Flash Pyrometry Techniques for Health Hazard Evaluation

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USACHPPM
Readiness thru Health
Flash pyrometry techniques needed for single flash events.
Wanted: Simple field method to evaluate flash radiation hazards

- Needed for health hazard occupational exposure studies
  - Need to improve retinal thermal & blue light flash evaluations
  - Witness detectors exist for skin and corneal thermal injury
  - Adjunct passive cameras exist for retinal thermal injury potential
  - Needed to evaluate direct sources like blackbody radiators
- Flash pyrometry methods should be based on the eye
- Method should error on side of overstating the hazards
  - Excessive interference from a chemical flash contains intense blast, acoustic, other electromagnetic energy, and thermal debris
  - Commercial radiometers/photometers may be: delicate, susceptible to this noise, not portable, and manpower intensive
  - Pyrometry might work for single flash and continuous sources
Third-Generation Skin & Corneal Lyon Witness Board Detector
Construction Materials for Witness Detector are Less Available Today
There really is physics & biophysics behind using the LWB detector!
Calibration Data for Carbon and White Paper
Lyon Big Eye Retinal Exposure Detector Has H$_2$O and Eye’s F-No
Simple Field Fresnel Camera to Estimate Flash Source Size
Properties of eye and a blackbody radiator near its melting point.

Characteristics of Water, Blackbody, & Eye

- Water (H₂O)
- Blackbody $\varepsilon = 1$
- Photometric $T = 3500$ deg K

![Graph showing transmission of water and blackbody emission](image)
Terrestrial Solar Irradiance and the Eye

- Blue line: 2-cm H$_2$O X100%
- Green line: CIE Photopic
- Orange line: W/cm$^2$/1.629E-4

Graph shows the relative response versus wavelength (in nm) from 200 to 1400 nm. The wavelength range from 400 to 1400 nm is the retinal hazard region.
Broadband Versus Spectral

- Broadband Detectors:
  - Advantages:
    - rugged solid state detector
    - portable & battery operated
    - cost effective
    - reasonably accurate
    - easy to calibrate
  - Disadvantages:
    - spectral mismatch
    - limited λ range
    - manpower intensive

- Spectroradiometer:
  - Advantages:
    - can be superior data
    - portable & battery operated
  - Disadvantages:
    - may not work for msec
    - limited λ range
    - expensive & delicate
    - interference potential
    - complex & cumbersome
    - manpower intensive
Planck & Wein Blackbody Laws
Temperature Scale Review

- \( \text{deg C} = \text{deg K} - 273.15 \)
- \( \text{deg F} = \frac{9}{5} (\text{deg K}) - 459.67 \)

- Comparing: 5500 deg Kelvin = 5227 deg Celsius = 9440 deg Fahrenheit
Principle (Law) of Conservation of Radiance

• Luminance is directly related to radiance.
• A source cannot be made “brighter” by any optical means such as a lens or reflector.
• All optical means tend to degrade the resulting source radiance and luminance.
• Direct viewing of the actual source provides the greatest radiance value.
Standard Terms and Units for Extended Sources

• power \( (W = J/s) \) & energy \( (J = W\cdot s) \)
• irradiance \( (W/cm^2) \) & illuminance \( (lm/cm^2) \)
• radian (rad), degree (deg), & steradian (sr)
• radiance \( (W/cm^2\cdot sr) \) & luminance \( (lm/cm^2\cdot sr) \)
• radiant exposure \( (J/cm^2) \) & integrated-illuminance \( (lm\cdot s/cm^2) \)
• integrated-radiance \( (J/cm^2\cdot sr = W\cdot s/cm^2\cdot sr) \) & integrated-luminance \( (lm\cdot s/cm^2\cdot sr) \)
• luminous efficacy \( (lm/W = lm\cdot s/J) \)
• time \( (s = m/60 = hr/3600) \)
## Common Unit Conversions

