UV Measurement For Formulators

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Anything that you can measure, you have a better chance of controlling. Things that you do not measure become the cause of mysterious problems

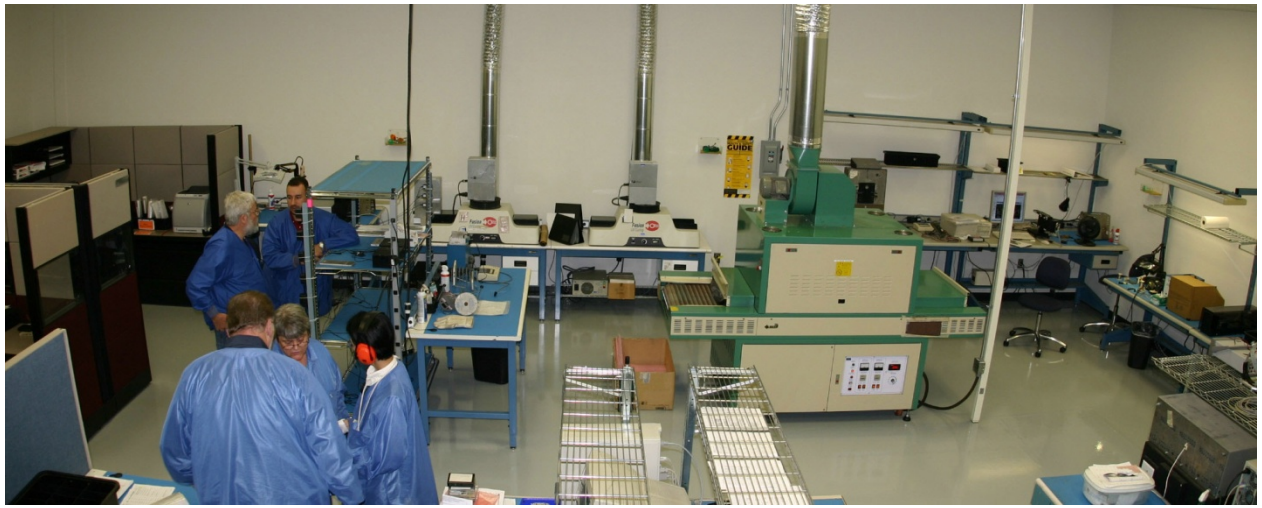
- Larry Goldberg, Beta Industries

Not everything that counts can be counted, and not everything that can be counted counts.

- Albert Einstein

EIT Facilities

EIT Facilities



UV Measurement Needs

End-Users

- Is the process running consistently?
- Is the process running within the spec?
- Troubleshooting
- Record keeping/Traceability

- Tend to be ***relative*** measurements.

Formulators/Suppliers

- Establish a specification
- Determine a process window
- Optimize a process
- Help customers troubleshoot

- Tend to be ***absolute*** measurements.

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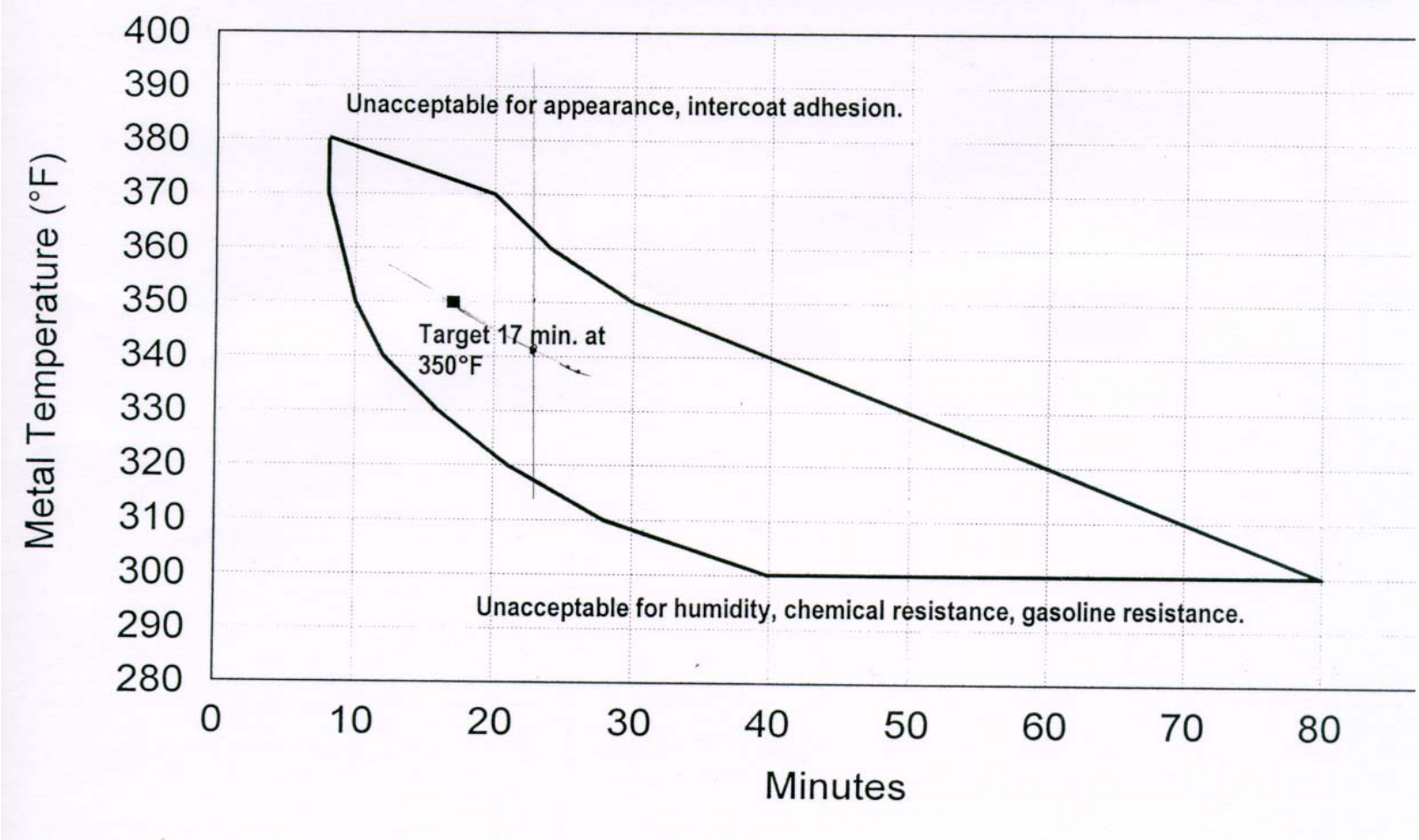
Communication

