New Rules for Lighting SSL-101

Design Lights Consortium
Stakeholder Meeting

October 28th

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Course Number: JWC-0002-0912

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DESIGNLIGHTS CONSORTIUM

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DESIGNLIGHTS CONSORTIUM

Course Description

New Rules for Lighting
SSL - 101

LED technology is changing the entire lighting world, from design to applications to language, creating a vast amount of confusion among the participants. Assumptions based on previous lighting experience with other technologies can be misleading, creating real risks for specifiers, installers, facility managers and end users. This course will provide an understanding of the basics of LED technology along with its new rules. LEDs' origins in the semi-conductor world will be examined to see why this relationship often creates conflict and confusion in the lighting world. Fundamental differences between LED and traditional lighting will be discussed. New industry standards such as LM-79, LM-80 and TM-21 will be reviewed. How CCT and CRI differ with LED lighting will be examined. Attendees will come away with a better understanding of LED characteristics and ways to reduce the risk of project failure.

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Learning Objectives

New Rules for Lighting
SSL - 101

1) How LEDs differ from traditional light sources in the method in which they produce light, and how those differences can affect the design of lighting projects
2) Haitz's Law and what the rapid changes in LED technology mean to the lighting professional
3) Review LED technology including issues such as binning and directionality.
4) Heat and its effect on LED lighting performance

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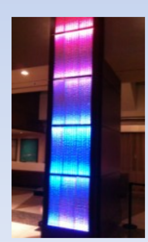
Course Outline

1. Introduction – A brief history of solid-state lighting technology
2. Physics of LEDs – How LEDs work
3. Standards – New rules more measurements
4. Final Thoughts – New rules for lighting



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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

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Introduction

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 having nothing to do with LEDs

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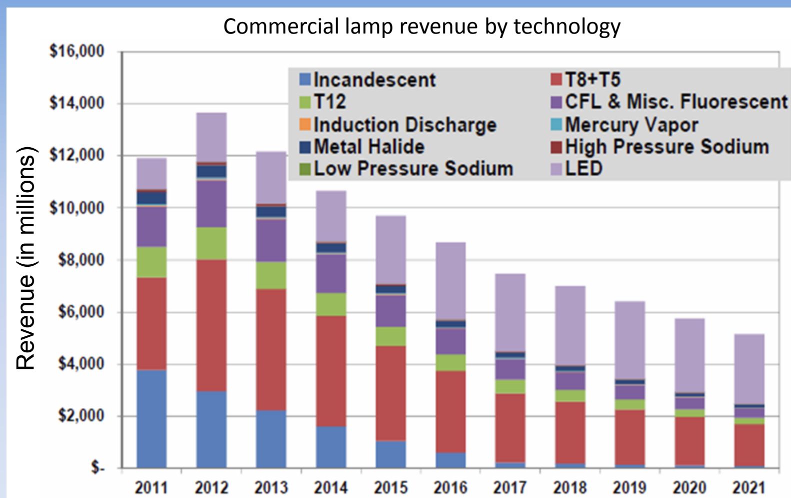
Introduction

LEDs Share in the Lighting Market



Source: Pike Research

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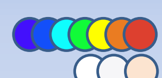
Introduction

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
- \+ No mercury
- \+ Integrates well 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)

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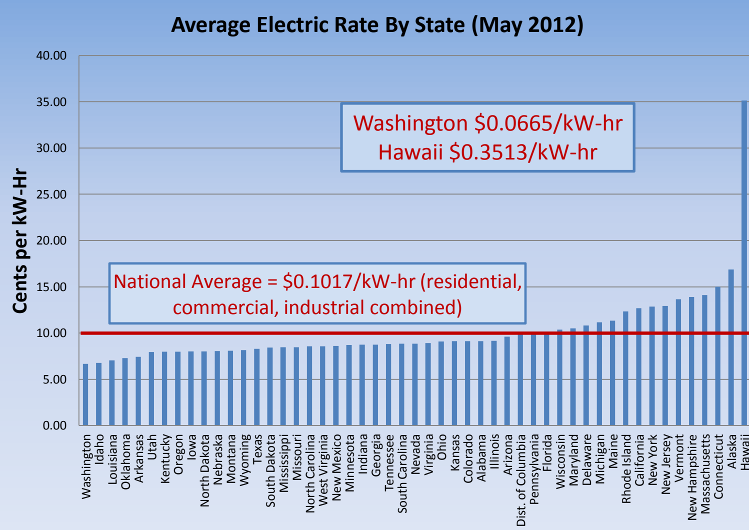
Why Should I Care About LEDs – It is a matter of economics



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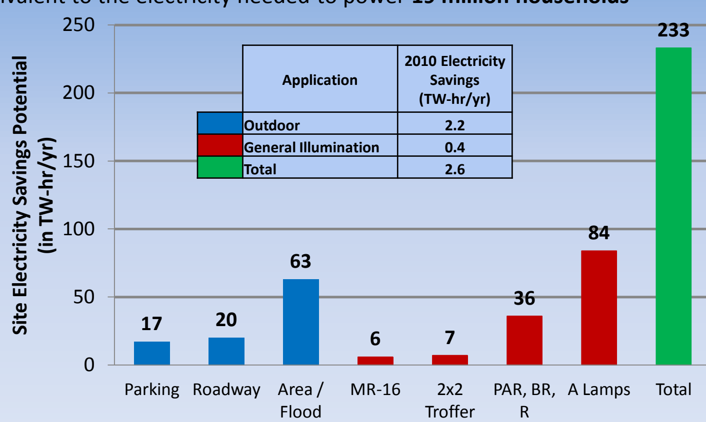
INTRODUCTION

Why Should I Care About LEDs?

- Total electricity savings potential of niche LED lighting applications: **233 TWh/yr**
- Equivalent to the electricity needed to power **19 million households**



Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications, Navigant Consulting, Inc., January 2011: www.ssl.energy.gov/tech_reports.html

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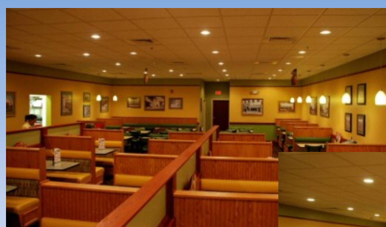
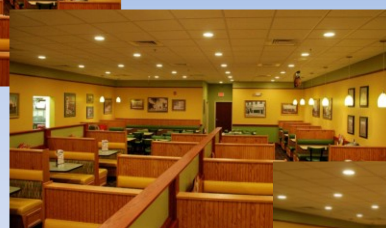
Introduction

Why Should I Care About LEDs? – They work!



Incandescent 5,135 W



LED 948W

Friendly's Restaurant, Westfield MA

Makes use of directionality

Source Cree

LED (2 Years Later)

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Introduction

Culture Clash – Not the first lighting revolution to confuse people

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Introduction

Culture Clash – The Origins of SSL

- Henry Joseph Round first observed electroluminescence in silicon carbide (SiC) in 1907 while checking the crystals for possible use as detectors used for demodulation of radio-frequency signals in radios
- Electroluminescence was reported again in 1923, by O.V. Losev of the Nijni-Novgorod Radio Laboratory in Russia
- B. Gudden and R.W. Pohl conducted experiments in Germany in the late 1920s with phosphors made from zinc sulfide doped with copper (ZnS:Cu).
- The next recorded observation of electroluminescence was by Georges Destriau in 1936 who came up with the term "electroluminescence" to refer to the phenomenon he observed
- In 1961, Bob Biard and Gary Pittman at Texas Instruments, discovered that GaAs emitted infrared radiation when electric current was applied. They received the first patent for an infrared LED

- In 1962, Nick Holonyak at General Electric developed the first practical visible light LED

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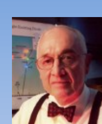
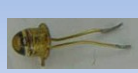
Introduction

Culture Clash – Some LED milestones

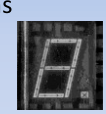


1962 First LED (Holonyak at GE) 0.001 lumens



1960's Red LEDs (HP & Monsanto) 0.01 lumens

1970's First consumer products - Watches, calculators



1980's Green LEDs 0.1 lumens

1990's Blue LEDs (Nakamura at Nichia) 1 lumen

2000's High flux packages 100+ lumens

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Culture Clash – Semi-conductor versus Lighting industries

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

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Introduction

Culture Clash – Semi-conductor versus Lighting industries

LED wafer fabrication facility

Courtesy Ron Bonne
Philips Lumileds

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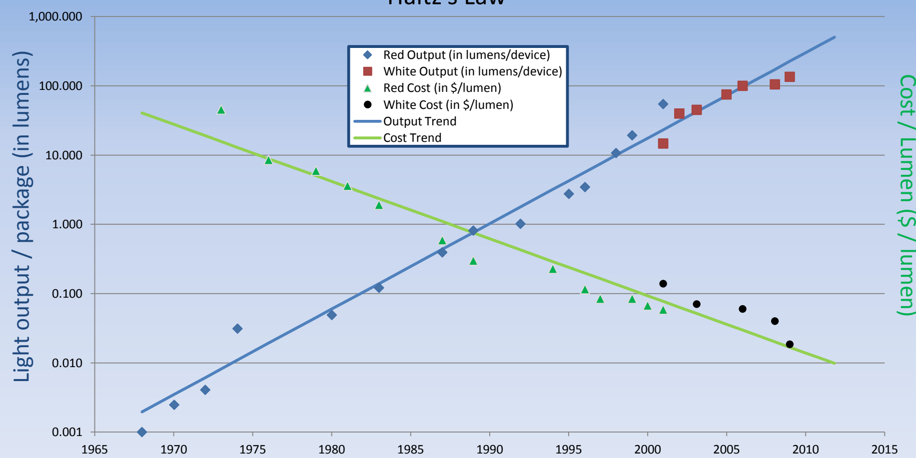
Introduction

