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Lighting and illumination engineering
II. Sources: modeling and realities

J. Koshel

The Univ. of Arizona & Photon Engineering, LLC
U.S.A.

Strada Costiera 11, 34151 Trieste, Italy - Tel.+39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it

Lighting and illumination engineering
II. Sources: modeling and realities

16 February 2010 – 9.00 to 10.00

John Koshel
College of Optical Sciences – The Univ. of Arizona &
Photon Engineering, LLC

Source Modeling is Important

- Most important design aspect that is overlooked:
  - Often a simple and ineffective model is assumed
  - Errors can be dramatic: 25% and up
  - If done correctly, then errors are due to tolerances (that is another lecture) in manufacturing process
- Aspects that Need to be Addressed:
  - Geometry of the source (Geometry)
  - Emission properties of the source (Rays)
  - Optical characteristics of source components (Properties)
  - Tolerances of the source (future lecture, touched upon today)

Source Modeling Makes a Great Course to learn how to use the Software

Source Modeling Introduction

Incandescent, Fluorescent, HID, LEDs, …

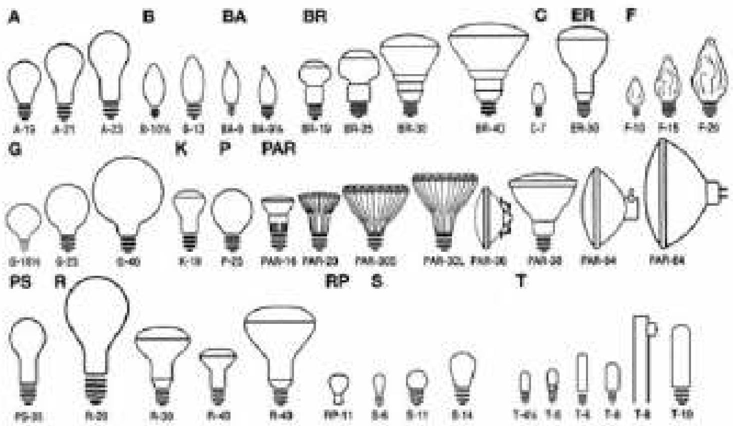
Probably the most import part of the Illumination Design Process

Source Types

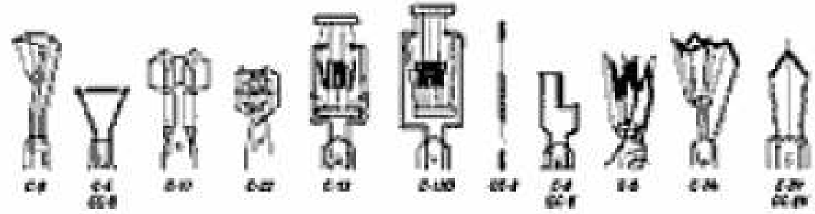
- Incandescent:
  - Filaments or ribbons
  - Resistive: heat up and emit "greybody" radiation
  - Not very efficient in visible
  - Dying breed
- Arc lamp:
  - High voltage passed through a vapor between two electrodes
  - Plasma is formed, which emits in the visible
  - Inefficient to efficient (Na)
  - Susceptible to line emission
  - Examples: HP and LP Na, Hg, HID, Metal vapor
- Fluorescent:
  - High voltage passed through some vapor (e.g., Hg)
  - Emit in the UV and a phosphor on the bulb emits into the visible
  - Very efficient source
  - Not a green source – increasingly not wanted
- LED:
  - Current passed through semiconductor to give narrow spectral emission
  - White light with integration of phosphor
  - Increasingly efficient, with 100 lm/W the metric for replacing incandescent
  - Expensive
  - Be cautious of data sheets

Bulb Characteristics

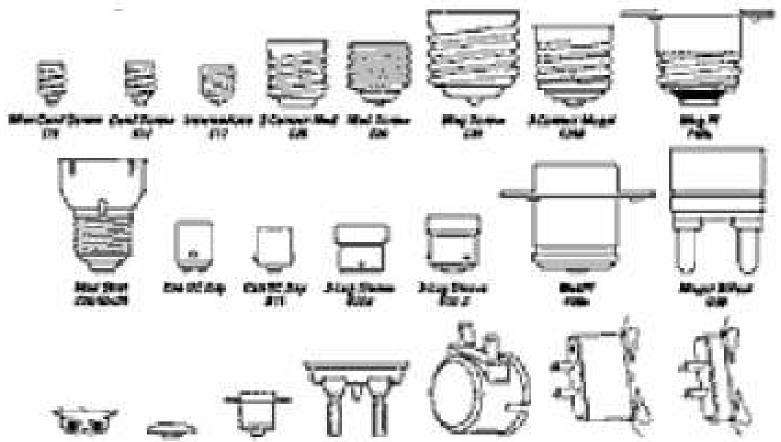
Envelope



Filament

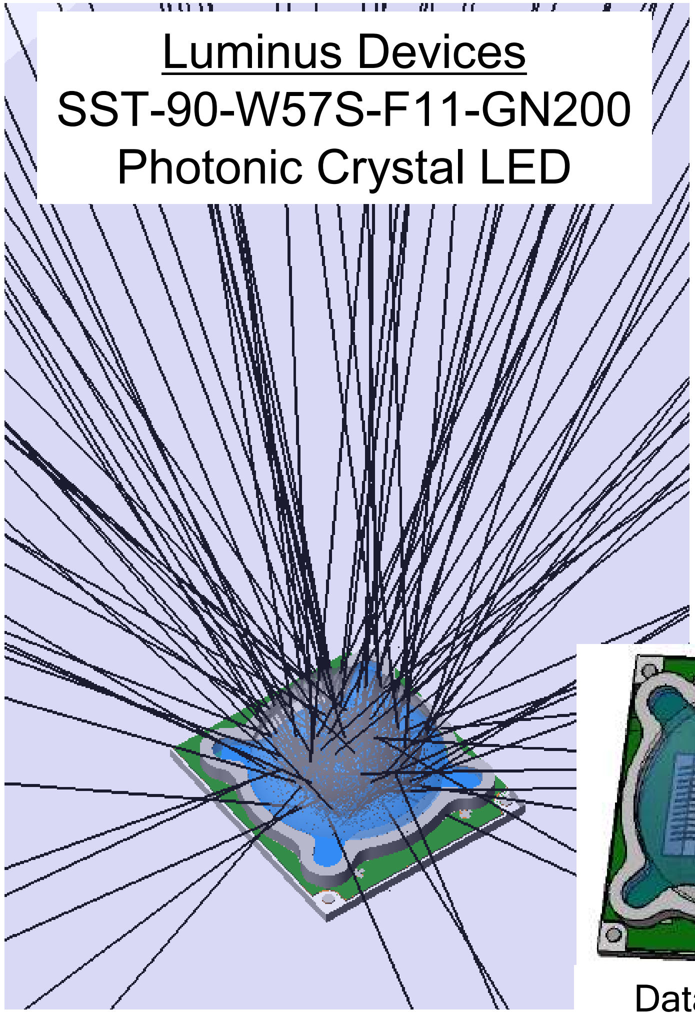


Base

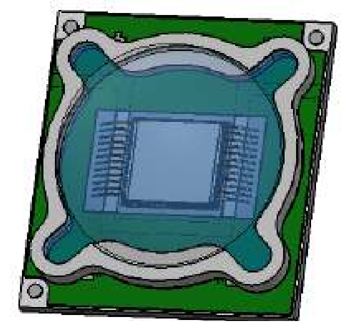


Source Software Models

- Use source libraries:
  - Software companies have a lot of this data
  - Manufacturers, especially LEDs, supply this data
- If no geometry, generate it:
  - Rays only
  - Simple model: put in the basics - emitter and outer geometry
  - Complex model: model everything, typically in CAD
- If no rays, generate them:
  - Assign a surface (or volume) source to the desired objects (volume)
  - Trace rays
  - Calculate intensity distribution
  - Make changes till you get agreement
  - Use an optimizer to perfect



Model Results



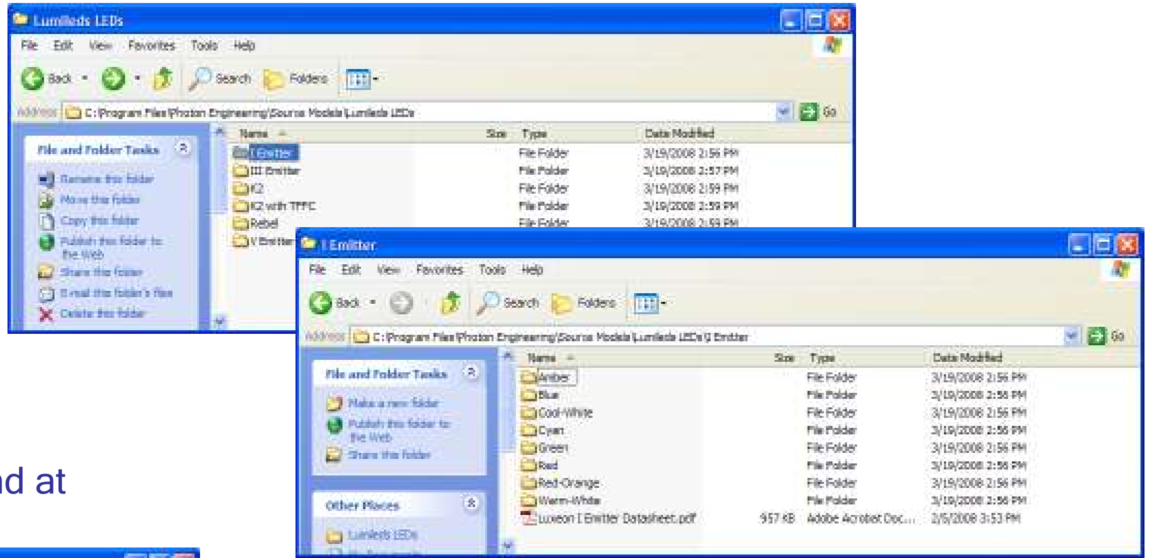
Data Sheet

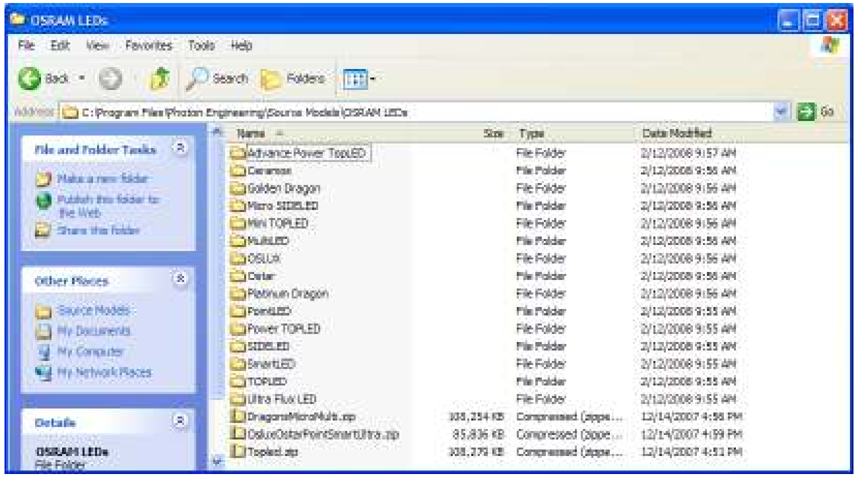
Source Library Description

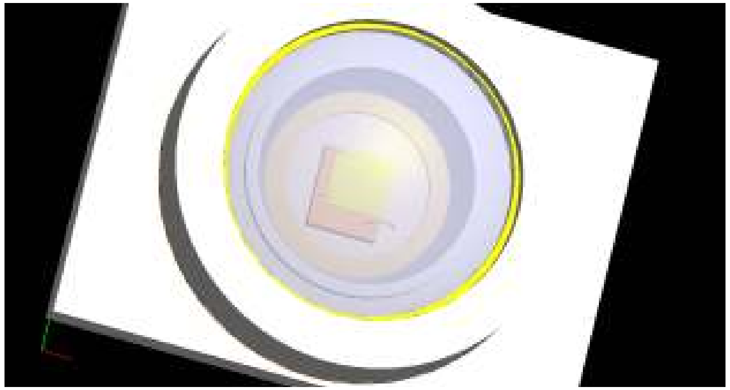
- Source Libraries Can Include:
  - Geometry
  - Optical Characteristics
  - Default Ray Set
  - Help files.
- Most Source Libraries are for Automotive Sources:
  - Incandescent,
  - High-Intensity Discharge (e.g., Arcs), and
  - High-Brightness LEDs.
- Other Bulbs Added as Needed:
  - Customer Demand,
  - Customer Contract,
  - Customer-Supplied Data, and
  - Interest by Individual Software Companies.
- Software Companies Always Appreciate Suggestions!