Powder Cure Requirements

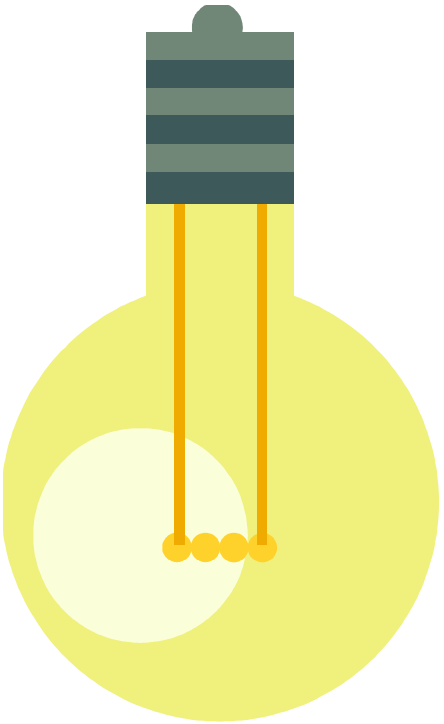
Manufacturer's Recommended Specifications



Content

- Principles of UV Measurement
- What to measure
- How to measure
- Role of UV Sources
- Specification details
- Instrument/User error
- Instrument selection

Practical Advice or Numerical Examples



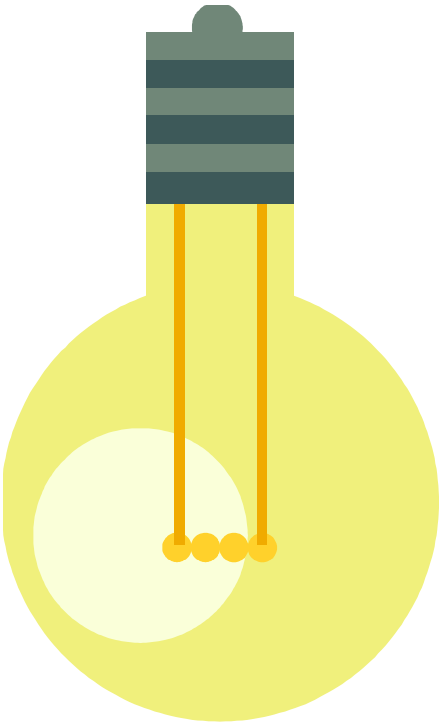
Wavelength

Peak Irradiance

Energy Density

Terms / Units

Wavelength (“light”)	=	Nanometers
Peak Irradiance (“intensity”)	=	Watts / cm^2 (“watts”)
Energy Density (“dose”)	=	Joules / cm^2 (“joules”)



