



U.S. Department of Energy  
Energy Efficiency and Renewable Energy

# The Nuts and Bolts of LEDs (LEDs 101)

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August 8, 2006



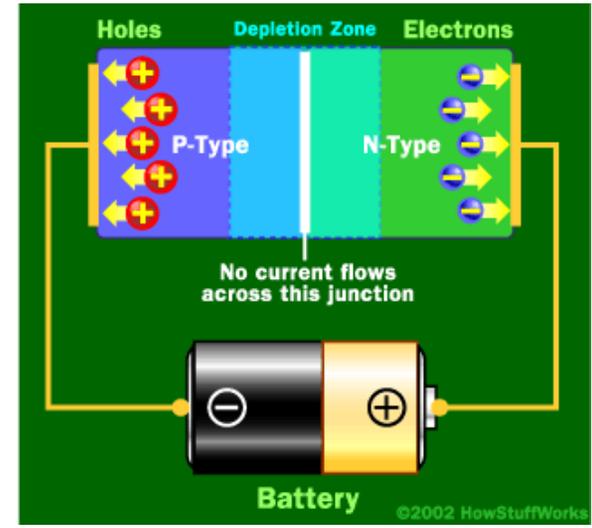
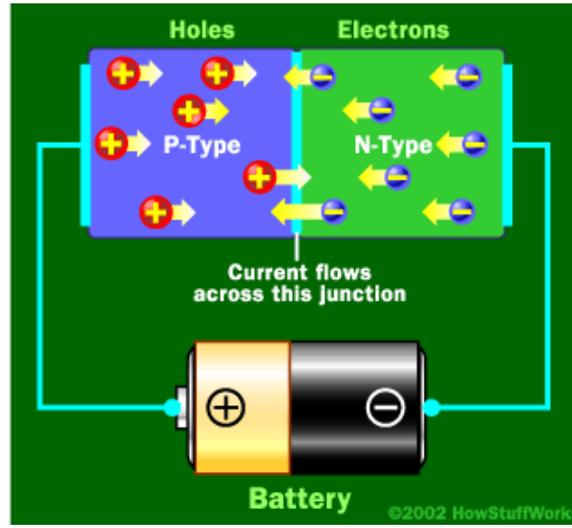
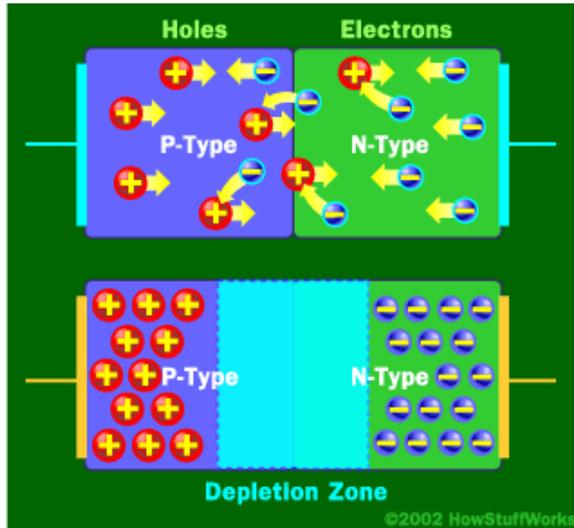


# Outline

- **How do they work?**
- **Energy efficiency of white LEDs**
- **How do LEDs make white light?**
- **Color issues**
- **Effects of Heat**
- **Standards and test procedures**
  - **Life**
  - **Light Output**



# How does an LED Work?





# How does an LED make Light?

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When current flows across a diode, negative electrons move one way and positive holes move the other way.

CONTINUE >

The diagram shows a cross-section of a diode with a blue p-region on the left and a green n-region on the right. Red circles with '+' signs represent holes moving to the right, and blue circles with '-' signs represent electrons moving to the left. A magnified view below shows a hole and an electron moving in opposite directions.

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The holes exist at a lower energy level than the free electrons, so when a free electron falls it loses energy.

CONTINUE >

The diagram is similar to the first one, but a yellow arrow points from a blue electron in the n-region down to a red hole in the p-region, representing recombination.

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This energy is emitted in the form of a light photon. The size of the electron's "fall" determines the energy level of the photon, which determines its color. A bigger fall produces a photon with a higher energy level and therefore a higher light frequency.

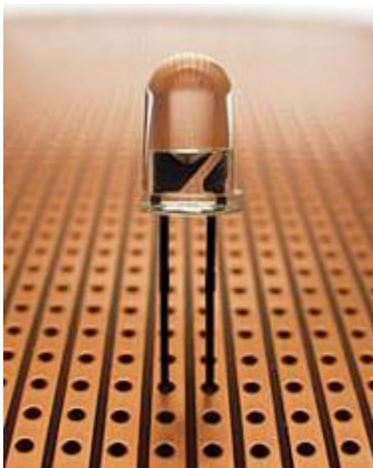
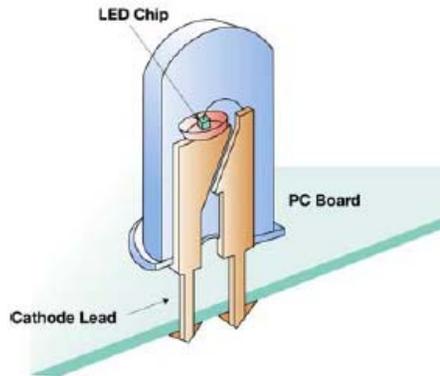
CONTINUE >

The diagram shows a blue electron falling from a higher energy level to a lower energy level, with a yellow and blue photon being emitted.