FRED LED Source Library

- Extensive List from:
  - Philips Lumileds
  - OSRAM
  - Cree (about complete)
- Includes:
  - Minimum: Outer Geometry
  - Maximum: Inner Geometry
  - Ray Files
  - Larger Ray Files can be found at manufacturer websites



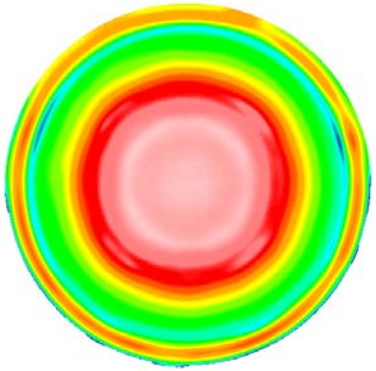


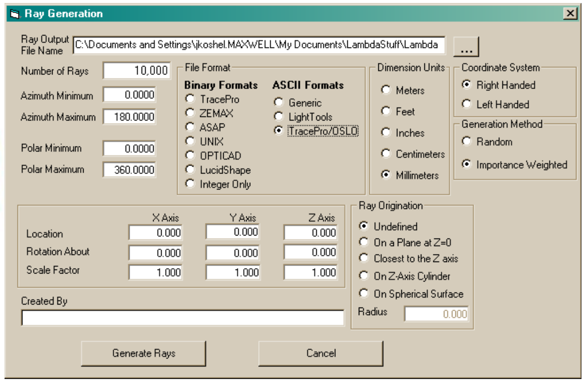


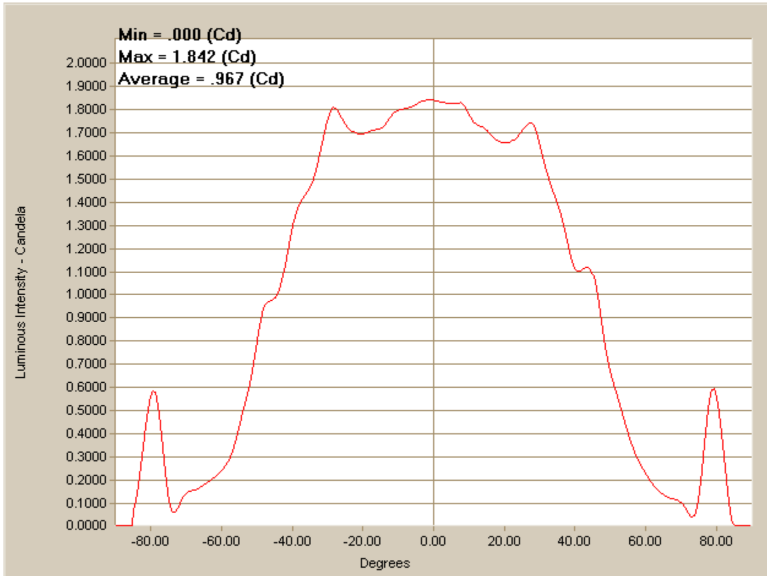
Radiant Imaging Source

- Can import rays of a source from Radiant Imaging.
- Generate the rayset within ProSourceTM.
- Need to install ProSource on your computer
  - www.radimg.com
  - it costs money
- Radiant Imaging can also measure the luminance/radiance for a source you supply to them.
- When Using in Software Model do not Included Source Geometry with Ray Generation!

<u>LED Example: Cree Blue 7090 XLamp</u>



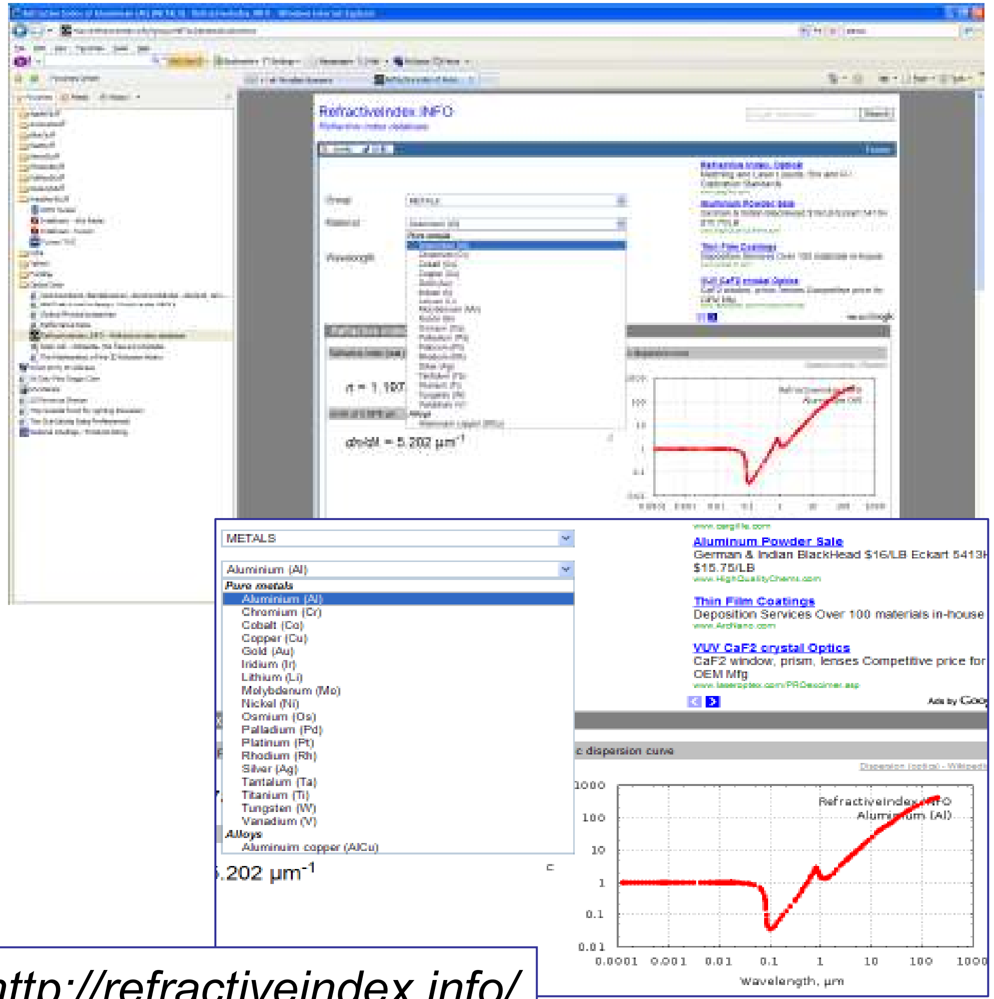




Material and Surface Characteristics

- Materials:
  - Find out what materials are used and then assign accordingly
  - Consult the literature
  - Visit manufacturer websites
  - Look at the examples in models
- Surfaces:
  - If you can find a complex index of refraction, you have the surface characteristics too
  - Assign an appropriate scatter function - we will talk about this toward the end of the course
  - Visit manufacturer websites
  - Look at the examples in models

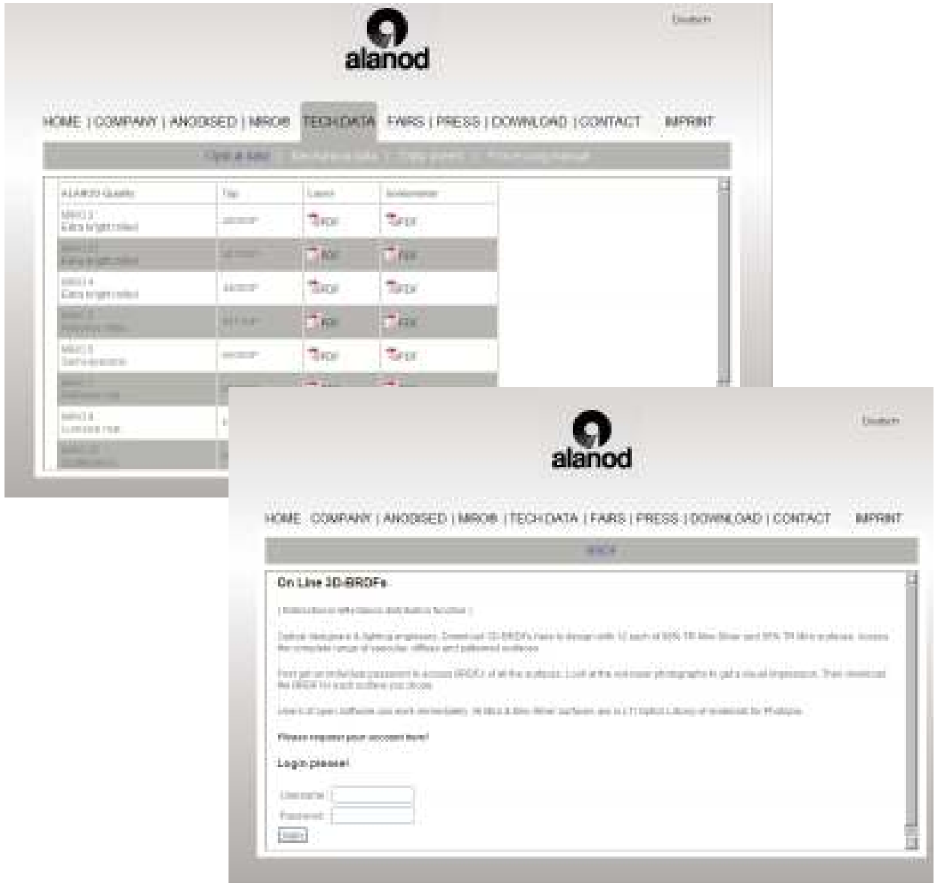
- NOTE: finding optical property data is the item that may require the most of your time. Based a lot on experience, so ask questions



http://refractiveindex.info/

Example: Alanod Website

- Alanod makes high reflectivity aluminum sheets
- Great reflective material
- They have a number of metals
  - Varying specular and diffuse reflectivities
  - MIRO 1 - MIRO 8 are examples
- Website provides a wealth of data:
  - Public: the basics of the materials/surfaces
  - Private: BRDF & specular/diffuse reflection parameters
  - You must be willing to search and ask for data
- NOTE: you will not be able to find all the data, so be ready to make educated guesses

