Flash Pyrometry Techniques for Health Hazard Evaluation

TERRY L. LYON
Physicist/Master Consultant
Laser/Optical Radiation Program

USA Center for Health Promotion & Preventive Medicine
ATTN: MCHB-TS-OLO, 5158 Blackhawk Road
Aberdeen Proving Ground, MD 21010-5403
(410) 436-5069/3932
Terry.Lyon@us.army.mil

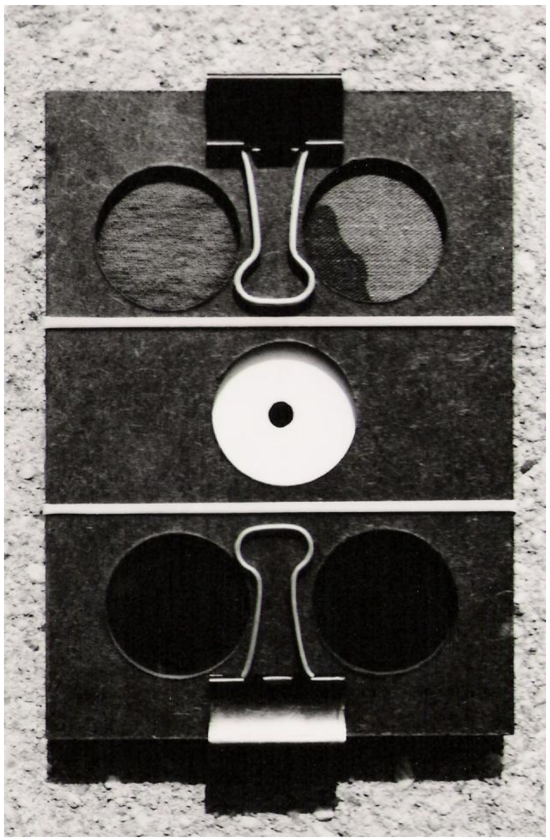
USACHPPM

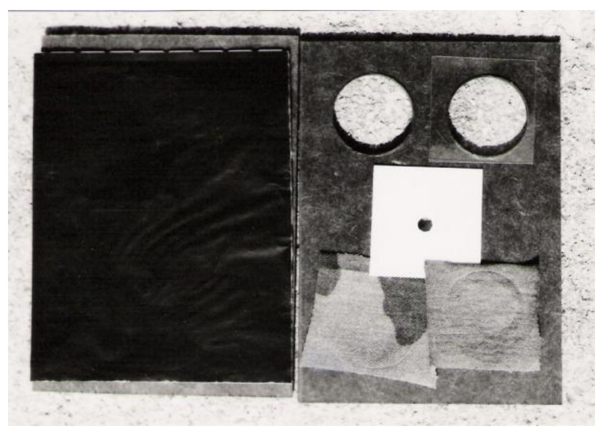
Flash pyrometry techniques needed for single flash events

Wanted: Simple field method to evaluate flash radiation hazards

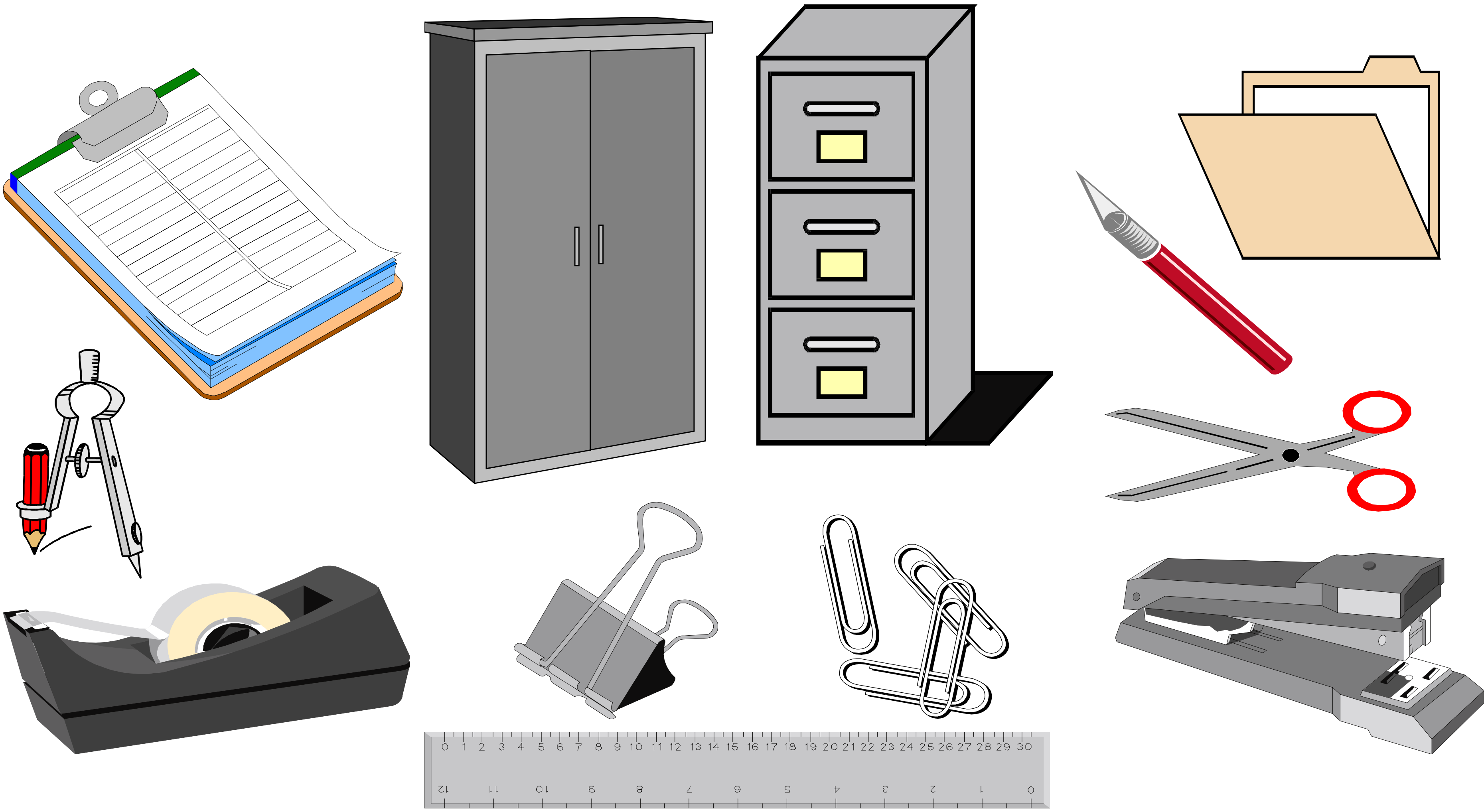
- Needed for health hazard occupational exposure studies
  - Need to improve retinal thermal & blue light flash evaluations
  - Witness detectors exist for skin and corneal thermal injury
  - Adjunct passive cameras exist for retinal thermal injury potential
  - Needed to evaluate direct sources like 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

