The Darker Side of LEDs

Indiana Electrical Expo 08

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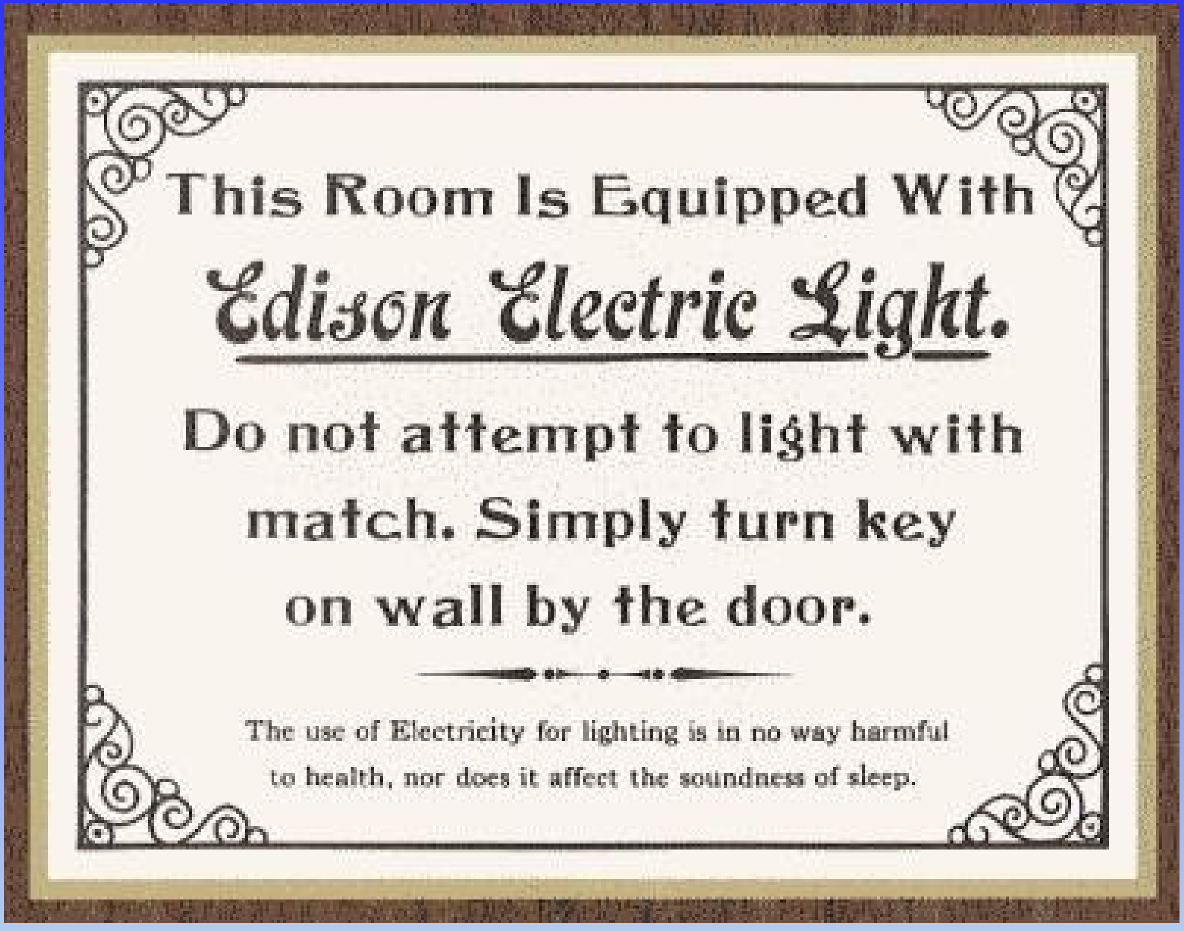
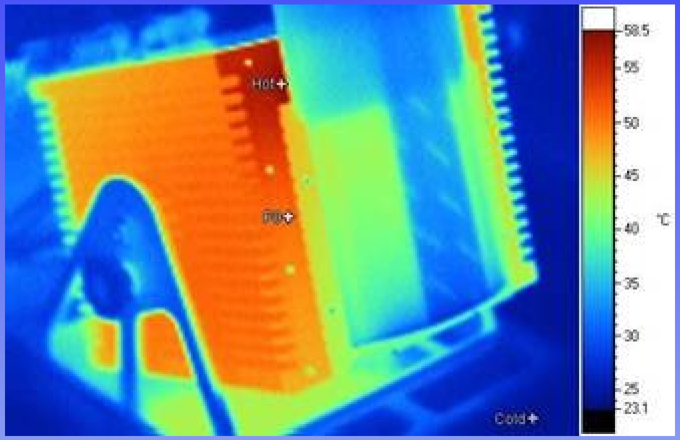
Introduction to LEDs



Outline

- Introduction
- Electronics Issues
- Binning Issues
- Thermal Issues
- Lifetime Issues
- System Issues
- Looking on the Bright Side
- Summary



Introduction to LEDs

The Solid State Lighting Industry is in a major growth mode

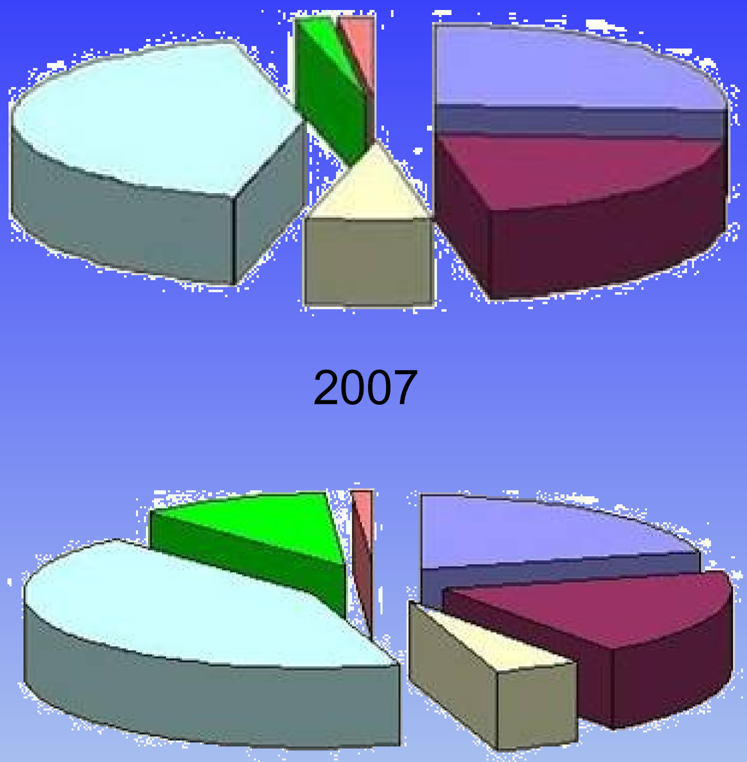
Improvement in light output of high flux LEDs are rapidly giving rise to many new applications and products, particularly in the general illumination area

Haitz's Law: LED output increases by a factor of 20 while cost decreases by a factor of 10 every 10 years

Sales of High Power LEDs (devices) were $330M in 2007 and are forecast to be over $1.4B by 2012

Introduction to LEDs

Percentages of the Lighting Market



2007

2012

Light Sources (2007 / 2012)

Other (2% / 1%)

LED (2% / 11%)

Linear Fluorescent (42% / 43%)

HID (7% / 5%)

Compact Fluorescent (21% / 19%)

Incandescent/Halide (26% / 21%)

Strategies in Light 2008

Introduction to LEDs

LEDs are showing up in more and more applications

Color changing

Ben Franklin Bridge
Philadelphia

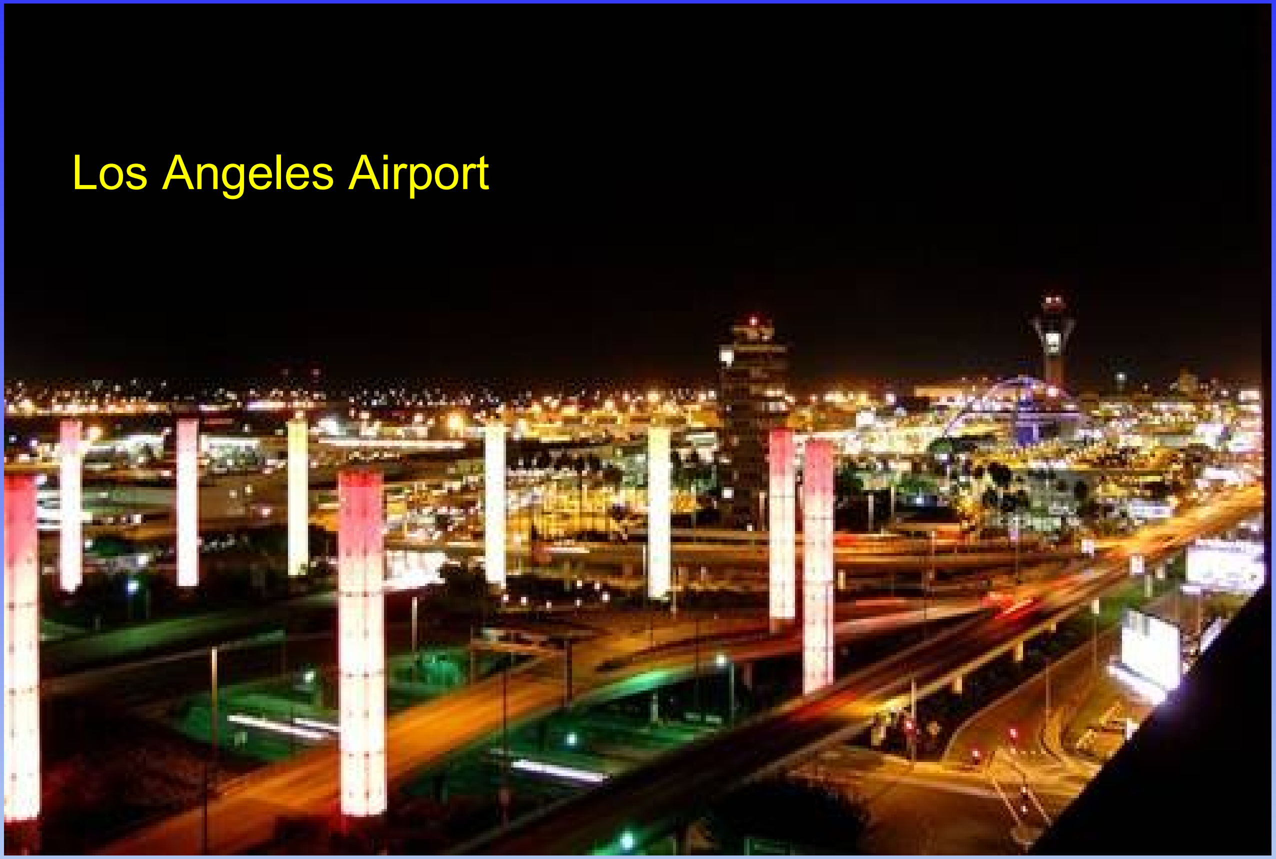
Boeing 787
Dreamliner

Introduction to LEDs

Architectural

Hard Rock Hotel
Las Vegas

Introduction to LEDs



Street/Parking Area Lighting

Oakland, CA

Racine, WA

Courtesy BetaLED

A quick quiz:

LEDs are the most efficient light sources available Maybe

LEDs are safe because they are low voltage devices Maybe

LEDs don't generate any heat No

LEDs last forever Depends on your definition of "forever"

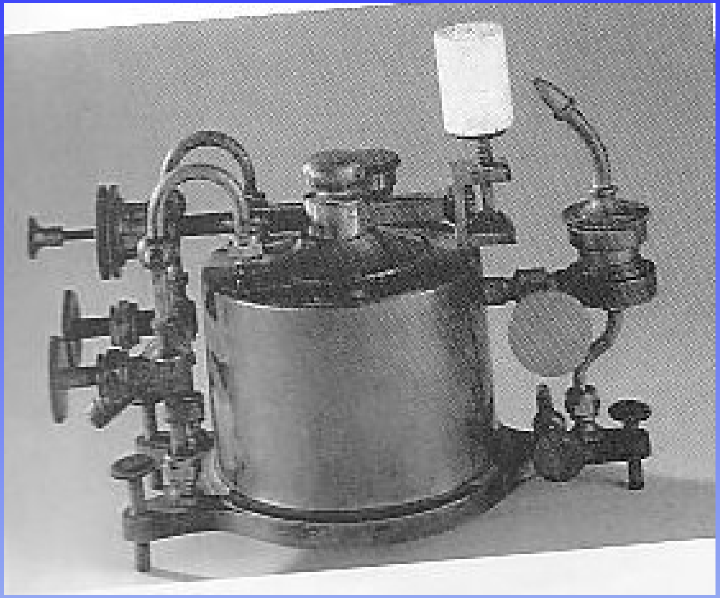
LEDs are just like other light sources (only better) No

LEDs are simple to work with No

LEDs are a major element in the future of lighting Definitely

Introduction to LEDs

Limelight - the first solid-state lighting device (introduced by Thomas Drummond in 1826)



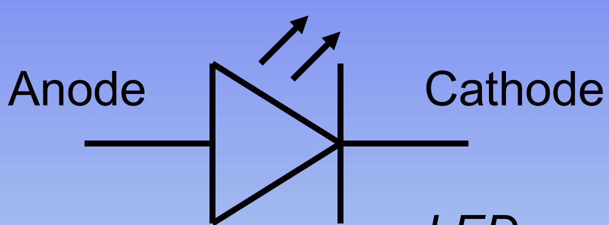
Cylinder of lime (calcium oxide) which is heated to a state of dazzling brilliancy by the flame of the oxy-hydrogen blowpipe

Introduction to LEDs

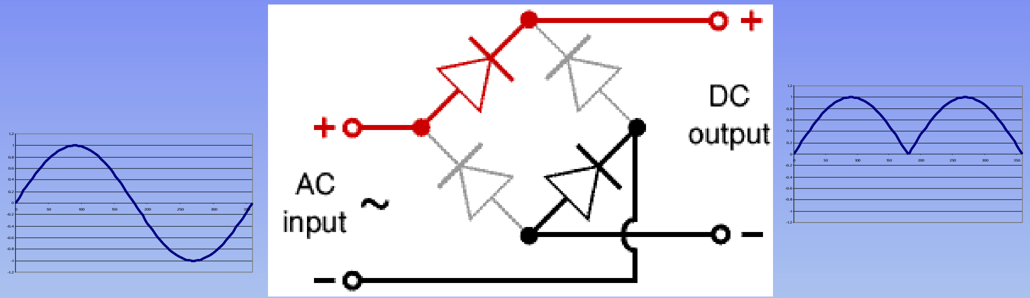
What is a diode?

A diode is a component that restricts the directional flow of charge carriers. Essentially, a diode allows an electric current to flow in one direction, but blocks it in the opposite direction. Thus, the diode can be thought of as an electronic version of a check valve. Circuits that require current flow in only one direction typically include one or more diodes in the circuit design.

Wikipedia



LED Symbol



Diode Rectifier Bridge

Introduction to LEDs

How do you make LEDs?