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<th>To Obtain Number Of:</th>
<th>Multiply Number Of:</th>
<th>By This Factor:</th>
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</thead>
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<td>lumen/steradian = lm/sr</td>
<td>candela = cd = candlepower</td>
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<td>lm/cm² = phot</td>
<td>footcandle = 1 lumen/ft²</td>
<td>0.00108</td>
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<tr>
<td>lm/cm² = phot</td>
<td>lumen/m² = lux</td>
<td>0.00001 = 10⁻⁴</td>
</tr>
<tr>
<td>lm/cm²-sr = stilb</td>
<td>candela = cd = candlepower</td>
<td>1/(luminous area in cm²)</td>
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<tr>
<td>lm/cm²-sr = stilb</td>
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<tr>
<td>lm/cm²-sr = stilb</td>
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<td>footlambert = 1/π cd/ft²</td>
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<td>1/π = 0.318</td>
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<tr>
<td>lm/cm²-sr = stilb</td>
<td>cd/ft² = π footlamberts</td>
<td>0.00108</td>
</tr>
</tbody>
</table>
Adverse Health Effects

- Potential for permanent retinal injury from retinal thermal and blue light
- Potential for skin and corneal thermal injury from absorbed optical radiation
- Potential for skin and corneal injury from actinic ultraviolet radiation
- Secondary safety concerns from temporary visual loss
Extended Source > 0.1 rad
Retinal Thermal Limits

\[ L_R \ [W/(cm^2 \text{sr})] = \sum_{380}^{1400} L_\lambda \cdot R(\lambda) \cdot \Delta \lambda \]

\[ L_R [W/(cm^2 \text{sr})] \leq \frac{3.2}{\alpha \cdot t^{1/4}} \quad 0.00063 \text{ to } 0.25 \text{ s} \]

\[ \alpha [\text{rad}] = \frac{(1+w)}{2r} \]

\[ L_R [W/(cm^2 \text{sr})] \leq \frac{4.5}{\alpha} \]
Extended Source $> 0.1$ rad
Retinal Blue-Light Limits

\[ L_B \left[ \text{W/(cm}^2\text{sr)} \right] = \sum_{305}^{700} L_\lambda \cdot B(\lambda) \cdot \Delta \lambda \]

\[ L_B \leq \frac{100 \left[ \text{J/(cm}^2\text{sr)} \right]}{t \left[ \text{s} \right]} \]

\[ t_{\text{max}} \left[ \text{s} \right] = \frac{100 \left[ \text{J/(cm}^2\text{sr)} \right]}{L_B} \]
Effective Thermal & Blue Radiance vs Temperature

Effective Thermal Retinal
\[ L_r = 10^{(2.42 \ln(T) - 17.9)} \]

Effective Blue Retinal
\[ L_b = 10^{(3.8 \ln(T) - 30.5)} \]
What can be achieved with an effective $\text{Im/W=Im-s/J}$ for the eye

- The effective radiance can be determined from a luminance measurement.
- Possible to assign an effective source temperature to CW and flash sources.
- Adjunct tool for hazard evaluation.
- Tool for single flash events, $\text{Im/W = Im-s/J}$
Three Broadband Processes

• Calculate peak $W/cm^2$-sr weighted to $R_\lambda$ to find peak source $T$
  – This is the preferred technique and may not be possible in a harsh environment
  – Measure $W/cm^2$ or $J/cm^2$ thru $R_\lambda$ filter at known distance
  – Overstate by <20% using $H_2O$ filter to simulate the eye
  – Measure source effective area if possible
  – Measure flash duration if possible
  – Technique works for all sources CW and flash

• Calculate peak $Im/cm^2$-sr weighted to $V_\lambda$ to find peak source $T$
  – This is the traditional technique and may not be possible in a harsh environment
  – Measure $Im/cm^2$ or $Im$-s/cm$^2$ at known distance
  – Measure source effective area if possible
  – Measure flash duration if possible
  – Technique works for all direct radiation sources CW and flash

