A Guide to LED Lighting Basics

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On behalf of the U.S. Department of Energy
and NETL Morgantown

Copyright Materials

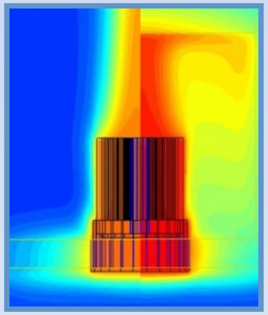
Learning Objectives

A Guide to LED Lighting Basics

1. Critical differences between LED and traditional light sources
2. How to distinguish good from poor SSL products and applications
3. The role of thermal management in successful solid-state lighting applications
4. Relationship between life and cost for LED products

Course Outline

1. Introduction – Why should I care about LEDs?
2. Lifetime and Cost – A critical relationship for LEDs
3. What's Different – LED technology as compared to traditional light sources
4. Technology Limitations – Characteristics to be aware of with solid-state lighting
5. Standards – The need for new metrics



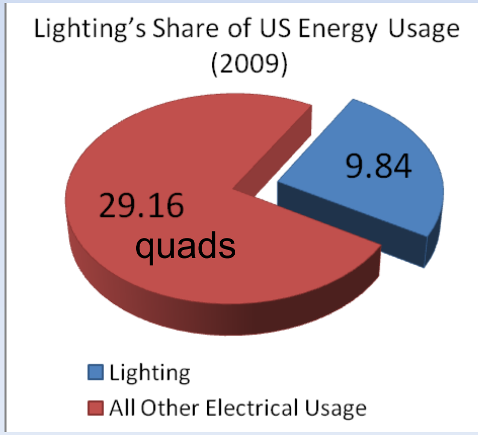
Break

6. Applications – What are the good ones?
7. LED Products – Where to turn for guidance
8. Items of Importance to Building Owners/Facility Mgrs
9. Final Thoughts – Some general rules

Introduction

Why Should I Care About LEDs?

- By 2030 the US Department of Energy has estimated that LED technology has the potential to produce yearly energy savings of 190 terawatt-hours
  - Equivalent of 24 large (1,000 MW) power plants
  - Reduction of 25% of present energy consumption for lighting
  - Equates to approximately $15 billion savings in today's dollars
  - Greenhouse gas emissions reduced by 31.4 million metric tons of carbon
- Spanning 2010 – 2030, the cumulative energy savings are estimated to total approximately 1,488 terawatt-hours
  - Representing approximately $120 billion at today's energy prices
  - Over that same time period, greenhouse gas emissions would be reduced by 246 million metric tons



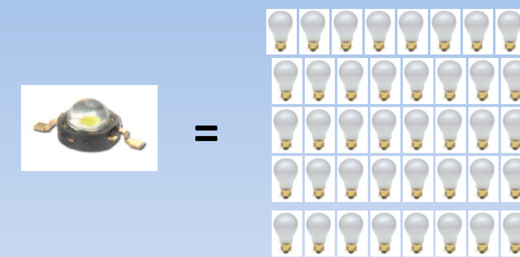
Data Source: DOE 2010 SSL R&D MYPP

Source: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_energy-savings-report_10-30.pdf

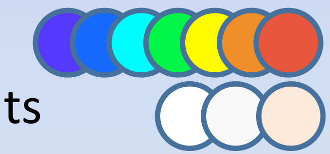
Introduction

Why Should I Care About LEDs?

LEDs are like no other conventional lighting source

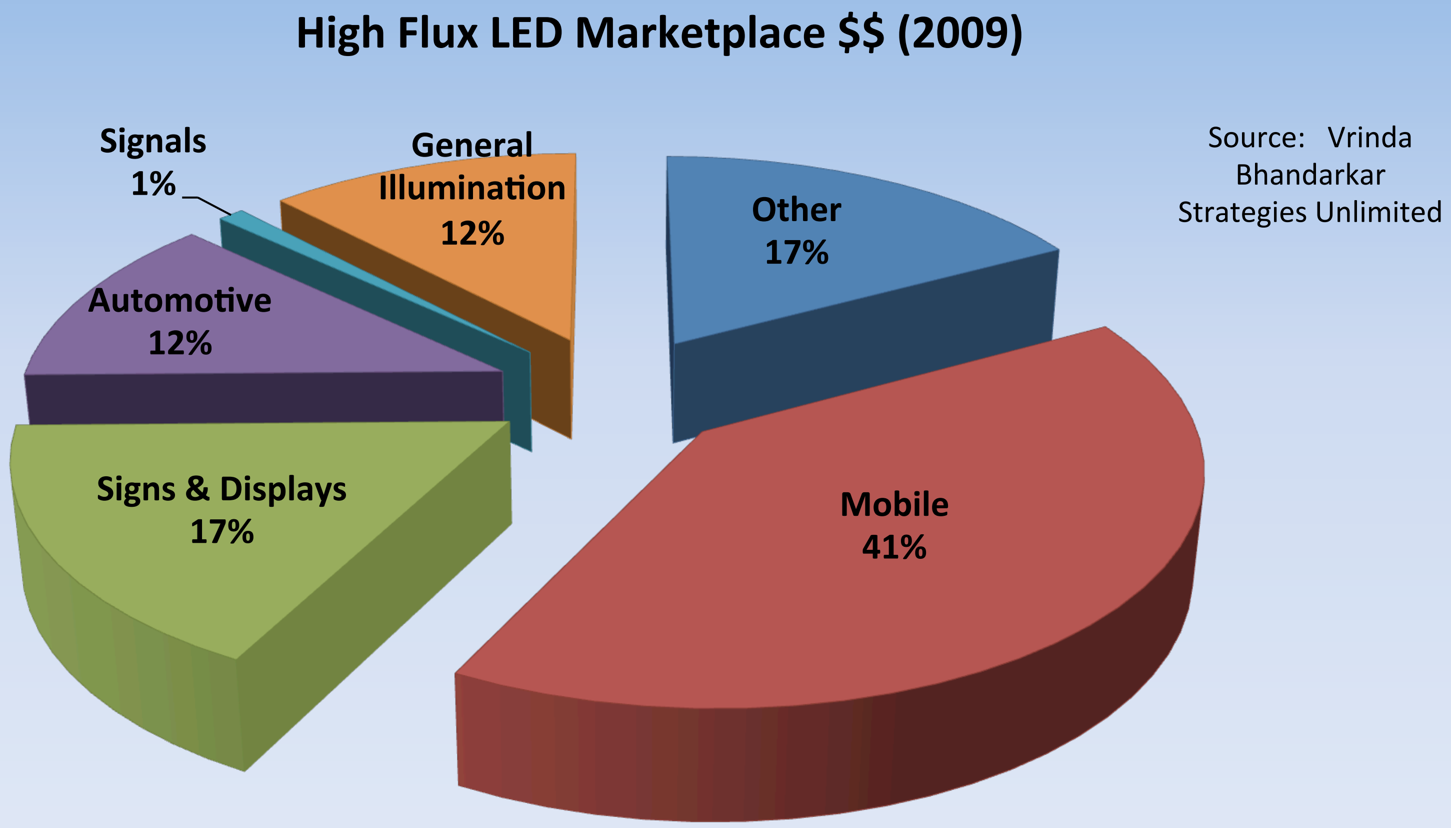


- \+ Potentially longest[1] life of any lighting sources
- \+ Very high energy efficiency
- \+ Small size and instant on allows new applications
- \+ Produces color light directly without filtering
- \+ Integrates will with other semiconductor electronic elements
- \- Thermal management requirements
- \- Cost
- \- New technology brings unfamiliar issues to architects, lighting designers, building owners and facilities managers

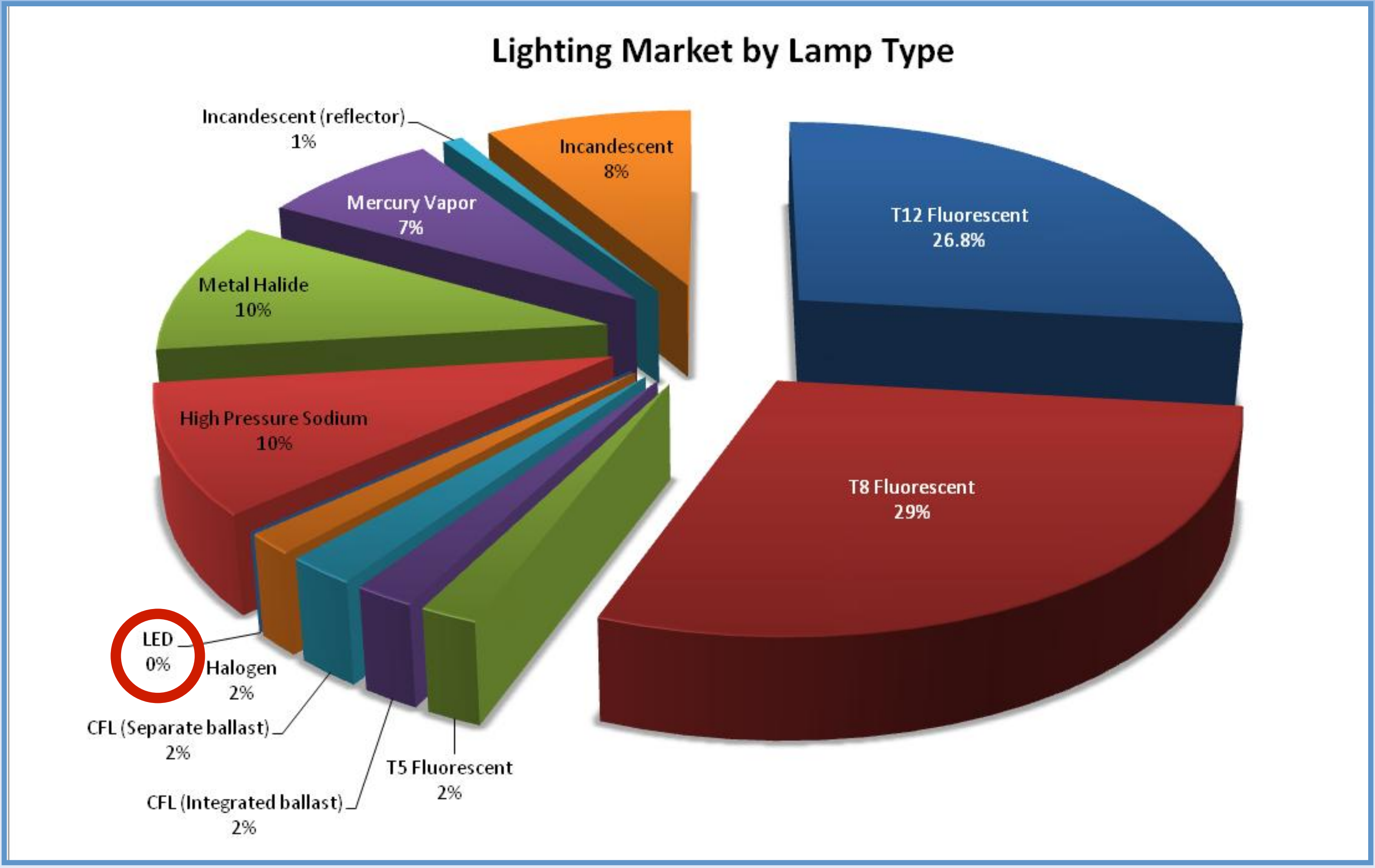


[1]Note: Some manufacturers have introduced products claiming long lifetimes: fluorescent tubes (40,000 hours); induction (100,000 hours)

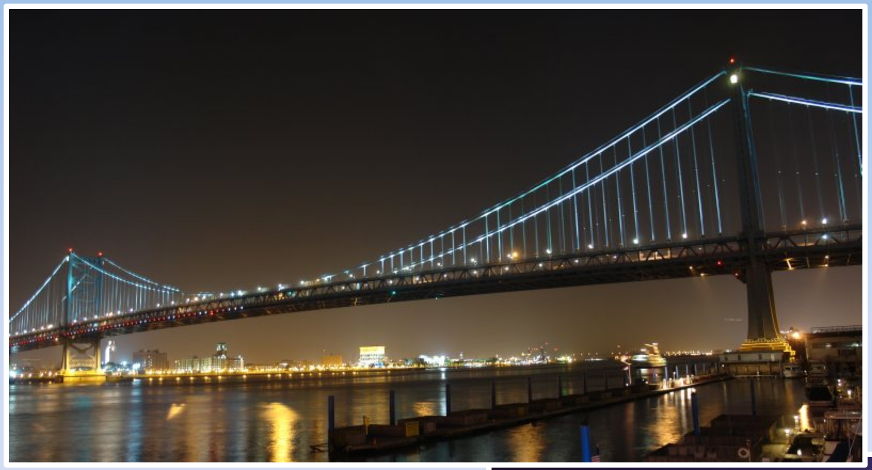
Background – LEDs Market Segments



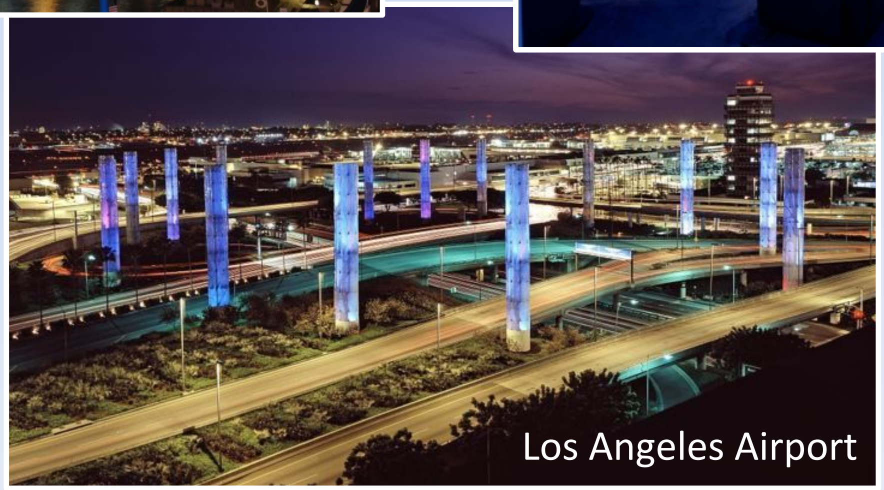
The Lighting Market – Types of lamps in use



Applications – Color changing



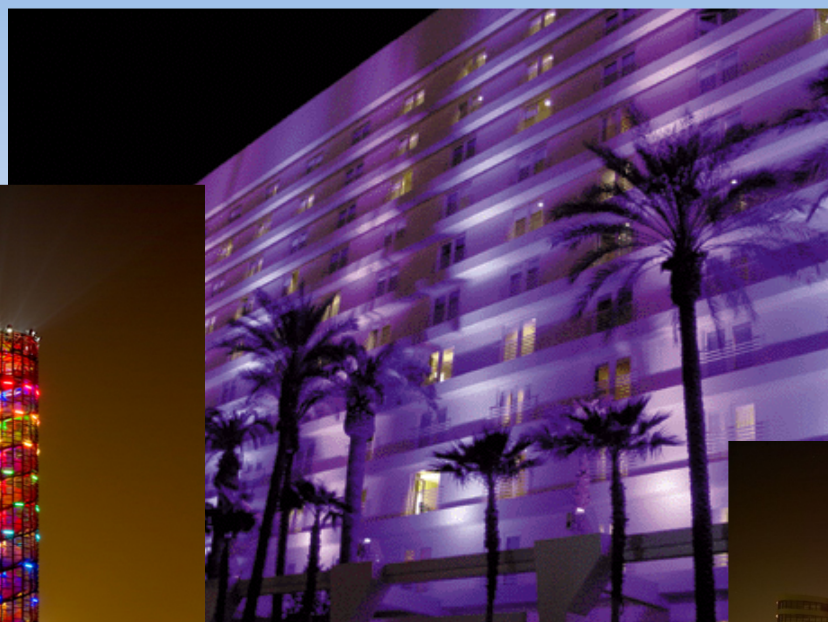
Ben Franklin Bridge
Philadelphia



Los Angeles Airport

Boeing 787
Dreamliner

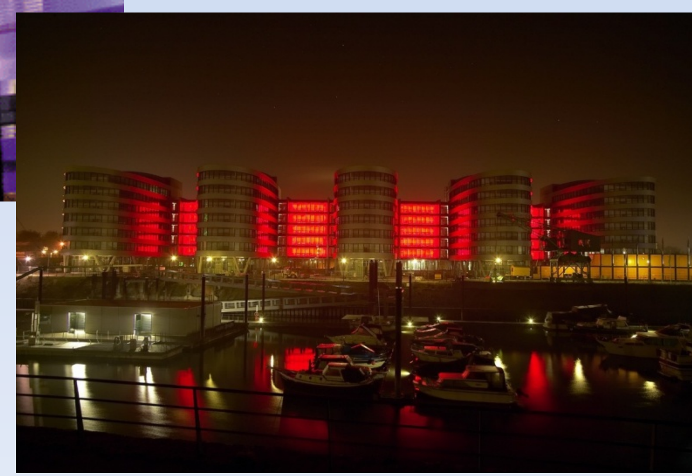
Applications – Architectural



Hard Rock Hotel
Las Vegas

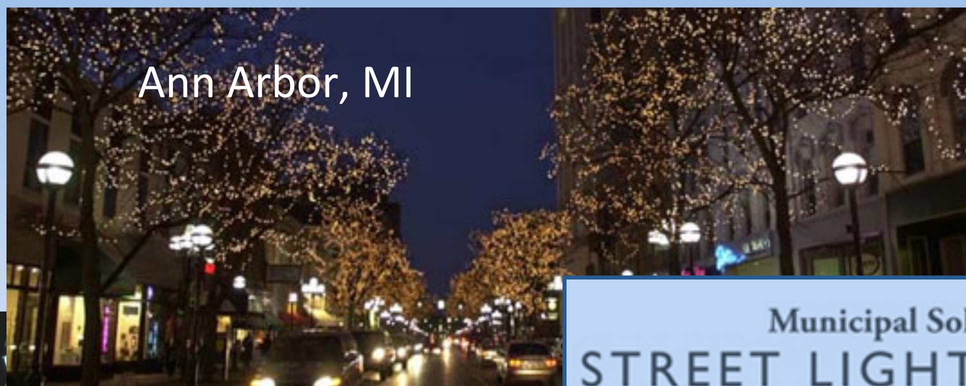
"Water Cube"
Beijing China

Full Moon Tower
Tainjan, China



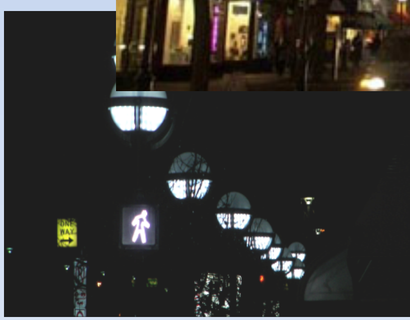
Five Boats
Duisburg, Germany

Applications – Street and Area Lighting



Municipal Solid-State
STREET LIGHTING
CONSORTIUM

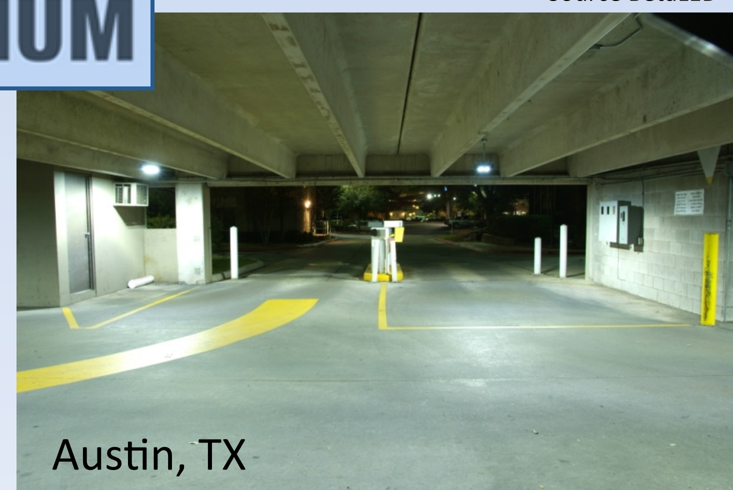
Source BetaLED



Source US DOE

Toronto, Canada

Source LED Magazine



Introduction

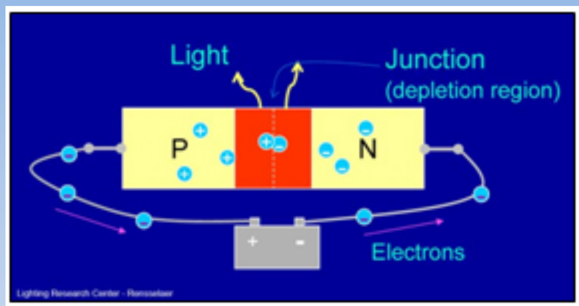
What have you heard about LEDs?

- They don't produce any heat
- They last forever
- Anyone who isn't installing LED-based products everywhere is foolish
- There is a conspiracy to limit the use of LEDs
- There is a conspiracy to force the use of LEDs
- They don't work
- They are too expensive

What is the truth about LEDs?

- They **do** produce heat – just not as much
- They **don't** last forever – just longer than other sources
- Anyone who isn't considering installing LED-based products for some applications is foolish
- They don't work if misapplied
- They are expensive but costs continue to drop
- There is a conspiracy by physicists to force the metric system on everyone but that has nothing to do with LEDs

What is an LED?



An LED (**L**ight **E**mitting **D**iode) consists of a chip of semiconducting material treated to create a structure called a p-n (positive-negative) junction

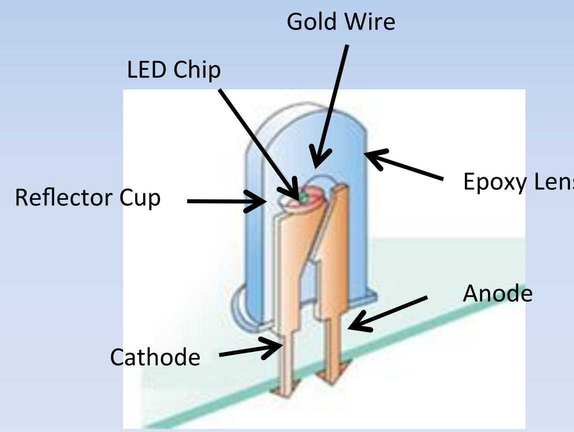


Diagram of a 5mm LED

The <u>heatsink</u> is what allows the high flux LED to generate much more light

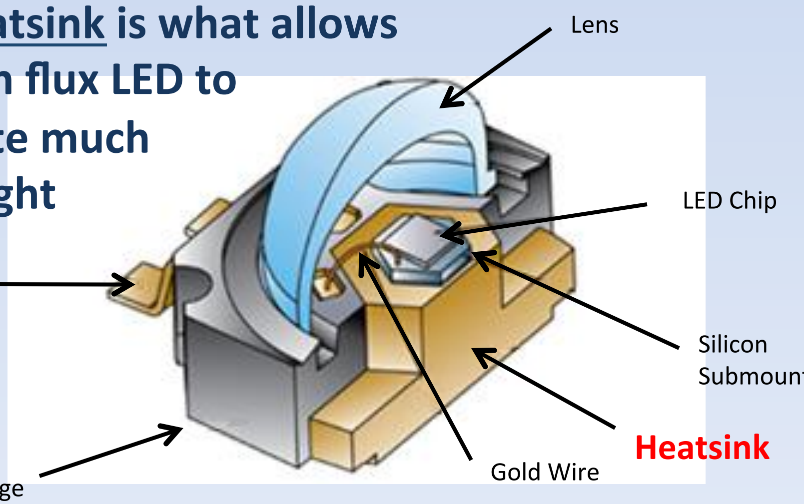
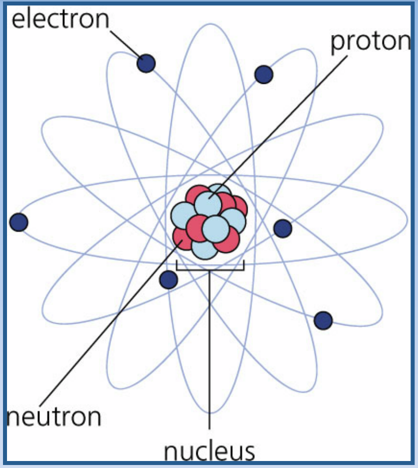


Diagram of a high flux LED

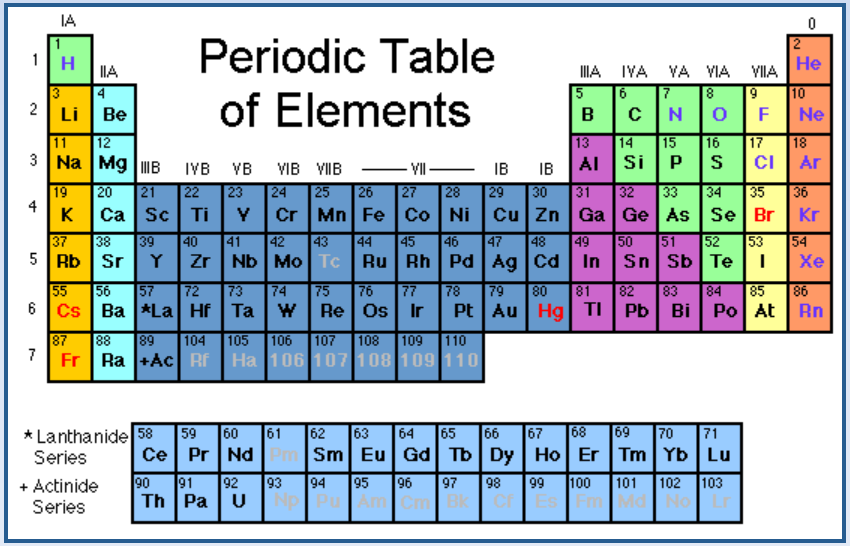
Introduction

Physics of LEDs – Some atomic physics

Electrons "orbit" around the nucleus and can be in either their "ground" (lowest energy) state or "excited" (higher energy) states. To get the electron in an excited state requires input of energy.

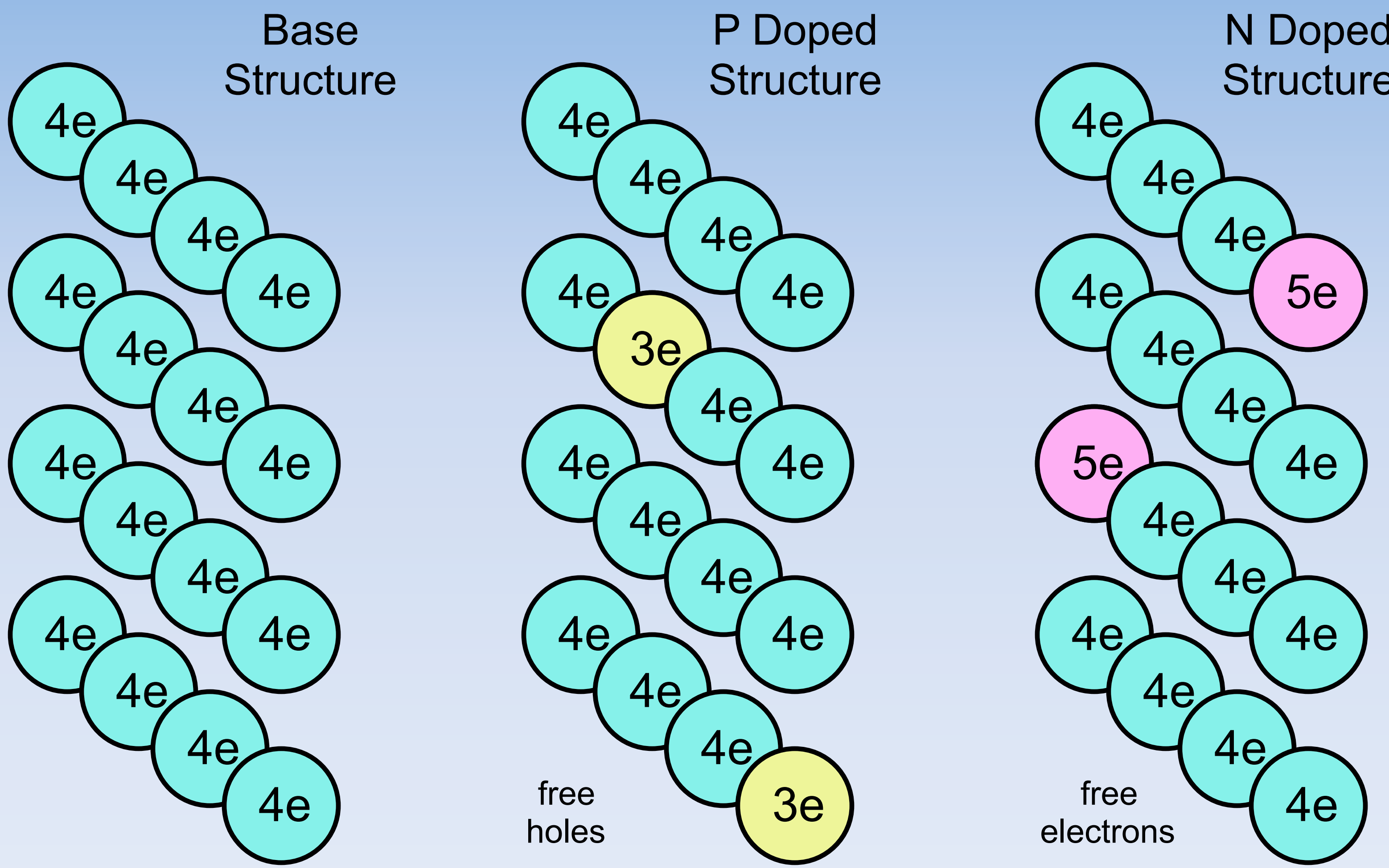


The electrons form "shells" around the nucleus, typically with 8 electrons per shell. These shells give rise the Periodic Table. The outer shell is called the valence band. As an example all elements in Column V have 5 electrons in their outer valence shell.



Introduction

Physics of LEDs – Semiconductor “doping”



Physics of LEDs – What are LEDs made of

Group IIA	Group IIIA	Group IVA	Group VA	Group VIA
	5 **B** Boron 10.811	6 **C** Carbon 12.0107	7 **N** Nitrogen 14.006	8 **O** Oxygen 14.006
	13 **Al** Aluminum 126.981	14 **Si** Silicon 28.0955	15 **P** Phosphorus 30.973	16 **S** Sulfur 32.065
30 **Ze** Zinc 65.38	31 **Ga** Gallium 69.723	32 **Ge** Germaniu m 72.61	33 **As** Arsenic 74.921	34 **Se** Selenium 78.96
48 **Cd** Cadmium 112.411	49 **In** Indium 114.818	50 **Sn** Tin 118.710	51 **Sb** Antimony 121.760	52 **Te** Tellurium 127.60

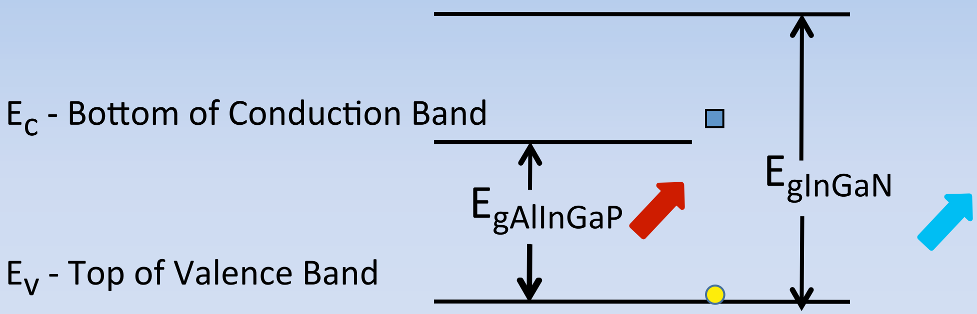
(peach)	Transition Elements
(yellow)	Other Metals
(cyan)	Metaliods
(pink)	Other non metals

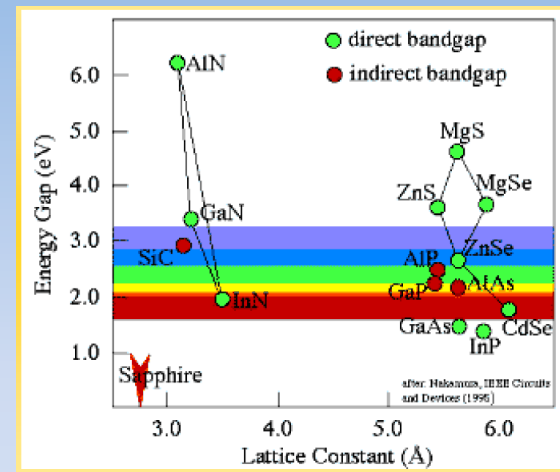
AlInGaN

AlInGaP

How does the LED make light?

Bandgaps – Different gaps, different colors





Source: Ian Ferguson, NC University

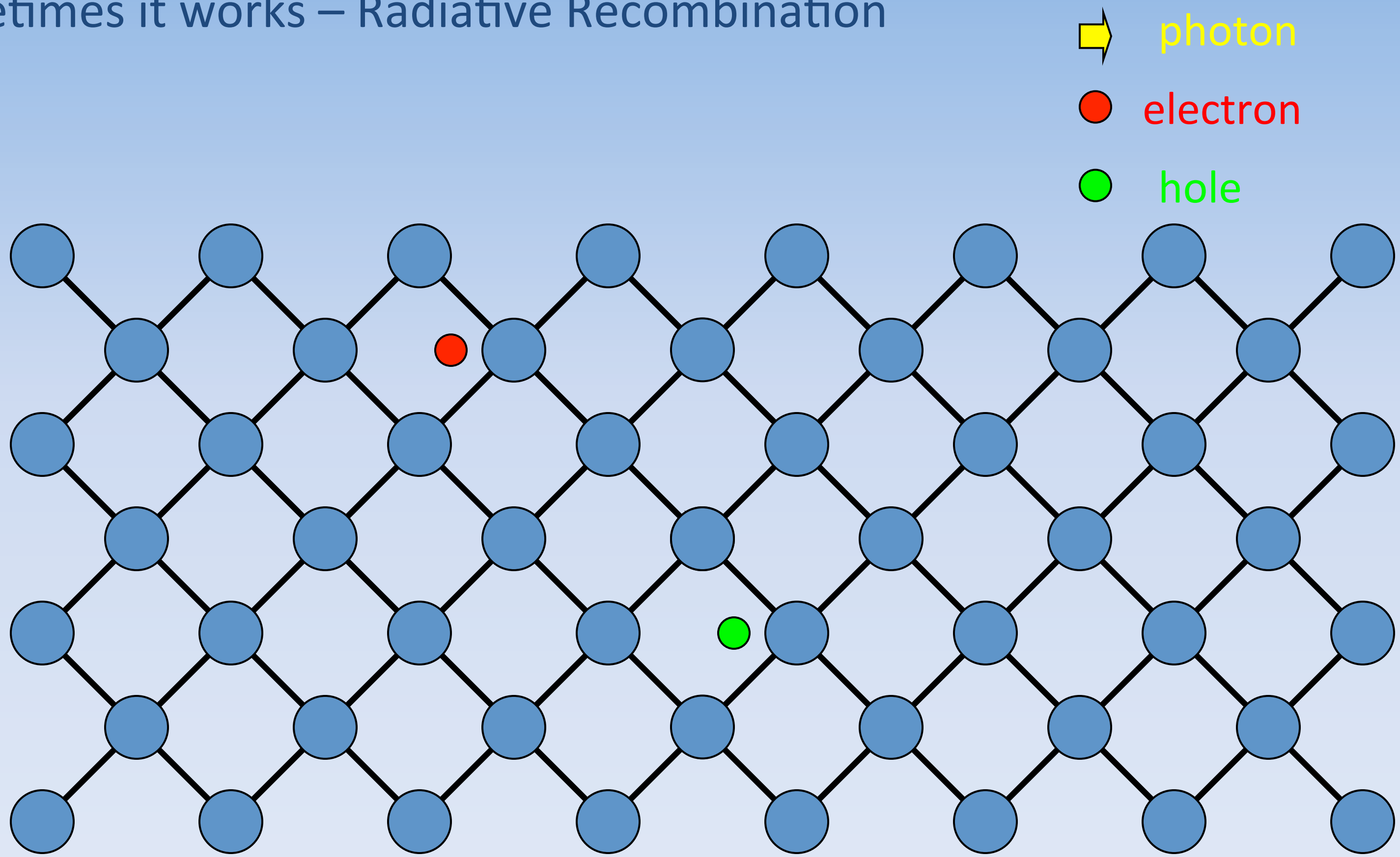
Electron Hole Photon

Smaller bandgap ➔ Lower energy ➔ Longer wavelength photon ➔ **Red**

Larger bandgap ➔ Higher energy ➔ Shorter wavelength photon ➔ **Blue**

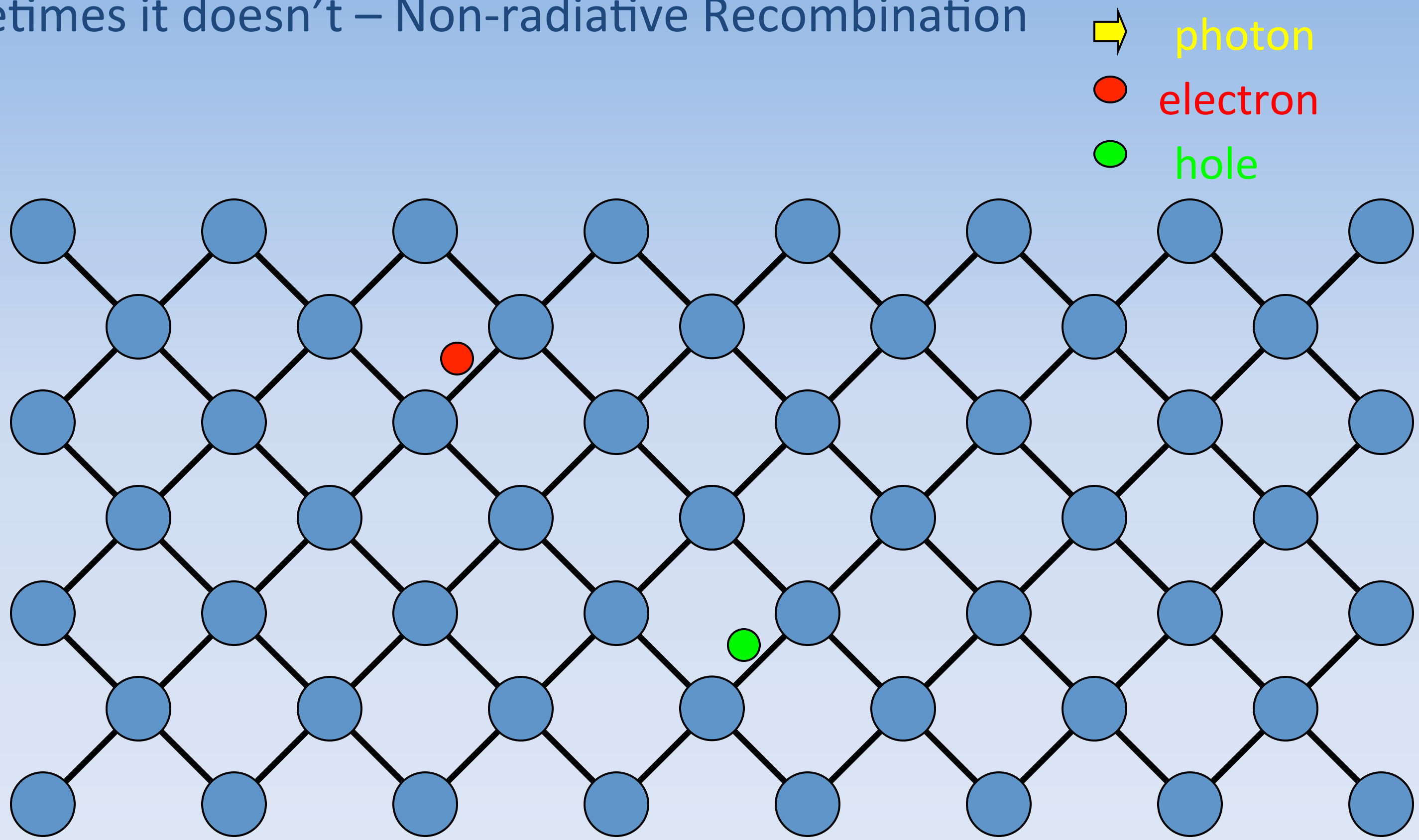
How does the LED make light?

Sometimes it works – Radiative Recombination



How does the LED make light?