Wavelength

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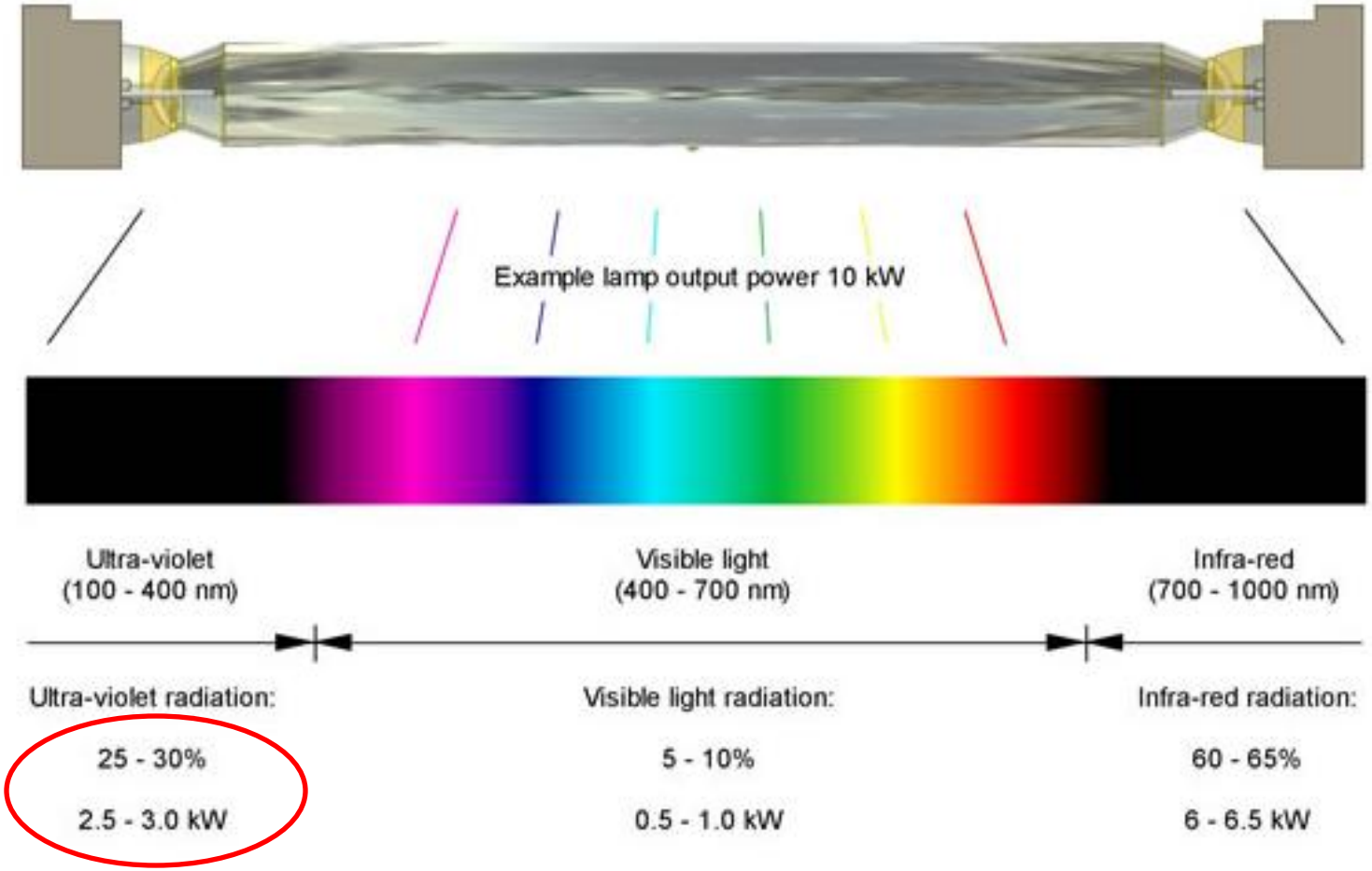