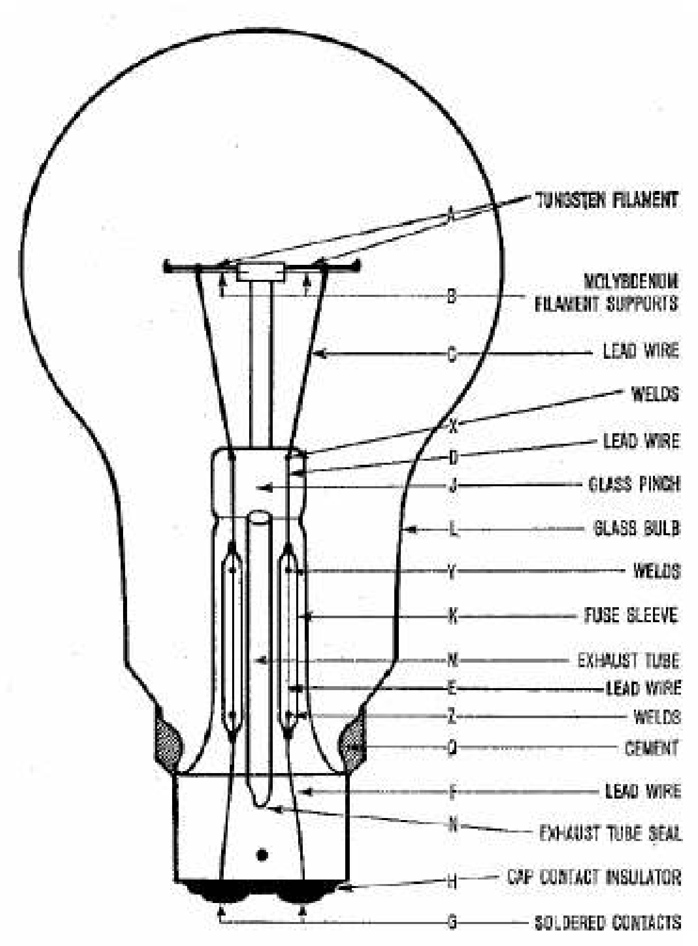


Source Modeling

Incandescent Sources
Arc Sources
LED Sources
Fluorescent Sources

Filament Source Modeling

Tungsten Bulb



- Equation of Spectral Radiance For Tungsten:

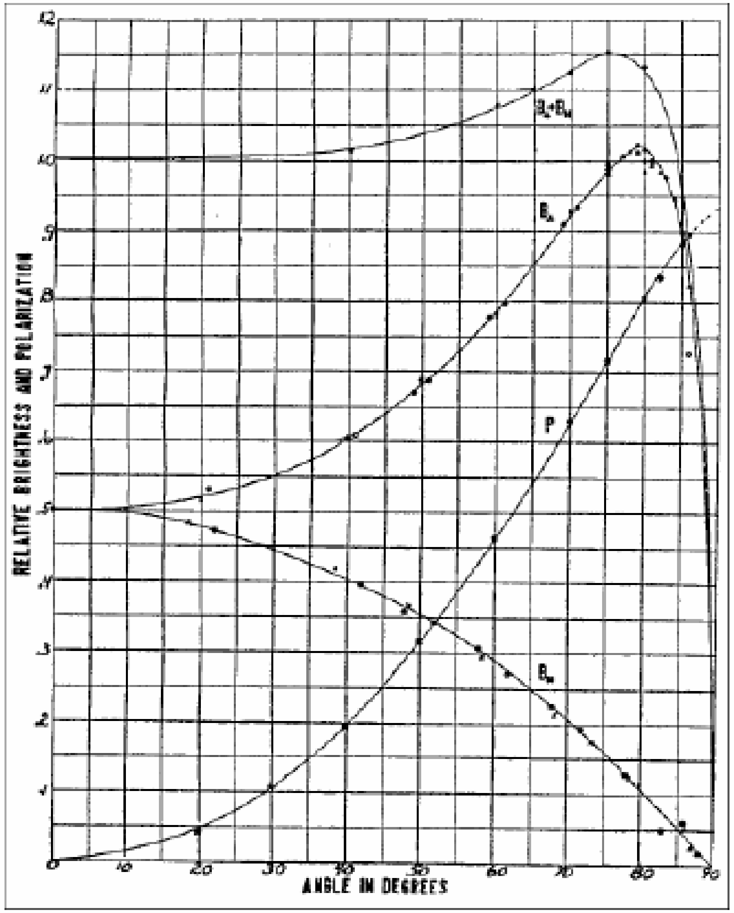
$$L_\lambda = \frac{\varepsilon(\lambda;\theta,\phi)c_1}{\pi\lambda^5}\cdot\frac{1}{\left(e^{c_2/\lambda T}-1\right)}$$

- Equation useful for modeling and interpolation:

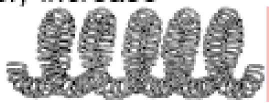
$$E_\lambda = \frac{e^a e^{b/\lambda}}{\lambda^5}\left[A_0 + A_1\lambda + A_2\lambda^2 + A_3\lambda^3 + \ldots\right]$$

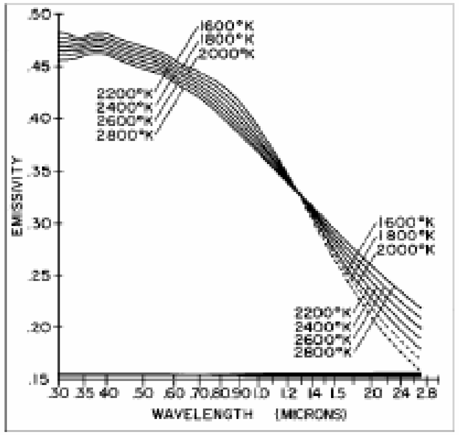
  - Term $e^a e^{b/\lambda}$ models spectral variation of emissivity
  - Polynomial models minor fluctuations
  - from NBS TN 594-13

Emissivity of Tungsten

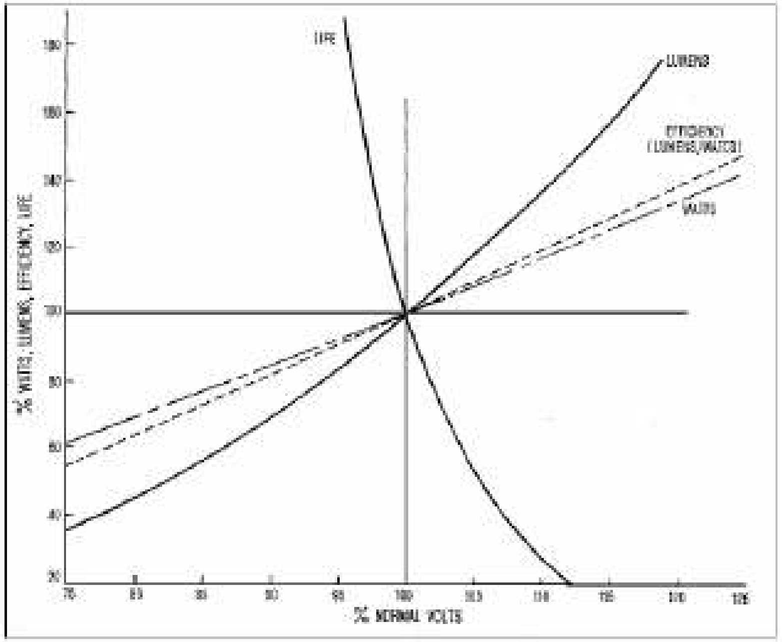


- Emissivity enhancement:
  - Start by winding filament wire into a coil
    - Inter-reflections effectively increase emissivity
  - Make a coiled coil
  - Reflector can be used to redirect unneeded energy back onto filament
    - Virtually eliminates observable polarization





Why do Tungsten Bulbs Fail?



- Filament evaporates, depositing brown film on inside of envelope
- Uneven evaporation causes thinning, creating "hot spots" which evaporate even faster
- Filament crystallizes during high-temperature operation; moderate rate on AC, much faster on DC

$$\frac{\text{light}}{\text{rated light}} = \left(\frac{\text{voltage}}{\text{rated voltage}}\right)^{3.4}$$

$$\frac{\text{life}}{\text{rated life}} = \left(\frac{\text{voltage}}{\text{rated voltage}}\right)^{-13}$$

Life degrades at a “power” rate around 4x faster than light emitted!

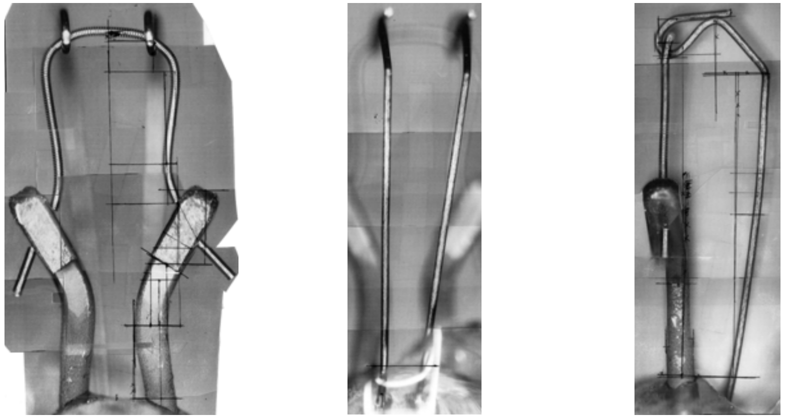
Potential Solutions

- Addition of halogen (I, Br, Fl, Cl) creates regenerative cycle – Tungsten-Halogen:
  - Evaporated tungsten combines with halogen
  - Resulting halide decomposes at "hot spot", plating tungsten
- Advantages:
  - Longer life at high filament temperatures
  - Lumen efficiency greater than conventional
  - Superior lumen maintenance (long-term stability)
  - Smaller physical size for given wattage
- Disadvantages:
  - High envelope temperature required (>250°C) to maintain regenerative cycle
  - Fire hazard
  - Internal pressure and UV content require safety measures
  - Quartz envelope requires greater care
  - More costly

- Refractory Metals:
  - Tantalum, molybdenum
  - Lower melting point than tungsten
  - Higher vapor pressure than tungsten
  - Low emittance at operating temperatures
  - Susceptible to oxidation
- Noble Metals:
  - Platinum, Palladium, Iridium
  - Lower melting points
  - Resistant to oxidation
- Alloys:
  - 80Ni-20Cr (Nichrome,)
  - Resistance essentially constant with temp
  - Resistant to oxidation

Image Stitching

- Take a series of pictures of the source, holding the magnification constant across all pictures.
- Stitch images together, properly overlapping and thus cropping out "reimaged" aspects
- Note that contrast and illumination level may vary between images.
- Generate CAD:
  - Digitize the pictures and/or
  - Measure the surfaces