Sometimes it doesn't – Non-radiative Recombination



Creates heat instead of light

Introduction

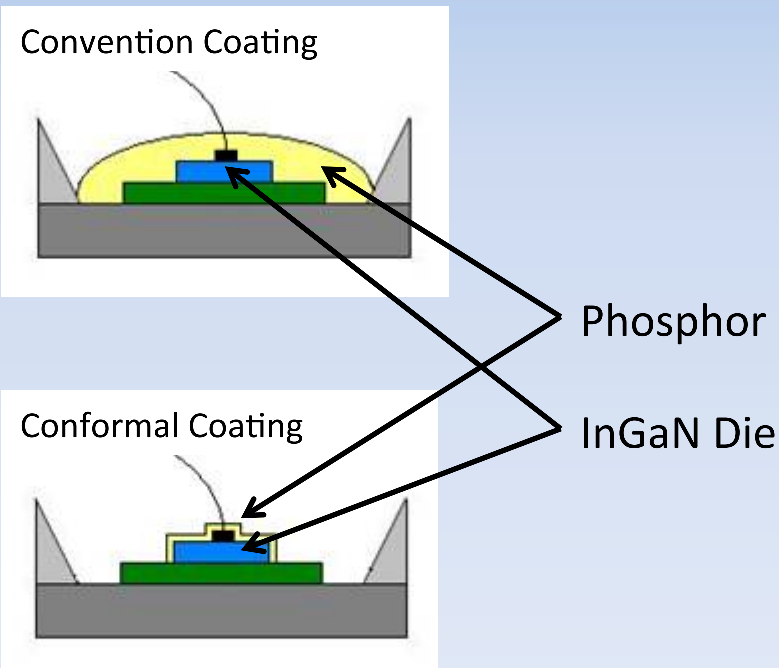
LED wafer fabrication facility

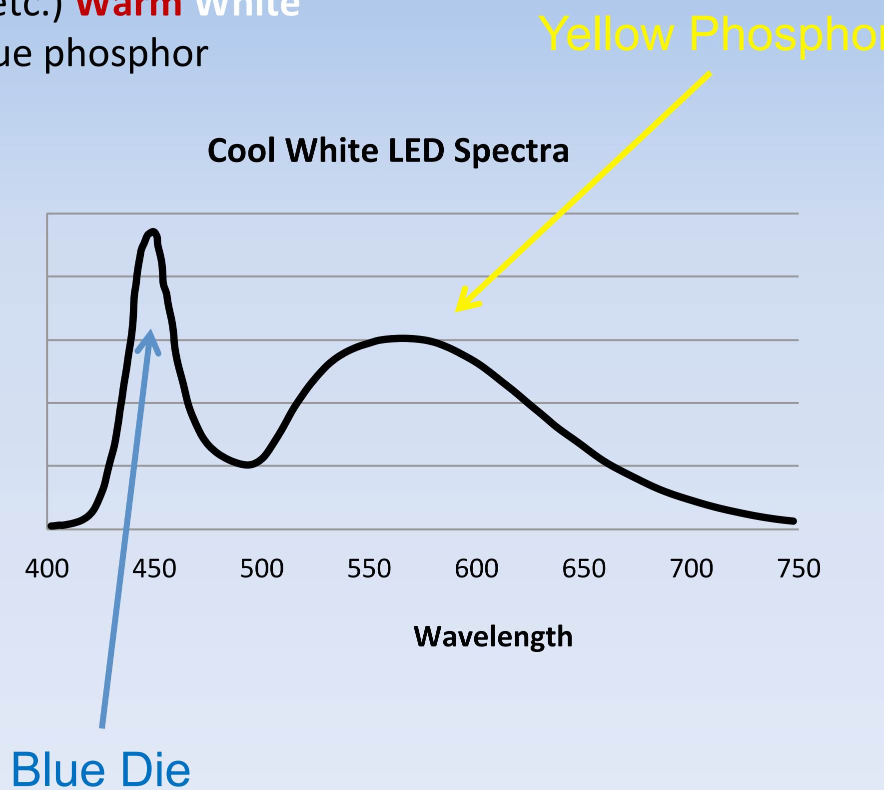
Courtesy Ron Bonne
Philips Lumileds

How Do You Make a White LED?

Downconverting Phosphor

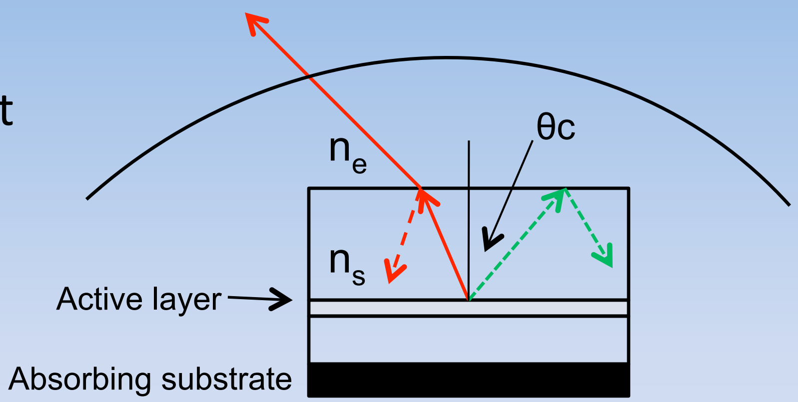
- Blue LED + YAG **Cool White**
- Blue LED + YAG + Other phosphor (red, green, etc.) **Warm White**
- UV LED + Red phosphor + Green phosphor + Blue phosphor





How Do You Get the Light Out of an LED?

Due to the high Index of Refraction of the semiconductor (n_s) as compared to the dome material (n_e), by Snell's law, photons exiting the active layer at angles greater than the escape cone angle θ_c will be reflected back into the semiconductor and will not exit the device.



This gives rise to LED's high directionality

Many approaches have been explored to improve extraction efficiency. Some device manufacturers cut the sides of the chips to provide better exit angles and extract more light while others rough the surfaces of the chips to create optical interfaces which can improve the overall light extraction. A third approach is to use what are known as photonic crystals to reduce certain propagation modes (reflected) and increase others (exiting).

Source: Lumileds

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Break

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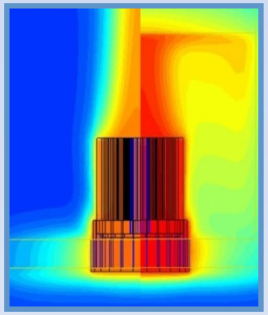
9. Final Thoughts – Some general rules



Lifetime/Cost

Long Lifetimes

An Automotive Example – The low end

- 108 HP engine capable of 105 mph (approximately)
- 1.6L Ecotec 4 cylinder engine w 5 speed manual transmission
- Auxiliary audio input jack
- Cloth reclining bucket seats
- 5-passenger seating
- OnStar® for the first six months
- Oil-Life Monitor
- Tire Pressure Monitor
- 14" steel wheels
- 60/40 split-folding rear seats fold down independently

Chevrolet 2011
Aveo
$11,225

Lifetime/Cost

An Automotive Example – The high end

- 638 HP engine capable of 205 mph
- 6.2L supercharged V8 engine with 6 speed manual transmission
- Bluetooth® wireless technology for select phones
- Heated Sport seats with power adjustable lumbar support
- Power passenger seat
- OnStar® for the first six months
- Memory Package
- Universal Home Remote transmitter
- Carbon-ceramic brake rotors capable of operating at 1,000 ^{O}C
- Bose® seven-speaker sound system with navigation
- SiriusXM Satellite Radio with one-year subscription
- Power-telescoping steering column
- Custom Leather-Wrapped Interior Package
- Luggage shade and cargo net
- Build your own engine option ($5,800)
- Delivery of car at National Corvette Museum in Bowling Green, KY
- 427 hood emblem
- Two-day high performance driving school experience

Chevrolet 2011
ZR1 3ZR Corvette
$121,700

A Lighting Example – The low end

- 60 Watts
- 800 lumens

Incandescent
800 lumen Light
Bulb
$0.50

Lifetime/Cost

A Lighting Example – The midrange

- 13 Watts
- 800 lumens

Compact Fluorescent 800 lumen Light Bulb $3.00

Payback as compared to an incandescent lamp is about 480 hours based on the average US utility rate of $0.1109/kW-hr

LIFETIME/COST

A Lighting Example – The high end

- 12 Watts
- 800 lumens

Solid-state
800 lumen
Light Bulb
$25.00

Economics works only if lifetime / maintenance is considered

Ignoring maintenance, payback as compared to a CFL would be about 198,400 hours based on the average US utility rate of $0.1109/kW-hr

Lifetime/Cost

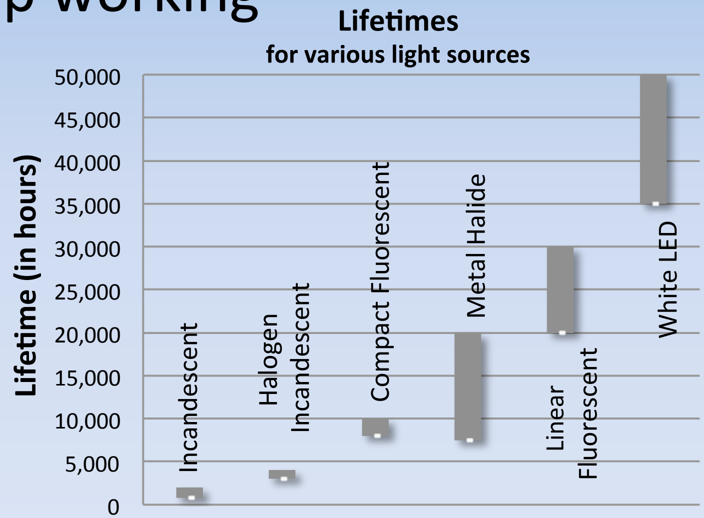
Cost Comparison – Various light sources

Source Type	Cost per kilolumen
Incandescent (60W)[1]	$0.50
Fluorescent (32W T8 w/ballast)[1]	$4.00
Compact Fluorescent (13W)[1]	$2.00
Compact Fluorescent (13W - dimmable)[1]	$10.00
HPS (100W)[2]	$1.25
Metal Halide (100W)[2]	$3.15
LED (dimmable replacement for 60W)[1]	$50.00
OLED Panel[1]	$2,560.00

[1] DOE SSL R&D Multi-Year Program Plan (March 2011/Updated May 2011)
[2] LED Transformations

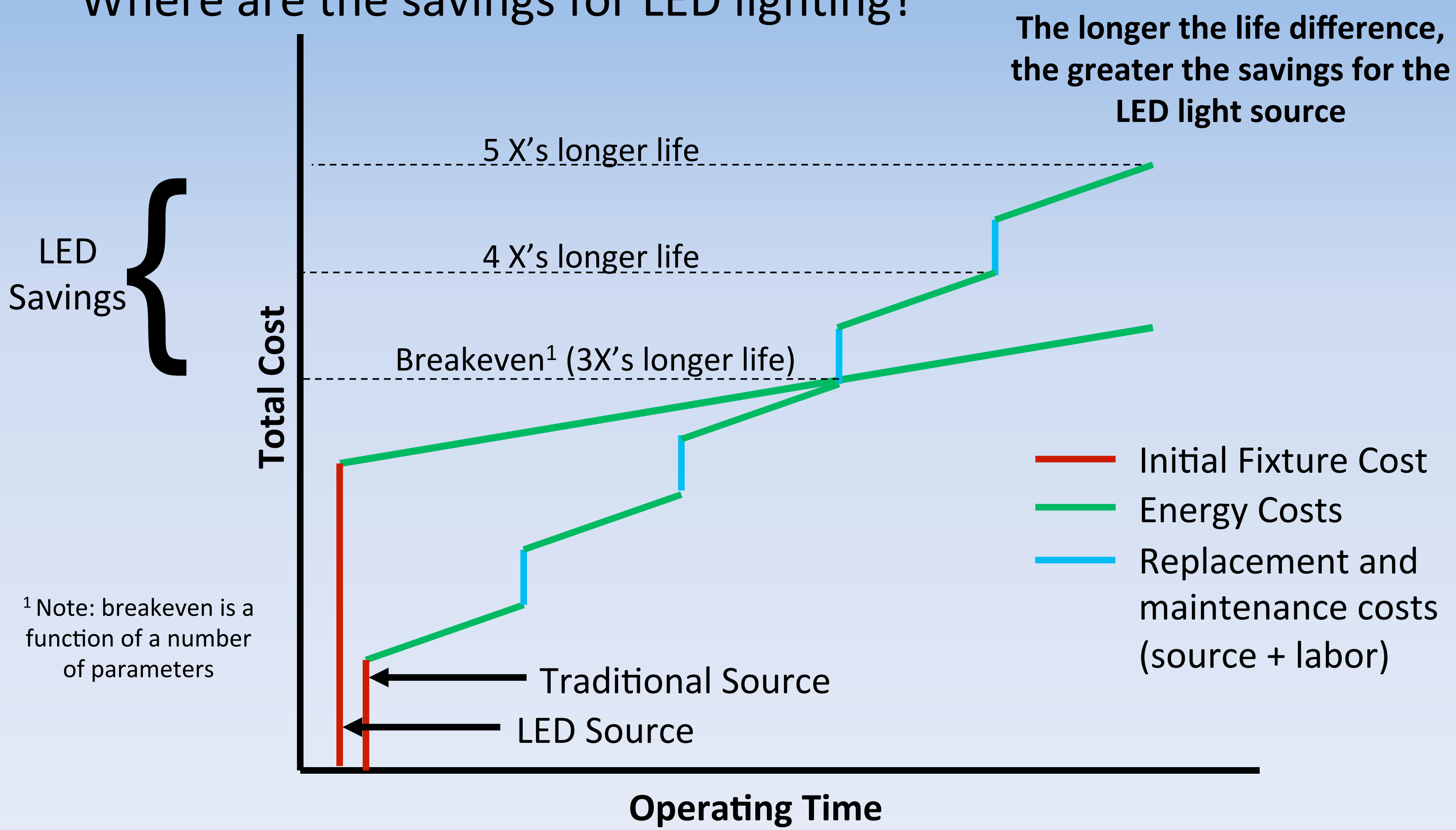
Long Lifetimes

- Traditional light sources fail catastrophically due to electrodes which weaken or become contaminated and eventually fail, causing the lamp to stop working
- LEDs rarely fail catastrophically
  - Light output gradually decreases over operating time
  - End of life is typically defined to be when light output reaches 70% of initial value
    - Raises issue for designers – how to warn users that product has exceeded end-of-life and is producing less light than the application may require
  - Lifetime highly dependent on temperature (ambient and device as well as operating current



Why do We Care? – Longer life = greater payback

Where are the savings for LED lighting?



LED Economics

However there are other parts of the lighting system besides the LED devices themselves that can fail or require maintenance

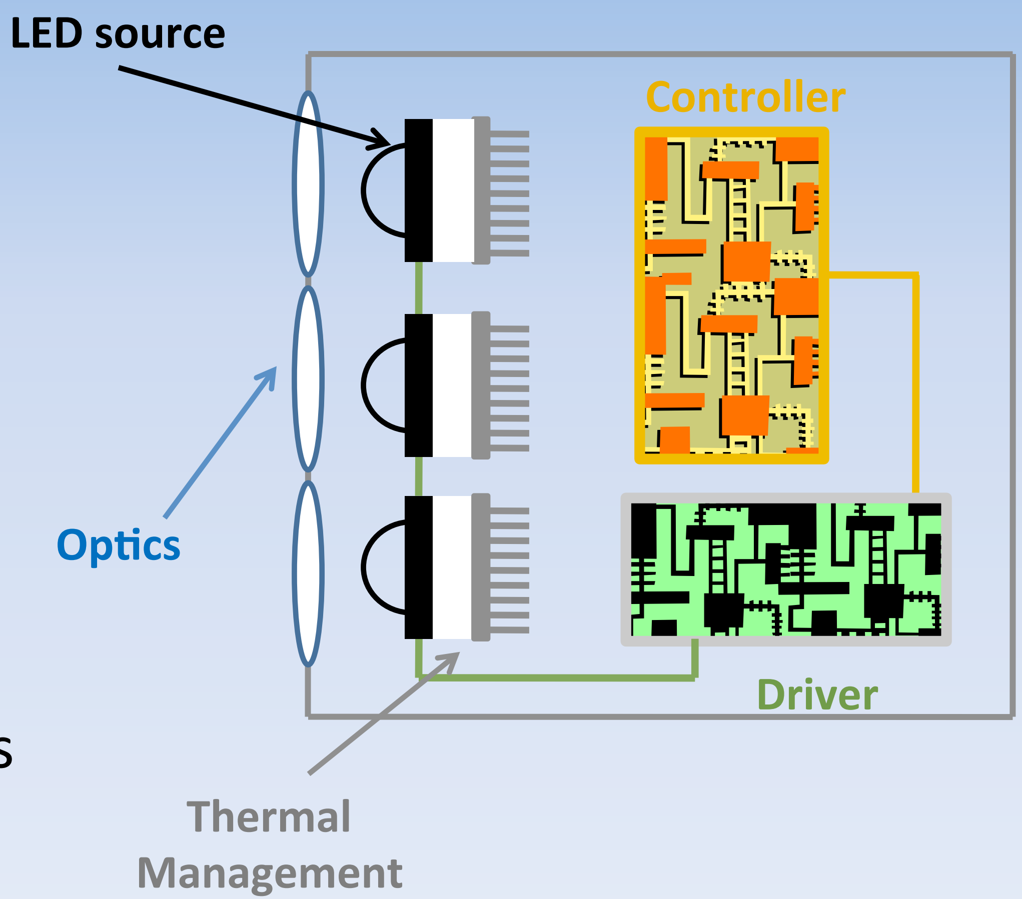
- Driver and Control Electronics (including dimmers, energy management systems) – component failures, lightning strikes and other electrical transients
- Optics – yellowing, cracking, voids, dirt buildup
- Heat sinks –bird droppings, insect nests
- Housings – mechanical stress, water intrusion, connectors

How easy is it to repair/replace damaged components?

Luminaire Lifetime – A Luminaire is a System

The failure of any one component can cause the entire system to stop functioning

Luminaire designers make trade-offs among the components, depending on the desired performance criteria – for example the number of LEDs ($$$) versus drive current (lifetime)

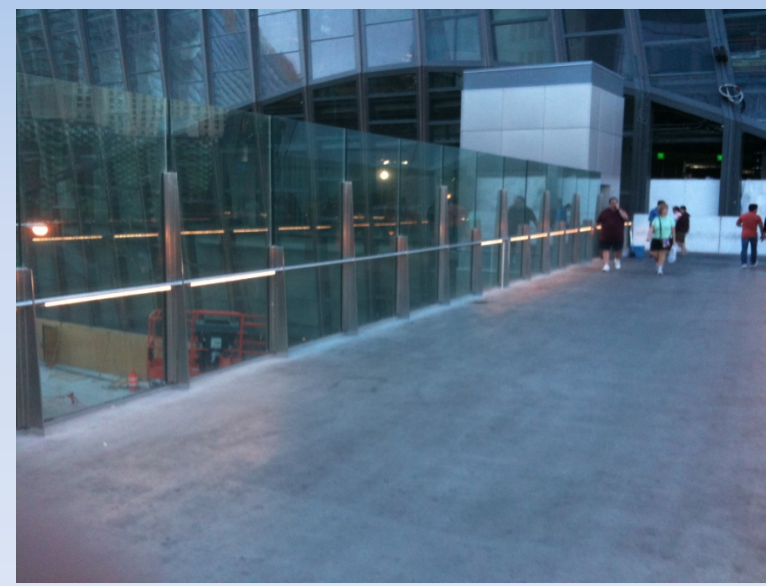


Lifetime/Cost

Reliability – Depends on the driver as well

Two examples of failures caused by the driver

Stop & Shop, Raritan, NJ – 6 weeks

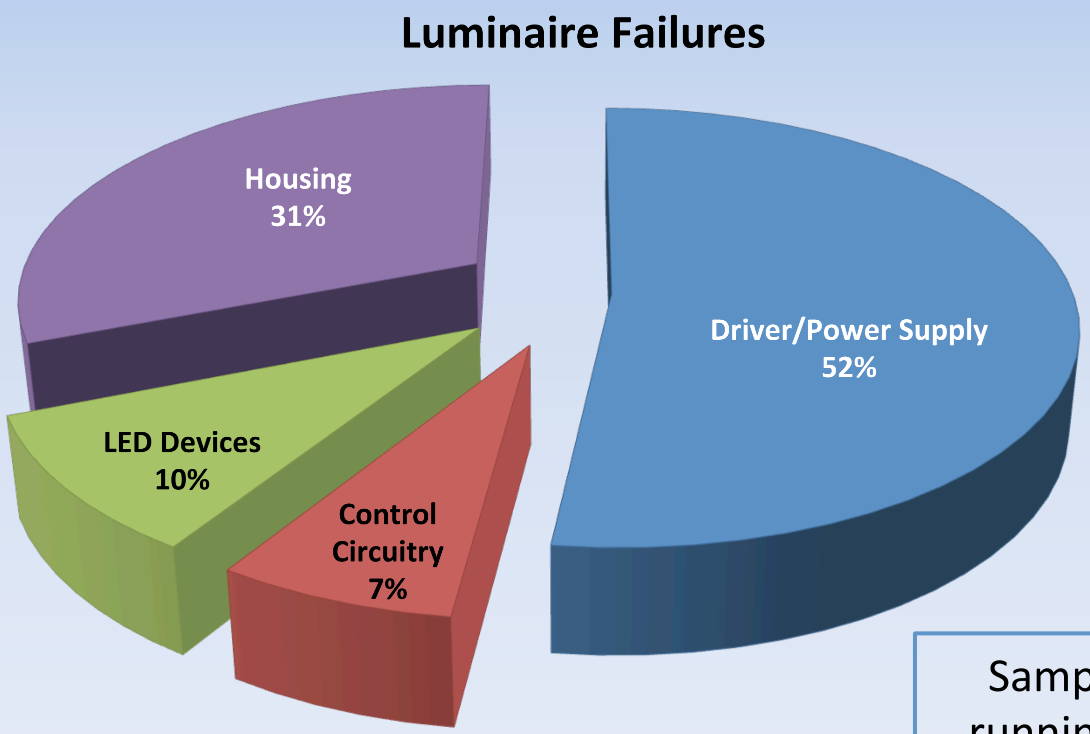


City Center, Las Vegas – 5 months

Not quite 50,000 hours!

Reliability – What is the weakest link?

The lighting industry has put the emphasis on the LED device performance and is only now recognizing that there are other critical components which contribute to decreased lifetime



Sample of 5200 units running for 6000 hours

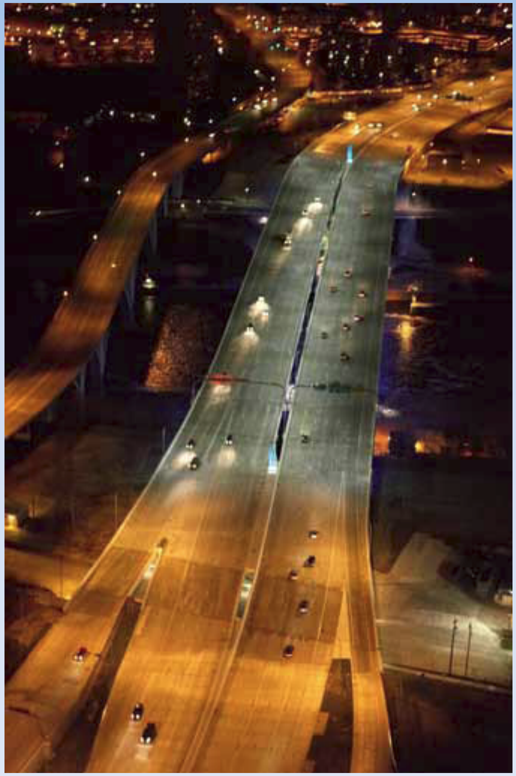
Data Source: Appalachian Lighting Systems, Inc.

Measuring LED Lifetime – What else can go wrong?

LED luminaires are systems…

From the original DOE Gateway Report:

"At the prevailing average nighttime temperature in Minneapolis, the manufacturer projects that the luminaires would need to operate for several decades to reach this level of lumen depreciation [70% of original lumen output], estimating only about a 12% loss after 20 years."



From a recent interim DOE Report:

"Continuing decrease detected in average illumination on the ground, roughly 12% from initial after a few [15] months."

Measuring LED Lifetime – What else can go wrong?

Reasons for decrease had nothing to do with the performance of the LEDs used:

Reason #1: "Earlier design used an optical gel to fill void between LED lens and proprietary *nano-optic*. Over time, a bubble forms in the gel that causes step change in both lumen distribution and output. The measured optical gel impact on these two samples corresponds to 6.6% and 7.4% reductions in total lumen output."

Light Bar (Initial)

Light Bar (after 54 weeks of temperature cycling)

Reason #2: Dirt Depreciation

Site	Years of Operation	Lumen Output (Dirty Lens)	Lumen Output (Clean Lens)	Lumen Dirt Depreciation
I-35W	1.25	14520	15227	4.60%
I-35W	1.25	14670	15245	3.80%

Would translate to a 9 year lifetime to due dirt depreciation alone!

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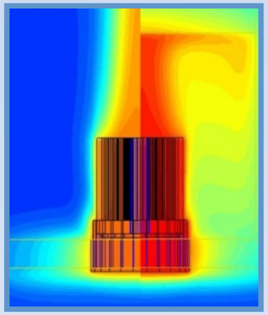

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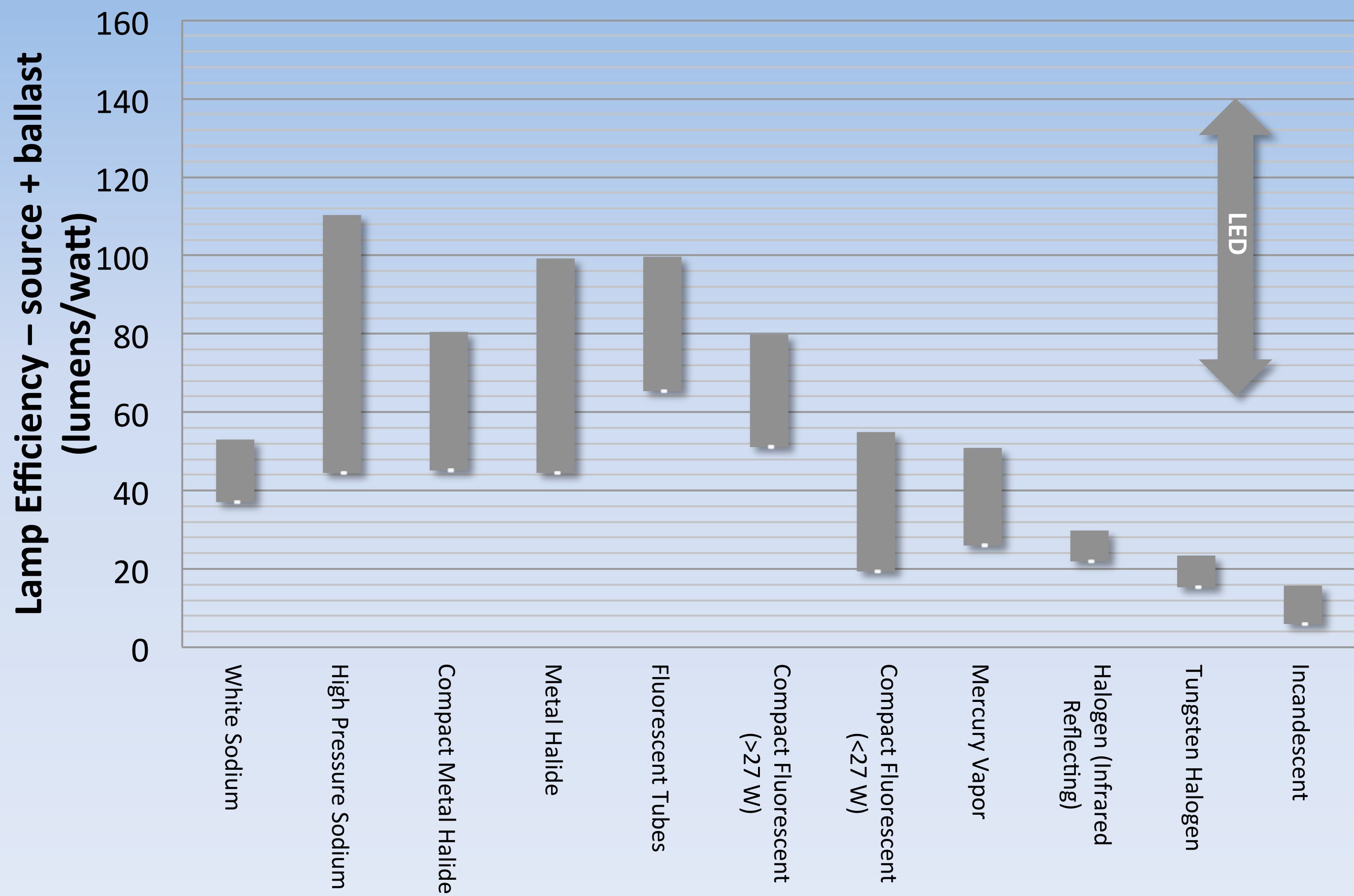
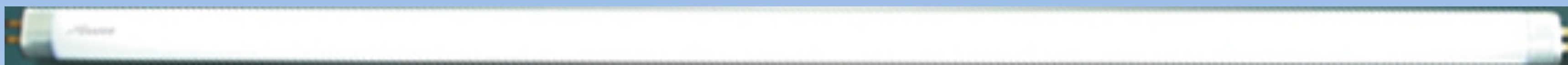
What's Different

Potentially Highest Energy Efficiency



What's Different

Small Size

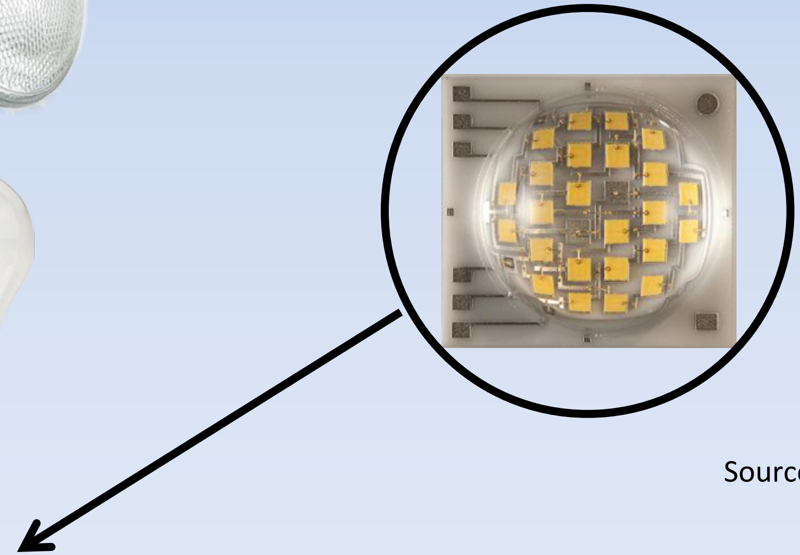


T5 Fluorescent
1350 lumens

75W PAR 38 Halogen
1100 lumens

75W Incandescent
1200 lumens

Cree MP-L LED
1200 lumens

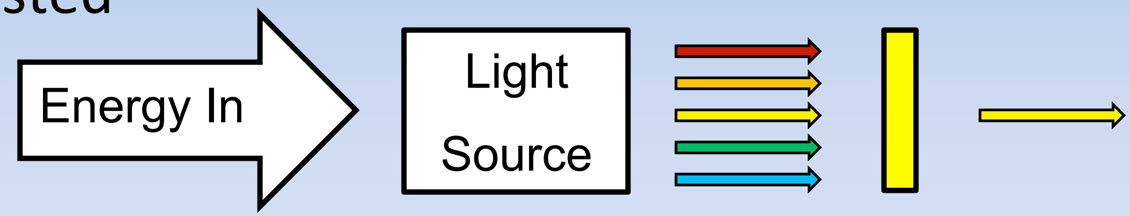


Source: Cree

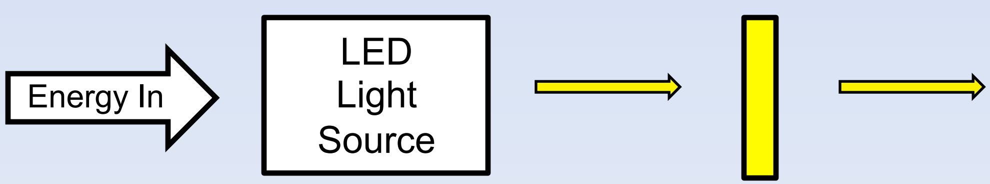
What's Different

Direct Color Creation

- For color lighting applications, traditional light sources use energy to create white light which then is filtered to create the desired color. The energy used to create the other colors is wasted



- LED light sources create the color directly leading to greatly improved energy efficiency

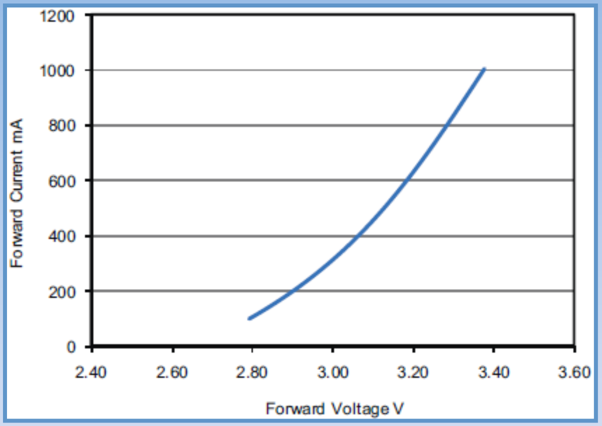


What's Different

Drivers – Basics

Why do we need drivers in the first place?

- LEDs are non-linear devices (I_f vs. V_f) with a forward voltage that is temperature dependent – light output is best controlled by regulating current
- LEDs are diodes and therefore will only operate when current flows in one direction
- LEDs are low voltage devices (with typical forward voltages ranging from 2.8 – 3.5 V). They require some minimum conditioning and/or protection
- The light source that LEDs replace with the greatest improvement in efficacy (incandescent) are purely resistive loads with a Power Factor equal to 1 – therefore it is desirable for the driver circuitry to provide a power factor as close as possible to 1
- Drivers also need to control harmonic current effects on the mains



Source: Philips Lumileds data sheet

What's Different

Drivers – A fundamental point

The lifetime of the driver affects the lifetime of the luminaire

Drivers are like any other electronic power supply with their performance and reliability a function of:

- The environment in which they operate
- The quality of the components used
  - Electrolytic capacitors – age due to drying out of electrolytic
  - FETs, rectifiers, etc. which can be stressed by heat and vibration
  - Other components which are affected by heat, moisture, shock and vibration
- The skill and care with which they are designed and built
- The stress to which they are subjected in the field

Drivers come in many different shapes and sizes – often they are about the same size as a fluorescent ballast

Driver Characteristics – Efficiency

Driver Efficiency – ratio of the output power to the input power

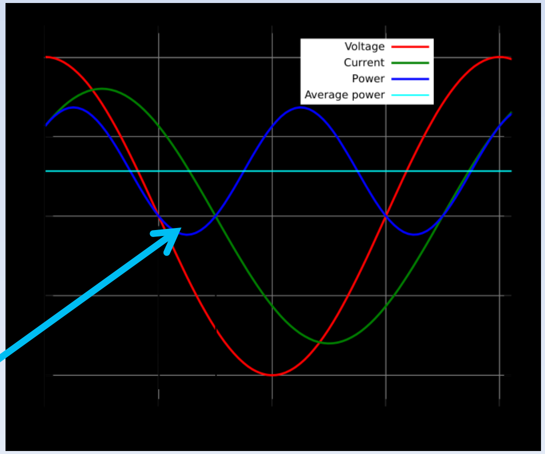
- Typical efficiencies range from 75% to 90% for SMPS
  - Losses due to switching, resistances, transformers, etc.
  - Driver should not draw power if load is turned off (Energy Star requirement)

Power factor – real vs. apparent (consumed + stored) power

- Low power factor results in excess power delivery
- Power factor defined as

$$PF = \frac{\text{Real Power}}{\text{Apparent Power}} = \frac{\text{Watts}}{\text{Volts x Amps}} \leq 1$$

- Some Utilities are concerned about PF as low PF can result in additional power transmission losses

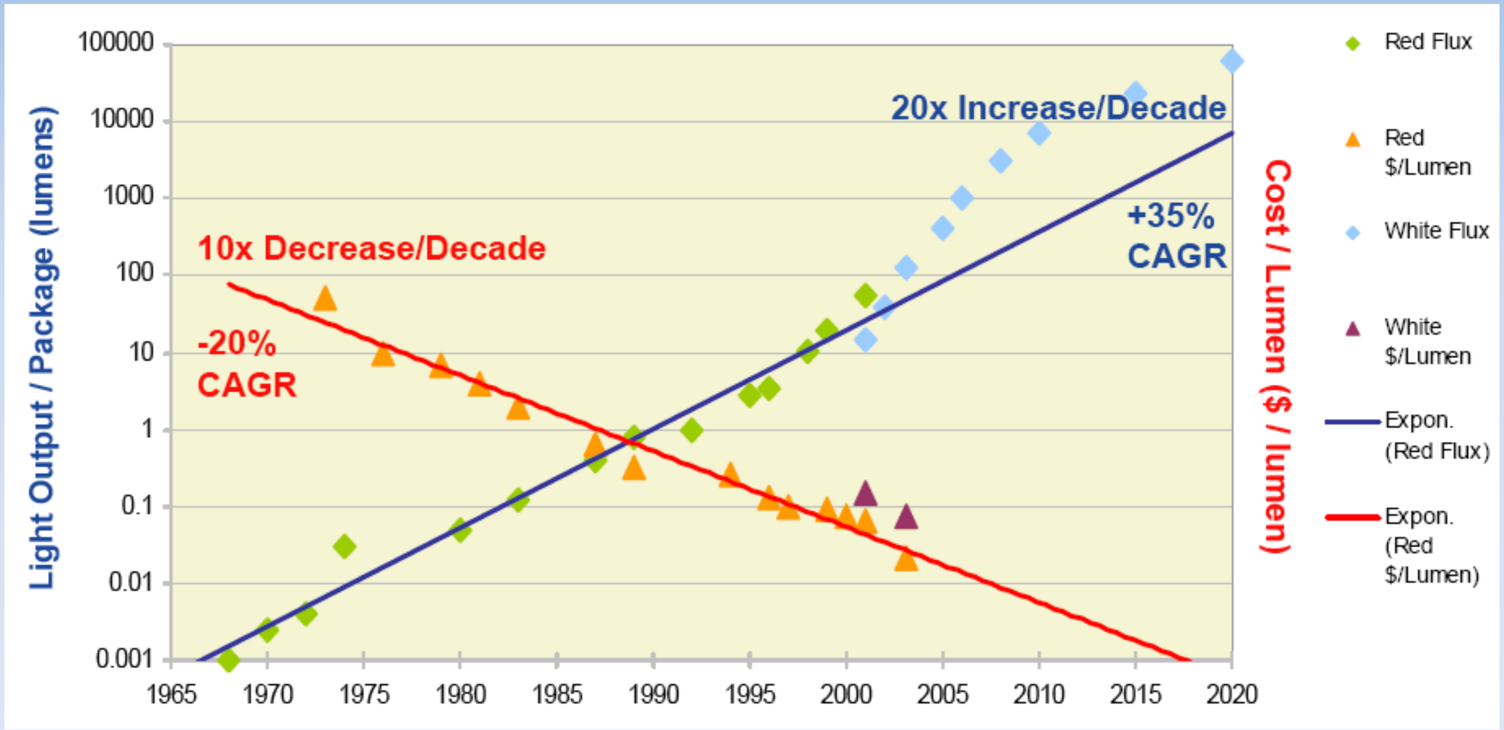


Culture Clash – Not the first time

What's Different

Rate of Development

LEDs follow a development rule known as Haitz's Law



Source: Roland Haitz & Lumileds

Obsolescence – Often driven by economics

Ad from 1891 for Edison lamps

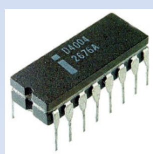
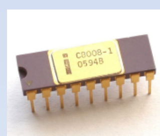
That is $10.37 in today's dollars or about $0.05/ lumen

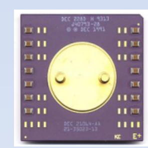
Also note that lifetime has only improved about 66% in 110 years!

Culture Clash – Change

The traditional lighting industry moves at a relatively slow pace with styles changing regularly, but technology remaining relatively constant

The semiconductor industry moves at a rapid rate with components changing constantly. It is the epitome of the "disposable" society

(1971) 4 bit 8 bit 16 bit 32 bit 64 bit (1991)

In the Solid-State Lighting world, these two cultures clash head-on with major implications for both

What's Different

Culture Clash – Obsolescence

Architectural products may be installed for 20 years or more

- Will the LED luminaire last that long?
  - Don't ignore mechanical finishes (rust, stress cracks, etc.)
- What maintenance is required to insure a 20+ year life?
  - For example, replacing a yellowed lens cover
- How easy is it to replace components that fail?
  - The integrated driver that made the product less expensive to purchase may make it more expensive to repair
- If replacement components exist, how long will they be available?
- When refurbished, will the luminaire perform the same (CCT, light output, light distribution, etc.)?

What's Different

Culture Clash – Obsolescence

Time frames for Lighting Specifiers and Architects bidding major jobs can be 2 to 3 years from bid to actual purchase of luminaire products for installation

- Price will probably not be an issue since LED-based products historically decrease in price each year by 25% or more
- Availability could be an issue since LED devices are in a constant state of change
  - Many small solid-state lighting companies with little or no track record will be at a major disadvantage

Early 20th century light fixture

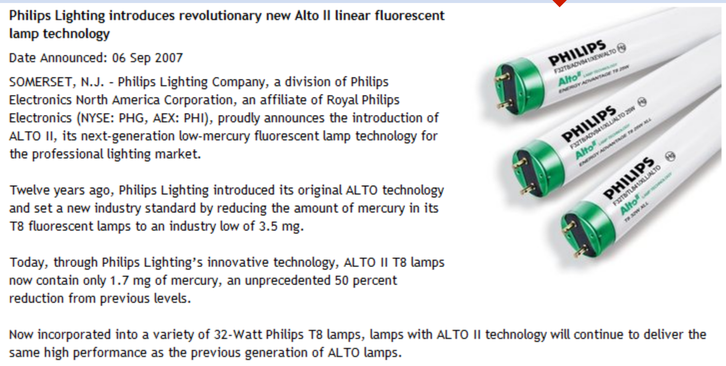
Source:
Scot Hinson
Modeliving

What's Different

Obsolescence – Some things don't change

A 1942 Magazine ad for General Electric fluorescent lamps

A 2007 news release from a lighting magazine on an improved fluorescent lamp



Philips Lighting introduces revolutionary new Alto II linear fluorescent lamp technology

Date Announced: 06 Sep 2007

SOMERSET, N.J. - Philips Lighting Company, a division of Philips Electronics North America Corporation, an affiliate of Royal Philips Electronics (NYSE: PHG, AEX: PHI), proudly announces the introduction of ALTO II, its next-generation low-mercury fluorescent lamp technology for the professional lighting market.