• Measure $Im/W = Im$-s/J thru $H_2O$ filter to find an effective source $T$
  – Useful adjunct especially for flash sources
  – Measure $W$-s/cm$^2$ & $Im$-s/cm$^2$ with same view and distance
  – No need for source area & flash duration
  – Technique works only for direct radiation sources CW and flash
Theoretical Blackbody Radiance through 2-cm water filter

$$T \sim \frac{20000}{[10.4 - \ln(L_r)]}, \quad 2500 < T < 5000$$
Source Temperature Range

- 3500 deg K represents an upper temperature for pure blackbody solid-surface radiators
- Above 3500 deg K most metals are molten
- 3500 deg K separates surface emitters from others such as confined and open electric arc radiators
- Arcs contain a blackbody spectrum with emission lines that are fairly broad at high power levels
- The usual design goal is to increase lm/W for efficiency
- Little gained in luminous efficiency beyond 5500 deg K
- Rotating carbon arcs near 6000 deg K are brightest
- Upper limit of ~ 6000 deg K for electrically generated
- By comparison, the thermite reaction is only 2500 deg K
Blackbody Luminance Versus Temperature

\[ T = \frac{25400}{16.5 - \ln(L)} \]

where \( T \) = deg K and \( L \) = lm/cm^2-sr

![Graph showing the relationship between temperature and luminance](image)
What is Luminous Efficacy?

• Lumen/watt generally related to efficiency.
• Watts can be total electrical input power.
• Watts can be total optical radiation power.
• Choose watts related to a standard eye.
• Retinal Hazard Region: 400 to 1400 nm.
• The eye mostly consists of water, ~2 cm.
• Choose watts thru 1 or 2-cm of water.
• Integrated levels of lm-s/J = lm/W and can determine an effective flash temperature.
Blackbody Luminous Efficacy With $\text{H}_2\text{O}$ Filter

\[ T = \frac{26000}{(17.5 - K^{0.5})} \quad \text{for } T < 4500 \]

\[ T = 38.61 \times K - 778 \quad \text{for } T > 4500 \text{ deg K} \]
Calculating the peak radiance and luminance can introduce errors

- Calculate Peak Radiance in $W/(cm^2$-sr)
  - Peak irradiance in $W_p/cm^2 \sim (J/cm^2)/(~FWHM$ duration)
  - Peak $L_r \sim W_p / [(cm^2)(solid angle at r)]$
  - Solid angle $\sim (1/e$ source area) / $r^2$

- Calculate Peak Luminance in $lm/(cm^2$-sr)
  - Peak illuminance in $lm_p/cm^2 \sim (lm-s/cm^2)/(~FWHM$ duration)
  - Peak $L_\lambda \sim lm_p / [(cm^2)(solid angle at r)]$
  - Solid angle $\sim (1/e$ source area) / $r^2$

- Direct measurement for peak values is best but flash duration and source size are still needed
Im/W Preliminary & Tests

- Calibrate detectors using similar source
- Design test so detectors view source only
- Check Im/W ratio with a portable lamp
- Conduct a preliminary blind test
- Consider passive detectors for source size
- Use electronic means for flash duration
Multi-kW calibration box with 3 standard lamps & power supply
1 kW FEL Standard Lamp at 8.000 amps and 50 cm

- Irradiance 250 - 4500 nm: 28.62 mW/cm²
- Irradiance 4.5 – 10 um: ~0.828 mW/cm²
- Irradiance thru 2-cm H₂O filter: 9.475 mW/cm²
- Irradiance with Radiometric Silicon: ~9.75 mW/cm²
- Illuminance: 758.9 ft-cd = 0.8167 lm/cm²
- Luminous Efficacy: 86.22 lm/W, effective thru H₂O
- Source Temperature: Calculated as 3165 deg K
- Retinal Thermal Irradiance: 8.055 mW/cm²
- Retinal Blue Light Irradiance: 0.3093 mW/cm²
- Actinic Ultraviolet Irradiance: 3.334 uW/cm² or 15 min
- Reflectance Standard Luminance: 0.2570 lm/(cm²-sr)
- Reduced Temperature: 2856 deg K at 6.850 amps
- Candlepower: 2042 cd or lm/sr
Effective Thermal & Blue Radiance vs Temperature