Semi-Conductor Heritage – Improved performance and lower cost

Technological Push – Higher output and lower cost

Haitz's Law



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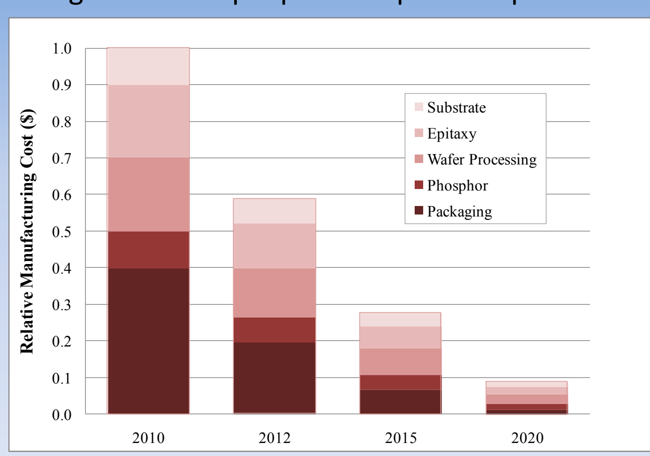
Introduction

Semi-Conductor Heritage – Improved performance and lower cost

LED Package Costs – rapid price drops are expected



Source: Data provided by the 2011 Manufacturing Workshop and Roundtable Attendees

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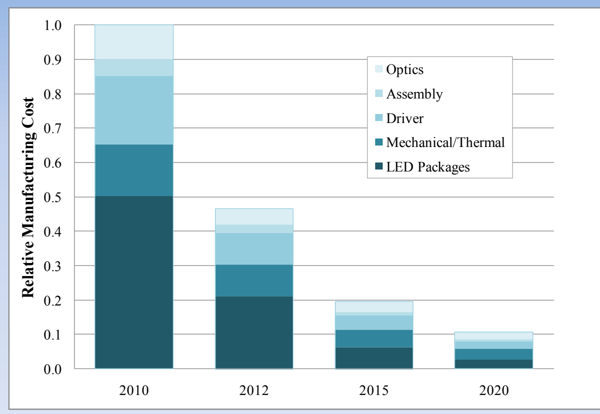
Introduction

Semi-Conductor Heritage – Improved performance and lower cost

LED efficacy improvements lead to cost reductions in other areas as well

Besides reduction in LED cost (Hait'z law), improvements in efficacy will reduce power and heat requirements, thereby lowering the cost for power supplies (drivers) and heat sinks



Source: DOE Manufacturing Workshop consensus

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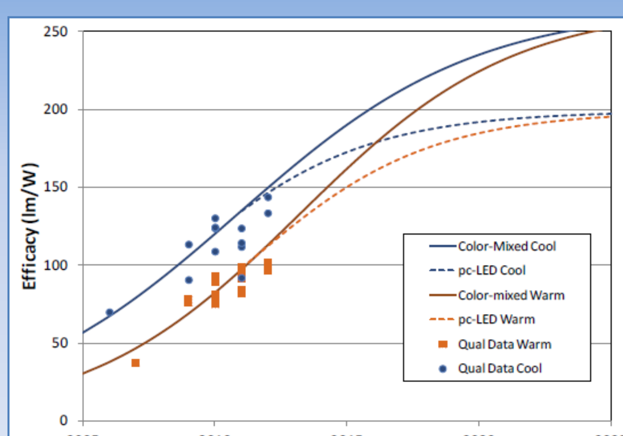
Introduction

Semi-Conductor Heritage – Improved performance and lower cost

White Light LED Package Efficacy Projections for Commercial Product



Source: DOE Multiyear Plan April 2012 p. 68

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INTRODUCTION

Semi-Conductor Heritage – 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

Source:
Scot Hinson
Modeliving

Early 20th century light fixture

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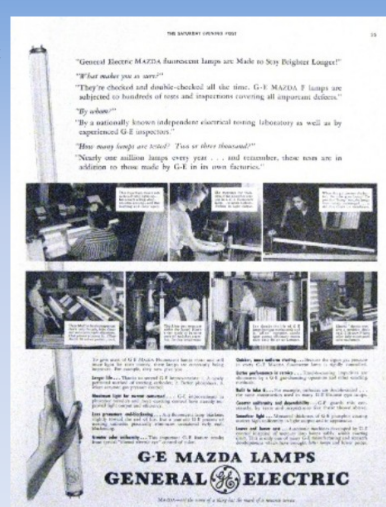
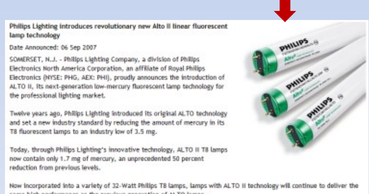
INTRODUCTION

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.

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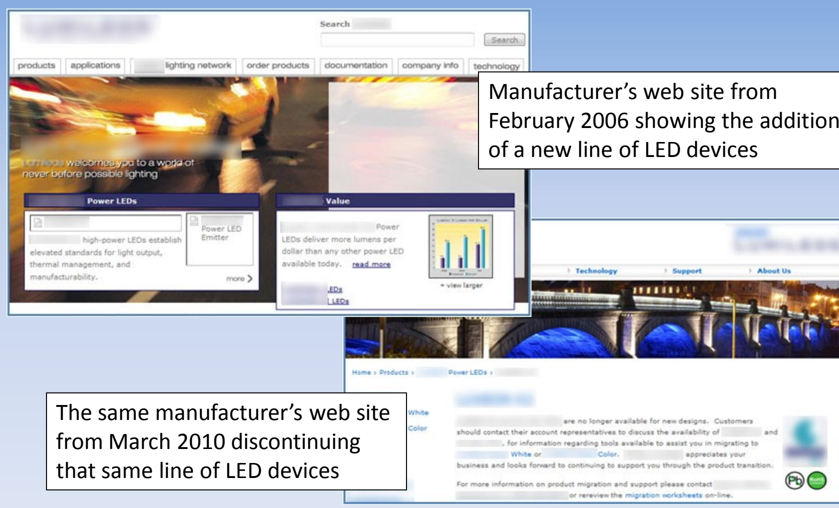
INTRODUCTION

Obsolescence – 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

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INTRODUCTION

Obsolescence – Can lead to unexpected consequences

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

INTRODUCTION

Different Cultures – Electronics vs. Lighting Industries

- Obsolescence is expected in the electronics industry, but new to the lighting industry, creating a culture "clash"
- LED Products tend to be designed as individual units with minimum consideration of modularity
- If there are controls, they tend to be specific to that particular device
- Creates issues for the overall lighting industry
- Cost is not the only barrier to market acceptance of LED lighting – lack of interchangeability is a major obstacle

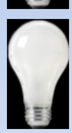
INTRODUCTION

Everything is Different – New names and shapes

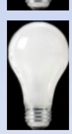
Traditional Lamp Suppliers

- Sylvania

- Philips



- GE



LED Suppliers

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

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Introduction

New Names & Shapes in Lighting – Compatibility

It is not just the LEDs that come in many flavors!

Will a replacement driver be available for your product 3 or 4 years from when you purchase the luminaire?

How about the optics?

