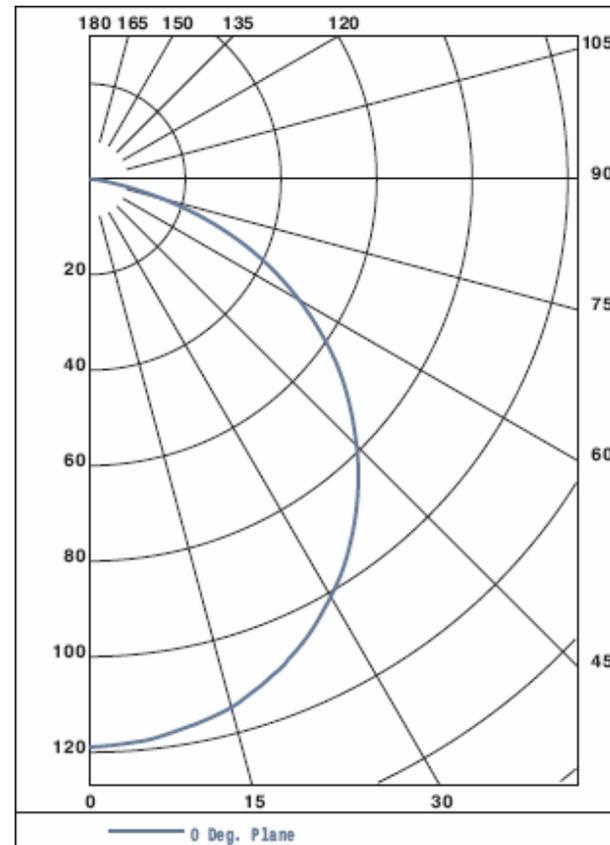
Polar candela distribution curve
CPTP 06-01-02 gonio-ambient

DOE SSL CPTP results may not be used for commercial purposes under any circumstances. See "No Commercial Use Policy" (<https://www.eere.energy.gov/ssl/cptp/>) for more information.



Commercial Product Testing

- Testing for
 - Luminaire light output, efficacy
 - Power characteristics
 - Beam and intensity
 - Spectral power distribution, CCT, CRI
- Findings to date
 - Tested performance << claimed performance
 - Tested products under-performed CFLs and some incandescents
- SSL Design Industry News editorial





Technology Demonstrations

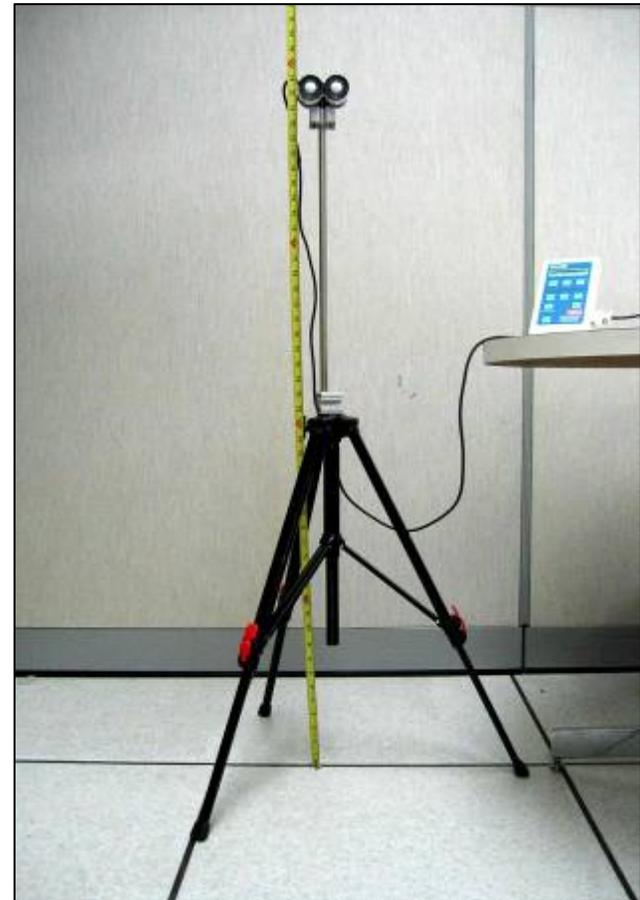
- Purpose: field demo advanced technology in general illumination applications; leverage demo with closely linked promotional effort
- Downlights anticipated but open to others via competitive solicitation





Technology Demonstrations

- Manufacturers provide equipment
- DOE finds partners & host sites, conducts testing, publicizes results and helps promote follow-up sales
- Evaluations to focus on light quality, occupant responses
- RFP to be issued to manufacturers in February





Other Technology Demonstrations

- Solar Decathlon
- DOE Showcase

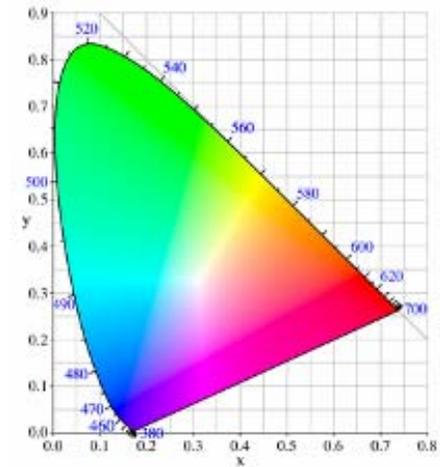




Standards & Test Procedures Support

Key Measurement Issues

- Measurement of luminous flux
 - Luminous efficacy
 - Luminaire efficacy
- Chromaticity and color rendering
- Electrical characteristics
- Drivers
- Life rating (lumen depreciation)
- Definitions and nomenclature





Standards and Test Procedures Support



- DOE workshops in Mar & Oct 2006
- In process:
 - Photometric Measurement (LM-79)
 - Lumen Depreciation (LM-80)
 - Chromaticity (ANSI C78.377A)
 - Electrical performance (ANSI C78.XX3)
 - SSL-LED power supply (ANSI C82.XX1)
 - Definitions/nomenclature (IESNA RP-16)
- New standards expected June 2007



User/Buyer Guidance

- Developed draft ENERGY STAR criteria for SSL luminaires for general illumination
- Publicly issued on Dec 20, 2006
- Stakeholder workshop on February 8, 2007 in DC





Coordination & Leadership

- Federal government is largest U.S. energy consumer
 - Working with FEMP to identify opportunities for early SSL applications
- Organize workshops, joint projects for key partners, including
 - Efficiency organizations, utilities
 - Lighting industry professionals
 - Fixture manufacturers
 - DC Workshop planned for April (Date to be announced soon)



Design Competitions

- Lighting for Tomorrow
- Partnership with ALA and CEE approved through 2008
 - Niche applications
 - Cutting edge design
- Expert judges
- Publicity
- New lighting design (not fixture) competition being considered