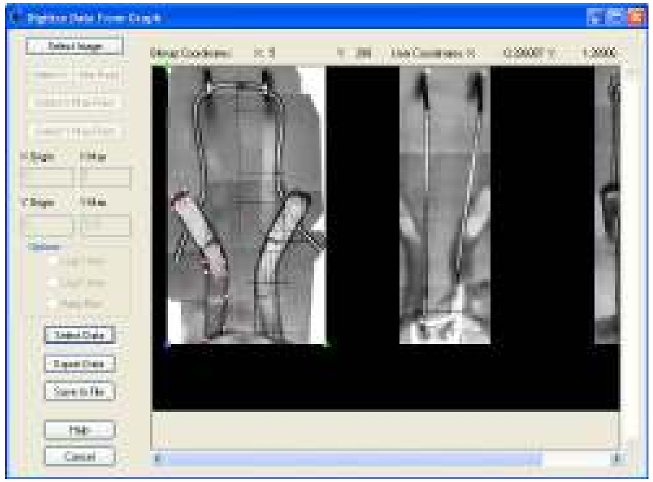


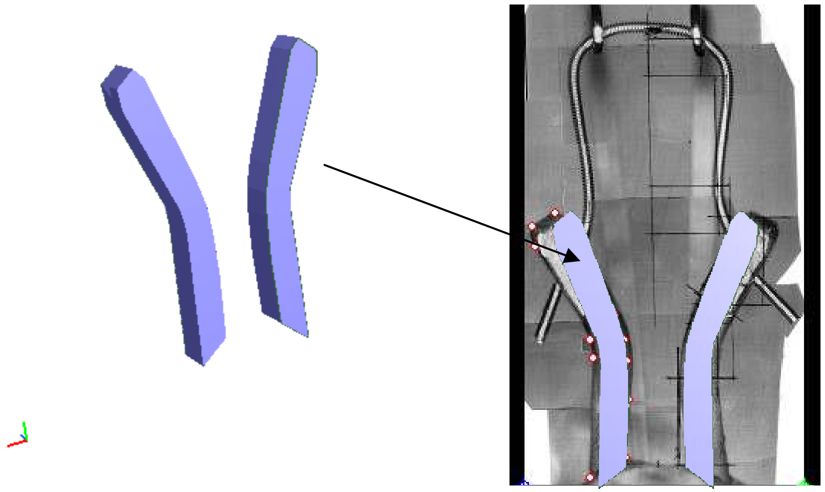
Side View

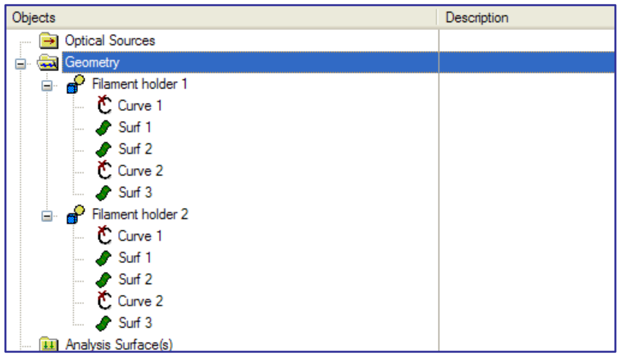
Courtesy: J. Lee and J. Greivenkamp, "Modeling of Automotive Interior Illumination Systems," Opt. Eng., July 2004.

Image Digitizing

- Optical design software has the ability to digitize picture data
  - Import the picture
  - Assign spatial extents
  - Pick points on the surfaces
  - Assign to a curve in the model
  - Use the curves to create physical geometry:
    - Extrude
    - Revolve
    - Use as a bounding surface







Physical Measurement of the Source

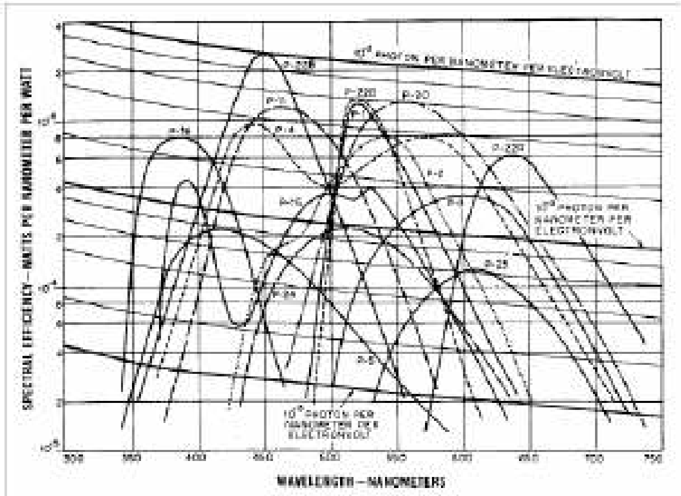
- Take pictures of the source
- Get a data sheet if at all possible
- Time to get your hands dirty:
  - Measure all external aspects of the bulb
  - Affix tape over the glass of the source
  - Crush the glass or snap the tip of the bulb – use vise grips or similar tool
  - Unwrap the tape
  - Measure the thickness of the glass with calipers
  - Measure the filament:
    - Count the number of coils
    - Measure the length of the filament between its holders
    - Measure the position of the filament on the holders
    - Measure the diameter of the whole coil
    - Measure the thickness of the filament
  - Follow a similar recipe for the other objects of the source
- Use CAD to generate the model:
  - Use any symmetry that you can, i.e., build the curves and rotate to create geometry, make one filament and replicate it to create the other
  - Use image digitizing to enhance accuracy
- Assign Optical Properties

Fluorescent Source Modeling

Phosphors and Fluorescent Lamps

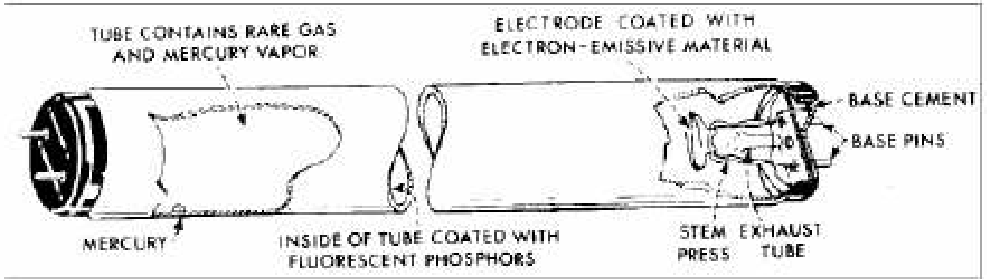
Phosphors

- Characteristics:
  - temperature dependent
  - many colors available
  - many persistences available
- Used in **fluorescent lamps**, **LEDs**, cathode-ray tubes, x-ray and gamma-ray screens, UV detectors, charged-particle detectors, identification inks, safety paints and fabrics, screens, flat panel displays, FEDs, image converters, etc.



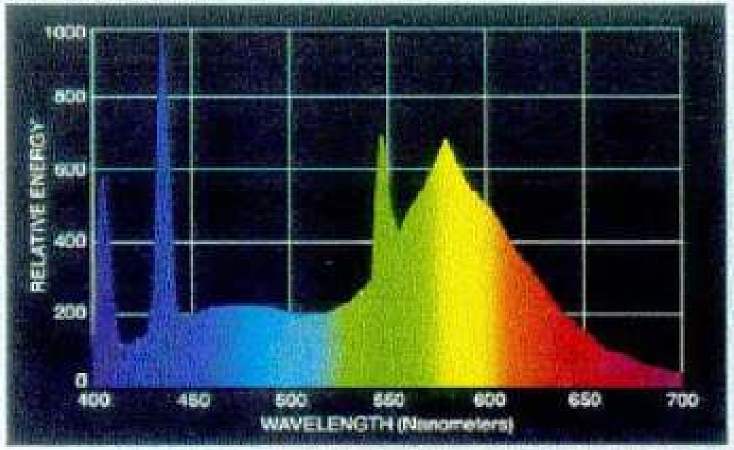
Fluorescent Lamps

- Phosphor excited by radiation from mercury discharge predominant excitation from 254 nm Hg line
- Many phosphors available with varying color characteristics
  - daylight, colors, plant growth
  - spectrum comes from phosphor and Hg lines
  - tri-phosphors more efficient
- Characteristics:
  - Long lifetime (10,000 hours)
  - High efficiency (40-70 lm/W)
  - Low radiance extended source
  - Dc, ac and rf operation
  - Needs help getting started – HV ballast

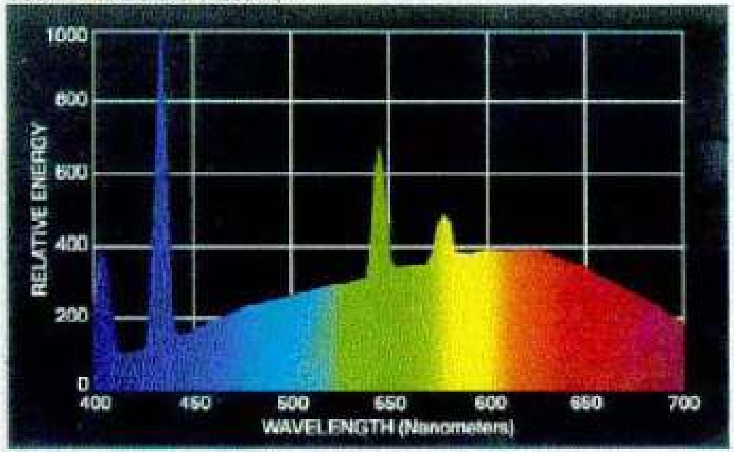


Some Phosphor Spectra

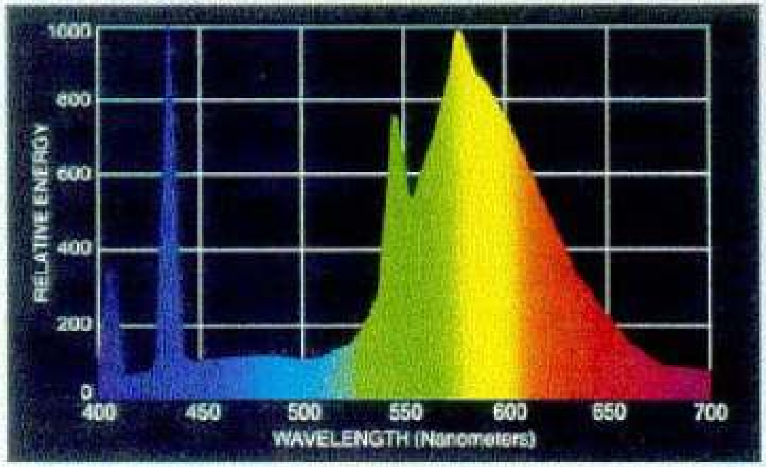
Cool White (4100 K)



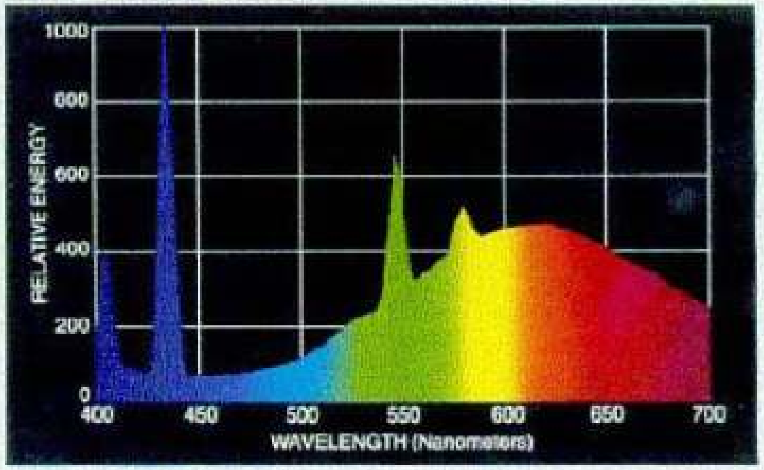
Cool White Deluxe (4200 K)



Warm White (3000 K)