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Introduction

Zhaga Consortium – One possible solution for compatibility

- Promotes the interchangeability of LED light engines for all applications in general lighting by specifying their interfaces and enabling easy identification of compliant products.
- Benefits:
  - Stable design platforms for luminaire makers
  - Future proof light engines which can be second sourced and upgraded by specifying:
    - Mechanical and thermal fit with the heat sink
    - Size of the light emitting surface
    - Height of the light emitting surface
    - Photometric properties of the light emitting surface
- Potential market impact:
  - Create market confidence in LED lighting solutions which stimulates the growth of the application of LEDs

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Introduction

Zhaga Consortium – One possible solution for compatibility

Just because everyone starts with the same components does not mean that everyone gets the same result

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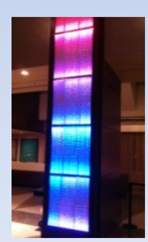
Course Outline

1. Introduction – A brief history of solid-state lighting technology
2. Physics of LEDs – How LEDs work
3. Standards – New rules more measurements
4. Final Thoughts – New rules for lighting



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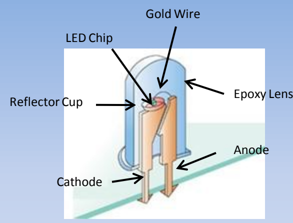
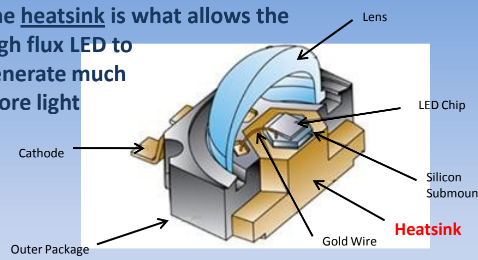
Physics of LEDs

Basic Types of LEDs

The heatsink is what allows the high flux LED to generate much more light





Typical construction for a 5mm LED

Typical Flux = 3 lm

Number of LEDs to equal the output of a 60W incandescent light bulb > 250

Typical construction for a High Flux LED

Typical Flux > 100 lm

Number of LEDs to equal the output of a 60W incandescent light bulb < 8

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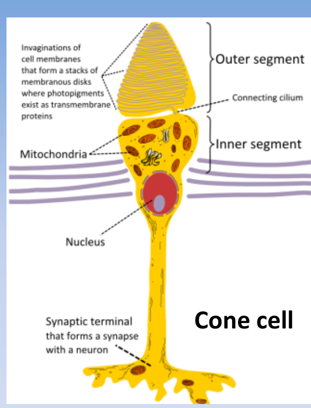
Physics of LEDs

Light Terminology – The eye receptors



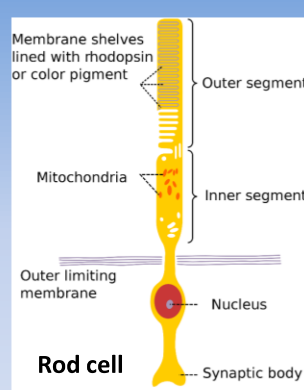


Image Source: Ivo Kruusamagi, Wikipedia

Some differences:

1. Three types of cone cells (long, medium and short wavelengths); one type of rod cell
2. Rods are about 100 times more sensitive to light than cones
3. Multiple rod cells terminate on one interneuron amplifying the signal but giving them less image resolution
4. Cones have a faster response time to light stimuli making them more sensitive to temporal changes

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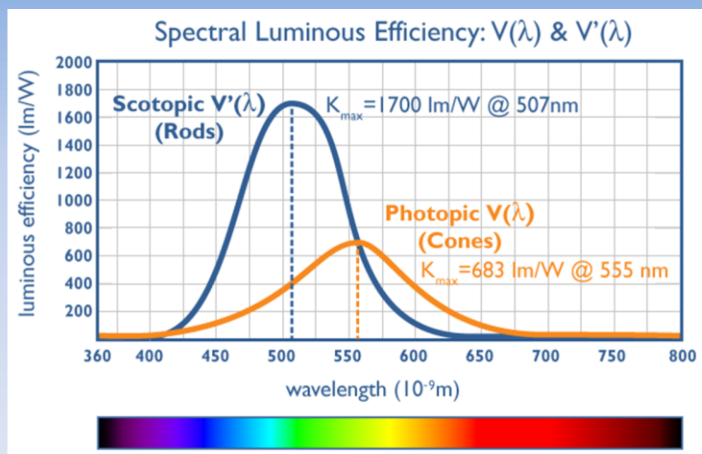
Physics of LEDs

Light Terminology – The eye receptors

Response difference between rods and cones



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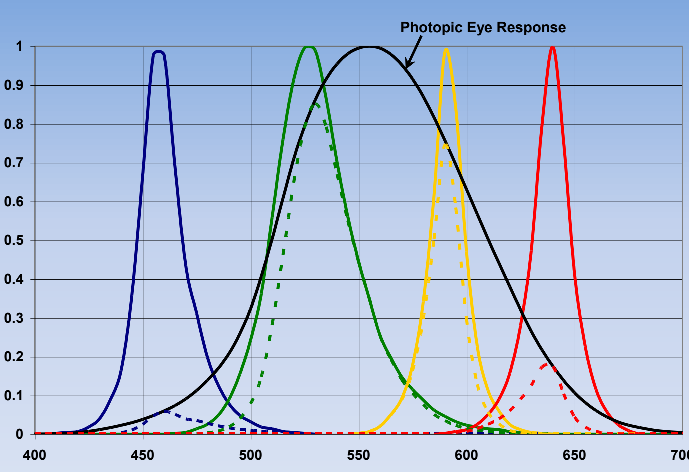
Physics of LEDs

Light Terminology – The eye's response to color



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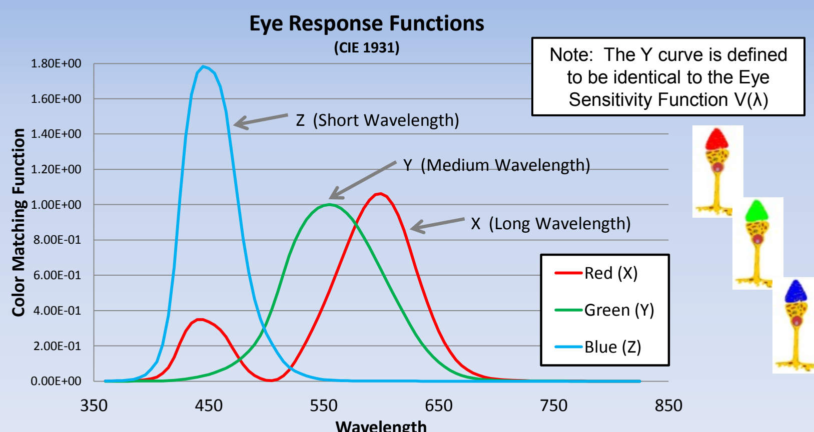
Physics of LEDs

Light Terminology – The Color Matching Functions

Each of the three cone cells responds differently to light depending on wavelength. A single cone's response is ambiguous. To determine color, multiple cones must be triggered and the brain compares responses to determine color. Color matching functions for the eye response are shown here.



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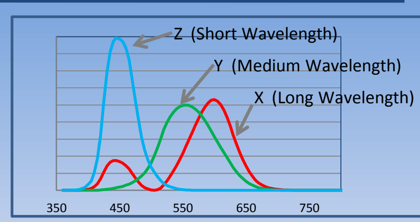
Physics of LEDs

Light Terminology – A coordinate system for color

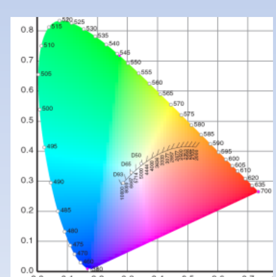
X, Y and Z are the spectral response curves for the three different cone receptors in the eye. If the eye response to a color stimulus is given by X, Y and Z, we can define a color coordinate system as the relative stimulus given by the following equations:



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

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

With x + y + z = 1 by definition, only two coordinates are necessary to define a color



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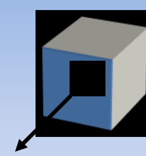
Physics of LEDs

Terminology – Color related to temperature

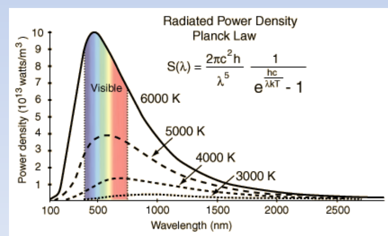
Blackbody Radiator is a device that absorbs all electro-magnetic radiation that falls on it. Its emissivity is equal to 1.

Planck's Radiation Law describes the radiation emitted from a blackbody radiator.



As the Blackbody Radiator is heated up, the spectral peak of the radiated light shifts toward the shorter wave-length (blue) portion of the spectrum.

This results in the higher temperature output being referred to as "cool" since it is more toward the blue side of the spectrum.



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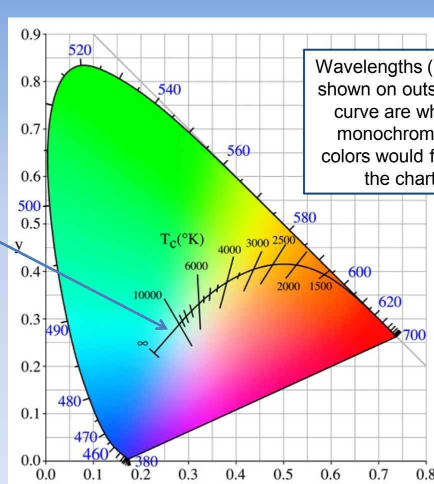
Physics of LEDs

Terminology – Color related to temperature

Plankian Blackbody Curve



Wavelengths (in nm) shown on outside of curve are where monochromatic colors would fall on the chart

CCT	Light Source
1500 K	Candlelight
2680 K	40 W incandescent lamp
3000 K	200 W incandescent lamp
3200 K	Sunrise/sunset
3400 K	Tungsten lamp
3400 K	1 hour from dusk/dawn
5000-4500 K	Xenon lamp/light arc
5500 K	Sunny daylight around noon
5500-5600 K	Electronic photo flash
6500-7500 K	Overcast sky
9000-12000 K	Blue sky