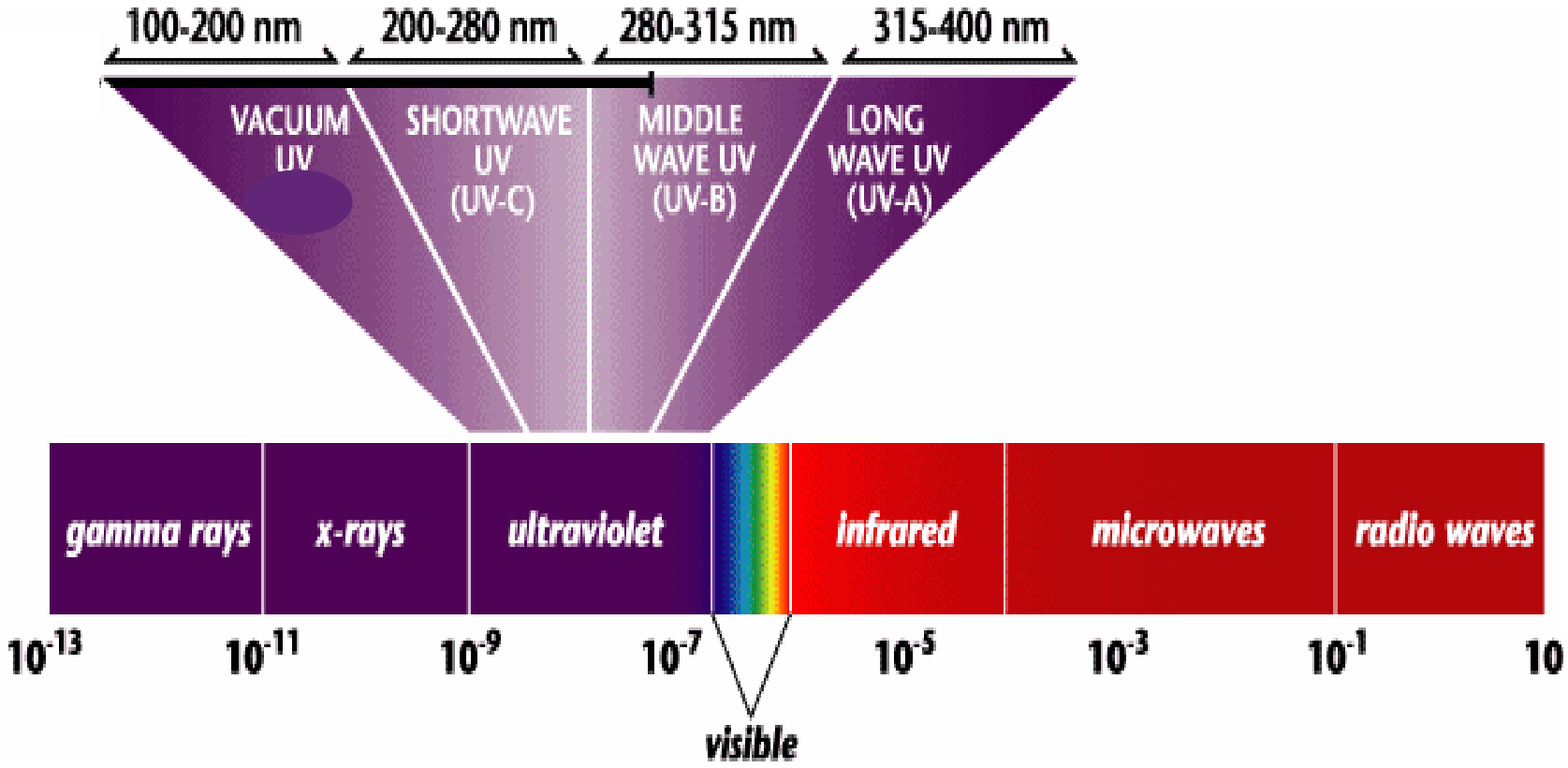
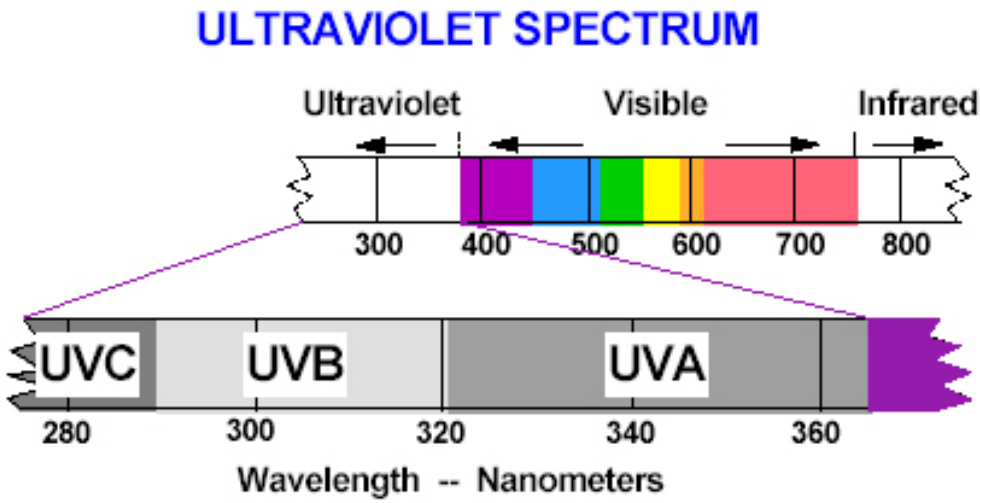