AlInGaP
Red, Red-Orange
Yellow

AlInGaN
Green, Blue,
White

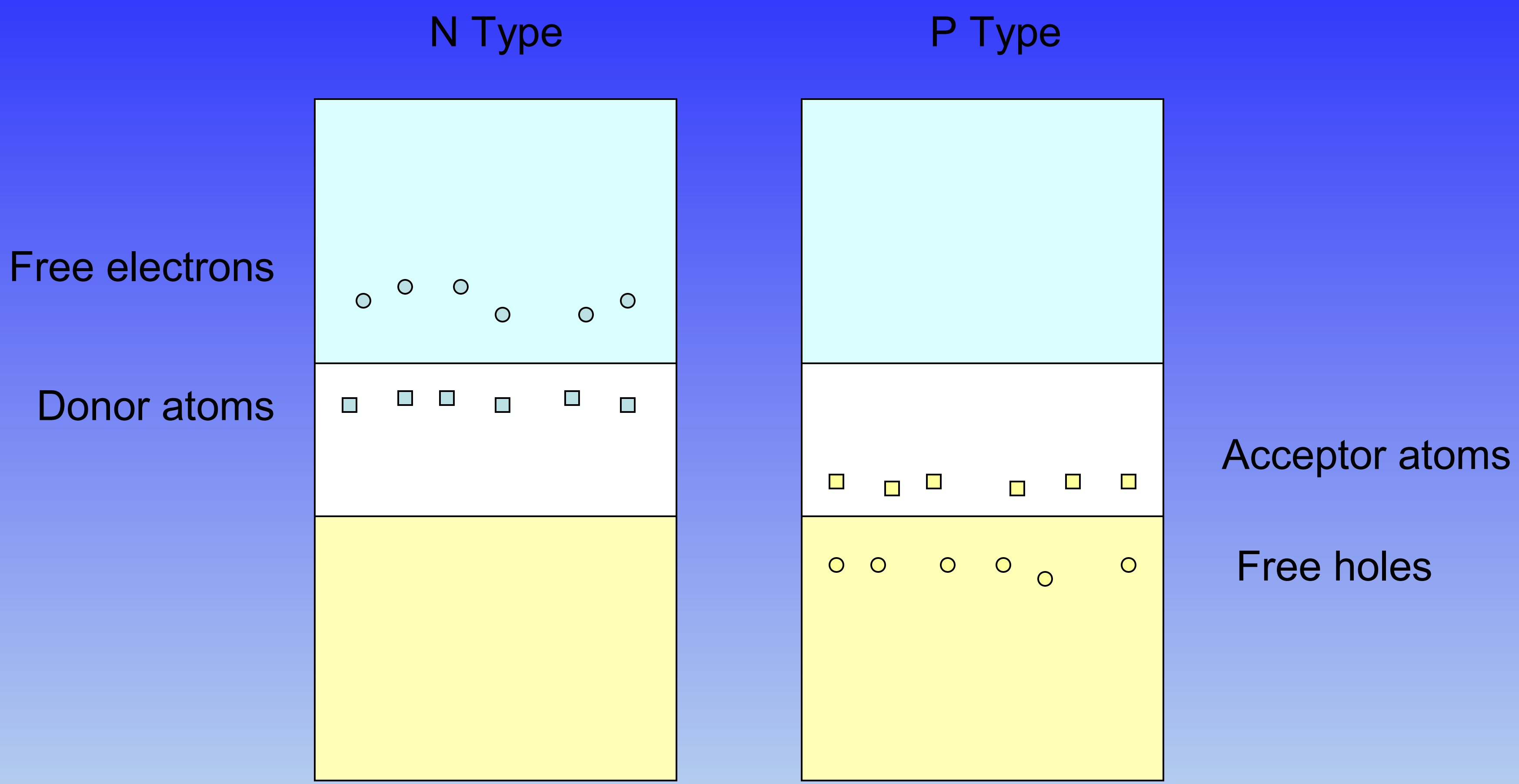
Group IIIA	Group IVA	Group VA
5 **B** Boron 10.811	6 **C** Carbon 12.0107	7 **N** Nitrogen 14.006
13 **Al** Aluminum 126.981	14 **Si** Silicon 28.0955	15 **P** Phosphorus 30.973
31 **Ga** Gallium 69.723	32 **Ge** Germanium 72.61	33 **As** Arsenic 74.921
49 **In** Indium 114.818	50 **Sn** Tin 118.710	51 **Sb** Antimony 121.760

Base Elements
P-Type Dopants
N-Type Dopants

Substrates
Silicon Carbide (SiC)
Sapphire (Al_2O_3)

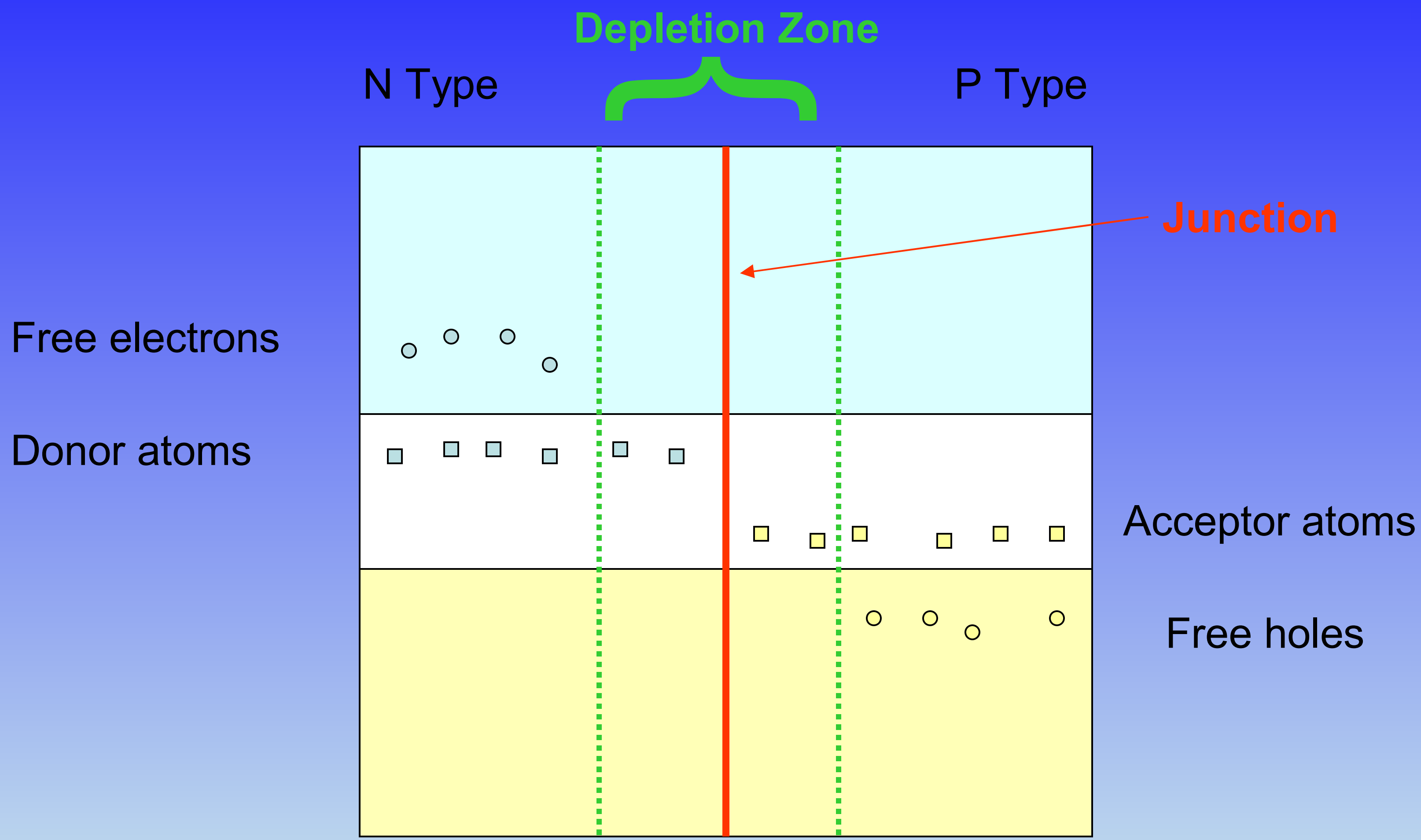
Introduction to LEDs

Physics of a diode



Introduction to LEDs

Physics of a diode (cont'd)



Introduction to LEDs

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

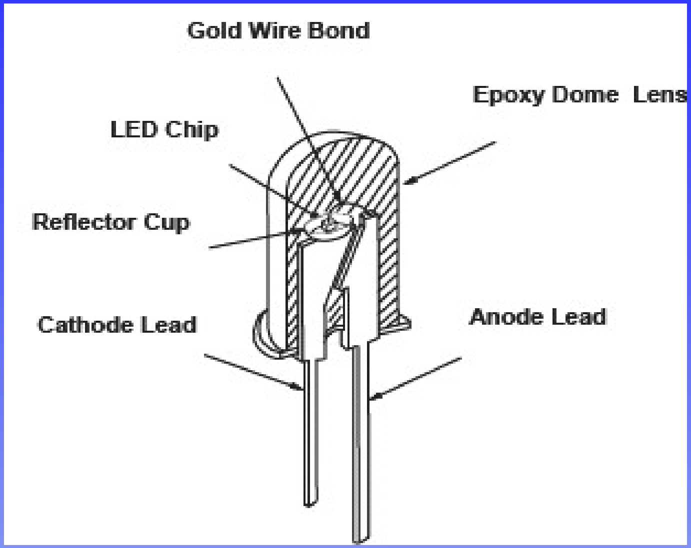
1980's Green LEDs 0.1 lumens

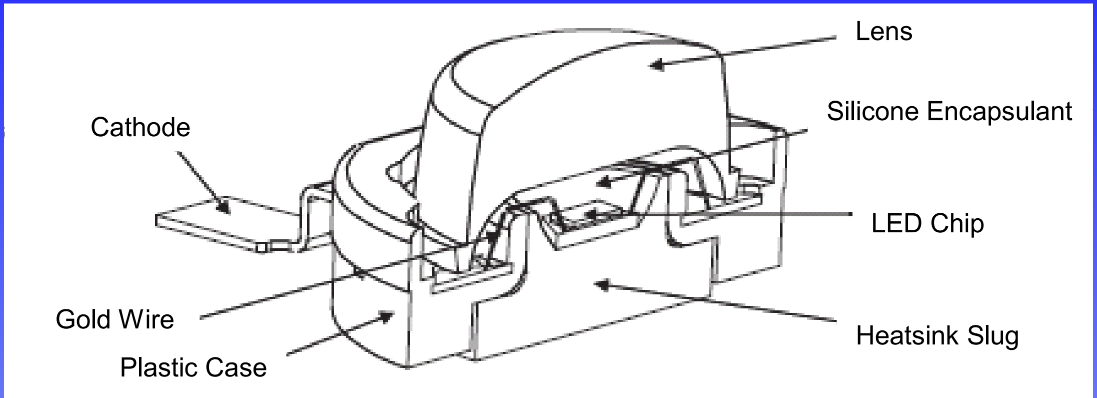
1990's Blue LEDs (Nakamura at Nichia) 1 lumen

2000's High flux packages 100 lumens

Introduction to LEDs

Types of LEDs





Typical construction for a 5mm LED

Typical Flux = 3 lm

Number of LEDs to equal the output of a 60W incandescent light bulb = 200

Typical construction for a High Flux LED

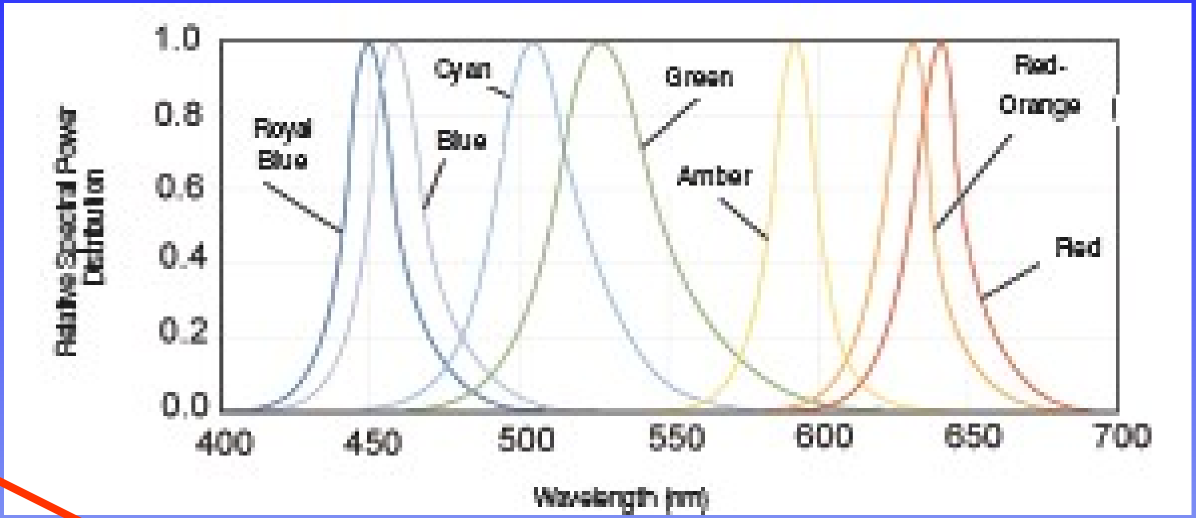
Typical Flux > 70 lm

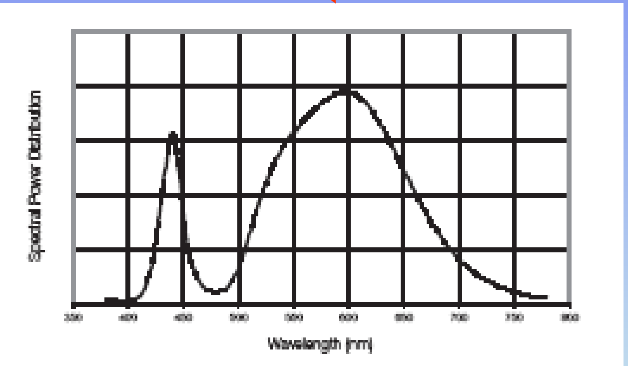
Number of LEDs to equal the output of a 60W incandescent light bulb < 12