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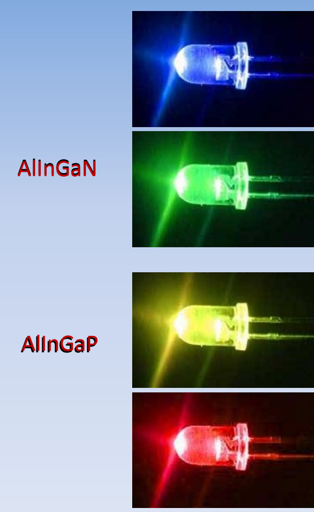
Physics of LEDs

LED chemical composition

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

Color dependent on bandgap which is set by type of dopant used

- Transition Elements
- Other Metals
- Metaliods
- Other non metals



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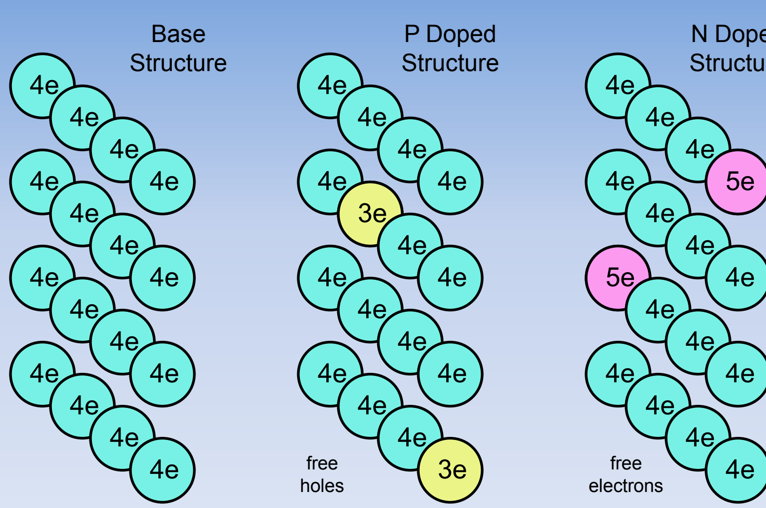
Physics of LEDs

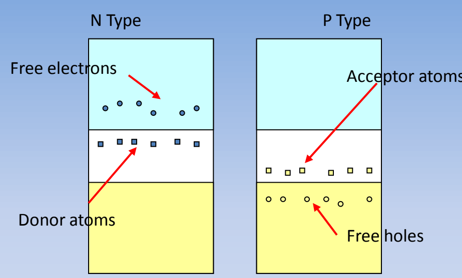
Semiconductor "Doping"



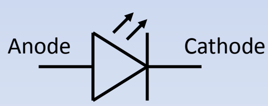
DESIGNLIGHTS CONSORTIUM

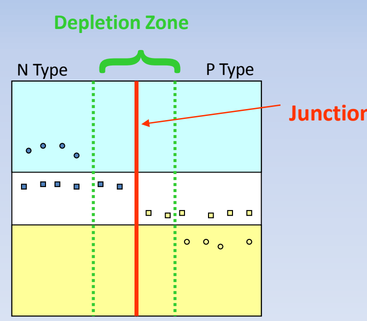
Physics of LEDs

The Parts of an LED – P and N materials



It takes a minimum voltage applied to the diode to get electrons and holes to flow across this depletion zone





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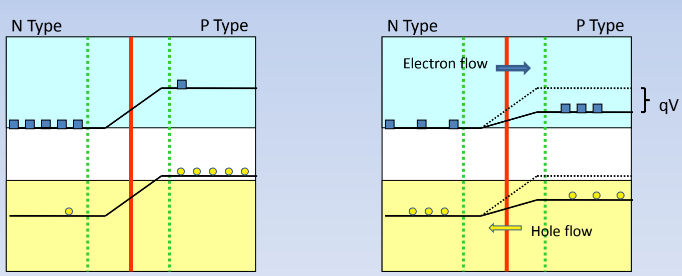
Physics of LEDs

The Parts of an LED – P and N materials

- Depletion zone creates a barrier which limits flow of carriers (electrons and holes)
- Applying a forward voltage V lowers that barrier and allows carriers to flow across the junction



Forward voltage applied

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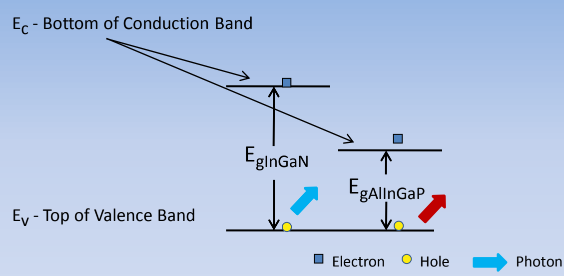
Physics of LEDs

Bandgaps – Different gaps, different colors

For metals E_g is small; for insulators E_g is very large. Materials between these two extremes are known as semiconductors



Material	Symbol	Band gap (eV) @ 300K
Silicon	Si	1.11
Germanium	Ge	0.67
Silicon carbide	SiC	2.86
Aluminum phosphide	AlP	2.45
Aluminium arsenide	AlAs	2.16
Aluminium antimonide	AlSb	1.6
Aluminium nitride	AlN	6.3
Diamond	C	5.5
Gallium(III) phosphide	GaP	2.26
Gallium(III) arsenide	GaAs	1.43
Gallium(III) nitride	GaN	3.4
Gallium antimonide	GaSb	0.7
Indium(III) phosphide	InP	1.35
Indium(III) arsenide	InAs	0.36
Zinc oxide	ZnO	3.37
Zinc sulfide	ZnS	3.6
Zinc selenide	ZnSe	2.7
Zinc telluride	ZnTe	2.25
Cadmium sulfide	CdS	2.42
Cadmium selenide	CdSe	1.73
Cadmium telluride	CdTe	1.49
Lead(II) sulfide	PbS	0.37
Lead(II) selenide	PbSe	0.27
Lead(II) telluride	PbTe	0.29

When electrons and holes combine, the resulting photon has a wavelength related to the bandgap energy given by

$\lambda = 1239 / E_g$

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

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

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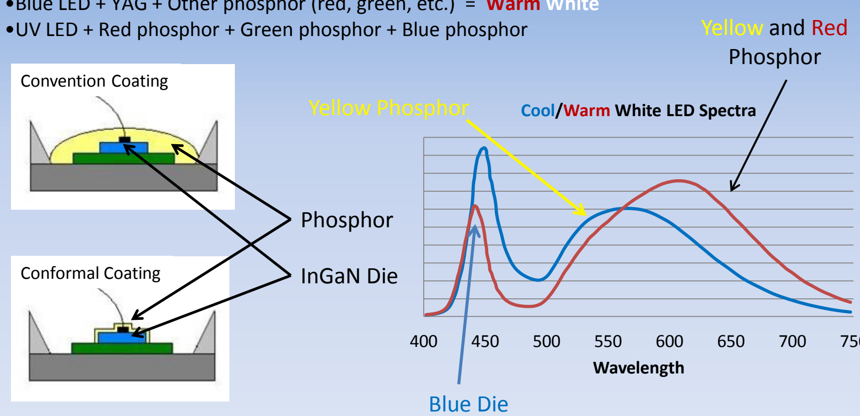
Physics of LEDs

How Do You Make a White LED?

Downconverting Phosphor

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



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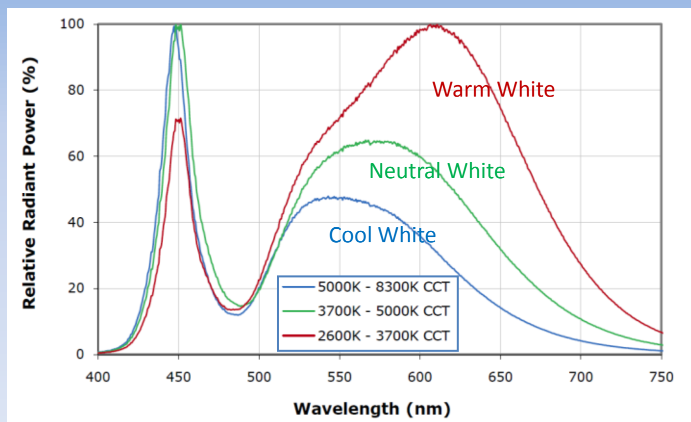
Physics of LEDs

How Do You Make a White LED?

Adding red to the phosphor mix produces light in the long wavelength region of the spectrum yielding a warmer light (lower CCT)



Source: Cree XP-G data sheet

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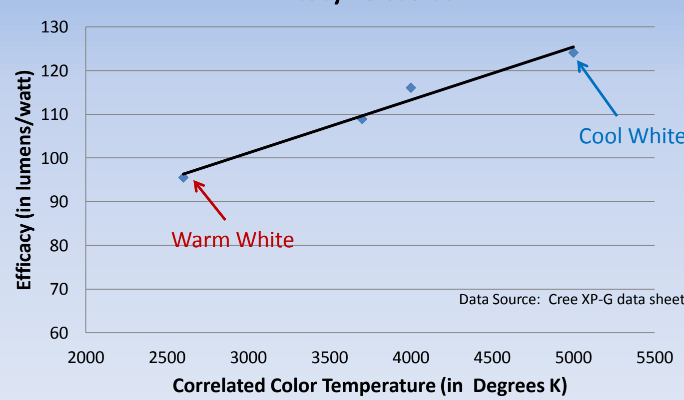
Physics of LEDs

How Do You Make a White LED?

