Evaluation of LED and Broadband Sources

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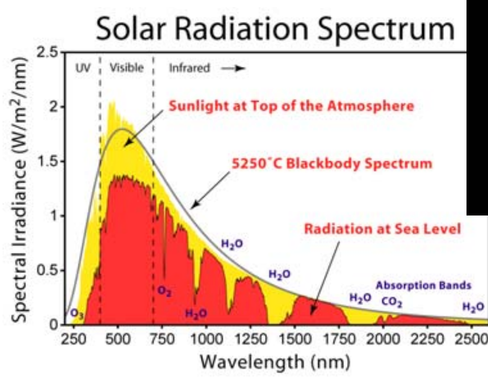
Topics to be addressed …

- Sources: types, applications & characteristics
- Basics: viewing angle, point vs. extended source, system of units
- Exposure guidelines
- Field measurement
- Numerical estimates

Sources



Source Characteristics

- Incoherent radiation
- Polychromatic
- Inhomogeneous spatial distribution
- Geometric optics
- Extended sources

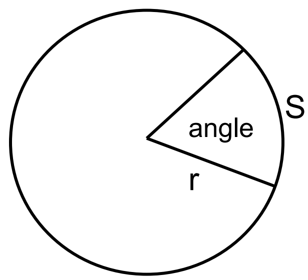
Basics

- Planar & solid angles
- Viewing angle
- Point vs. extended source
- Units: Two Systems
  - Photometry
  - Radiometry

Basics: Planar & Solid Angles

- Planar angles
  - Metric – radian (rad), milliradian (mrad)
  - Used to describe angular subtense & viewing angle, α
- Solid angle, Ω
  - Metric – steradian (sr)
  - Used to describe spatial extent (size) of an object
- Both angles are mathematically unitless

Planar Angle Measurement



NOTE: angle is mathematically unitless; radian is assigned.

1 radian = 57.3°

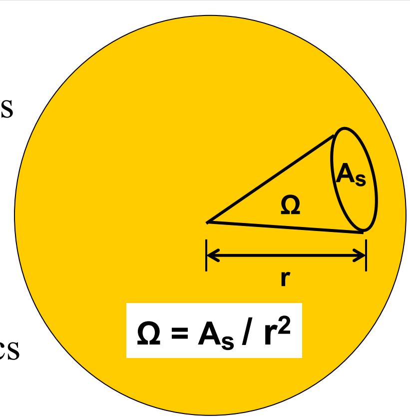
2π radians = 360°

1 rad = 1000 mrad

$$\underset{\text{(radians)}}{\theta} = \frac{\text{arc length (S)}}{\text{radius (r)}}$$

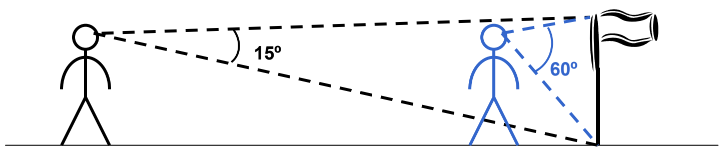
Solid Angle

- A measure of how "big" an object appears to an observer.
- Used in describing source brightness.
- Describes spatial emission characteristics of a source.



Angular Subtense – Viewing Angle

The angular size (subtense) of the flag pole depends on its distance from your eye.



For small angles, the angular subtense (in radians) of an object is the object's size (height) divided by its distance from the observer's eye.

ACGIH: Viewing Angle, α

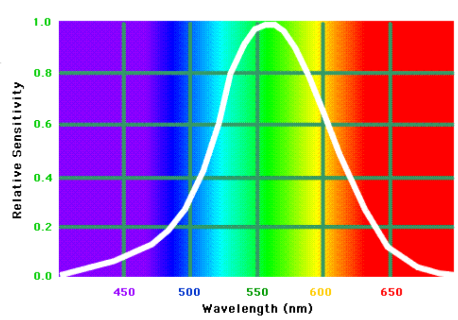
- Circular lamp
  - α = lamp diameter ÷ viewing distance
  - $\alpha = d/r$
- Oblong lamp (mean dimension)
  - α = (length + width) ÷ (2 x viewing distance)
  - $\alpha = (l+w)/2r$