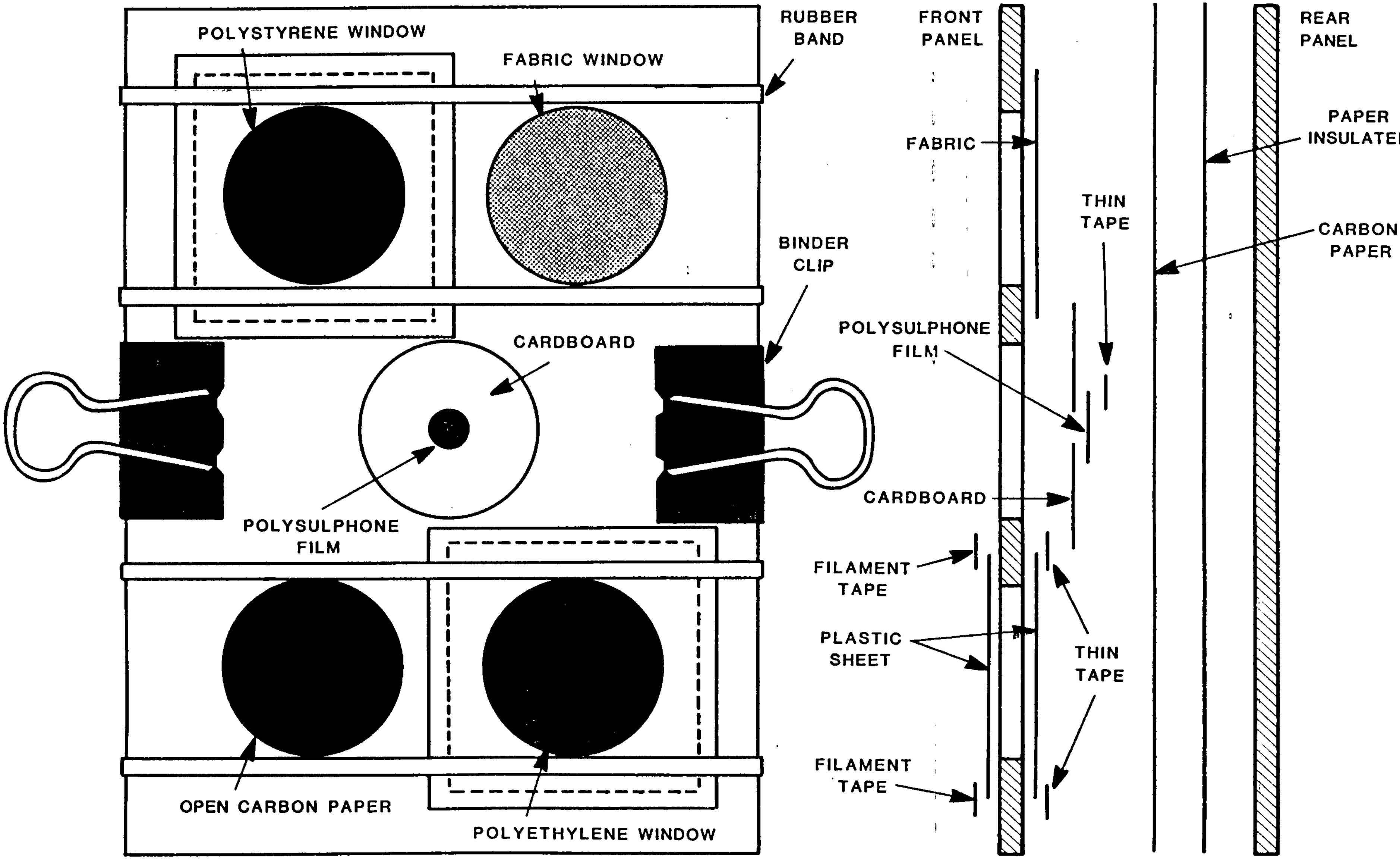




Construction Materials for Witness Detector are Less Available Today

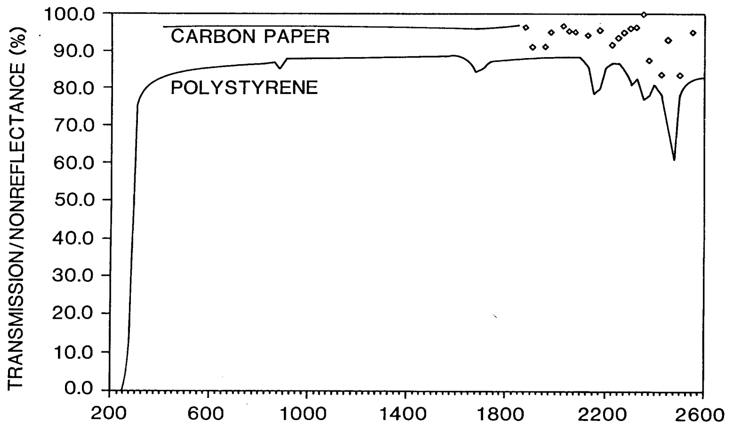


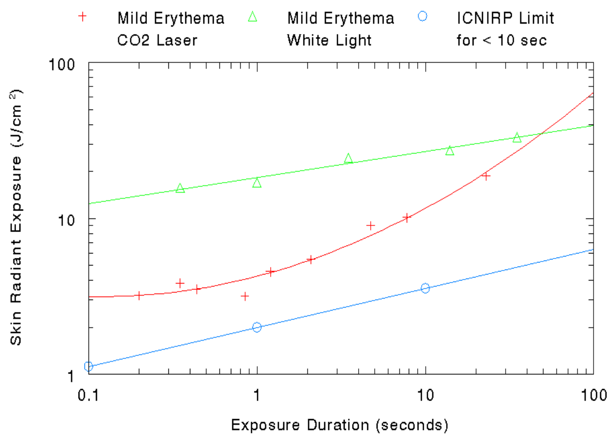
FRONT VIEW SIDE VIEW

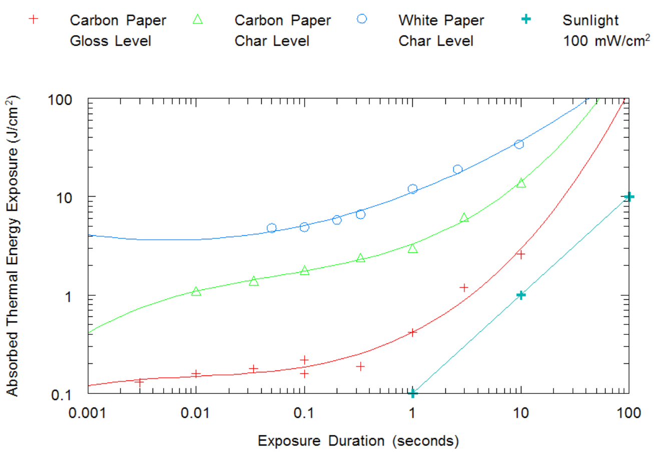


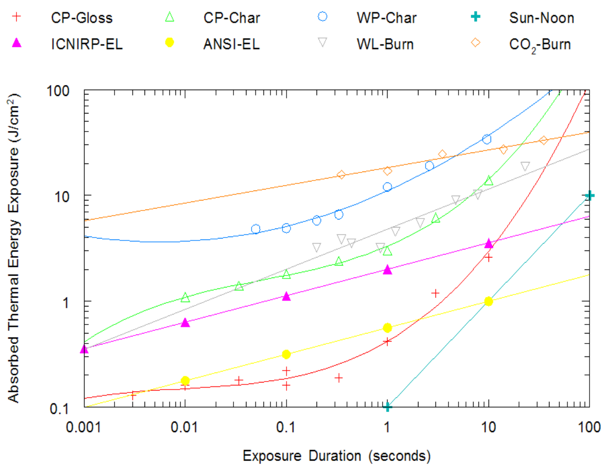
DRAWN TO FULL SCALE

There really is physics & biophysics behind using the LWB detector!