Adding red to the phosphor mix also reduces the efficacy of the LED due to the lower lumen output of the red phosphor

LED Efficacy versus CCT



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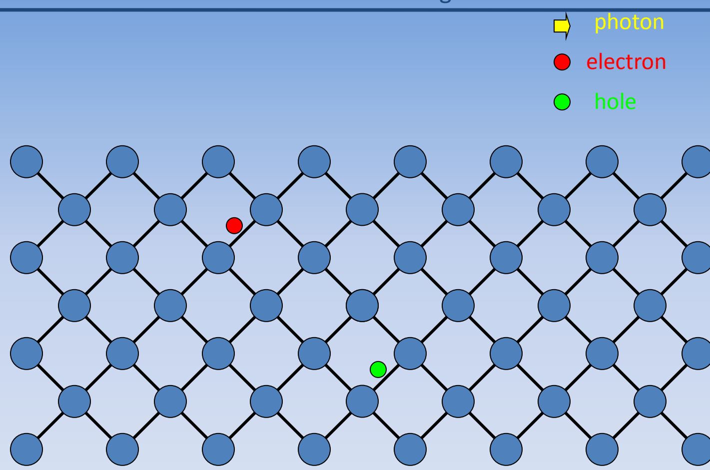
Physics of LEDs

Radiative recombination – Photon generation



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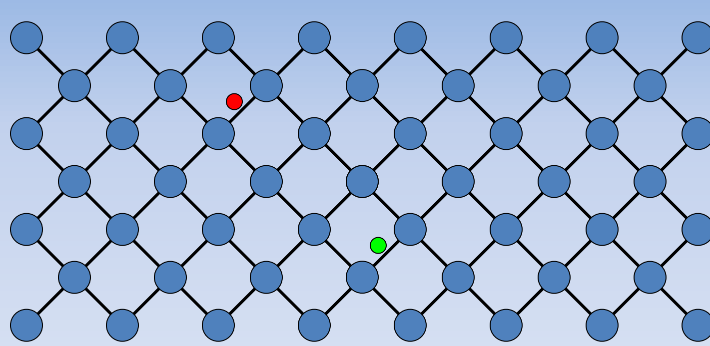
Physics of LEDs

Nonradiative recombination – Phonon or heat generation



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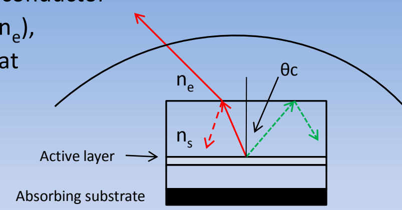
Physics of LEDs

Light extraction

Due to the high Index of Refraction of the semiconductor (n_s) as compared to the epoxy 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.



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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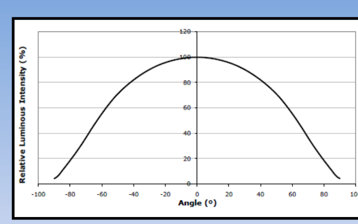
DESIGNLIGHTS CONSORTIUM

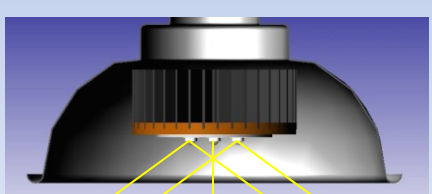
Physics of LEDs

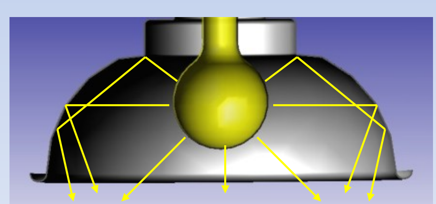
Photometric Considerations – Equivalent to traditional sources

What does "equivalent" mean?

- 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







In properly designed fixtures, this **might** be a benefit

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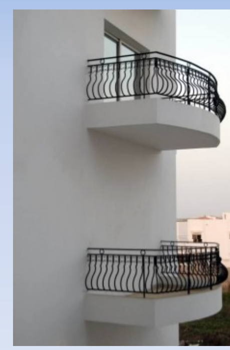
Physics of LEDs

Equivalence – Defining the term

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.



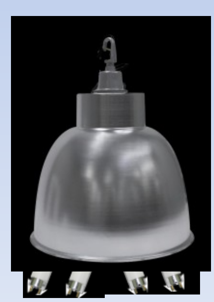
Are these two balconies equivalent?
Maybe not

Physics of LEDs

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

DESIGNLIGHTS CONSORTIUM

Physics of LEDs

Equivalence – Some cautions

Equivalency is a slippery slope when it comes to specifying LED lighting products. At a minimum consider the following:

- Total lumen output
  - Example: Energy Star requirements for replacement lamps as shown in table at right
- Total power consumed by luminaire (including all drivers, transformers, etc.)
- Intensity measurements over the target area (CBCP)
- Output used for ambient lighting (e.g. overall photometric light distribution)

Nominal wattage of lamp to be replaced (watts)	Minimum initial light output of LED lamp (lumens)
25	200
35	325
40	450
60	800
75	1,100
100	1,600
125	2,000
150	2,600

Data Source: Energy Star Requirements for Integral LED Lamps

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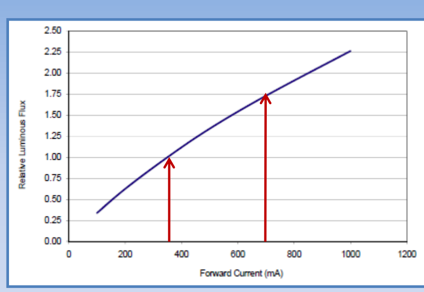
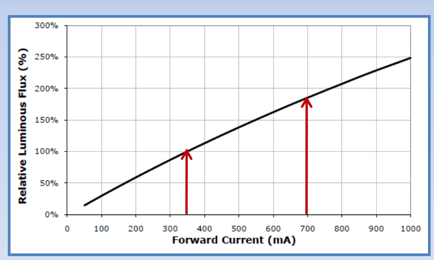
Physics of LEDs

LED Effects – Loss of efficacy due to "droop"



Philips' Lumileds ANSI Binned Rebel White

Droop is the loss of efficacy at higher power



Cree XP-G White

In these examples, doubling the drive current only increases the flux output by 75%

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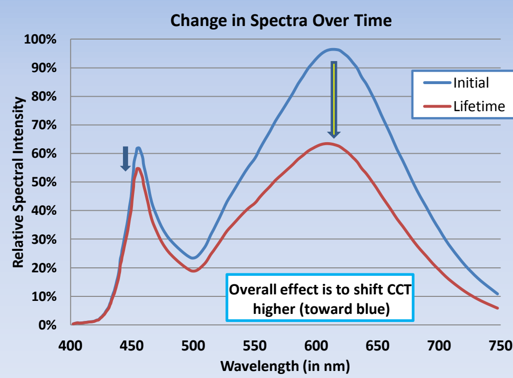
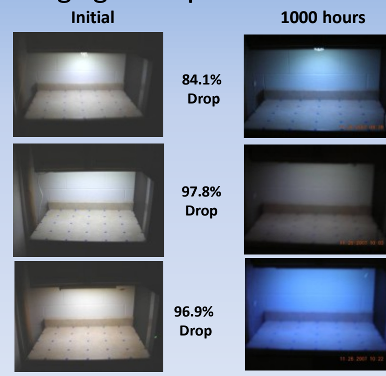
Physics of LEDs

LED Effects – Spectral content shift over time for white LEDs

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





Source: Cree

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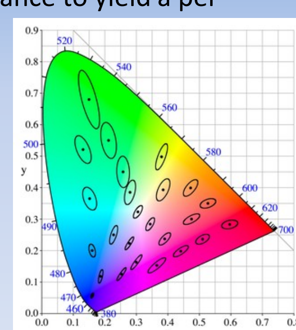
Physics of LEDs

Photometric Considerations – 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.

These distances, called steps, actually represent standard deviations. A one step MacAdam ellipse means that 68.3% of the test subjects could distinguish the difference between a color at the center of the ellipse and one on the boundary. Similarly, a two-step ellipse means 95.4% could distinguish a difference; three-step 99.4%, etc.



Plot for test subject PGN
Ellipses shown 10 times actual size

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Physics of LEDs

Photometric Considerations – Color Rendering Index

"Color rendering is a general expression for the effect of a light source on the color appearance of objects in conscious or subconscious comparison with their color appearance under another (reference) light source."