Example lamp output power 10 kW
Ultra-violet
(100 - 400 nm)
Visible light
(400 - 700 nm)
Infra-red
(700 - 1000 nm)
Ultra-violet radiation:
25 - 30%
2.5 - 3.0 kW
Visible light radiation:
5 - 10%
0.5 - 1.0 kW
Infra-red radiation:
60 - 65%
6 - 6.5 kW

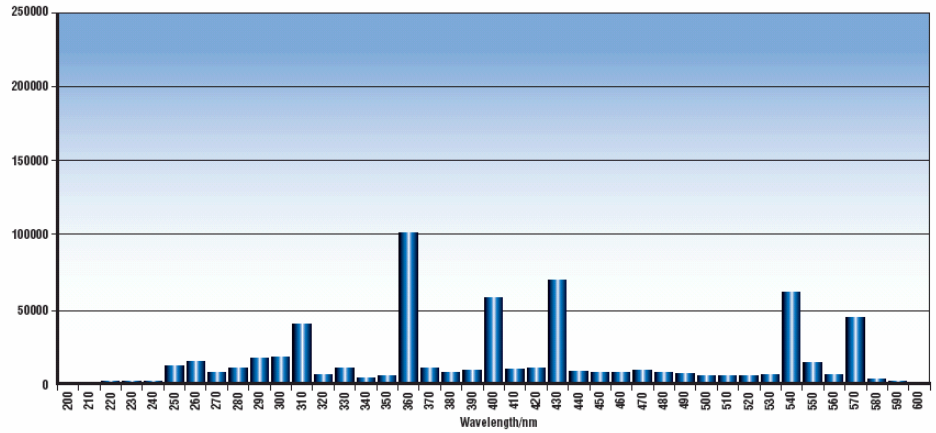
λ = Wavelength

For UV Curing **~ 200 nm** through **~ 400 nm**

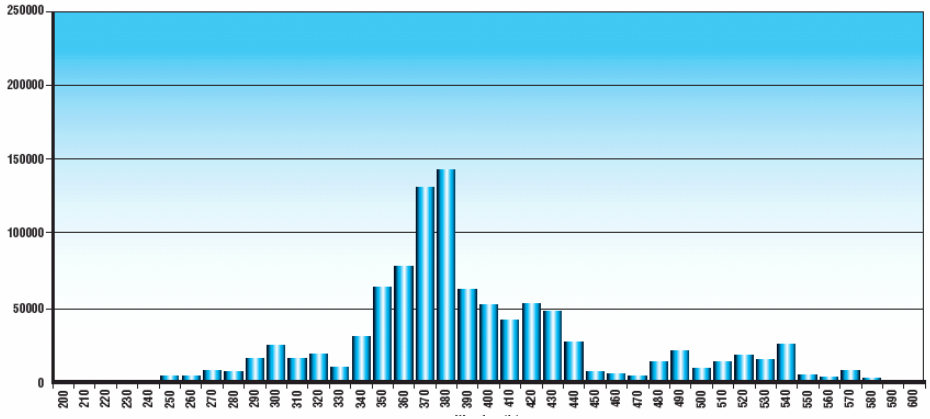




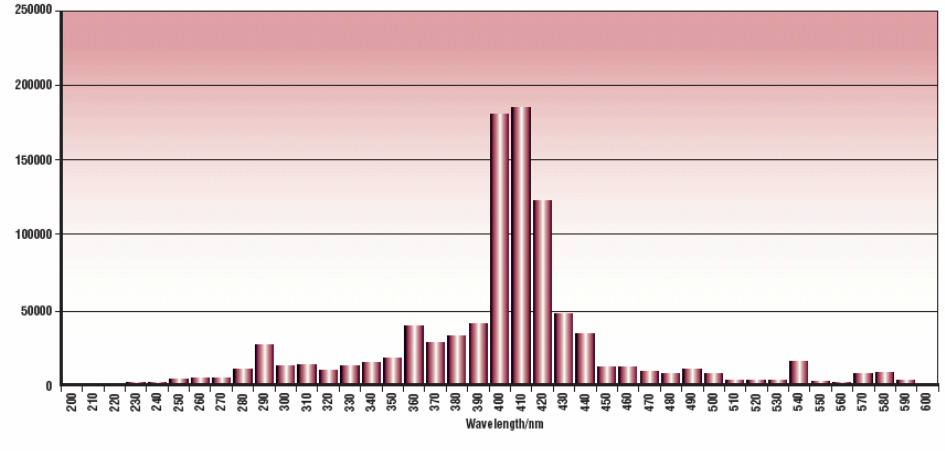
- **UVA:** 320-390nm Long-wave, black light, UV Inks,
- **UVB**: 280-320nm Middle-wave, erythemal response, medical applications – helps provide durability.
- **UVC**: 200-280nm Short-wave, germicidal (254 nm), absorbed by DNA, clear coats, surface cure, tack, chemical or scratch resistance
- **UVV**: 395-445nm Ultra Long-wave, wood products, opaques/whites, thick coats, adhesion, depth of cure
- **VUV** (Vacuum UV): 100-200 nm, Ozone < 200 nm