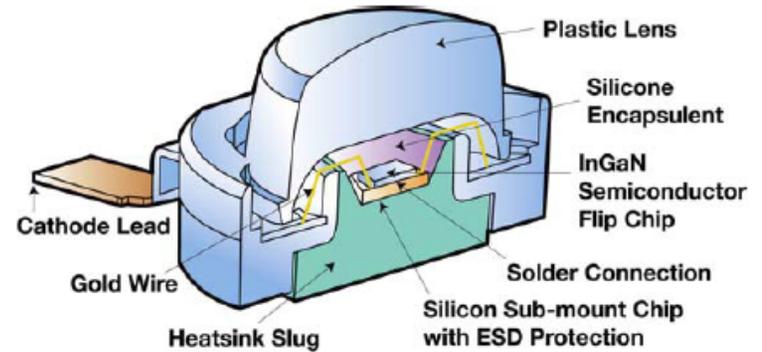


# LED Types

## Indicator

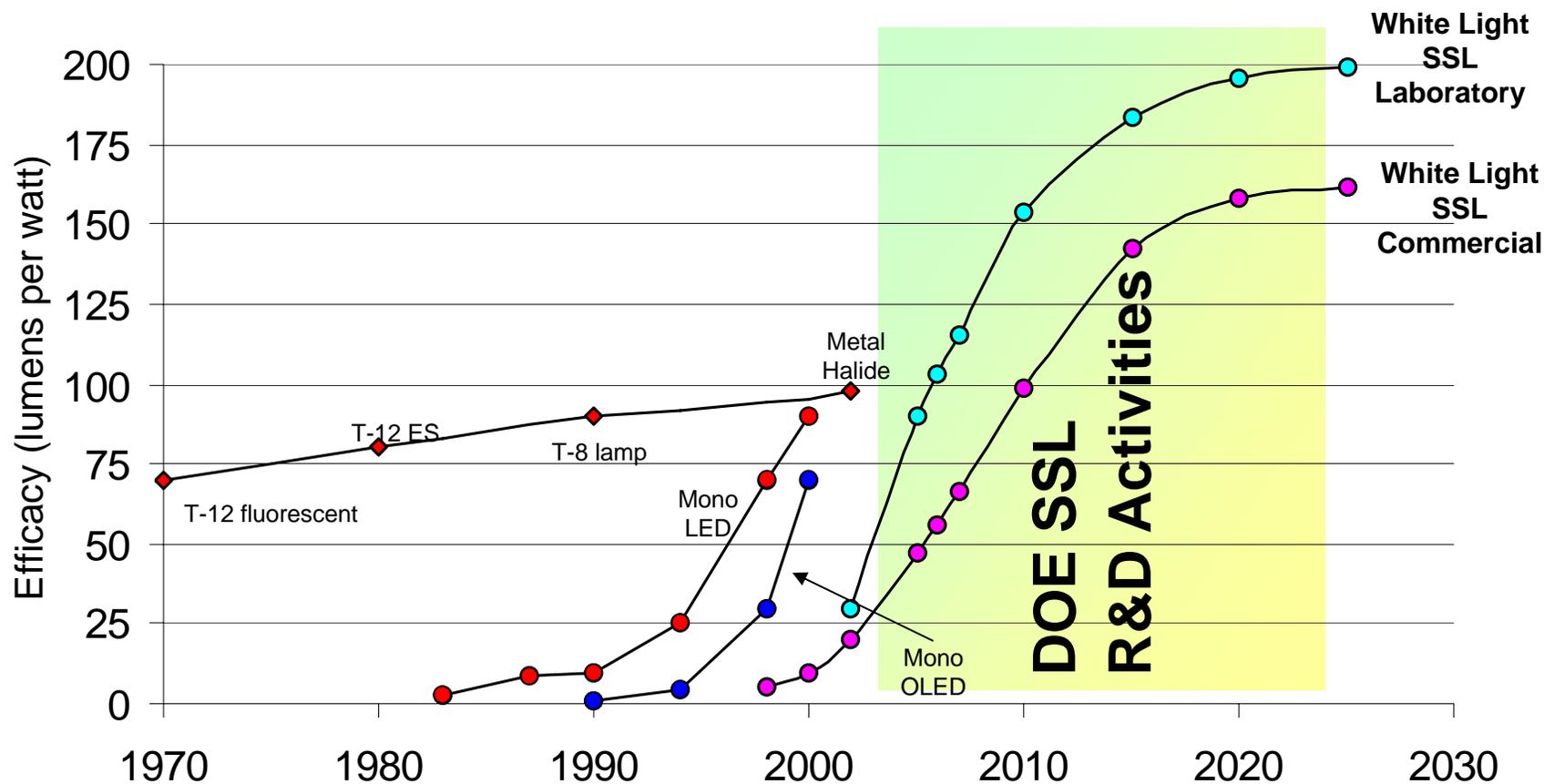


## Illuminator





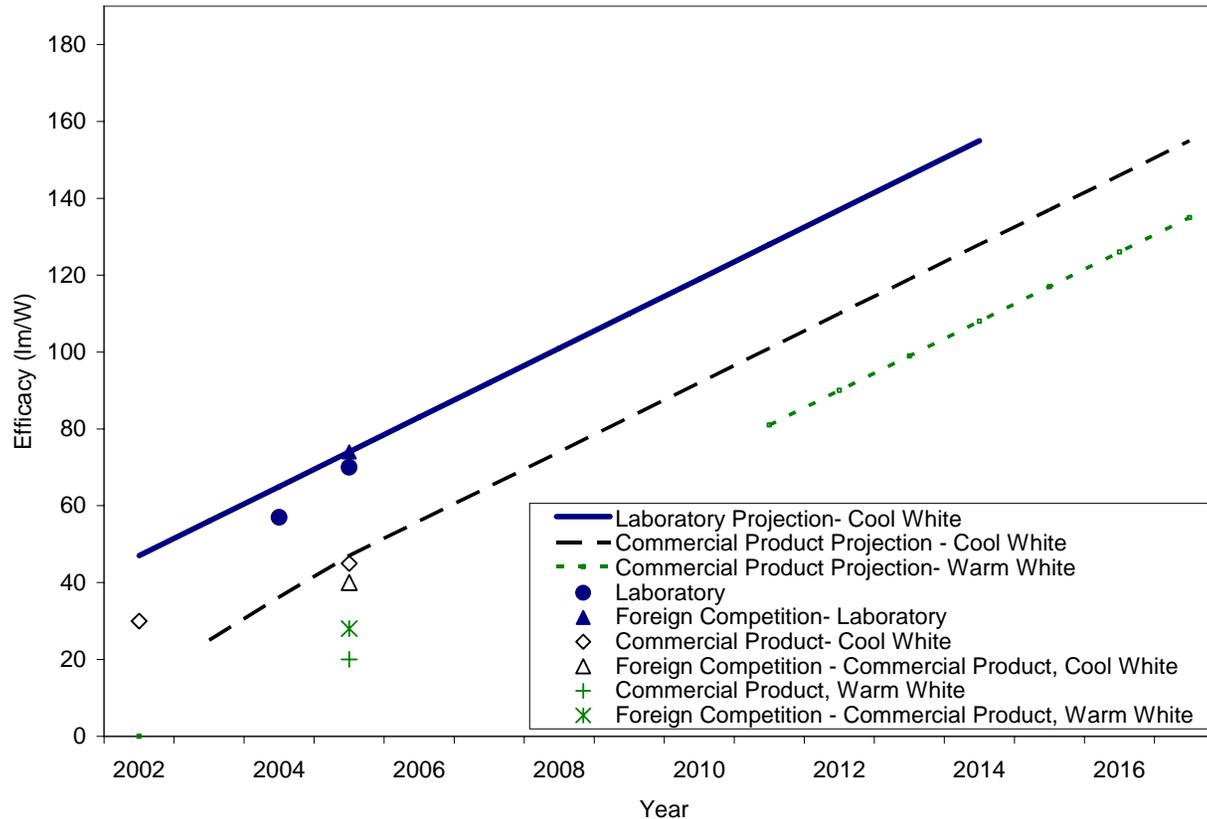
# Accelerated R&D for White Light SSL



*SSL Laboratory and Commercial Curves, revised September 2004*



# White-Light LED Efficacy Targets



*Note: Efficacy projections assume CRI=70 → 80, Color temperature = 5000-6000°K, 350ma drive current, and lamp-level specification only (driver/luminaire not included), reasonable lamp life.*



# Efficiency and Cost of White-Light Sources

## Source efficacy (2006)

- Incandescent (75W) ~13 lm/W
- Fluorescent (T8) ~83 lm/W
- HID (Metal Halide) ~100 lm/W
- **SSL (White LED) ~50 lm/W**

## Normalized retail lamp price (2006)

- Incandescent (75W) ~0.60 \$/klm
- Fluorescent (T8) ~0.73 \$/klm
- HID (Metal Halide) ~1.27 \$/klm
- **SSL (White LED) ~50.00 \$/klm**