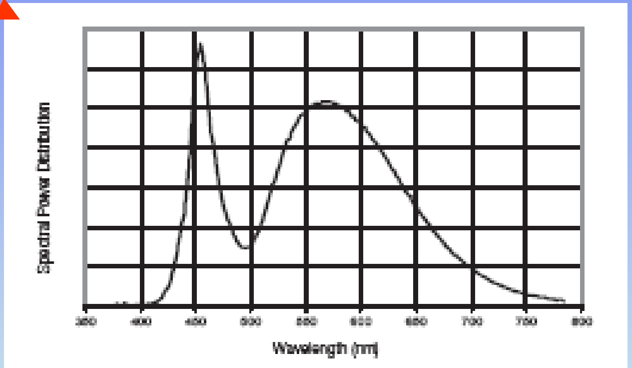
Introduction to LEDs

Two Types based on color

- Monochromatic
- White
  - Cool
  - Neutral
  - Warm





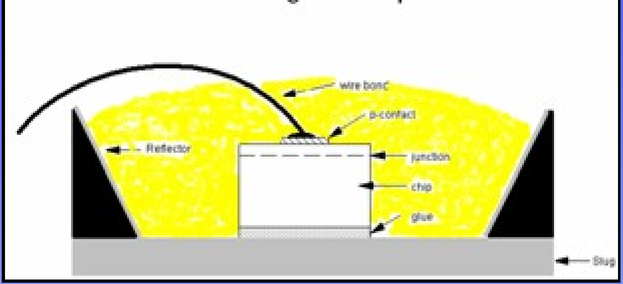


White LEDs—Phosphor Methods

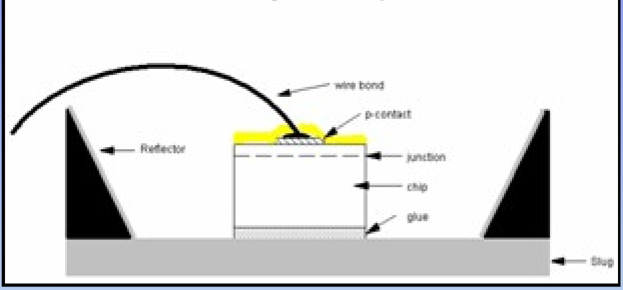
Visible LED Pump + Phosphor Method

Blue LED + YAG (Yttrium-Aluminum-Garnet) **Cool White**

Blue LED + YAG + Other phosphor (red, green, etc.) **Warm White**



Conventional Coating of Phosphor Granules

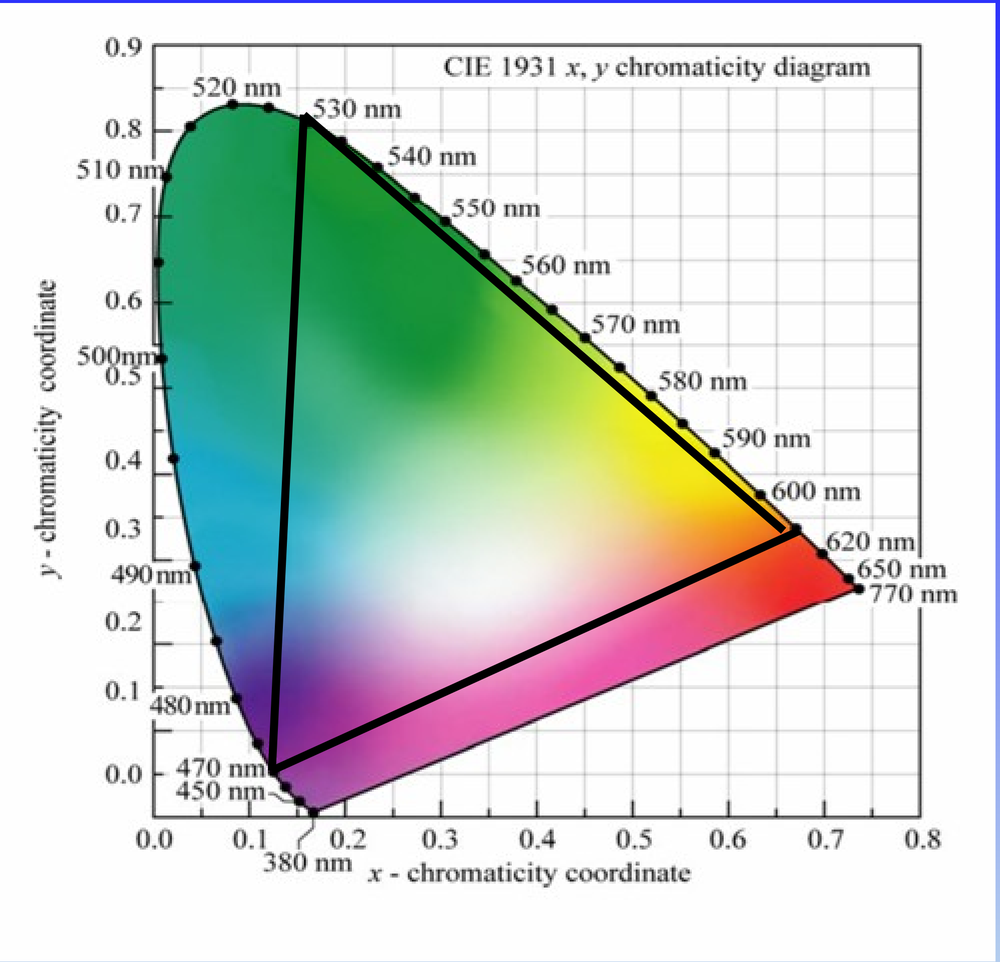


Conformal Coating of Phosphor Granules

Light source is smaller and often allows for a smaller secondary optic

Introduction to LEDs

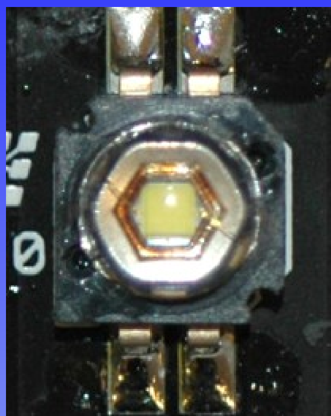
RGB Method of Creating White



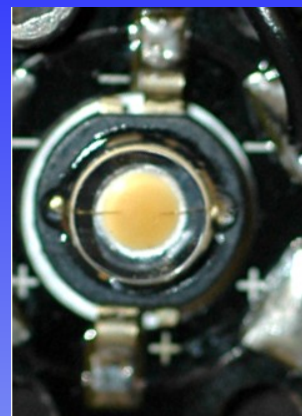
Introduction to LEDs

White LEDs

Lumileds



Lumileds

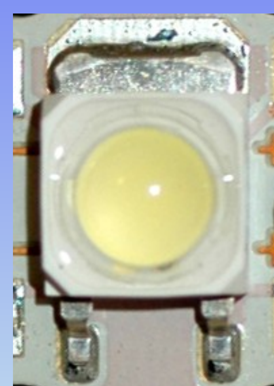


Seoul Semiconductor

Osram

Cree

Nichia



Lumileds Rebel

How do LEDs compare with other sources?

Efficacy of Various Light Sources

Light Type	Data Sheet lm/W	Usable* lm/W	Lifetime (hrs)
Incandescent	17	10-17	3k
Halogen	20	12-20	10k
T12 fluorescent	60	40-50	20k
Metal halide	65-70	35-40	10k-20k
T8 fluorescent	85-90	65-70	20-30k
T5 fluorescent	90	62	30k
High-pressure sodium	95-110	55-65	24k
Best-in-Class Power LED	99	65-75	> 50k
Low-pressure sodium	120-140	65-75	16k

* Typical expected performance in real-life applications. Based on mean lumens, and including ballast/driver, thermal equilibrium. and typical fixture Coefficient of Utilization losses.

Figure courtesy Mark McClear, Cree

Introduction to LEDs

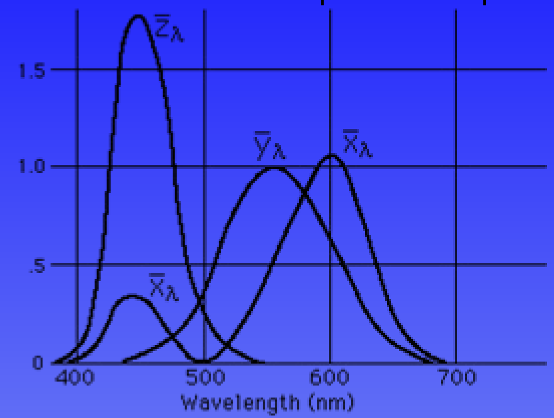
$\bar{X}$, $\bar{Y}$ and $\bar{Z}$ are the spectral response curves for the three different cone receptors in the eye. If the eye response to a color stimulus is given by X, Y and Z, we can define a color coordinate system as the relative stimulus given by the following equations:

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

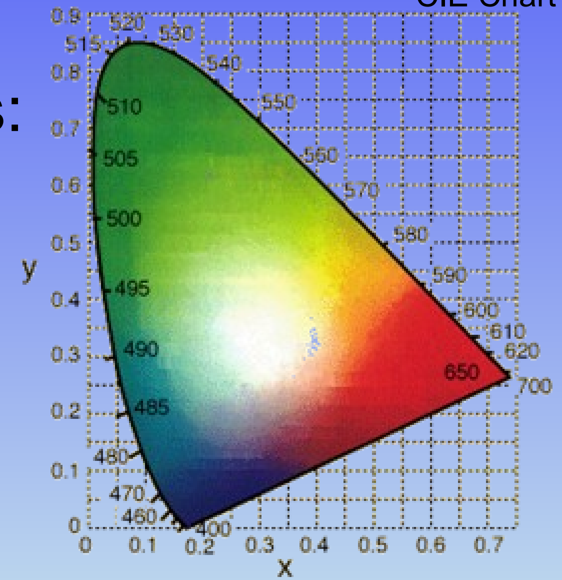
$$z = \frac{Z}{X + Y + Z}$$

With X + Y + Z = 1 by definition only two coordinates are necessary to define a color.

Spectral Response

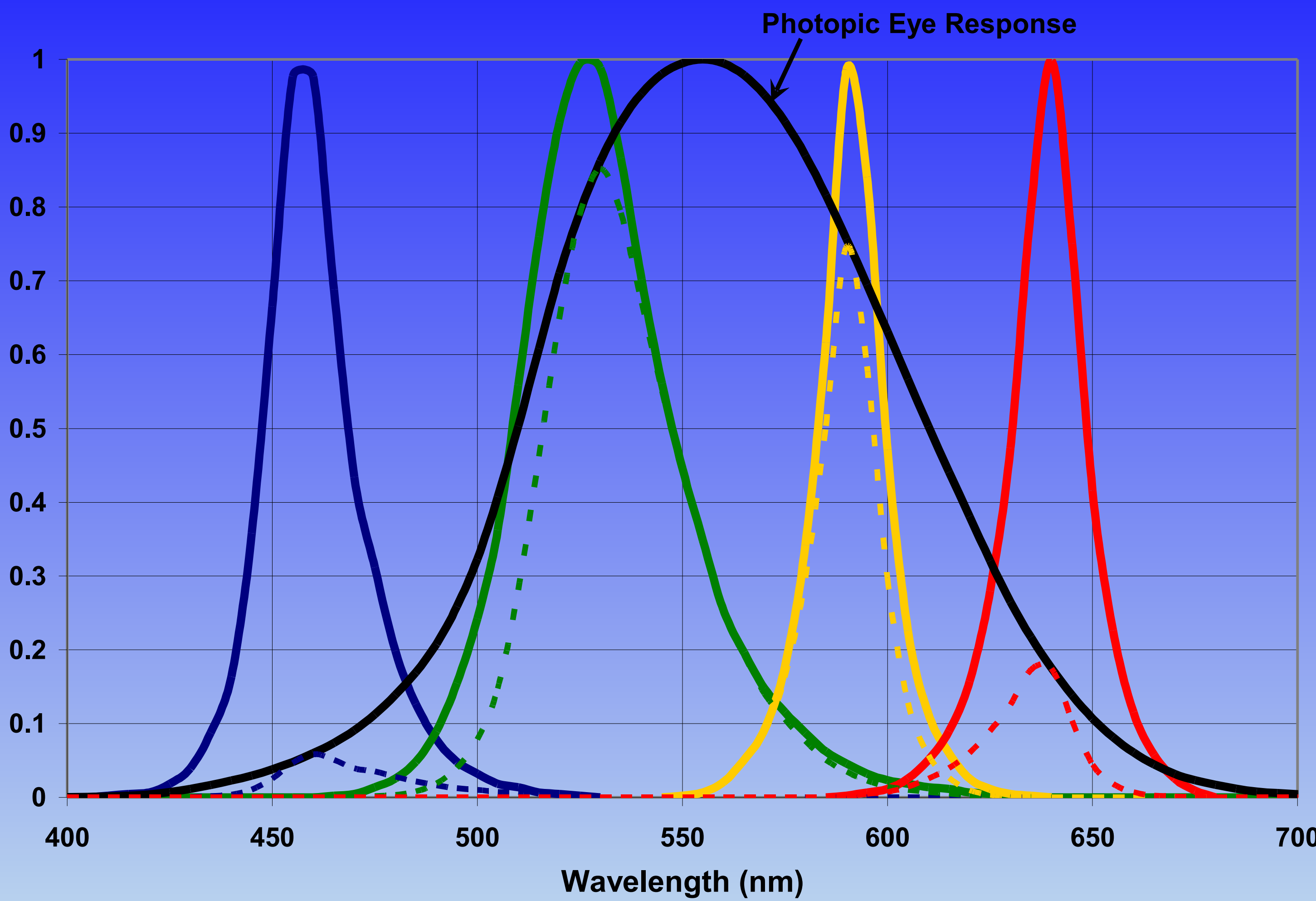


CIE Chart



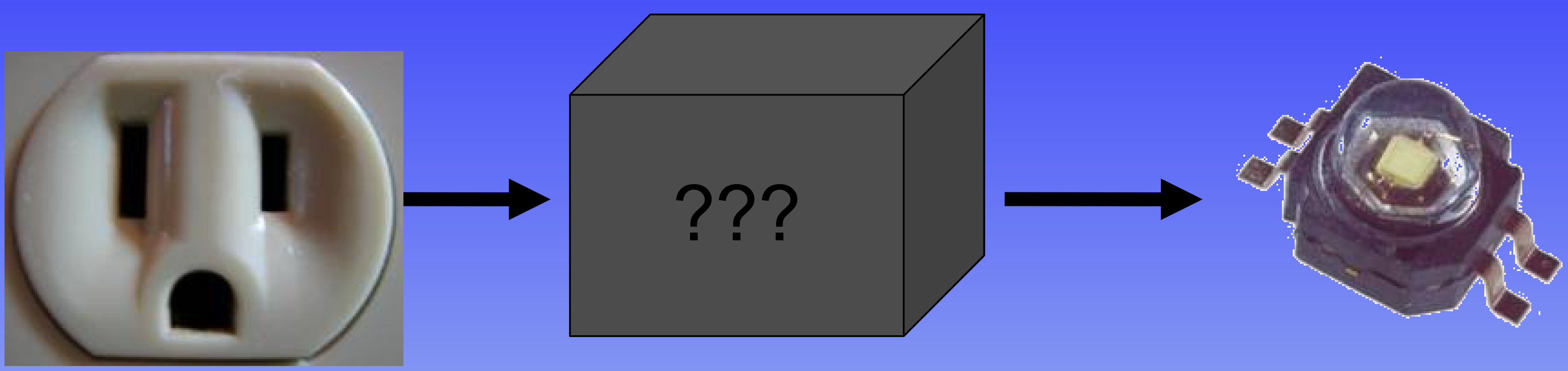
Introduction to LEDs

Radiometric Flux to Luminous Flux



Electronics Issues

Power Supplies / Drivers



Inside the black box

Electronics Issues

LED drivers (power supplies)

- Why do we need drivers (power supplies) in the first place?
  - LEDs are non-linear devices (V_f vs. I_f) and typically require constant current sources
  - Incandescent light bulbs are purely resistive loads with PF = 1
  - Drivers usually incorporate circuitry to produce PF's close to 1
  - Drivers also need to control harmonic current effects on the mains
    - ATHD regulated in many countries
- Life
  - LED life versus driver life
  - Elements which limit driver lifetime
    - Electrolytic capacitors—aging due to drying out of electrolytic
    - FETs, rectifiers, etc. which are stressed by heat and vibration
    - Other components affected by heat, moisture, environment
- Agency Approvals
  - Confusion as to how to list products
  - The light engine
- Size
  - Drivers equivalent to fluorescent ballasts

Electronics Issues

Choosing a LED Driver

- Custom or off-the-shelf?
  - How many LEDs? Functional requirements?
- AC/DC or DC/DC?
  - What is the input source?
- Simple driver: resistor in series
  - OK for low power applications
- Linear regulator
  - e.g. LM317 regulator IC
- Switch mode power supply (SMPS)
  - Buck, Boost, Buck-Boost, Flyback, SEPIC, etc.
- Constant current with feedback
  - Closed loop system gives best performance

Electronics Issues

Components Affected by Heat

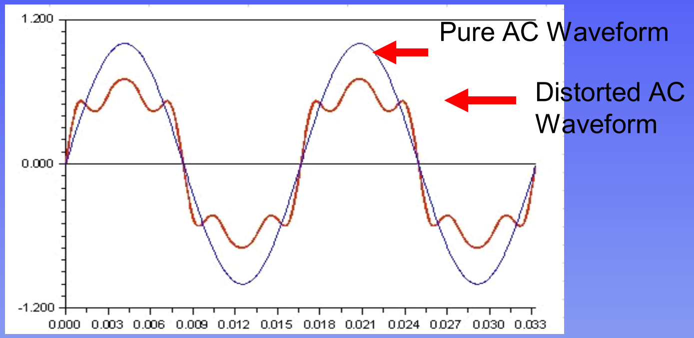
- LEDs Typical maximum junction temperatures of 125°C
  - Implies external maximum temperatures of 105°C (based on thermal resistance of the LED package)
- FETs Typical maximum junction temperatures of 125°C
- Capacitors Values can change by 10-20% or more as temperatures increase and drift as the component ages
- Large ceramic capacitors are sensitive to mechanical stresses which can cause failures

Electronics Issues

Efficiency

- Typical efficiencies range from 75% to 90% for SMPS
- Losses due to switching, resistances, transformers, etc.
- Poor power factor results in excess energy use

$$PF = \frac{\text{Watts}}{\text{Volts} \times \text{Amperes}} \leq 1$$



- LEDs are non-linear loads which create distortion on the supply line
- Driver should not draw power if load is not on (Energy Star requirement)
- Efficiency as a function of load power
  - 90% at full power
  - <70% efficiency at partial power