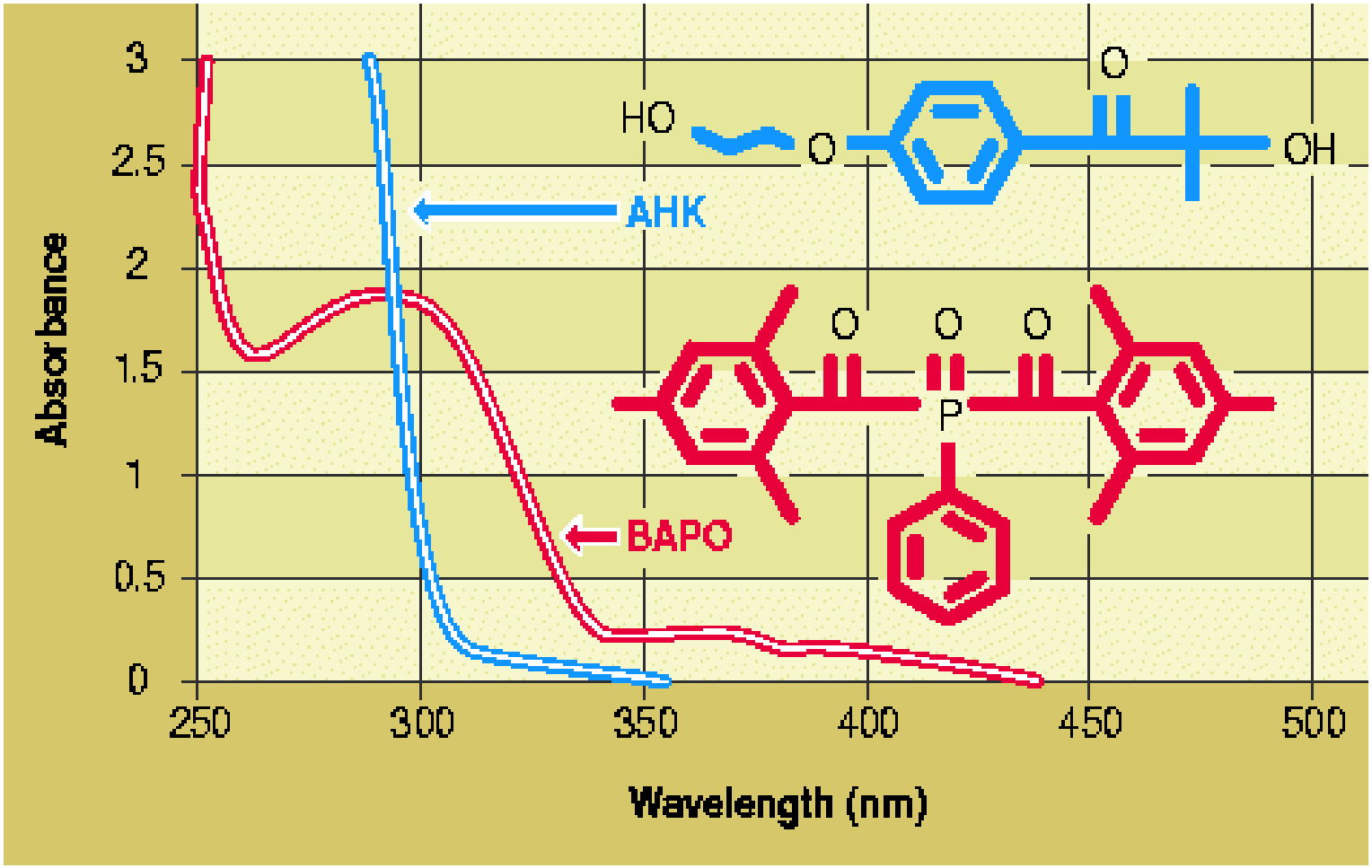
Mercury Lamp Spectra
“H” Lamp



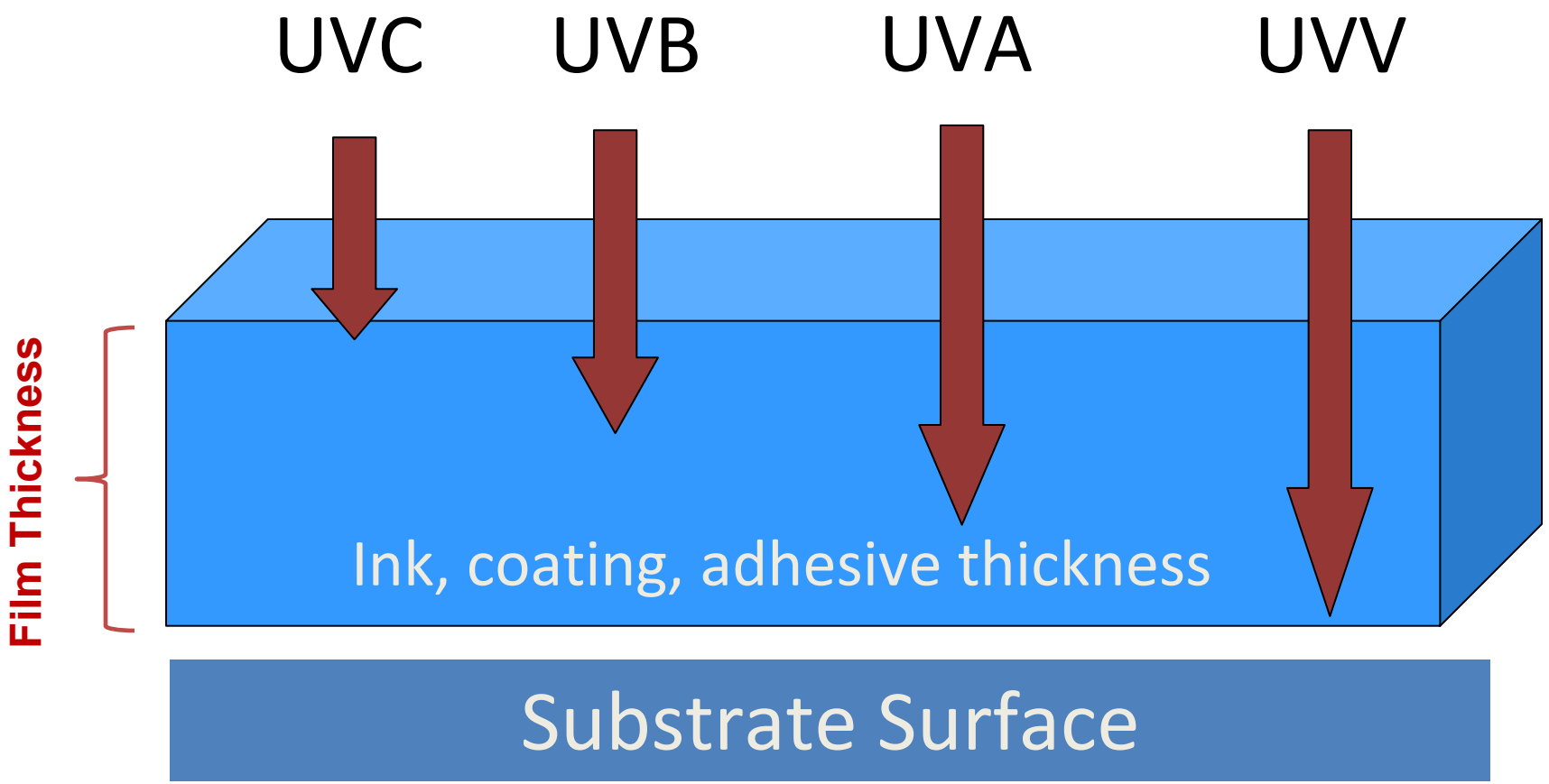
Iron Additive Lamp Spectra
“D” Lamp