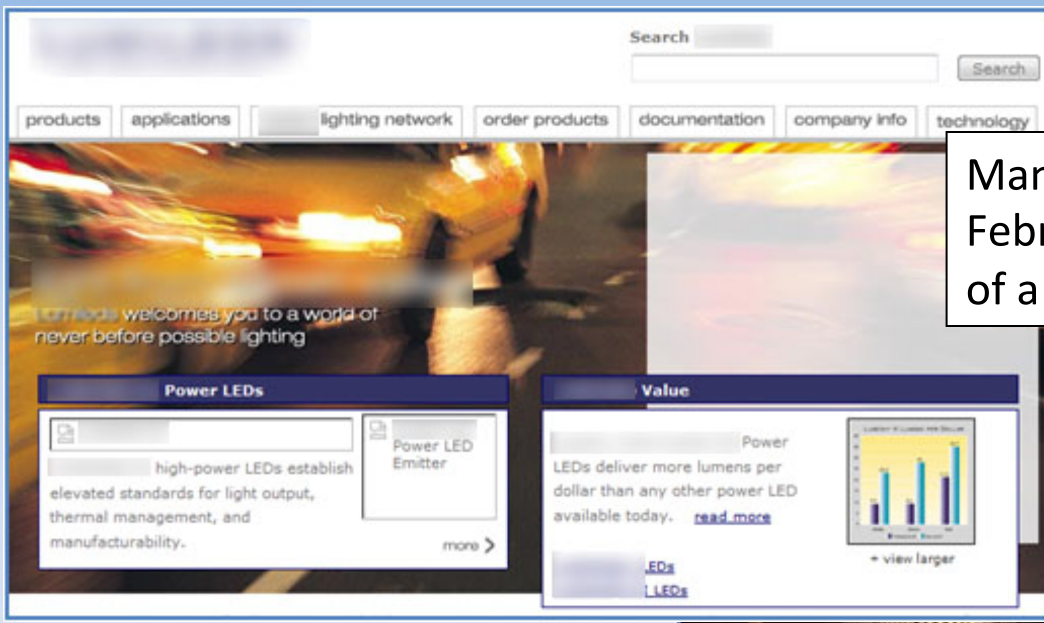
Twelve years ago, Philips Lighting introduced its original ALTO technology and set a new industry standard by reducing the amount of mercury in its T8 fluorescent lamps to an industry low of 3.5 mg.

Today, through Philips Lighting's innovative technology, ALTO II T8 lamps now contain only 1.7 mg of mercury, an unprecedented 50 percent reduction from previous levels.

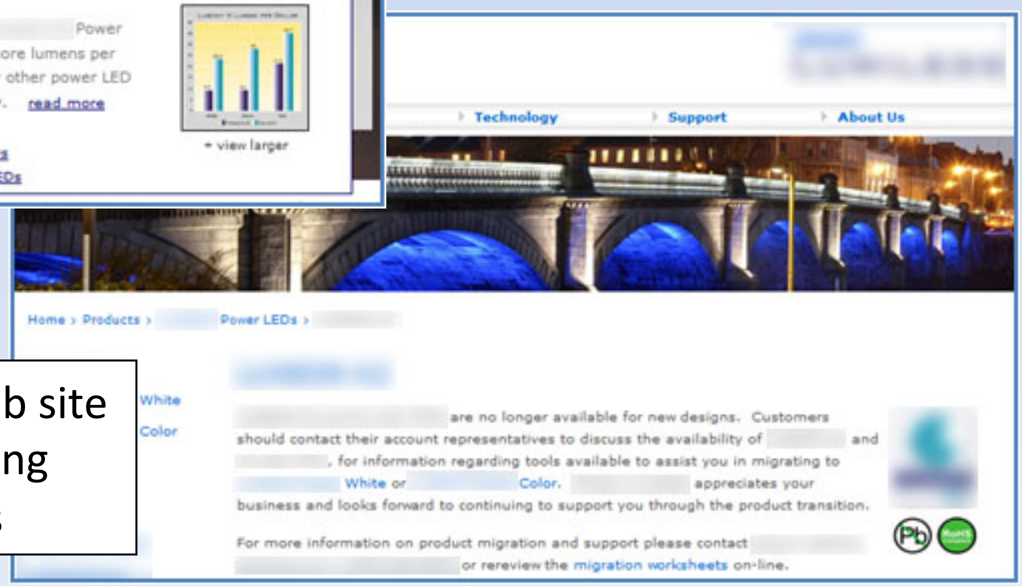
Now incorporated into a variety of 32-Watt Philips T8 lamps, lamps with ALTO II technology will continue to deliver the same high performance as the previous generation of ALTO lamps.

What's Different

Obsolescence – And some things do



Manufacturer's web site from February 2006 showing the addition of a new line of LED devices



The same manufacturer's web site from March 2010 discontinuing that same line of LED devices

What's Different

New Names & Shapes in Lighting

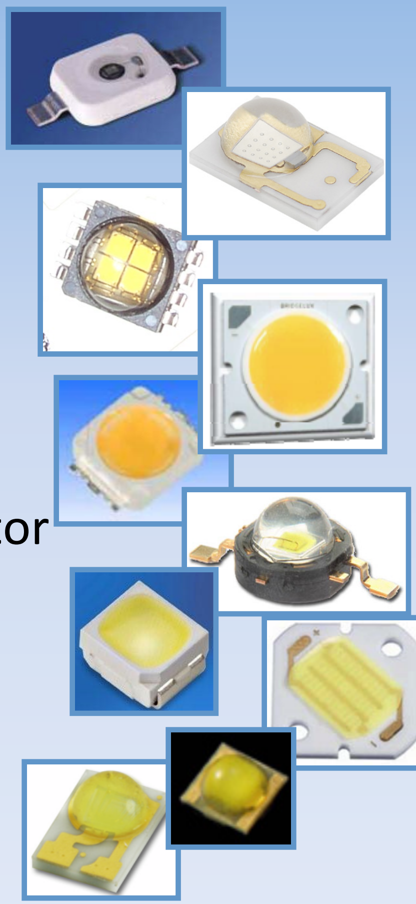
Traditional Lamp Suppliers

- Sylvania

- Philips

- GE

LED Suppliers



- Osram
- Lumileds
- Cree
- Bridgelux
- Nichia
- Seoul Semiconductor
- Toshiba
- Sharp
- Toyota Gosei
- Edison Opto
- and many more…

WHAT'S DIFFERENT

Compatibility

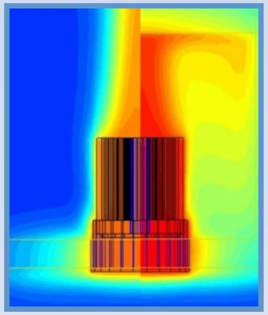
One issue where the cultures can agree is that a need exists for standardization where/when possible in sources and components

- Computer industry suffered from this issue
  - Operating Systems (Windows versus Apple versus Linux)
  - Storage Media

- Movie Industry has gone through the same issue twice over the last 20 years
  - Beta versus VHS tape formats
  - BluRay versus HD-DVD high definition DVD formats
- Standardization efforts must be timed correctly, so as to not stifle innovation

Course Outline

1. Introduction – Why should I care about LEDs?
2. Lifetime and Cost – A critical relationship for LEDs
3. What's Different – LED technology as compared to traditional light sources
4. Technology Limitations – Characteristics to be aware of with solid-state lighting
5. Standards – The need for new metrics



Break

6. Applications – What are the good ones?
7. LED Products – Where to turn for guidance
8. Items of Importance to Building Owners/Facility Mgrs
9. Final Thoughts – Some general rules

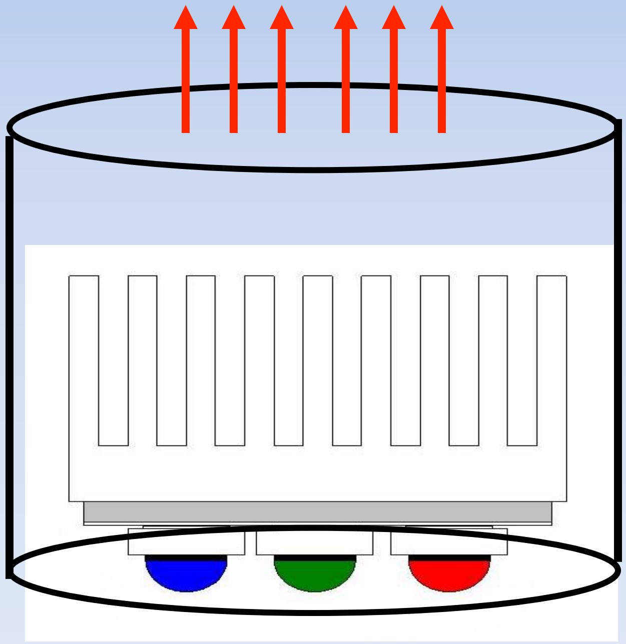
Technology Limitations

Thermal Management – Where the heat goes

LED Fixture

Conducted Heat

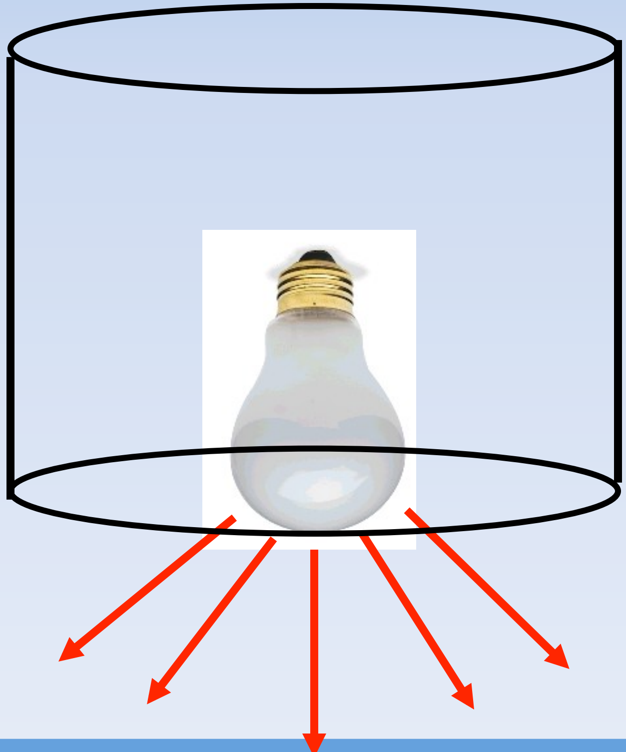
Comes out the back



Incandescent Fixture

Radiated Heat

Comes out the front



Technology Limitations

Thermal Management – Incandescent versus LED luminaires

Source	Efficacy (lm/W)	Heat Loss (%)		
		Radiation	Convection	Conduction
Incandescent	15	90	5	5
Fluorescent	95	40	40	20
HID	120	90	5	5
LED	100	5	5	90

A fixture using a 60W incandescent light bulb produces 900 lumens[1] of light and must dissipate **3 watts** of heat via conduction

A fixture using LEDs as the light source would require 9 LEDs to achieve the same 900 lumens[1]. The input power to the fixture would be (assuming a V_f of 3.2V and current of 312mA)

Power = 9 x 3.2V x 312mA = 9.0W

The fixture would need to conduct **8.1 watts** of heat (9W x 90%)

[1] Ignoring luminaire efficiencies

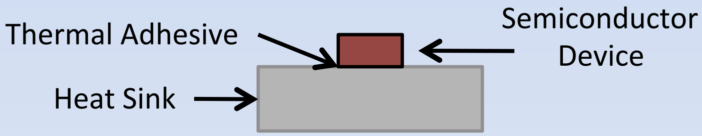
Technology Limitations

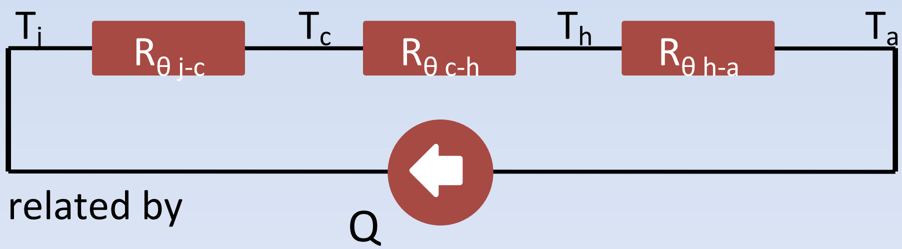
Thermal Calculations – Thermal Resistance (R_θ)

Heat flow can be modeled by analogy to an electrical circuit where:

Q (heat flow) is analogous to electrical current and indicates the power dissipated
T (temperatures) is analogous to voltage
R_θ (thermal resistance in $^{O}C/W$) is analogous to electrical resistance and
Heat sources are represented to current sources/sinks

In the simple model below, a semiconductor device is attached directly to a heat sink which is exposed to the ambient air. Semiconductor manufacturers supply the thermal resistance value $R_{\theta\ j\text{-}c}$ between the junction and the case of the device. Similarly thermal adhesive and heat sink manufacturers supply the case-to-heat sink $R_{\theta\ c\text{-}h}$ and heat sink-to-ambient $R_{\theta\ h\text{-}a}$ thermal resistances.





For this case the total power dissipated, Q is related by

$$(T_j - T_a) \quad = \quad Q \times (R_{\theta\ j\text{-}c} + R_{\theta\ c\text{-}h} + R_{\theta\ h\text{-}a})$$

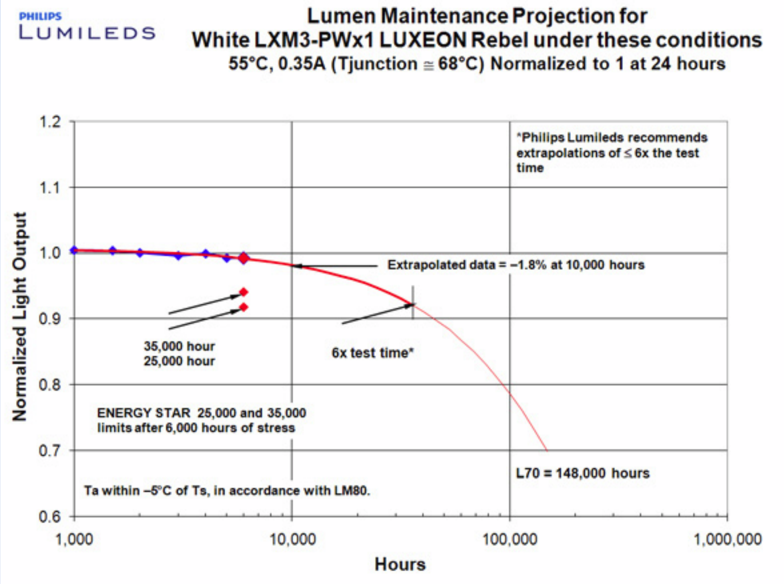
where T_j is the junction temperature of the semiconductor device and T_a is the ambient air temperature. For reference T_c is the case temperature of the semiconductor device and T_h is the heat sink temperature.

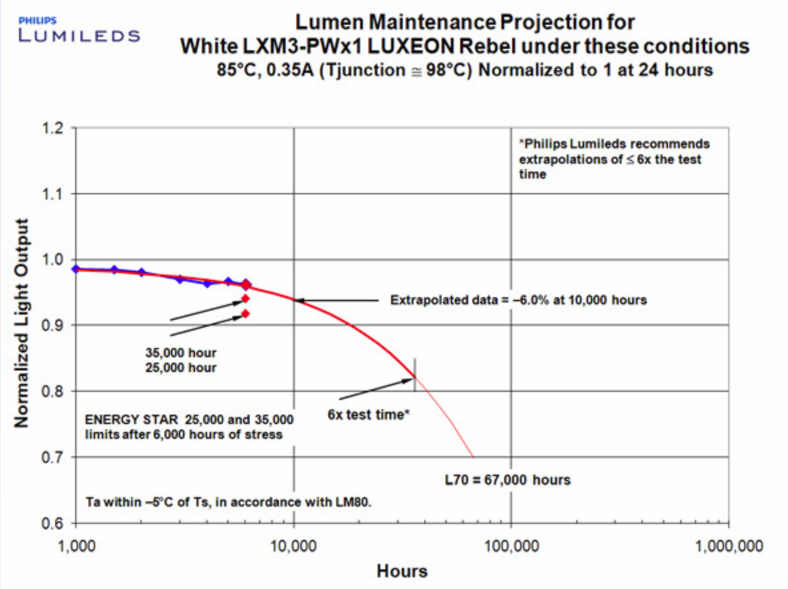
Technology Limitations

Effect of Heat on Lifetime

LED Lifetime with ambient temperature of 55^{O}c is 148,000 hours

LED Lifetime with ambient temperature of 85^{O}c is 67,000 hours





Source: Lumileds

Technology Limitations

Thermal Management – What is wrong with this picture?

A number of MR-16s were installed in a luminaire made of aluminum housings. The luminaire was installed under a glass atrium in a part of the world which receives a considerable amount of sun.

How would this fixture work?

Would this one work any better?

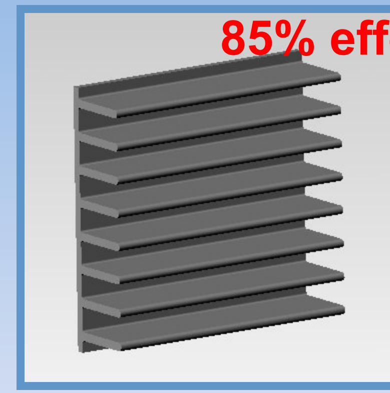
The MR-16 is designed to create air flow over the slots or fins along its shell

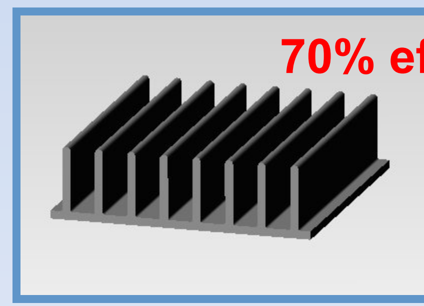
The result—major failures within a couple of weeks of installation

Technology Limitations

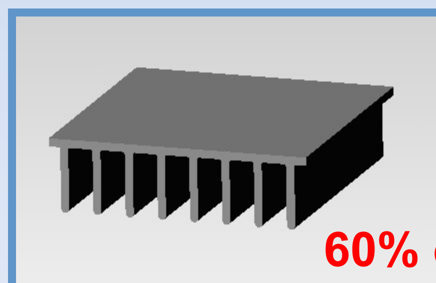
Luminaire Orientation Can Effect Lifetime

Luminaire manufacturers must take desired orientations into account when designing thermal management system for products



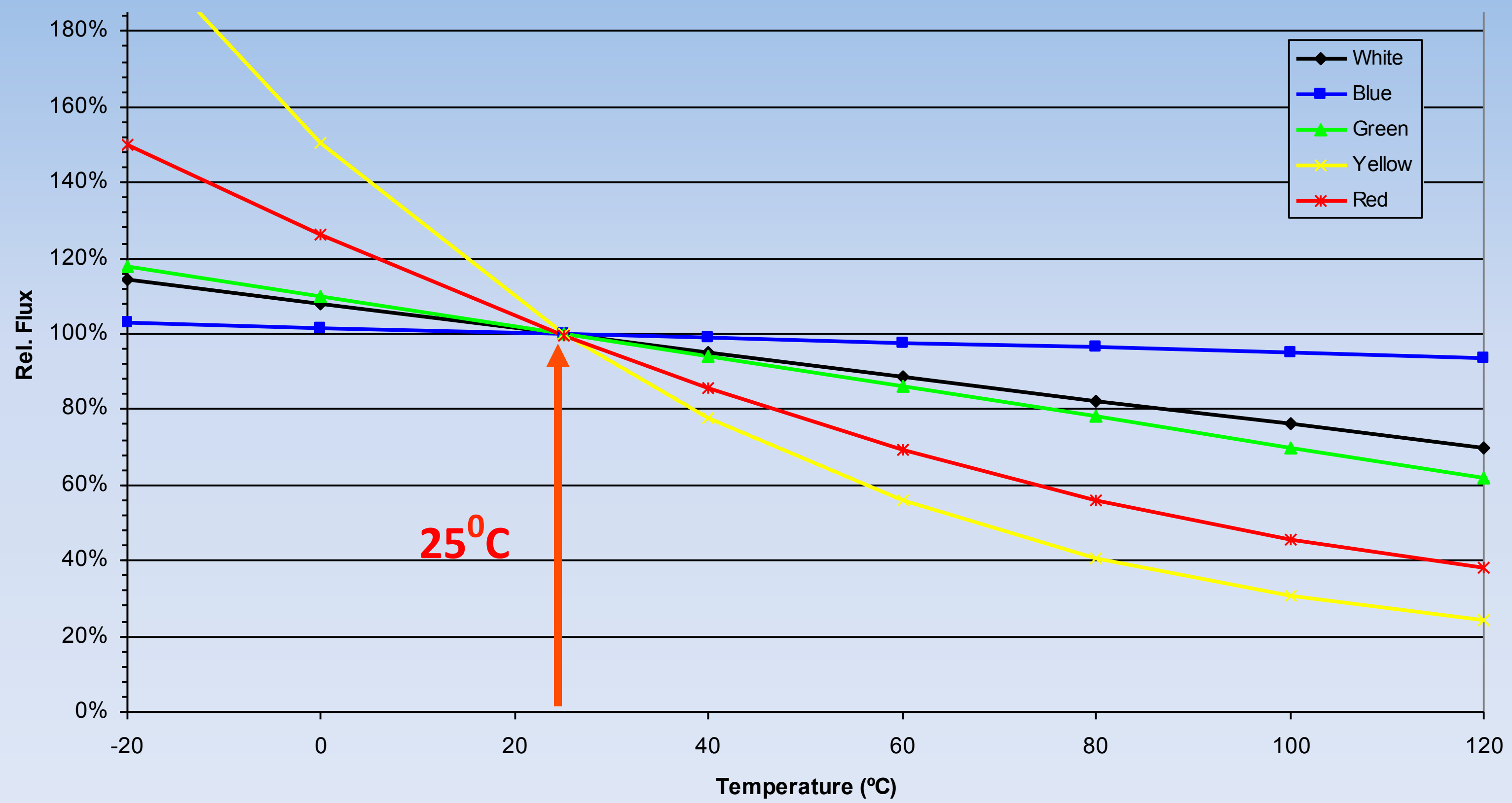


LM-79 testing standard requires the luminaire be tested in the orientation in which it will be mounted



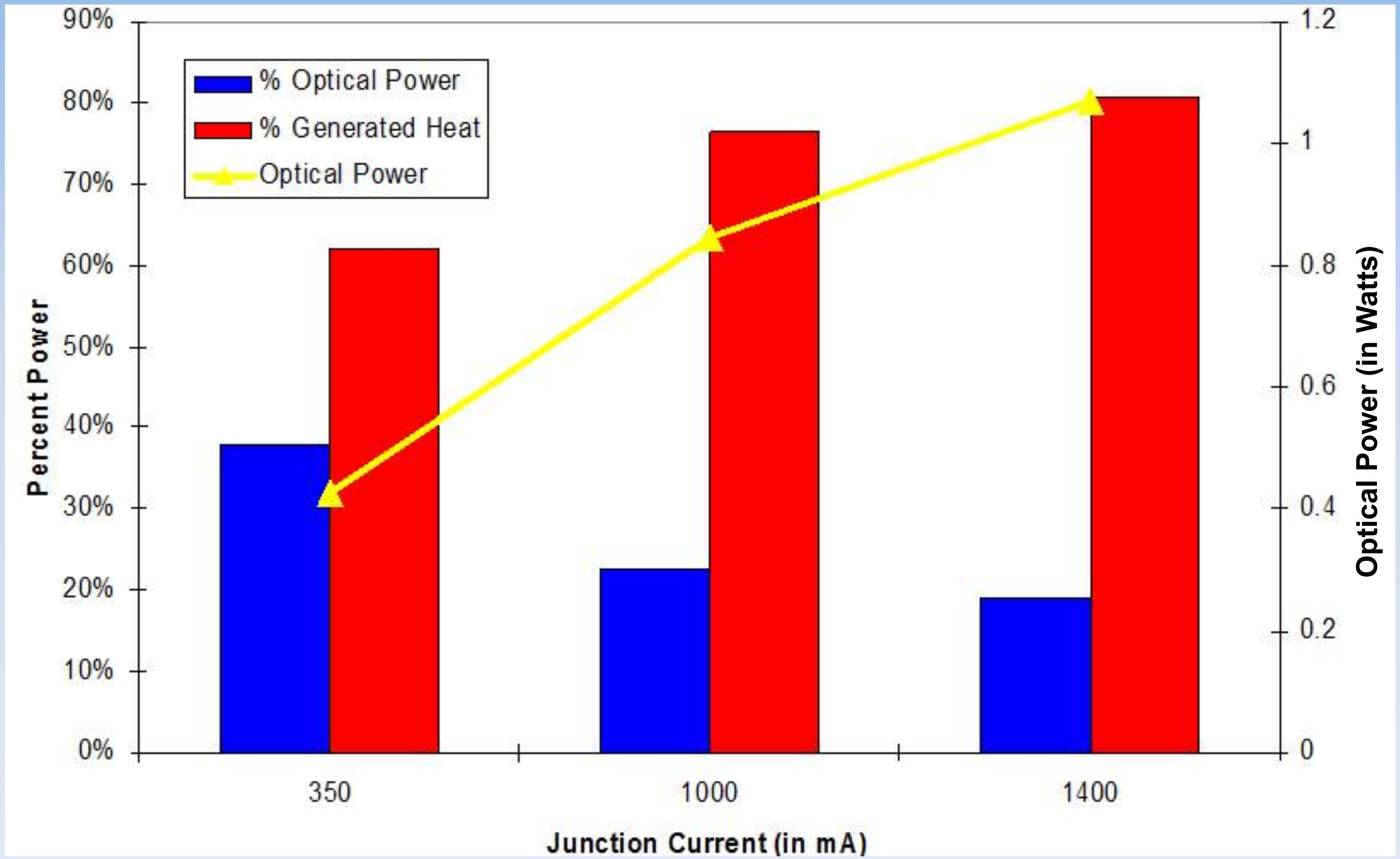
Technology Limitations

Thermal Considerations – Effect on light output



Technology Limitations

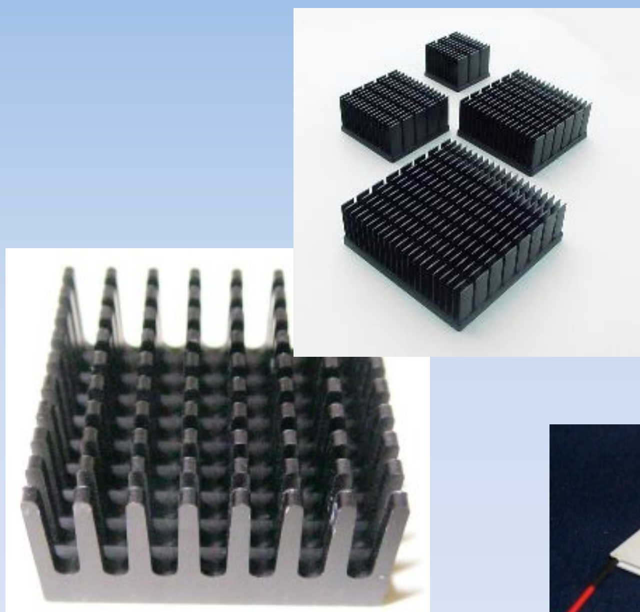
Thermal Calculations – LED efficiency as a function of input power



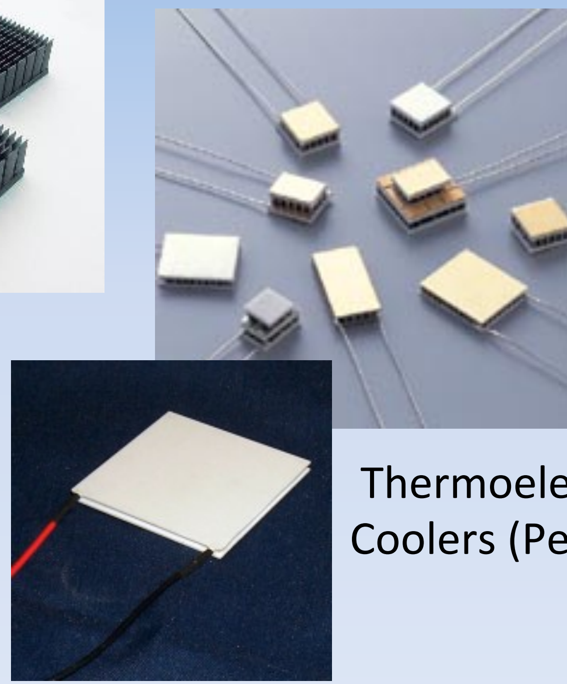
Data courtesy Ian Ferguson, UNC

Technology Limitations

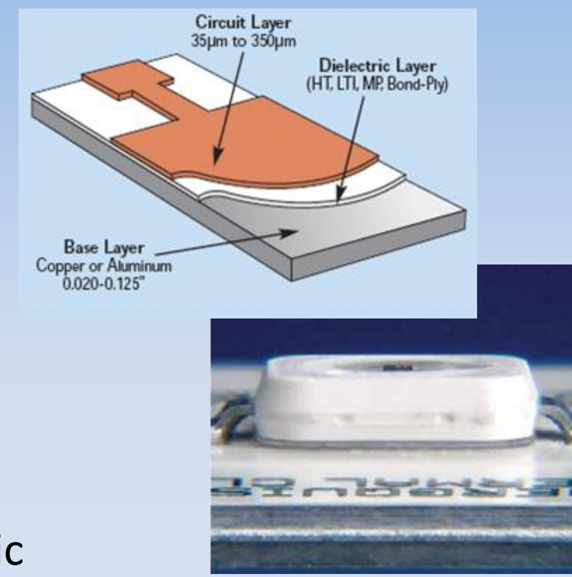
Thermal Devices – Many choices



Heat Sinks

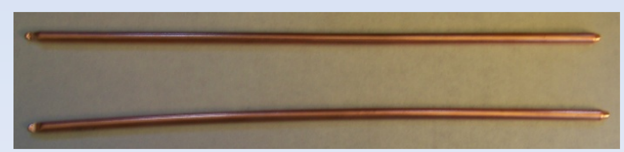


Thermoelectric Coolers (Peltier)



Metal Core PCBs

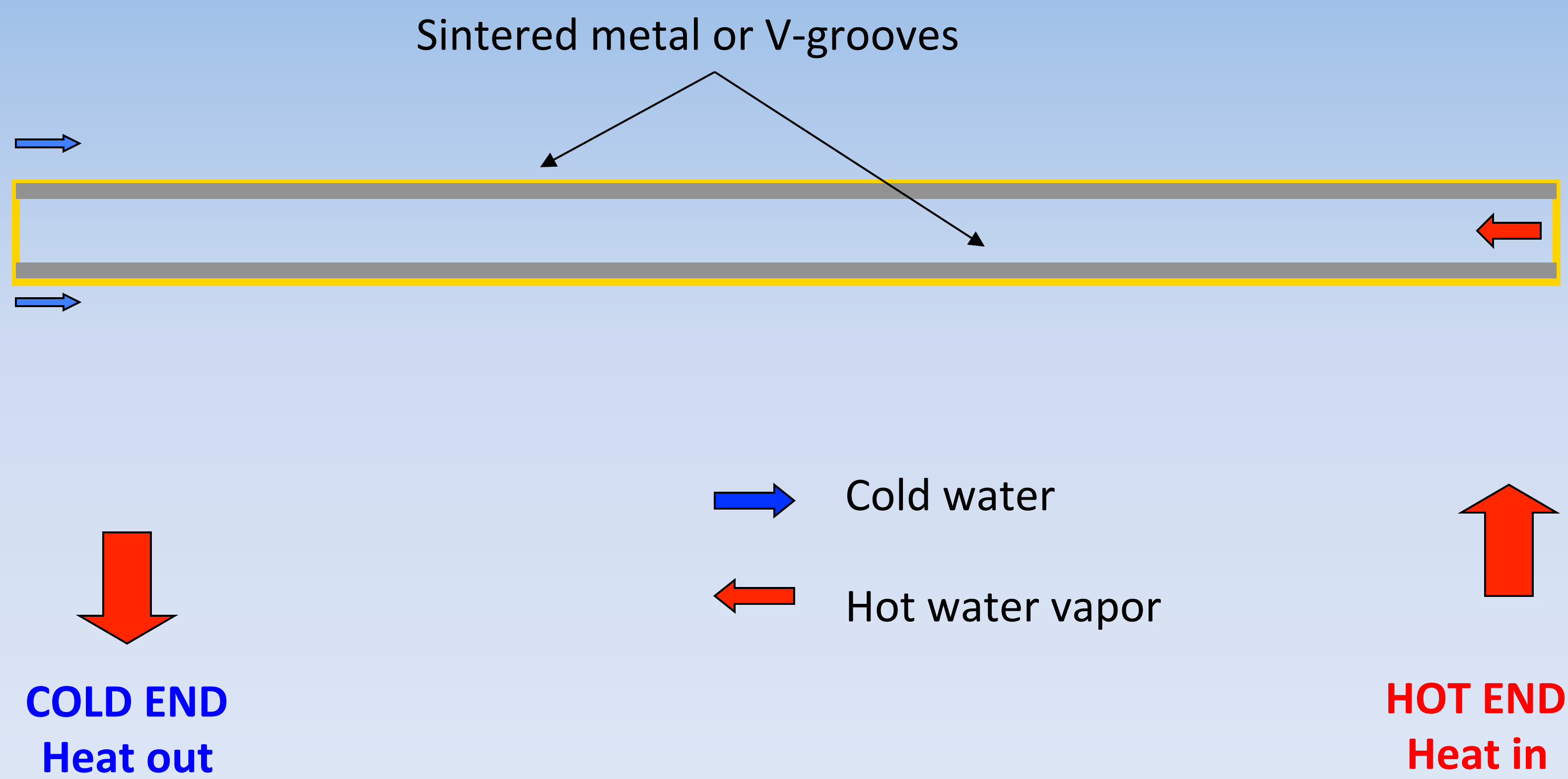
Piezo fans



Heat Pipes

Technology Limitations

Thermal Devices – How do heat pipes work?



Technology Limitations

Thermal Calculations – Problems with thermal management

- Luminaire manufacturers are not used to dealing with the same level of complexity for this issue
  - Historically, most of their heat goes out the front of the luminaire
  - Industry is not familiar with heat pipes, MCPCBs, heat sinks, etc.
  - Some manufacturers don't even know they need to worry about it!
    - Consequently, Architects and Lighting Designers do
- Installers are not familiar with these issues for the same reason
  - Installing products where they shouldn't go
- Another example of the two different worlds colliding

Technology Limitations

Color Matching / Color Shift

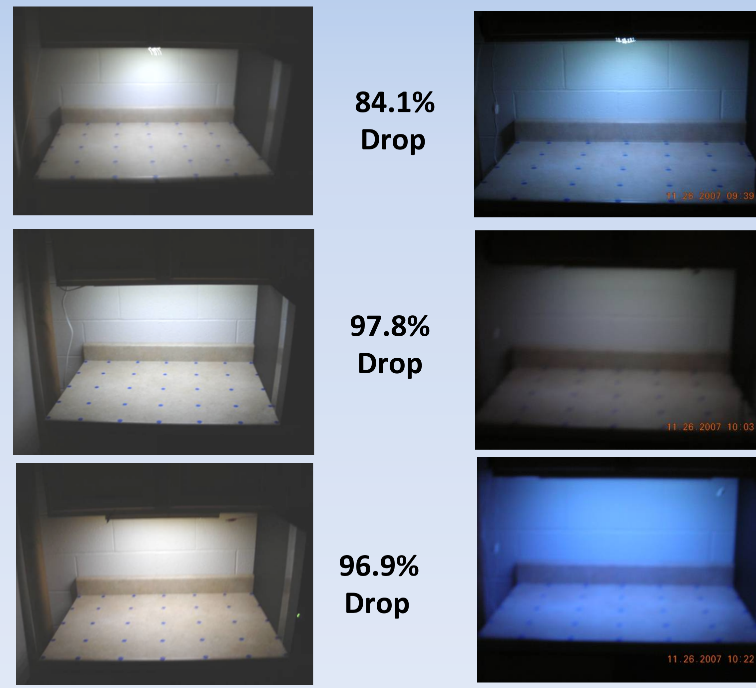
Supplier quality and testing is critical to successful projects

White is white is white?

Particularly in linear wall wash applications, this lack of color consistency is non acceptable

Is blue?

Initial **1000 hours**

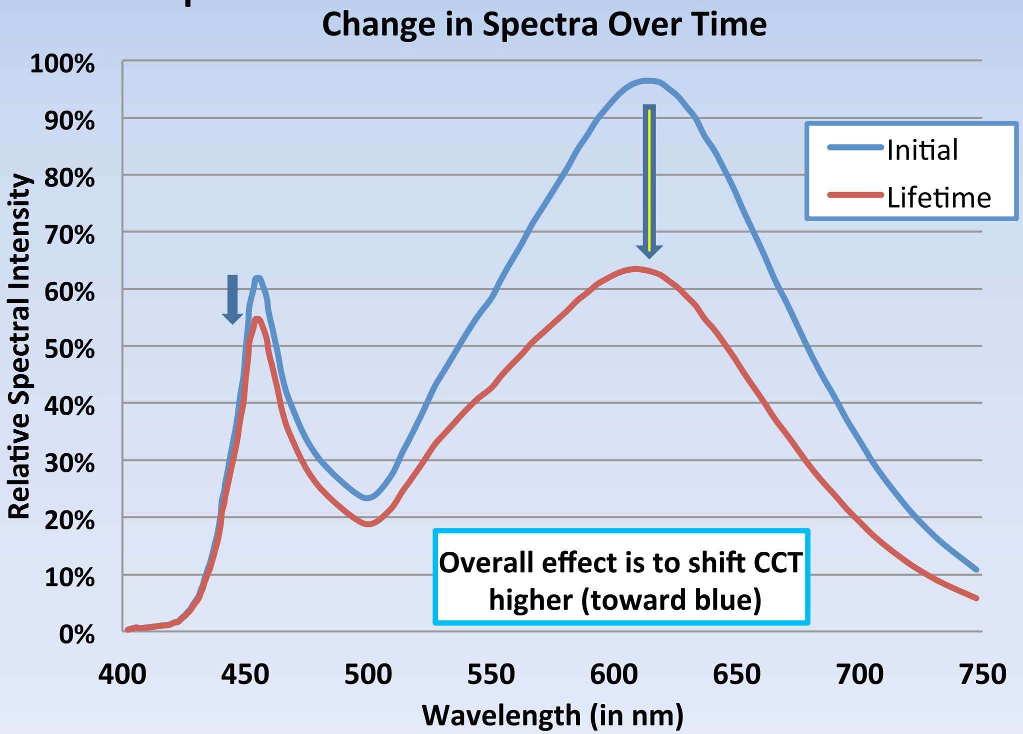


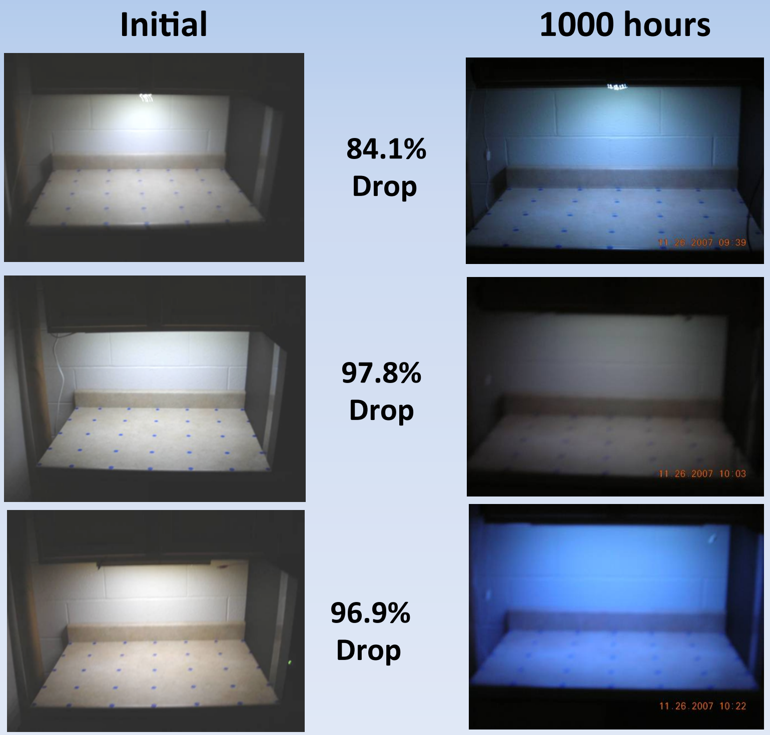
Source: Cree

Technology Limitations

Color Matching / Color Shift

What causes this shift from white to blue? Phosphor degrades faster than the blue die over time shifting light output to blue





Source: Cree

Technology Limitations

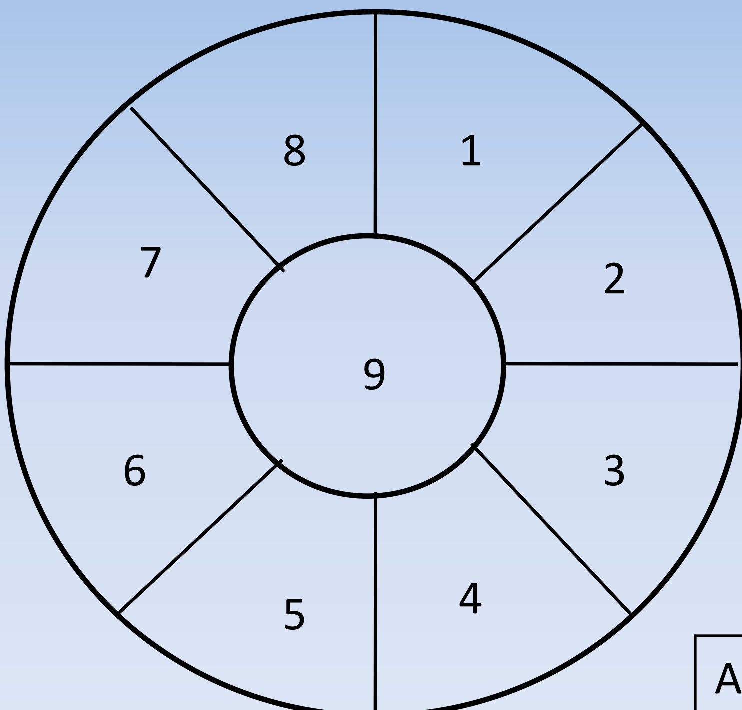
What is Binning?

- Binning is a sorting process used by the LED device manufacturers to allow them to sell all of the product they produce
- Three parameters are typically binned
  - Flux output
  - Color
  - Forward voltage (V_f)
- Each die is measured individually and product is sold in reels of identically binned components
- Bins vary by manufacturer

Technology Limitations

Why do Manufacturers Bin?