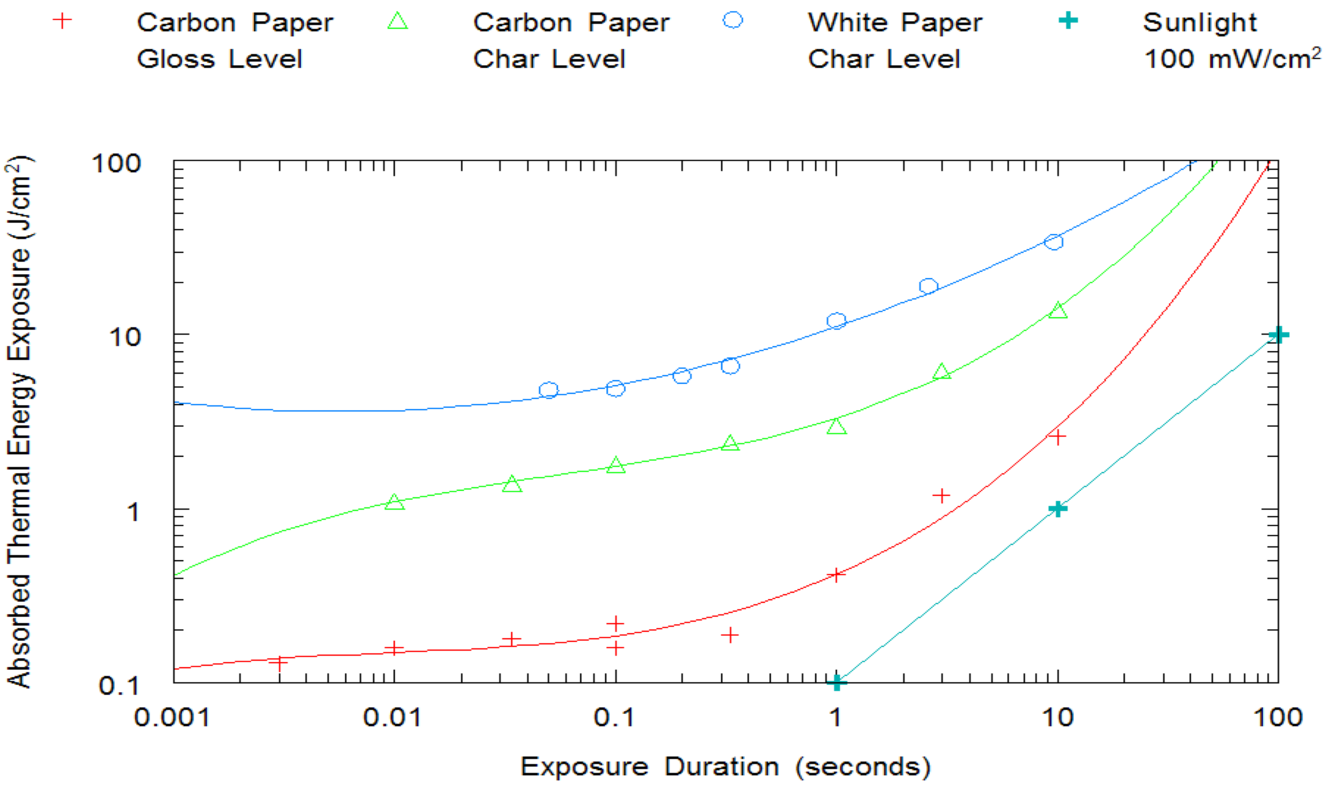




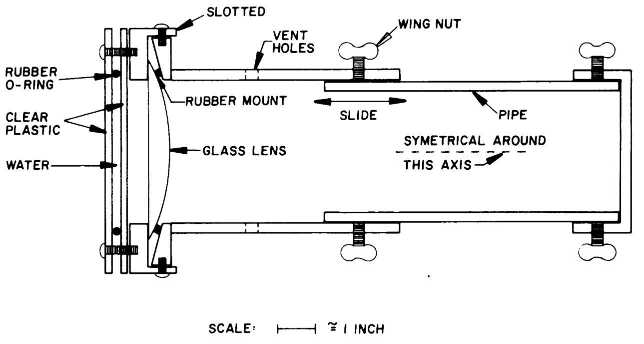


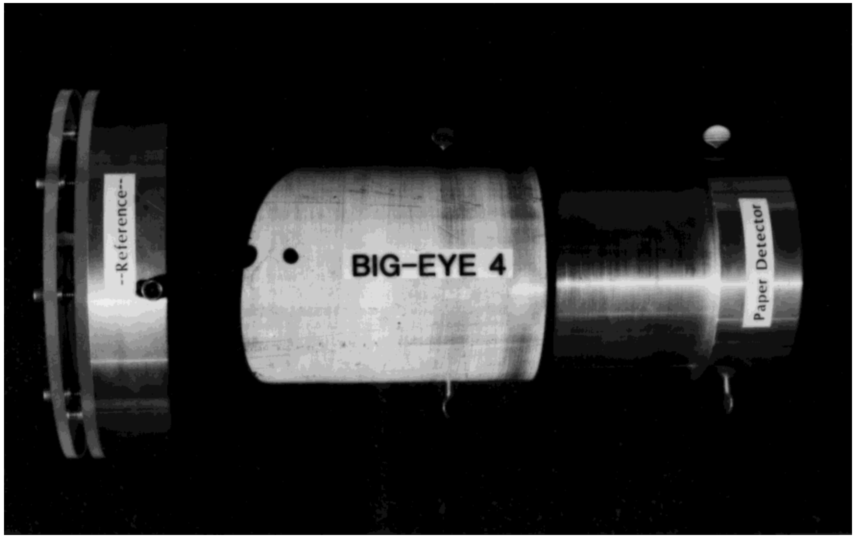


Calibration Data for Carbon and White Paper



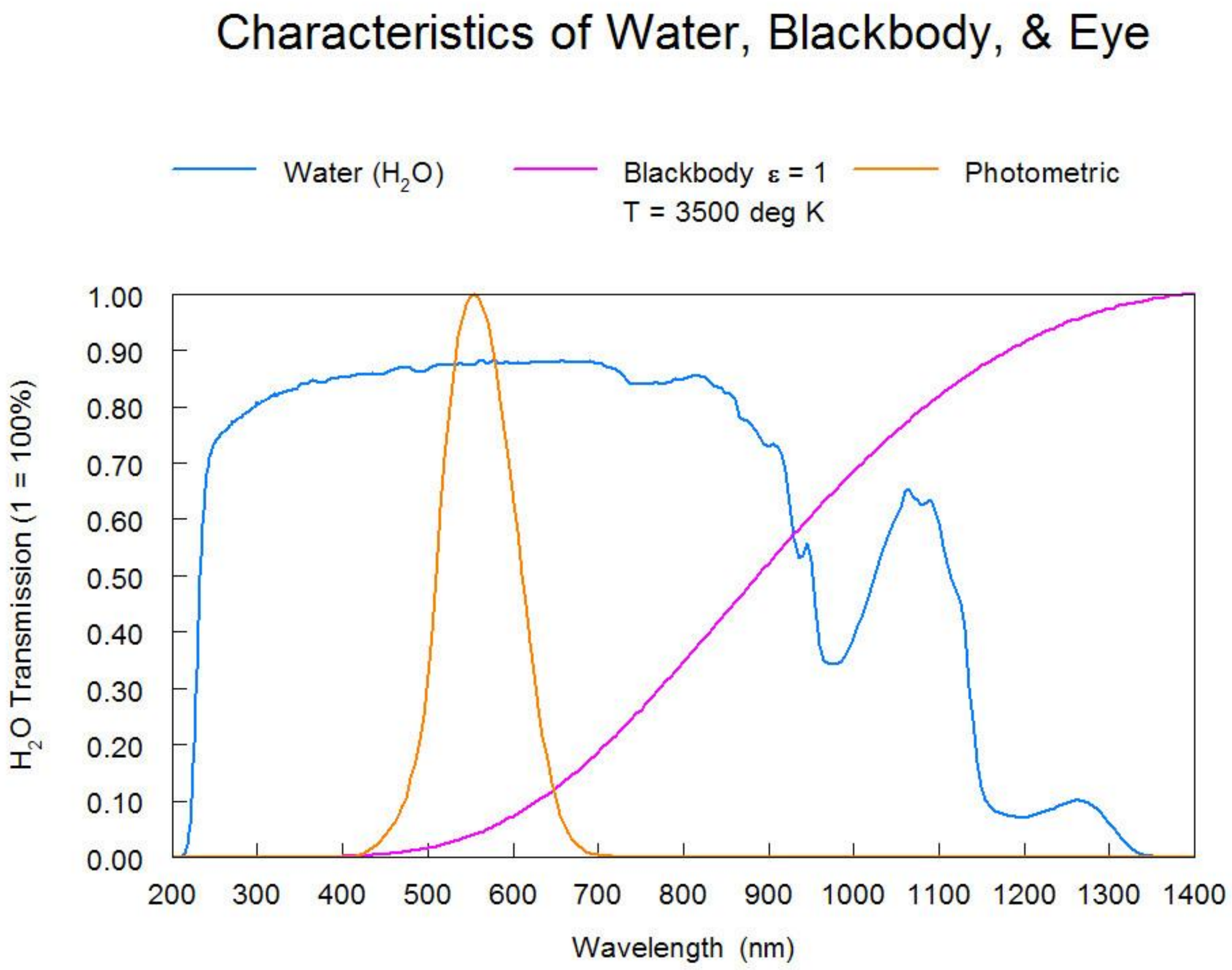
Lyon Big Eye Retinal Exposure Detector Has H_2O and Eye's F-No



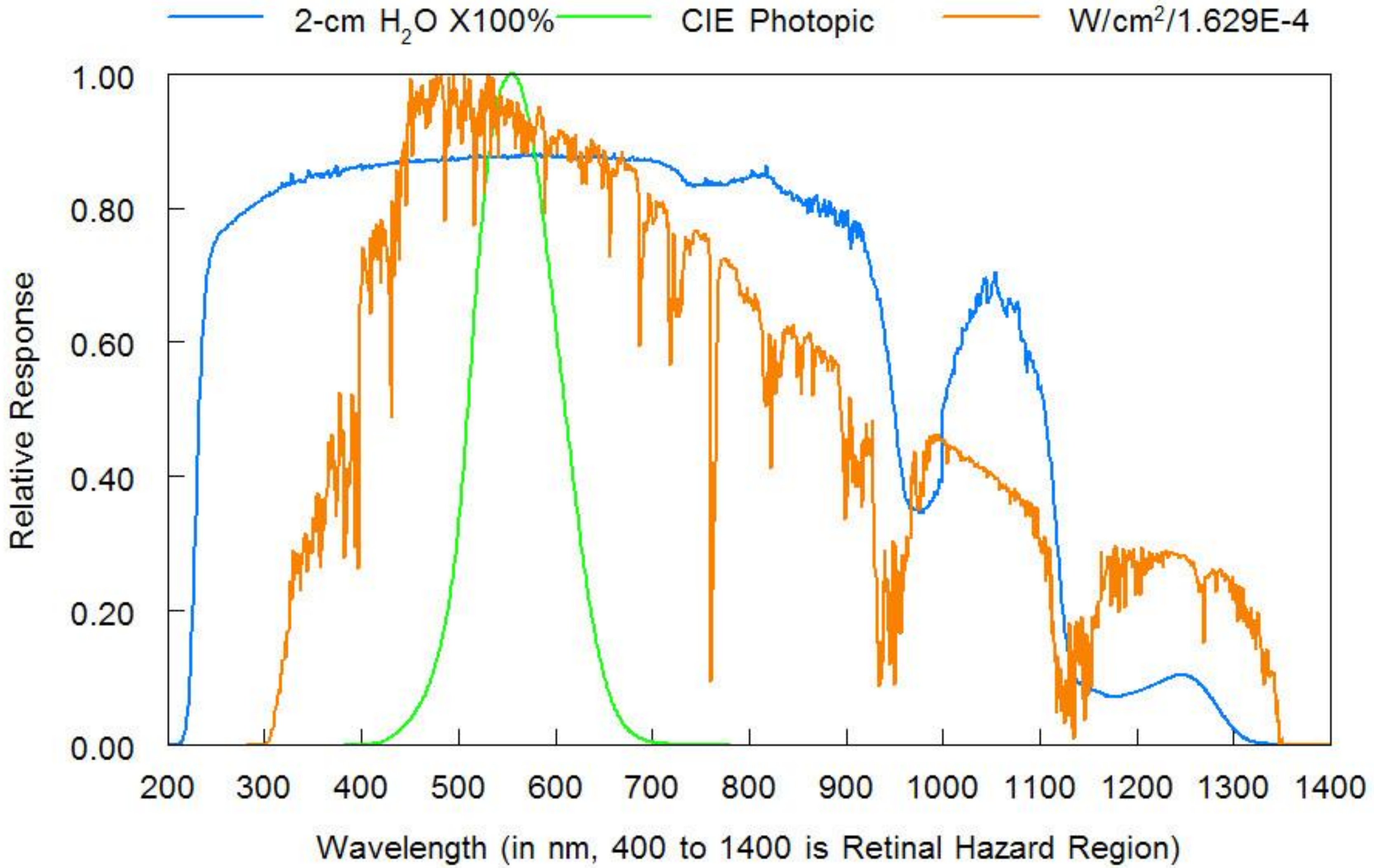


Simple Field Fresnel Camera to Estimate Flash Source Size

Properties of eye and a blackbody radiator near its melting point.



Terrestrial Solar Irradiance and the Eye

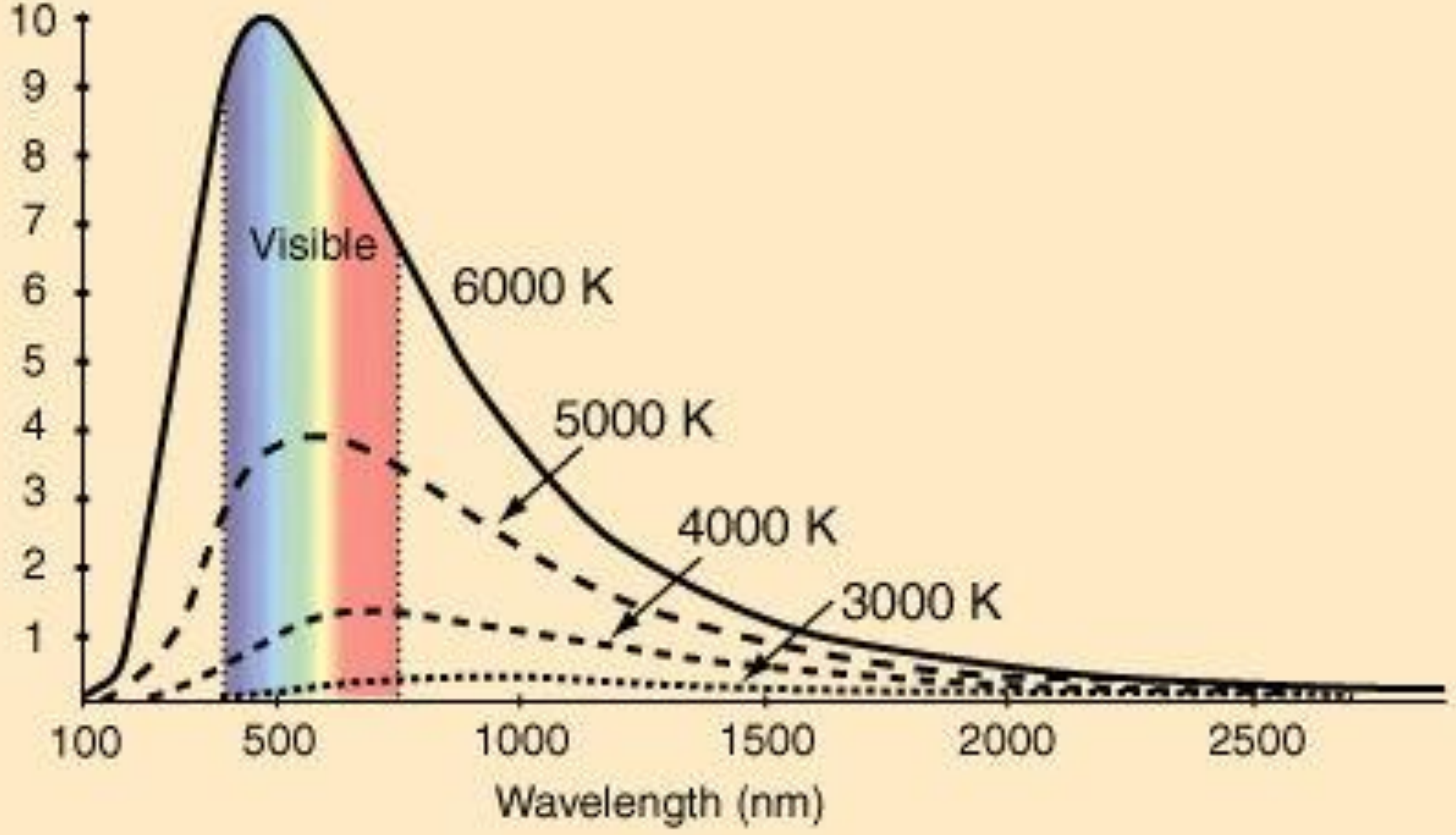


Broadband Versus Spectral

- 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

- deg C = deg K - 273.15
- deg F = 9 (deg K)/5 - 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-s)
- irradiance (W/cm^2) & illuminance (lm/cm^2)
- radian (rad), degree (deg), & steradian (sr)
- radiance (W/cm^2-sr) & luminance (lm/cm^2-sr)
- radiant exposure (J/cm^2) & intergrated-illuminance (lm-s/cm^2)
- integrated-radiance (J/cm^2-sr = W-s/cm^2-sr) & integrated-luminance (lm-s/cm^2-sr)
- luminous efficacy (lm/W = lm-s/J)
- time (s = m/60 = hr/3600)