Small Source vs. Extended Source

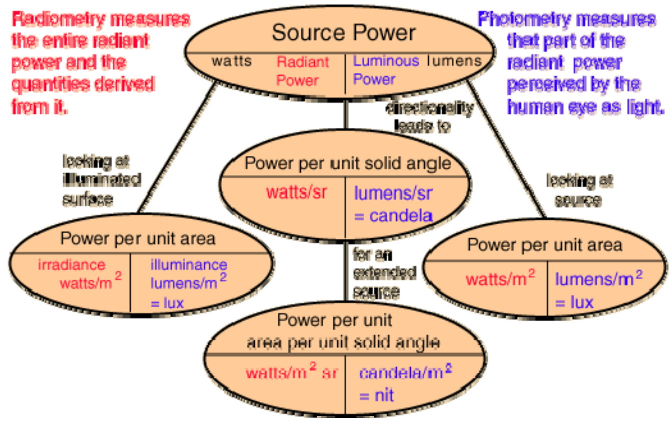
- ACGIH separates small and large sources at $\alpha = 100$ mrad (0.1 rad) for thermal hazards
- ACGIH & ICNIRP define $\alpha < 11$ mrad retinal photochemical limit for blue-light hazard – ACGIH & ICNIRP

Units: Two Systems of Measurement

- Photometry – adjusted for response of human eye to visible λ
- Radiometry – physical measure of optical radiation



Relationship between Radiometry & Photometry Quantities



http://hyperphysics.phy-astr.gsu.edu/hbase/vision/radphocon.html#c1

Radiometric Photometric

Quantity	Unit	Quantity	Unit
Radiant energy, H	joule (J)	Luminous energy, Q_v	lumen-s
Radiant power, Φ	watt (W)	Luminous power, F	lumen (lm)
Irradiance, E	W/m^2	Illuminance, E_v	lux (lx)
Radiant intensity, I	W/sr	Luminous intensity, I_v	candela (cd)
Radiance, L	$W/m^2 \cdot sr$	Luminance, L_v	cd/m^2

Conversion: Luminous & Radiant Power

- Use spectral luminous efficacy, V(λ)
  - V(λ) –from tables of standard luminosity data
- Use maximum spectral luminous efficacy, K_m
- Photopic vision
  - V(λ) = 1 at 555 nm
  - $10^{-4} < V(\lambda) < 1$ at other λ
  - K_m = 683 lm/W at 555 nm

Example

- Determine the equivalent luminous power for 15 W at 500 nm, where V(λ) = 0.3230.

- $F_\lambda = K_m V(\lambda)\Phi$
- F_λ = 683 lumen/W x 0.323 x 15 W
- F_λ = 3309 lumens

If the quantity name …

- is preceded by "spectral," then it refers to a narrow band of wavelengths
  - e.g., spectral irradiance, W/cm^2•nm
- includes "effective," then the quantity has been "weighted" (i.e., multiplied by) some function
  - e.g., effective irradiance, E_{eff}, weighted against some biological action spectrum

Exposure Guidelines

- American Conference of Governmental Industrial Hygienists (ACGIH)
- Illuminating Engineering Society of North America (ANSI / IESNA)
- International Commission on Nonionizing Radiation Protection (ICNIRP)

Specific Guidelines

- Broadband UVR
- UV-A (thermal & photochemical)
- Luminance
- Retinal thermal hazard
- Blue-light hazard
- Aphakic hazard
- Thermal hazard to cornea & lens
- IR-A (near IR) hazard where strong visual stimulus is absent

ACGIH TLVs: IOR (1)

Name	Metric	λ (nm)	Hazard Function
Actinic UV	E_{eff}	180-400	S(λ)
UV-A	E_{UV}	320-400	----
Retinal thermal injury	L_R	380-1400	R(λ)
Retinal thermal injury (<0.01 cd/cm^2)	L_{NIR}	770-1400	R(λ)
Cornea/lens thermal	E_{IR}	770-3000	----

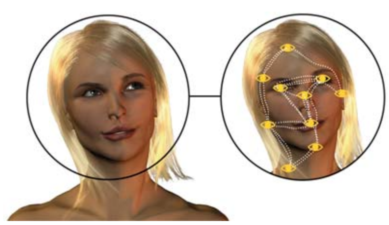
IOR = incoherent optical radiation

ACGIH TLVs: IOR (2)