Two wafers in the same batch with the following results



	λ (in nm)		Vf (in V)		Output (in mW)	
	A	B	A	B	A	B
1	465	465	3.57	3.62	2.27	2.37
2	464	463	3.54	3.62	2.03	2.05
3	461	456	3.5	3.53	1.66	2.05
4	461	463	3.42	3.47	1.48	1.49
5	458	451	3.29	3.39	0.64	1.16
6	462	466	3.46	3.46	1.73	1.36
7	463	463	3.52	3.55	2.25	1.8
8	464	463	3.56	3.6	2.13	1.83
9	464	465	3.53	3.56	1.77	1.36

A temperature difference of only 1°C in a reactor with operating temperature of 1050°C can greatly affect emission wavelength of the resulting dies

Source: Data from Ian Ferguson, UNC

Technology Limitations

Bin Choices – Example from one manufacturer

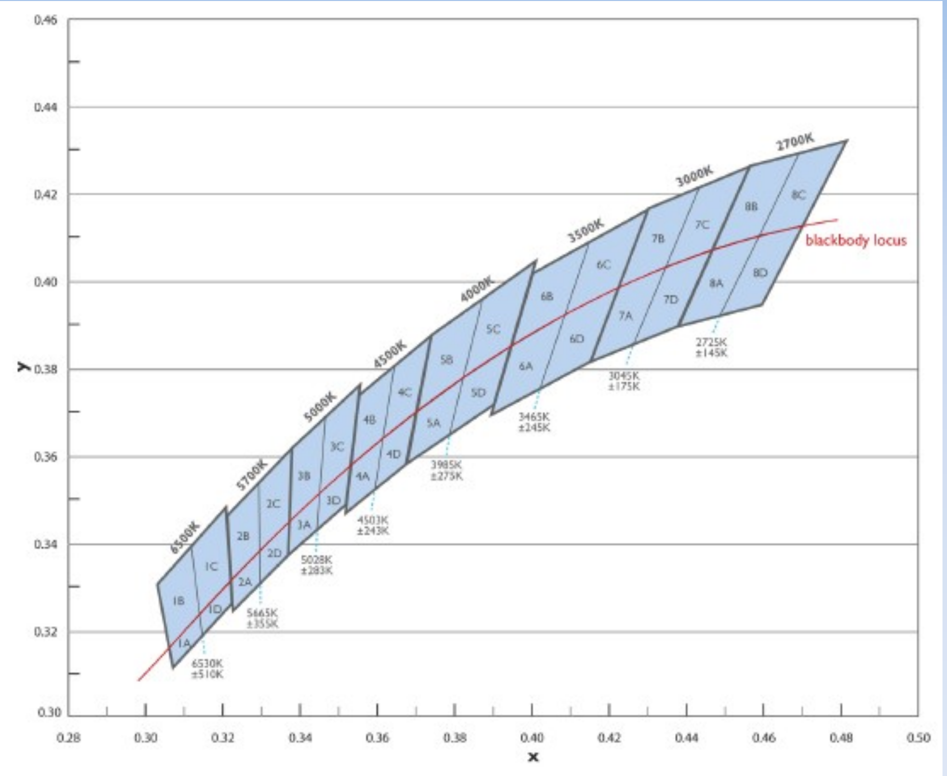
Flux Bins

Flux Bins - All Colors		
Bin Code	Minimum Photometric Flux (lm)	Maximum Photometric Flux (lm)
H	50	60
J	60*	70
K	70**	80
L	80	90
M	90	100
N	100	120
P	120	140
Q	140	160
R	160	180
S	180	200

Voltage (V_f) Bins

V_f Bins		
Bin Code	Minimum Forward Voltage (V)	Maximum Forward Voltage (V)
B	2.55	2.79
C	2.79	3.03
D	3.03	3.27
E	3.27	3.51
F	3.51	3.75
G	3.75	3.99

Color Bins

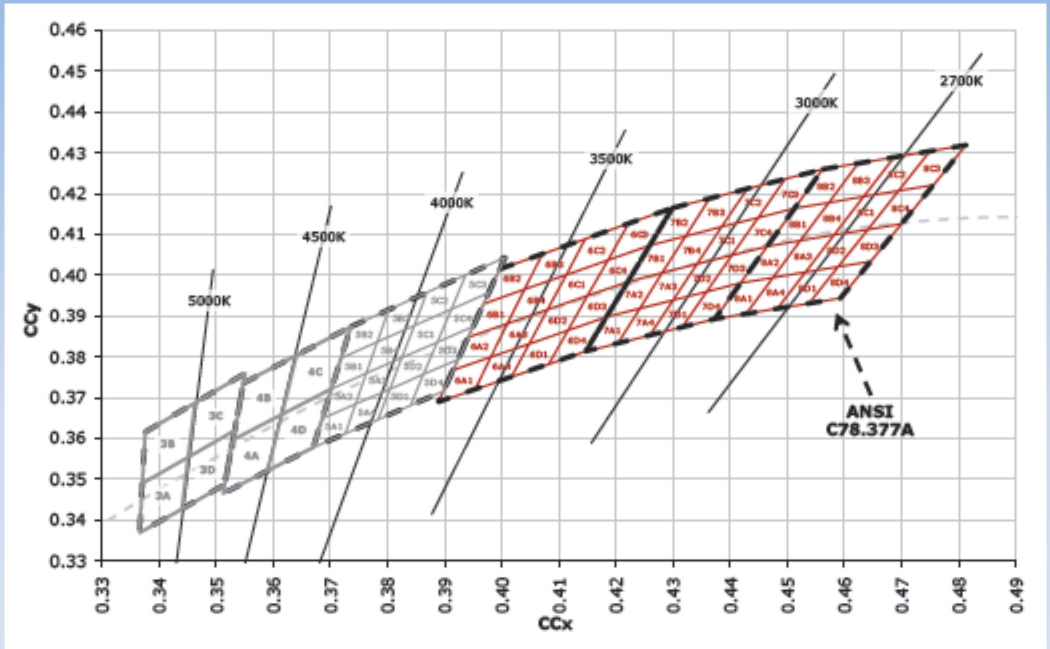


Technology Limitations

Bin Choices – Example from second manufacturer

Flux Bins

Group Code	Min. Luminous Flux @ 350 mA (lm)	Max. Luminous Flux @ 350 mA (lm)
J	23.5	30.6
K2	30.6	35.2
K3	35.2	39.8
M2	39.8	45.7
M3	45.7	51.7
N2	51.7	56.8
N3	56.8	62.0
N4	62.0	67.2
P2	67.2	73.9
P3	73.9	80.6
P4	80.6	87.4
Q2	87.4	93.9
Q3	93.9	100
Q4	100	107
Q5	107	114
R2	114	122
R3	122	130
R4	130	139
R5	139	148
S2	148	156



Color Bins

Voltage (V_f) Bins

Forward Voltage Group	Min. Forward Voltage @ 350 mA	Max. Forward Voltage @ 350 mA
B	1.75	2.0
C	2.0	2.25
D	2.25	2.5
E	2.5	2.75
F	2.75	3.0
G	3.0	3.25
H	3.25	3.5
J	3.5	3.75

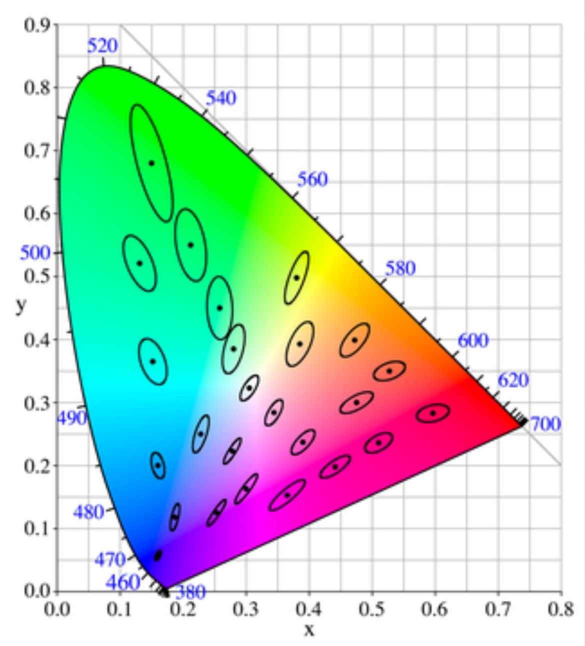
Amber, red-orange and red only

Technology Limitations

How Color Bins are Defined – MacAdam Ellipses

In 1943 David MacAdam analyzed the color differences of closely spaced points in the chromaticity diagram. He found that any two points must have a minimum geometrical distance to yield a perceptible difference in color.

Dividing the area of the chromaticity diagram by the average area of a MacAdam ellipse, shows that humans can discern approximately 50,000 distinct chromaticities. If variations in luminance are taken into account, this number increases to greater than 10^6.



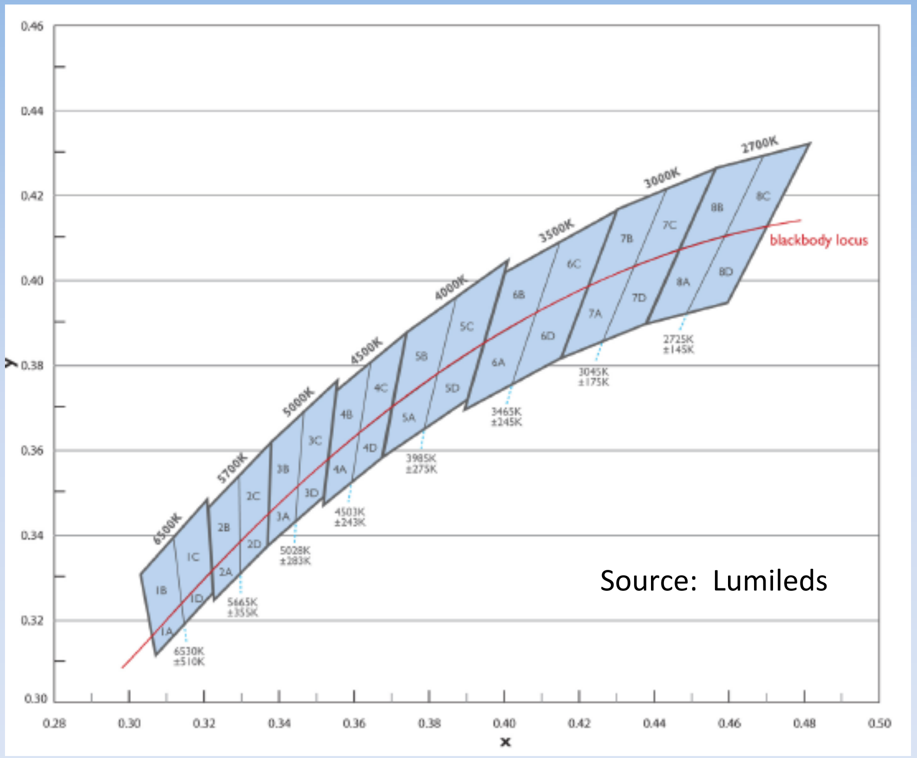
Plot for test subject PGN
Ellipses shown 10 times actual size

Technology Limitations

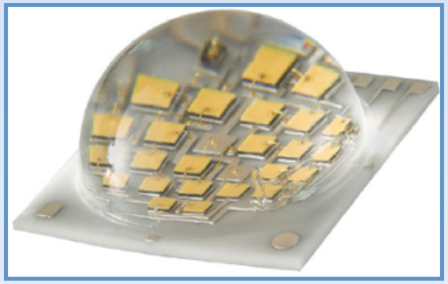
Color Binning

Customers purchasing the widest range of bins get the lowest prices. It then becomes their responsibility to produce consistent color products.

At least one manufacturer with a multi-chip product is mix/matching within the device to provide consistent color.



Source: Lumileds



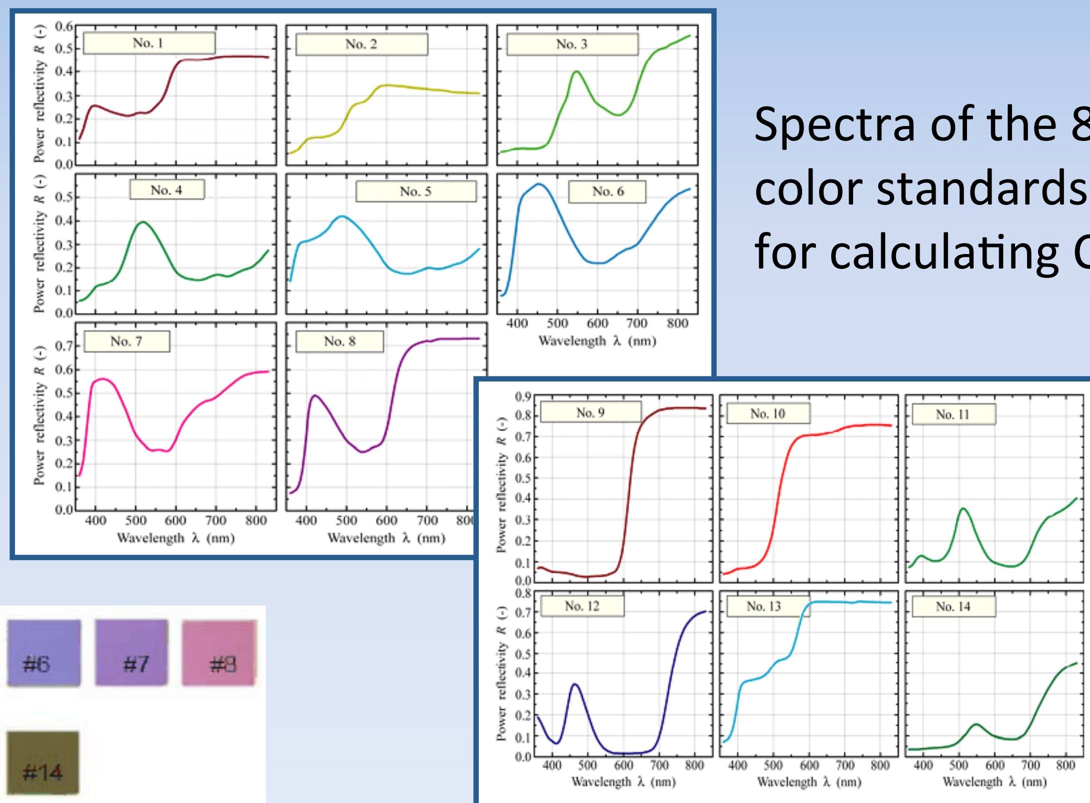
Source: Cree

Technology Limitations

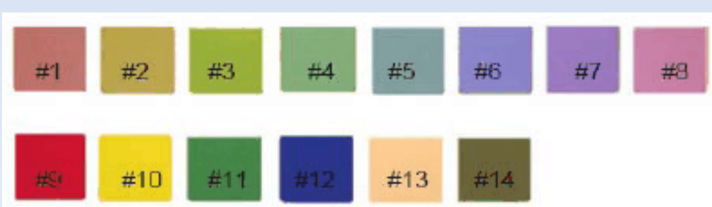
Measuring Color – What is Color Rendering Index?

CRI is a calculated value based on the difference in chromaticity of a series of 8 (or 14) different colors (CIE Color Space) when illuminated with a reference light source versus a test subject light source.

It is a measure of a light source's ability to show colors realistically as compared to familiar sources (e.g. an incandescent bulb or the sun)



Spectra of the 8 (14) color standards used for calculating CRI



Technology Limitations

Measuring Color – What is wrong with CRI?

- None of the reflective samples used to calculate Ra are highly saturated
  - Poor rendering of saturated colors even with high Ra
- Method of calculating Ra creates problems
  - Simple averaging of test samples can result in high Ra even if the source renders one or two colors poorly – LEDs are especially susceptible to this problem due to their peaked spectra
  - Optimizing lamp spectra can increase Ra yet still yield poor color rendering due to low chromatic saturation and too few samples used
- All deviations of object color appearance are considered equal
  - In practice, increases in chromatic saturation observed with certain sources is considered desirable since they can enhance perceived brightness and provide better visual clarity

Technology Limitations

Measuring Color – What is wrong with CRI?

CRI values for some typical light sources:

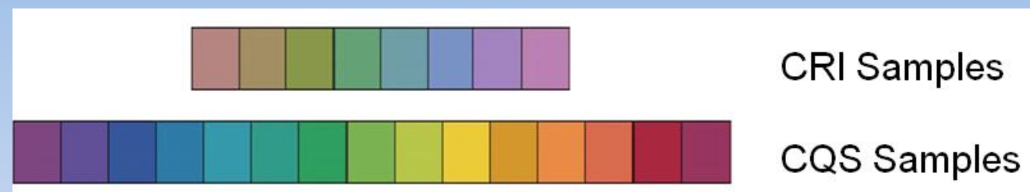
	R_a	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	R_{10}	R_{11}	R_{12}	R_{13}	R_{14}
Fluorescent Cool White	64	56	77	90	57	59	67	74	33	-84	45	46	54	60	94
Fluorescent Warm White	51	42	70	90	38	41	54	65	11	-111	31	18	25	47	94
Metal Halide	67	59	84	88	63	67	84	67	21	-113	69	63	78	67	92
Mercury (Clear)	18	-9	32	51	7	8	8	47	-4	-299	-58	-17	-21	1	70
High Pressure Sodium	24	15	66	55	-5	14	56	37	-45	-197	46	-29	34	21	71
Tungsten Halogen	100	100	100	100	100	100	99	100	100	100	99	100	100	100	100

Notice that for Metal Halide, even though its overall CRI (R_a) is 67, it has an R_9 value of -113 which can produce poor renderings with deep red objects (e.g. human skin tones).

Technology Limitations

Measuring Color – Color Quality Scale could be an improvement

- New Color Samples chosen
  - Highest chroma
  - Even hue spacing
  - Commercially available



Source: Davis & Ohno, NIST

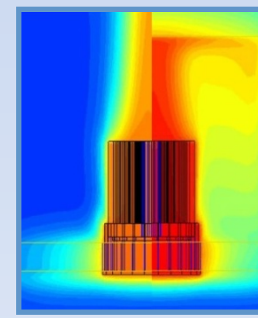
- New calculation method using RMS
  - ensure that large hue shifts of any sample have notable influence on the value of CQS

$$\Delta E_{RMS} = \sum_{i=1}^{i=15} \sqrt{(1/15) \times \sum \Delta E_i^{\,2}}$$

- Scale factors used for standard sources with extreme CCT
- Log factor used to remove negative values
- Work is ongoing at NIST to finalize CQS as a new standard

Course Outline

1. Introduction – Why should I care about LEDs?
2. Lifetime and Cost – A critical relationship for LEDs
3. What's Different – LED technology as compared to traditional light sources
4. Technology Limitations – Characteristics to be aware of with solid-state lighting
5. Standards – The need for new metrics



Break

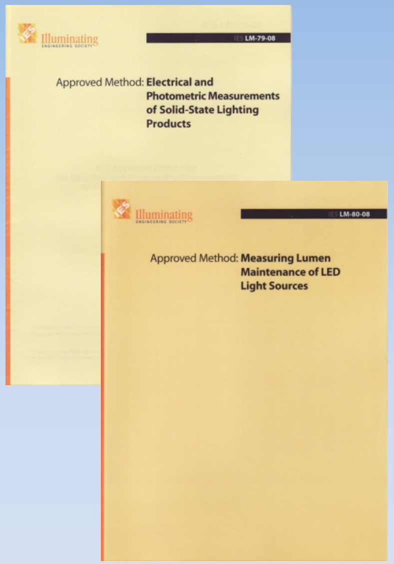
6. Applications – What are the good ones?
7. LED Products – Where to turn for guidance
8. Items of Importance to Building Owners/Facility Mgrs
9. Final Thoughts – Some general rules

What Everyone Wants – The ultimate solution

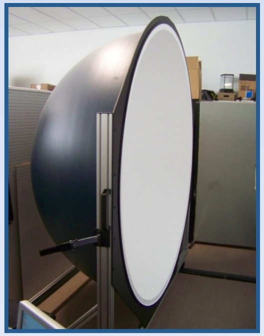
If only choosing solid-state luminaires was this simple…

Standards

- **LM-79-08** *Approved Method: Electrical and Photometric Measurements of Solid-State Lighting Products*
  - Describes testing procedure for evaluating light distribution from LED-based luminaires



- **LM-80-08** *Approved Method for Measuring Lumen Depreciation of LED Light Sources*
  - Describes testing procedure for measuring lumen depreciation of LED devices
  - Does not describe how to evaluate data taken



- **ANSI C78.377-2008** *Specifications for the Chromaticity of Solid-State Lighting Products for Electric Lamps*
  - Describes binning structure to specify LED device colors

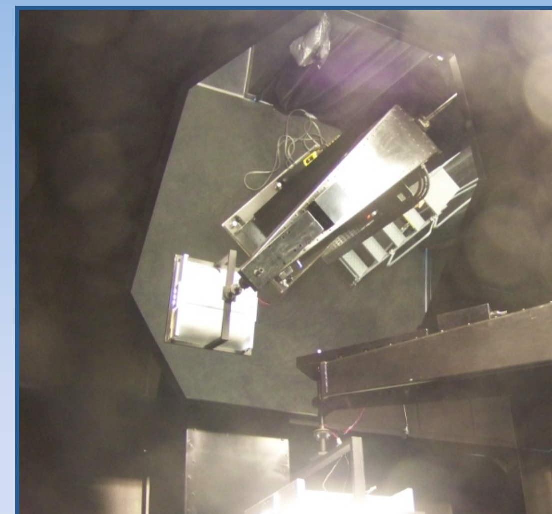
Standards

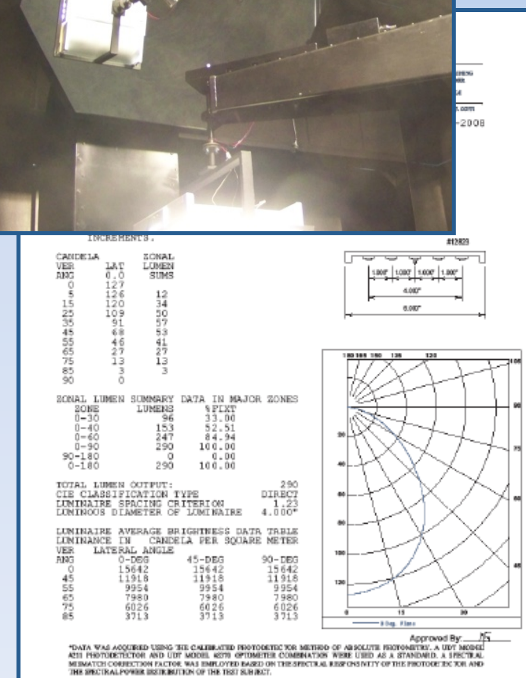
IESNA LM-79-08 – Goniophotometer Method

Data output:

- Spatial Lumen Distribution
- Total Luminous Flux
- Zonal Lumen Sums
- IES format file
- Spatial Color Uniformity

Measurement made using absolute photometry





INCREMENTS.

CANDELA VER ANG	LAT 0.0	ZONAL LUMEN SUMS
0	127	
5	126	12
15	120	34
25	109	50
35	91	57
45	68	53
55	46	41
65	27	27
75	13	13
85	3	3
90	0	

ZONAL LUMEN SUMMARY DATA IN MAJOR ZONES

ZONE	LUMENS	%FIXT
0-30	96	33.00
0-40	153	52.51
0-60	247	84.94
0-90	290	100.00
90-180	0	0.00
0-180	290	100.00

TOTAL LUMEN OUTPUT:	290
CIE CLASSIFICATION TYPE	DIRECT
LUMINAIRE SPACING CRITERION	1.23
LUMINOUS DIAMETER OF LUMINAIRE	4.000"

LUMINAIRE AVERAGE BRIGHTNESS DATA TABLE
LUMINANCE IN CANDELA PER SQUARE METER

VER ANG	LATERAL ANGLE 0-DEG	45-DEG	90-DEG
0	15642	15642	15642
45	11918	11918	11918
55	9954	9954	9954
65	7980	7980	7980
75	6026	6026	6026
85	3713	3713	3713

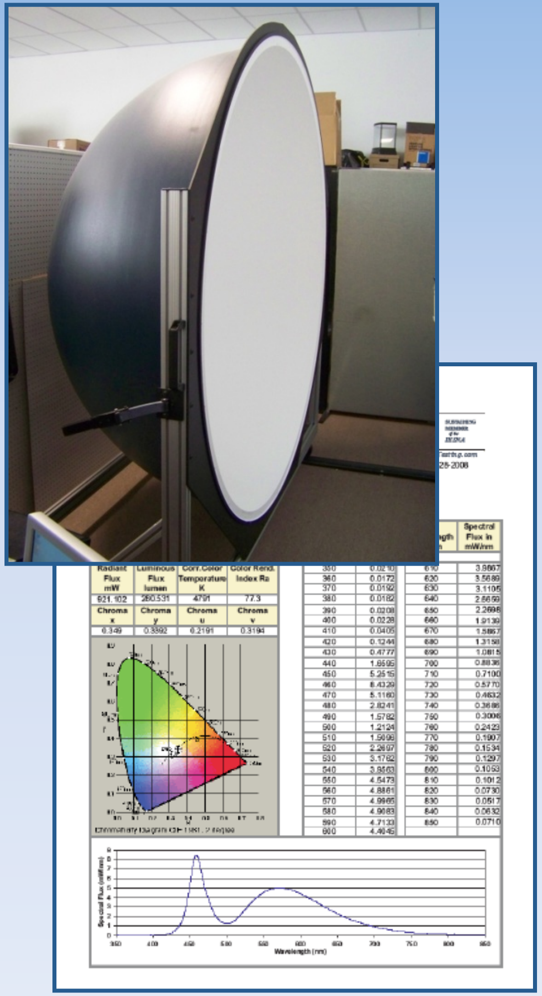
Approved By:

*DATA WAS ACQUIRED USING THE CALIBRATED PHOTODETECTOR METHOD OF ABSOLUTE PHOTOMETRY. A UDT MODEL 4211 PHOTODETECTOR AND UDT MODEL 4370 OPTOMETER COMBINATION WERE USED AS A STANDARD. A SPECTRAL MISMATCH CORRECTION FACTOR WAS EMPLOYED BASED ON THE SPECTRAL RESPONSIVITY OF THE PHOTODETECTOR AND THE SPECTRAL POWER DISTRIBUTION OF THE TEST SUBJECT.

IESNA LM-79-08 – Integrating Sphere Method

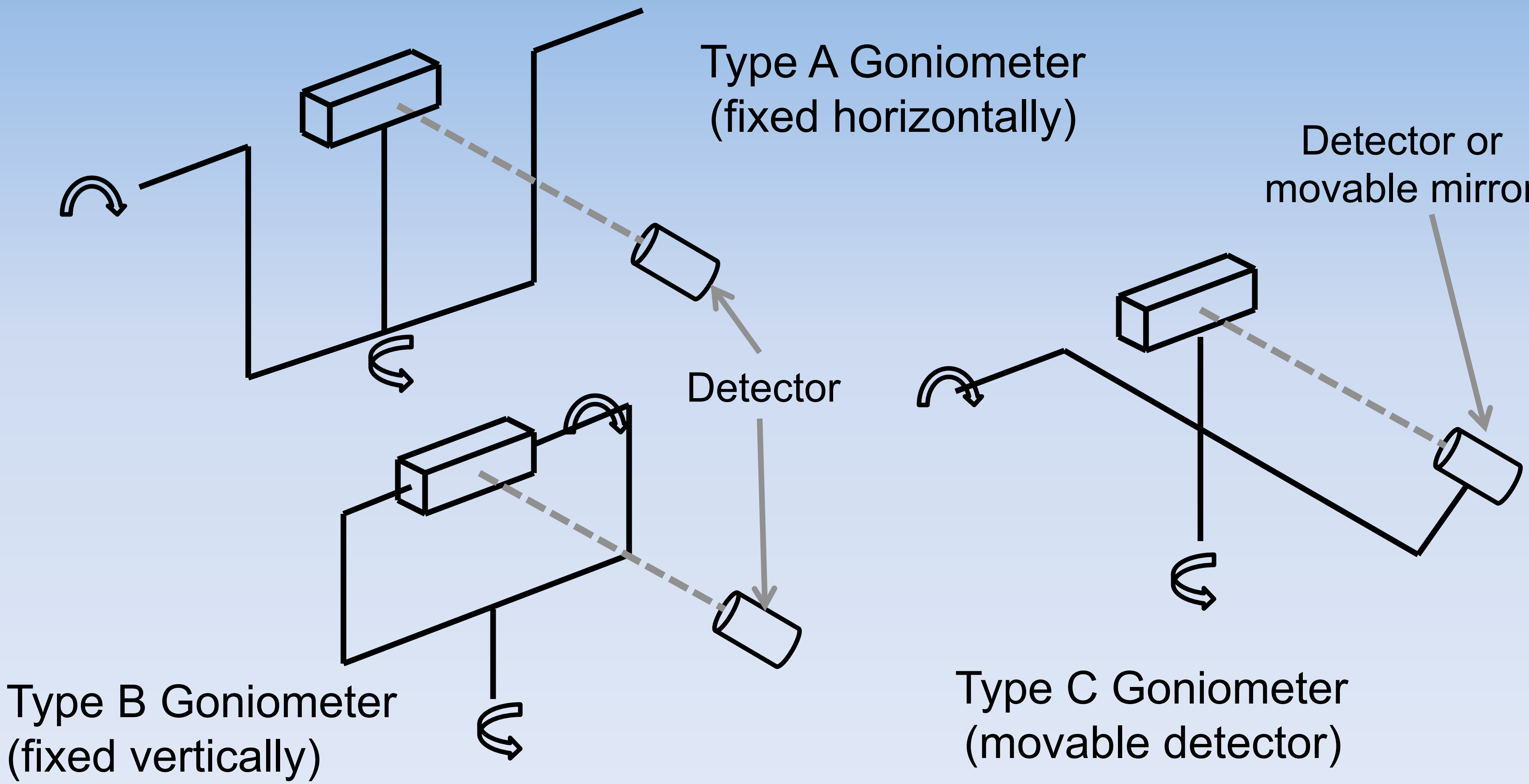
Data output:

- Total Luminous Flux
- Spectral Power Distribution
- Chromaticity Coordinates
- CRI
- CCT



Electrical measurements of input voltage, current and power are reported as well as part of the LM-79 test report

IESNA LM-79-08 – Types of goniometers



Reference: IES Lighting Handbook (9th Edition)

IESNA LM-79-08 – Dissecting a report

Make sure model number matches what is being purchased →

General description of luminaire under test

Description of test equipment used to make measurements

Should have two signatures to insure proper QA procedures

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REPORT NUMBER: XXX-XX DATE: 6/20/08 PAGE 1 of 7
PREPARED FOR: SSL Manufacturer X

CATALOG NUMBER: ENERGY STAR 1A

LUMINAIRE: EXTRUDED DARK BRONZE COLORED METAL HOUSING WITH MOLDED BLACK PLASTIC END CAPS, ONE BLACK CIRCUIT BOARD WITH NINE LEDS, CLEAR FLAT PLASTIC LENS.

LAMP: NINE WHITE MULTI-CHIP LIGHT EMITTING DIODES (LEDS), VERTICAL BASE-UP POSITION.

LED DRIVER: Generic Driver #1

GONIOMETRIC INSTRUMENTATION: ITL Moving Mirror Goniophotometer - 25.25' Test Distance
Yokogawa WT210 Digital Power Meter
Elgar CW2501 AC Power Source
Omega HH-81 Digital Thermometer with Type J thermocouples

SPECTRORADIOMETRIC INSTRUMENTATION: Yokogawa WT210 Digital Power Meter
Optronic Laboratories OL770 Spectroradiometer
1.5 meter integrating sphere
Elgar CW2501 AC Power Source
BK Precision 1745A DC Power Source

OBJECT OF TEST: Measure distribution photometry and input electrical parameters on the goniophotometer. Report candela distribution and calculated lumen output. Using the supplied LED driver, measure the total flux output in lumens, Correlated Color Temperature (CCT), Color Rendering Index (CRI), Chromaticity Coordinates (x/y; u'/v'), and Spectral Power Distribution (SPD) of the unit and input electrical parameters when operated in the integrating sphere. Using a DC power supply, measure the total flux output in lumens, Correlated Color Temperature (CCT), Color Rendering Index (CRI), Chromaticity Coordinates (x/y; u'/v'), and Spectral Power Distribution (SPD) of the unit and input electrical parameters when operated in the integrating sphere at 24 volts DC. Measure surface temperature of the unit at one location.

PROCEDURE: The luminaire was supplied by client with an unknown number of burn hours. The luminaire was prewarmed overnight before each test. Stabilization data was recorded to assure stabile operation (stabilization data available on request). Distribution photometry and input electrical data were measured with the unit mounted on the goniophotometer. CCT, CRI, x/y and u'/v' chromaticity coordinates, SPD, total flux, and input electrical data were measured with the unit operating in the integrating sphere. In order to measure the mean performance, twenty data sets were averaged using the Optronics OL770. A Type J thermocouple was attached to the surface of the unit to measure operating temperature (see photograph in the report for location). All data are traceable to the National Institute of Standards and Technology. Goniometric and one Spectroradiometric test were performed with the unit operated at 120V AC in a 25 +/-1 degree Celsius free air ambient. The second Spectroradiometric test was performed at 24 volts DC.

Checked: R BERGIN
Approved: R BEATTIE

THIS REPORT IS BASED ON PUBLISHED INDUSTRY PROCEDURES. FIELD PERFORMANCE MAY DIFFER FROM LABORATORY PERFORMANCE.

IESNA LM-79-08 – Dissecting a report

Data taken with a moving mirror goniophotometer

Description of the luminaire components (e.g. # of LEDs, driver used, etc.

Output intensity as a function of angle

Fixture efficacy

Spacing criteria for lighting designers

Graphical depiction of intensity distribution

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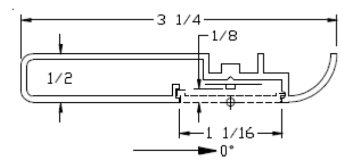
REPORT NUMBER: XXX-XX DATE: 6/20/08 PAGE 2 of 7
PREPARED FOR: SSL Manufacturer X

CATALOG NUMBER: ENERGY STAR 1A
LUMINAIRE: EXTRUDED DARK BRONZE COLORED METAL HOUSING WITH MOLDED BLACK PLASTIC END CAPS, ONE BLACK CIRCUIT BOARD WITH NINE LEDS, CLEAR FLAT PLASTIC LENS.
LAMP: NINE WHITE MULTI-CHIP LIGHT EMITTING DIODES (LEDS), VERTICAL BASE-UP POSITION.
TOTAL INPUT WATTS = 11.0 AT 120.0 VOLTS, 0.1250 AMPS
MOUNTING: SURFACE
LED DRIVER: Generic Driver #1
NOTE: DATA SHOWN IS ABSOLUTE FOR THE SAMPLE PROVIDED AT RATED INPUT VOLTAGE (120VAC) TO THE LED DRIVER.



CANDELA DISTRIBUTION

	0.0	22.5	45.0	67.5	90.0	FLUX
0	154	154	154	154	154	
5	153	154	153	153	153	15
15	147	147	147	147	148	42
25	136	137	137	137	138	63
35	121	121	122	122	123	76
45	101	101	102	103	104	79
55	76	76	77	78	79	69
65	46	47	47	48	49	47
75	19	19	18	19	19	20
85	1	1	1	1	1	2
90	0	0	0	0	0	

ZONAL LUMEN SUMMARY

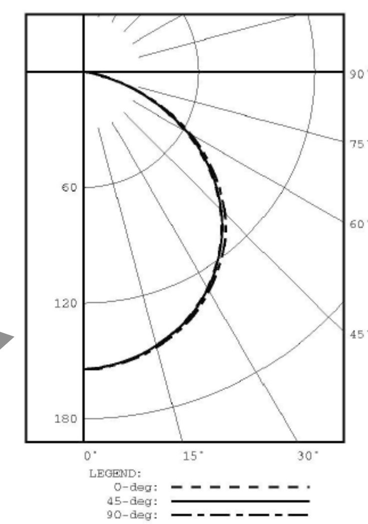
ZONE	LUMENS	%FIXT
0- 30	119	29.0
0- 40	196	47.6
0- 60	343	83.5
0- 90	411	100.0
90-180	0	0.0
0-180	411	100.0

EFFICACY = 37.36 Lm/W
CIE TYPE - DIRECT

PLANE	0-DEG	90-DEG
SPACING CRITERIA	1.2	1.3
LUMINOUS LENGTH	1.063	18.188

LUMINANCE DATA IN CANDELA/SQ M

ANGLE IN DEG	AVERAGE 0-DEG	AVERAGE 45-DEG	AVERAGE 90-DEG
45	11452.	11531.	11826.
55	10567.	10735.	11042.
65	8764.	8897.	9258.
75	5731.	5638.	5917.
85	552.	644.	1288.



THIS REPORT IS BASED ON PUBLISHED INDUSTRY PROCEDURES. FIELD PERFORMANCE MAY DIFFER FROM LABORATORY PERFORMANCE.

Source: Design Lights Consortium

IESNA LM-79-08 – Dissecting a report

Data taken with a moving mirror goniophotometer

Luminous intensity distribution data can be used to evaluate other lighting metrics of SSL product performance. For example, although Center Beam Candle power (CBCP) and Beam Angle are often not included in LM-79 reports, they can be approximated from tabular intensity data

Note: zonal lumens sums provides the amount of lumens within a specified angular region.

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REPORT NUMBER: XXX-XX DATE: 6/20/08 PAGE 3 of 7
PREPARED FOR: SSL Manufacturer X

CANDELA DISTRIBUTION

	0.0	22.5	45.0	67.5	90.0
0.0	154	154	154	154	154
2.5	154	154	154	154	154
5.0	153	154	153	153	153
7.5	152	153	152	152	152
10.0	151	151	150	150	151
12.5	149	149	149	149	150
15.0	147	147	147	147	148
17.5	145	145	145	145	146
20.0	142	143	142	143	143
22.5	139	140	140	140	141
25.0	136	137	137	137	138
27.5	133	133	133	134	135
30.0	129	130	130	130	131
32.5	125	126	126	126	127
35.0	121	121	122	122	123
37.5	117	117	117	118	119
40.0	112	112	112	113	115
42.5	107	107	107	108	110
45.0	101	101	102	103	104
47.5	95	96	96	97	99
50.0	89	90	90	91	92
52.5	83	83	83	85	86
55.0	76	76	77	78	79
57.5	69	69	70	71	72
60.0	61	62	63	63	65
62.5	54	54	55	56	57
65.0	46	47	47	48	49
67.5	39	39	39	41	41
70.0	31	32	32	33	33
72.5	25	25	25	26	26
75.0	19	19	18	19	19
77.5	11	12	13	12	13
80.0	4	5	7	7	7
82.5	1	1	3	4	4
85.0	1	1	1	1	1
87.5	0	0	0	0	0
90.0	0	0	0	0	0

ZONAL LUMEN SUMMARY

0- 5	4.
5- 10	11.
10- 15	18.
15- 20	24.
20- 25	29.
25- 30	34.
30- 35	37.
35- 40	39.
40- 45	40.
45- 50	39.
50- 55	36.
55- 60	32.
60- 65	27.
65- 70	20.
70- 75	13.
75- 80	6.
80- 85	1.
85- 90	0.

Zonal lumen sums

Detailed luminous intensity distribution

THIS REPORT IS BASED ON PUBLISHED INDUSTRY PROCEDURES. FIELD PERFORMANCE MAY DIFFER FROM LABORATORY PERFORMANCE.

Source: Design Lights Consortium

Standards

IESNA LM-79-08 – Dissecting a report

Data taken with a moving mirror goniophotometer

Coefficients of utilization tables are used by lighting designers to describe the optical properties of room surfaces (floors, ceilings and walls).

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REPORT NUMBER: XXX-XX DATE: 6/20/08 PAGE 4 of 7
PREPARED FOR: SSL Manufacturer X

COEFFICIENTS OF UTILIZATION - ZONAL CAVITY METHOD

EFFECTIVE FLOOR CAVITY REFLECTANCE 0.20

RC	80				70				50			30			10			0
RW	70	50	30	10	70	50	30	10	50	30	10	50	30	10	50	30	10	0
0	120	120	120	120	117	117	117	117	112	112	112	107	107	107	103	103	103	100
1	110	106	102	98	108	104	100	97	99	96	94	95	93	91	92	90	88	86
2	101	93	86	81	98	91	85	80	87	82	78	84	80	76	81	78	75	73
3	92	82	74	68	90	80	73	67	77	71	66	75	69	65	72	68	64	62
4	84	73	64	58	82	71	63	57	69	62	56	67	61	56	64	59	55	53
5	78	65	56	50	76	64	56	49	62	54	49	60	53	48	58	52	48	46
6	72	59	50	43	70	58	49	43	56	48	43	54	48	42	53	47	42	40
7	66	53	44	38	65	52	44	38	51	43	38	49	43	38	48	42	37	35
8	62	48	40	34	60	48	40	34	46	39	34	45	39	34	44	38	34	32
9	58	45	36	31	56	44	36	31	43	36	31	42	35	30	41	35	30	28
10	54	41	33	28	53	41	33	28	40	33	28	39	32	28	38	32	28	26

ALL CANDELA, LUMENS, LUMINANCE, AND VCP VALUES IN THIS REPORT ARE BASED ON ABSOLUTE PHOTOMETRY. THE COEFFICIENT OF UTILIZATION VALUES ARE BASED ON THE TOTAL ABSOLUTE LUMEN OUTPUT OF THIS LUMINAIRE SAMPLE.

THIS REPORT IS BASED ON PUBLISHED INDUSTRY PROCEDURES. FIELD PERFORMANCE MAY DIFFER FROM LABORATORY PERFORMANCE.