Common Unit Conversions

To Obtain Number Of:	Multiply Number Of:	By This Factor:
lumen/steradian = lm/sr	candela = cd = candlepower	1
lm/cm^2 = phot	footcandle = 1 lumen/ft^2	0.00108
lm/cm^2 = phot	lumen/m^2 = lux	0.0001 = 10^{-4}
lm/cm^2-sr = stilb	candela = cd = candlepower	1/(luminous area in cm^2)
lm/cm^2-sr = stilb	cd/cm^2 = stilb	1
lm/cm^2-sr = stilb	cd/m^2 = nit	0.0001 = 10^{-4}
lm/cm^2-sr = stilb	footlambert = 1/π cd/ft^2	0.000343
lm/cm^2-sr = stilb	millilambert = 10 apostilb	0.000318
lm/cm^2-sr = stilb	lambert = 0.01 apostilb	1/π = 0.318
lm/cm^2-sr = stilb	cd/ft^2 = π footlamberts	0.00108

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

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

$$L_R\,[W/(cm^2 sr)] \le \frac{3.2}{\alpha \bullet t^{1/4}}$$

0.00063 to 0.25 s

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

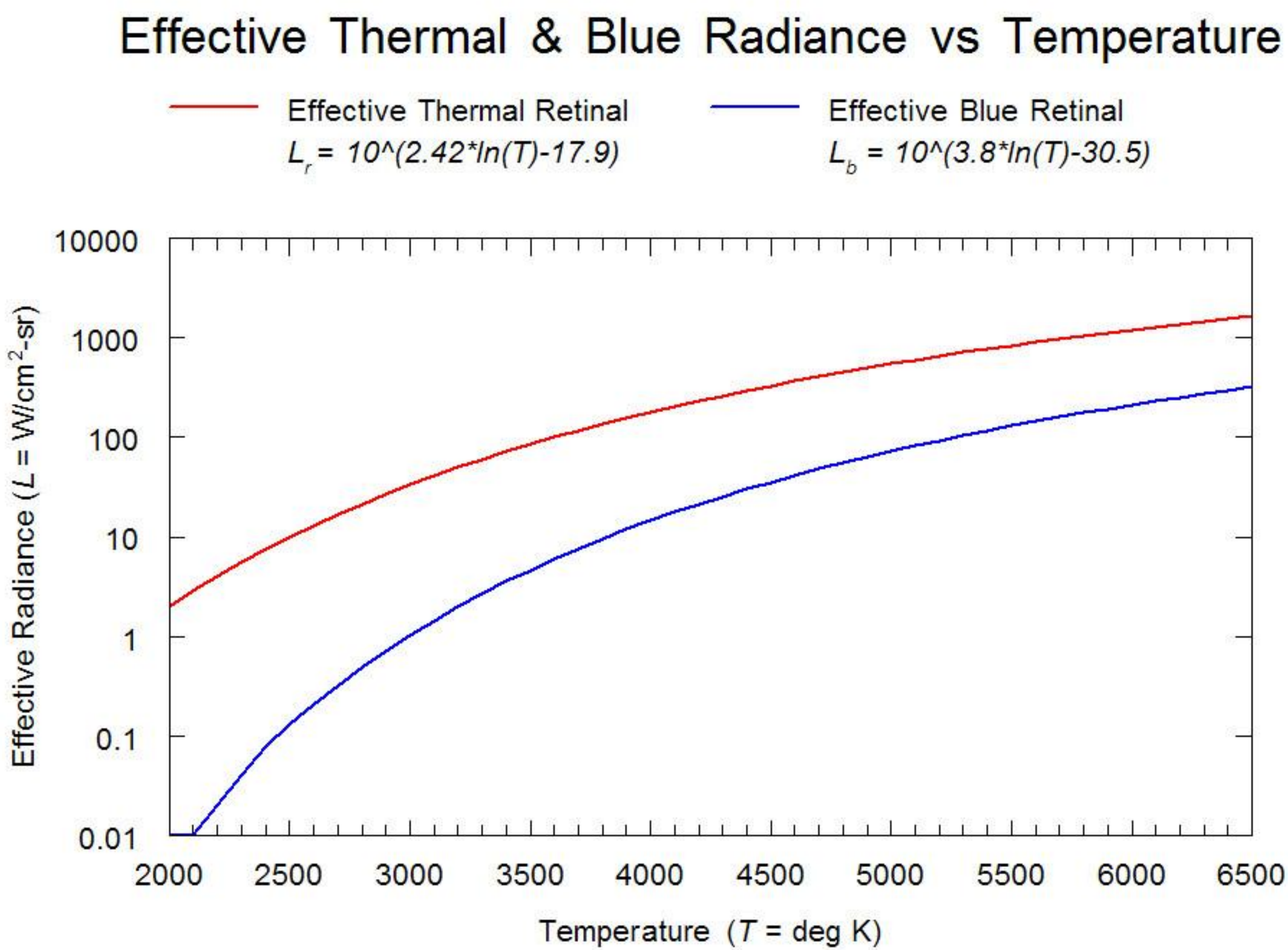
$$L_R\,[W/(cm^2 sr)] \le \frac{4.5}{\alpha}$$

Extended Source > 0.1 rad Retinal Blue-Light Limits

$$L_B\,[\mathrm{W/(cm^2 sr)}] = \sum_{305}^{700} L_\lambda \bullet B(\lambda) \bullet \Delta\lambda$$

$$L_B \le \frac{100\,[\mathrm{J/(cm^2 sr)}]}{t\,[\mathrm{s}]}$$

$$t_{max}[\mathrm{s}] = \frac{100\,[\mathrm{J/(cm^2 sr)}]}{L_B}$$



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)
10000
1000
100
10
1
0.1
0.01
Effective Radiance (L = W/cm2-sr)
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
Temperature (T = deg K)

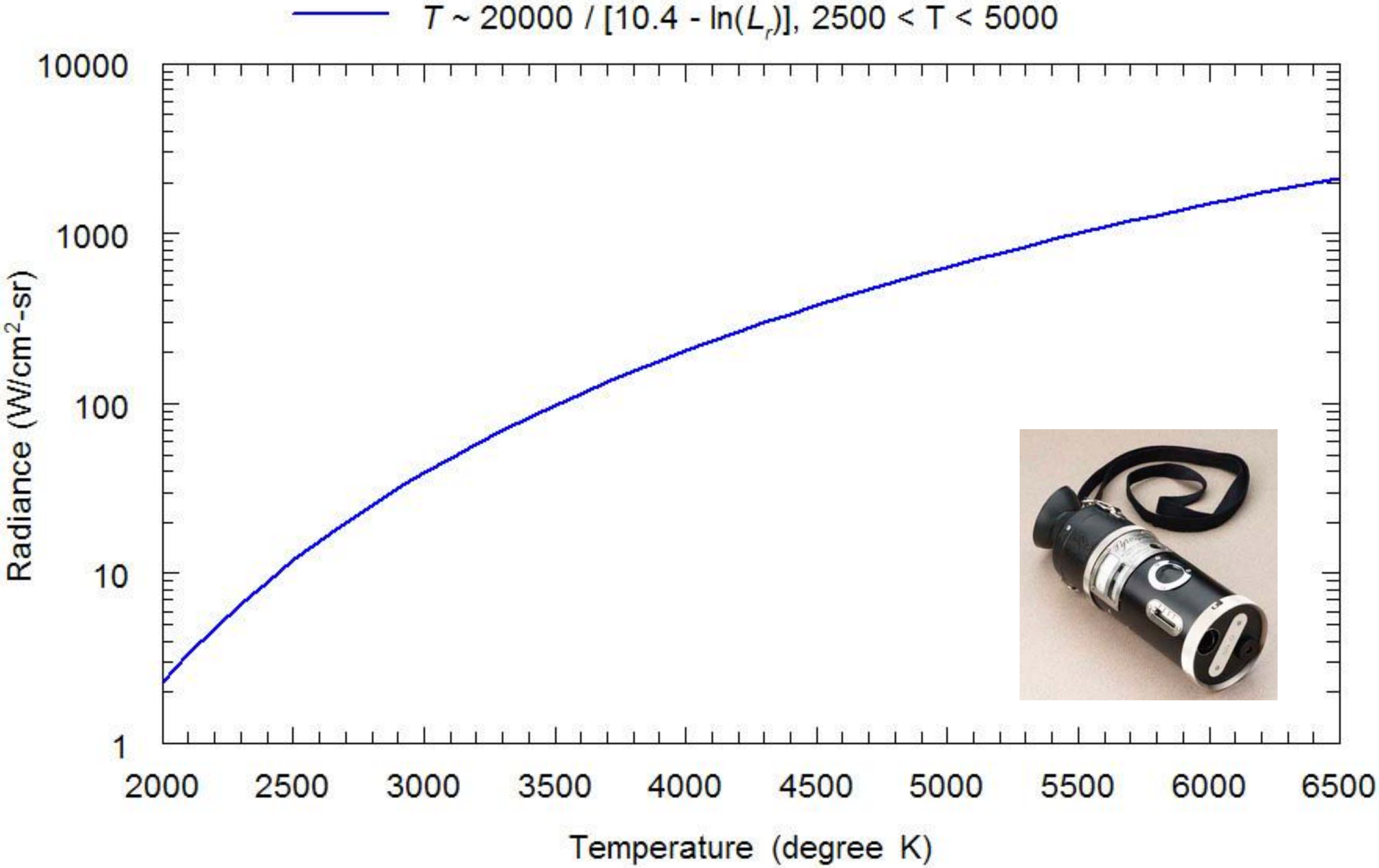
What can be achieved with an effective lm/W=lm-s/J for the eye