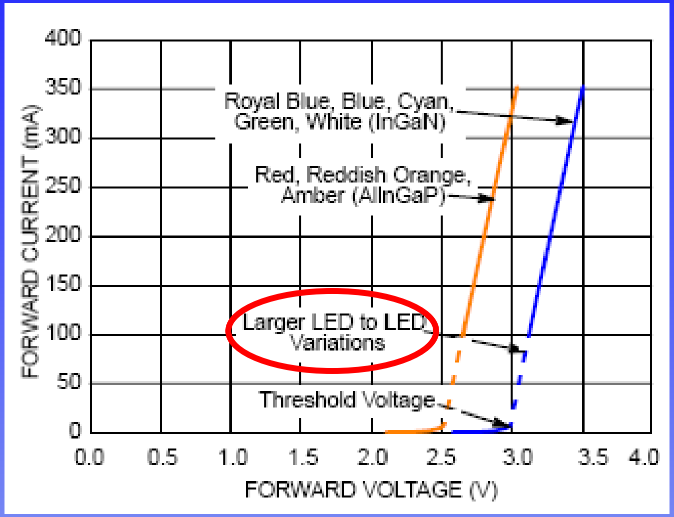
Electronics Issues

Forward Voltage

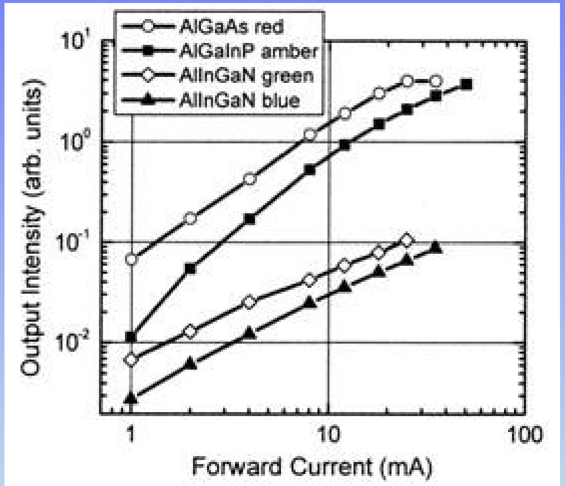
- Forward voltage V_f is roughly equal to the bandgap energy of the LED semiconductor divided by the elementary charge

  $$V_f = E_g / q$$

  where $q = 1.6 \times 10^{-19}$ coulombs



- Output intensity of typical high brightness LEDs depends on the forward current I_f



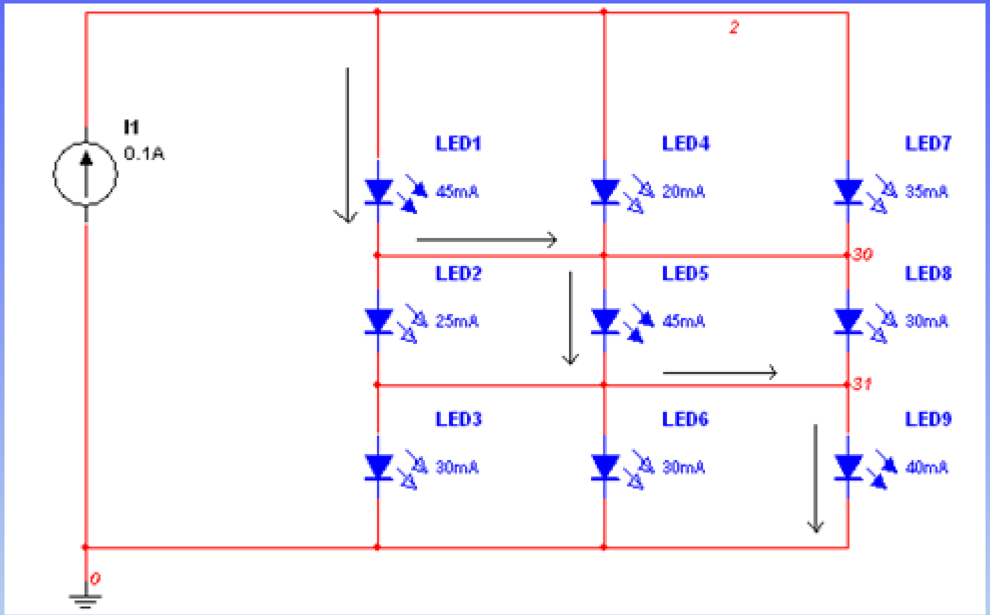
- Forward voltages of parallel strings must be balanced

Electronics Issues

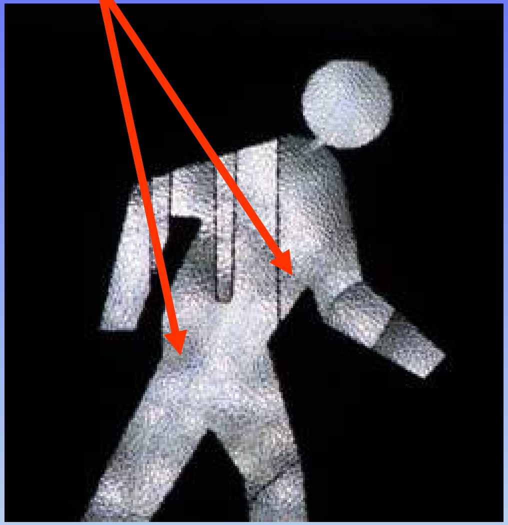
"Current Hogging"

Branch paths are linked to minimize effect of open LEDs

Potential of too much current being drawn through remaining branches resulting in those branches failing prematurely due to higher currents



Dark spots caused by "current hogging"



Electronics Issues

- UL has until recently looked at LED lights under the 1598 Luminaire Standard

- UL has recently introduced a new approach for LED (Outline of Investigation—Introduced January 2007)
  - 8750 LED Light Sources for Use in Lighting

- Power supplies are listed under either
  - 2108 Low Voltage Lighting Systems
  - 1012 Power Units Other Than Class 2
  - 1310 Class 2 Power Units

Electronics Issues

- EN60598--Generic Luminaire standard - split further into 30 sub-sections – e.g. roadway light, stage light, etc.
- EN55015--EMC emission limits are higher for lighting products, additional requirement to test for low frequency magnetic fields; other standards for EMC susceptibility - flicker, brownouts, ESD, etc.
- EN 61000-3-2--Harmonics and power factor
- EN60825 (Class 2)—Laser Standard under which LEDs presently fall; expected to be revised for LEDs - the deep blue LEDs have most cause for concern when used with narrow beam optics
- EN61347—control equipment; split into sections for types of control gear - new section in draft for LED control equipment

Binning for Flux and Color:

Binning Issues

Variation in Flux, Vf for various Cool White LEDs (as of 2006)

	Dice #	Viewing Angle Degees	Typical Lumens 350 mA	500 mA	700 mA	1000 mA	1400 mA	1500 mA	Typical Current mA	Typical Voltage Vf	Typical Power W	Thermal Restist-ance °C/W	Rise LED Only °C	Max Junction °C	CRI
Osram LW W5SG Cool	1	120	21-39	41					350	3.8	1.3	9	12	125	80
Osram ZW W5SG Cool	1	120	33-71	60					350	3.2	1.1	15	17	125	80
Osram LW W5SN Cool	1	120			52-97				700	3.8	2.7	8	21	135	80
Osram LW W5SM Cool	1	120		64					350	3.2	1.1	15	17	125	80
Osram LEW E3A Cool	6	120			300				700	22.5	15.8	3.6	57	150	80
Osram LEW E3B Cool	6	120			420				700	22.5	15.8	3.6	57	125	80
Osram LEW E2A Cool	4	120			200				700	15	10.5	5	53	150	80
Osram LEW E2B Cool	4	120			280				700	15	10.5	5	53	125	80
Lumileds LXHL-PW01 Cool	1	120	45						350	3.42	1.2	15	18	135	70
Lumileds LXHL-DW01 Cool	1	Side-emit	40.5						350	3.42	1.2	15	18	135	70
Lumileds LXHL-BW02 Cool	1	Batwing	45						350	3.42	1.2	15	18	135	70
Lumileds LXHL-PW09 Cool	1	120			65	80			700	3.7	2.6	13	34	135	70
Lumileds LXHL-DW09 Cool	1	Side-emit			58	70			700	3.7	2.6	13	34	135	70
Lumileds LXHL-PW03 Cool	4	150			87.4				700	6.84	4.8	8	38	135	70
Lumileds LXK2-PW etc Cool	1	150	52.5		87.5	110		135	1000	3.72	3.7	9	33	150	70
Nichia NCCW002, etc Cool	1	35,70,120	42	?					350	3.7	1.3	17	22	105	80
Nichia NS6W083 Cool	4	120	60	?					350	3.6	1.3	10	13	120	80
Cree XL7090 Cool	1	100	52		?				350	3.5	1.2	17	21	125	75
Cree 3XL7090 Cool	1	100			76				700	4	2.8	17	48	145	75
Cree XL7090XR Cool	1	100	53.5		?				350	3.5	1.2	8	10	145	75
Seoul Semi W10190 Cool	1	70,110	52						350	3.5	1.2	8	10	125	70
Seoul Semi W10290 Cool	2	70,110			103				700	3.5	2.5	6	15	125	70
Seoul Semi W10490 Cool	4	70,110					178		1400	3.5	4.9	4	20	125	70
Cotco LD-700AWN1-70 Cool	1	70	27						350	3.6	1.3	15	19	125	

Source: Curran & Peck—Comparison of White LEDs, Lightfair 2006

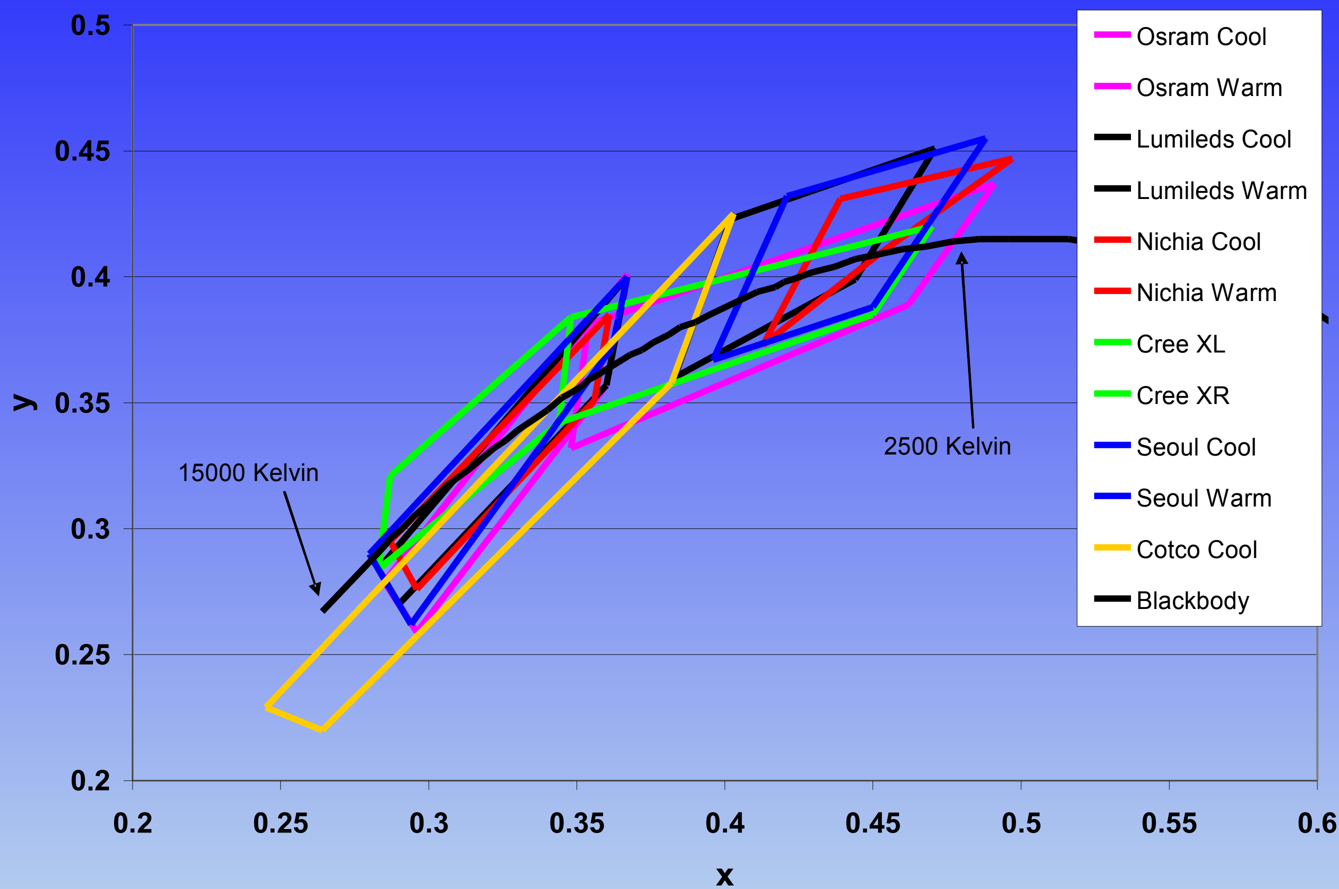
Binning Issues

Flux Choices from one manufacturer

Group Code	Min. Luminous Flux @ 350 mA (lm)	Max. Luminous Flux @ 350 mA (lm)
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

Binning Issues

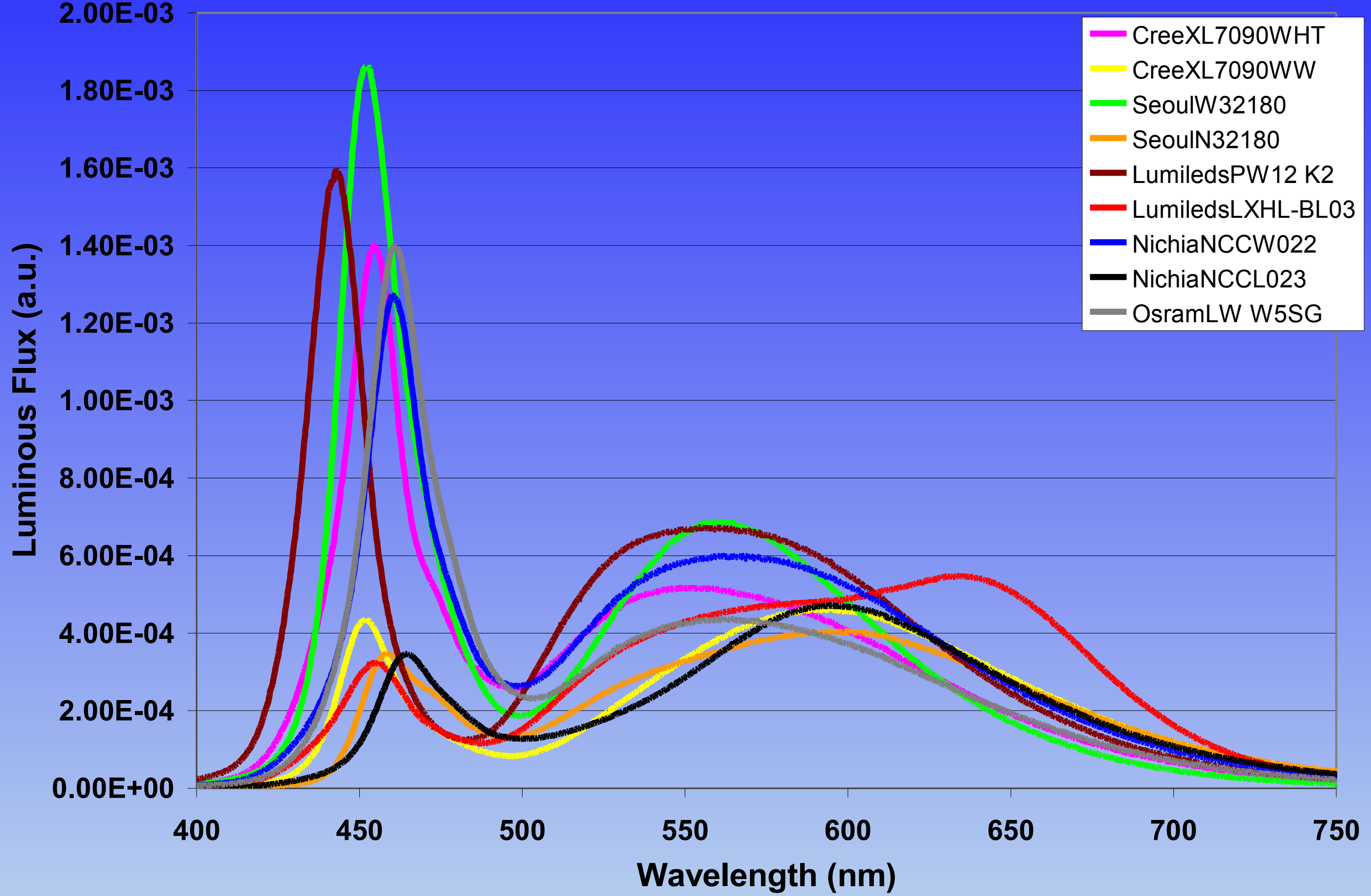
Color bins from various LED manufacturers