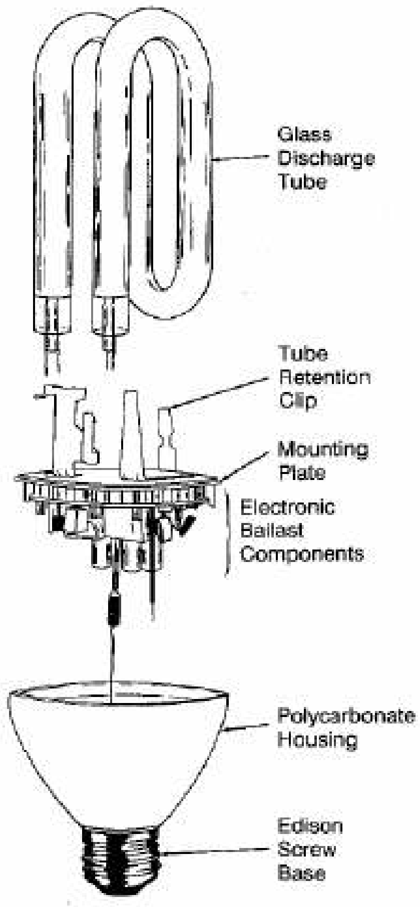
Warm White Deluxe (3000 K)



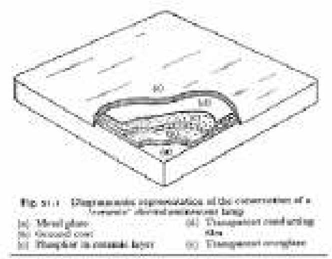
CFL and EL Sources

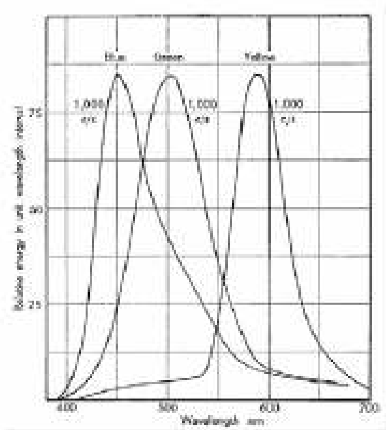
Compact Fluorescent Sources

- Small, replace standard incandescent bulb, ~ ¼ power for same light
- High efficiency due to tri-phosphors and high frequency solid-state electronic ballast
- Available in several colors
- Lifetime to 12000 hours
- Interference with nearby radios & TVs
- Expensive to buy, cheap to run



- Electroluminescent Sources
- Excitation of a phosphor by an AC field
  - Low power - very efficient
  - Low radiance (to 200 nit) - quasi-Lambertian
  - Color selection limited to available phosphors
  - Large areas, complex shapes possible
  - Output dependent upon voltage, temperature, frequency
  - Stable, long lifetime
- Used for displays, backlighting, watches (Indiglo®), X-ray film densitometry

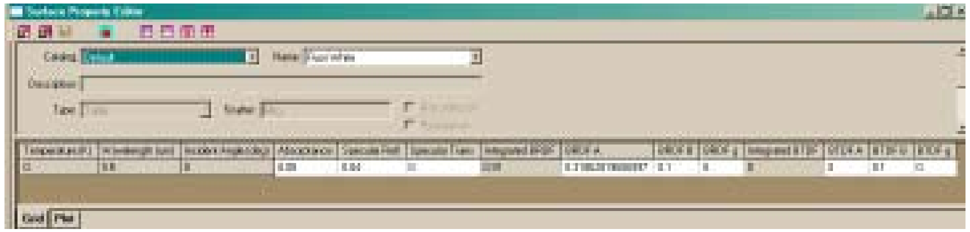




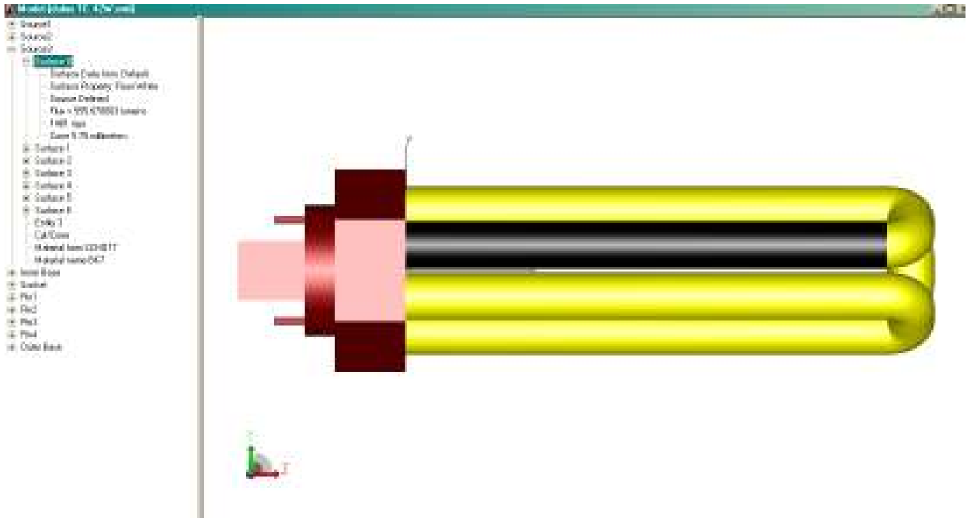
Fluorescent Source Model Steps

- Develop Geometry
  - Tubes
  - Base
  - Pins
- Assign Optical Properties:
  - Emission Surfs: Fluor White
  - Other Surfs: Use Intuition or Measurements
- Assign Flux and Rays
- Trace Rays & Compare to Measurements

- Fluor White:



- Geometrical Model



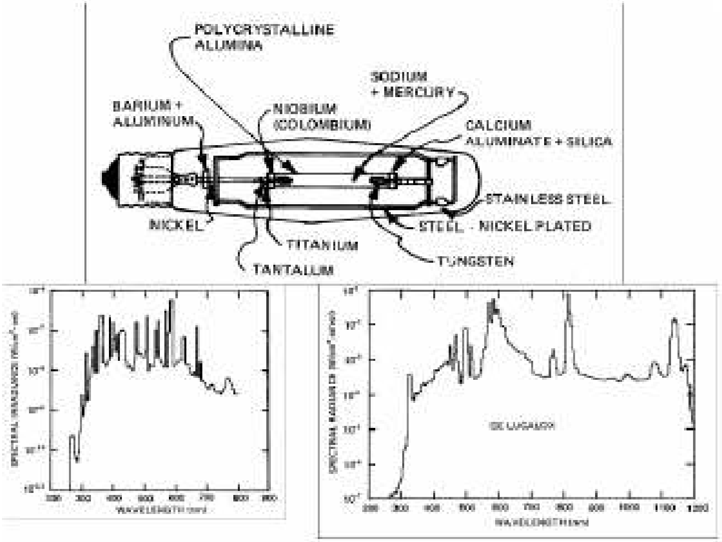
Fluorescent Source Modeling

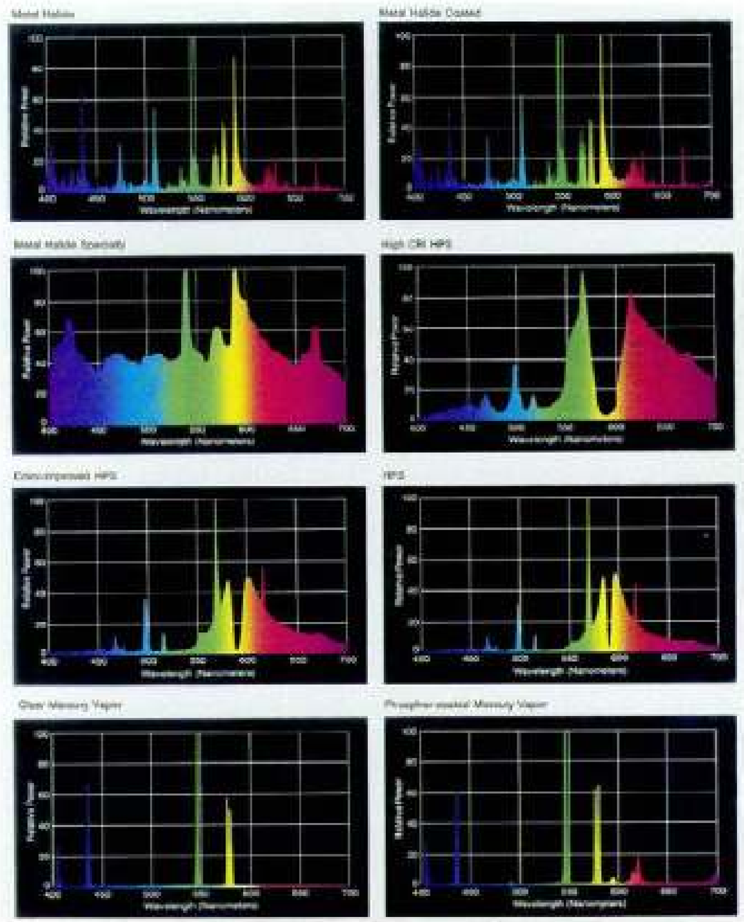
- Shown Model does not Include:
  - Spatial Emission Distribution
  - Effects on Radiation Incident on Phosphor
  - Color Properties of the Phosphor Emission
  - Lifetime Characteristics of Phosphor
- These are Advanced Topics, but:
  - Experience Shows that Simple Fluorescent Model Works Quite Well – Except for Color
  - Area Open for More Investigation, Especially Phosphors

Arc Source Modeling

HID Sources

- Combination of arc discharge and phosphor sources, possibly with some useful thermal radiation
- Confine arc in semi-transparent, refractory housing with phosphors applied externally
- Add metallic halides (Na, Tl, In, Sc, Dy)
- Output combination of lines + phosphor





Arc Source Modeling

- Geometry:
  - Model the geometry with the same method as the filament source
- Rays:
  - How does one assign rays to the gap in between the electrodes?
    - Surface or volume tube?
    - Surface or volume cone?
    - Surface or volume arc?
  - Hard to do with just assuming a shape
  - Tends to be a volume source
  - Arc is brighter near cathode
  - The term "arc" is appropriate - curvature due to forces inside bulb.

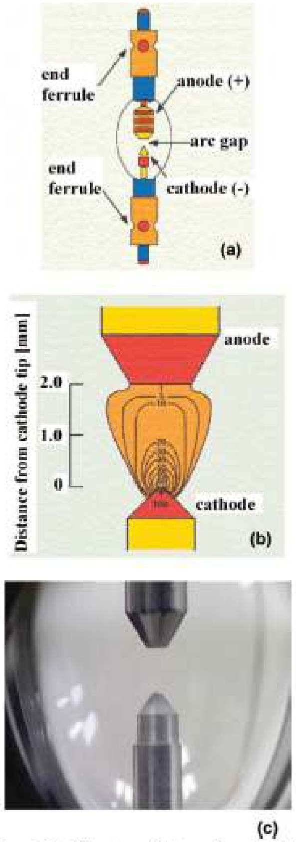


Fig. 1. (Color online) Short-arc discharge lamp. (a) Schematic [9]. (b) Typical radiance distribution from the arc of a 150 W xenon lamp, restricted to visible emission (relative to a maximum of 100% near the cathode tip) [9]. (c) Our photograph of the electrodes prior to ignition.

Courtesy: D. Nakar, et al, "Radiometric characterization of ultrahigh radiance xenon short-arc discharge lamps," *Appl. Opt.,* **47** (2008)..