- 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, lm/W = lm-s/J

Three Broadband Processes

- Calculate peak W/cm^2-sr weighted to R_λ 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_λ 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 lm/cm^2-sr weighted to V_λ to find peak source T
  - This is the traditional technique and may not be possible in a harsh environment
  - Measure lm/cm^2 or $lm\text{-}s/cm^2$ 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 lm/W = lm-s/J thru H_2O filter to find an effective source T
  - Useful adjunct especially for flash sources
  - Measure W-s/cm2 & lm-s/cm2 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



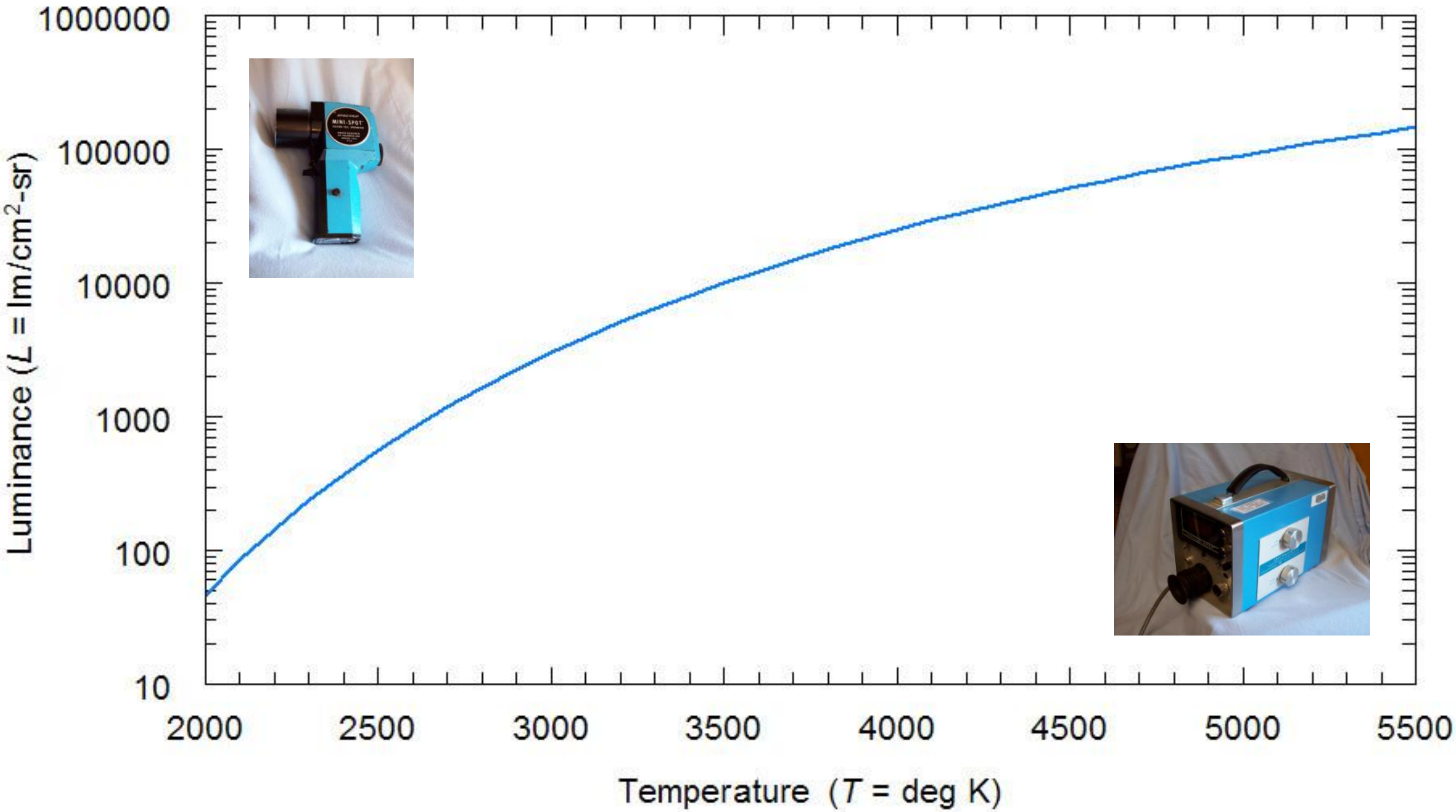
Source Temperature Range

- 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

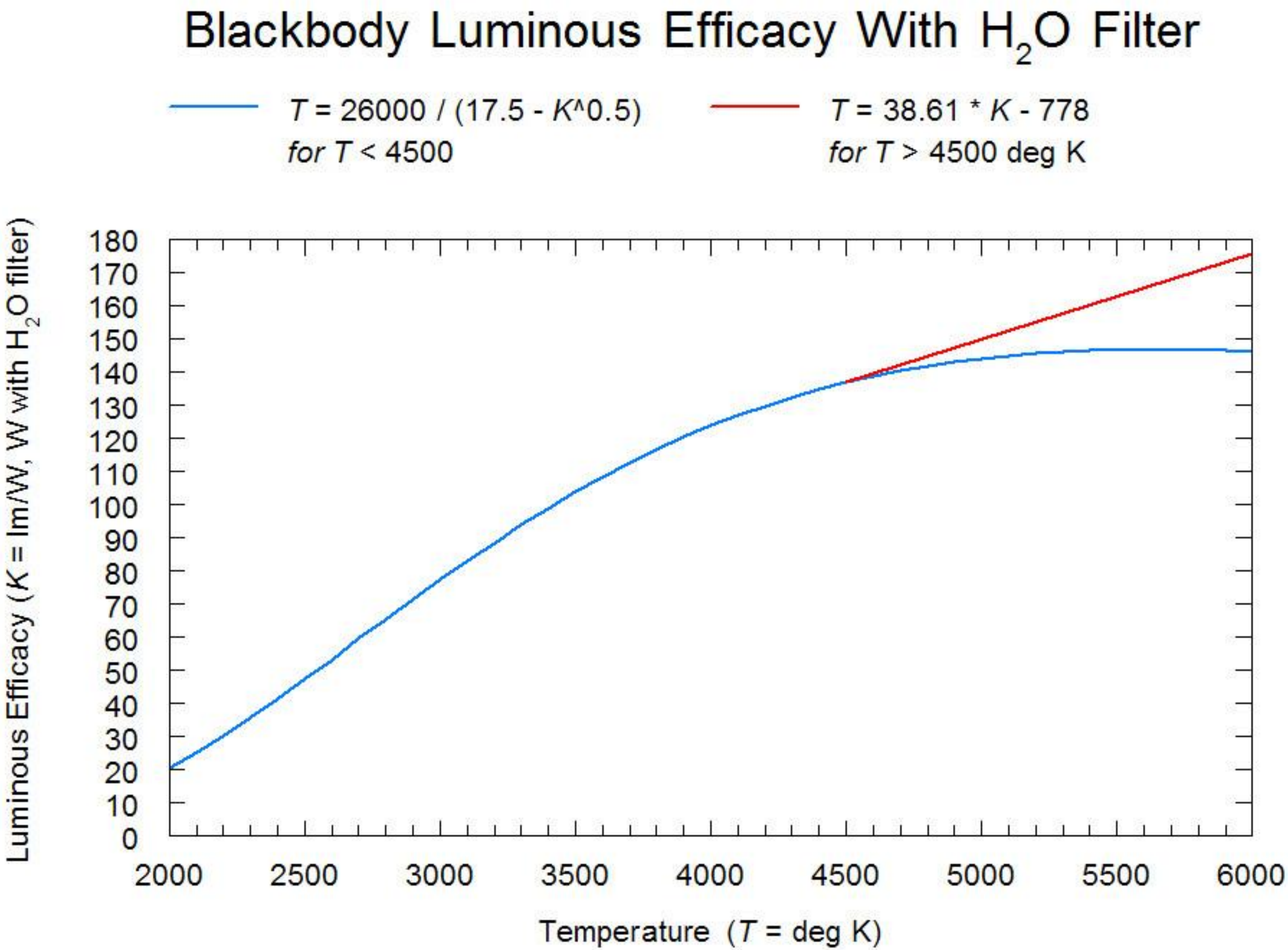
$T = 25400 / [16.5 - \ln(L)]$

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



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 H2O Filter
T = 26000 / (17.5 - K^0.5)
for T < 4500
T = 38.61 * K - 778
for T > 4500 deg K
Luminous Efficacy (K = lm/W, W with H2O filter)
Temperature (T = deg K)
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
2000
2500
3000
3500
4000
4500
5000
5500
6000

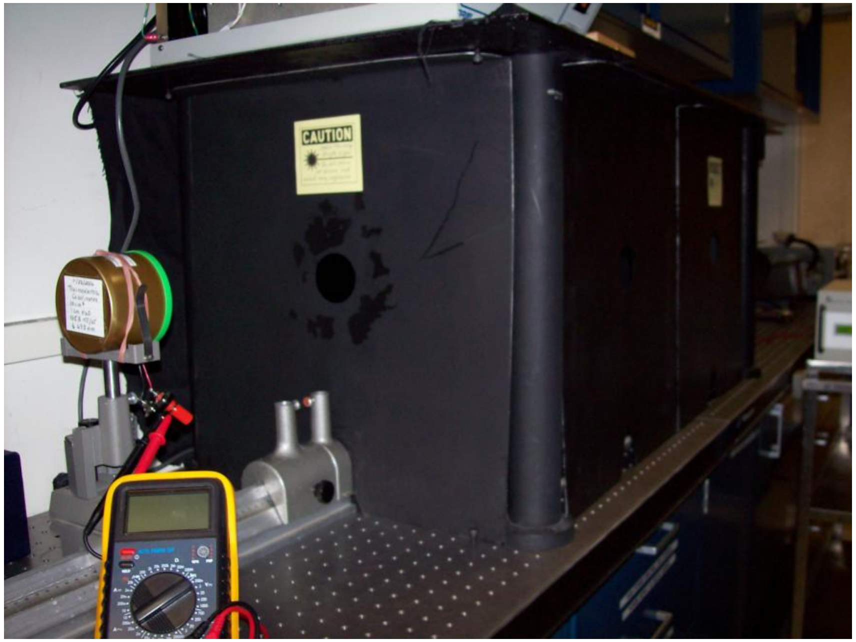
Calculating the peak radiance and luminance can introduce errors