Source: Curran & Peck—Comparison of White LEDs, Lightfair 2006

Binning Issues

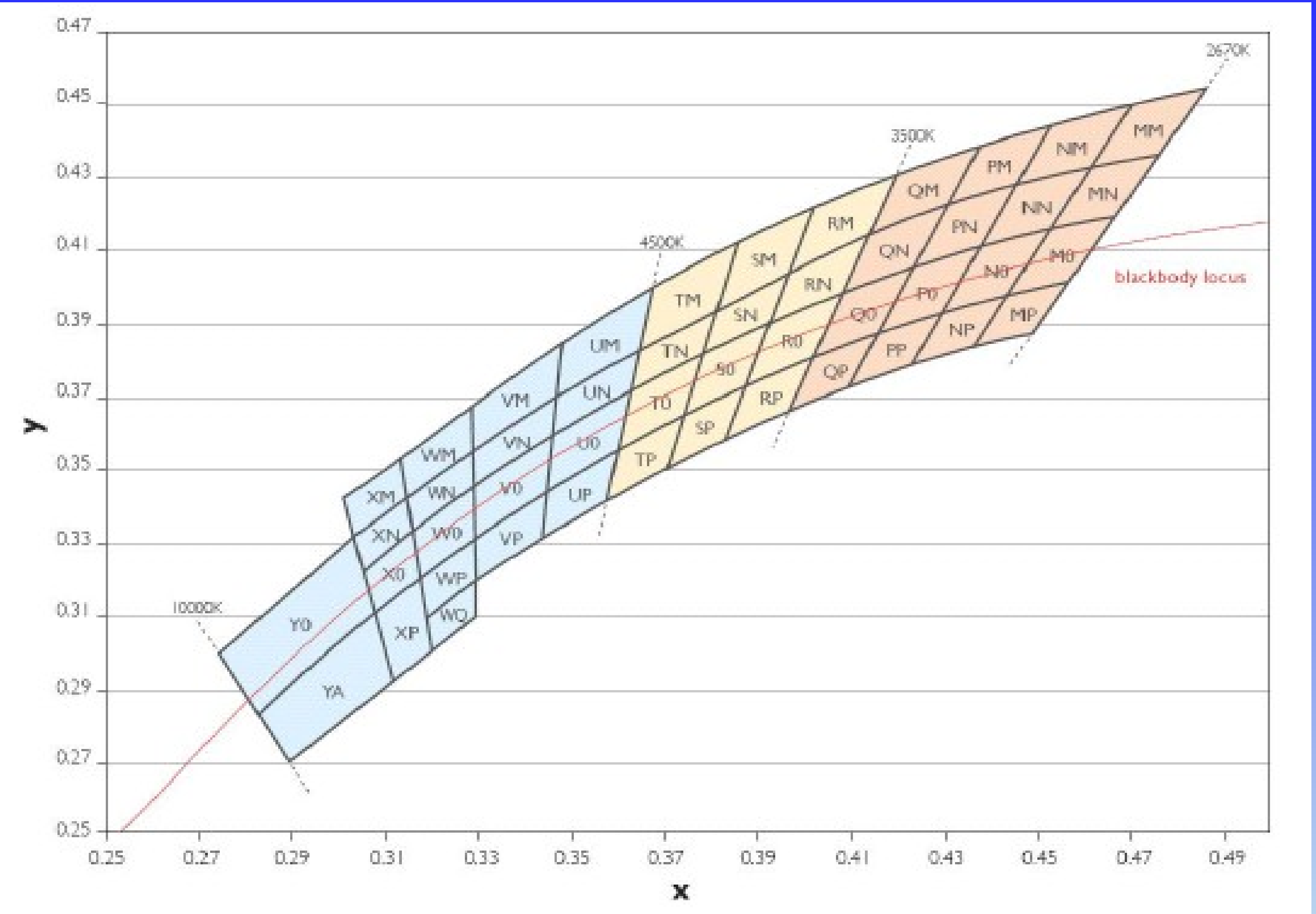
Spectra for various white LEDs



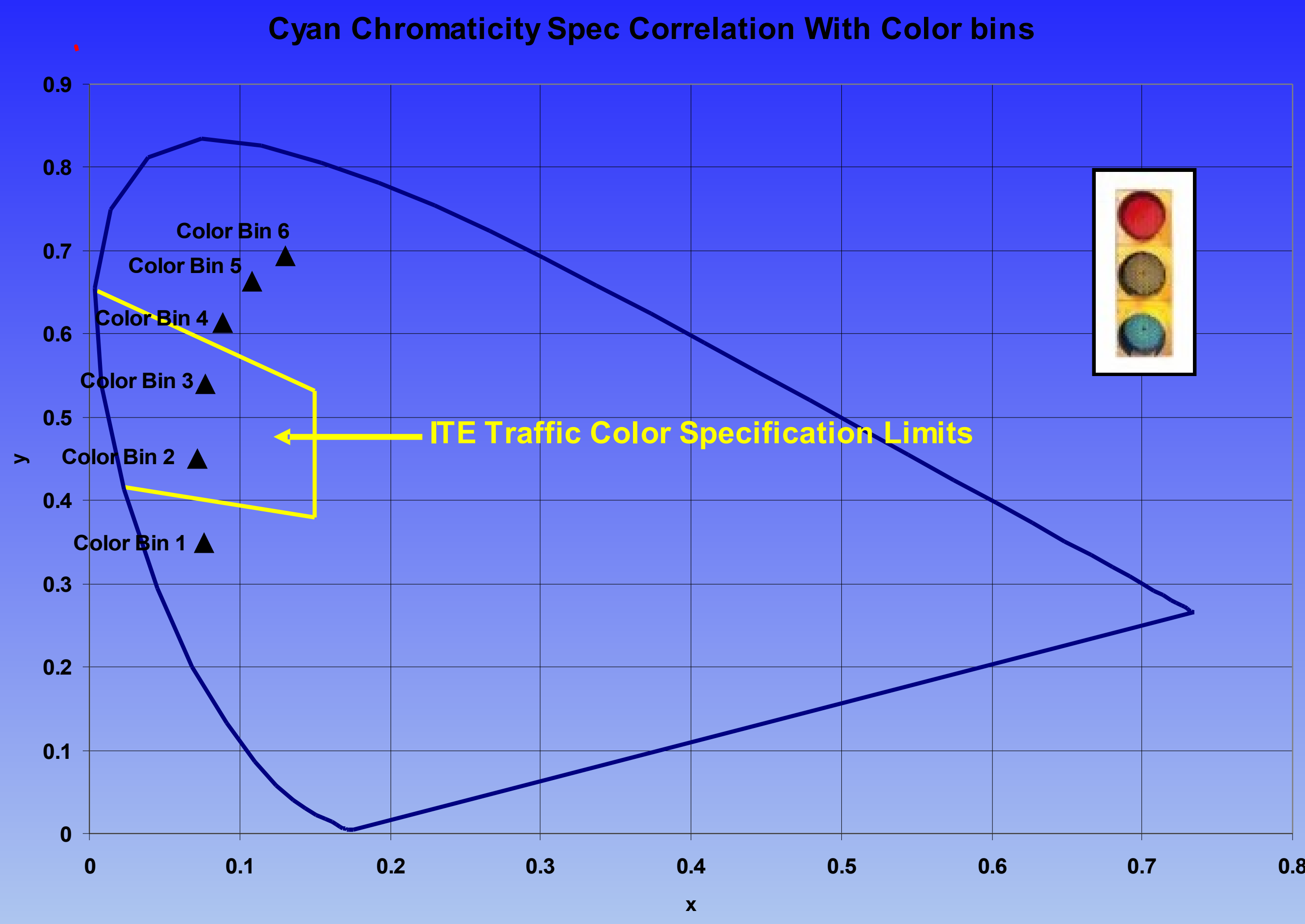
Source: Curran & Peck—Comparison of White LEDs, Lightfair 2006

Binning Issues

Example from one LED manufacturer—47 bins!

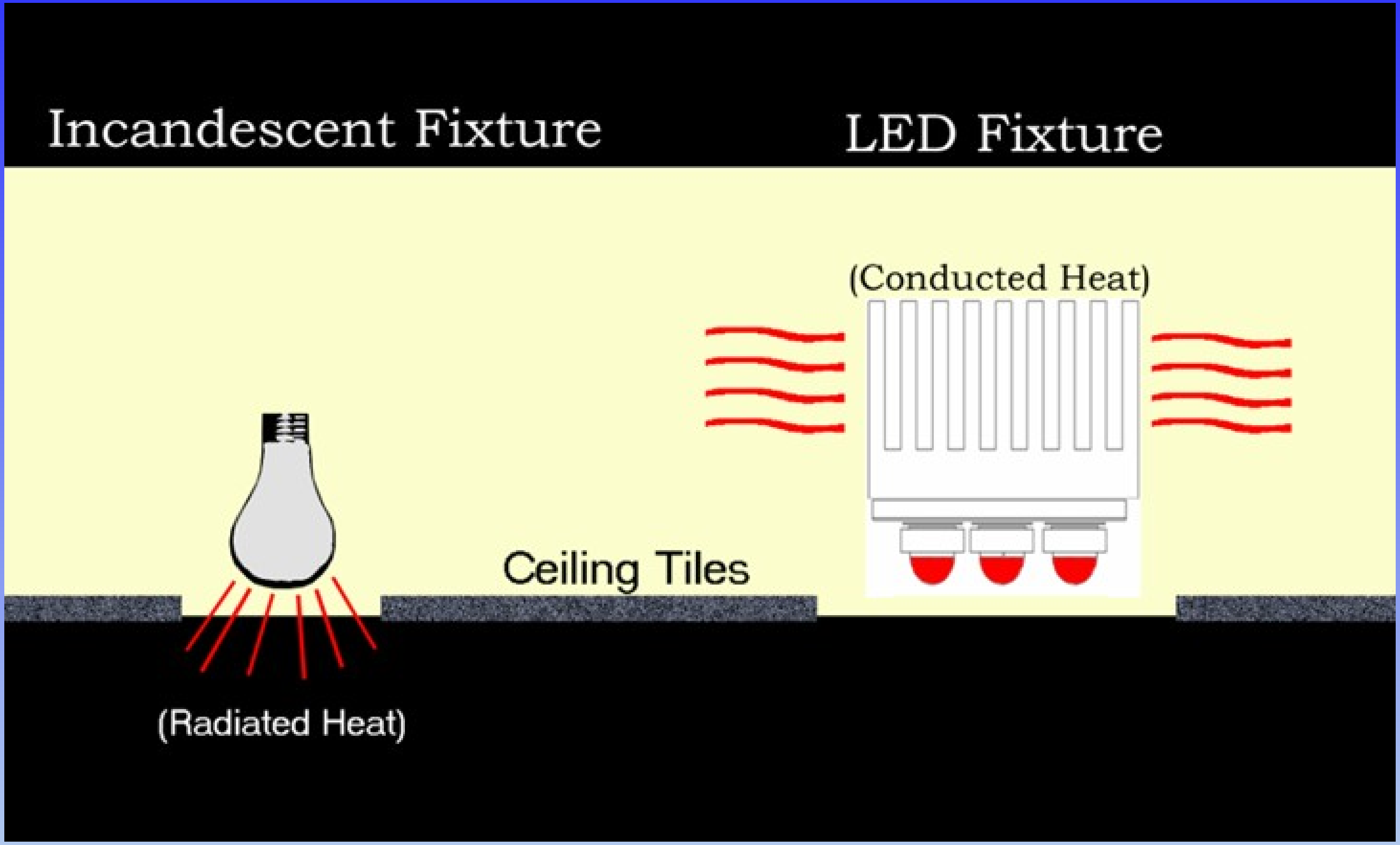


Binning Issues



Thermal Issues

Why is it a problem?



Thermal Issues

Source	Efficacy (lm/W)	Heat Loss (%)		
		Radiation	Convection	Conduction
Incandescent	15	90	5	5
Fluorescent	90	40	40	20
HID	100	90	5	5
LED	75	5	5	90

A fixture using a 60W incandescent light bulb will produce about 900 lumens of light. The fixture will need to dissipate 3W of heat via conduction (60W x 0.05 = 3W).

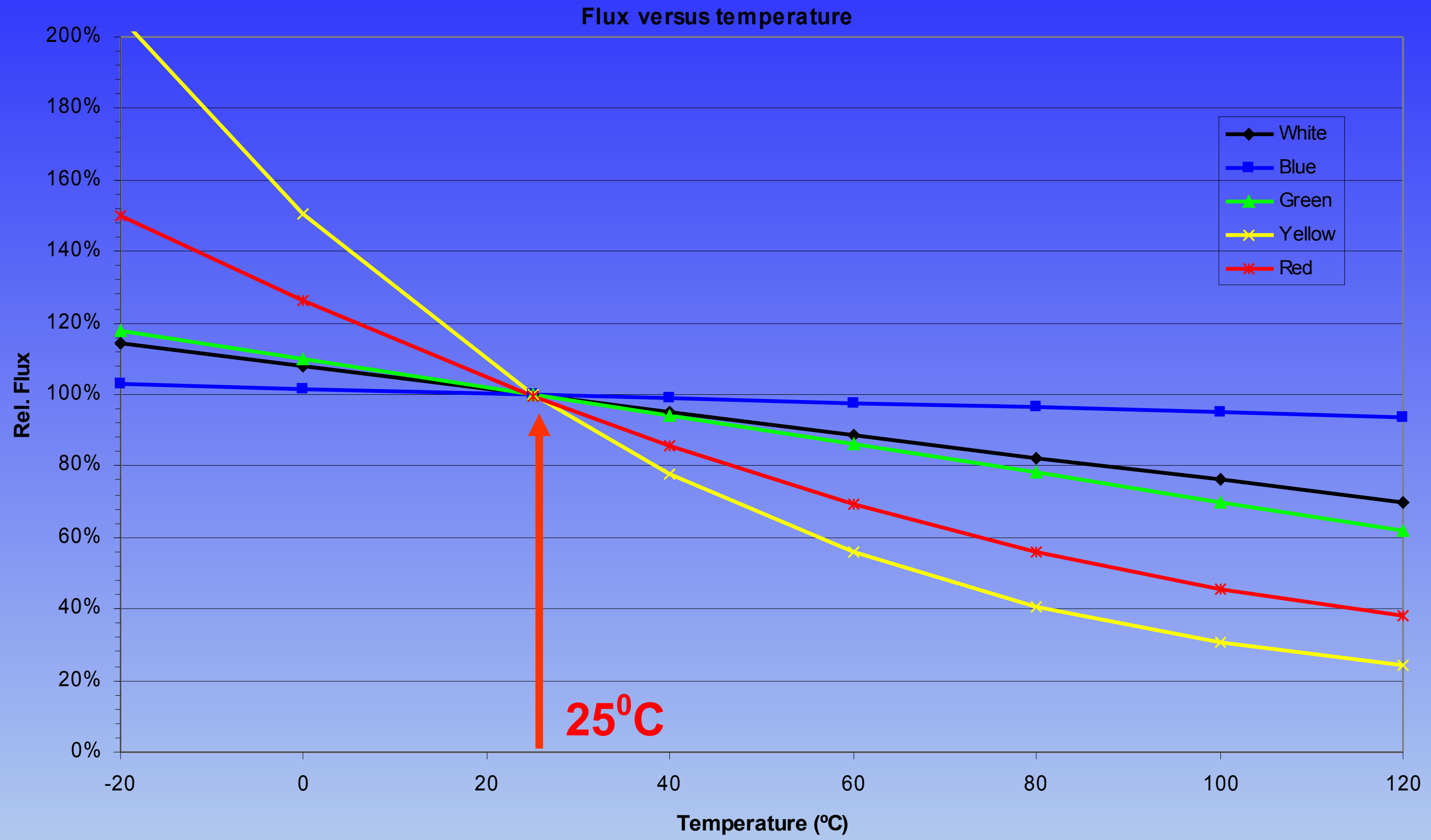
A fixture using LEDs as the light source would require 12 LEDs to achieve the same 900 lumens of light (900/75 = 12). The input power to the fixture would be (assuming a Vf of 3.2V and current of 350mamps)