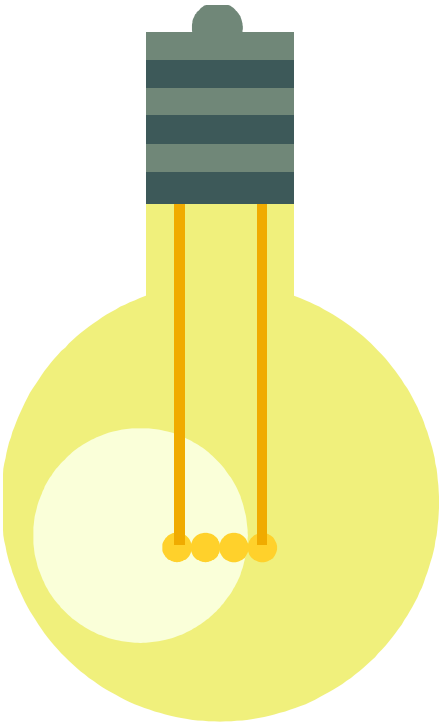


Gallium Additive Lamp Spectra
“V” Lamp


Absorbance
3
2.5
2
1.5
1
0.5
0
250
300
350
400
450
500
Wavelength (nm)
AHK
BAPO
HO
O
O
OH
O
O
O
P