Name	Metric	λ (nm)	Hazard Function
Blue light (ext. source)	L_B	305-700	B(λ)
Blue light (<11 mrad)	E_B	304-700	B(λ)
Blue light - aphakic	L_B	305-700	A(λ)
Blue light - aphakic	E_B	305-700	A(λ)

Viewing Angle, α = 11 mrad

- Studies of welders with retinal lesions
- Angular subtense of welding arc
  - Dimension of lesion suggested 11 mrad
  - True angle was ~1 to 1.5 mrad
- Cause: saccadic eye movements



Ref.: How Stuff Works.com

Format of Exposure Limits: UVR

$$E_{eff} = \sum_{180}^{400} E_\lambda S(\lambda)\Delta\lambda$$

Where E_{eff} = effective irradiance relative 270 nm

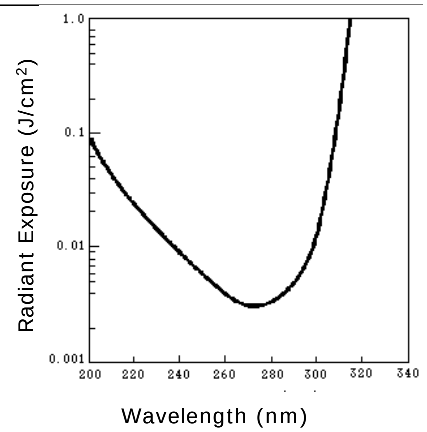
E_λ = spectral irradiance ($W/cm^2 \cdot nm$)

$S(\lambda)$ = relative spectral effectiveness (unitless)

$\Delta\lambda$ = bandwidth in nm

UVR Broadband Guideline

- Envelope guideline
- Smooth curve drawn to include threshold data for acute eye & skin effects
- Lowest at 270 nm



Format of Exposure Limits

Measured or calculated quantity

Bandwidth or calculation interval

$$E_{eff} = \sum_{180}^{400} E_\lambda S(\lambda)\Delta\lambda$$

Hazard (weighting) function

Where E_{eff} = effective irradiance relative 270 nm

E_λ = spectral irradiance ($W/cm^2 \cdot nm$)

$S(\lambda)$ = relative spectral effectiveness (unitless)

$\Delta\lambda$ = bandwidth in nm

Other Examples

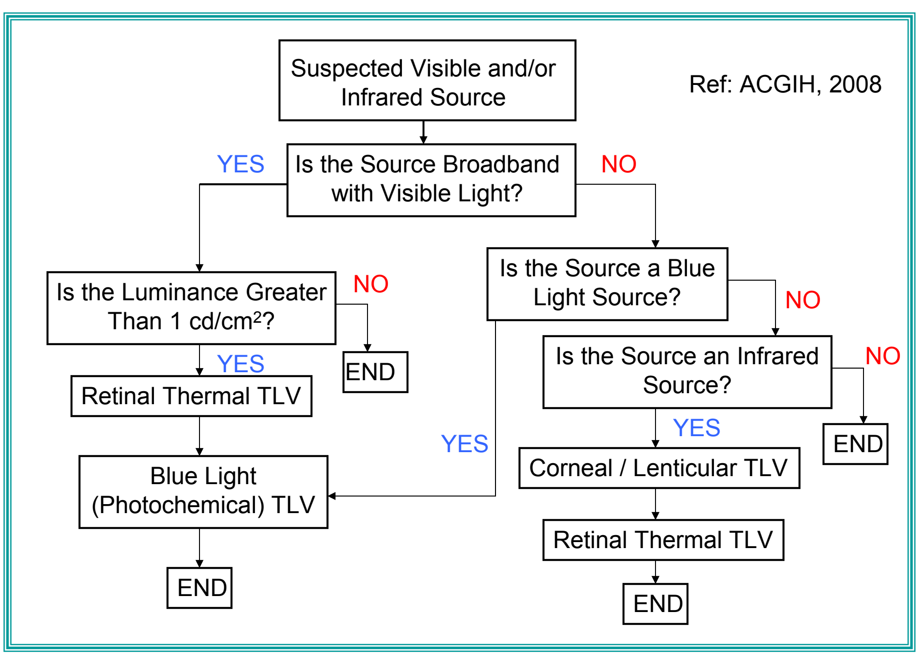
Blue-light radiance, large source $$L_B = \sum_{305}^{700} L_\lambda B(\lambda)\Delta\lambda$$