Power = 12 x 3.2V x 0.350amp = 13.4W

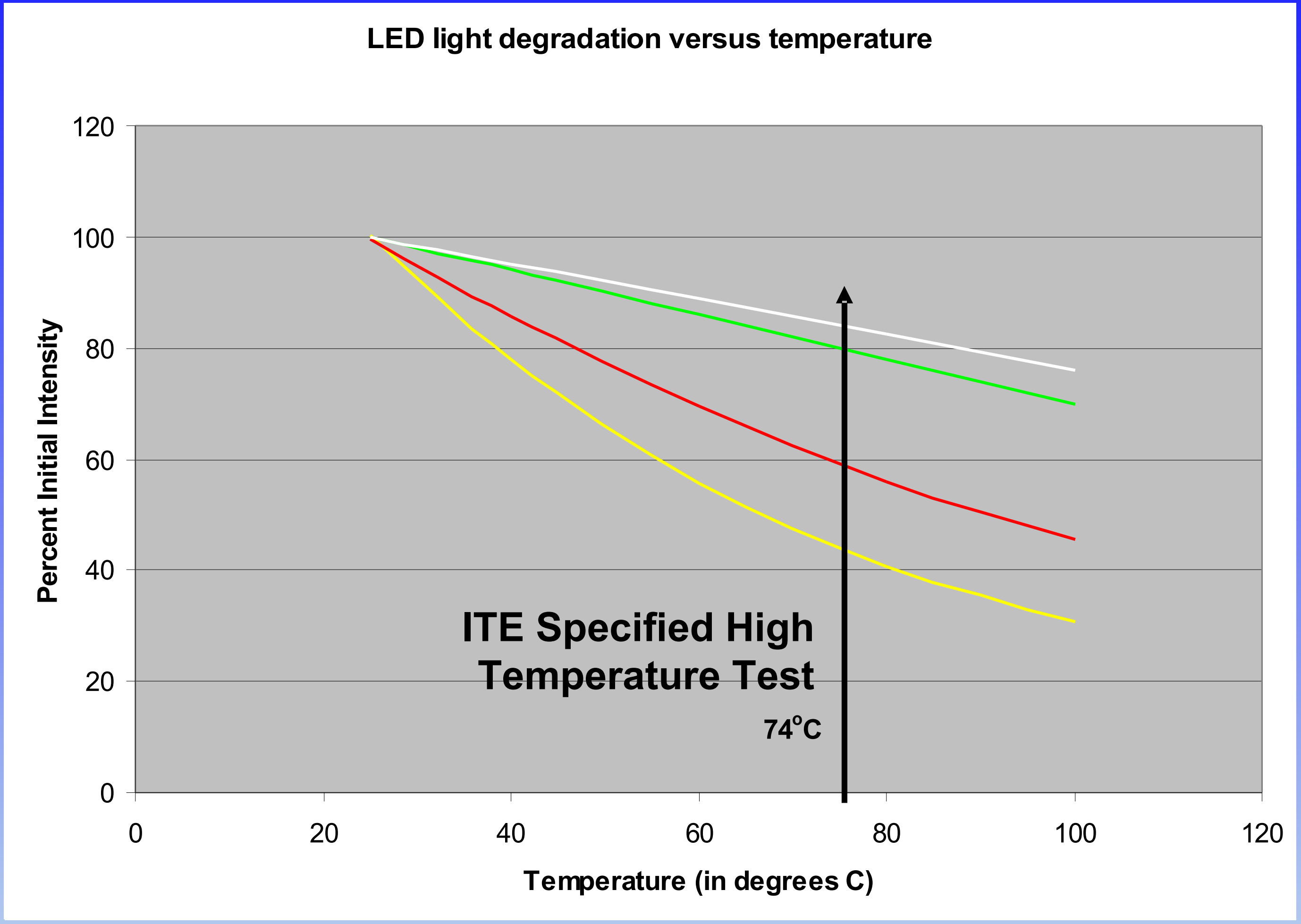
The fixture would need to conduct 90% of that heat or approximately 12.1W (about 4 times the heat of the incandescent bulb).