- Effective Thermal Retinal
  \[ L_r = 10^{(2.42\ln(T)-17.9)} \]
- Effective Blue Retinal
  \[ L_b = 10^{(3.8\ln(T)-30.5)} \]
Relatively Flat Solar W/cm² in Visible

- \( W/cm²/1.629E-4 \)
- CIE Photopic

**Wavelength (in nm for the visible region)**

**Relative Response**
Terrestrial US Solar Data

- Angles for the Sun:
  - Angular Subtense: \( \approx \frac{(1.392 \times 10^9 \text{ m})}{(1.496 \times 10^{11} \text{ m})} = 9.305 \text{ mrad} \)
  - Solid Angle: \( \approx \frac{\pi (1.392 \times 10^9 \text{ m}^2)}{4 (1.496 \times 10^{11} \text{ m})^2} = 6.800 \times 10^{-5} \text{ steradian} \)

- Terrestrial Illuminance from the Sun:
  - Total Illuminance: \( 10.95 \text{ lm/cm}^2 / 929 = 10,170 \text{ ft-cd} \) from ASTM spectrum to 4 \( \mu \text{m} \)
  - Measured illuminance: \( \approx 10.8 \text{ lm/cm}^2 / 929 = 10,000 \text{ ft-cd} \) limited view

- Luminance, temperature, candlepower of the Sun:
  - Calculated Luminance: \( \approx \frac{10.95}{6.800 \times 10^{-5}} = 161,000 \text{ lm/(cm}^2\text{-sr}) \)
  - Sun’s Apparent Surface Temperature: \( \approx 5600 \text{ deg K} \)
  - Candlepower: \( \approx 10.95 \times (1.498 \times 10^{13})^2 = 2.46 \times 10^{27} \text{ cd or lm/sr} \)

- Terrestrial Irradiance from Sun:
  - Total Irradiance: \( 95.68 \text{ mW/cm}^2 \) for 280 to 4000 nm from ASTM spectrum to 4 \( \mu \text{m} \)
  - Retinal Thermal Irradiance: \( 60.58 \text{ mW/cm}^2 \)
  - Irradiance thru \( \text{H}_2\text{O} \): \( \approx 66.29 \text{ mW/cm}^2 \) for glass cell & 2-cm \( \text{H}_2\text{O} \)
  - Measured Irradiance thru \( \text{H}_2\text{O} \): \( \approx 62 \text{ mW/cm}^2 \) limited view
  - Percent of Irradiance in Retinal Hazard Region: 63.3%, 69.3% \( \text{H}_2\text{O} \) & \( \approx71\% \) measured
  - Blue light irradiance: \( \approx 9.436 \text{ mW/cm}^2 \)
  - Irradiance for Radiometric Silicon: best current guess \( \approx 62.5 \text{ mW/cm}^2 \) limited view

- Radiance of the Sun:
  - Retinal Thermal Radiance: \( \approx 891\text{W/(cm}^2\text{-sr}) \)
  - Sun’s Radiance thru \( \text{H}_2\text{O} \): \( \approx 975 \text{ W/(cm}^2\text{-sr}) \)
  - Radiance error thru \( \text{H}_2\text{O} \) compared to MPE: < 10 %
  - Effective Blue Light Retinal Radiance: \( \approx 139 \text{ W/(cm}^2\text{-sr}) \)
  - Sun’s Total Radiance: \( \approx 1410 \text{ W/(cm}^2\text{-sr}) \)

- Luminous Efficacy of the Sun:
  - Sun & Sky Luminous Efficacy: 165.19 lm/W thru \( \text{H}_2\text{O} \) & 114.44 lm/W to 4 \( \mu \text{m} \)
  - Measured Luminous Efficacy: \( \approx 170 \text{ lm/W vs 146.6 lm/W 5600 K blackbody} \)