IESNA LM-79-08 – Dissecting a report

Data taken with an integrating sphere and spectroradiometer

Total luminaire flux output (lumens)

Color coordinates x,y (CIE 1931) and u',v' (CIE 1976)

CRI (Color Rendering Index) & CCT (Correlated Color Temperature)

System (luminaire) efficacy

Spectral radiant power as a function of wavelength expressed in mW/nm (milliwatts/nanometer)

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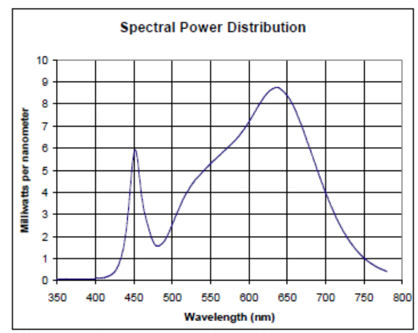
REPORT NUMBER: XXX-XX DATE: 6/20/08 PAGE 5 of 7
PREPARED FOR: SSL Manufacturer X

CATALOG NUMBER: ENERGY STAR 1A 120V AC Power Supply

RESULTS:

SPECTRORADIOMETRIC TESTING IN INTEGRATING SPHERE	
PHOTOMETRIC	
Total Integrated Flux (Lumens)	407*
SPECTRORADIOMETRIC	
Observer	CIE 1931 2 degree
Chromaticity Ordinate x	0.4302
Chromaticity Ordinate y	0.3840
Observer	CIE 1976 2 degree
Chromaticity Ordinate u'	0.2550
Chromaticity Ordinate v'	0.5122
Correlated Color Temp CCT (K)	2945
Color Rendering Index (CRI)	96
Total Radiant Flux (milliWatts)	1579*
ELECTRICAL	
Input Voltage (Volts AC)	120.0
Input Current (mA AC)	140
Input Power (Watts)	11.03
EFFICACY	
Lumens/Watt	36.90



*NOTE: Proper calibration of integrating spheres for measuring total flux output of non-directional lamps will produce reliable, repeatable results within the calibration tolerances of the equipment used. However, measurement of lamps with significant self absorption and/or directional output, even when these effects are compensated for, are likely to have a greater variation in results compared to the flux output calculated from a goniophotometric exploration since these artifacts do not affect the goniophotometric results. For this test, the integrating sphere was calibrated using a directional incandescent flux standard with a distribution similar to the luminaire under test, per IESNA LM78-06.

THIS REPORT IS BASED ON PUBLISHED INDUSTRY PROCEDURES. FIELD PERFORMANCE MAY DIFFER FROM LABORATORY PERFORMANCE.

Source: Design Lights Consortium

IESNA LM-79-08 – Dissecting a report

Data taken with an integrating sphere and spectroradiometer

Spectral power distribution from previous graph in table form

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REPORT NUMBER: XXX-XX DATE: 6/20/08 PAGE 6 of 7
PREPARED FOR: SSL Manufacturer X

CATALOG NUMBER: ENERGY STAR 1A 120V AC Power Supply

RESULTS:

Tabulated Spectral Power Distribution

Wavelength (nm)	mWatts/nm	Wavelength (nm)	mWatts/nm
350.0	0.05603	570.0	5.93580
360.0	0.06347	580.0	6.27734
370.0	0.07386	590.0	6.68525
380.0	0.07380	600.0	7.19331
390.0	0.07092	610.0	7.77944
400.0	0.08313	620.0	8.31587
410.0	0.12536	630.0	8.67000
420.0	0.24214	640.0	8.69811
430.0	0.71856	650.0	8.35533
440.0	2.29940	660.0	7.73539
450.0	5.77792	670.0	6.87621
460.0	3.81615	680.0	5.89537
470.0	2.26049	690.0	4.89720
480.0	1.56966	700.0	3.96361
490.0	1.80451	710.0	3.12733
500.0	2.54969	720.0	2.41106
510.0	3.36319	730.0	1.83129
520.0	4.04462	740.0	1.36823
530.0	4.56607	750.0	1.01847
540.0	4.93993	760.0	0.75361
550.0	5.29140	770.0	0.55396
560.0	5.62200	780.0	0.40785

THIS REPORT IS BASED ON PUBLISHED INDUSTRY PROCEDURES. FIELD PERFORMANCE MAY DIFFER FROM LABORATORY PERFORMANCE.

Source: Design Lights Consortium

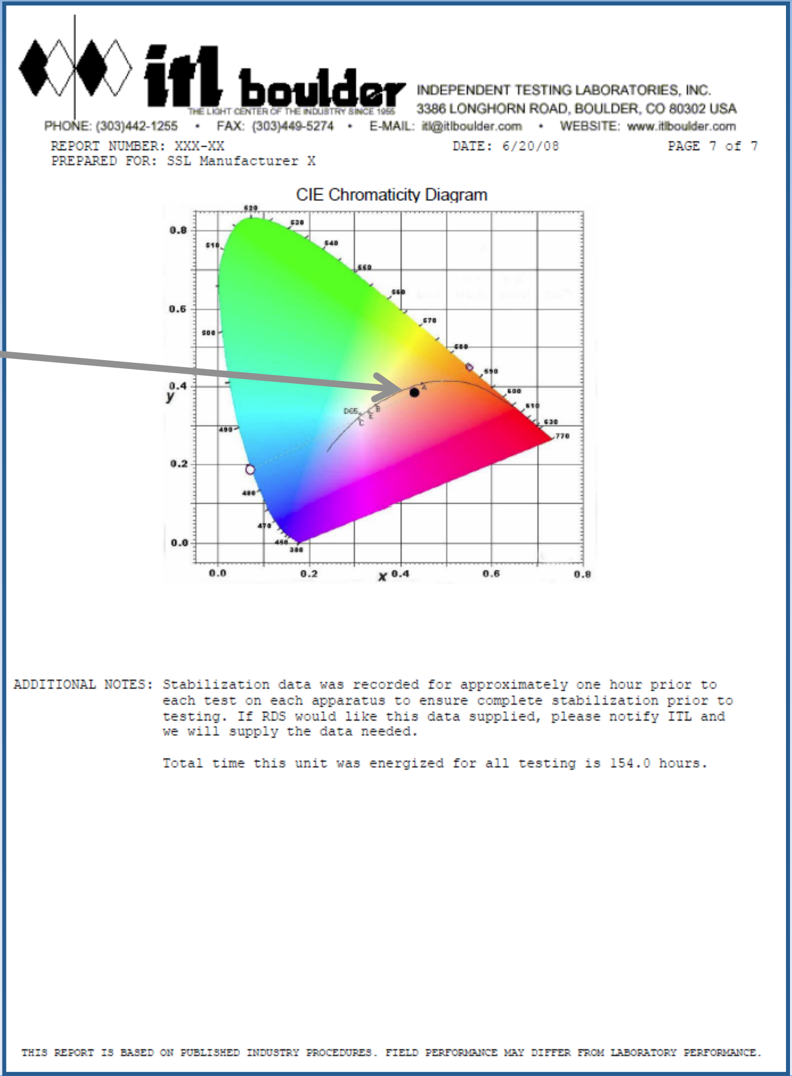
Standards

IESNA LM-79-08 – Dissecting a report

Data taken with an integrating sphere and spectroradiometer

Graph showing where the luminaire light output falls with respect to the blackbody curve. Products which fall too far from the curve can appear to have a "pink" or "green" tint.

Note: For luminaires with non-uniform spectral distribution, all chromaticity values are averaged over two vertical planes and a non-uniformity of chromaticity, Δu'v' is determined as the maximum coordinate deviation on the CIE diagram.


itl boulder
THE LIGHT CENTER OF THE INDUSTRY SINCE 1955
INDEPENDENT TESTING LABORATORIES, INC.
3386 LONGHORN ROAD, BOULDER, CO 80302 USA
PHONE: (303)442-1255 • FAX: (303)449-5274 • E-MAIL: itl@itlboulder.com • WEBSITE: www.itlboulder.com

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PREPARED FOR: SSL Manufacturer X

CIE Chromaticity Diagram

ADDITIONAL NOTES: Stabilization data was recorded for approximately one hour prior to each test on each apparatus to ensure complete stabilization prior to testing. If RDS would like this data supplied, please notify ITL and we will supply the data needed.

Total time this unit was energized for all testing is 154.0 hours.

THIS REPORT IS BASED ON PUBLISHED INDUSTRY PROCEDURES. FIELD PERFORMANCE MAY DIFFER FROM LABORATORY PERFORMANCE.

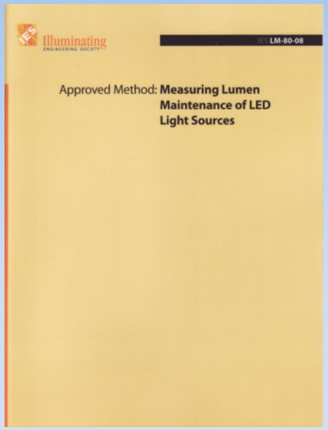
Standards

IESNA LM-79-08 – Manufacturer's reputation is extremely important

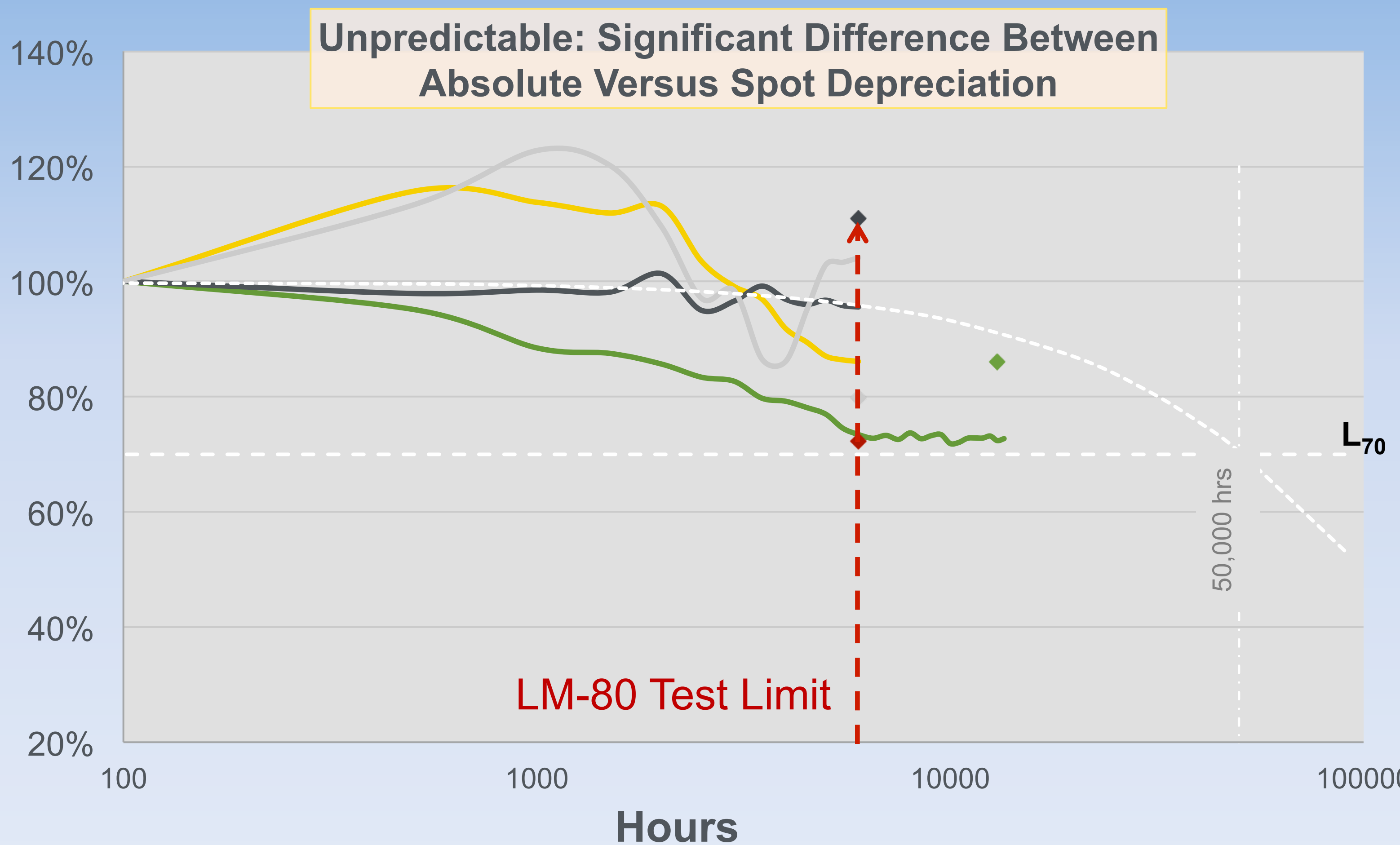
- The LM-79 "Only" report – the only luminaire that will ever achieve this performance is locked up in an engineering department closet somewhere
  - Do a small pilot run with off-the-shelf components before committing to a large project, particularly with a new manufacturer or supplier
- The LM-79 "Redacted" report – LM-79 reports don't have large black blocks in the report anywhere, particularly where efficacy, CCT or CRI numbers usually go
  - Check with the testing lab to verify results
- The LM-79 "Improved" report – Photoshop is a wonderful lighting tool that can greatly improve a product's performance.
  - Check with the testing lab to verify results

IESNA LM-80-08 – Measuring lumen depreciation

- Publication took almost a year longer than expected due to disagreements among stakeholders
- Testing for a minimum of 6000 hours
- Lumen depreciation of devices, not the luminaires
- Measurements made at specific drive currents and three different case temperatures
  - 55^{O}C, 85^{O}C and manufacturer's choice for third temperature
- Does not specify how to extrapolate LED lifetime



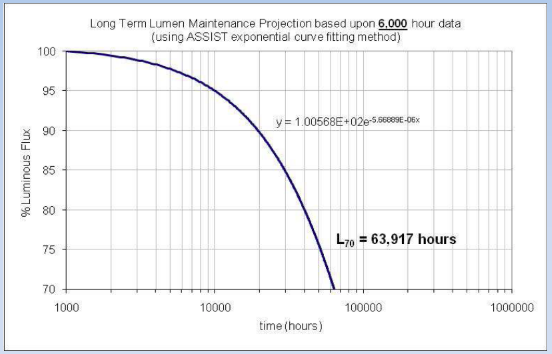
Measuring LED Lifetime – Variability in early performance



CALiPER Round 10 data, www.ssl.energy.gov/caliper.html

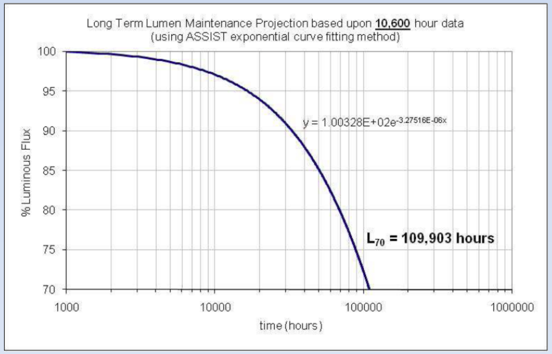
Measuring LED Lifetime – This variability can drastically effect results

- It is difficult to predict the long term performance of a device with only early lifetime data

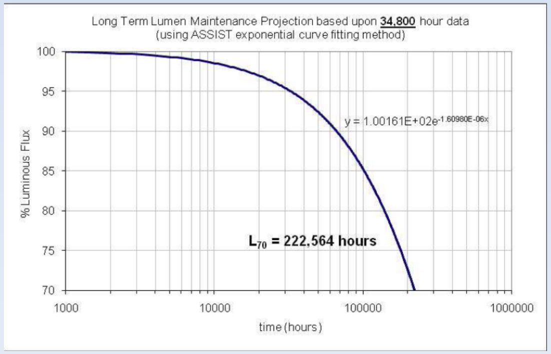


6,000 Hours of data

10,600 Hours of data



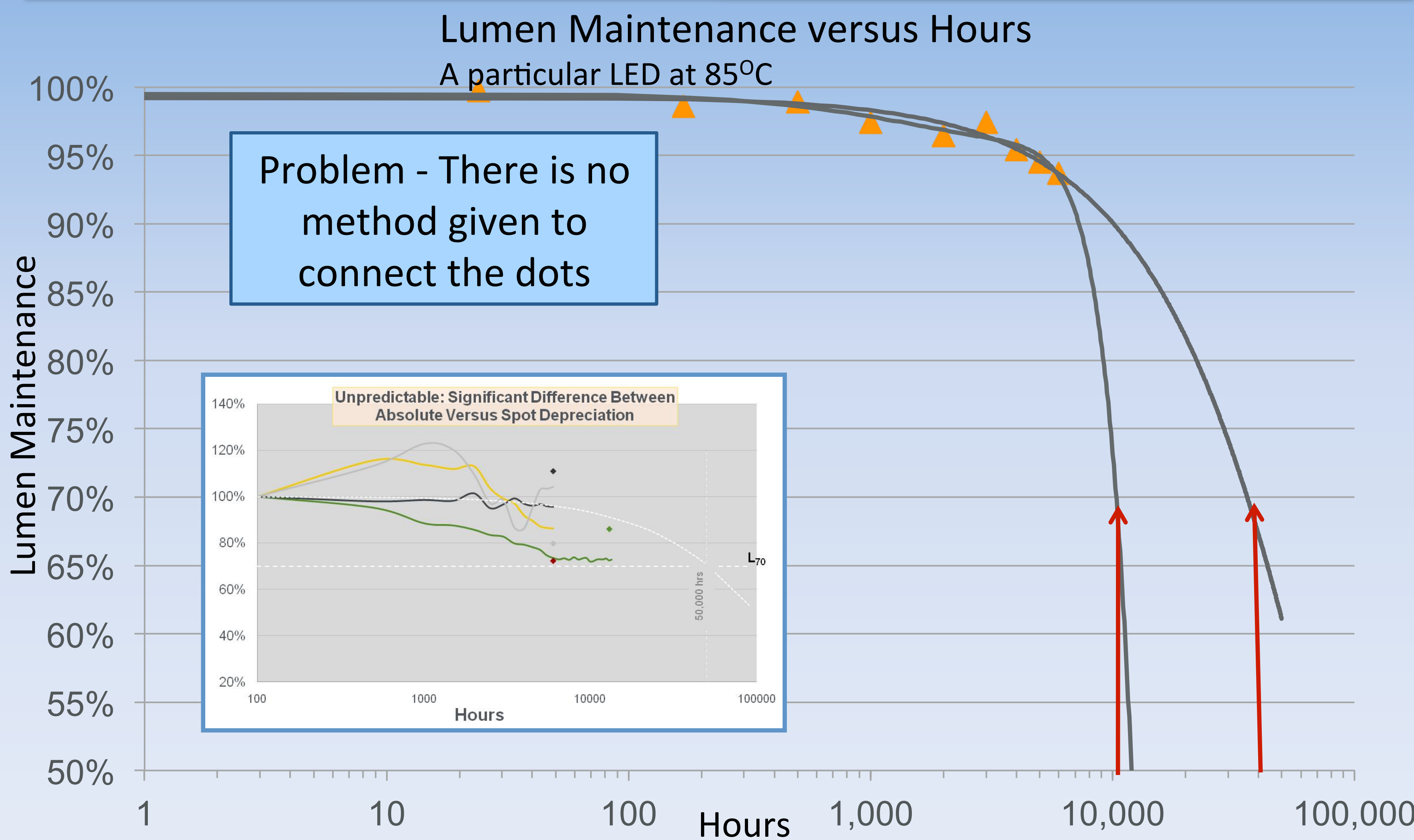
34,800 Hours of data



Almost 3.5 X's longer predicted lifetime than the 6,000 hour results

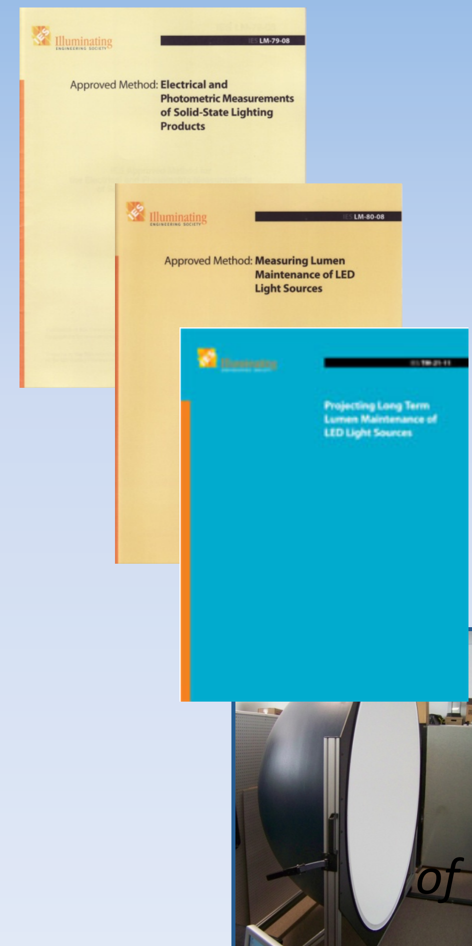
Source: Cree

Standards – "Tested" to LM-80



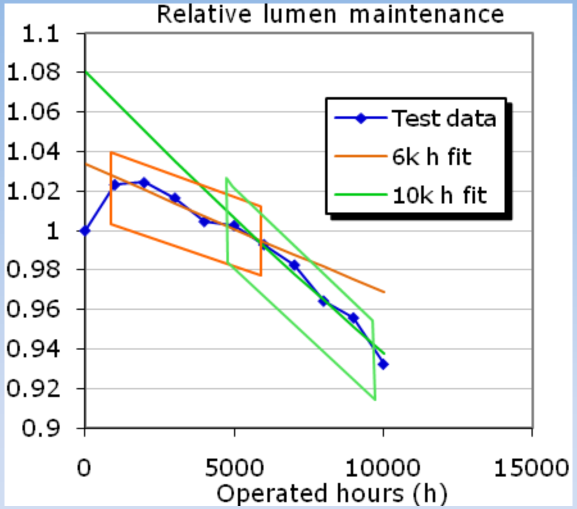
Standards – TM-21 the missing part of LM-80

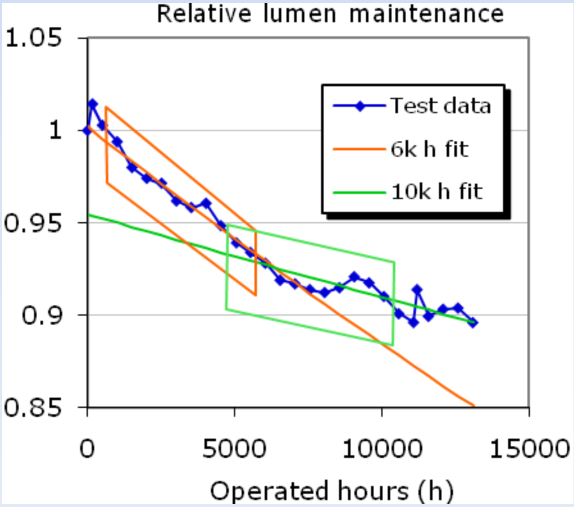
- **LM-79-08** *Approved Method: Electrical and Photometric Measurements of Solid-State Lighting Products*
  - Describes testing procedure for evaluating light distribution from LED-based luminaires
- **LM-80-08** *Approved Method for Measuring Lumen Depreciation of LED Light Sources*
  - Describes testing procedure for measuring lumen depreciation of LED devices
  - Does not describe how to evaluate data taken
- **TM-21-11** *Projecting Long Term Lumen Maintenance of LED Light Sources*
  - Provides an approved method for estimating the light loss over time for an LED
- **ANSI C78.377-2008** *A Specifications for the Chromaticity of Solid-State Lighting Products for Electric Lamps*
  - Describes binning structure to specify LED device colors



The Fix for LM-80 – TM-21

- Initial data variability (i.e., "hump") is difficult for models to evaluate (0-1000 hr). Later data exhibits more characteristic decay curve of interest
  - Non-chip decay (encapsulant, etc.) occurs early and with varying effects on decay curve
  - Later decay is chip-driven and relatively consistent with exponential curve
  - Verification with long duration data sets (>10,000 hr) shows better model to reality fit with with last 5000 hours of 10,000 hour data
- For 6,000 (LM-80 minimum) and up to 10,000 hours of data use the last 5,000 hours;
- For > 10,000 hours use the last ½ of the collected data





Material courtesy Erik Richman, PNNL

Standards

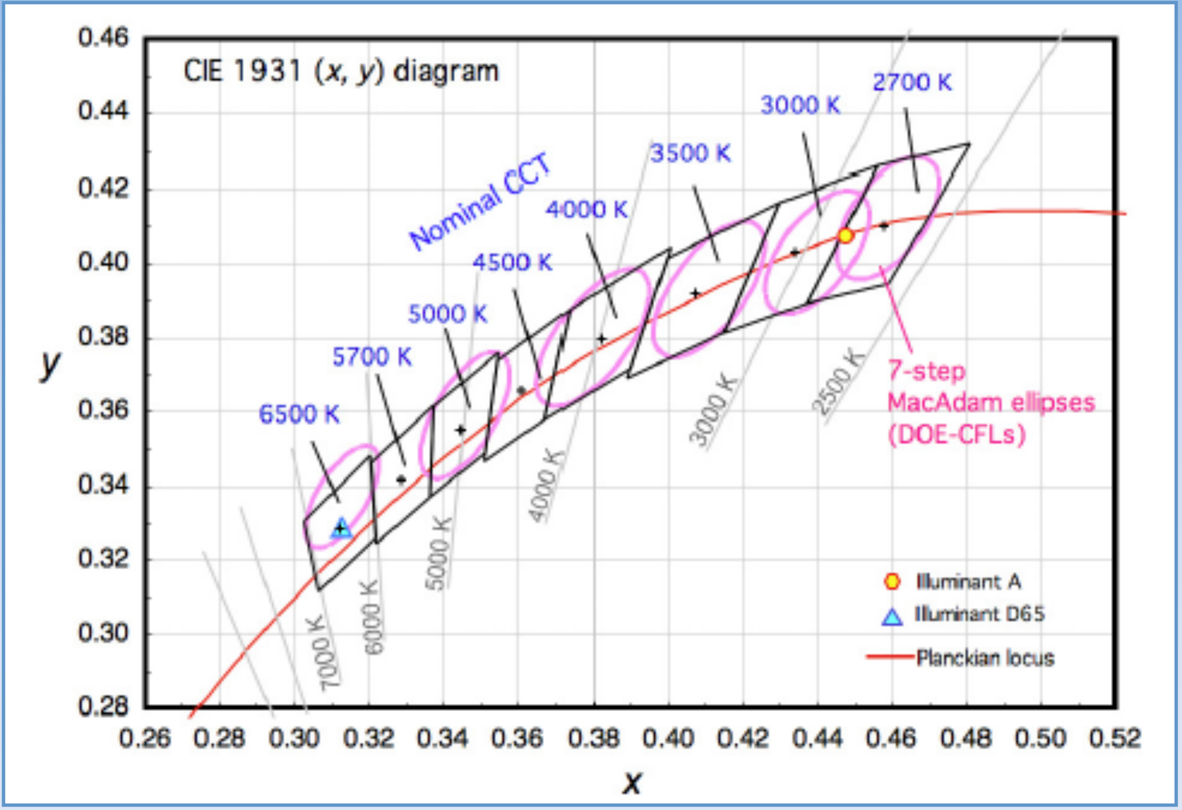
ANSI C78.377-2008 – Chromaticity Standards

- Purpose is to specify the range of chromaticities recommended for general lighting with Solid State Lighting products
- Ensure that white light chromaticities can be communicated to consumers
- Control circuitry and heat sinks incorporated in product
- Both fixtures incorporating light sources as well as integrated LED lamps
- Indoor lighting applications only
- Products that intentionally produce tinted or colored light not included

ANSI C78.377-2008 – Chromaticity Standards

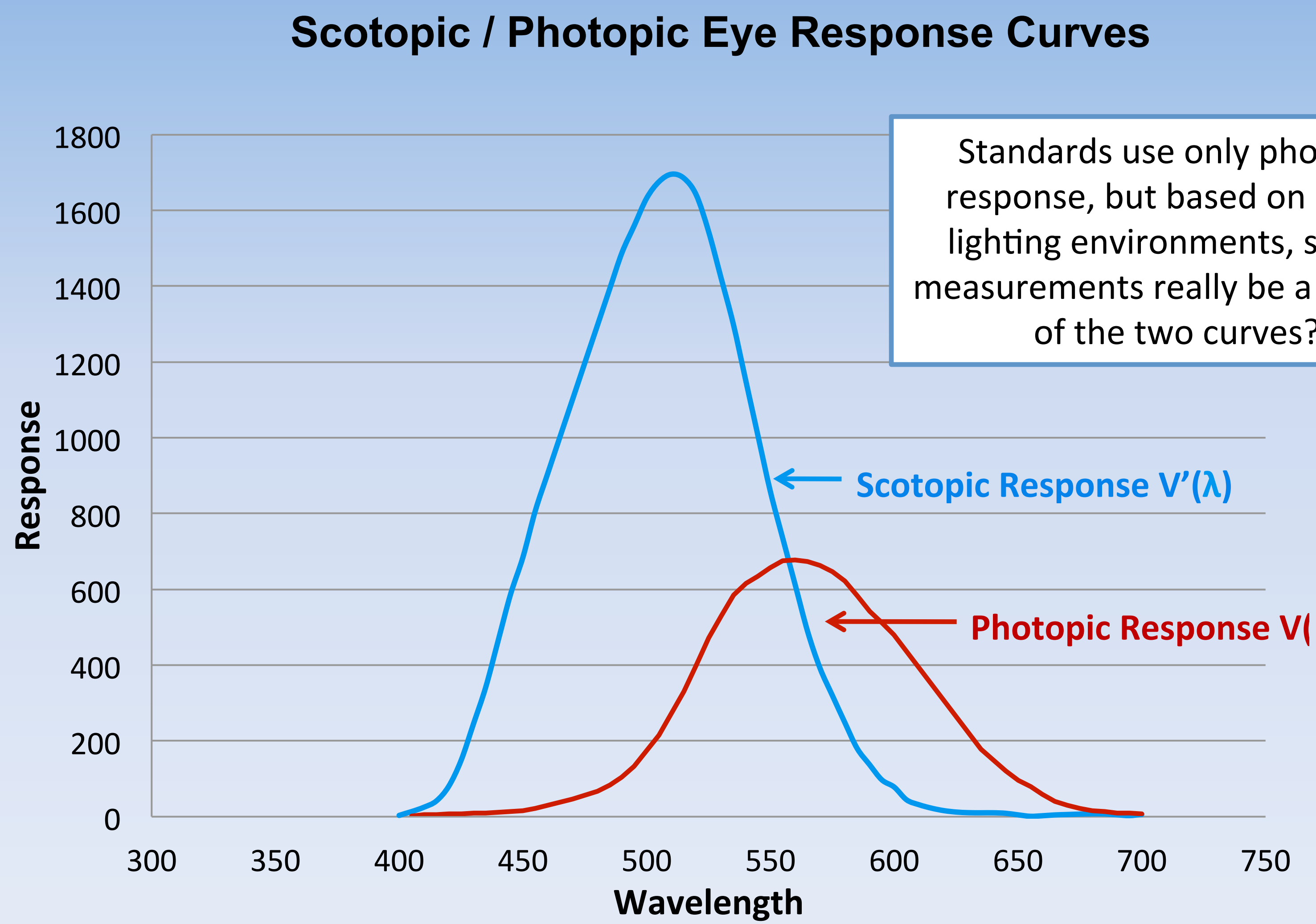
Specifies 8 different standard color bins for LEDs, based on a 7-step MacAdam ellipse

But as we have previously seen, this still leaves a very wide range in each “bin” which is not acceptable in many lighting applications



Source: ANSI C78.377-2008

"Spectrally Enhanced Lighting" – Scotopic or photopic response?

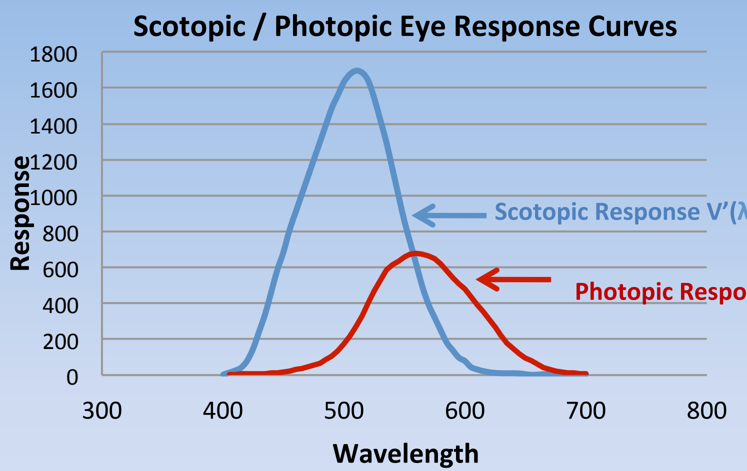


Standards use only photopic response, but based on actual lighting environments, should measurements really be a mixture of the two curves?

Spectrally Enhanced Lighting – Why is this important for LEDs?

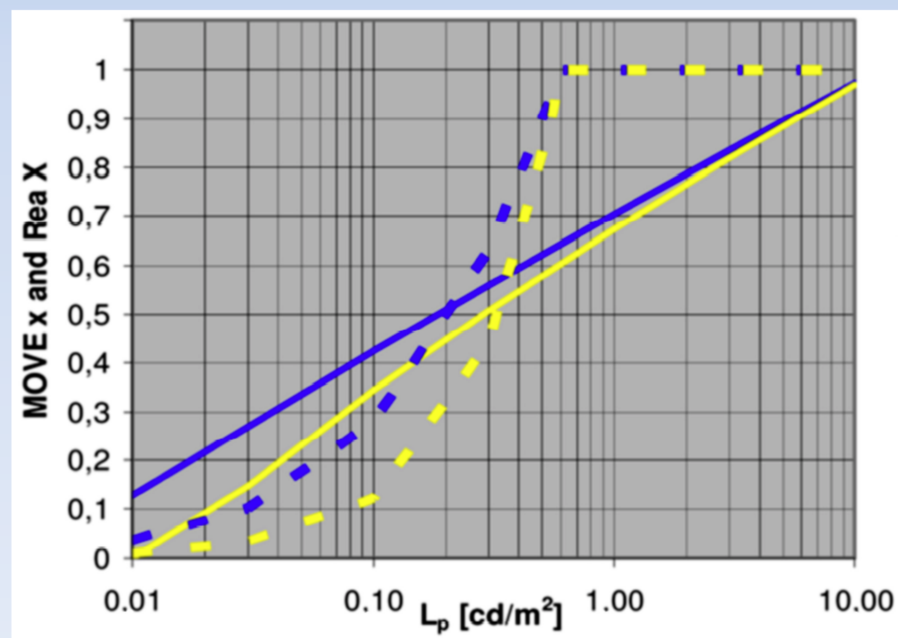
- White LEDs tend to be more efficient at higher CCT – cool white devices typically have higher efficacies than warm white
- For the same amount of light output (measured with a standard illuminance meter), light sources with a higher CCT can have been reported in some field surveys as appearing brighter in outdoor environments than those with lower CCT
  - Potential energy savings because more efficient (higher CCT) LEDs can be used, and the actual light output of the higher CCT source can be decreased, while maintaining equivalent perceived brightness
- **This has caused major discussions in the lighting industry, particularly with respect to LED outdoor street/area lighting**
  - The IES standards are still based on photometric measurements alone
  - Luminaire manufacturers publishing the S/P ratio (scotopic/ photopic)

Spectrally Enhanced Lighting – Mesopic region response?



$$V_m(\lambda) = (1 - x)\, V'(\lambda) + x\, V(\lambda)$$

X is a function of the light intensity with at least two different views of how it should be related. The solid lines are from the CIE (MOVE) and dotted lines are from LRC (Rea). Blue lines are for sources with high radiant power in the short wavelengths and yellow for sources with low radiant power in the short wavelengths



Other than Standards – Ways to reduce risk

Pilot, Pilot, Pilot

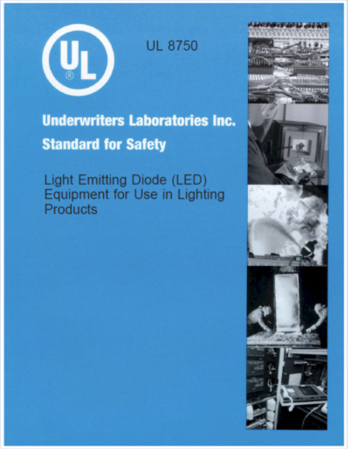
- Without a proven means of predicting long-term performance of LED products (not just the LED devices), running pilot programs offers some means of reducing the risk
- Examples of issues from DOE's Gateway program
  - I35 Bridge – optic coupling issue
  - San Francisco Street – cut-off was too sharp for residents
  - Intercontinental Hotel – flickering due to dimming circuit incompatibility
  - FDR Drive – failures included flickering as well as simple water intrusion
  - Wal-Mart – management not satisfied with performance on asphalt lots
  - Nike – false triggering increased proportionally to wind speed

Break

Standards – Agency Listings (US)

Underwriters Laboratories, one of the major safety listing agencies in the United States, has spent considerable effort trying to understand how to evaluate and list LED equipment and LED-based luminaires.

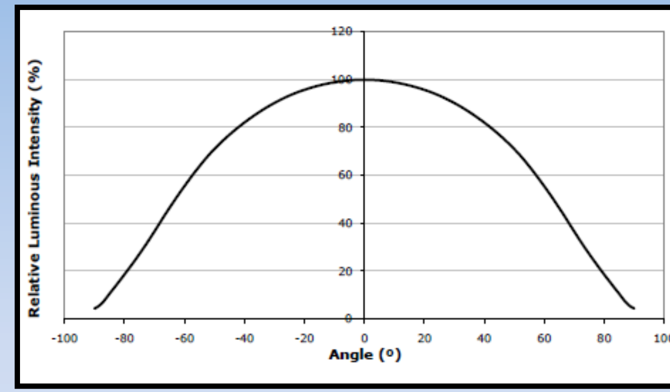
- Originally LED luminaires were tested under 1598 as incandescent lamps
- New 8750 Outline of Investigation "Light Emitting Diode (LED) Light Sources for Use in Lighting Products" was issued in January 2007
- Converted to Standard 8750 "Light Emitting Diode (LED) Equipment for Use in Lighting Products" was issued in November 2009

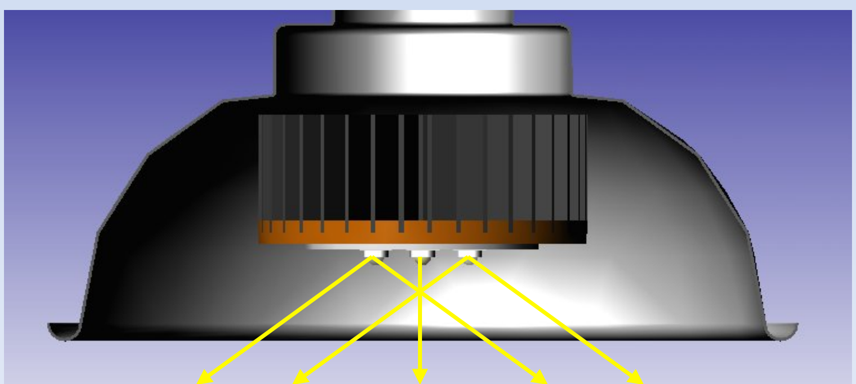


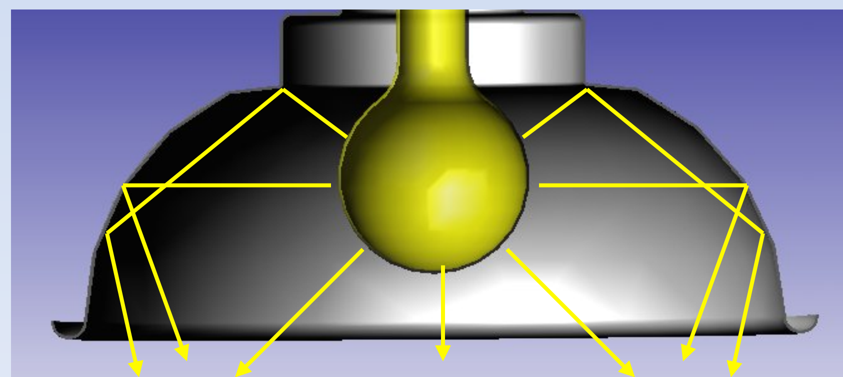
- LED drivers are covered by UL 8750, but can also be listed (as appropriate) under:
  - UL 1012 – Power units other than Class 2
  - UL 1310 – Class 2 Power units
  - UL 61950-1 – The Standard for Information Technology Equipment Part 1: General Requirements, UL 60950-1
- UL 8750 requirements supplement existing end-product requirements

LED Light Output – "Equivalent" to conventional sources?

- From previous discussion LED devices have highly directional light output unlike conventional light sources
- In directional fixtures such as downlights, this results in much less wasted light trapped in the fixture



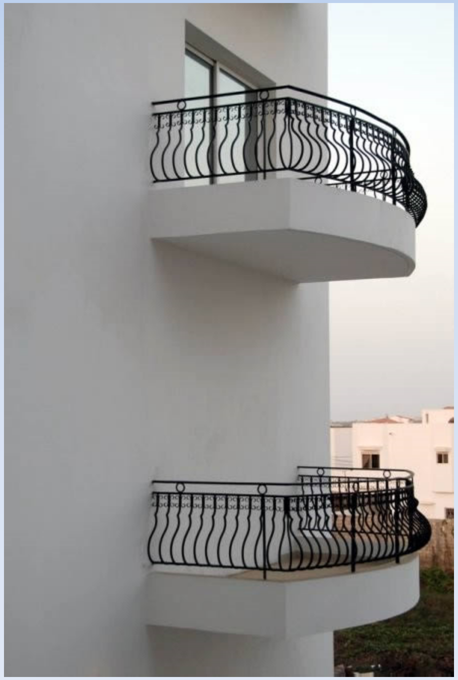




The Word "Equivalent"

Definitions

- Corresponding or virtually identical, especially in effect or function
- A state of being essentially equal
- Like in signification or import
- A person or thing equal to another in value or measure or force or effect or significance etc.