- Calculate Peak Radiance in W/(cm^2-sr)
  - Peak irradiance in W_p/cm^2 ~ (J/cm^2)/(~FWHM duration)
  - Peak L_r ~ W_p / [(cm^2)(solid angle at r)]
  - Solid angle ~ (1/e source area) / r^2
- Calculate Peak Luminance in lm/(cm^2-sr)
  - Peak illuminance in lm_p/cm^2 ~ (lm-s/cm^2)/(~FWHM duration)
  - Peak L_λ ~ lm_p / [(cm^2)(solid angle at r)]
  - Solid angle ~ (1/e source area) / r^2
- Direct measurement for peak values is best but flash duration and source size are still needed

lm/W Preliminary & Tests

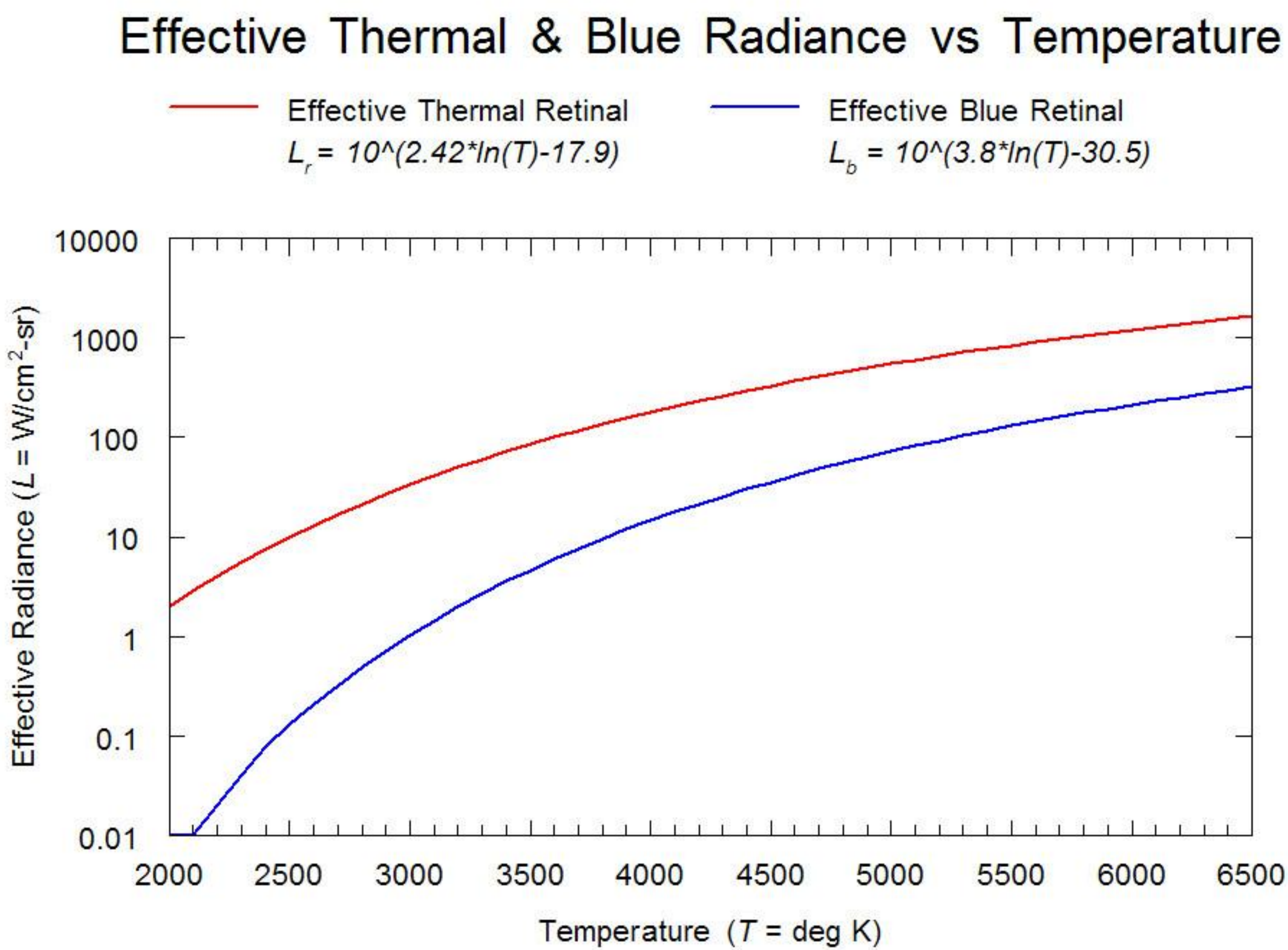
- Calibrate detectors using similar source
- Design test so detectors view source only
- Check lm/W ratio with a portable lamp
- Conduct a preliminary blind test
- Consider passive detectors for source size
- Use electronic means for flash duration

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/cm^2
- Irradiance 4.5 – 10 um: ~ 0.828 mW/cm^2
- Irradiance thru 2-cm H_2O filter: 9.475 mW/cm^2
- Irradiance with Radiometric Silicon: ~ 9.75 mW/cm^2
- Illuminance: 758.9 ft-cd = 0.8167 lm/cm^2
- Luminous Efficacy: 86.22 lm/W, effective thru H_2O
- Source Temperature: Calculated as 3165 deg K
- Retinal Thermal Irradiance: 8.055 mW/cm^2
- Retinal Blue Light Irradiance: 0.3093 mW/cm^2
- Actinic Ultraviolet Irradiance: 3.334 uW/cm^2 or 15 min
- Reflectance Standard Luminance: 0.2570 lm/(cm^2-sr)
- Reduced Temperature: 2856 deg K at 6.850 amps
- Candlepower: 2042 cd or lm/sr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Effective Radiance (L = W/cm2-sr)
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2500
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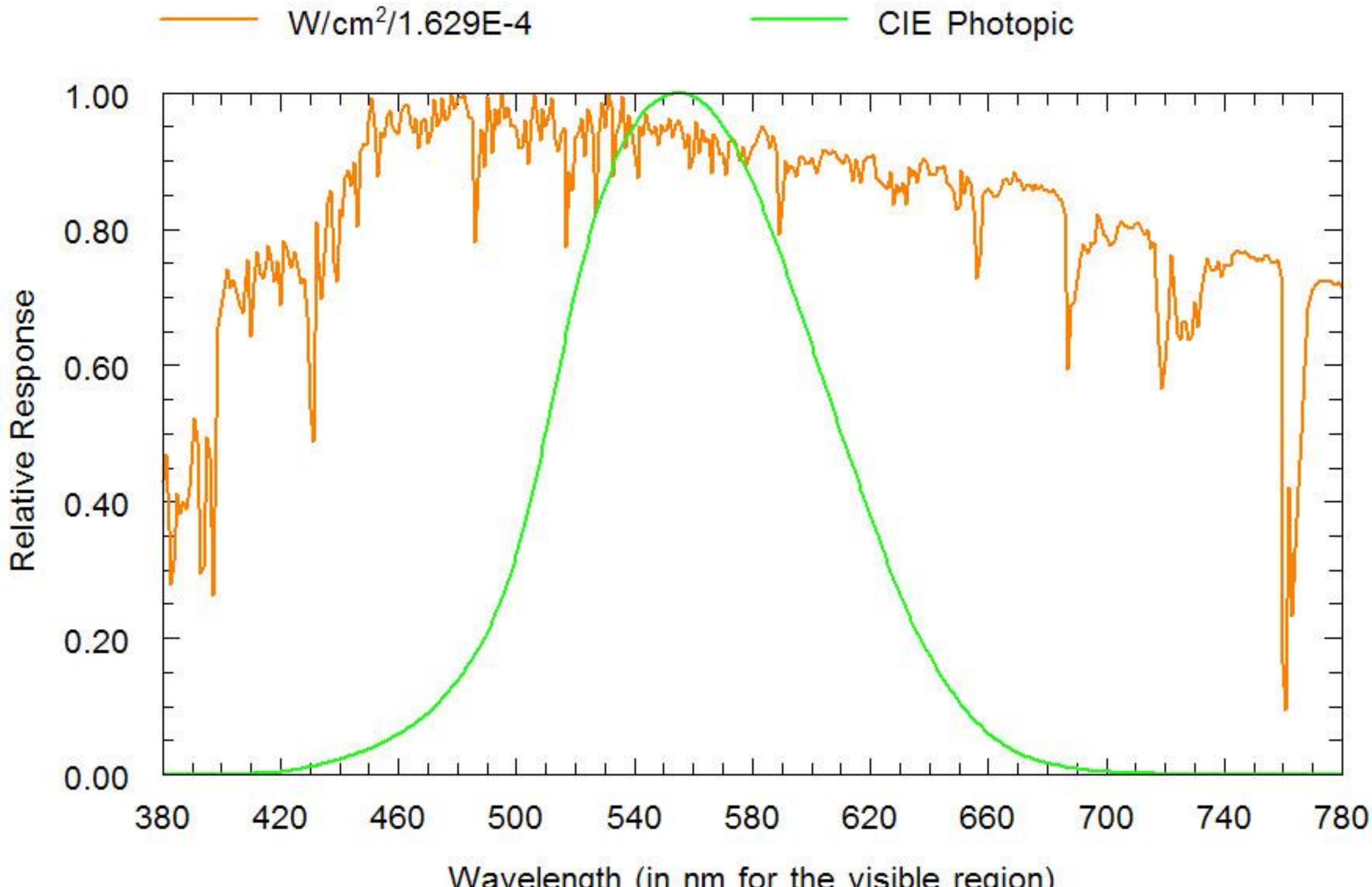
6000
6500
Temperature (T = deg K)