Arc Source Ray Generation

- You need the source luminance distribution
- Ray set file:
  - Accurate
  - Very few sources have good data available
- Do the simple tube or cone
  - Expect sizable errors, especially if light is incident on the source geometry again
- Luminance measurement
  - Image a small section of the source gap
  - Repeat over several view agles
  - Can include the spectral characteristics
- Single digital image capture of a source:
  - Inverse Abel method
  - Assumes rotational symmetry around the axis of the lamp
- Several digital image captures of the source
  - Essentially measures the luminance
  - What Radiant Imaging is doing with ProSource
- NOTE:
  - You can get separate angular distributions as a function of pixel position.
  -

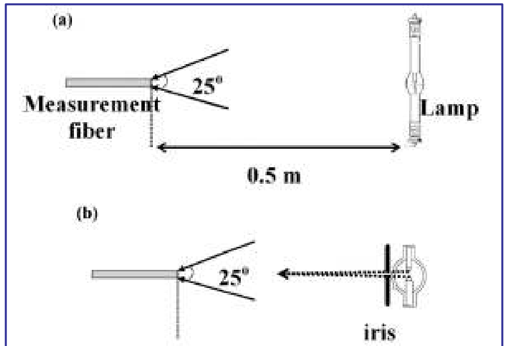
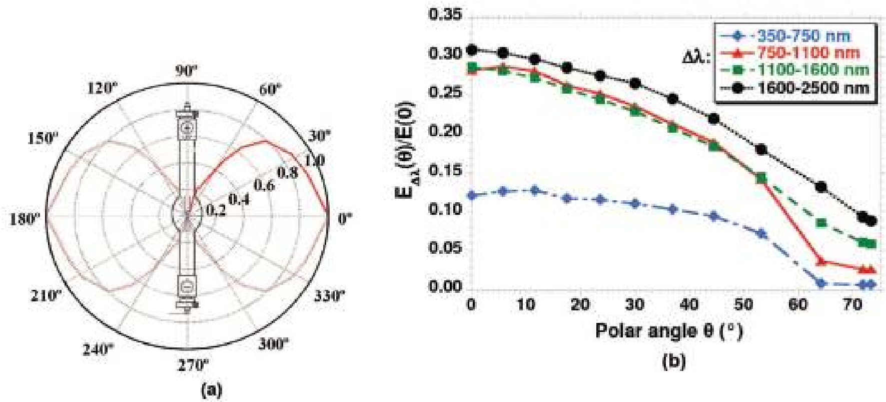


Fig. 3. Schematic of measuring lamp irradiance with a fiber-optic spectrometer for (a) the entire lamp and (b) the electrode gap only.



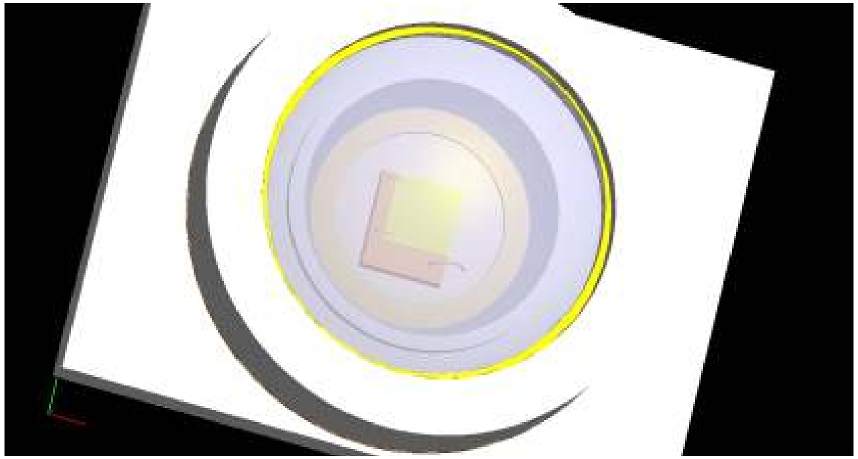
LED Source Modeling

Die Modeling

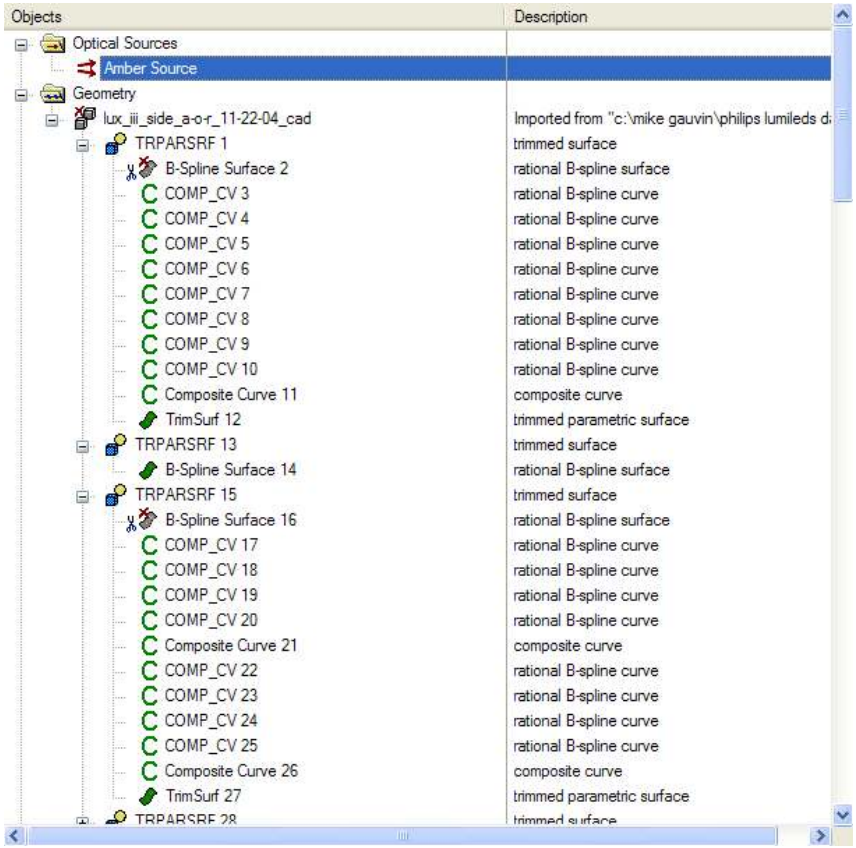
Data Sheet Modeling

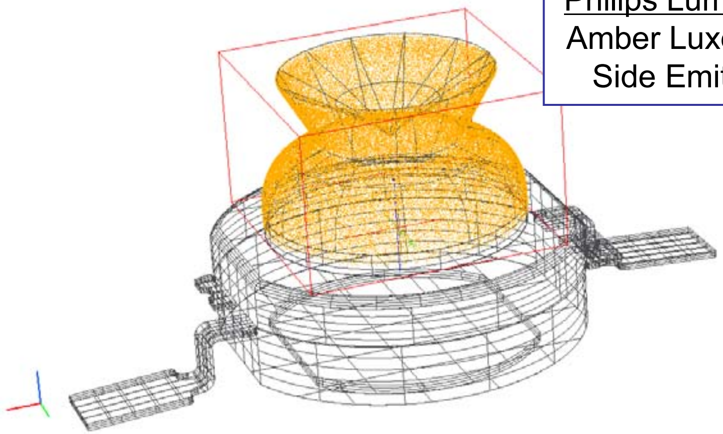
LED Die Modeling

- Model Geometry of LED:
  - Minimum: Reflector Cup, Die, and Epoxy Lens.
  - Maximum: Layers within Die.
- Benefits:
  - Minimum: Agreement Can be quite Good.
  - Maximum: Great Agreement and Complete Source Model Allowing Design, Optimization, and Tolerancing.
- Detriments:
  - Minimum: Time Consuming, Number of Iterations
  - Maximum: Very Time Consuming, Lengthy Ray Traces
- Emitting Surfaces:
  - Minimum: Top and Sides of Die.
  - Maximum: Active Layer(s) within the die.
- Optical Properties:
  - Minimum: Epoxy Index and Shape; Cup Reflectivity, Angle and Position.
  - Maximum: Minimum Plus Die Absorption, Shape, and Index.



Maximum: LED Geometrical Modeling



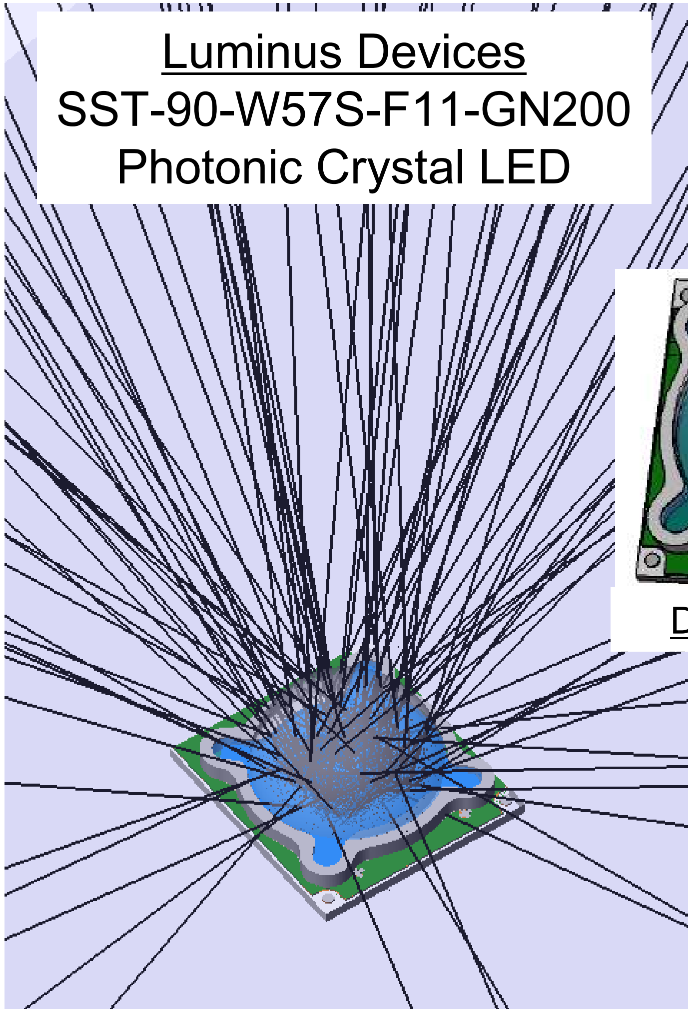


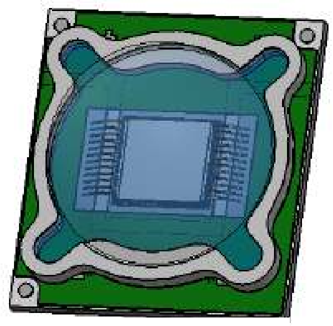
Philips Lumileds
Amber Luxeon I
Side Emitter

- As with filament: build the geometry based on measurements, data sheet, and pictures
- Generate rays:
  - Use ray set files if possible
    - Trace Rays to external sphere
    - Reverse rays and make LED absorber
    - Trace rays back to source
    - Reverse rays and save to a file
  - If no ray set file, assign rays to surfaces

Example: LD SST-90 Supplied Source Model

- Source CAD Model Obtained from Luminus Devices:
  - IGES file
  - Imported into FRED Software
  - Geometry Checked and Corrected
  - Visualization Attributed Modified
- Source Ray File Obtained from Luminus Devices:
  - FRED fcr ray file format
  - Three Ray file sizes
    - 10k rays
    - 100k rays
    - 1M rays
  - Radiant Imaging ProSource rs8 File Downloaded so Arbitrary Ray Files Can be Created