Source: IESNA Lighting Handbook (9th Edition)

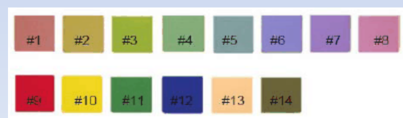
$$\Delta E_i = \sqrt{\Delta U_i^2 + \Delta V_i^2 + \Delta W_i^2}$$

where U, V and W are the 1964 Uniform Color Coordinates

$$R_i = 100 - 4.6\,\Delta E_i$$

where R_i is the Color Rendering Index for the specific color sample *i*

$$CRI = (1/8) \times \sum_{i=1}^{i=8} R_i$$



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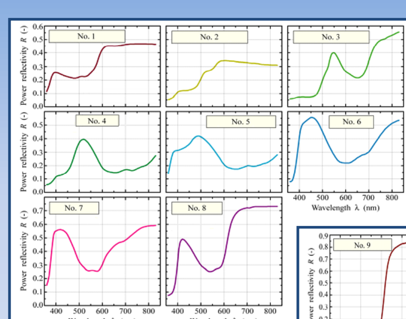
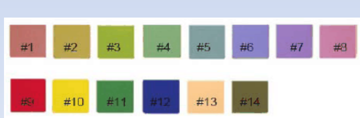
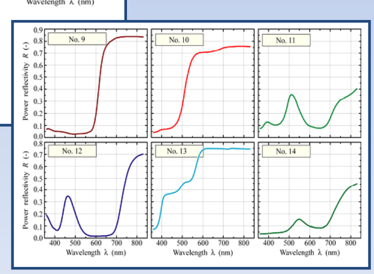
Physics of LEDs

Photometric Considerations – Color Rendering Index



Power reflectivity curves which define the CIE test-color samples used to calculate CRI





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Physics of LEDs

Photometric Considerations – 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).

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Physics of LEDs

Photometric Considerations – 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 (for example Metal Halide and R_9) – 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

Physics of LEDs

Photometric Considerations – Color Quality Scale

- 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

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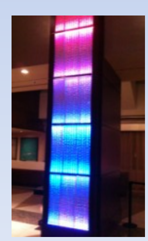
Course Outline

1. Introduction – A brief history of solid-state lighting technology
2. Physics of LEDs – How LEDs work
3. LED Standards – New rules for measurements
4. Final Thoughts – New rules for lighting



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LED Standards

Measuring the Revolution – A whole new set of rules

- Life
- Lumen Output
- Color Temperature (CCT)
- Color Rendering (CRI)
- Binning
- Power
- Efficiency/Efficacy
- Electrical
- Form Factors
- Safety

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DESIGNLIGHTS CONSORTIUM

LED Standards

Terminology – Some photometric definitions

- Candela—The luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540 x 10^{12} hertz and that has a radiant intensity in that direction of 1/683 watt per steradian. [a fundamental SI unit]
- Lumen—The luminous flux of a source that emits one candela into a solid angle of one steradian.
- Illuminance—The luminous intensity incident on a surface of one square unit of measure; given as lux in metric units and as foot-candles (fc) in English units where

  1 fc = 10.76 lux

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DESIGNLIGHTS CONSORTIUM

LED Standards

Terminology – Some historical photometric definitions

- Early English – One candlepower was the light produced by a pure spermaceti candle weighing one sixth of a pound and burning at a rate of 120 grains per hour.
- 1948 – CIE: New candle is such that the brightness of the full blackbody radiator at the temperature of solidification of platinum (2046^{O}K) is 60 new candles per square centimeter
- 1967 – CIE: The candela is the luminous intensity, in the perpendicular direction, of a surface of 1/600 000 square meter of a black body at the temperature of freezing platinum under a pressure of 101 325 newtons per square meter.
- 1997 – CIE: The modern definition of the candela was adopted. An arbitrary (1/683) term was chosen so that the new definition would exactly match the old definition.

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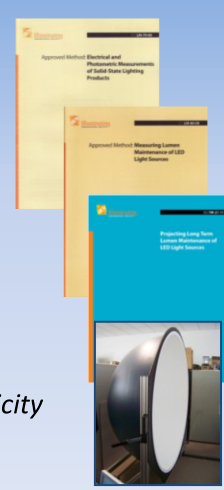
LED Standards

Standards – Help manage the risks

- **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 the method for determining when the "useful lifetime" of an LED is reached
- **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



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LED Standards

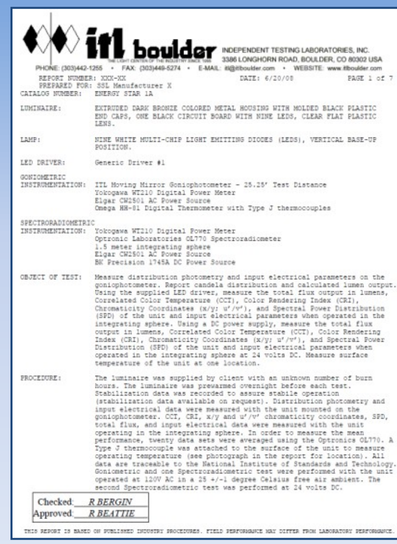
IESNA LM-79-08 – Dissecting a report

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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Source: Design Lights Consortium

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LED Standards

IESNA LM-79-08 – Dissecting a report

Data taken with a moving mirror goniophotometer

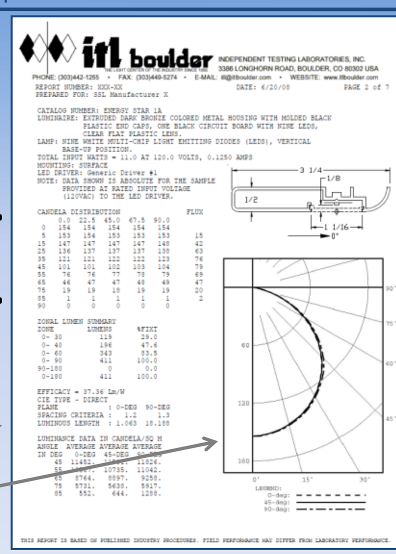
Description of the luminaire components (e.g. # of LEDs, driver used, etc.

Output intensity as a function of angle

Fixture efficacy

Spacing criteria for lighting designers

Graphical depiction of intensity distribution



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LED Standards

IESNA LM-79-08 – Dissecting a report

Data taken with an integrating sphere and spectroradiometer

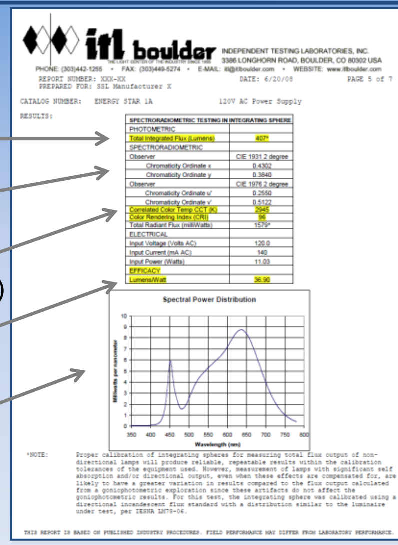
Total luminaire flux output (lumens)

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 nW/nm (milliwatts/nanometer)



Source: Design Lights Consortium

DESIGNLIGHTS CONSORTIUM

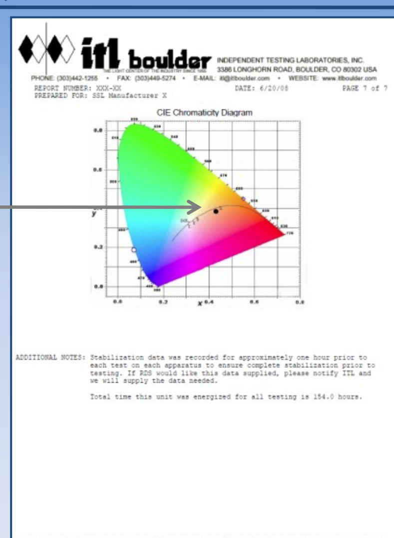
LED Standards

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.



Source: Design Lights Consortium

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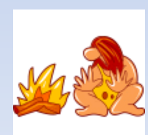
LED Standards

Lifetime Considerations – How long do light sources last?

• The sun	>4.5 billion years (so far)
• Candle	<12 hours
• Oil Lamp	<24 hours
• Incandescent	1k-2k hours
• Fluorescent	5k-24k hours
• Mercury Vapor	10k-20k hours
• Sodium Vapor	24k hours
• Metal Halide	10k-20k hours
• 5mm LEDs	<10k hours
• High Power LEDs	>50k hours



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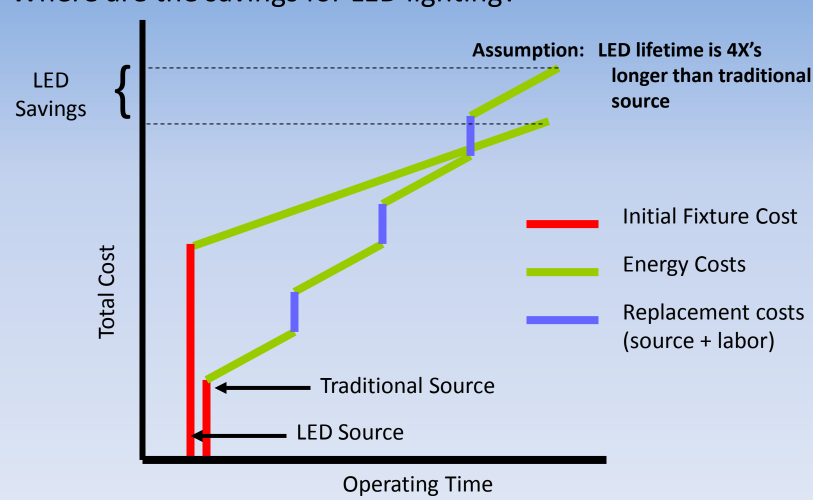
LED Standards

LED Economics – Energy and Maintenance Savings

Where are the savings for LED lighting?