- ACGIH Permissible Exposure
  - New MPE Thermal Viewing: Exceeds exposure limit for 0.25 sec
  - ACGIH MPE Blue-Light Viewing: Does not exceed for 0.25 sec
Benjamin Franklin’s Candle

- **Source size:** $0.3 \times 0.3 \text{ cm} = 0.09 \text{ cm}^2$
- **Measurement distance:** 15 cm
- **Solid angle:** $\frac{0.09}{(15)^2} = 0.0004 \text{ sr}$
- **Irradiance:** $0.12 \text{ mW/cm}^2 \text{ thru H}_2\text{O}$
- **Radiance:** $0.3 \text{ W/(cm}^2-\text{sr)} \text{ thru H}_2\text{O}$
- **Illuminance:** $0.40 \text{ mlm/cm}^2$
- **Luminance:** $0.0004/.0004 = 1 \text{ lm/(cm}^2-\text{sr)}$
- **Luminous efficacy:** $.0004/.00012 = 3.3 \text{ lm/W}$
- **Temperature:** 1500–1700 deg K
- **Candlepower:** $.0004*(15)^2 = 0.09 \text{ cd or lm/sr}$
- **Hazards:** No retinal thermal nor retinal blue light but skin & cornea thermal to ~2 cm
Tungsten-Halogen Desk Lamp

- Electrical input power: 35 watts
- Measurement distance: 1 m
- Source size not determined
- Illuminance: \(~0.019 \text{ lm/cm}^2\)
- Irradiance thru H\(_2\)O: \(~0.22 \text{ mW/cm}^2\)
- Effective luminous efficacy: 86 lm/W
- Effective temperature: 3150 deg K
- Candlepower: 190 cd or lm/sr
Consumer Handheld Spotlight

- 15 million candlepower rating
- Measurement distance: 5 m
- Reflector diameter: 21.2 cm
- Illuminance: ~ 0.97 lm/cm²
- Irradiance thru H₂O: ~ 11 mW/cm²
- Percent thru H₂O: 40 %
- Luminous Efficacy: ~88 lm/W
- Temperature: ~3200 deg K
- Beam Spread: 2 degrees
- Candlepower: 240,000 cd or lm/sr
Basics: Sylvania No. 2 Flashbulb

- Flashbulb globe diameter: spherical ~6 cm diameter
- Flash source diameter: ~ a 5 cm sphere
- Measurement distance: 400 cm from flashbulb
- Source angular subtense: $\alpha \sim 5/400 = 0.0125$ rad
- Source solid angle: $\Omega \sim (5)^2/(1.27)(400)^2 = 123 \mu$sr
- Flash duration: $t \sim 16$ ms FWHM Si det & movies
- Integrated illuminance: $E_\mu \sim 29.9$ ft-cd-s/929 = 0.0322 (lm-s)/cm$^2$ and a peak of 0.0624 (lm-s)/cm$^2$
- Total radiant exposure: $H \sim 934$ $\mu$W-s/cm$^2$ or $\mu$J/cm$^2$
- Radiant exposure thru $\text{H}_2\text{O}$: $H \sim 365$ $\mu$J/cm$^2$
- Percent of total thru $\text{H}_2\text{O}$: 365/934 = 39%
- Luminous efficacy thru $\text{H}_2\text{O}$: $K \sim$ ave of lm/W = 116 lm/W
- Effective flash temperature: $T \sim 3860$ deg K
- Luminous efficacy to 4000 nm: $K \sim 35$ lm/W
- Blue light radiant exposure: $H \sim 34$ $\mu$J/cm$^2$
- Integrated candlepower: $(.0322)(400)^2 = 5150$ cd-s or lm-s/sr
- Peak candlepower: $\sim 5150/0.016 = 320,000$ cd or lm/sr
- Lumen-second: $\sim (5150)(4\pi) = 65,000$ lm-s
Results: Sylvania No. 2 Flashbulb