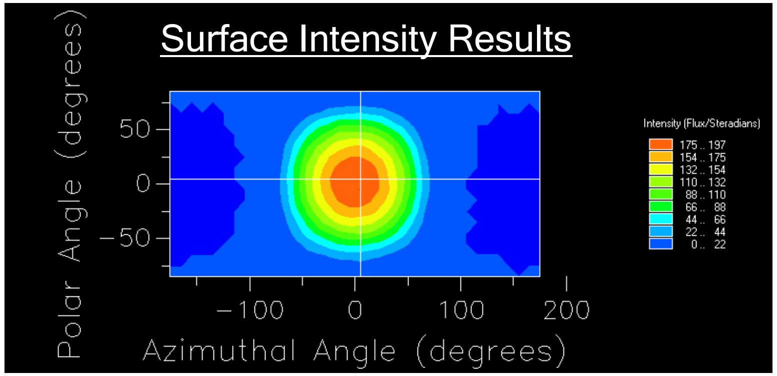
Data Sheet

Model Results

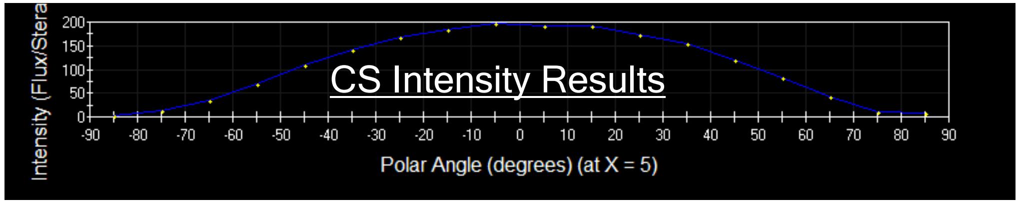
College of Optical Sciences
The University of Arizona

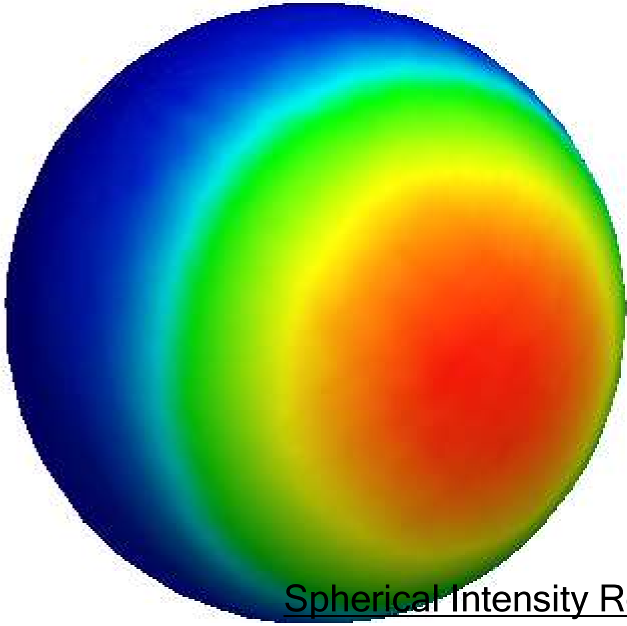
LD SST-90 Source Results

- Intensity Distribution
  - Shown in Three Diagrams
    - Cross Section (Bottom Left)
    - Surface Plot (Top Right)
    - Spherical Plot (Bottom Right)
  - Agrees with Data Sheet
    - See Next Page
  - Scale the source flux as desired



- Feel Confident that the Source is Model is Good.

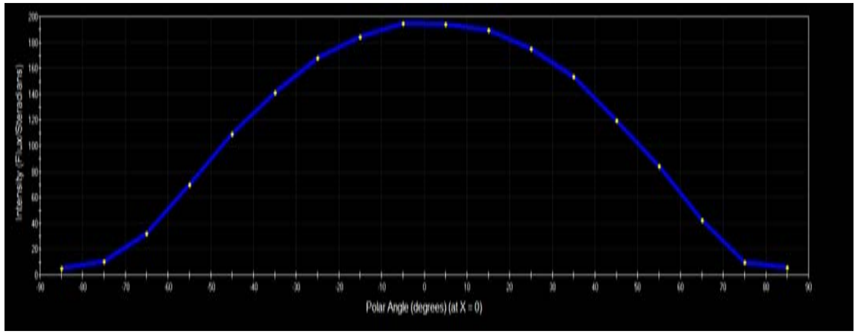


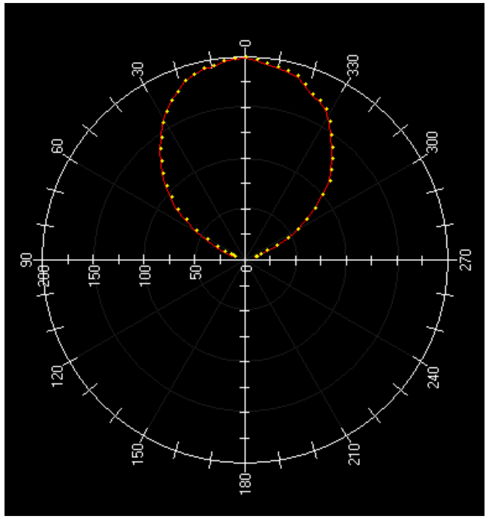


Spherical Intensity Results

Intensity Comparison: Model to Sheet

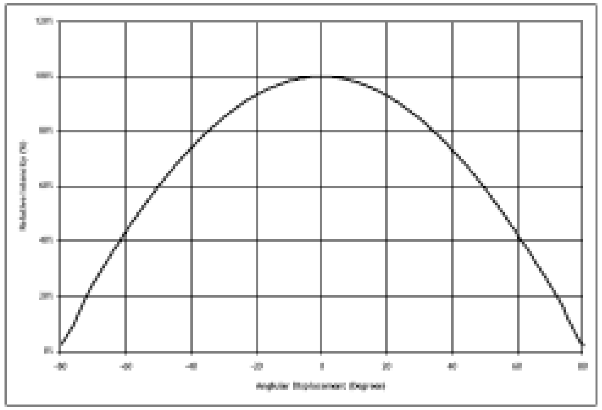
Model Results





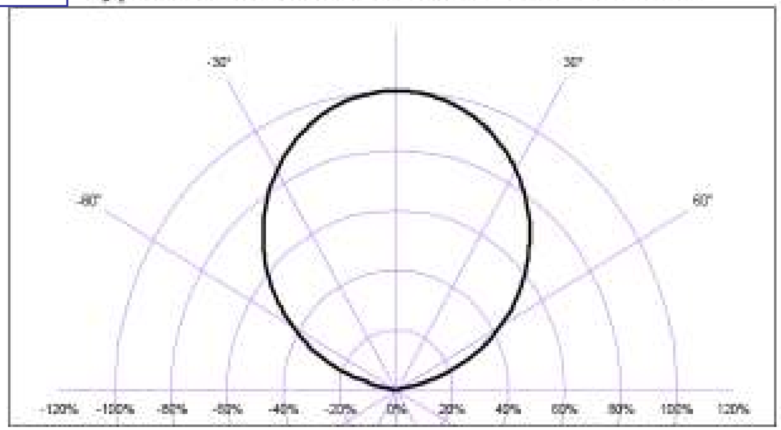
Data Sheet

Typical Angular Radiation Pattern for White



Luminus Devices
SST-90-W57S-F11-GN200
Photonic Crystal LED

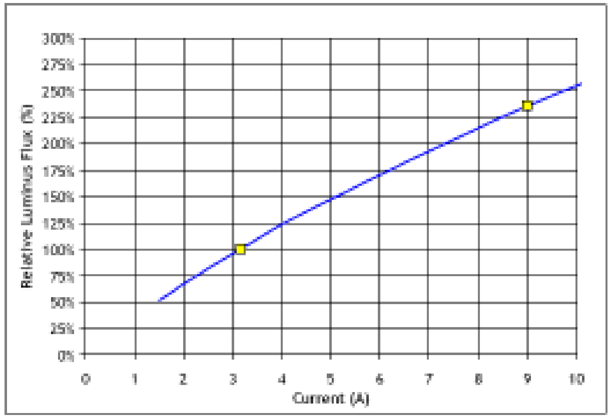
Typical Polar Radiation Pattern for White



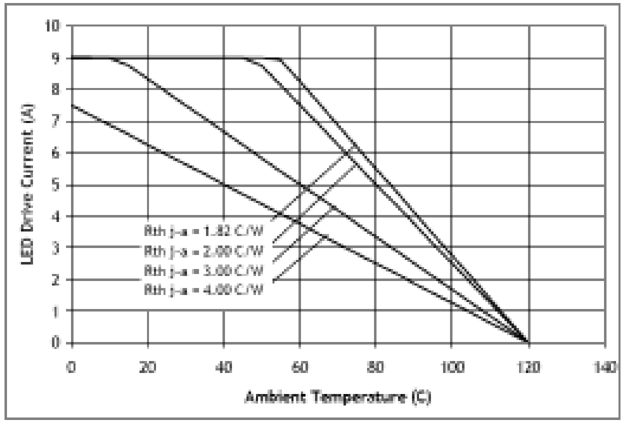
Aside: Other LED Factors

- Thermal environment:
  - Current is derated dependent on the ambient temperature and thermal resistance
  - Data sheets give values typically for 25-degrees C
  - Red and amber LEDs are especially susceptible
- Relative output:
  - Flux output changes as a function of drive current
  - Set flux correctly for thermally derated current
- Other factors affected by temperature:
  - Peak wavelength
  - Drive voltage
  - Lifetime

Relative Output Flux vs. Forward Current[1]



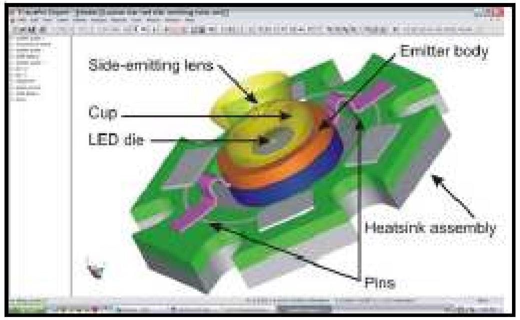
Current Derating Curve



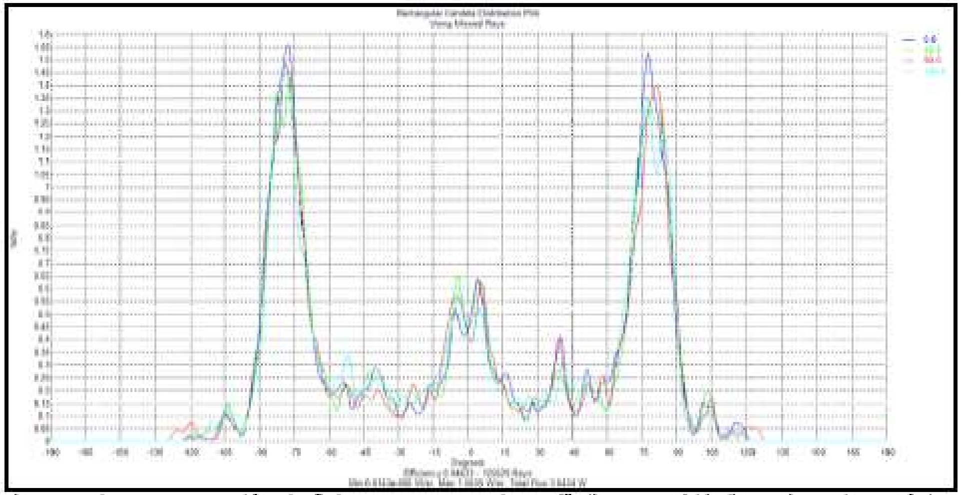
Luminus Devices
SST-90-W57S-F11-GN200
Photonic Crystal LED