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LED Standards

A Lighting Example – The low end

- 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

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LED Standards

A Lighting Example – The high end

- 12 Watts
- 800 lumens

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

Solid-state 800 lumen Light Bulb $25.00

Economics works only if lifetime / maintenance is considered

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DESIGNLIGHTS CONSORTIUM

LED Standards

Lifetime Considerations – How long will LED luminaires last?

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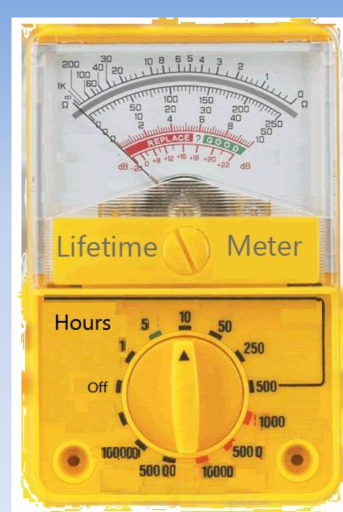
DESIGNLIGHTS CONSORTIUM

LED Standards

What Everyone Wants – The ultimate solution

If only choosing solid-state luminaires was this simple…



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DESIGNLIGHTS CONSORTIUM

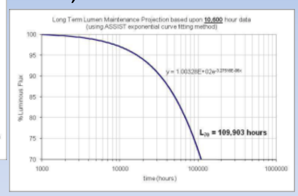
LED Standards

Lifetime Considerations – A measurement issue

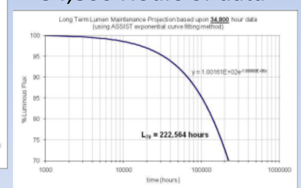
It is difficult to predict the long term performance of a device with only early lifetime data

6,000 Hours of data

10,600 Hours of data



34,800 Hours of data



Source: Cree

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

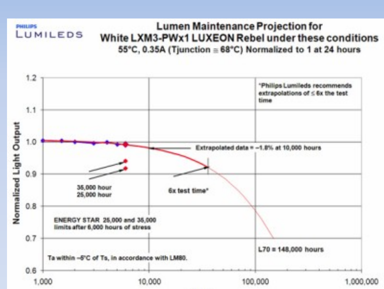
DESIGNLIGHTS CONSORTIUM

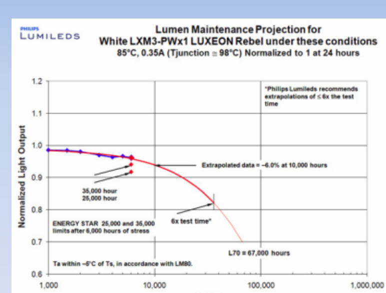
LED Standards

Lifetime Considerations – Effect of ambient temperature

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



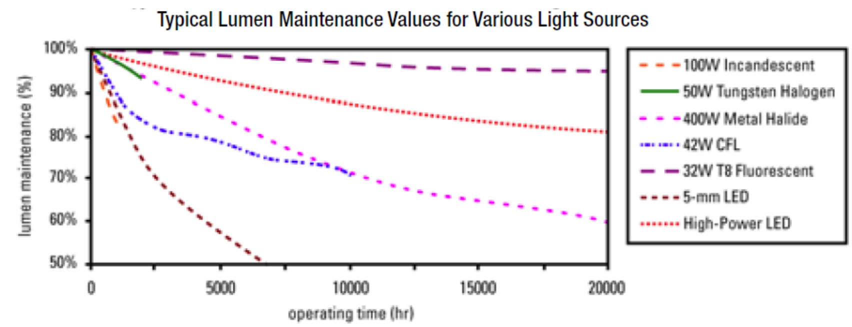


Source: Lumileds

DESIGNLIGHTS CONSORTIUM

LED Standards

Lifetime Considerations – How do various light sources compare?



Source: Adapted from Bullough, JD. 2003. *Lighting Answers: LED Lighting Systems.* Troy, NY. National Lighting Product Information Program, Lighting Research Center, Rensselaer Polytechnic Institute.

Source: US Department of Energy

DESIGNLIGHTS CONSORTIUM

LED Standards

Lifetime Considerations – Even incandescent….

light sources will last a long time if you take care of them. This one has been running for over 108 years!

Unlike many other light sources, LEDs don't fail prematurely due to rapid on/off cycles. In fact, rapidly cycling LEDs on and off is one means of controlling their output intensity

What's that spell?

Fire Station #6
Livermore-Pleasanton Fire Department

DESIGNLIGHTS CONSORTIUM

LED Standards

IESNA LM-80-08 - Measuring lumen depreciation

- Specifies test measurement conditions and points at which to take data - 0 to 6,000 hours in 1,000 hour increments with option to test to 10,000 hours
- Lumen depreciation of devices, not the luminaires
- Measurements based on L70 and L50 at specific drive currents and three different case temperatures
  - 55°C
  - 85°C
  - Manufacturer's choice for third temperature
- Does not specify how to extrapolate the data taken to arrive at a predicted lifetime – New standard TM-21 specifies this

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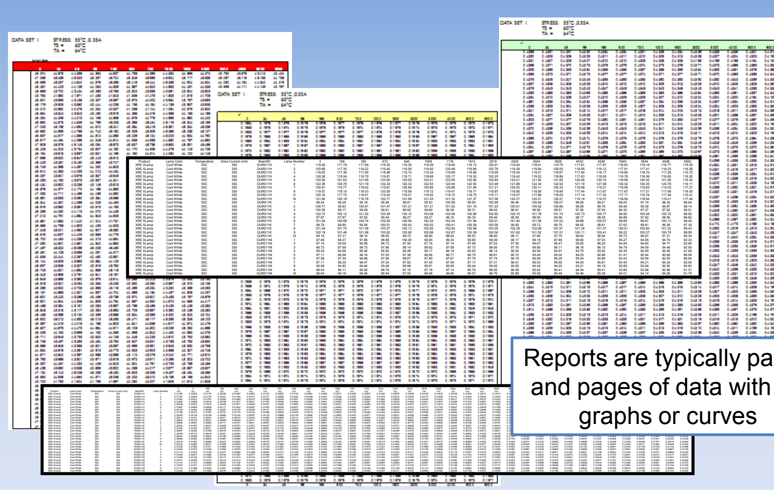
DESIGNLIGHTS CONSORTIUM

LED Standards

IESNA LM-80-08 – Measuring lumen depreciation



Reports are typically pages and pages of data with no graphs or curves

Source: Mark McClear, Cree

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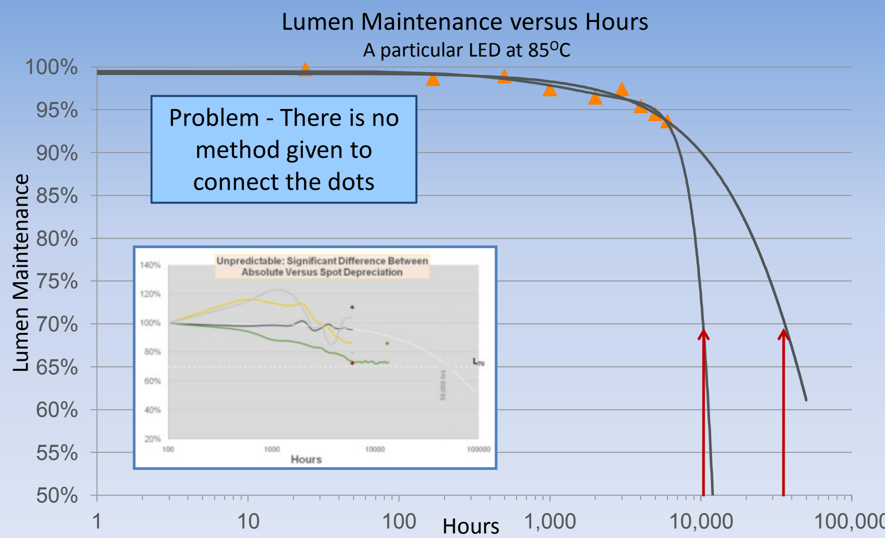
DESIGNLIGHTS CONSORTIUM

LED Standards

Standards – "Tested" to LM-80



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LED Standards

The Fix for LM-80 – TM-21

- Recommended number of sample test units is a minimum of 20 units
  - Allows extrapolation of test data to 6 times actual test time
  - If less than 20 units, extrapolation of test data is limited to 5.5 times actual test time
- Test method is not valid for sample sizes of less than 10 units
- Recommended curve-fit is an exponential least squares fit using the following equation:

$$\Phi(t) = B \exp(-\alpha t)$$

where $\Phi(t)$ is the averaged normalized luminous flux output over time
B is a projected initial constant derived by the least squares fit
and α is the decay rate constant derived by the least squares fit