- Measured integrated illuminance: $E \sim 0.0624 \text{ (lm-s)/cm}^2$
  - Integrated luminance: $\sim 0.0624/0.000123 = 507 \text{ (lm-s)/(cm}^2\text{-sr})$
  - Peak luminance: $L_\odot \sim 507/0.016 = 31,700 \text{ lm/(cm}^2\text{-sr})$
  - Peak flash temperature: $T \sim 4140 \text{ deg K}$
- Total radiant exposure for all radiation: $H \sim 930 \ \mu\text{J/cm}^2$
  - Integrated radiance: $\sim 930/123 = 7.56 \text{ J/(cm}^2\text{-sr})$
  - Peak radiance for all radiation: $\sim 7.56/0.016 = 473 \text{ W/(cm}^2\text{-sr})$
- Radiant exposure thru $\text{H}_2\text{O}$: $H = 365 \ \mu\text{J/cm}^2$
  - Integrated radiance through $\text{H}_2\text{O}$: $\sim 365/123 = 2.97 \text{ J/(cm}^2\text{-sr})$
  - Peak radiance thru $\text{H}_2\text{O}$: $\sim 2.97/0.016 = 185 \text{ W/(cm}^2\text{-sr})$
  - Peak flash temperature: $T \sim 4160 \text{ deg K}$
- Estimated retinal thermal exposures:
  - $\sim 122 \text{ W/(cm}^2\text{-sr})$ for 3860 deg K
  - $\sim 180 \text{ W/(cm}^2\text{-sr})$ for 4140 deg K
  - $\sim 185 \text{ W/(cm}^2\text{-sr})$ for 4160 deg K
- Estimated & measured retinal blue light exposures:
  - Peak blue light irradiance: $\sim 34/0.016 = 2 \text{ mW/cm}^2$
  - Peak blue light radiance: $0.002/0.000123 = 16.3 \text{ W/(cm}^2\text{-sr})$
  - $\sim 7.62 \text{ W/(cm}^2\text{-sr})$ for 3860 deg K
  - $\sim 14.1 \text{ W/(cm}^2\text{-sr})$ for 4140 deg K
  - $\sim 14.7 \text{ W/(cm}^2\text{-sr})$ for 4160 deg K
Summary: Sylvania No. 2 Flashbulb

- **Retinal thermal hazard evaluation:**
  - Radiance thru $\text{H}_2\text{O}$: 185 W/(cm$^2$-sr)
  - Hazard: $(.356)(185)/(3.2)(5) = 4.1$ meters
  - 7X50 hazard distance: 28.8 meters

- **Retinal blue light hazard evaluation:**
  - Blue light radiance: 16.3 W/(cm$^2$-sr)
  - True: $16.3 < 6250 = 100/.016$
  - Does not exceed the blue light MPE

- **Comparing Im, W, & Im/W methods:**
  - $\text{Im}/\text{W}$: ~7% lower $T$ and required more data
  - $\text{Im}$: same but required more data
  - $\text{W}$: benchmark worked well
UDT Model 40a & 40x Mid-70’s
Scientech 360001 calorimeter inside isoparibol enclosure

0.3 to 30 μm, 5.08 cm², ~ 98 mV/W, & 14 sec
IL1700 with Broadband Detector & Hood with a 2-cm Water Filter
SED(SEL) 623 1mm Quartz Window
From Manufacturer Specifications

625 624 & 623 computer
Practical High Irradiance & Wide-Angle Calorimeter
Wide-Angle Water Calorimeter
Any Questions?

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Readyness thru Health
LBE Detector Calibration

• Need to add figure
Some Past & Present Integrating Radiometers & Photometers

• **Photometric**
  - IL 1400a
  - IL 1700, SED 033
  - UDT 40X, Photometric
  - EG&G 550, 580
  - Tektronix J-17, J 1803
  - Optronic Labs, 730A
  - Photo Research, PR1980PL
  - Gossen, Luna Pro
  - Gigahertz-Otics
  - Newport

• **Radiometric**
  - IL 1700, SED 623 & blue light
  - UDT 40X, Radiometric
  - Gigahertz-Optics, retinal thermal & blue light
  - Scientech Calorimeters
  - Newport