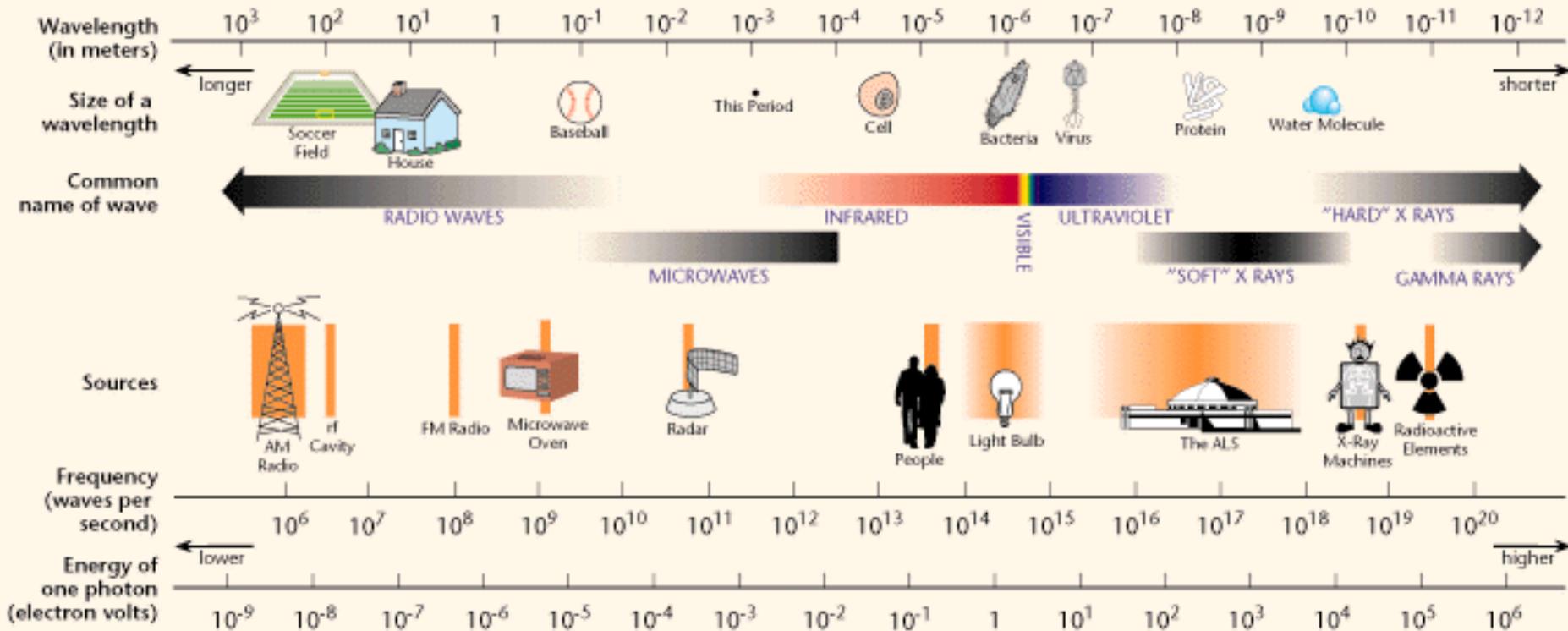
\*manufacturer data

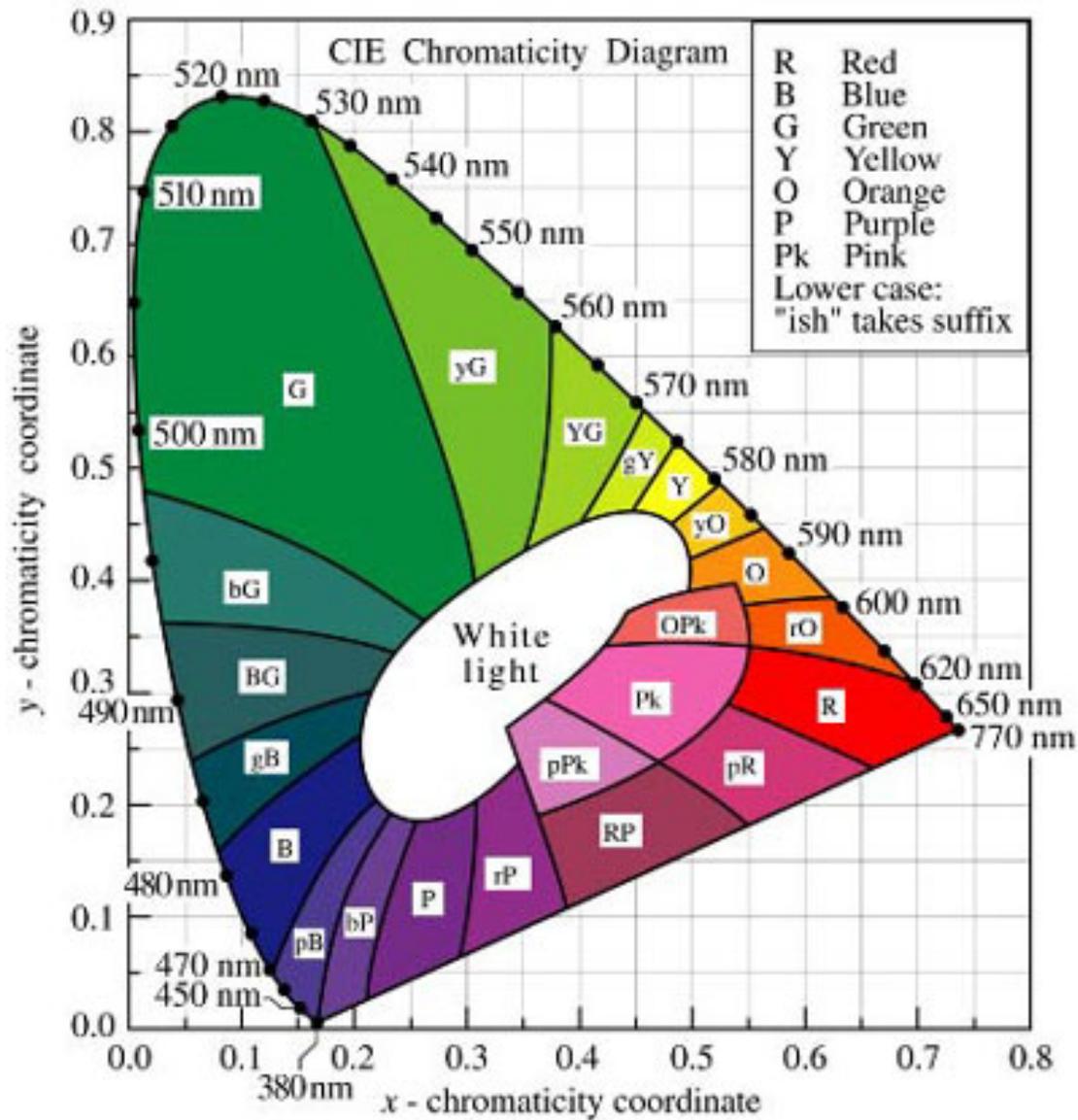


**Research is improving SSL efficacy while decreasing price**



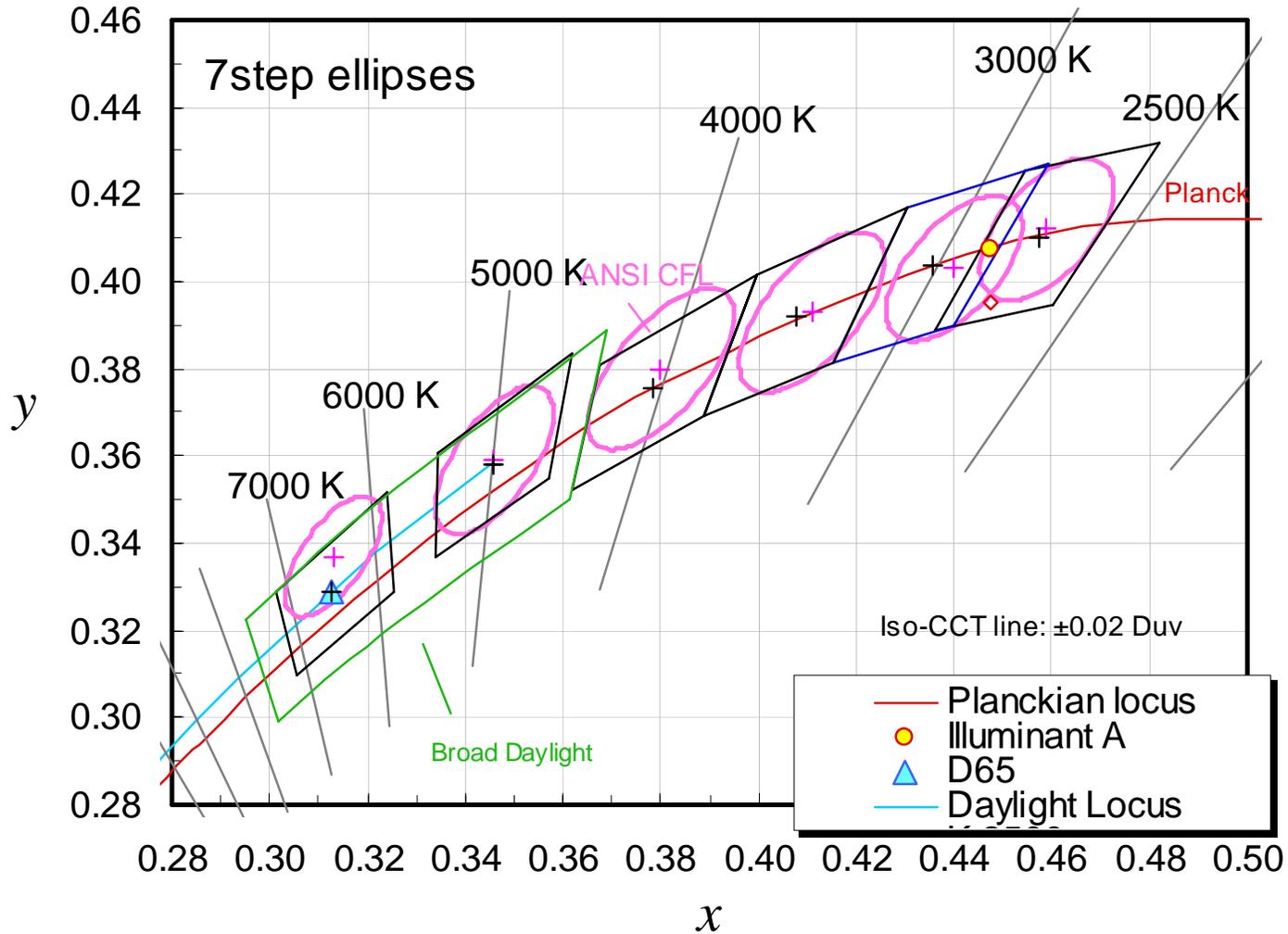
# THE ELECTROMAGNETIC SPECTRUM







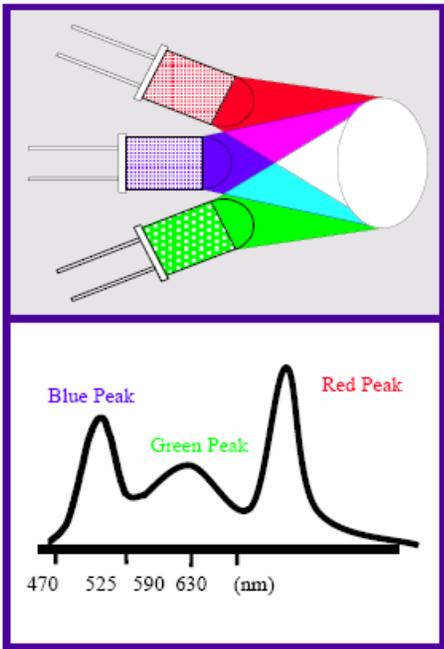
### CIE 1931 x,y Chromaticity Diagram





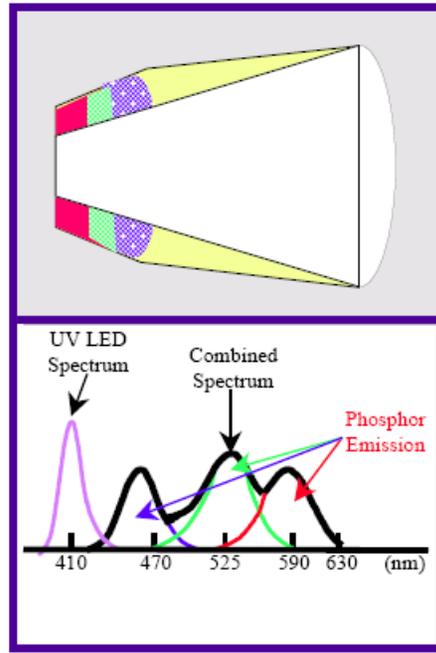
# Methods to Create White Light

### Red + Green + Blue LEDs



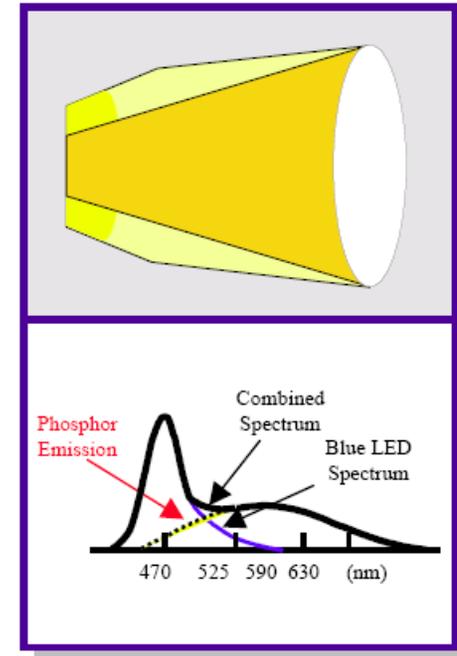
- Dynamic color tuning
- Excellent color rendering
- Large color gamut

### UV LED + RGB Phosphor



- White point tunable by phosphors
- Excellent color rendering
- Simple to create white

### Blue LED + Yellow Phosphor



- Simple to create white
- Good color rendering



# White Light SSL Challenges

- **Lifetime – lumen maintenance, heat management**
- **Efficacy – improving rapidly**
- **Color Quality**
- **Luminous Flux**
- **Cost**
- **Standards and test procedures**
- **Ready or Not**





# Color Quality Issues

- **Correlated color temperature (CCT)**
  - Color appearance of white light
  - High CCT sources look "cooler" and bluer
  - Low CCT sources look "warmer" and more yellow
  - Higher efficacy LEDs typically have high CCT
- **Color consistency**
  - Different color appearance within shipments of white LEDs
  - Color shifts over time with LED degradation
- **Color rendering index (CRI)**