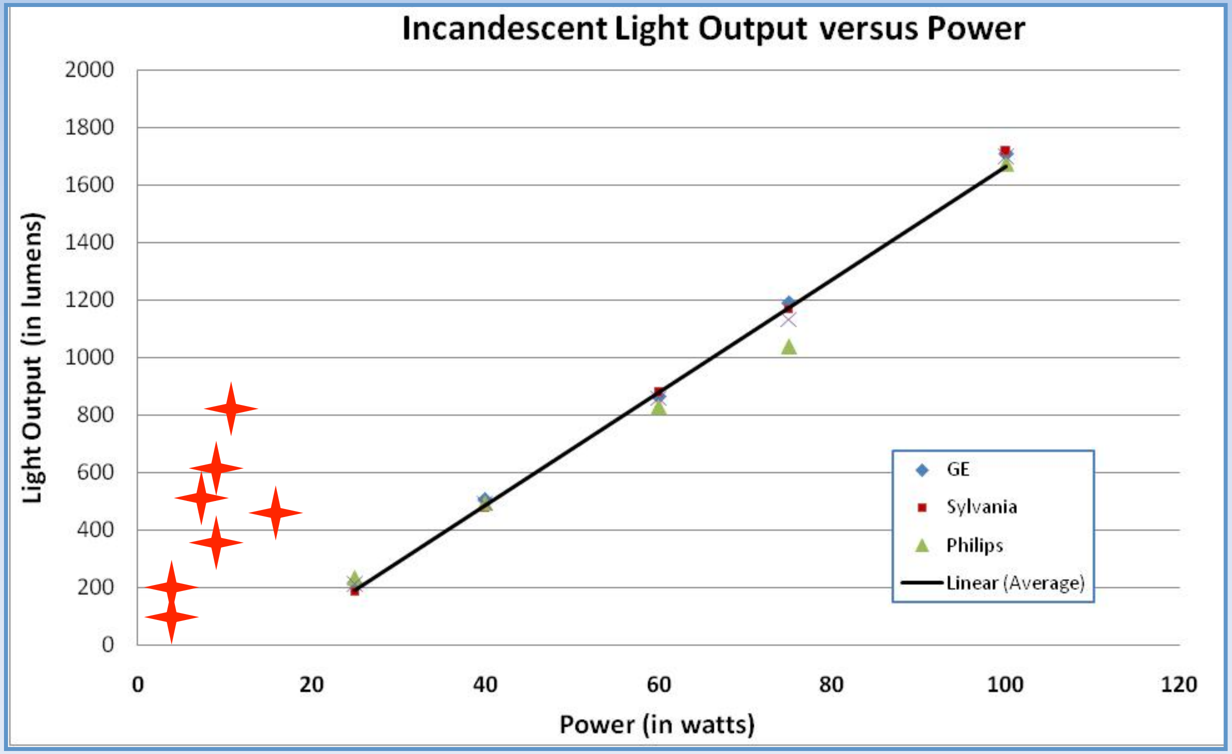


Are these two balconies equivalent?
Maybe not

The Word "Equivalent"

Incandescent lamp light output can be accurately conveyed by listing the lamp's power (wattage)

LED-based lamps do not show the same linear relationship due to the differences in device efficacy



Source: LED Transformations

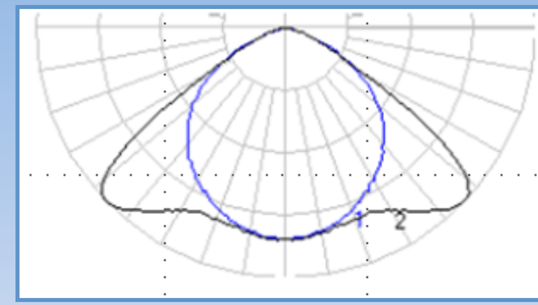
Equivalence – Defining the term

Since LED technology is different from most other light sources, the industry feels it necessary to sell LED products by talking about "equivalency"

- Do manufacturers compare 150W incandescent lamps to 4' T8 fluorescent tubes?
- Do lighting designers specify landscape walkway lights based on what fraction of a 400W Metal Halide the light puts out?
- Or how about this for specifying the output of a HID highbay….

The confusion and misinformation resulting from the use of this "equivalent" approach makes having useful standards more critical

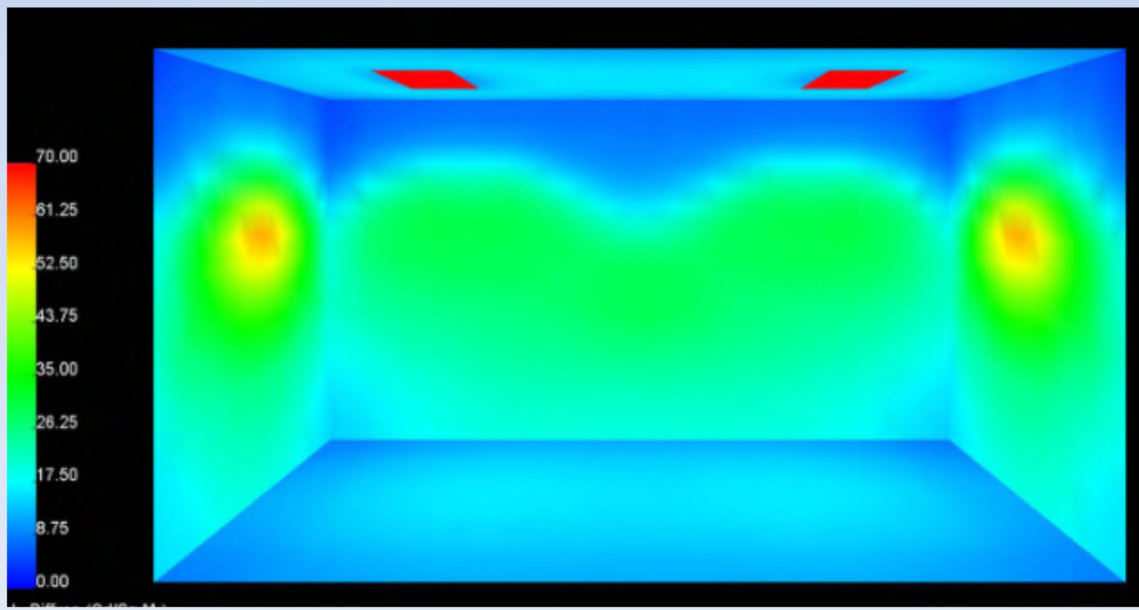
The Word "Equivalent" – Fluorescent replacements



2x4 parabolic louver
Fluorescent T8

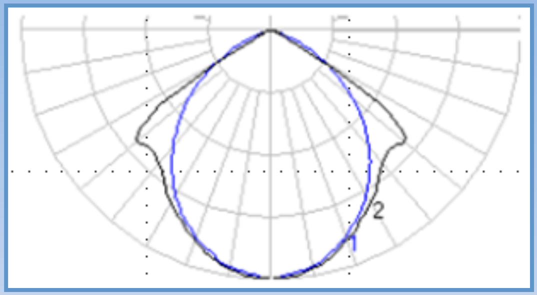
0.92 LLD
0.95 LDD
0.88 BF (n/a)

0.65 W/ft^2
25 fc (average)
1.9 max/min



Source: Tuenge & Myer, DOE PNNL

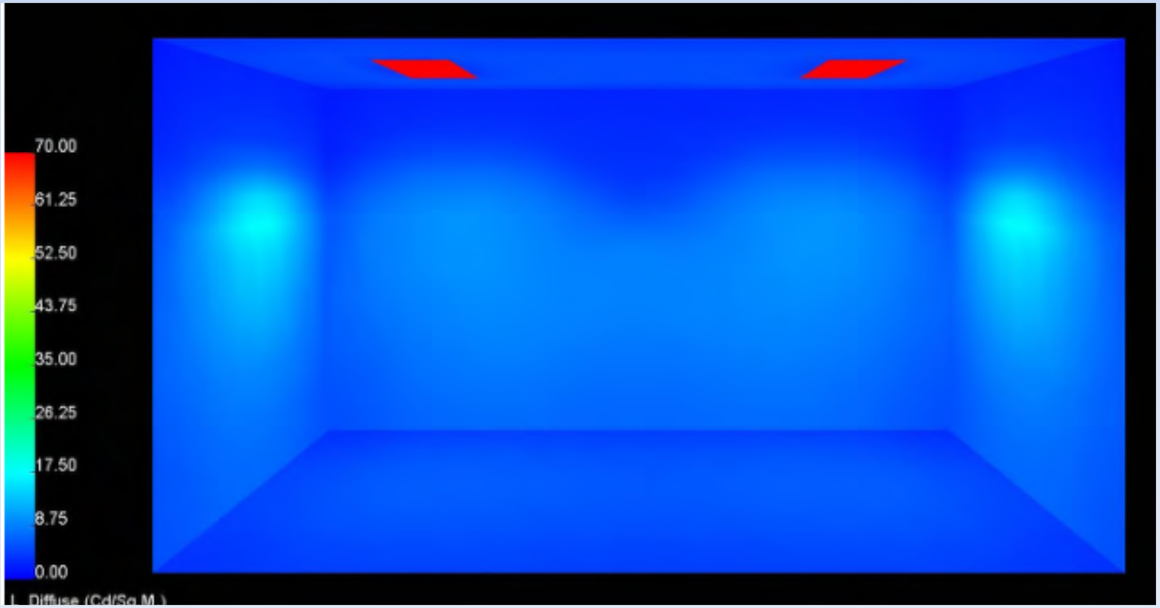
The Word "Equivalent" – Fluorescent replacements



2x4 parabolic louver
LED Replacements

0.70 LLD
0.95 LDD
1.00 BF

0.44 W/ft^2
10 fc (average)
2.3 max/min



Source: Tuenge & Myer, DOE PNNL

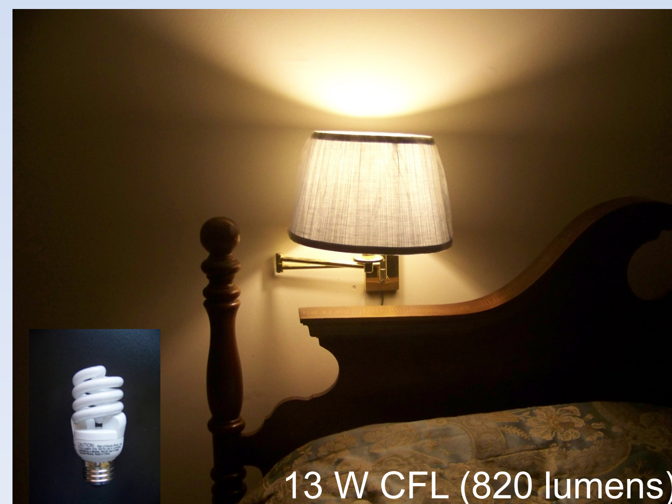
The Word "Equivalent" – LED vs. conventional sources


60 W Incandescent (800 lumens)

Note the lack of downward light


8 W LED (430 lumens)


12 W LED (800 lumens)


13 W CFL (820 lumens)

The Word "Equivalent" – Of course you can just lie!

Evidently there is a new standard for the light output of a 60W incandescent lamp (which previously put out around 800 lumens)

LED 60 watt replacement bulb- consumes only 8 watts of energy.

Reviewed 1 times | Write a Review | Tell a Frien

Description | Specifications | Reviews

You may

Comparable to a 60 watt light

- Bulb Shape: Globe Standard Bulb
- Base Type: E26, E27, B22 standard screw
- Brightness: 370 lumens Cool White Frosted 300 lumens Warm White Frosted
- Only 8 watts
- Comparable to a: 60 watt incandescent bulb
- Voltage: 85-265VAC
- Color: Warm White and White
- ColorTemp: 3000-3500K Warm White | 5000-6000K Natural White
- Beam Angle: 320 degrees
- CRI: Warm White:66 Cool White:77
- Operating Temp: -30C to 40C (-22F to 104F)
- Storage Temp: -30C to 40C (-22F to 104F)
- Avg. Life: 35,000 hours
- Lens types: Frosted
- Diameter: 2.25in (57.15mm)
- Length: 4.5in (114.3mm)
- Weight: 8 Ounces

Obviously photons from LED must be more visible than those from incandescent sources so you need less

Dimmable LED Light Bulb, E27, Day White, 5 Watt, 80 LEDs,

Click for more Photos

LARGER PHOTO | EMAIL A FRIEND

Description | Technical Specs

Commercial Grade / High Quality LED A19 Retrofit Bulbs - DIMMABLE

Wattage: 4.5W (5 Watts)
Lumen: 300LM
Color Temperature: Day White @ 5000-7000K
CRI: 80
Dimensions: Length @ 145mm, Diameter @ 60mm (4.7"L x 2.2"W) (MOL: 5.25")
Central Lux: 30 Lux/3m
Lighting Angle: 180 degrees C
Life Hours: > 30,000 Hours
LED Count: 80 LED's
Length/Base: E27
Housing Temperature: Less than 35 deg C

led light bulbs 6watt 120v set of 2 comparable to 75w light each - $38 (LA)

Date: 2010-03-18, 10:30PM PDT
Reply to: sale-rngdw-1650897455@craigslist.org [Errors when replying to ads?]

Kit = (2) led light 6watt each set total of 12watt = 150watt of light comparable to a incandescent bulb

2. 75watt incandescent bulb that run all night cost over $10 A month. 2 led light that run the same time only cost $ .65 cents (this is all set at .15 cents per KWH)

All sale are cash in hand call for info 323 252-6344 (9 a.m to 9 p.m) or shaun1elec@sbcglobal.net Thanks shaun

These are simply the brightest globe type LED light bulbs available today. They have a standard screw in base consuming ONLY 6W but giving 300 Lumens!
They fit your existing light fixtures (E27). They are comparable to a 75 watt incandescent bulb, but only use 70% less of the power. These bulbs work from 100 Volts to 240 Volts AC.

Marketing Phrases – "Comparable to what?"

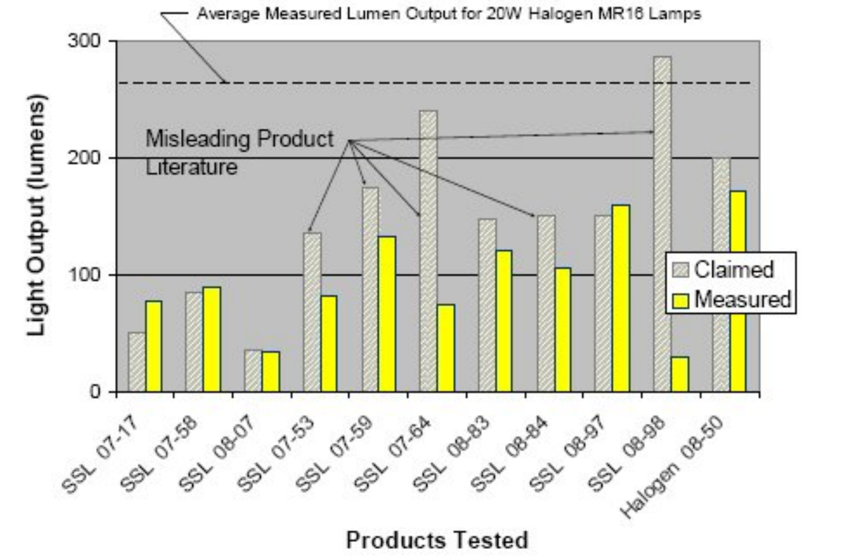
Energy Saving Concept:

- Replace every 150W incandescent lamp with a 75W lamp
  - Energy savings will be 50%
  - Cost will be about $1.00 per lamp
- Replace every 100W incandescent lamp with a 60W lamp
  - Energy savings will be 40%
  - Cost will be about $1.00 per lamp
- For even more energy savings, unscrew the lamp!

An example of "equivalent" – MR-16

- Dozens of manufacturers are offering LED replacements for halogen MR-16 lamps.
- Many of these claim to be "equivalent" to 35W or 50W halogen lamps. However...

"In CALiPER testing to date, the performance of LED MR16 replacement lamps varied greatly. Power usage for the LED replacements is considerably lower than for halogen MR16 lamps. However, light output and intensity for the tested LED products falls significantly short of the halogen benchmark levels, limiting the usefulness of LED MR16 lamps as a one-for-one replacement in typical highlighting and accent applications." Source: CALiPER Benchmark Report Nov. 2008



Measured Light Output of Halogen MR16 Lamps and LED Replacements Compared to Manufacturers' Reported Values

Dimming – What do we expect to occur?

What happens when you dim an incandescent lamp?

- Intensity of light is reduced
- Color shifts more to the red side of the spectrum as the lamp filament runs cooler
- Efficacy drops

What happens when you dim an LED replacement lamp?

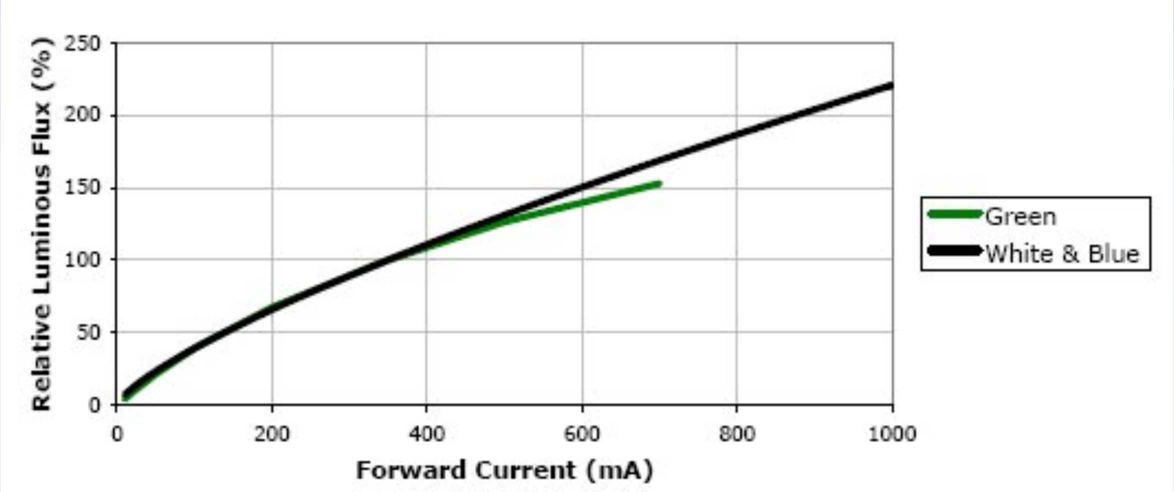
- Depends on the dimmer and method of dimming
- Color stays consistent
- Efficacy stays constant or may even increase
- It may not work at all!

Dimming and Energy Savings – It is a still a matter of economics

Energy savings = 100%

Dimming – How to dim LEDs?

One method is to simply reduce the current going to the LEDs. This is called 'linear' or 'analog' or 'CCR' (constant current reduction) dimming



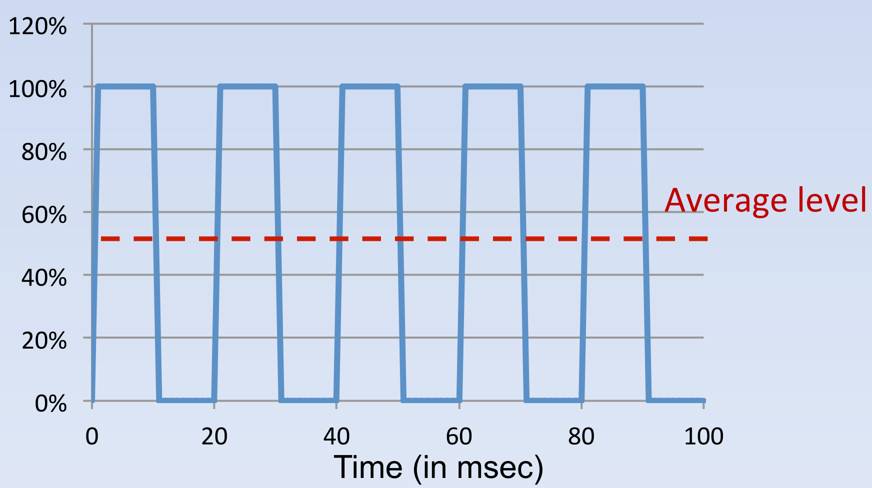
Light output is a function of the forward current

Note that eye response is not a linear function. Reducing the light output by 50% will not result in the human observer seeing a 50% reduction.

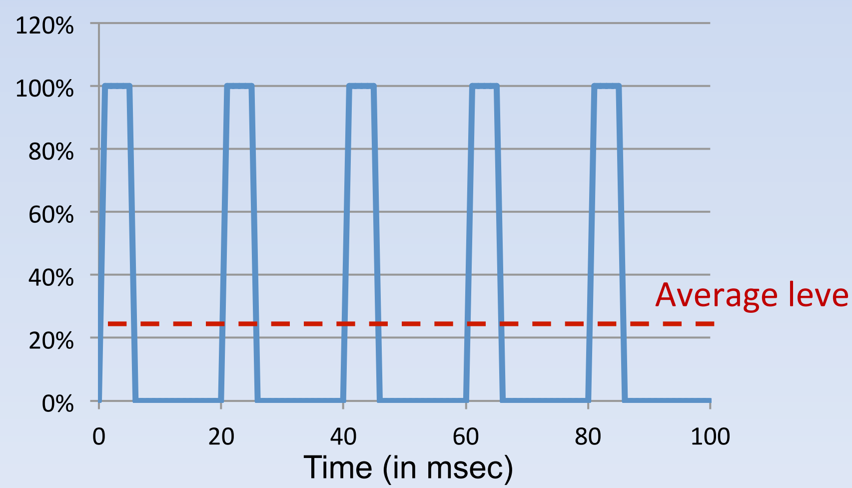
Dimming – How to dim LEDs?

A second method consists of rapidly turning the LED on and off. The longer the total off period, the dimmer the light appears. The faster the on/off cycle rate, or PWM frequency, the less likely flicker will be perceived. This is called pulse-width modulation (PWM) dimming.

50% Duty Cycle



25% Duty Cycle



Light output is directly proportional to the on time.

Dimming Issues – Potential Problems

- Because LED systems work differently from those of incandescent lamps, dimming is often an issue
- LED drivers must be designed to be compatible with line-voltage dimmers (of which there are many types)
  - Many line-voltage products not compatible (like CFLs) with certain dimmers
  - Many low voltage LED systems with certain step-down transformers are not compatible with certain dimmers
- One dimmer manufacturer provides a matrix showing compatibility and functionality with various manufacturers' luminaires/or drivers

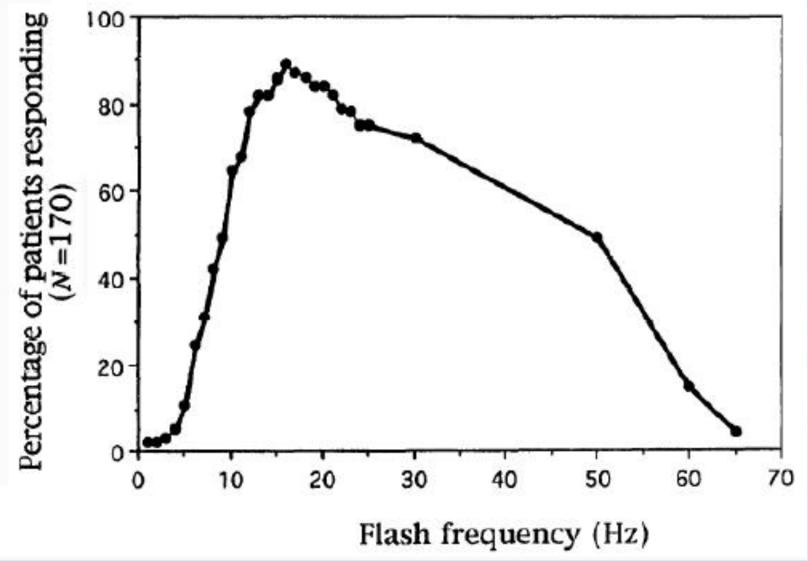
LED PRODUCT COMPATIBILITY MATRIX

Manufacturer	Model	Description	Dimming Range*	Compatible [illegible] Product?
[illegible]	Hi-lume LED driver	Driver	100% -1%	YES
[illegible]	Xitanium	Current Driver	Not Specified	YES
[illegible]	Xitanium	PWM Driver	100% - Off	YES
[illegible]	eW PowerCore	Strip Light	100% - 15%	YES
[illegible]	eW Profile : 11"	Under Cabinet Light	100% - 15%	YES
[illegible]	eW Profile : 41"	Under Cabinet Light	100% - 15%	YES
[illegible]	eW Downlight	Downlight	100% -15%	YES
[illegible]	Downlight	6" Downlight	100% - 5%	YES
[illegible]	LR4	4" Downlight	100% - 20%	YES
[illegible]	LR6	6" Downlight	100% - 20%	YES
[illegible]	LR6 - 230V	6" Downlight	100% - 20%	YES
[illegible]	LR24	24" x 24"	100% - 5%	YES
[illegible]	Tetra dimming module	Driver	Not Specified	YES
[illegible]	LED Cove Light	Cove Light	100% - 3%	YES
[illegible]	Downlight	Downlight	Not Specified	YES
[illegible]	LED-18-350-120-D	Driver	100% - 0.1%	YES
[illegible]	LED-36-700-120-D	Driver	100% - 0.1%	YES
[illegible]	Calculite 10W	Downlight	N/A	YES
[illegible]	Calculite 20W	Downlight	N/A	YES
[illegible]	Par 30	Par 30 lamp	Not Specified	YES
[illegible]	OT Dim	Driver	100% - Off	YES

Dimming Issues – Danger of flicker

At lower frequencies (typically 3 – 70 Hz), it can be a health hazard to people with photosensitivity (0.025% of the population) possibly resulting in epileptic seizures. The response depends on the following characteristics

- Brightness of light
- Contrast with background illumination
- Percentage of the retina receiving the stimulation
  - More sensitive in the central vision
- Wavelength of light

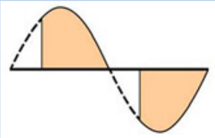


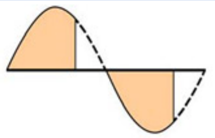
Source: Draft of IEEE PAR1789

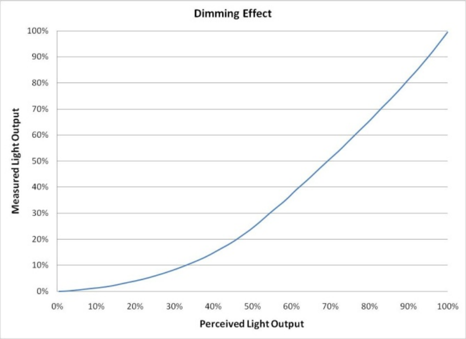
Other Lighting Controls – Types of lighting control

There are a number of different types of lighting controls, each with its own advantages and disadvantages

- Power line or Phase-cut
  - Leading edge or Forward Phase
    - Largest (by far) installed base
    - Historically designed for incandescent sources
    - Works fine with sources on magnetic low voltage transformers
  - Trailing edge or Reverse Phase
    - Much smaller installed base
    - Historically designed for sources on electronic low voltage transformers
    - Nearly always requires a neutral wire
  - When using this type of control
    - Make sure product conforms to existing standards
    - Verify compatibility with manufacturers
- 0 – 10 V (Three Wire)
  - Separate control and power signals
  - Precise, less prone to noise, but requires 3rd wire
- DALI Digital Control
- DMX 512 Digital Control





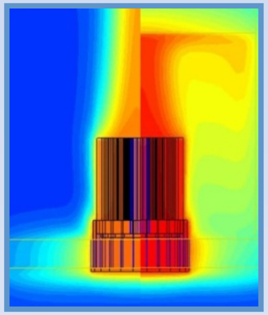


Perceived versus actual dimming level

Course Outline

1. Introduction – Why should I care about LEDs?
2. Lifetime and Cost – A critical relationship for LEDs
3. What's Different – LED technology as compared to traditional light sources
4. Technology Limitations – Characteristics to be aware of with solid-state lighting
5. Standards – The need for new metrics

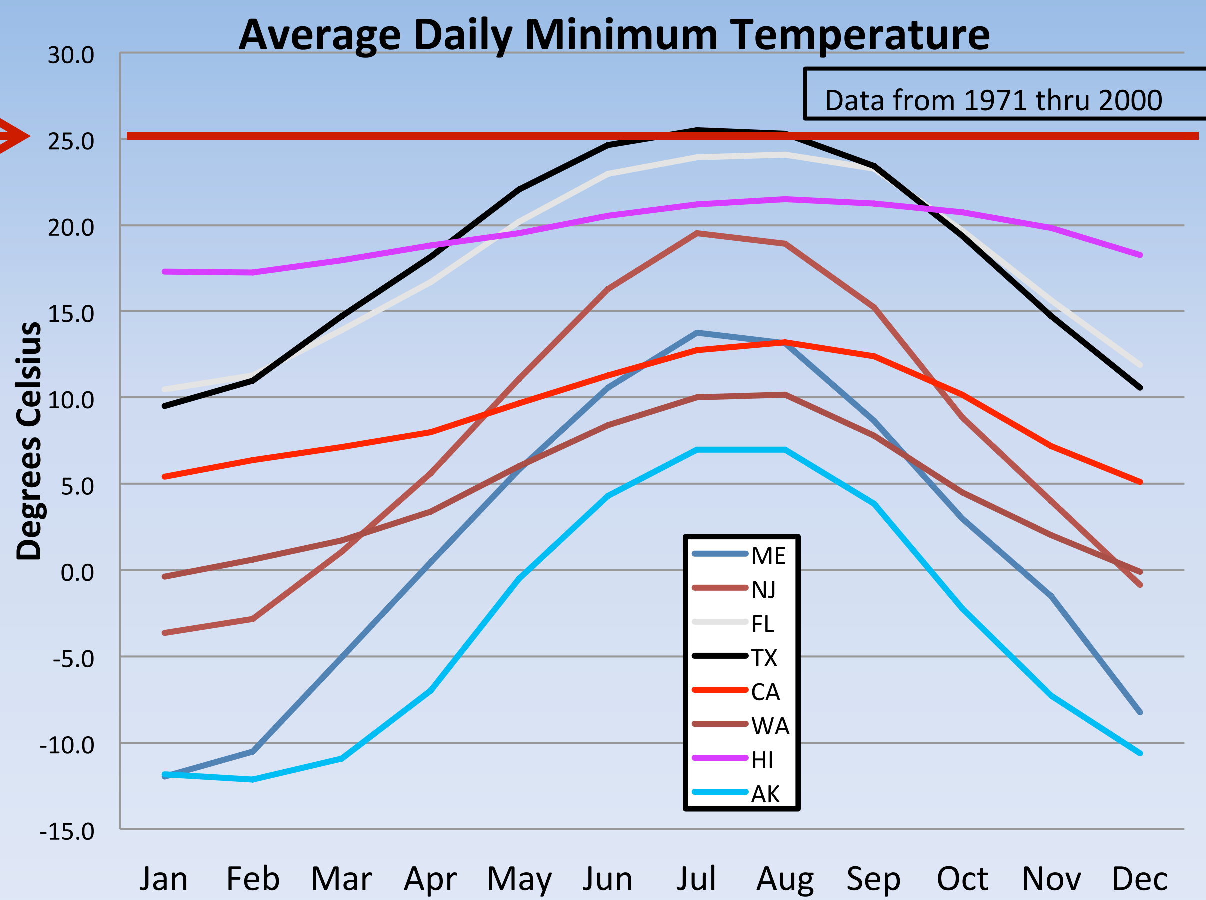
Break



6. Applications – What are the good ones?
7. LED Products – Where to turn for guidance
8. Items of Importance to Building Owners/Facility Mgrs
9. Final Thoughts – Some general rules

Outdoors – Temperature and Street & Area Lighting

Average nighttime temperature is well within reasonable limits for LEDs

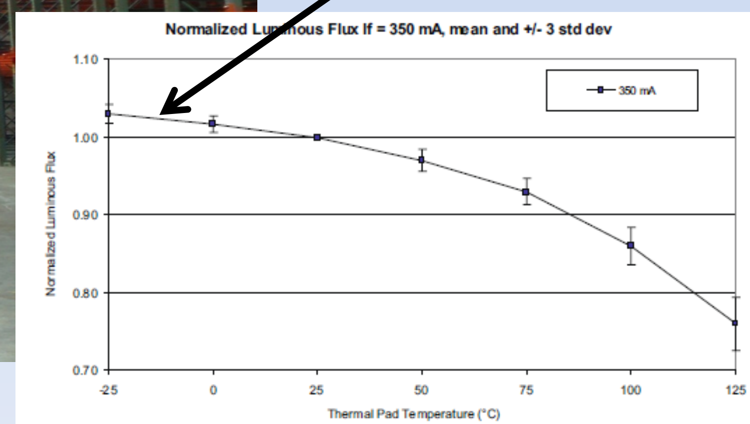


Source: NOAA

Units typically do not operate during daylight hours

Cold Areas – Cold Storage & Freezer Cases

Light output and power consumption increase slightly at lower temperatures



Source: Lumileds

Unlike fluorescent sources which produce less light at lower temperatures

Vandal Prone Areas – Small size helps

Which of these two devices looks more likely to survive a vandal attack in a school or prison?

Again taking advantage of LED's small size and directionality

LED Emergency Light

Source: Dual-Lite

Traditional Emergency Light

Vibration Resistance – Less chance of catastrophic failure

With no filament or electrodes to break, LEDs offer significant improvement over conventional light sources in high vibration and shock environments

Wingtip light of an Eclipse VLJ

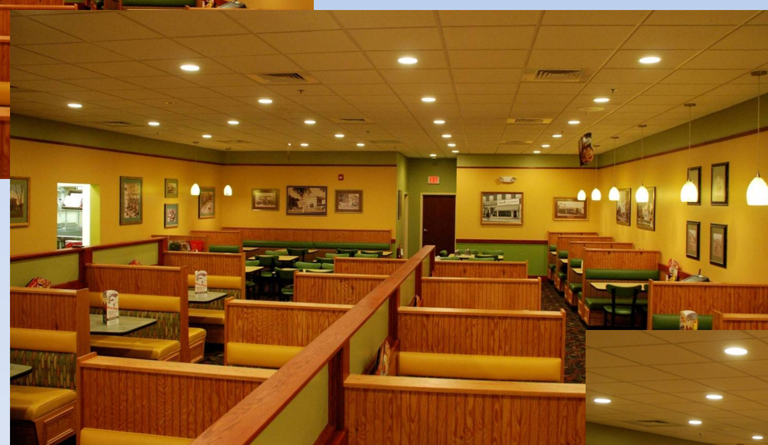
Interior of the Boeing 787 Dreamliner

Source: LED Transformations

Applications

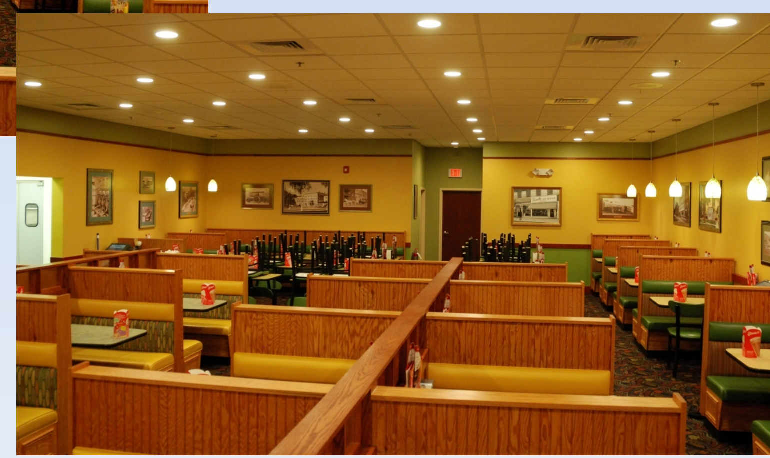
Downlight – Good

Incandescent 5,135 W



LED 948W

LED (2 Years Later)



Makes use of directionality

Source Cree

Applications

Good Ones – Freezer Cases

Gateway Report
October 2009

Stop 'n Shop, Raritan NJ

Source: LED Transformations

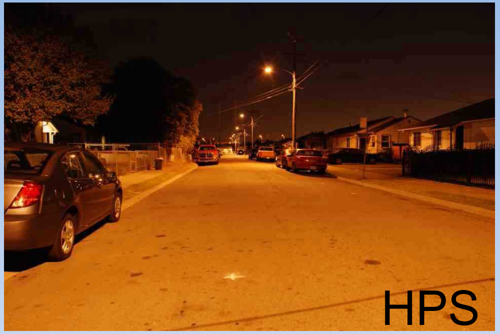
Albertson's Grocery, Eugene OR

LEDs performance improves
at lower temperatures

Albertson's results are part of a Gateway demonstration program available at:
http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/gateway_freezer-case.pdf

Street and Area Lighting – Some Demonstration Programs

- Street and Roadway Lighting
  - Oakland, CA
  - San Francisco, CA
  - Minneapolis, MN
- Walkway Lighting
  - Atlantic City, NJ
- Parking Lots and Garages
  - West Sacramento, CA
  - Portland, OR



Gateway Report
Phase II January 2008
Phase III November 2008

	New Construction				Retrofit			
Luminaire Type	**Initial Investment**	**Incremental Cost**	**Annual Savings**	**Simple Payback (Years)**	**Initial Investment**	**Incremental Cost**	**Annual Savings**	**Simple Payback (Years)**
HPS	$346.00				$0			
Phase II LED (vs. HPS with Spot)	$833.00	$487.00	$42	11.6	$833	$833	$42	19.8
Phase II LED (vs. HPS with Group)	$833	$487	$33	14.9	$833	$833	$33	25.5
Phase III LED (vs. HPS with Spot)	$605	$259	$52	5	$605	$605	$52	11.6
Phase III LED (vs. HPS with Group)	$605	$259	$43	6.1	$605	$605	$43	14.2

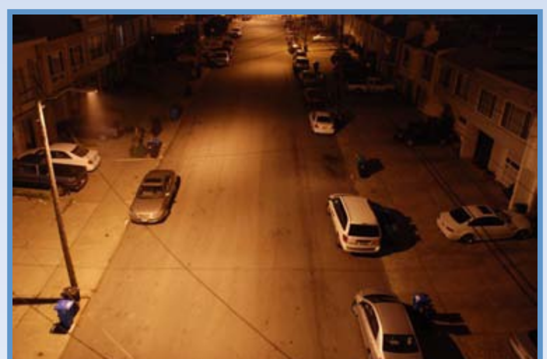
Applications

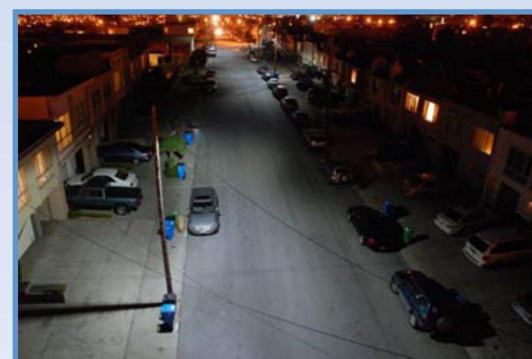
Street and Area Lighting – Some Demonstration Programs

- Street and Roadway Lighting
  - Oakland, CA
  - San Francisco, CA
  - Minneapolis, MN
- Walkway Lighting
  - Atlantic City, NJ
- Parking Lots and Garages
  - West Sacramento, CA
  - Portland, OR

	New Construction		Retrofit	
Luminaire	Simple Payback (Years)	15-Year NPV	Simple Payback (Years)	15-Year NPV
Mfg 1	6.3	$306.72	10.8	$99.72
Mfg 2	13.3	-$16.09	18.1	-$223.09
Mfg 3	3.7	$512.32	7.4	$305.34
Mfg 4	15.3	-$96.43	20.4	-$303.43

Gateway Report
December 2008


HP Sodium


LED Mfg. 1

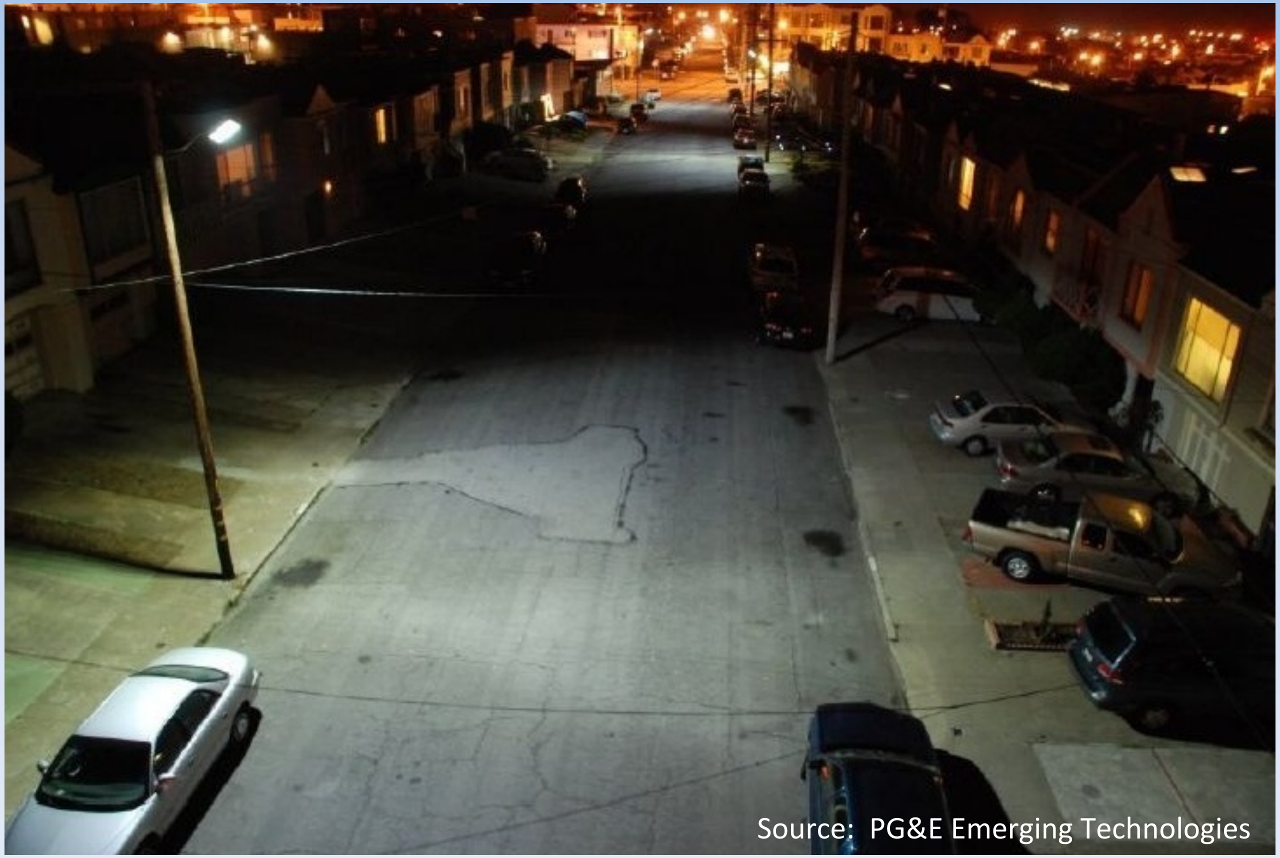
Street and Area Lighting – San Francisco Street Demonstration

Four city blocks were chosen and the HPS sources replaced with different manufacturer's LED products. This is the view originally with high pressure sodium

HPS

LEDs for Street and Area – San Francisco Street Demonstration

The same view with LED fixtures



LED

Be Careful What you ask for – You might get it

- Will users accept the sharp cut-off that LED sources can provide (e.g. street lights, sidewalks; lampshades)?
- Be cautious of light emitted between 80^{O} and 90^{O} – Contributes to disability and discomfort glare
- Is the environment over lit?
  - How much is spec and how much habit?
- How important is uniformity?
- What effect does CCT have on perception of brightness?