Thermal Issues

Effect on Light Output

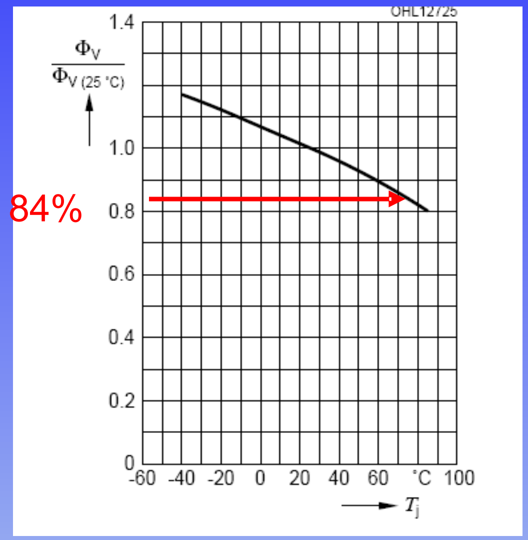


Thermal Issues

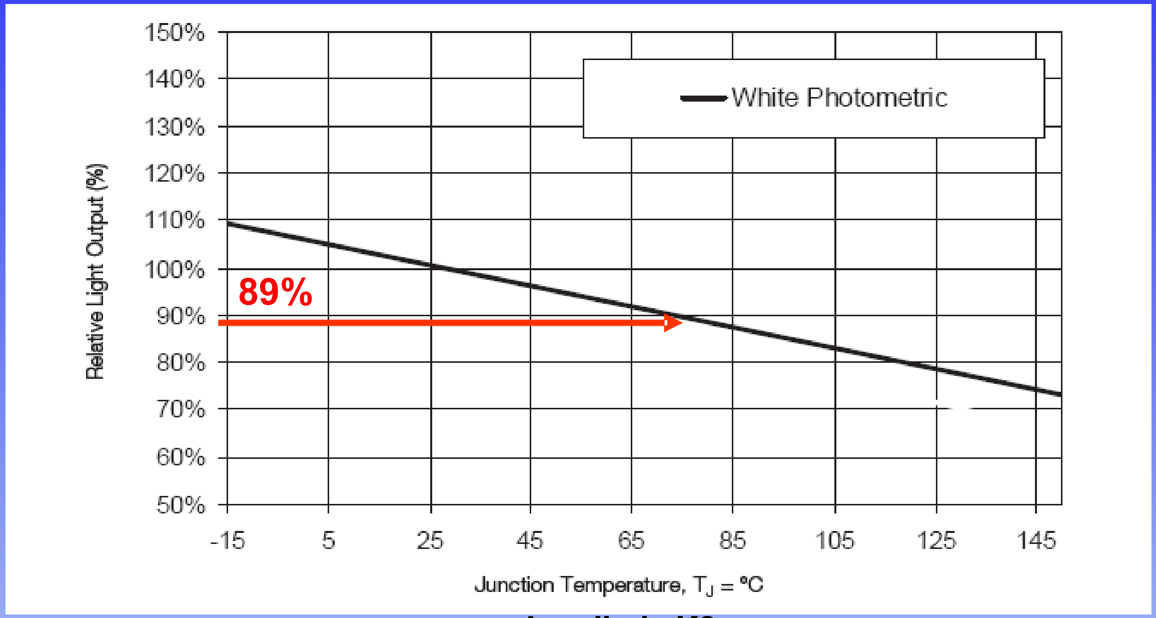


Thermal Issues

Examples of light output reduction due to increased LED junction temperature



Osram Golden Dragon

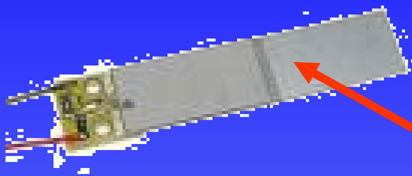


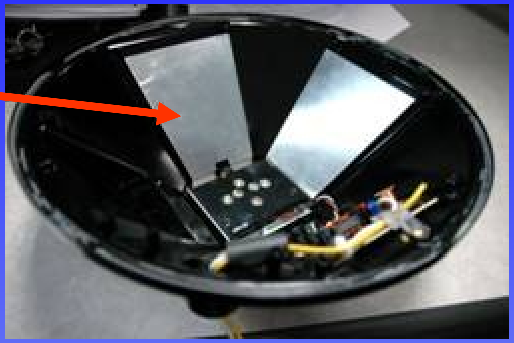
Lumileds K2

Source: Osram/Lumileds data sheets

Thermal Issues

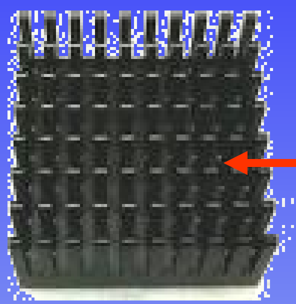
Devices to help dissipate heat





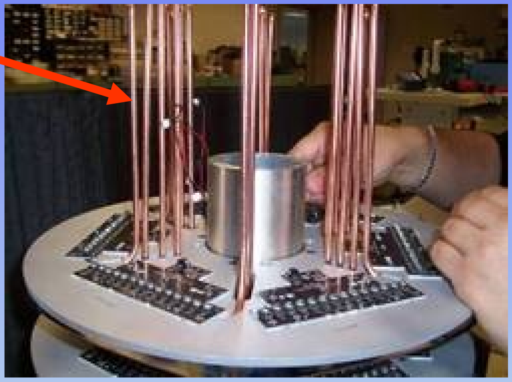
Heat Spreader

Piezo fan



Heat Sink

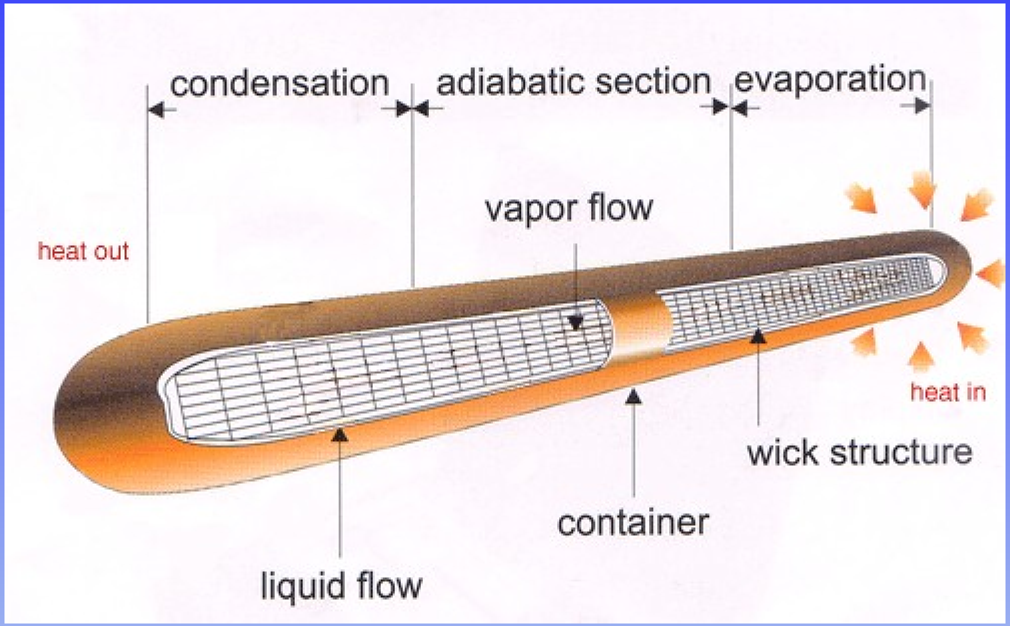
Heat pipes



Thermo-electric Cooler

Thermal Issues

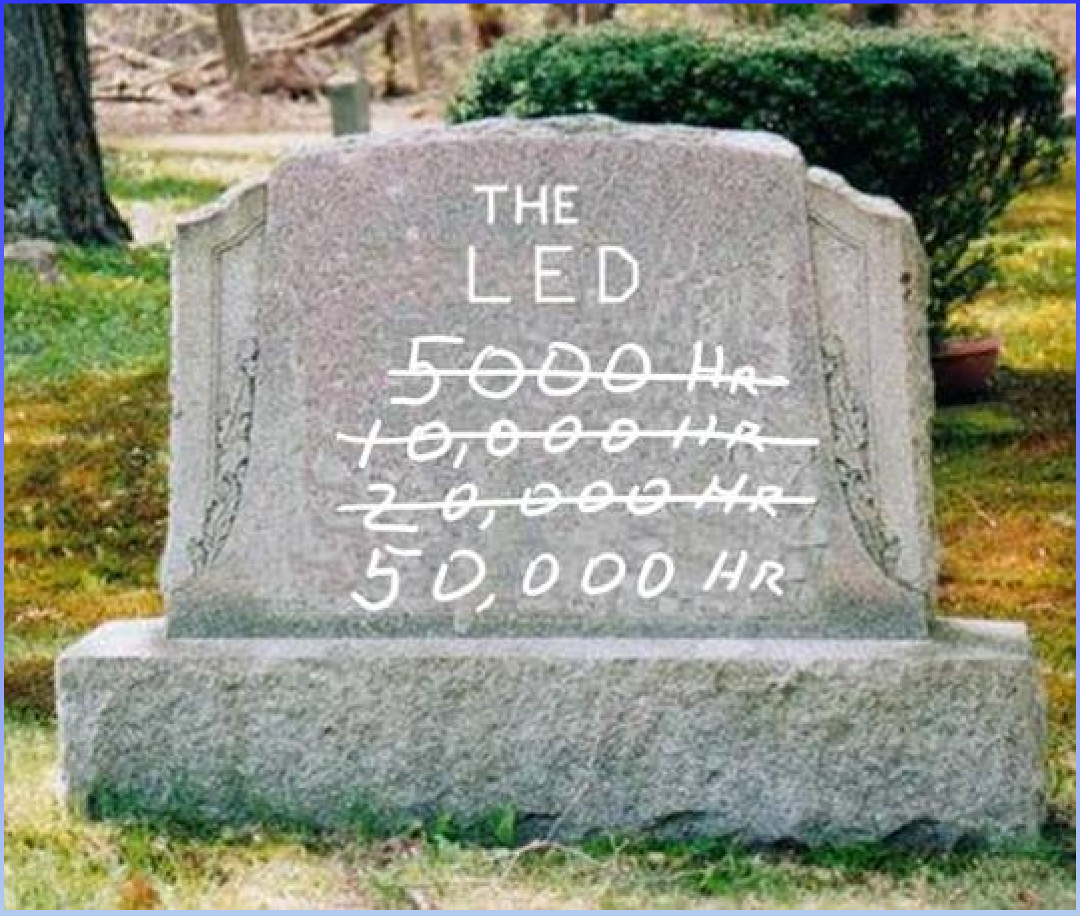
How a Heat Pipe Works



Hot End

Cold End

Lifetimes

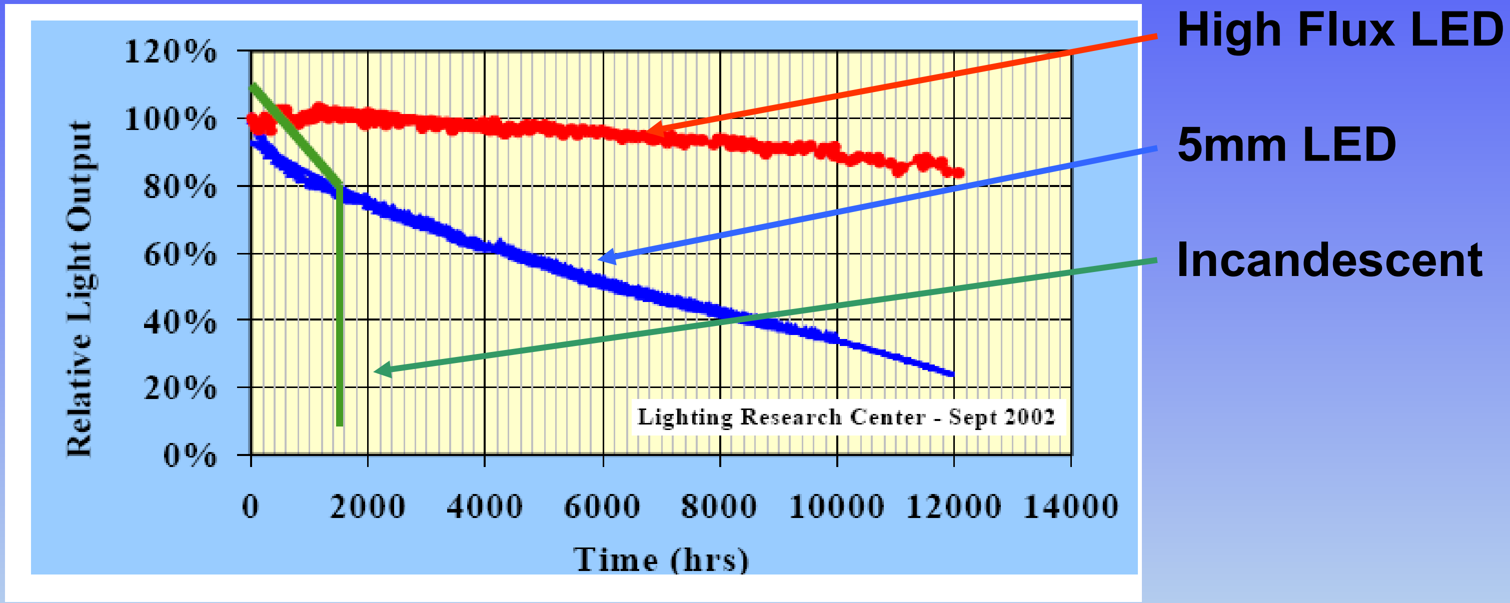


Lifetimes

Traditionally, lifetime is the time it takes for 50% of the population of incandescent bulbs to fail

LED light sources don't fail catastrophically—Define EOL by reduction in light output from initial values,

for example, 70% or 50% of initial value.

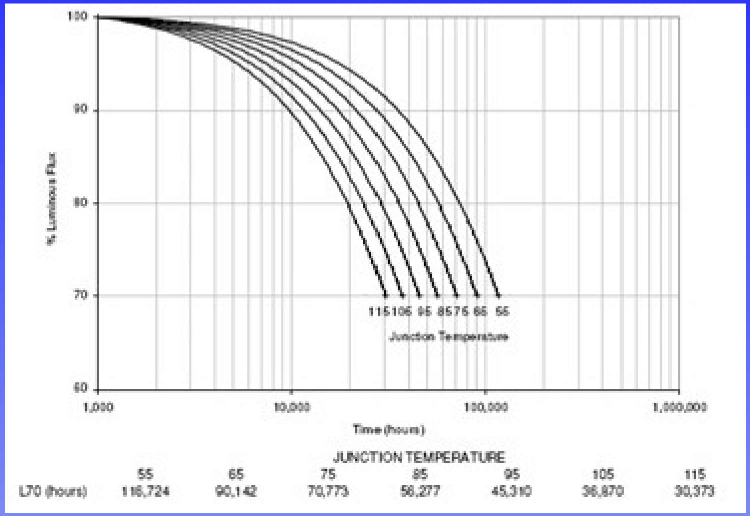


Lifetimes

- What does lifetime mean?
  - Reading the fine print: 70%, 50%, conditions of test
- Do LED luminaire fixtures need to be designed with replaceable light sources?
  - How long will a fixture remain in use?
  - Is it easier to replace the source or the whole luminaire?
- How to signal that a light needs to be replaced?
  - Flash something?
  - Make it fail completely?

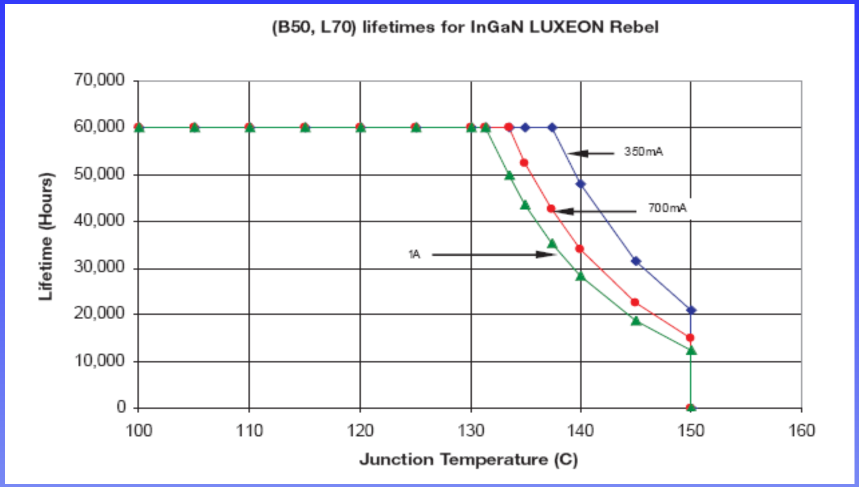
Lifetimes

Consistency in Measuring Lifetimes?



Courtesy Mark McClear, Cree

Cree



Lumileds Data Sheet

Lumileds

Standards are coming:

IESNA LM-79 Approved Method for the Electrical and Photometric testing of Solid-State Lighting Devices

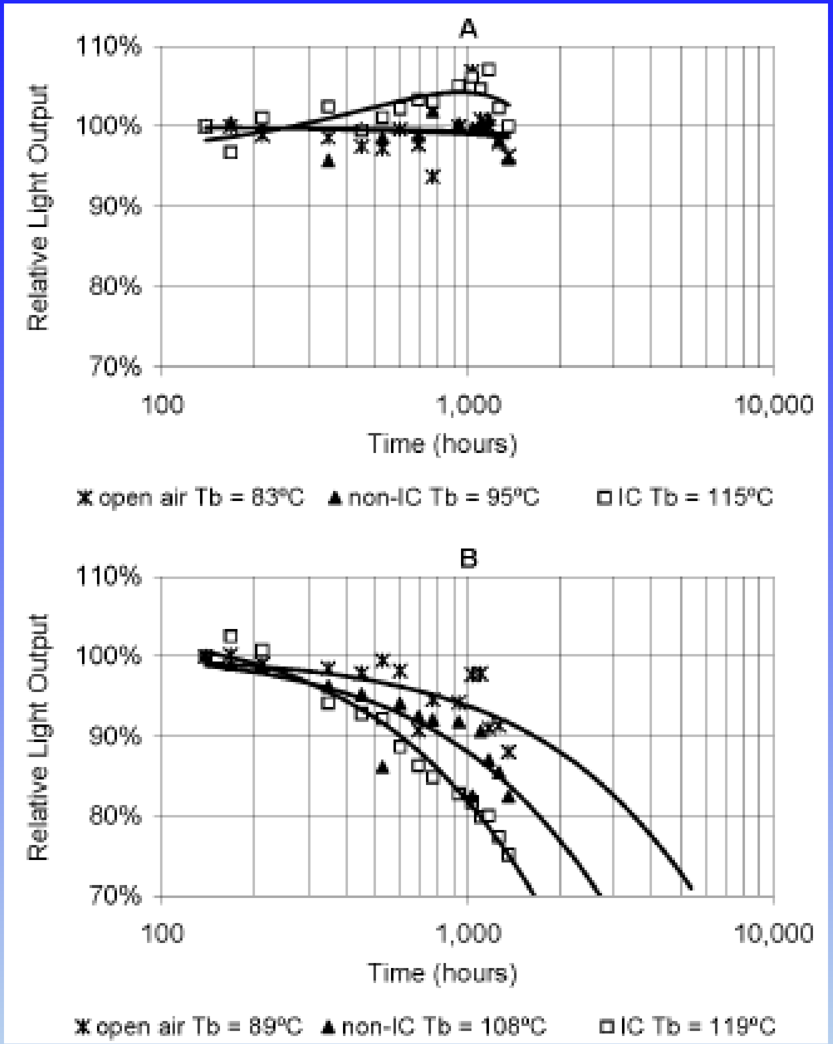
IESNA LM-80 Approved Method for Measuring Lumen Depreciation of LED Light Sources (still in committee)

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

Lifetimes

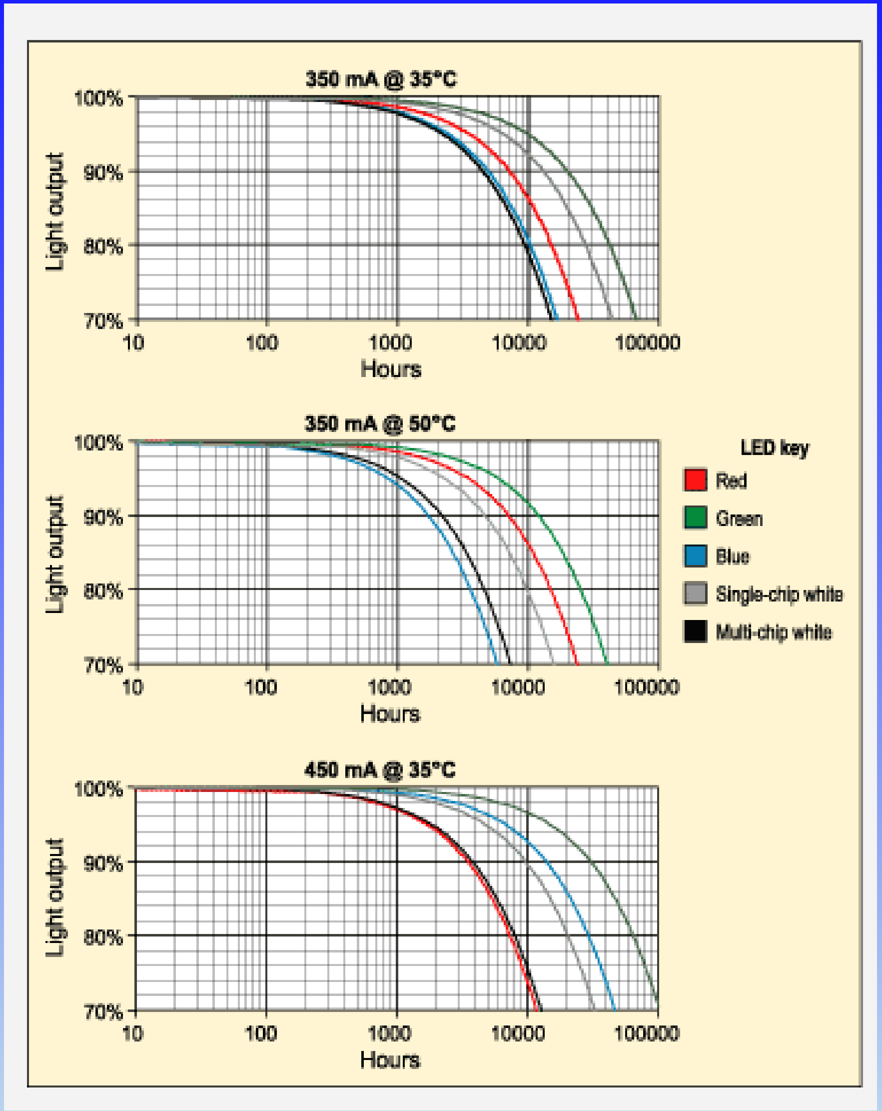
Long life LED fixtures?

Two 26 W downlights were tested by the Lighting Research Center. It is obvious that B is not going to last much long than an incandescent light bulb for the 119 degree case.



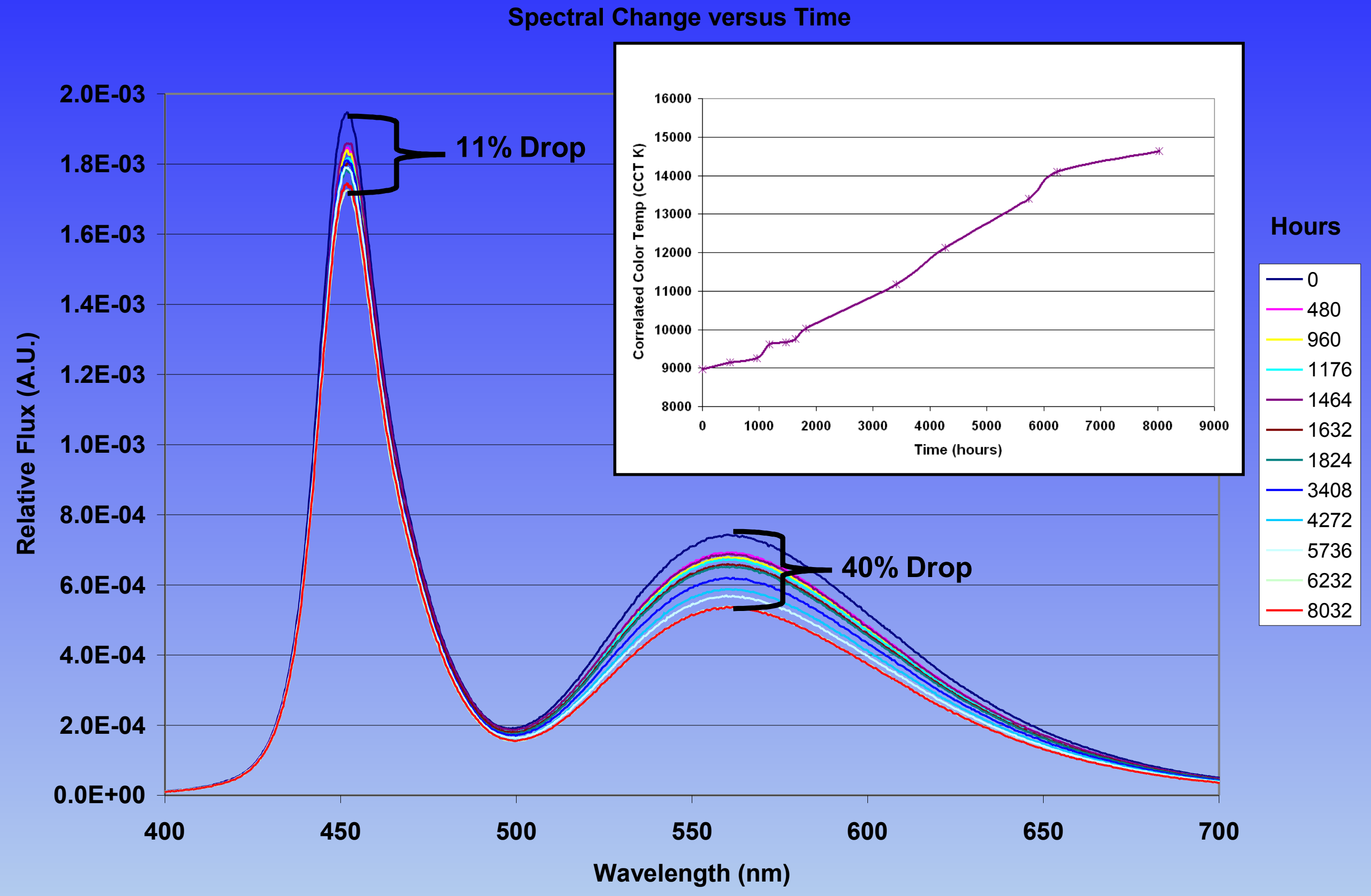
Lifetimes

Thermal Effect on LED lifetimes



Data from LRC

Color Shift with Operating Time



Source: Curran & Peck—Comparison of White LEDs, Lightfair 2006

Lifetimes

LED Failure Modes:

•L70—Light output reduced by 30% from initial value or color shift by more than 4 MacAdam ellipses

•Open

•Shorted

Assume LED #2 opens:

Figure 1) No current through #1,2,3; 700mamps goes through #4,5,6; Overall light output reduced by 20% (#4,5,6 will be approximately 60% brighter and will fail prematurely)

Figure 2) No current flows; no light output

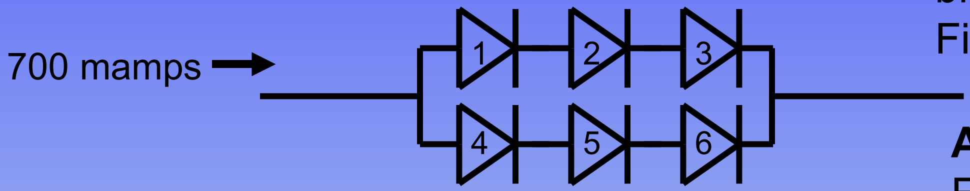


Figure 1

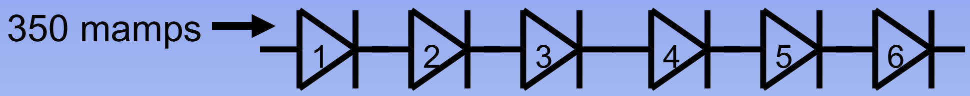


Figure 2

Assume LED #2 shorts:

Figure 1) 420mamps through #1,2,3
280mamps through #4,5,6
Overall light output reduced by approximately 22%

Figure 2) 350mamps through #1,2,3,4,5,6; overall light output reduced by approximately 17%

System Issues

Needs to Look Like a Lightbulb

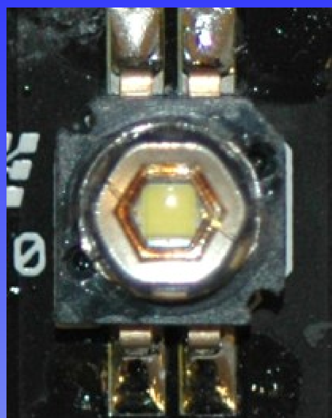
+

=

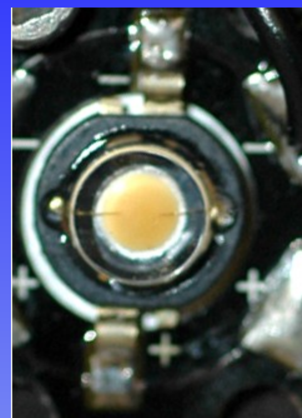
System Issues

LEDs come in many shapes & sizes

Lumileds



Lumileds

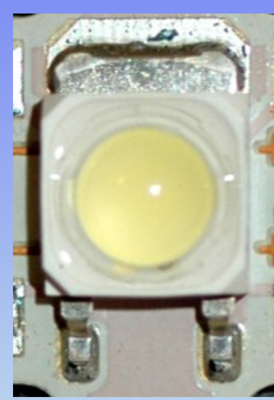


Seoul Semiconductor

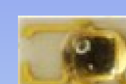
Osram

Cree

Nichia

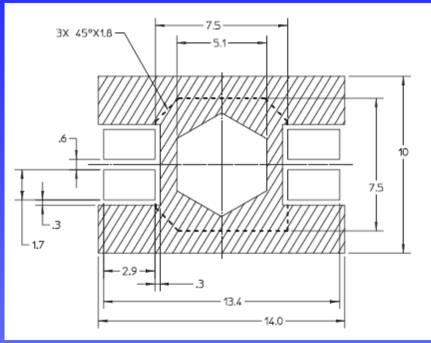


Lumileds
Rebel

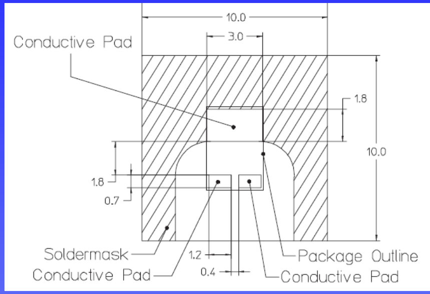


System Issues

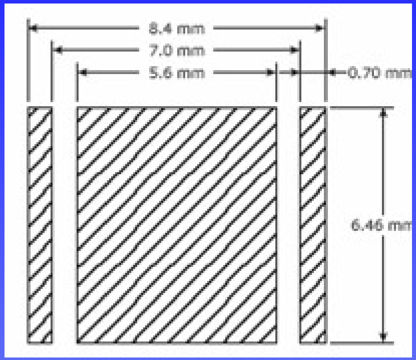
So do their attachment specifications:



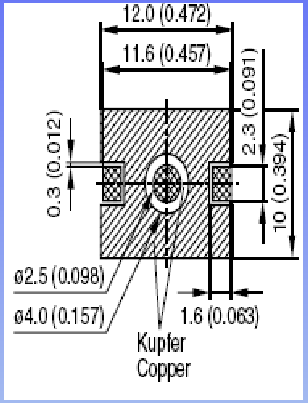
Lumileds K2



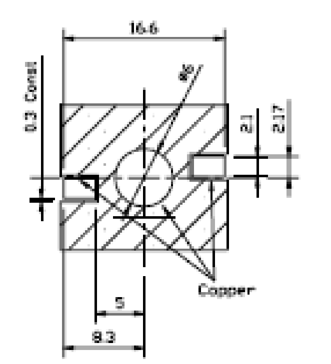
Lumileds Rebel



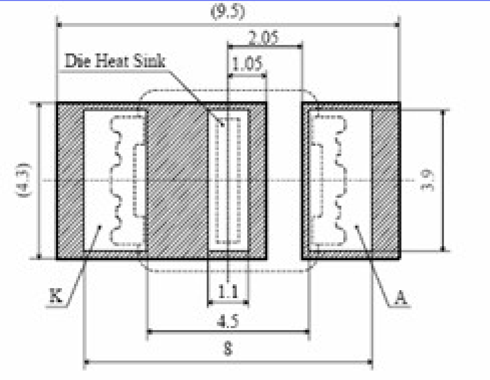
Cree XR-E



Osram
Golden Dragon



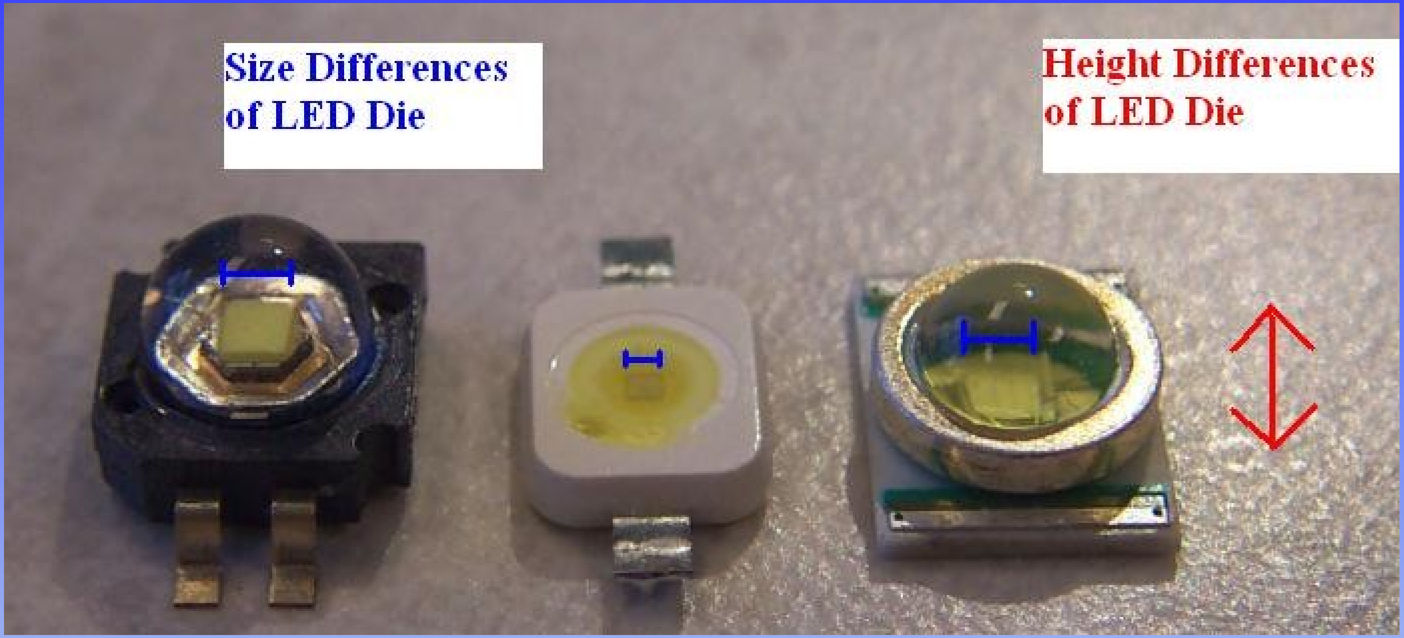
Seoul P4



Nichia
NS6W083

System Issues

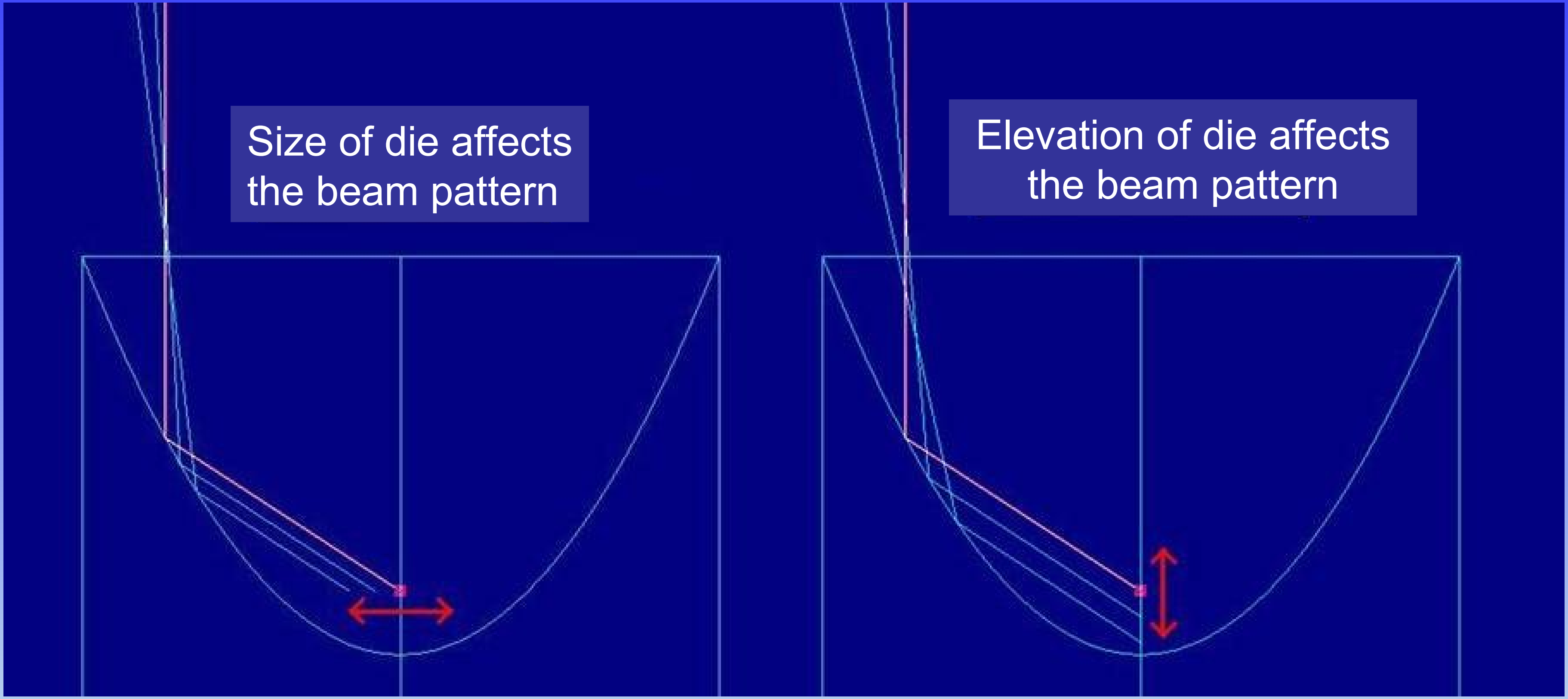
Differences in physical LED parts



Lumileds	Osram	Cree
Luxeon K2	Golden Dragon	XRE
1mm x 1mm	0.8mm x 0.8mm	1mm x 1mm

System Issues

Effect on optical performance with different die sizes and heights



Courtesy John Peck, Dialight

System Issues

- When a light bulb fails:
  - It stops producing photons
  - Its impedance goes infinite
- When LEDs “fail”
  - Still produce photons
  - System never directly sees LEDs electrically

System Issues

Intellectual Property

- Major minefield in product development
- Most LED manufacturers have licensing agreements in place or have cross-licensed IP
- Fights are now moving down the development chain
  - System control
  - Optics
  - Color mixing

Looking on the Bright Side

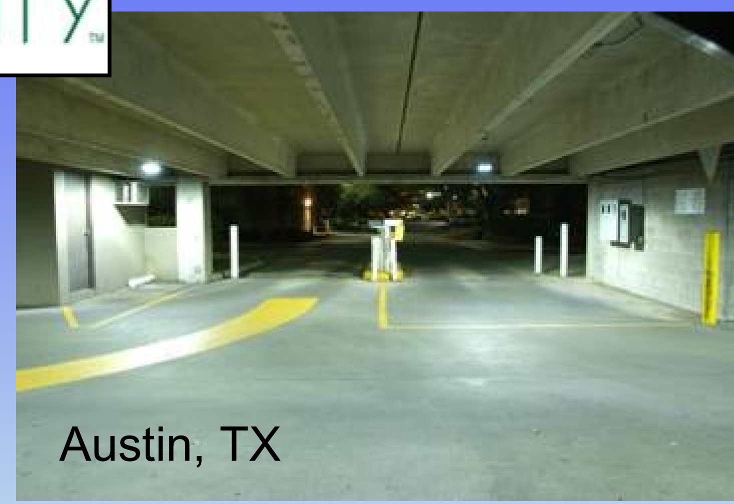
Courtesy Relume

Courtsey BetaLED

LEDCITY

Toronto, Canada

Courtsey Leotech



Courtsey BetaLED

Looking on the Bright Side

Friendly's Restaurant, Westfield MA

Incandescent 5,135 W

LED 948W

Courtesy Cree

Summary

Things to Consider

- Color
  - Binning and changes over time/temperature
- Thermal Management
  - Significant amount of internal heat to dispose of
- Flux--$$$--Lifetime
  - Be selective on applications
- Driver Electronics
  - Lifetime of LEDs doesn't matter if driver fails

But don't ignore LEDs—They represent a significant percentage of the future lighting marketplace

Summary

A future generation may someday be looking at an exhibit like this:

A device used in the early part of this century to replace non-functioning light sources

Acknowledgements

- Mark McClear Cree
- John Peck Dialight

Thank You

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