## Efficiency & Quality Trade-offs

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Color Temperature\*



Efficacy



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Color Temperature\*



Efficacy



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CRI\*



Efficacy



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Heat



Efficiency / Output



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Heat



Life / Durability

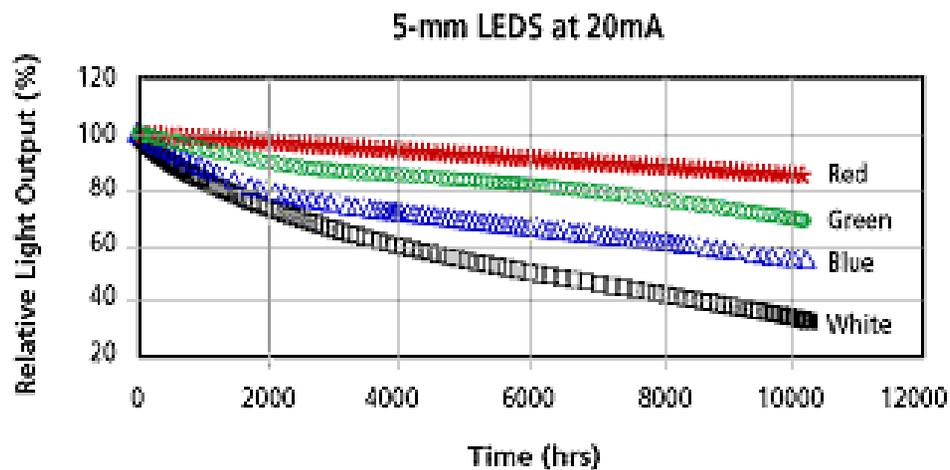
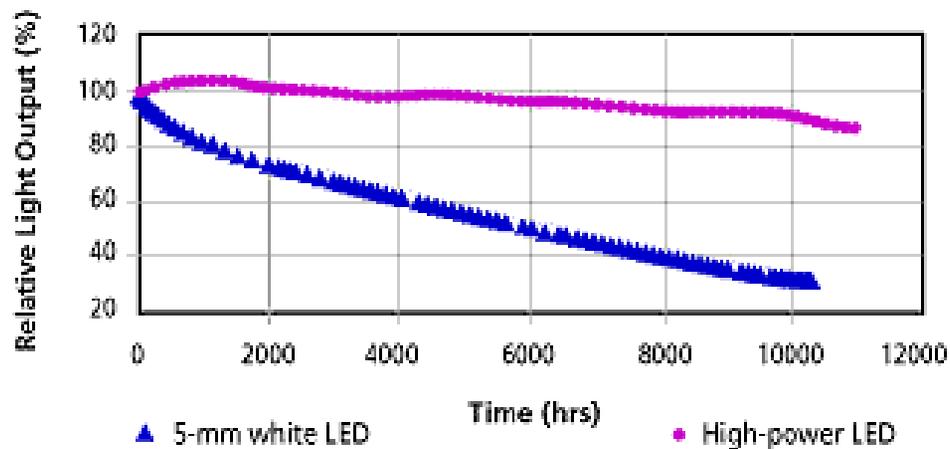


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\* Phosphor-converted LEDs



# Light Output for LED types



Courtesy of LRC



# So you thought LEDs don't create heat?

## Power Conversion for “White” Light Sources

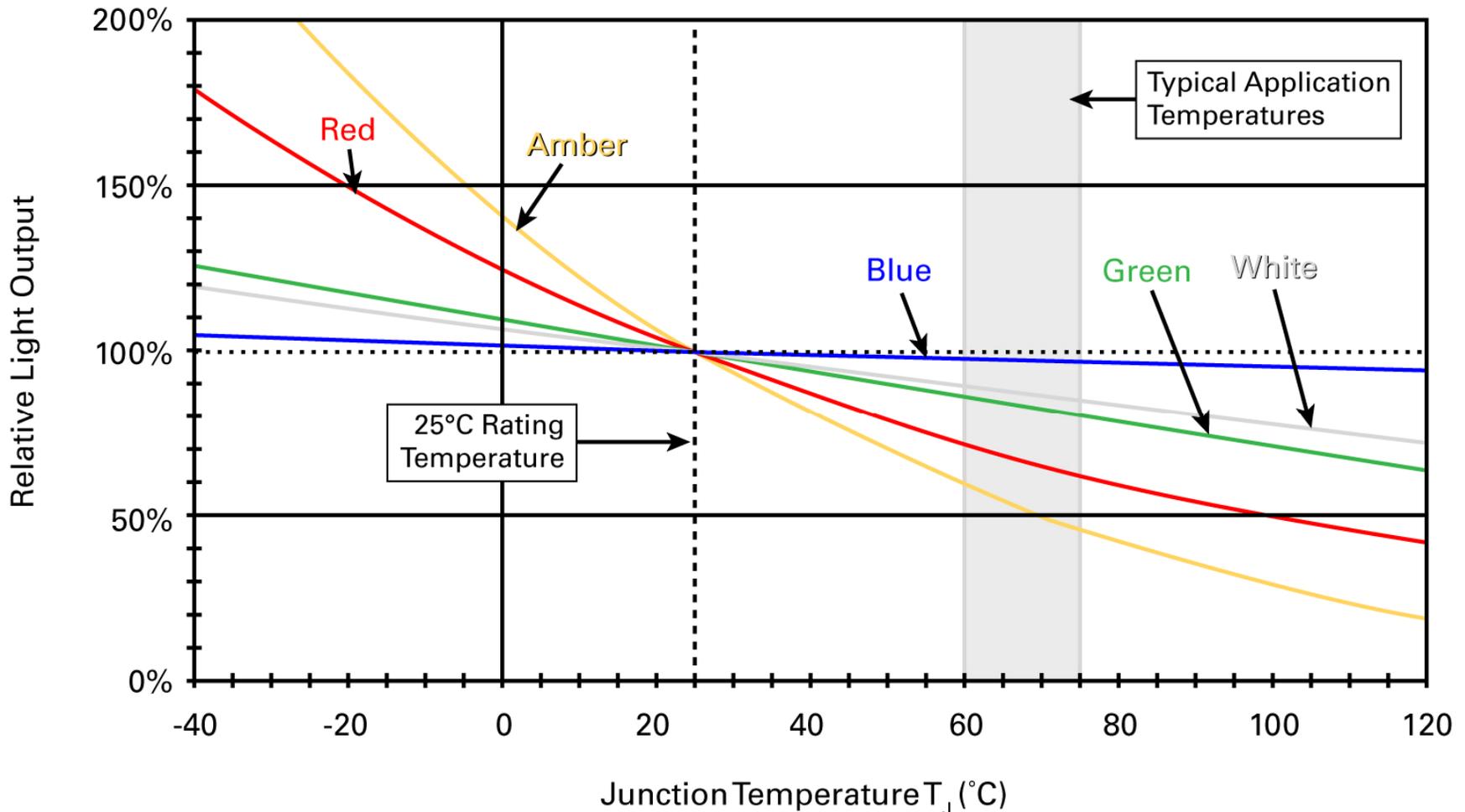
	<b>Incandescent<sup>†</sup></b> (60W)	<b>Fluorescent<sup>†</sup></b> (Typical linear CW)	<b>Metal Halide<sup>‡</sup></b>	<b>LED</b>
Visible Light	7.5 %	21 %	27 %	10-15 %
Infrared	73.3 %	37 %	17 %	~ 0 %
Ultraviolet	0 %	0 %	19 %	0 %
Total Radiant Energy	80.8 %	58 %	63 %	10-15 %
Heat (Conduction + Convection)	19.2 %	42 %	41 %	85-90 %
Total	100 %	100 %	100 %	100 %