Relatively Flat Solar W/cm² in Visible



Terrestrial US Solar Data

- Angles for the Sun:
  - Angular Subtense: ~ (1.392 X 10^9 m) / (1.496 X 10^{11} m) = 9.305 mrad
  - Solid Angle: ~ [π X (1.392 X 10^9)^2] / [4 X (1.496 X 10^{11} m)^2] = 6.800 X 10^{-5} steradian
- Terrestrial Illuminance from the Sun:
  - Total Illuminance: 10.95 lm/cm^2 / 929 = 10,170 ft-cd from ASTM spectrum to 4 μm
  - Measured illuminance: ~ 10.8 lm/cm^2 / 929 = 10,000 ft-cd) limited view
- Luminance, temperature, candlepower of the Sun:
  - Calculated Luminance: ~ 10.95/ 6.800 X 10^{-5} = 161,000 lm/(cm^2-sr)
  - Sun's Apparent Surface Temperature: ~ 5600 deg K
  - Candlepower: ~ 10.95 X (1.498 X 10^{13})^2 = 2.46 X 10^{27} cd or lm/sr
- Terrestrial Irradiance from Sun:
  - Total Irradiance: 95.68 mW/cm^2 for 280 to 4000 nm from ASTM spectrum to 4 μm
  - Retinal Thermal Irradiance: 60.58 mW/cm^2
  - Irradiance thru H_2O: ~ 66.29 mW/cm^2 for glass cell & 2-cm H_2O
  - Measured Irradiance thru H_2O: ~ 62 mW/cm^2 limited view
  - Percent of Irradiance in Retinal Hazard Region: 63.3%, 69.3% H_2O & ~71% measured
  - Blue light irradiance: ~ 9.436 mW/cm^2
  - Irradiance for Radiometric Silicon: best current guess ~ 62.5 mW/cm^2 limited view
- Radiance of the Sun:
  - Retinal Thermal Radiance: ~ 891W/(cm^2-sr)
  - Sun's Radiance thru H_2O: ~ 975 W/(cm^2-sr)
  - Radiance error thru H_2O compared to MPE: < 10 %
  - Effective Blue Light Retinal Radiance: ~ 139 W/(cm^2-sr)
  - Sun's Total Radiance: ~ 1410 W/(cm^2-sr)
- Luminous Efficacy of the Sun:
  - Sun & Sky Luminous Efficacy: 165.19 lm/W thru H_2O & 114.44 lm/W to 4 μm
  - Measured Luminous Efficacy: ~ 170 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 x 0.3 cm = 0.09 cm^2
- Measurement distance: 15 cm
- Solid angle: $0.09/(15)^2 = 0.0004$ sr
- Irradiance: 0.12 mW/cm^2 thru H_2O
- Radiance: 0.3 $W/(cm^2\text{-sr})$ thru H_2O
- Illuminance: 0.40 mlm/cm^2
- Luminance: 0.0004/.0004 = 1 $lm/(cm^2\text{-sr})$
- Luminous efficacy: .0004/.00012 = 3.3 lm/W
- Temperature: 1500–1700 deg K
- Candlepower: $.0004*(15)^2 = 0.09$ 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 lm/cm^2
- Irradiance thru H_2O: ~0.22 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/cm^2
- Irradiance thru H_2O: ~ 11 mW/cm^2
- Percent thru H_2O: 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: α ~ 5/400 = 0.0125 rad
- Source solid angle: $\Omega \sim (5)^2/(1.27)(400)^2 =$ 123 μsr
- Flash duration: *t* ~ 16 ms FWHM Si det & movies
- Integrated illuminance: E_ν ~ 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* ~ 934 μW-s/cm^2 or μJ/cm^2
- Radiant exposure thru H_2O: *H* ~ 365 μJ/cm^2
- Percent of total thru H_2O: 365/934 = 39 %
- Luminous efficacy thru H_2O: *K* ~ ave of lm/W = 116 lm/W
- Effective flash temperature: *T* ~ 3860 deg K
- Luminous efficacy to 4000 nm: *K* ~ 35 lm/W
- Blue light radiant exposure: *H* ~34 μJ/cm^2
- Integrated candlepower: ~(.0322)(400)^2 = 5150 cd-s or lm-s/sr
- Peak candlepower: ~5150/.016 = 320,000 cd or lm/sr
- Lumen-second: ~ (5150)(4π) = 65,000 lm-s

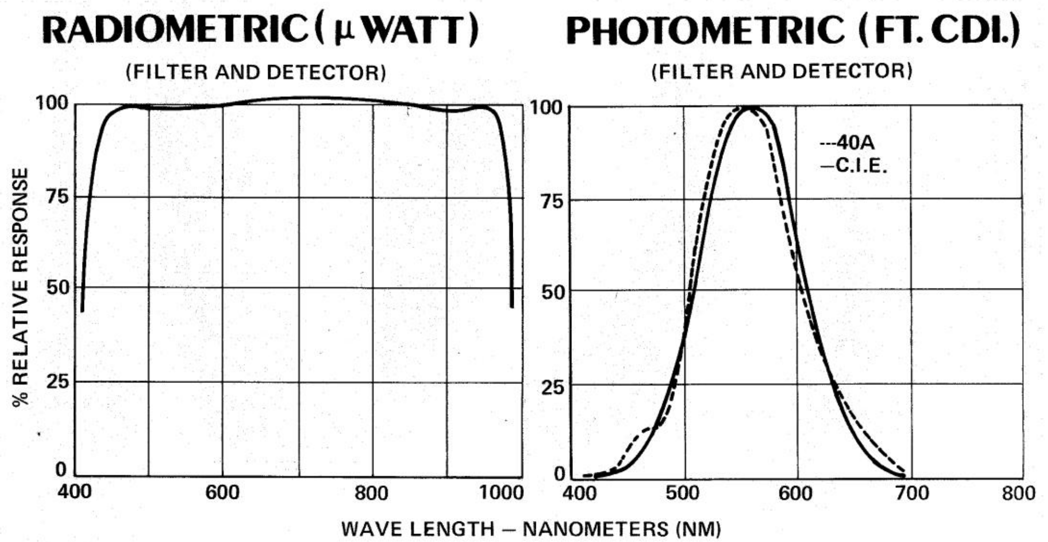
Results: Sylvania No. 2 Flashbulb

- Measured integrated illuminance: E ~ 0.0624 (lm-s)/cm^2
  - Integrated luminance: ~.0624/.000123 = 507 (lm-s)/(cm^2-sr)
  - Peak luminance: L_υ ~507/.016 = 31,700 lm/(cm^2-sr)
  - Peak flash temperature: T ~4140 deg K
- Total radiant exposure for all radiation: H ~930 μJ/cm^2
  - Integrated radiance: ~930/123 = 7.56 J/(cm^2-sr)
  - Peak radiance for all radiation: ~7.56/.016 = 473 W/(cm^2-sr)
- Radiant exposure thru H_2O: H = 365 μJ/cm^2
  - Integrated radiance through H_2O: ~365/123 = 2.97 J/(cm^2-sr)
  - Peak radiance thru H_2O: ~2.97/.016 = 185 W/(cm^2-sr)
  - Peak flash temperature: T ~4160 deg K
- Estimated retinal thermal exposures:
  - ~ 122 W/(cm^2-sr) for 3860 deg K
  - ~ 180 W/(cm^2-sr) for 4140 deg K
  - ~ 185 W/(cm^2-sr) for 4160 deg K
- Estimated & measured retinal blue light exposures:
  - Peak blue light irradiance: ~ 34/.016 = 2 mW/cm^2
  - Peak blue light radiance: .002/.000123 = 16.3 W/(cm^2-sr)
  - ~ 7.62 W/(cm^2-sr) for 3860 deg K
  - ~ 14.1 W/(cm^2-sr) for 4140 deg K
  - ~ 14.7 W/(cm^2-sr) for 4160 deg K

Summary: Sylvania No. 2 Flashbulb

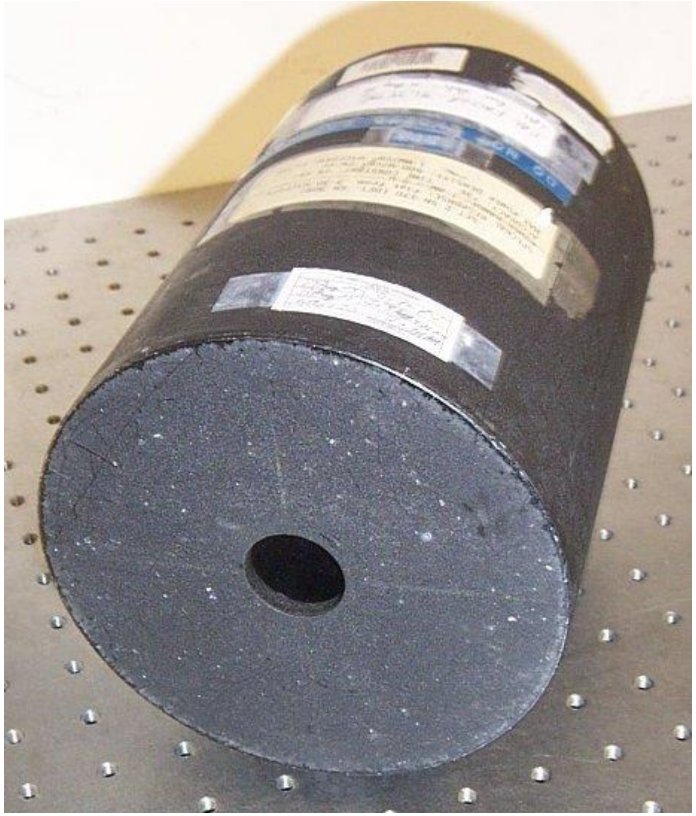
- Retinal thermal hazard evaluation:
  - Radiance thru H_2O: 185 W/(cm^2-sr)
  - Hazard: (.356)(185)/(3.2)(5) = 4.1 meters
  - 7X50 hazard distance: 28.8 meters
- Retinal blue light hazard evaluation:
  - Blue light radiance: 16.3 W/(cm^2-sr)
  - True: 16.3 < 6250 = 100/.016
  - Does not exceed the blue light MPE
- Comparing lm, W, & lm/W methods:
  - lm/W: ~7% lower *T* and required more data
  - lm: same but required more data
  - W: benchmark worked well