- Extrapolation above the operating temperature used in the LM-80 test shall not be performed

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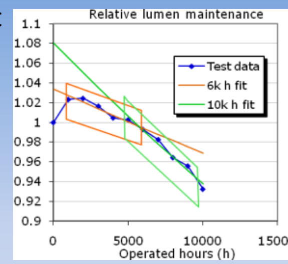
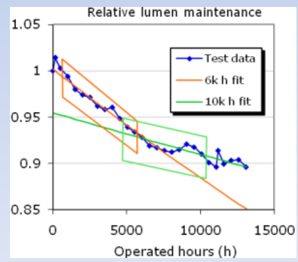
LED Standards

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 Eric Richman, PNNL

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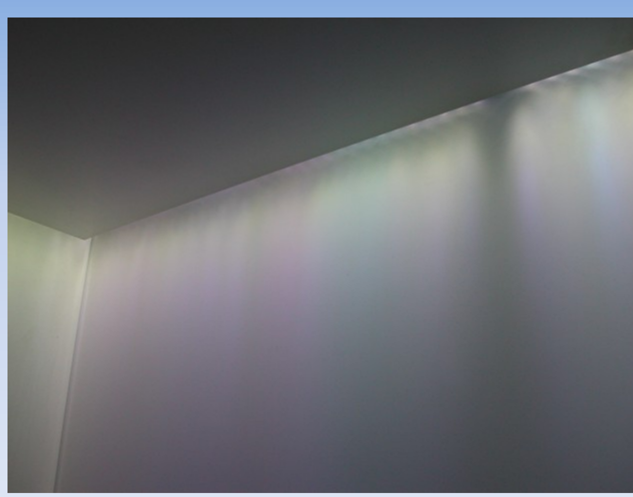
LED Standards

Photometric Considerations – Quality of Light



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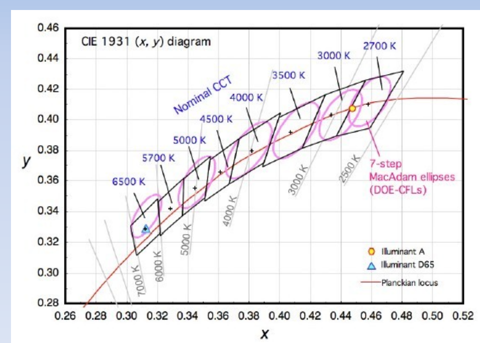
LED Standards

ANSI C78.377-2008

Specifications for the Chromaticity of Solid State Lighting Products

- 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



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DESIGNLIGHTS CONSORTIUM

LED Standards

Energy Star – General requirements for all luminaires

Highlights of Luminaire Criteria (V1.1) – **effective 4/1/12**

- New versions includes all light sources, not just LED
- Indoor luminaires shall have a minimum CRI of $R_a \geq 80$
- Lumen Maintenance:
  - Fluorescent/HID (shipped with product) – Average rated life shall be ≥10k hrs
  - Fluorescent/HID (shipped separate) – 80% of initial lumens at 40% rated life (4k hours minimum)
  - LED Residential – 25k hrs Indoor, 35k hrs Outdoor
  - LED Commercial – 35k hrs commercial
- Power Factor:
  - Fluorescent – Residential PF ≥ 0.5; Commercial PF ≥ 0.9
  - HID – PF ≥ 0.9
  - LED – Products drawing ≤ 5W PF ≥ 0.5
  - LED – All other products PF ≥ 0.7 Residential; PF ≥ 0.9 Commercial
- Color Maintenance (LED only): The change of chromaticity over the first 6,000 hours of luminaire operation shall be within 0.007 on the CIE 1976 (u',v') diagram.

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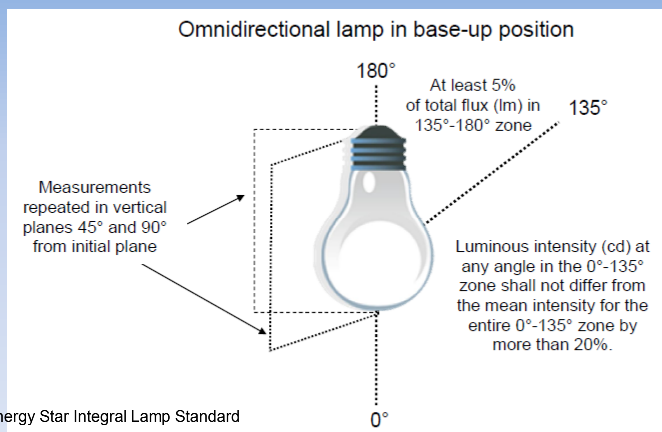
ENERGY STAR

LED Standards

Energy Star – Integral LED lamp requirements

Omnidirectional Lamps



Source: Energy Star Integral Lamp Standard

DESIGNLIGHTS CONSORTIUM

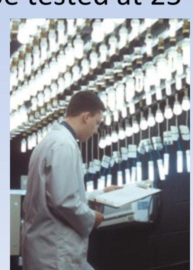
ENERGY STAR

LED Standards

Energy Star – Integral LED lamp requirements

Lifetime and Lumen Maintenance Testing

- Minimum of 6,000 hours of full lamp testing
  - 10 samples (5 with base up; 5 with base down)
  - Temperature requirements
    - Lamps < 10W and all decorative to be tested at 25^{O}C
    - Lamps > 10W to be tested at 45^{O}C
- Rapid cycle stress testing
  - 2 minutes ON; 2 minutes OFF
  - One cycle per two hours minimum life
    - 7,500 cycles for lamps with 15,000 hour life
    - 12,500 cycles for lamps with 25,000 hour life



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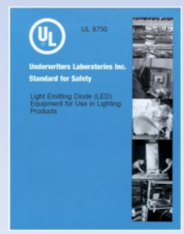
LED Standards

Agency Listings

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-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
- Power supplies (drivers) are tested under
  - UL 1012 – Power units other than Class 2
  - UL 1310 – Class 2 Power units
  - UL 2108 – Low voltage lighting systems



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LED Standards

Field Measurements – Sources of error

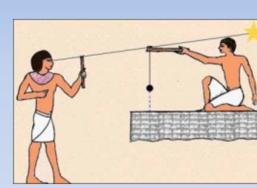
When evaluating field measurements, keep in mind the following:

Measurement Error

- 4% output between different samples
- 2.4% difference between goniophotometer and integrating sphere
- 2% difference between laboratories

Sample Size

- More than one unit is needed
- More samples desirable / trade off with cost
- Warranty hard to enforce with a sample size of one



Pre-installation Measurements

- Cannot rely on manufacturer data (internal QA/QC)
- Significant measurement errors could be introduced if not pre tested
- Testing, documenting, installing, and retesting of same sample at same lab is ideal

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LED Standards

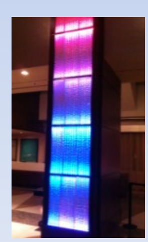
Additional Standards – Still missing a number of important ones

- Driver lifetime and reliability
- Luminaire lifetime
- Luminaire color shift
- Dimming for luminaires
- Flicker tolerances
- Transient protection
- Power quality

DESIGNLIGHTS CONSORTIUM

Course Outline

1. Introduction – A brief history of solid-state lighting technology
2. Physics of LEDs – How LEDs work
3. Standards – New rules more measurements
4. Final Thoughts – New rules for lighting



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Final Thoughts

Design Options – Be careful what you ask for; you might get it

- 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?
- 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

Cut-off Extremes

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Final Thoughts

Customer Checklist – Ask your supplier

1. Know your supplier
   a) How long in business?
   b) What is their track record?
   c) Who are their suppliers (LEDs and drivers in particular)?
2. Know your application
   a) Hot environment
      i. Potential shift in color
      ii. Reduced lifetime / lower light output
   b) Lighting controls
      i. Performance can be unpredictable
   c) Legacy wiring / transformers
3. Have realistic expectations
   a) There will be required maintenance
   b) There will be failures
4. Pilot, Pilot, Pilot
   a) You will not have thought of everything!

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Final Thoughts

Customer Checklist – Ask your supplier

5. Minimum standards
   a) LM-79 Testing
   b) LM-80 / TM-21 Testing
   c) Lighting Facts Label
   d) UL/ETL/CSA Listing
6. Clear performance expectations
   a. Acceptable range of initial/long term color variation
   b. Acceptable range of initial/long term light output
   c. Acceptable range of initial/long term luminaire efficiency
   d. Traditional performance parameters
      i. Weather resistance
      ii. Housing fixture wear
   e. Availability
      i. Initial orders
      ii. Subsequent orders
   f. Warranty – what is covered and what is not?

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Thank you for your time

Questions?

This concludes The American Institute of Architects Continuing Education Systems Program

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U.S. DEPARTMENT OF ENERGY
Energy Efficiency & Renewable Energy

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Thank You

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