Blue-light radiance, small source $$E_B = \sum_{305}^{700} E_\lambda B(\lambda)\Delta\lambda$$

Retinal thermal injury $$L_R = \sum_{380}^{1400} L_\lambda R(\lambda)\Delta\lambda$$

Exposure Evaluation: General Scope

- Wavelengths: 180 to 3000 nm
- Requires measurement if there is a strong visual stimulus
- Requires measurement if the source does not produce a strong visual stimulus but is
  - Rich in UV radiation (e.g., UVGI lamp)
  - Rich in IR radiation (e.g., IR heat lamp)



Hazard Evaluation

- Measurement
  - Primary method
  - Spectroradiometric methods
  - Radiometric methods
- Numerical estimates
  - Infrequently used

Evaluation: Spectral Content

- Emissions from lamps, arcs & blackbody sources may be quite broadband (UV, vis, IR)
- Lamps – spectral content from mfg. or meas.
- Few narrowband sources:
  - Low-pressure Hg-vapor lamps
  - LEDs

Field Instruments

- Radiometer – instrument used to detect and measure radiant energy or radiant power; usu. over a wide band of wavelengths

Detector & Input Optics

Diffuser

Weighting filter

Photodiode detector

Note: Elements are threaded apart for easy observation.

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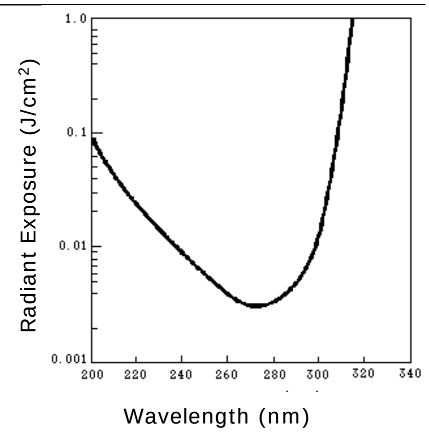
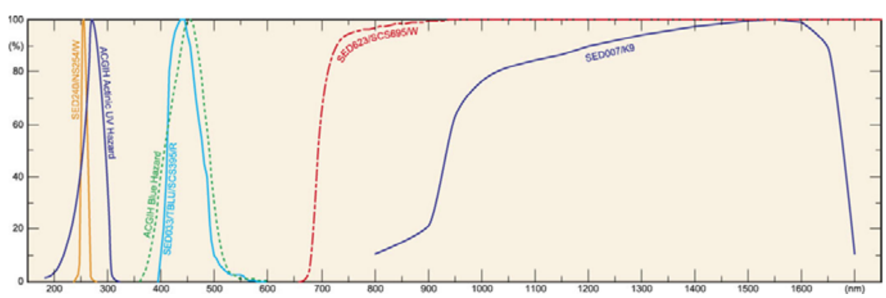


Weighting Filters

- Attempt to match biological sensitivity factors such as S(λ), B(λ), etc.