UDT Model 40a & 40x Mid-70's

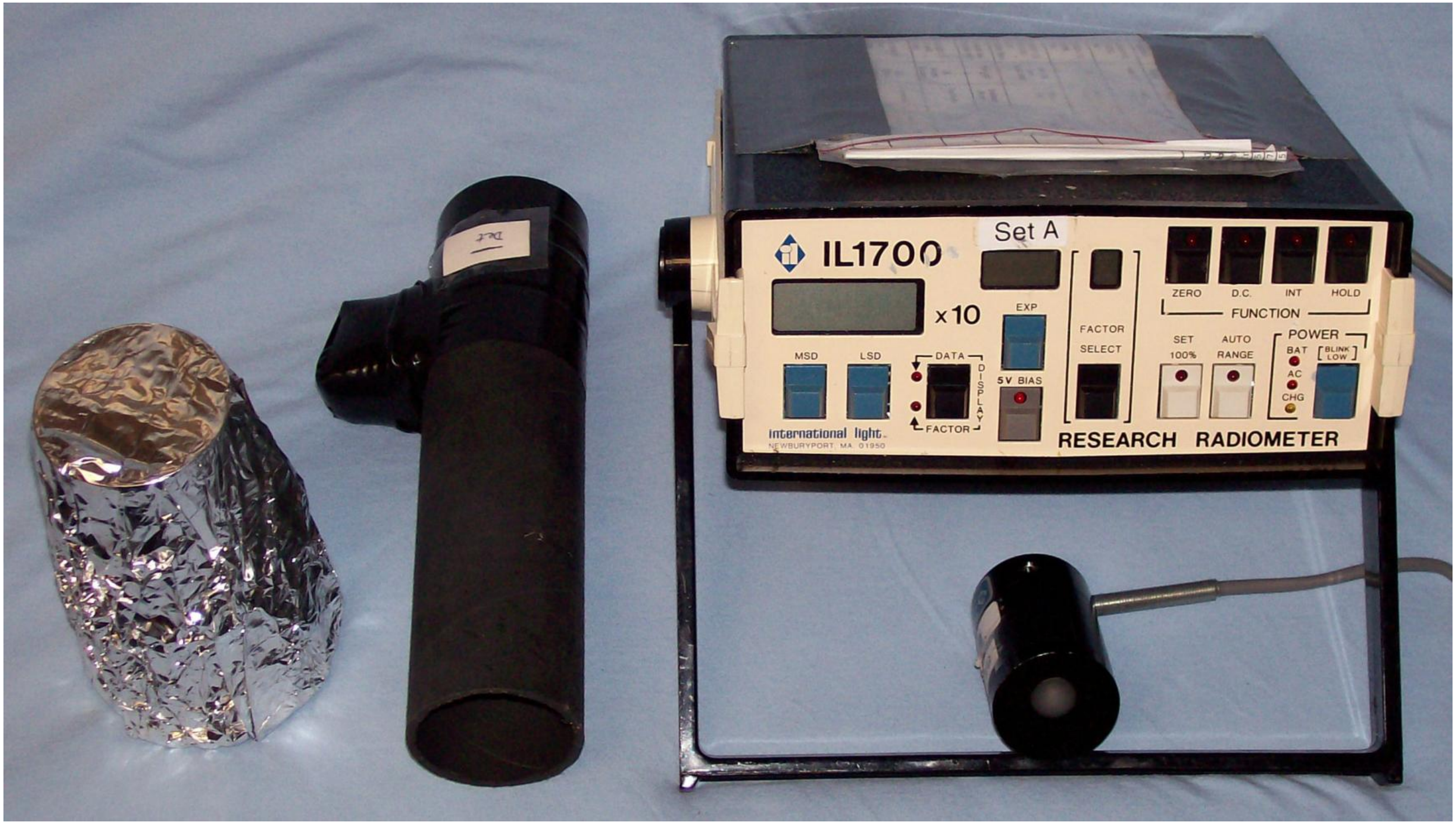


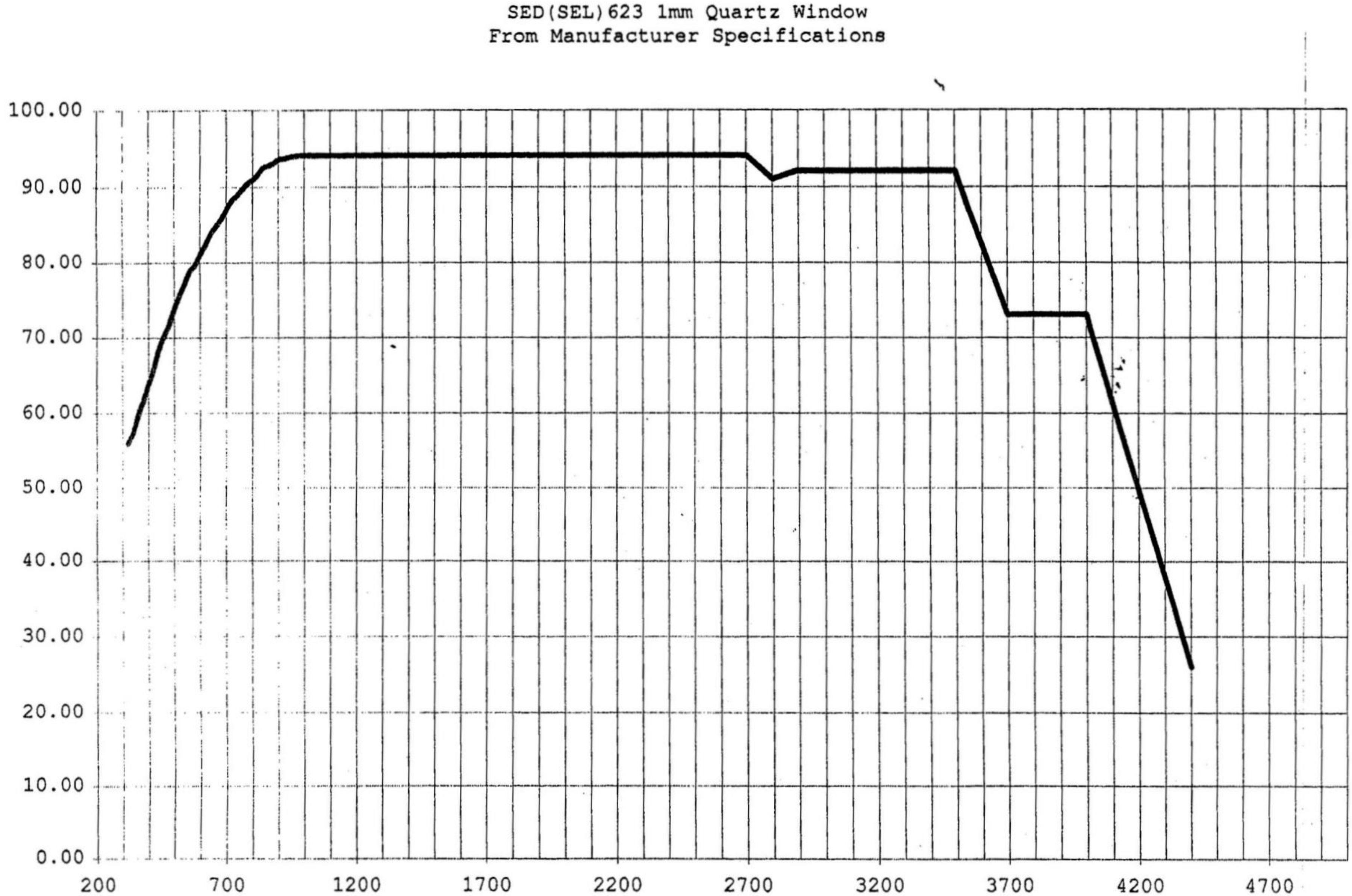
Scientech 360001 calorimeter inside isoparibol enclosure

0.3 to 30 μm, 5.08 cm^2, ~ 98 mV/W, & 14 sec



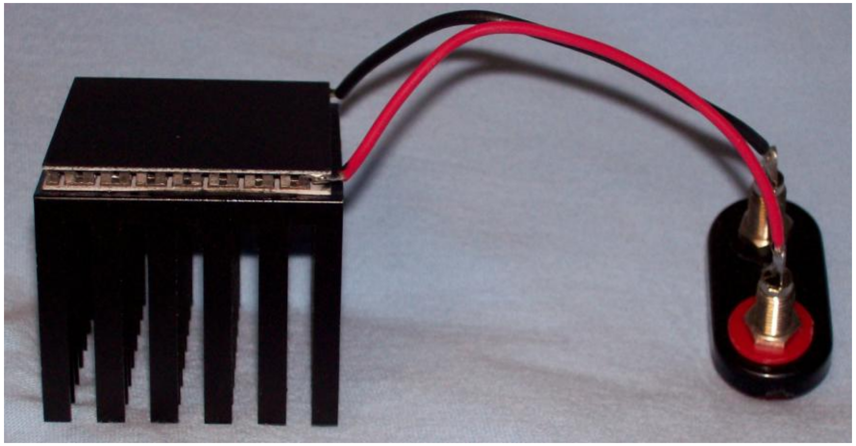
IL1700 with Broadband Detector & Hood with a 2-cm Water Filter

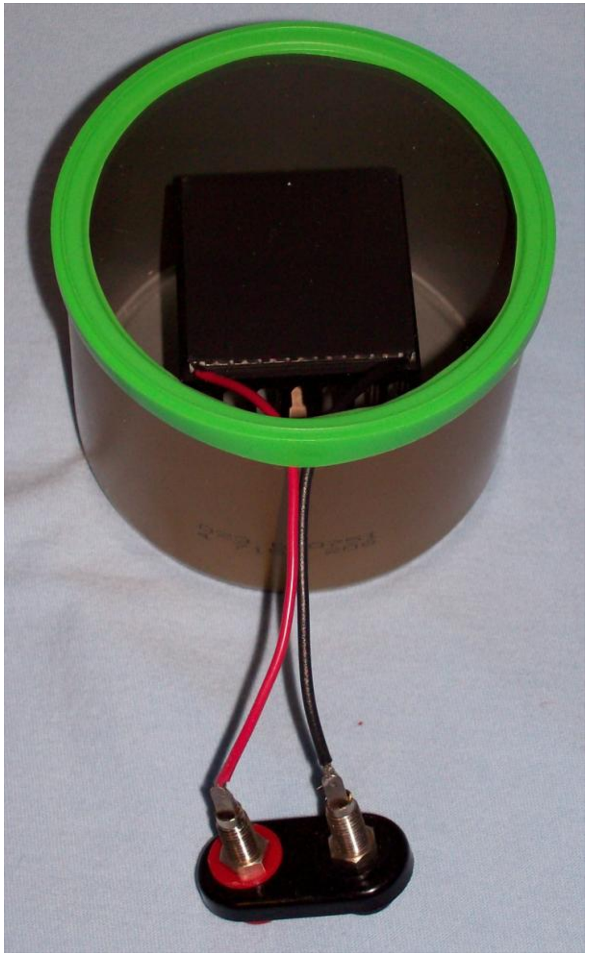




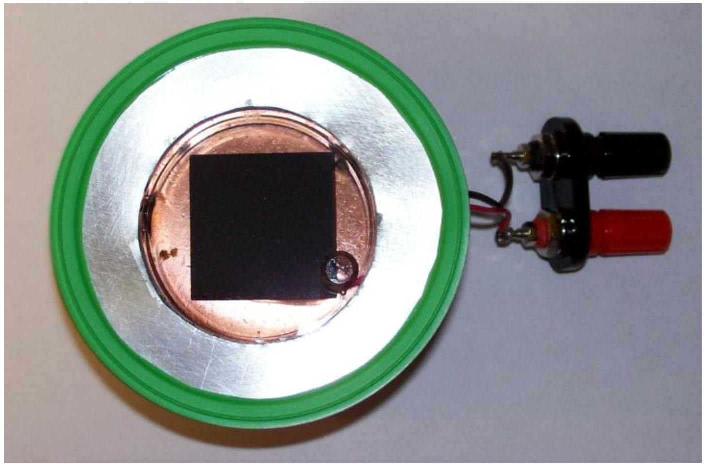
625 624 & 623 computer

Practical High Irradiance & Wide-Angle Calorimeter





Wide-Angle Water Calorimeter



Any Questions?

TERRY L. LYON
Physicist/Master Consultant
Laser/Optical Radiation Program

USA Center for Health Promotion & Preventive Medicine
ATTN: MCHB-TS-OLO, 5158 Blackhawk Road
Aberdeen Proving Ground, MD 21010-5403
(410) 436-5069/3932
Terry.Lyon@us.army.mil

USACHPPM

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