<sup>†</sup> IESNA Lighting Handbook – 9<sup>th</sup> Ed.

<sup>‡</sup> Osram Sylvania

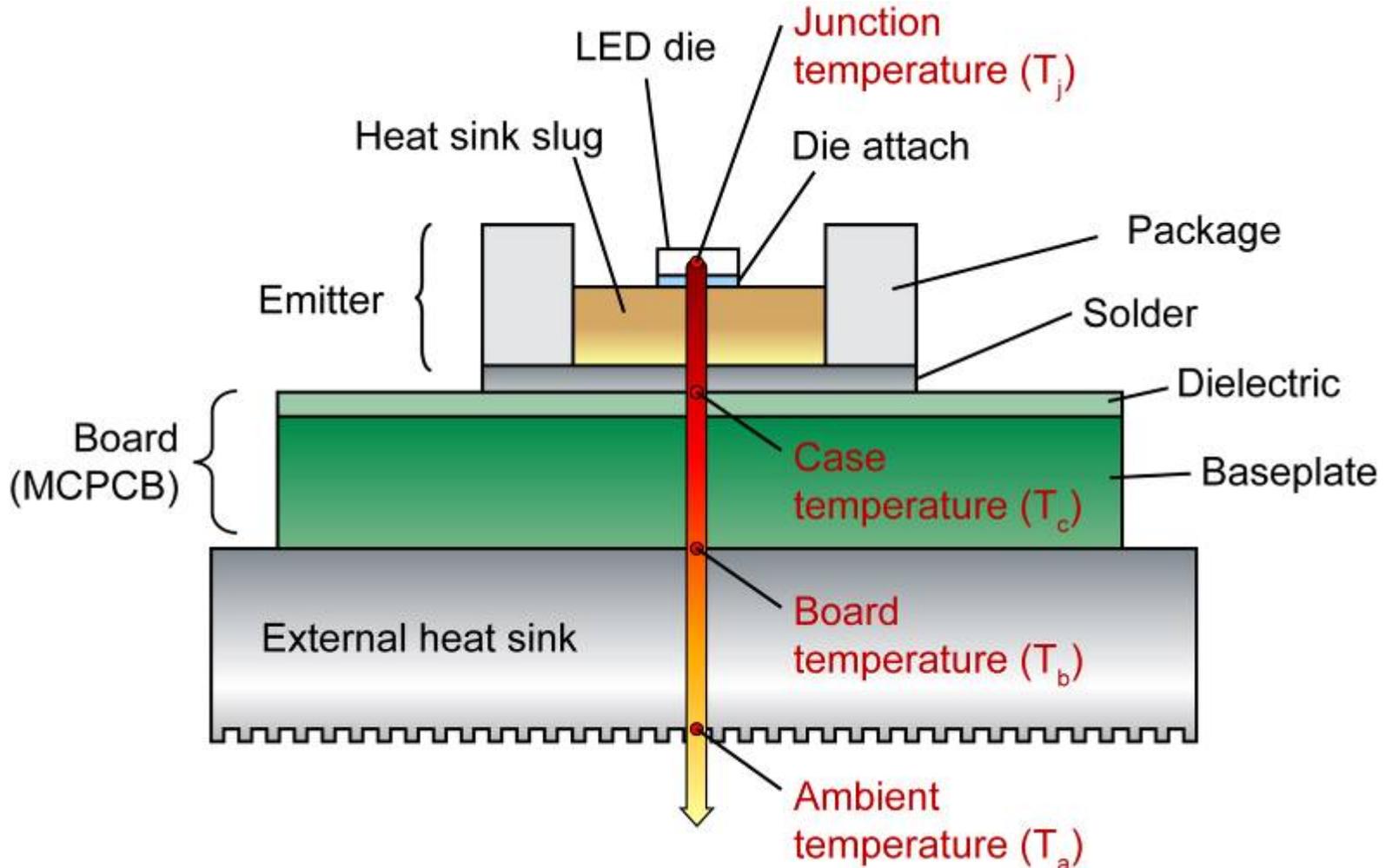


# Light Output vs. Junction Temperature ( $T_j$ )





# What Effects Junction Temperature?

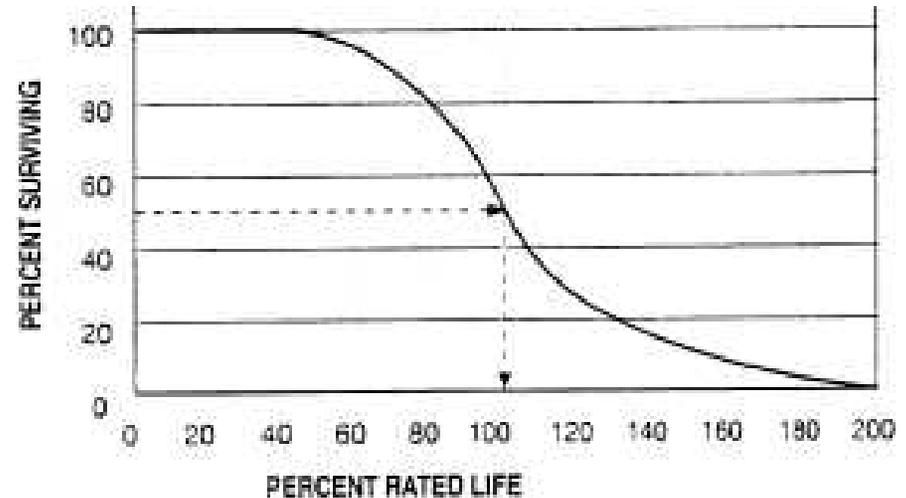




## Life Rating

- **Lumen depreciation vs. failure**
- **LED life definition may differ by application**
  - **L<sub>70</sub>** for general illumination
  - **L<sub>50</sub>** for indication
  - **L<sub>80</sub>** for some applications?
- ***ASSIST* recommends proposed method**

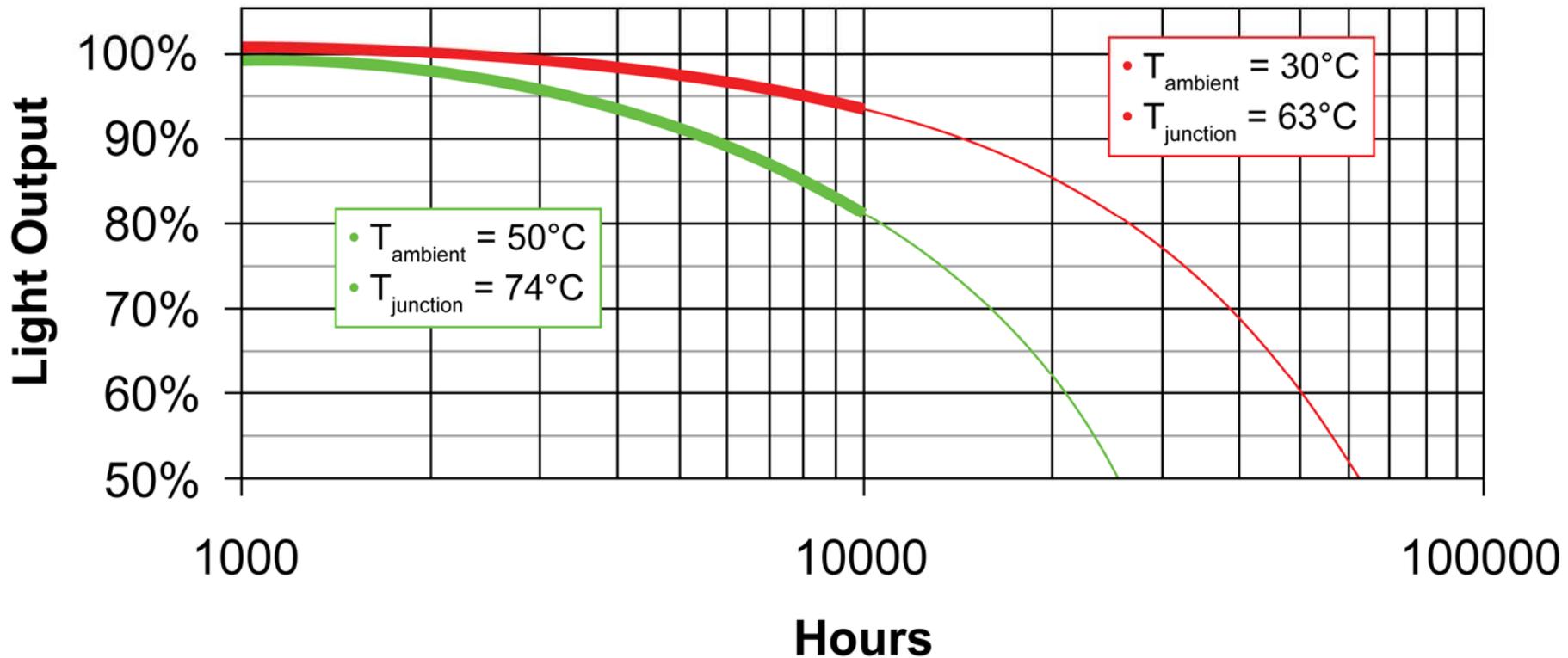
Typical lamp mortality curve