Cut-off Extremes

Parking Lots – Demonstration

Parking Lot (Manchester, NH)

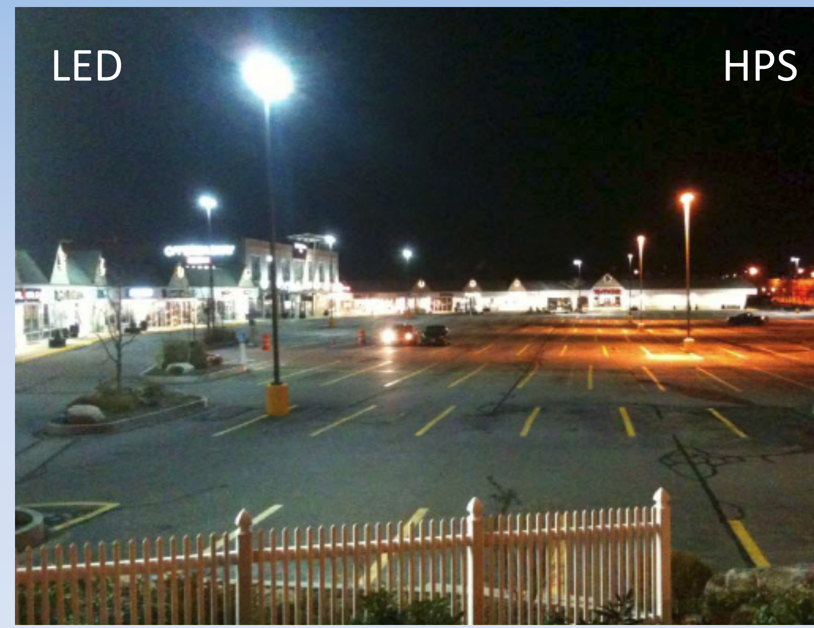


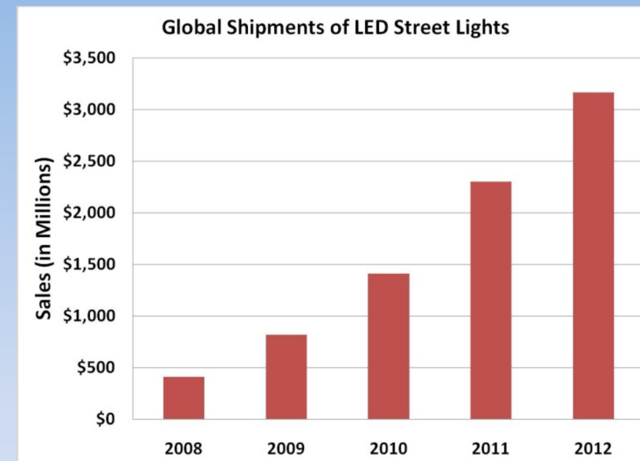
Table 3.2. Best-Case Payback using Actual Electric Rates and Actual Maintenance Costs

Type	Equipment Cost	Maintenance Cost[5]	Annual Energy Cost	Total Savings	Payback (years)
Existing		$11,000.08	$8,096.69		
Proposed PMH	$28,020.00	$9,821.50	$5,595.45	$3,679.82	7.61
LED	$47,125.00	$1,250.00	$2,590.77	$15,256.00	3.09

Gateway Report
June 2010

Applications

Bridge Lighting – Good



Source: Photonics Industry and Technology Development Association

Source: Eric Haugaard, Ruud Lighting

15% energy savings over previous HPS

Makes use of directionality

Gateway Report
August 2009

Applications

Cove Lighting – Good

Makes use of small form factor

LED Cove Lighting In Resort Casino

-30% Energy Saved vs. Proposed Neon

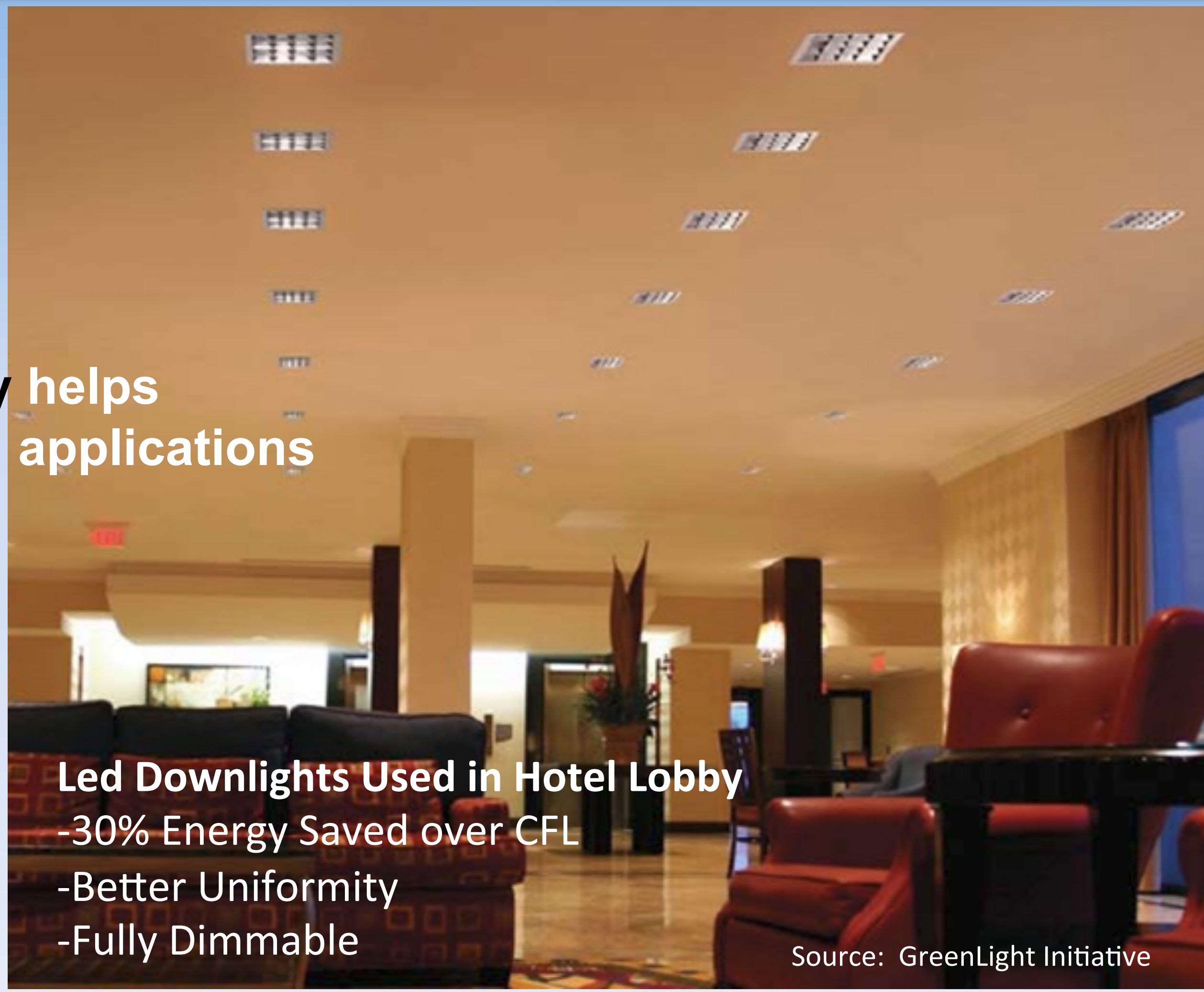
-No Mercury, Recyclable = Green Value for Hotel

Source: GreenLight Initiative

Applications

Good Ones – Indoor Commercial Downlights

Directionality helps in downlight applications



Led Downlights Used in Hotel Lobby

-30% Energy Saved over CFL

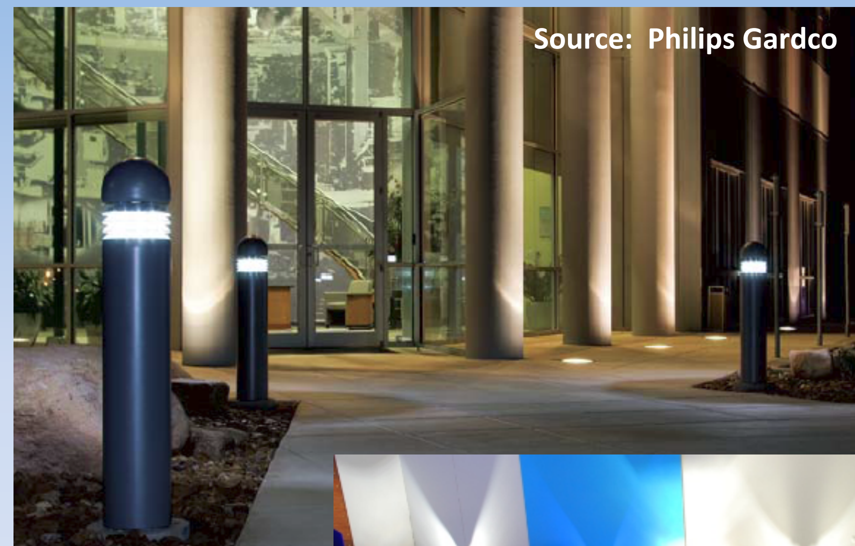
-Better Uniformity

-Fully Dimmable

Source: GreenLight Initiative

Task Lights / Bollards – Good


Source Luximo

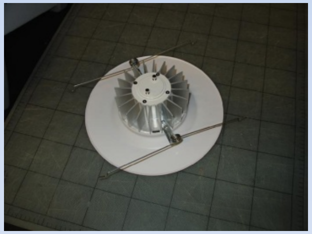

Source: Philips Gardco


Source: Lightscape Concepts & Design

Makes use of directionality and small form factor

LEDs for Residential Interiors – Overview

- For the Home
  - Downlights/Recessed Cans
  - Floor or Table Lamps
  - Wall Sconces
  - Night Lights



- Key Benefits and Limitations
  - High costs of fixtures, less time of use than Commercial Interiors and savings are usually during off-peak hours.
  - LEDs are less efficient at warm colors (<3500K) than at cool colors (>4100K).

LEDs for Residential Interiors – Payback Estimates

Gateway Report
October 2008

	Lamp Watts	Unit Cost	Hrs/Day	Annual kWh	Electricity Cost/Yr	Replacement Lamp Cost/year	Annual Operating Cost	LED Payback
LED Fixture	10	$140.00	4	14.6	$0.11	--	$1.61	--
Halogen (Low Level)	60	$80.00	4	87.6	$0.11	$6.12	$15.76	4.2
Halogen (High Level)	105	$80.00	4	153.3	$0.11	$6.12	$22.96	2.8
LED Module (LR-6)	12	$95.00	3	13.1	$0.11	--	$1.45	--
BR30	65	$3.50	3	71.2	$0.11	3.5	$11.33	9.6
PAR38	75	$3.50	3	82.1	$0.11	$3.50	$12.53	8.6

Source: ssl.energy.gov/gatewaydemos.html

LEDs for Residential Interiors – Undercounter

CSL - Creative Systems Lighting

Source: Kichler Lighting

LEDs for Residential Interiors – Downlights

Downlights make excellent use of the directionality of LEDs

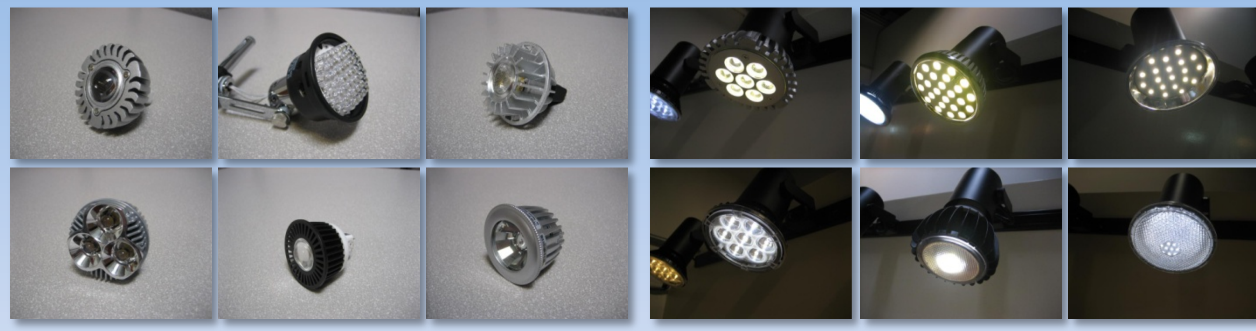
Source: Cree

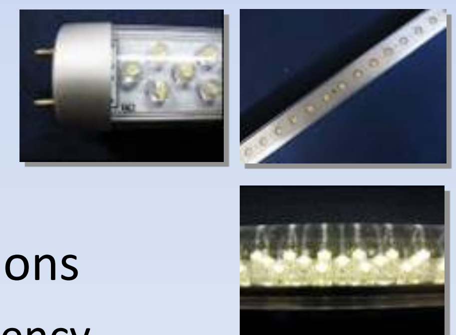
LEDs for Residential Interiors – Downlights

Source: Cree

LED Replacement Lamps – Many types

- Reflector Lamps
  - PARs
  - Floods
  - MR16s
- Incandescent
  - Standard A-lamp
  - Decorative lamps
- Fluorescent Tubes
- Key Benefits and Limitations
  - Long life and high efficiency
  - No mercury
  - Lamp envelope of replaced technology limits the design of the LED system (i.e. Heatsinks, optics, total output, etc.)





Applications

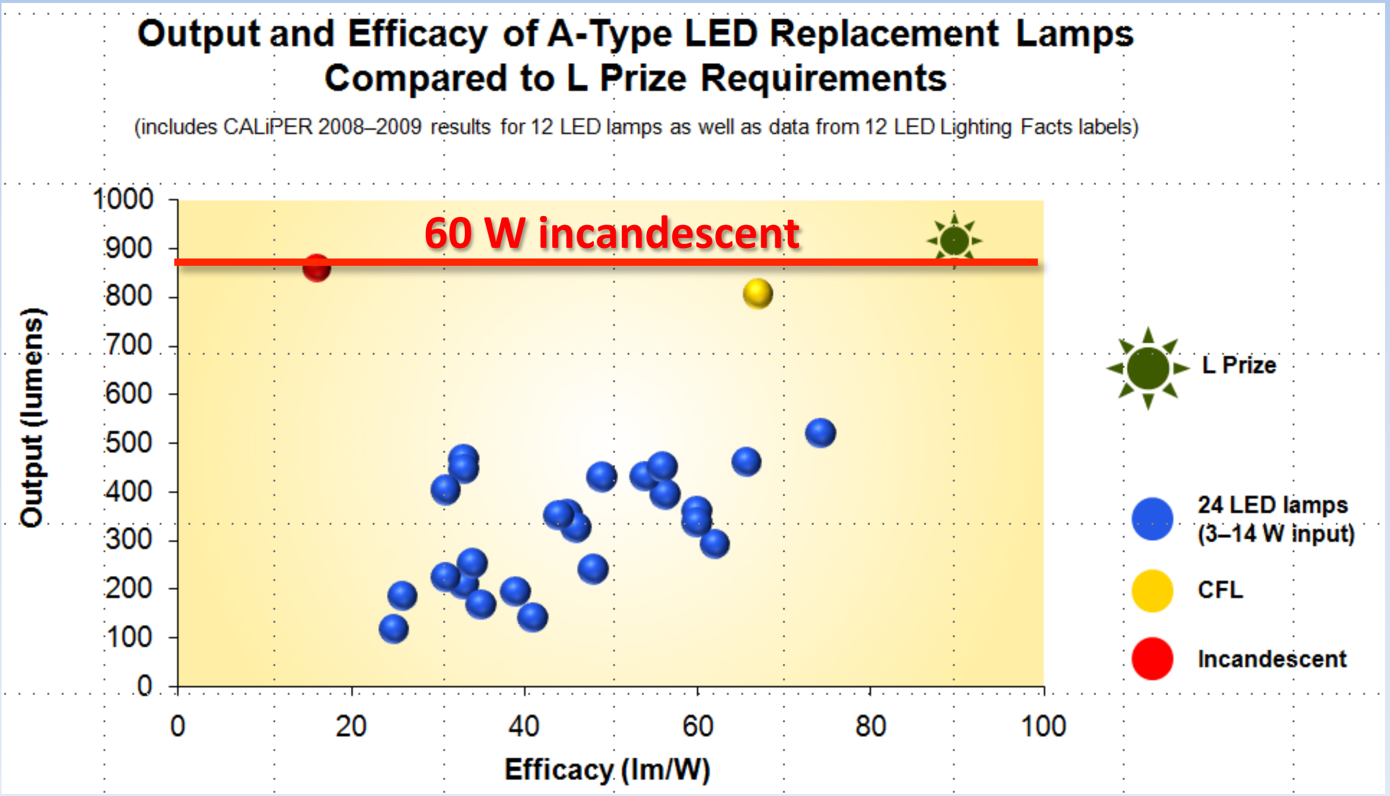
Good Ones & Bad Ones – Incandescent replacement lamps

Wide range of product performance available, from good to poor

Makes use of small form factor and high efficacy

Good Ones & Bad Ones – Incandescent replacement lamps

Until recently, LED replacement lamps did not match the lumen output of the incandescent lamps they are to replace



Source: Brodrick, L Prize Update, Lightfair 2010

Applications

Good Ones & Bad Ones – Incandescent replacement lamps

And the winner is…

Wednesday, August 3, 2011 (for immediate release):

Washington, D.C. – The U.S. Department of Energy today announced that Philips Lighting North America has won the 60-watt replacement bulb category of the Bright Tomorrow Lighting Prize (L Prize) competition. The Department of Energy's L Prize challenged the lighting industry to develop high performance, energy-saving replacements for conventional light bulbs that will save American consumers and businesses money.

Submitted in 2009, the Philips LED bulb successfully completed 18 months of intensive field, lab, and product testing to meet the rigorous requirements of the L Prize competition – ensuring that performance, quality, lifetime, cost, and availability meet expectations for widespread adoption and mass manufacturing. If every 60-watt incandescent bulb in the U.S. was replaced with the 10-watt L Prize winner, the nation would save about 35 terawatt-hours of electricity or $3.9 billion in one year and avoid 20 million metric tons of carbon emissions.

Source: Philips web site

	L Prize Requirement	Philips Result (average for 200 units)
Luminous flux (lumens)	> 900 lm	910 lm
Wattage (W)	≤ 10 W	9.7 W
Efficacy (lm/W)	> 90 lm/W	93.4 lm/W
Correlated color temperature (CCT)	2700 – 3000 K	2727 K
Color rendering index (CRI)	> 90	93

Source: DOE LPrize FAQs

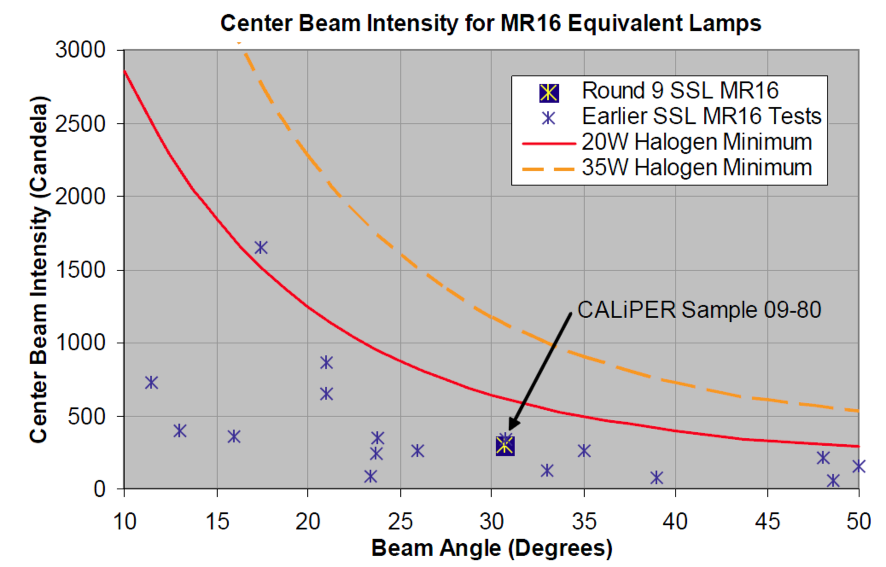
Good Ones & Bad Ones – Low wattage MR-16s (<20W)

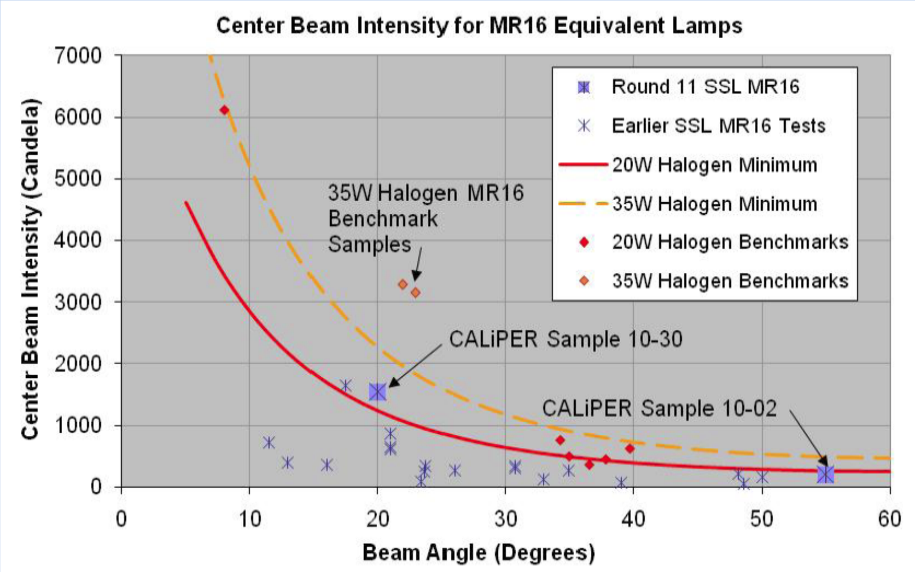
Hotel reception area
San Francisco CA

Source: LED Transformations

High Power MR-16s – Not So Good

Halogen versus LED-based MR-16 test results





Not so Good Ones – High wattage MR-16 (>20W)

Things to watch out for:

- CCT of halogen is typically 2800-3100K. LED CCT ranges from 2800 to 7000K.
- Wattage of LED product ranges from 1W to 10W.
- Efficacy is generally higher, but total lumens is much lower.
- Apples to oranges. Need to compare beam angle and candela ratings!!
- Lifetime claims do not match warranty. How does a product rated for 50k hours only come with a **ONE** year warranty?
- Voltage compatibility: Some products only work on AC or DC, or put out more light at DC than AC.
- Transformer and dimmer compatibility: many products don't dim, dim poorly, and/or won't work at all with certain types of electronic transformers. Read the fine print!"
- Thermal issues: Output and/or lifetime may degrade severely in enclosed fixtures!
- Cost is 10 times or more higher than a halogen equivalent.

Applications

Enclosures – Can have major effect on lamp performance

Lamp performance highly dependent on application/environment

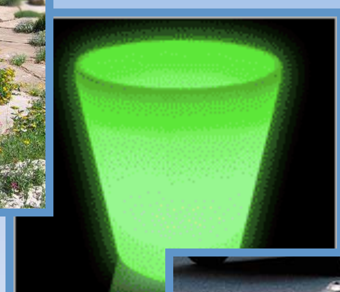
Open environment – T_j = 79.1^{O}C

Closed environment – T_j = 97.4^{O}C

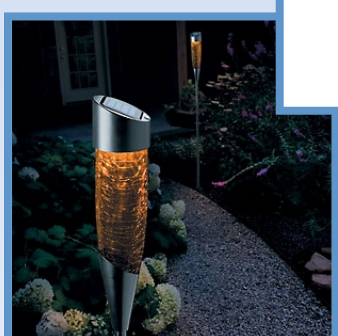
Higher temperature results in lower light output and shorter life

Source: Michael Poplawski, PNNL

Good Ones & Bad Ones – Solar Powered Walkway Lights





Makes use of small form factor and high efficacy

In general solar powered luminaires are an excellent application for SSL technology since LEDs are low voltage DC devices.

What makes most LED walkway lighting products <u>unsatisfactory</u> is the use of low output 5mm-type LEDs. A 7W traditional incandescent bulb typically puts out about 18 lumens versus the small LED which may put out around 3 lumens.

Controversial Ones – LED linear fluorescent replacements

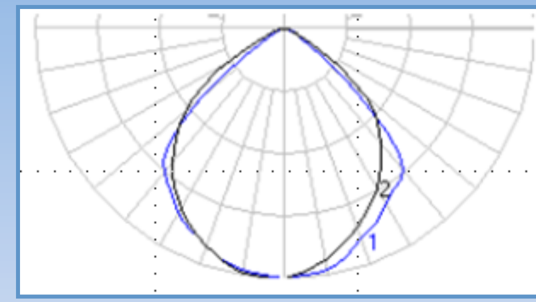
What makes this category controversial?

- Efficacy of traditional fluorescent tubes are on a par with present LED technology – about 100 lumens/Watt

- Fluorescent tube cost is much less that that of LEDs
  - $0.0008/lumen (linear fluorescent)
  - $0.014/lumen (LED device)
- Overall energy efficiency is highly dependent on the fixture in which the LED replacement tube is used
- Much of the LED replacement tube testing lags the average performance of current product offerings
- Variations in wiring configuration requirements for products currently on the market, some of which have recently been determined to be unsafe by CSA, and as a result not eligible for CSA listing

Applications

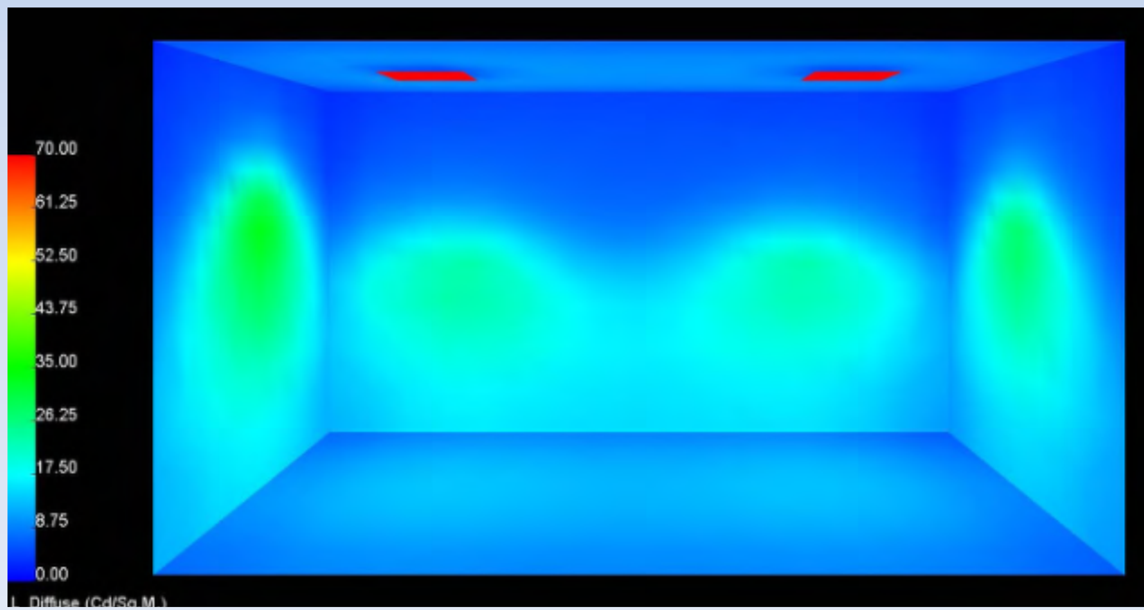
Fluorescent Replacements – Depends



2x2 parabolic
Fluorescent T8U

0.92 LLD
0.95 LDD
0.94 BF (n/a)

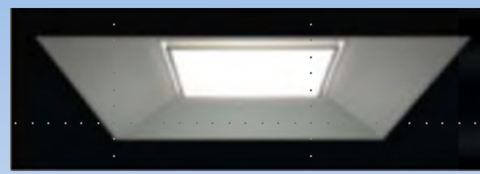
0.64 W/ft^2
20 fc (average)
2.5 max/min

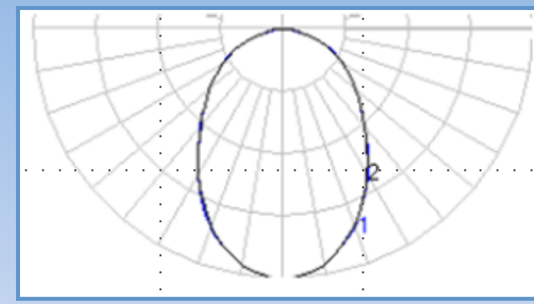


Source: Tuenge & Myer, DOE PNNL

Applications

Fluorescent Replacements – Depends

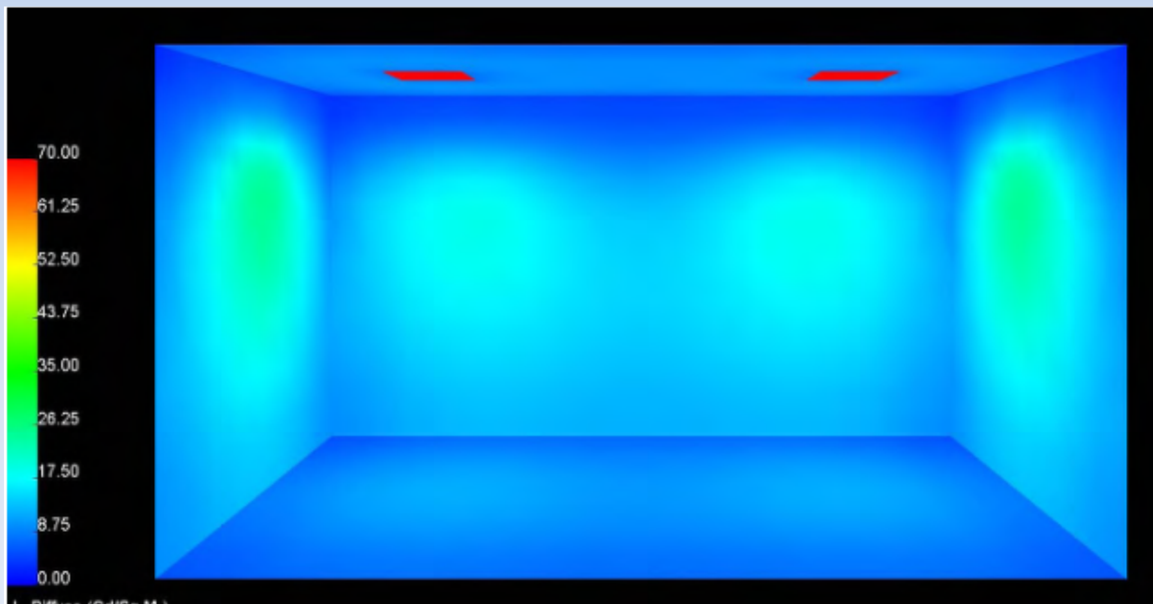




2x2 lensed
Integral LED

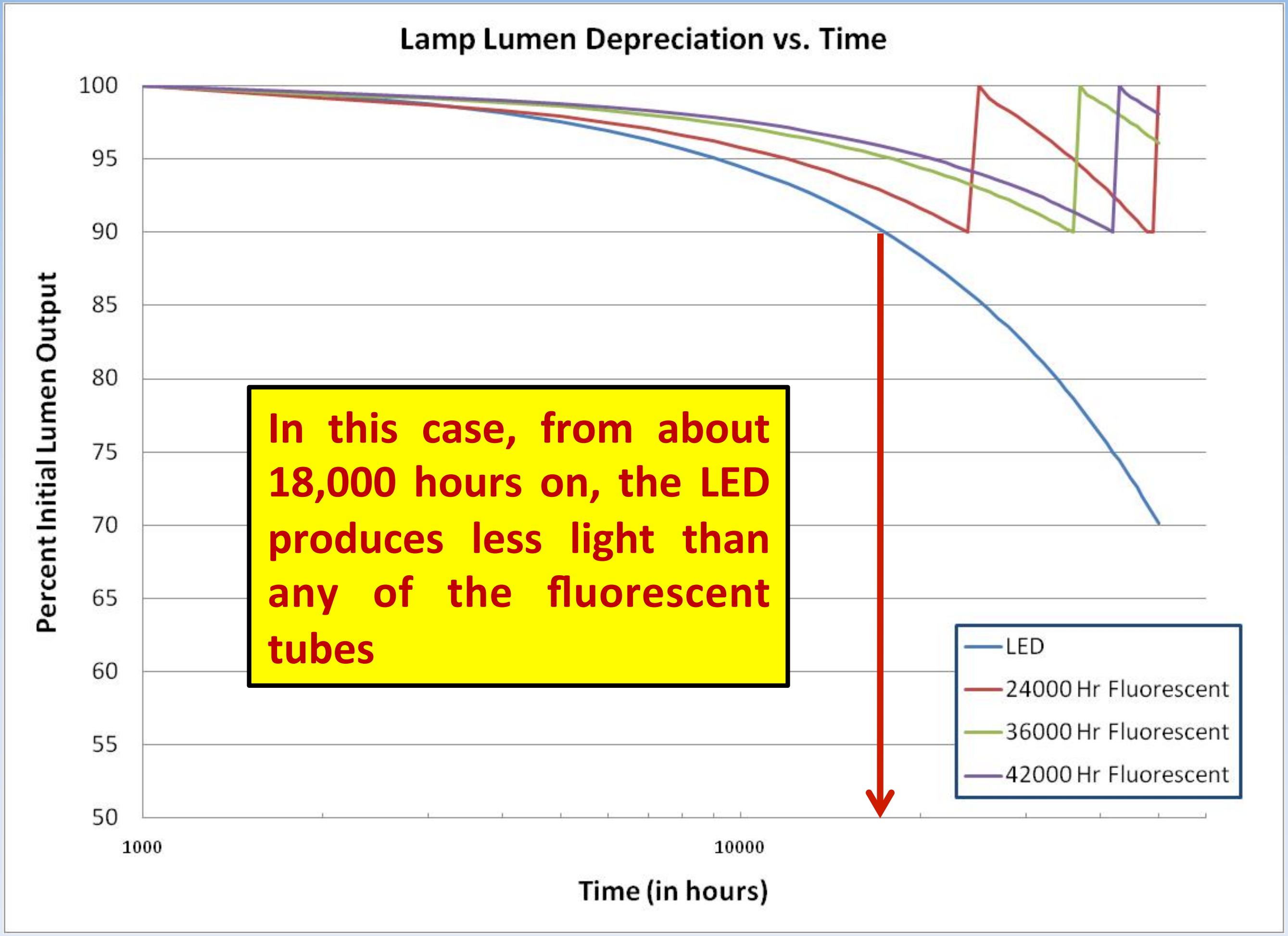
0.70 LLD
0.95 LDD
1.00 BF

0.45 W/ft^2
17 fc (average)
2.6 max/min



Source: Tuenge & Myer, DOE PNNL

Controversial Ones – Lamp lumen depreciation comparison



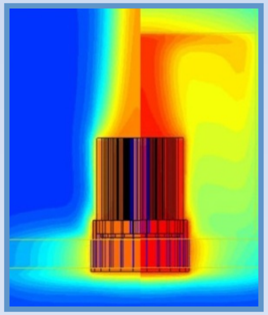
What Makes a Good Application – Based on current device efficacy

- Replacing a low efficacy light source
  - Incandescent
  - Halogen
- Replacing a fixture type with low optical efficiency
  - Downlights
  - Exterior bollards
  - Louvered products
  - Other directional fixtures
- As device efficacy increases and costs come down, this list will expand to encompass most traditional lighting sources

Course Outline

1. Introduction – Why should I care about LEDs?
2. Lifetime and Cost – A critical relationship for LEDs
3. What's Different – LED technology as compared to traditional light sources
4. Technology Limitations – Characteristics to be aware of with solid-state lighting
5. Standards – The need for new metrics

Break



6. Applications – What are the good ones?
7. LED Guidance – Where to turn for help
8. Items of Importance to Building Owners/Facility Mgrs
9. Final Thoughts – Some general rules

One Way to Determine What's Good - CALiPER

The DOE CALiPER program supports testing of a wide array of SSL products available for general illumination, using industry-approved test procedures. CALiPER test results:

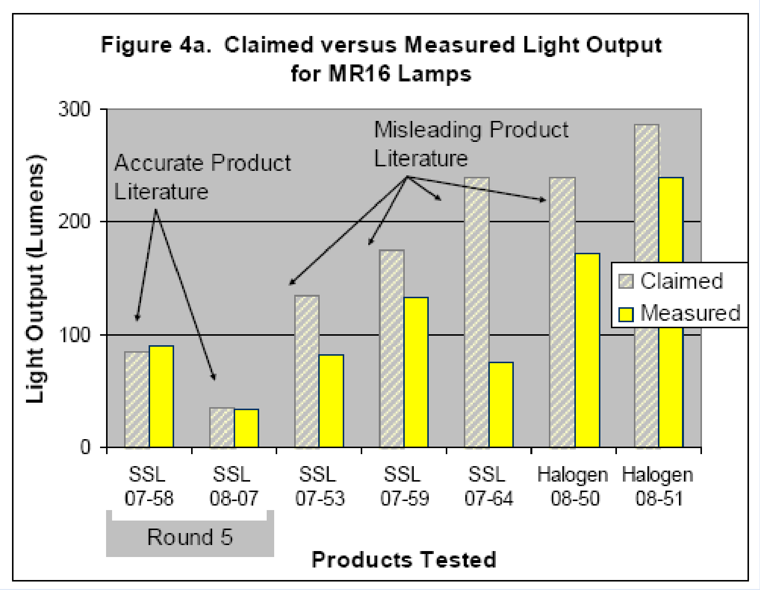
- Guide DOE planning for SSL R&D and market introduction activities, including ENERGY STAR® program planning
- Support DOE GATEWAY demonstrations and technology procurement activities
- Provide objective product performance information to the public in the early years, helping buyers and specifiers have confidence that new SSL products will perform as claimed
- Guide the development, refinement, and adoption of credible, standardized test procedures and measurements for SSL products

CALiPER – MR-16 Example

- Dozens of manufacturers are offering LED replacements for halogen MR-16 lamps.
- Many of these claim to be "equivalent" to 35W or 50W halogen lamps. However...

"In CALiPER testing to date, the performance of LED MR16 replacement lamps varied greatly. Power usage for the LED replacements is considerably lower than for halogen MR16 lamps. However, light output and intensity for the tested LED products falls significantly short of the halogen benchmark levels, limiting the usefulness of LED MR16 lamps as a one-for-one replacement in typical highlighting and accent applications."

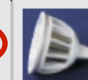
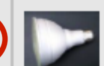
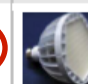
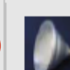
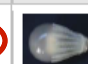
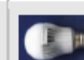
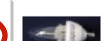
Source: CALiPER Benchmark Report Nov. 2008



CALiPER – Replacement Lamps

Results from Round 9 CALiPER testing (October 2009) show that a large number of LED product manufacturers are still not providing accurate performance data

Table 4. CALiPER ROUND 9 – Replacement Lamp Manufacturer Claims

Sample Type and CALiPER Reference	Manufacturer Claims	Actual Performance Level (e.g. Light Output, Efficacy, CBCP, Beam Angle)	Provides Accurate Product Reporting	
Replacement Lamp (MR16) 09-80	*180 lm*, (54-*69* lm/W) *Eq. to 35W halogen*	165 lm, 50 lm/W 304 cd, 31° **Less than average 20W halogen**	NO	
Replacement Lamp (R20) 09-78	230 lm, (32 lm/W) 7W=35W	263 lm, 42 lm/W 944 cd, 25° **Exceeds average 35W halogen**	YES	
Replacement Lamp (R30) 09-64	*Replaces 45W (450 lm, 128 lm/W) CRI=84, 30° beam*	186 lm, 54 lm/W CRI=71, 695 cd, 20° **Less than 20W eq.**	NO	
Replacement Lamp (PAR30) 09-76	*Eq. to 75W Incand. 550 lm, 70 lm/W 60-70° beam*	468 lm, 59 lm/W 190 cd, 100° **Eq. to 50W R30**	NO	
Replacement Lamp (PAR38) 09-63	*Replaces 45W (450 lm, 90 lm/W)*	289 lm, 58 lm/W 902 cd, 22° **Less than 25W eq.**	NO	
Replacement Lamp (A-lamp) 09-60	260 lm, (34.6 lm/W) *Replaces 40W incandescent*	251 lm, 34 lm/W **Eq. to 25W incandescent**	NO	
Replacement Lamp (A-lamp) 09-77	155 lm, (22 lm/W) Eq. to 25W	208 lm, 33 lm/W **Eq. to 25W incandescent**	YES	
Replacement Lamp (Candelabra) 09-65	*Replaces 40W (320 lm, 220 lm/W)*	67 lm, 45 lm/W **Less than average 15W incandescent**	NO	
Replacement Lamp (Candelabra) 09-74	30 lm, (12 lm/W) "Uses less energy than a 15W candelabra"	31 lm, 17 lm/W **Eq. to 7-15W night light**	YES (possibly misleading)	

CALiPER results are available at:
http://www1.eere.energy.gov/buildings/ssl/caliper.html

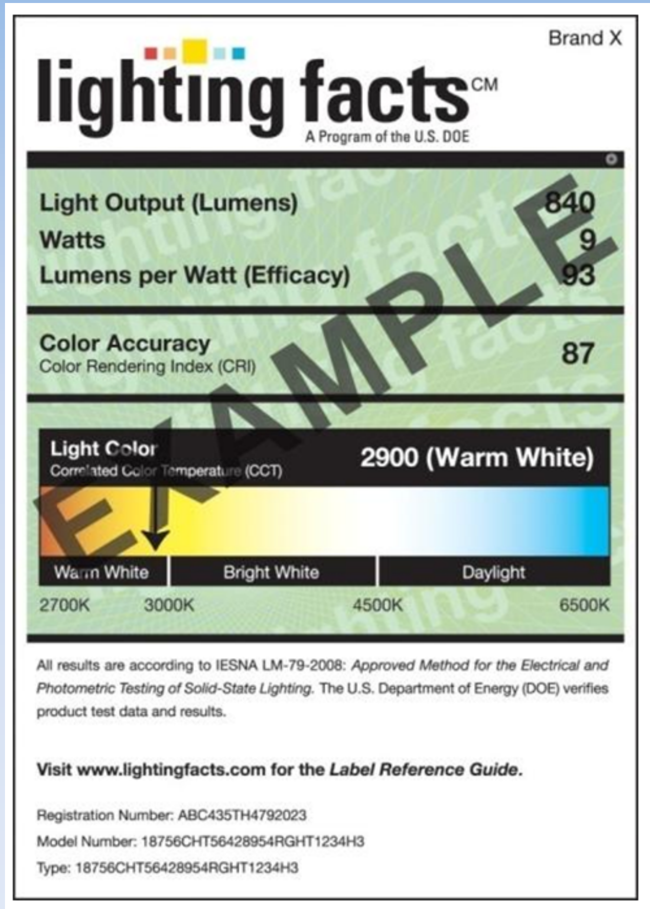
Lighting Facts Label – From DOE

Lighting Facts Label

Clear Representation of

- Light Output
- Power
- Efficacy
- Color
  - CRI
  - CCT

Results verified by third party testing using LM-79 testing methods



LED Guidance

Lighting Facts Label – From Federal Trade Commission

A slightly different label borrowing from the DOE version has been designed by the Federal Trade Commission to be placed on all new medium screw base lamps. Samples are shown below.