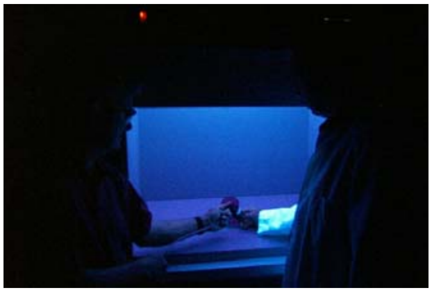
Courtesy: International Light

Instrument Companies

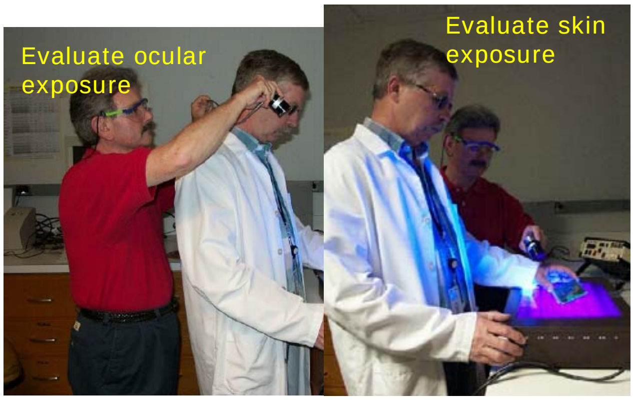
- International Light Technologies, Inc.
  - www.intl-lighttech.com/
- Gigahertz-Optik, Inc.
  - www.gigahertz-optik.com/database_en/html/index.html
- Solar Light
  - www.solar.com/

Emission vs. Exposure Measurements

- Emission meas.: fit the detector to tripod set near the source.
- Exposure meas.: detector is usu. hand held.
- Estimate distance between detector and source.



Evaluation: Field Measurements



Evaluating exposure to UV radiation

Overexposures by Measurement and/or Reported Health Effects

- UV-A curing applications
  - Conveyorized and spot
- Arc welding
  - Esp. skin (erythema; unreported)
- Plasma arc cutting
- Multi-kilowatt CO_2 laser welding
- UVGI lamps
  - HVAC maintenance
- Metal halide lamps
  - Gymnasium
- Outdoors
  - Photosensitization

Numerical Methods

- Few exist and these are infrequently used
- Estimates of maximum emission from welding arcs
- Projection systems
- Calculation for LEDs
- Best reference: Sliney & Wolbarsht, 1980

Welding Arcs

Effective UV irradiance (10-700 A)	$E_{eff} = (k_1 \times I^2) / r^2$ W/cm^2
Maximum luminance	$L_v = k_2 \times I^2$ cd/cm^2
IR Irradiance (750-2000 nm, 40-200 A)	$E = (k_3 \times I^2) / r^2$ W/cm^2

$k_1 = 2 \times 10^{-4}$ W/A^2 I = current in amperes, A

$k_2 = 2.0$ cd/cm^2 / A^2 R = distance in cm

$k_3 = 9 \times 10^{-4}$ W/A^2

LED Example

- Optical characteristics
  - $\lambda = 470$ nm
  - $I_v = 1200$ mcd = 1.2 cd
  - Source (chip) size: 280 μm × 280 μm
  - Lambertian source
- Determine potential for overexposure to blue-light TLV

Determine Appropriate TLV

- Depends upon viewing angle, α
- $\alpha = L/r = 0.028$ cm / 20 cm = 0.0014 rad
- $\alpha < 11$ mrad
- Appropriate TLV is E_B (W/cm^2)

Conversion to Radiant Intensity

- $I_v = I\ V(\lambda)\ K_m$, where I_v = cd = lm/sr

  I = W/sr

  $V(\lambda) = 0.090980$

  K_m = 683 lm/W
- $I = 1.2$ cd / (683 lm/W $\times$ 0.090980)
- $I = 0.0193$ W/sr

Determine Irradiance

- $E = I \cos\theta / r^2$
- $E = 0.0193$ W/sr / (20 cm)^2
- $E = 4.8 \times 10^{-5}$ W/cm^2

Exposure Limits: Small Source

$t \leq 10^2$ s: $E_B \leq \dfrac{0.01 \text{ J/cm}^2}{t \text{ (s)}}$

If $t = 10^2$ s, then $E_B = 10^{-4}$ W/cm^2

$t > 10^2$ s: $E_B \leq 10^{-4}$ W/cm^2

Comparison to E_B-TLV

- $E = 4.8 \times 10^{-5}$ W/cm^2
- $E_{B\,(TLV)} = 1 \times 10^{-4}$ W/cm^2
- Acceptable exposure
  - $E < E_B$ for $t > 100$ s per day

On-site Reviews & Classes

- Most organizations do not have an IOR safety program
- Where these exist, most evaluate only UVR
- More likely to exist within product safety
- Where programs exist, H&S personnel often do not understand the instruments and standards

Summary

- Sources of incoherent optical radiation abound.
- IOR includes most hazardous form of nonionizing radiation, UVR.
- Many organizations do not have resources to evaluate exposures.
- Most evaluations involve measurement.