# Temperature Effects on Life

## High Brightness White LED (350 mA)





# Standards and Test Procedures

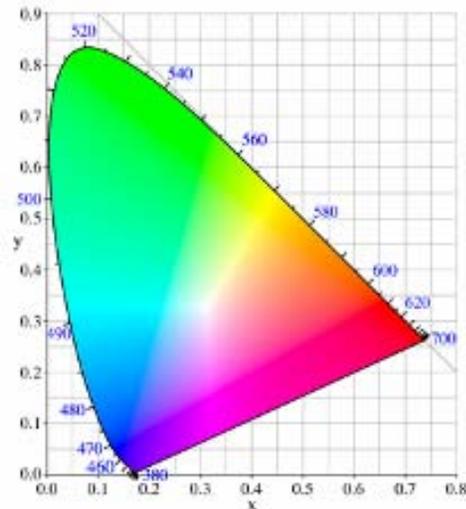


- **DOE hosted Mar 1 workshop in DC**
- **Standards groups working to the ENERGY STAR schedule**
- **DOE providing on-going technical support for standards development**



## Standards and Test Procedures

- **Test procedures under development**
  - Photometric measurements (IESNA LM-79)
  - Life-testing (IESNA LM-80)
  - Chromaticity (ANSI C78.XX1)
  - Electrical measurements (ANSI C78.XX3)
  - Definitions (ANSI C78.XX2)
- **Final procedures expected in May 2007**





## More Information

**<http://www.netl.doe.gov/ssl/>**

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