Brightness
820
lumens

Estimated Energy Cost
$7.23
per year

Front Label

Lighting Facts Per Bulb

Brightness	**820 lumens**
Estimated Yearly Energy Cost	**$7.23**
Based on 3 hrs/day, 11¢/kWh Cost depends on rates and use	
Life Based on 3 hrs/day	**1.4 years**
Light Appearance Warm — Cool 2700 K	
Energy Used	**60 watts**

Back Label

Lighting Facts Per Bulb

Brightness	**870 lumens**
Estimated Yearly Energy Cost	**$1.57**
Based on 3 hrs/day, 11¢/kWh Cost depends on rates and use	ENERGY STAR
Life Based on 3 hrs/day	**5.5 years**
Light Appearance Warm — Cool 2700 K	
Energy Used	**13 watts**
Contains Mercury For more on clean up and safe disposal, visit epa.gov/cfl.	

Labeling takes effect January 2012

Back Label
(lamps containing mercury)

Energy Star – SSL Luminaires

Highlights of Luminaire Criteria (V1.0)

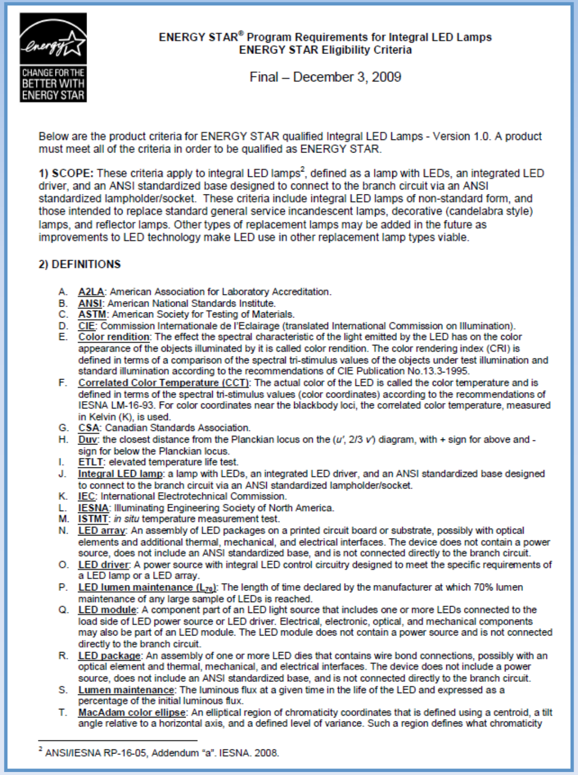
- Energy Star is a voluntary criteria
- Indoor luminaires shall have a minimum CRI of $R_a \geq 80$ (Was $R_a \geq 75$)
- Requires **zero** off-state power draw for the fixture; if controlled then < 1W (Was < 0.5W)
- Lumen Maintenance:
  - Residential – 25k hrs Indoor, 35k hrs Outdoor
  - Commercial – 35k hrs commercial
- Power Factor: Products drawing less than/equal to 5W require PF > 0.5; Products drawing > 5W require PF $\geq$ 0.7 (residential), PF $\geq$ 0.9 (commercial) (PF > 0.5 not previous included)
- ENERGY STAR qualification is not automatically granted for the life of a product model
- CCT shall be within one of the following groups: 2700K, 3000K, 3500K, 4000K, 5000K (commercial only) and within the ANSI C78-377-2008 chromaticity quadrangles (Dropped 4500K, 5700K and 6500K)
- EPA is pursuing a technology-neutral criteria. These criteria take effect April 1, 2012

Red indicates present SSL Criteria (V1.3)

LED Guidance

Energy Star – Integral LED lamp requirements

- Criteria was published December 3, 2009 and became effective August 10, 2010
- Scope
  - Omnidirectional replacement lamps
  - Directional replacement lamps
  - Decorative lamps
  - Non-standard lamps ~~removed 11/15/10~~ **Removal postponed 1/19/11**
  - ANSI lamp bases
- Not included in standard
  - Linear fluorescent replacement lamps
  - HIS replacement lamps
- EPA has released a draft of their technology-neutral replacement criteria, planned for release in spring 2012



ENERGY STAR® Program Requirements for Integral LED Lamps
ENERGY STAR Eligibility Criteria

Final – December 3, 2009

Below are the product criteria for ENERGY STAR qualified Integral LED Lamps - Version 1.0. A product must meet all of the criteria in order to be qualified as ENERGY STAR.

1) SCOPE: These criteria apply to integral LED lamps[2], defined as a lamp with LEDs, an integrated LED driver, and an ANSI standardized base designed to connect to the branch circuit via an ANSI standardized lampholder/socket. These criteria include integral LED lamps of non-standard form, and those intended to replace standard general service incandescent lamps, decorative (candelabra style) lamps, and reflector lamps. Other types of replacement lamps may be added in the future as improvements to LED technology make LED use in other replacement lamp types viable.

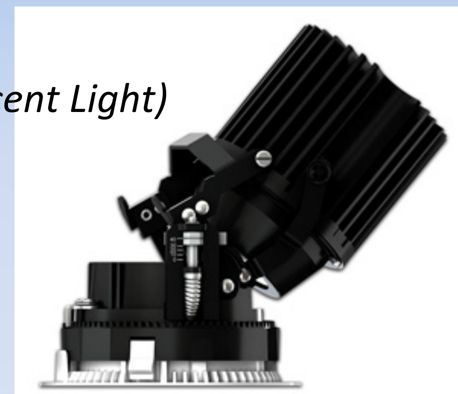
2) DEFINITIONS

A. A2LA: American Association for Laboratory Accreditation.
B. ANSI: American National Standards Institute.
C. ASTM: American Society for Testing of Materials.
D. CIE: Commission Internationale de l'Eclairage (translated International Commission on Illumination).
E. Color rendition: The effect the spectral characteristic of the light emitted by the LED has on the color appearance of the objects illuminated by it is called color rendition. The color rendering index (CRI) is defined in terms of a comparison of the spectral tri-stimulus values of the objects under test illumination and standard illumination according to the recommendations of CIE Publication No.13.3-1995.
F. Correlated Color Temperature (CCT): The actual color of the LED is called the color temperature and is defined in terms of the spectral tri-stimulus values (color coordinates) according to the recommendations of IESNA LM-16-93. For color coordinates near the blackbody loci, the correlated color temperature, measured in Kelvin (K), is used.
G. CSA: Canadian Standards Association.
H. Duv: the closest distance from the Planckian locus on the (u', 2/3 v') diagram, with + sign for above and - sign for below the Planckian locus.
I. ETLT: elevated temperature life test.
J. Integral LED lamp: a lamp with LEDs, an integrated LED driver, and an ANSI standardized base designed to connect to the branch circuit via an ANSI standardized lampholder/socket.
K. IEC: International Electrotechnical Commission.
L. IESNA: Illuminating Engineering Society of North America.
M. ISTMT: *in situ* temperature measurement test.
N. LED array: An assembly of LED packages on a printed circuit board or substrate, possibly with optical elements and additional thermal, mechanical, and electrical interfaces. The device does not contain a power source, does not include an ANSI standardized base, and is not connected directly to the branch circuit.
O. LED driver: A power source with integral LED control circuitry designed to meet the specific requirements of a LED lamp or a LED array.
P. LED lumen maintenance (L_{70}): The length of time declared by the manufacturer at which 70% lumen maintenance of any large sample of LEDs is reached.
Q. LED module: A component part of an LED light source that includes one or more LEDs connected to the load side of LED power source or LED driver. Electrical, electronic, optical, and mechanical components may also be part of an LED module. The LED module does not contain a power source and is not connected directly to the branch circuit.
R. LED package: An assembly of one or more LED dies that contains wire bond connections, possibly with an optical element and thermal, mechanical, and electrical interfaces. The device does not include a power source, does not include an ANSI standardized base, and is not connected directly to the branch circuit.
S. Lumen maintenance: The luminous flux at a given time in the life of the LED and expressed as a percentage of the initial luminous flux.
T. MacAdam color ellipse: An elliptical region of chromaticity coordinates that is defined using a centroid, a tilt angle relative to a horizontal axis, and a defined level of variance. Such a region defines what chromaticity

[2] ANSI/IESNA RP-16-05, Addendum "a". IESNA. 2008.

Next Generation Luminaires™ - 2010 Best in class winners

The Next Generation Luminaires™ (NGL) Solid State Lighting (SSL) Design Competition was created to recognize and promote excellence in the design of energy-efficient LED commercial lighting luminaires



NanoLED (Accent Light)
by USAI

fraqtir™ (Cove light)
by The Lighting Quotient

eW Burst Powercore (Facade Lighting)
by Philips Color Kinetics

Equo LED (Desk Lamp)
by Knocept Technologies, Inc

LED Guidance

Lighting for Tomorrow - 2011 LED winners

Aero 4-Head Fixed Trackcope LED
Designers Fountain

Bernie Chairside Reading Lamp
Holtkötter International, Inc

ULTRA RT4
Osram Sylvania

H4 LED 4-inch Adjustable Gimbal
Cooper Lighting

Versatile Area / Wall Light
Lithonia Lighting

CR4 Downlight
Cree Lighting

Gateway Program – Demonstrations in Various Applications

Demonstrations showcase high-performance LED products for general illumination in a variety of commercial and residential applications. Results provide real-world experience and data on state-of-the-art solid-state lighting (SSL) product performance and cost effectiveness.

Downlights Lane City Tour of Homes
Eugene, OR

Street Lighting
Oakland, CA

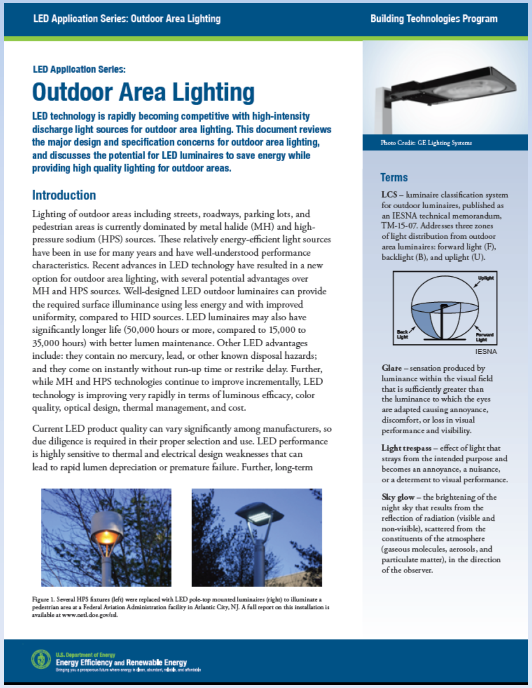
Freezer Case Lighting
Albertsons, Eugene OR

Raley's Supermarket
West Sacramento, CA

FAA Research Center
Atlantic City, NJ

Municipal Solid-State Street Lighting Consortium

To leverage the efforts of multiple cities pursuing evaluations of LED street lighting products, DOE has formed the Municipal Solid-State Street Lighting Consortium. The Consortium will collect, analyze, and share technical information and experiences related to LED street lighting demonstrations, and will also provide a consistent resource for evaluating new products on the market intended for street and area lighting applications.



LED Application Series: Outdoor Area Lighting — Building Technologies Program

LED Application Series:

Outdoor Area Lighting

LED technology is rapidly becoming competitive with high-intensity discharge light sources for outdoor area lighting. This document reviews the major design and specification concerns for outdoor area lighting, and discusses the potential for LED luminaires to save energy while providing high quality lighting for outdoor areas.

Photo Credit: GE Lighting Systems

Introduction

Lighting of outdoor areas including streets, roadways, parking lots, and pedestrian areas is currently dominated by metal halide (MH) and high-pressure sodium (HPS) sources. These relatively energy-efficient light sources have been in use for many years and have well-understood performance characteristics. Recent advances in LED technology have resulted in a new option for outdoor area lighting, with several potential advantages over MH and HPS sources. Well-designed LED outdoor luminaires can provide the required surface illuminance using less energy and with improved uniformity, compared to HID sources. LED luminaires may also have significantly longer life (50,000 hours or more, compared to 15,000 to 35,000 hours) with better lumen maintenance. Other LED advantages include: they contain no mercury, lead, or other known disposal hazards; and they come on instantly without run-up time or restrike delay. Further, while MH and HPS technologies continue to improve incrementally, LED technology is improving very rapidly in terms of luminous efficacy, color quality, optical design, thermal management, and cost.

Current LED product quality can vary significantly among manufacturers, so due diligence is required in their proper selection and use. LED performance is highly sensitive to thermal and electrical design weaknesses that can lead to rapid lumen depreciation or premature failure. Further, long-term

Figure 1. Several HPS fixtures (left) were replaced with LED pole-top mounted luminaires (right) to illuminate a pedestrian area at a Federal Aviation Administration facility in Atlantic City, NJ. A full report on this installation is available at www.netl.doe.gov/ssl.

Terms

LCS – luminaire classification system for outdoor luminaires, published as an IESNA technical memorandum, TM-15-07. Addresses three zones of light distribution from outdoor area luminaires: forward light (F), backlight (B), and uplight (U).

Uplight
Back Light
Forward Light
IESNA

Glare – sensation produced by luminance within the visual field that is sufficiently greater than the luminance to which the eyes are adapted causing annoyance, discomfort, or loss in visual performance and visibility.

Light trespass – effect of light that strays from the intended purpose and becomes an annoyance, a nuisance, or a determent to visual performance.

Sky glow – the brightening of the night sky that results from the reflection of radiation (visible and non-visible), scattered from the constituents of the atmosphere (gaseous molecules, aerosols, and particulate matter), in the direction of the observer.

U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

And Finally…

Third-party test results

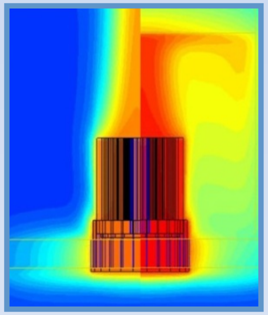
- Don't just take the luminaire manufacturer's word
- Reputable photometric test labs
  - DOE certified for CALiPER testing
  - NVLAP certified for LM-79 testing

Warranty Policy

- Is there a written end-of-life policy? How will spares be made available?
- Do all system components from SSL manufacturers have a warranty and labor to fix/replace?
- How long is the warranty? What exactly is covered?

Course Outline

1. Introduction – Why should I care about LEDs?
2. Lifetime and Cost – A critical relationship for LEDs
3. What's Different – LED technology as compared to traditional light sources
4. Technology Limitations – Characteristics to be aware of with solid-state lighting
5. Standards – The need for new metrics



Break

6. Applications – What are the good ones?
7. LED Products – Where to turn for guidance
8. Items of Importance to Building Owners/Facility Mgrs
9. Final Thoughts – Some general rules

Building Owners/ Facility Managers

Items of Importance - Reliability

Fifty-thousand hours sounds nice, but…

- LED products are specified in large part due to expectations of greatly increased hours or more of lifetime as compared to conventional sources
- How to insure those expectations are met:
  - Know what LEDs your supplier uses, and whether those LEDs have had LM-80 testing
  - Run pilot programs before committing to large projects
  - Know your supplier
  - Be highly skeptical of any expectation derived solely from the lifetime promise of the component LEDs
  - Does the lifetime promise make sense when compared to the warranty?
  - Evaluate ability to replace components in the field, e.g. drivers

Building Owners/ Facility Managers

Items of Importance - Availability

It doesn't save energy if you can't get it

- Lighting is typically ordered late in the construction process. Backorder status because vendor builds in batches or ships quarterly from overseas does not help.
- As more LED-based products become available, this should be less of an issue

Quantity	Catalog Number	Description	Ship Status	Unit Price	Total
5	DL - 2700-6-120	LED Downlight (2700K), 6" 120VAC	BACKORDERED	$119.95	$599.75
15	DL - 3000-8-120	LED Downlight (3000K), 8" 120VAC	BACKORDERED	$139.95	$2,099.25
50	CL - 3000-1-24	LED Cove Light (3000K), 1', 24VDC	BACKORDERED	$45.00	$2,250.00
10	WW - 3500-5-120	Wall Wash (3500K), 120VAC	BACKORDERED	$279.00	$2,790.00
15	DL - 3000-6-120	LED Downlight (3000K), 8" 120VAC	BACKORDERED	$139.00	$2,085.00
					$0.00
					$0.00
Total for this order					$9,824.00

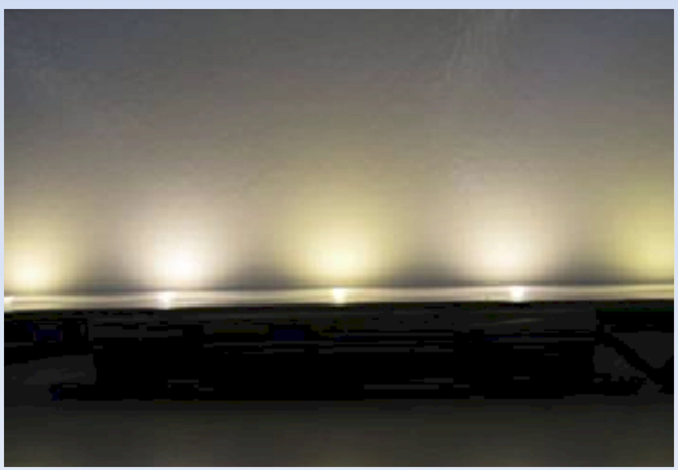
Building Owners/ Facility Managers

Items of Importance – Color consistency

Color changes can be a major issue

Is an issue due to binning which occurs with LED production as well as color shift due to phosphor/die changes over time

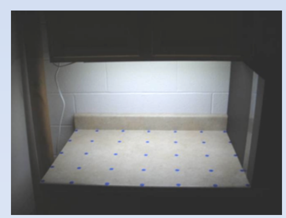
- Unit to unit
- Purchase to purchase



Source: Cree

Initial | **1000 hours**

84.1% Drop



97.8% Drop

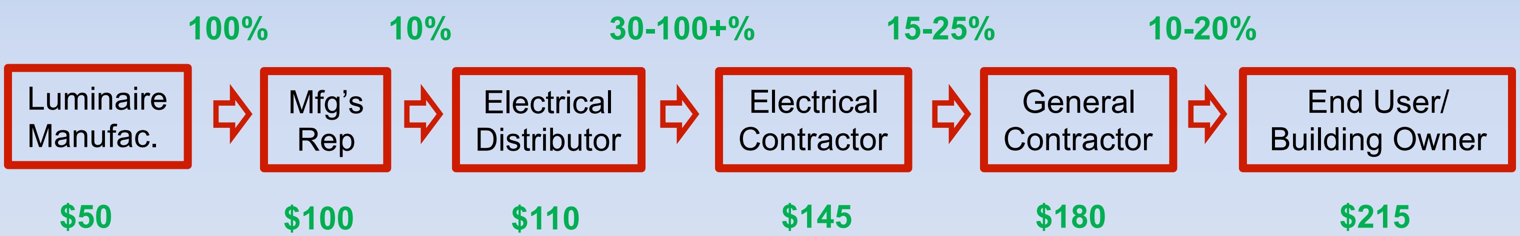
96.9% Drop

Building Owners/ Facility Managers

Items of Importance - Cost

A few mark-ups along the way

- ROI dependent of end user cost
  - Distribution chain markups can have a major effect on cost to building owners, particularly for higher cost LED-based products



- Utility rebates can make a major difference in ROI
  - Some utilities reluctant to provide rebates due to uncertainty in expected lifetime and luminaire efficiency performance
  - Energy Star ratings provide some assurance to utilities
  - Other review bodies such as Design Lights Consortium

Building Owners/ Facility Managers

Items of Importance - Cost

High but coming down

- Maintenance is still an necessary part of facilities services even with high lifetime LED-based products
  - Replacement of luminaire components
    - Drivers and control circuitry can fail prior to end of life for the LEDs
    - Lenses can yellow, covers crack, waterproof seals become brittle, etc.
    - Higher level(s) of protection from transient events (e.g. voltage surge, lighting) may be required to match/ensure rated lifetime
  - Cleaning
    - Dirt will still collect on surfaces no matter what light source is in the luminaire, adding to lumen depreciation
    - Dust, grease, etc. will collect on heat sink surfaces reducing the thermal efficiency of the luminaire and shortening its life if not maintained

Building Owners/ Facility Managers

Items of Importance – Energy Savings

One of the main reasons LEDs are considered in the first place

- Import aspect of LEED certification
  - Lighting consumes about 22% of the total electricity used in the US[1]
- "Green" building requirements
  - Corporations that are environmentally sensitive and consider it part of their social responsibility
- High tech image important to some owners
  - Can create problems when owners insist on applications which are presently questionable for LED technology
  - Particular problem when funds other than owner/occupier (e.g. ARRA) are being spent
- Federal, state and local requirements (e.g. Title 24 in CA)

[1] Source: DOE U.S. Lighting Market Characterization
Volume I: National Lighting Inventory and Energy Consumption Estimate (Sept 02)

Building Owners/ Facility Managers

Items of Importance – Rebates & Utilities

- Most utilities will not provide rebates unless the product is ENERGY STAR qualified. They are concerned about:
  - Accuracy of performance specifications
  - Reliability and life expectancy of product
- Creates problems with products such as LED T8 replacements which are not currently covered by any ENERGY STAR program
  - Alternative is a listing by a utility consortium such as DesignLights Consortium: http://www.designlights.org/

Items of Importance – Rebates & Energy Star

ENERGY STAR® Lighting Program Summary Chart

Region	State(s)	Partner Name	Annual Budget	Target Population	Incentives CFLs	Incentives Fixtures	Incentives SSL	Marketing / Outreach	Other	Program Dates
California	CA	City of Palo Alto Utilities	$75,000	25,000			√	√		April 1-May 15, 2010
		Los Angeles Dept. of Water & Power	*Not stated*	1.2 million	√			√	√	Varies by activity
		Modesto Irrigation District	$2.2 million	*Not stated*	√			√	√	Year-round
		Pacific Gas & Electric	$44 million	4.5 million	√	√	√	√		Year-round
		Sacramento Municipal Utility District	$2.4 million	520,000	√	√		√		Year-round
		San Diego Gas & Electric	$9.1 million	1.2 million	√	√	√	√		Year-round
		Southern California Edison	$20,704,981	4.5 million	√	√			√	January-December, 2010
Mid-Atlantic	MD	Baltimore Gas and Electric Company	*Not stated*	1.1 million	√	√		√		Year-round
		Southern Maryland Electric Cooperative	*Not stated*	140,000	√	√		√		Year-round
	MD, DC	Pepco	*Not stated*	900,000	√		√	√		Year-round
	MD, PA	Allegheny Power	*Not stated*	*Not stated*	√	√	√	√		Year-round
	PA	PECO	$19 million over four program years	1.4 million	√	√	√	√	√	Through May 2013
		Pennsylvania Department of Environmental Protection *(program information from 2009)*	$10,000	*Not stated*	√			√		'08-'09 School year
		PPL Electric Utilities	*Not stated*	*Not stated*	√			√	√	Through May 2013
	VA	Virginia Department of Mines, Minerals and Energy	*Not stated*	7.2 million				√		Year-round, strong focus in Oct '10
	WV	West Virginia Division of Energy	*Not stated*	1.8 million				√		Year-round
Midwest	IA	Cedar Falls Utilities	*Not stated*	17,500	√	√		√	√	Year-round
		Central Iowa Power Cooperative	$200,000	*Not stated*	√	√	√	√	√	Year-round
		Farmers Electric Cooperative	*Not stated*	*Not stated*	√	√	√	√		Year-round
	IA, IL, SD	MidAmerican	*Not stated*	*Not stated*	√	√		√		Varies by activity
	IA, IN, MN, ND, SD	WECC	*Not stated*	*Not stated*	√		√		√	Varies by activity
	IA, MN	Alliant Energy	*Not stated*	530,000	√	√		√		Varies by activity
	IL	Ameren Illinois Utilities	$5.9 million	1.2 million	√		√	√	√	Year-round
		ComEd	$14.2 million	3.8 million	√	√		√		Year-round
		Illinois Department of Commerce and Economic Opportunity	$10.14 million	*Not stated*	√	√	√	√		Year-round
	IL, IN, MN, MO	Midwest Energy Efficiency Alliance	*Not stated*	*Not stated*	√		√	√		Varies by activity
	KS	Black Hills Energy	$172,640	92,000	√			√		Through June 2010
		Westar Energy	*Not stated*	674,000				√		Year-round
	KS, MO	Kansas City Power & Light	$195,000	*Not stated*	√		√	√	√	Year-round
	MI	DTE Energy	$2.2 million	*Not stated*	√		√	√	√	Year-round
	MN	East Grand Forks Water and Light	*Not stated*	8,000	√	√	√	√		Year-round
		Marshall Municipal Utilities	$10,000	13,000	√	√	√	√	√	Year-round
		Minnesota Power	*Not stated*	137,000	√	√		√		Varies by activity
		North Itasca Electric Cooperative	$1,650	*Not stated*	√				√	Year-round

Source: 2010 ENERGY STAR® Summary of Lighting Programs By Energy Efficiency Program Sponsors (Revised 5/10)

Building Owners/ Facility Managers

Items of Importance – Rebates & Energy Star

ENERGY STAR® Lighting Program Summary Chart

Region	State(s)	Partner Name	Annual Budget	Target Population	Incentives			Marketing / Outreach	Other	Program Dates
					CFLs	Fixtures	SSL			
		Southern Minnesota Municipal Power Agency	Not stated	110,000	√	√		√	√	Year-round
		Xcel Energy	$389,768	1.3 million	√			√	√	Varies by activity
	MO	AmerenUE	*Not stated*	1.2 million	√	√		√	√	Varies by activity
		City Utilities of Springfield, Missouri	*Not stated*	*Not stated*				√	√	Year-round
		Empire District Electric	$158,000	*Not stated*	√	√		√		Year-round
	NE	Nebraska Energy Office	$34 million revolving pool	N/A	√	√	√		√	Year-round
	OH	American Electric Power Ohio	$5.6 million	1.26 million	√	√		√	√	Year-round
		Duke Energy	*Not stated*	*Not stated*	√			√	√	Varies by activity
		Dayton Power & Light (DP&L)	$2.7 million	*Not stated*	√			√		Year-round
	WI	Barron Electric Cooperative	*Not stated*	10,000	√				√	Varies by activity
		Vernon Electric Cooperative	$10,000	10,000	√	√	√	√	√	Year-round
		Wisconsin Focus on Energy	$4.8 million	2.5 million	√	√	√	√	√	Varies by activity
Northeast	CT	Connecticut Light and Power	$7.5 million	1.2 million	√	√		√	√	Year-round
		United Illuminating Company	$1.3 million	336,000	√	√		√	√	Year-round
	CT, MA, ME, NH, NJ, NY, RI, VT	Northeast ENERGY STAR Lighting Initiative	*Not stated*	15 million	√	√	√	√		Varies by activity
	MA	Belmont Municipal Light Department	*Not stated*	*Not stated*	√			√		Year-round
		Cape Light Compact	$16,640,684 statewide	158,000	√	√	√	√	√	Year-round
		National Grid Massachusetts	$16,640,684 statewide	1.2 million	√	√	√	√	√	Year-round
		NSTAR Electric	$16,640,684 statewide	770,000	√	√	√	√	√	Year-round
		UNITIL (Fitchburg Gas & Electric)	$16,640,684 statewide	*Not stated*	√	√	√	√	√	Year-round
		Western Massachusetts Electric Company	$16,640,684 statewide	200,000	√	√	√	√	√	Year-round
	ME	Efficiency Maine	$1.5 million	686,000	√			√	√	Year-round
	NH	New Hampshire Saves Program	*Not stated*	540,000	√	√	√	√		Year-round
	NJ	New Jersey Clean Energy Program	$10 million	Statewide	√	√	√	√	√	Year-round
	NY	Long Island Power Authority	$2 million	950,000	√	√		√		Year-round
		NYSERDA	$6.5 million	6 million	√	√	√	√		Year-round
	RI	National Grid Rhode Island	$ 1,010,000	478,000	√	√		√	√	Year-round
		Pascoag Utility District	$24,717	4,500	√	√		√	√	Year-round
	VT	Efficiency Vermont	$2 million	305,000	√	√	√	√	√	Varies by activity
Northwest	ID, WA, WY	PacifiCorp: Rocky Mountain Power (ID and WY) and Pacific Power (WA)	*Not stated*	776,543	√	√		√	√	Year-round
	ID	Idaho Falls Power *(program information from 2009)*	$36,000	*Not stated*	√	√		√		Fall 2009
		Idaho Power Company	*Not stated*	400,637	√	√	√	√	√	Varies by activity
	ID, MT, OR, WA	Bonneville Power Administration	$7.7 million	12 million	√	√	√	√	√	Through Sept. 2011
		Northwest Energy Efficiency Alliance	*Not stated*	*Not stated*	√	√		√	√	Varies by member organization
	ID, WA	Avista Utilities	*Not stated*	*Not stated*	√			√	√	Year-round

Source: 2010 ENERGY STAR® Summary of Lighting Programs By Energy Efficiency Program Sponsors (Revised 5/10)

Building Owners/ Facility Managers

Items of Importance – Rebates & Energy Star

ENERGY STAR® Lighting Program Summary Chart

Region	State(s)	Partner Name	Annual Budget	Target Population	Incentives: CFLs	Incentives: Fixtures	Incentives: SSL	Marketing / Outreach	Other	Program Dates
	OR	Columbia River PUD	*Not stated*	*Not stated*	√		√	√	√	Varies by activity
	OR	Coos-Curry Electric Cooperative	*Not stated*	*Not stated*	√					Through Sept. '11
	OR	Emerald PUD *(program information from 2009)*	*Not stated*	*Not stated*	√					Varies by activity
	OR	Energy Trust of Oregon	$1.1 million	1.3 million	√		√	√		Year-round
	OR	Pacific Power	*Not stated*	*Not stated*	√	√		√	√	Year-round
	WA	Clallam County PUD No. 1	$292,000	*Not stated*	√	√	√	√	√	Year-round
	WA	Modern Electric Water Company	*Not stated*	*Not stated*	√					Through Sept. 2010
	WA	Puget Sound Energy	*Not stated*	1 million	√	√		√	√	Year-round
	WA	Seattle City Light	$7 million	*Not stated*	√	√		√		Year-round
	WA	Snohomish County PUD No.1	$1.4 million	300,000	√	√	√	√	√	Year-round
	WA	Tacoma Power	$3.6 million-two year budget for 2009/2010	141,000	√	√		√		Varies by activity
	WA	Cowlitz PUD *(program information from 2009)*	*Not stated*	*Not Stated*	√				√	Varies by activity
Southeast	FL	City of Tallahassee Utilities	$50,000	93,000	√			√		Year-round
Southeast	FL	JEA	$1.5 million	360,000	√	√		√	√	Varies by activity
Southeast	GA	Georgia Power	*Not stated*	2.1 million				√	√	Year-round
Southeast	KY	Duke Energy	*Not stated*	*Not stated*	√			√	√	Varies by activity
Southeast	KY	E.ON U.S. (Louisville Gas & Electric and Kentucky Utilities)	$3.4 million	900,000	√				√	Year-round
Southeast	KY	Kentucky Department for Energy Development and Independence	*Not stated*	*Not stated*				√		Year-round
Southeast	MS	Mississippi Power	$20,000	*Not stated*				√	√	Year-round
Southeast	NC	Carteret-Craven Electric Cooperative	$30,000	50,000	√			√		Year-round
Southeast	NC	Central Electric Membership Corporation	$20,000	19,500	√					*Not stated*
Southeast	NC	Lumbee River Electric Membership Corporation	$11,415	11,000	√			√	√	Year-round
Southeast	NC, SC	Duke Energy	*Not stated*	*Not stated*	√			√	√	Year-round
Southeast	NC, SC	Progress Energy	*Not stated*	5 million	√			√		Year-round
Southeast	SC	South Carolina Energy Office	*Not stated*	4,561,242	√			√	√	Year-round
Southwest	AZ	Arizona Public Service	$5.6 million	1.1 million	√			√		Year-round
Southwest	AZ	Tucson Electric Power (TEP)	$1.5 million	400,000	√			√		Year-round
Southwest	AZ	Unisource Electric Services (UES)	$350,000	236,000	√			√		Year-round
Southwest	CO	Platte River Power Authority	$300,000	100,000	√					April '10–March '11
Southwest	CO	Xcel Energy	$3,127,951	1.3 million	√			√	√	Varies by activity
Southwest	CO	Colorado Springs Utilities	$305,000	*Not stated*	√			√	√	Year-round
Southwest	NV	NV Energy	$2.5 million	2.4 million	√	√		√		Year-round
Southwest	NM	El Paso Electric	$45,000	*Not stated*	√			√		Year-round
Southwest	NM	Public Service Co. of New Mexico (PNM)	*Not stated*	501,000	√	√		√	√	Year-round

Source: 2010 ENERGY STAR® Summary of Lighting Programs By Energy Efficiency Program Sponsors (Revised 5/10)

Building Owners/ Facility Managers

Items of Importance – Rebates & Energy Star

ENERGY STAR® Lighting Program Summary Chart

Region	State(s)	Partner Name	Annual Budget	Target Population	Incentives			Marketing / Outreach	Other	Program Dates
					CFLs	Fixtures	SSL			
		Xcel Energy	$754,977	*Not stated*	√					Varies by activity
	TX	CenterPoint	*Not stated*	1.9 million		√			√	Year-round
		Entergy	$500,000	25,000	√	√		√	√	Year-round
	UT	Rocky Mountain Power	*Not stated*	*Not stated*	√	√		√	√	Jan. 1 - March 31 and Oct. 1 – Dec. 31, 2010
National		National Energy Education Development (NEED) Project *(program information from 2009)*	$300,000	*Not stated*				√		Year-round

Source: 2010 ENERGY STAR® Summary of Lighting Programs By Energy Efficiency Program Sponsors (Revised 5/10)

Building Owners/ Facility Managers

Items of Importance – Rebates & Energy Star

GVEA Rebates

- Provides rebates to commercial members of up to $20,000
- Submit proposal to GVEA for consideration; rebate amount tied directly to reduced load or demand
- Covers cost of products and their installation
- Customer must contribute 2 years’ anticipated electric bill savings toward project cost
- Rebates up to $1,000/kW or 50% of project cost
- Pre and post power consumption measurements will be conducted to determine rebate amount

Items of Importance – Warranty

How is failure defined and who is on the hook if it fails?

- Determine exactly what is covered
  - Light output
  - Color shift
  - Power draw
  - Component failures (e.g. drivers, lenses, heat sinks)
- What does the warranty cover?
  - Replacement luminaire only
  - Replacement luminaire and labor to remove/reinstall
- Does the warranty sufficiently support the lifetime claim?
- Will the supplier still be in business to honor the warranty?

Building Owners/ Facility Managers

Items of Importance – Spares

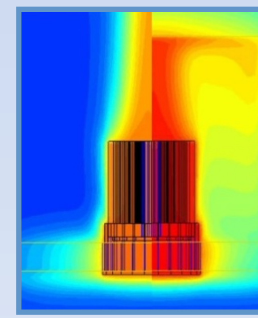
Some extra parts come in handy

- Building renovations on 10 to 20 year cycles
  - Lighting fixtures typically available for many years
  - Fixtures components can be replaced (e.g. lenses, ballasts, lamps, etc.)
- Owners expect to be able to replace fixtures over this period
  - Same style
  - Same color
  - Same light output
- Inventory
  - Balancing inventory costs versus availability of product
  - Backorders and obsolescence
  - Space is an issue since luminaires are typically larger than lamps

Course Outline

1. Introduction – Why should I care about LEDs?
2. Lifetime and Cost – A critical relationship for LEDs
3. What's Different – LED technology as compared to traditional light sources
4. Technology Limitations – Characteristics to be aware of with solid-state lighting
5. Standards – The need for new metrics

Break



6. Applications – What are the good ones?
7. LED Products – Where to turn for guidance
8. Items of Importance to Building Owners/Facility Mgrs
9. Final Thoughts – Some general rules

Final Thoughts

From the Specifier's Side

If you are a Lighting Designer, Architect, Utility, Municipality, etc.

- You and others in your firm need to become familiar with these issues if you (or they) are not presently up to date
- You should evaluate whether your supplier has addressed these issues adequately
- If they are new to you:
  - Find someone who is familiar with them and work with or hire them
  - Review literature available at DOE-SSL web site www.ssl.energy.gov as well as various manufacturers' web sites
  - Link up with some of the many groups involved in the solid-state lighting marketplace
    - Expect to hear conflicting viewpoints and strong opinions
  - Be prepared to have to re-specify a product during actual construction phase, and recover the cost of your time

Final Thoughts

From the Supplier's Side

Luminaire Manufacturers should provide a complete product:

- Quality of white light including color rendering, color temperature, radiation pattern, etc. Applications where the end-user must settle will be unsatisfactory no matter what "benefits" the product provides
- Consistency of light from fixture to fixture over temperature. In general, it is what the end-user is accustom to and expects
- Accurate lifetime reliability estimates – it is a fundamental premise of Solid-State Lighting and one of the things that justify the higher cost
- Support in volume; Device manufacturers promise a lot—the question is whether or not they can deliver
- Education of the customers including application engineering—so that they are applying the technology correctly to appropriate environments
- Define/Identify successor paths to discontinued products

Final Thoughts

From the User's Side

1. Temperature range specification for operation
   How does that compare with the maximum junction temperature for the LEDs used in the product?

2. Luminaire manufacturer
   - How long has the manufacturer been in business? What business?
   - Does the firm use brand name LEDs?
   - Were the LEDs tested to LM-80?

3. Warranty
   - Life expectancy of product (Energy Star requires at least a 3-year warranty)
   - What replacement costs are covered (e.g. installation labor, shipping, etc.)
   - What performance elements are warranted (e.g. CCT shift, lumen output, luminaire efficiency, etc.)

Final Thoughts

From the User's Side

4. Power Issues
   - Power Factor
   - Off-state power consumption (Energy Star requires < 0.5W)
   - Is the unit dimmable? With what controllers?
   - Step-down transformer compatibility for low-voltage retrofit products
5. Does it have a UL / ETL / CSA / applicable safety mark?
6. Chromaticity
   - Shift over time/temperature
   - Variation from fixture to fixture
7. Luminaire performance
   - Fixture efficiency (in lumens/Watt)
   - Delivered lumens (not just LED device performance)
   - IES files
   - LM-79 test results from approved third party laboratory
   - Lumen maintenance

Final Thoughts

A Simple Suggestion

Do not underestimate the use and practical application of simple COMMON SENSE

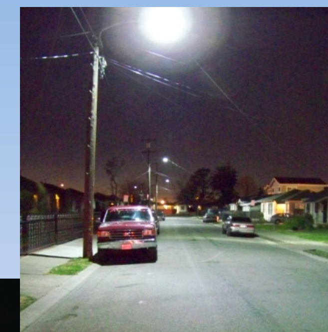
- If it seems too good to be true, it probably is
- If you can't understand how a product could do "that," there is a high likelihood that it probably "doesn't"
- If nobody else's product does "that" maybe this product does not do it either

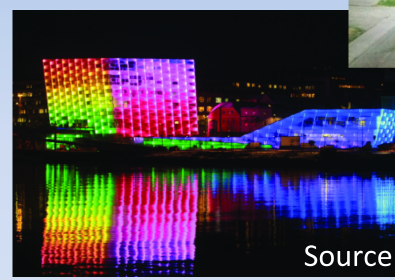
Which lamp would perform better?

Final Thoughts

Where are LED-Based Products Appropriate?

- Outdoor area & street lighting
- Downlighting
- Task lighting
- Display lighting
- Cove lighting
- "Architainment" environments
- Other applications that make use of LED's unique attributes
  - Small size
  - Directionality
  - Low temperature performance
  - Improved secondary optics performance due to die size





Source: Kelly Gordon, PNNL

Final Thoughts

A Lesson From History

- Think of how the microprocessor has changed the world over the last 30 years.

- The lighting world is about to undergo a change not seen since the invention of the incandescent lamp, and driven by that same semi-conductor industry.

Are you going to be ready for it?

Final Thoughts

DOE Resources

The Department of Energy offers a number of useful program to insure that quality products are available to the public and to further the adoption of efficient LED lighting

- SSL Quality Advocates
- Gateway Demonstration Program
- CALiPER
- Lighting for Tomorrow
- Next Generation Luminaires
- Municipal Consortium on LED Street Lights
- Technical Information Network for Solid-State Lighting
- DOE Funded R&D Programs

ssl.energy.gov

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Questions?

Thank You

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LED Transformations LLC
Your Guide to Solid State Lighting

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