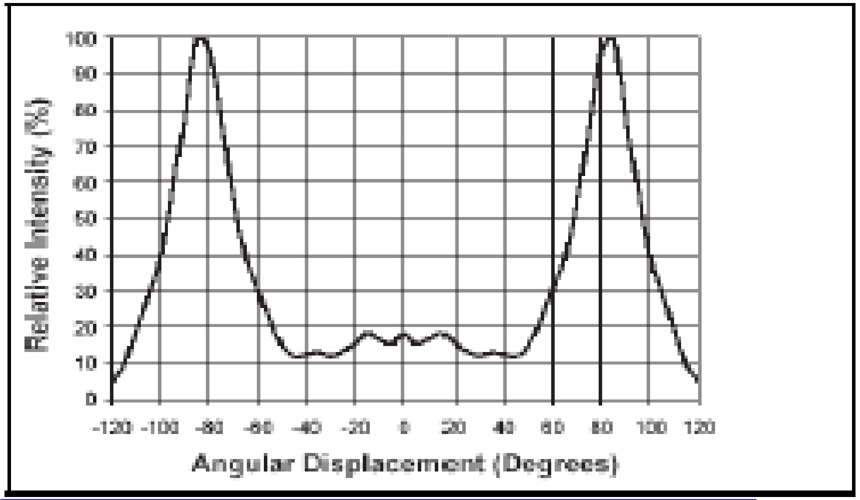
Minimum: Tracing Rays and Comparing

- Assign rays to die surfaces
- Trace Rays to Find Intensity / Irradiance Distribution:



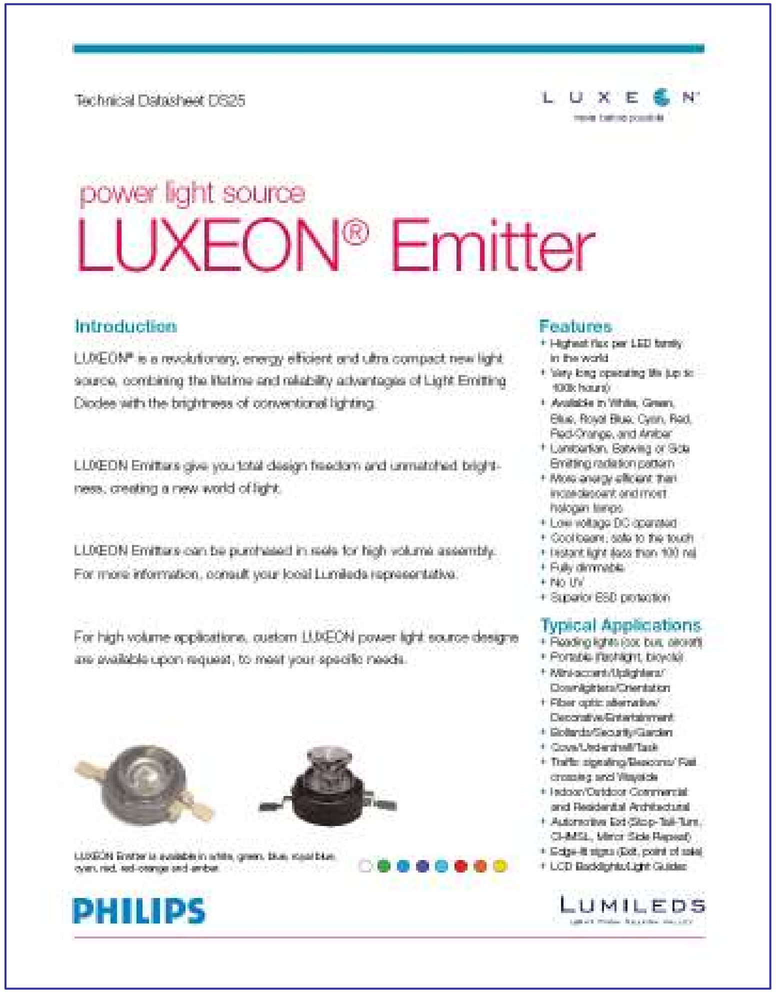
- Compare to the Data from Manufacturer or Your Measurements:





WARNING: Manufacturers Tend to Give Intensity Distribution. Must Make Measurements if Not Within Far Field! End Model Should Provide Good Results Over all Distances from the LED Source!

Barebones: LED Data Sheet Model



Technical Datasheet DS25

LUXEON

power light source

LUXEON® Emitter

Introduction

LUXEON® is a revolutionary, energy efficient and ultra compact new light source, combining the lifetime and reliability advantages of Light Emitting Diodes with the brightness of conventional lighting.

LUXEON Emitters give you total design freedom and unmatched brightness, creating a new world of light.

LUXEON Emitters can be purchased in reels for high volume assembly. For more information, consult your local Lumileds representative.

For high volume applications, custom LUXEON power light source designs are available upon request, to meet your specific needs.

LUXEON Emitter is available in white, green, blue, royal blue, cyan, red, red-orange and amber.

Features

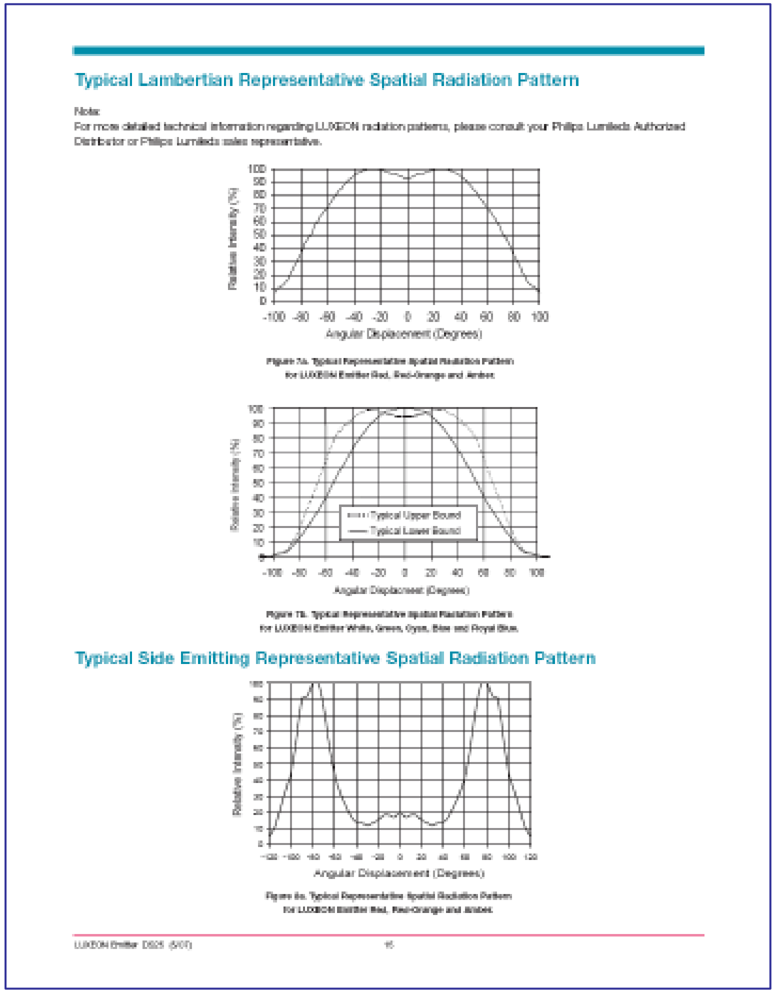
- Highest flux per LED family in the world
- Very long operating life (up to 100k hours)
- Available in White, Green, Blue, Royal Blue, Cyan, Red, Red-Orange, and Amber
- Lambertian, Batwing or Side Emitting radiation pattern
- More energy efficient than incandescent and most halogen lamps
- Low voltage DC operated
- Cool beam, safe to the touch
- Instant light (less than 100 ns)
- Fully dimmable
- No UV
- Superior ESD protection

Typical Applications

- Reading lights (car, bus, aircraft)
- Portable (flashlight, bicycle)
- Mini-accent/Uplighters/Downlighters/Orientation
- Fiber optic alternative/Decorative/Entertainment
- Bollards/Security/Garden
- Cove/Undershelf/Task
- Traffic signaling/Beacons/Rail crossing and Wayside
- Indoor/Outdoor Commercial and Residential Architectural
- Automotive Ext (Stop-Tail-Turn, CHMSL, Mirror Side Repeat)
- Edge-lit signs (Exit, point of sale)
- LCD Backlights/Light Guides

PHILIPS

LUMILEDS



Typical Lambertian Representative Spatial Radiation Pattern

Note:
For more detailed technical information regarding LUXEON radiation patterns, please consult your Philips Lumileds Authorized Distributor or Philips Lumileds sales representative.

Figure 7a. Typical Representative Spatial Radiation Pattern for LUXEON Emitter Red, Red-Orange and Amber.

Figure 7b. Typical Representative Spatial Radiation Pattern for LUXEON Emitter White, Green, Cyan, Blue and Royal Blue.

Typical Side Emitting Representative Spatial Radiation Pattern

Figure 8a. Typical Representative Spatial Radiation Pattern for LUXEON Emitter Red, Red-Orange and Amber.

LUXEON Emitter DS25 (5/07)

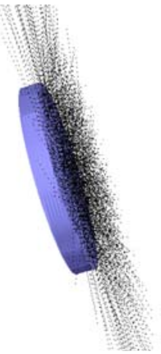
Philips Lumileds, Technical Datasheet DS25, 5/07.

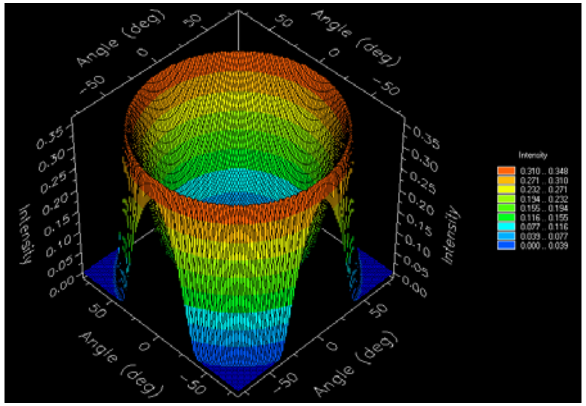
LED Data Sheet Modeling

- Make a disk emitter the basic size of the LED
- Assign a source to one surface of this disk
  - Use apodization to assign the angular distribution
    - Assign base isotropic source
    - Apodization sets flux
  - Can use image digitization
- This method is risky:
  - Assumes spatial symmetry
  - Has no geometry

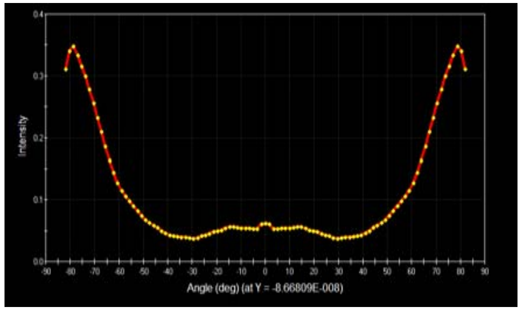
WARNING: This Method Only Works for Far Field!

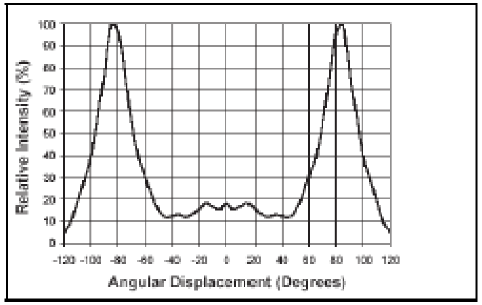
Setup and Ray Trace





Results and Comparison





Words About Sources

- As said previously….

There are too many types, too many shapes, too many sizes, too many everything….the best way to use the most appropriate source for your application is to do a literature search, keep up with advances, and be willing to try something new.

- There are many advanced things that you can do:
  - Look at aging issues
  - Incorporate tolerances into the model
  - Model the emission with the fundamental physics
- The material I showed you today is better than most do with their source models
  - To get to forefront look at the advanced topics in the recent literature