UV Relative Penetration





Wavelength

Peak Irradiance

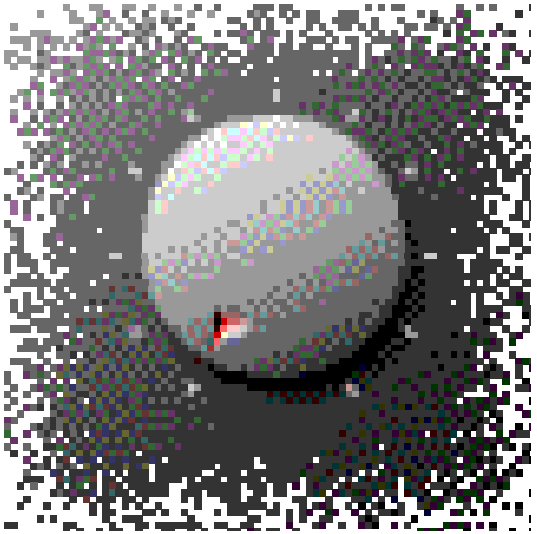
Energy Density

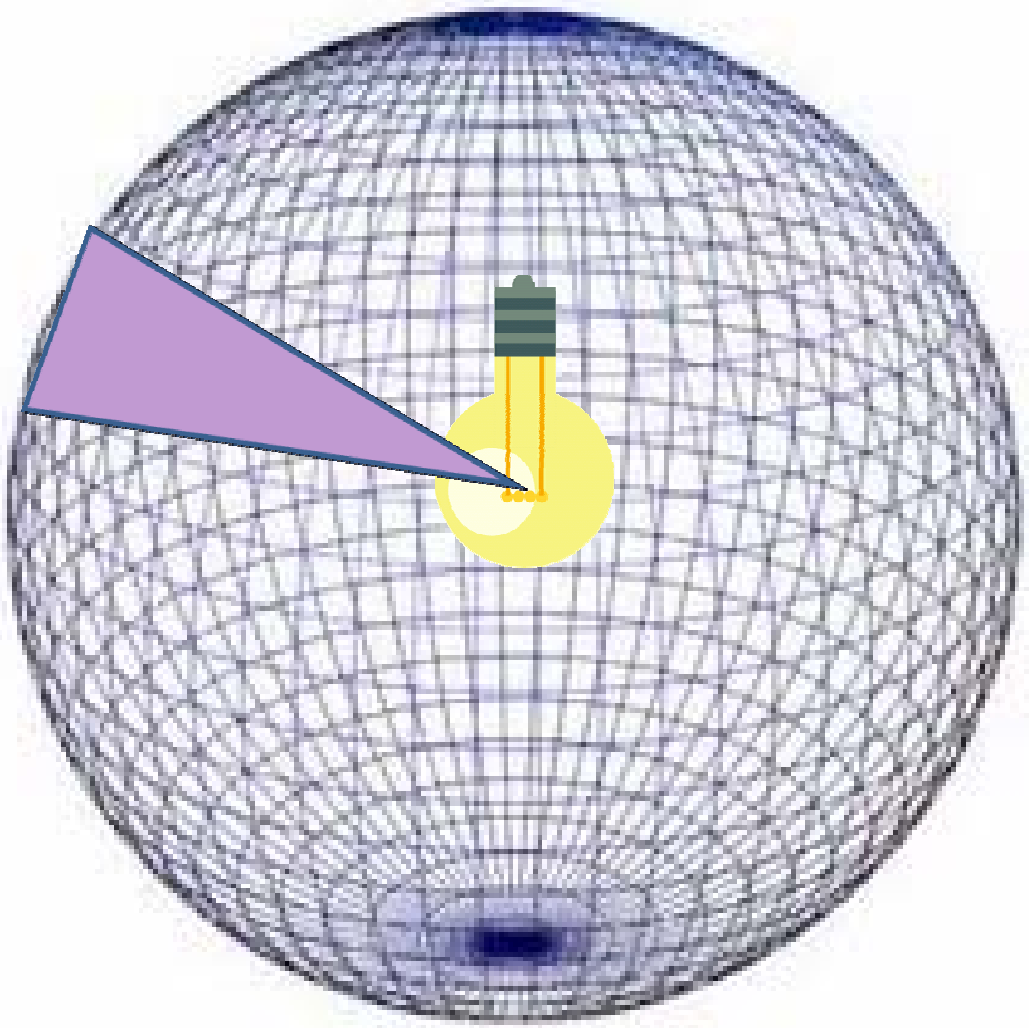
UV Lamp “Power” Designations

Describing a lamp is not the same as describing it’s output.

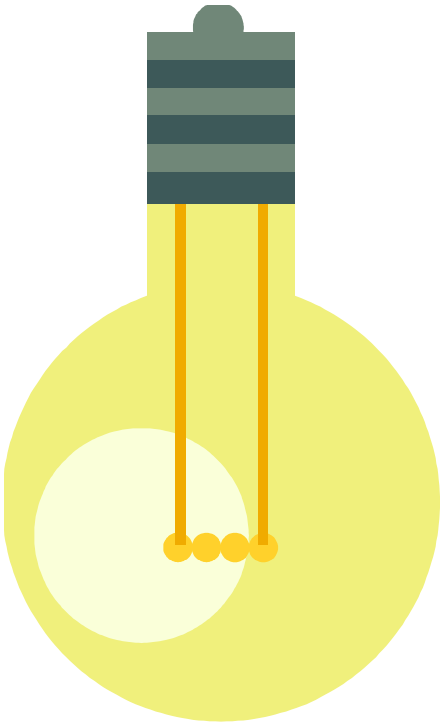
A 600 watt/inch lamp does not produce 600 watts/inch it consumes it.

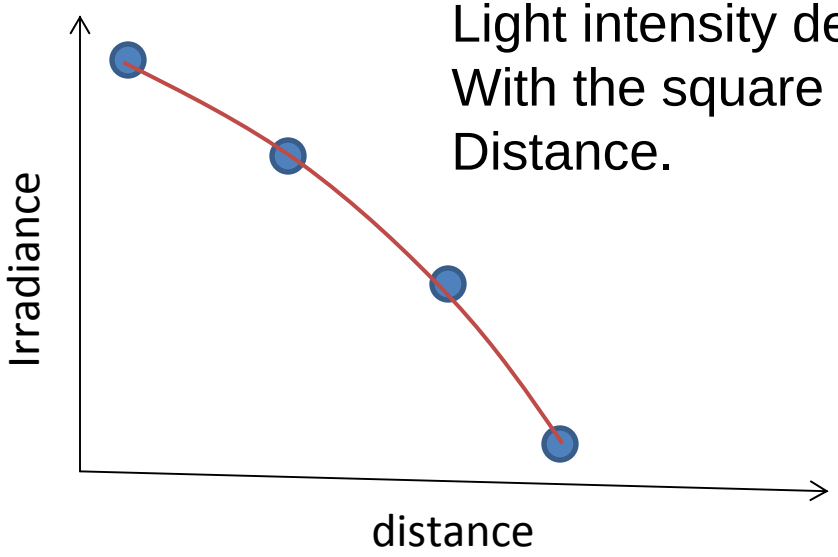
This is a measure of power applied ***to*** the “bulb” (the actual power consumption may be much higher still!)



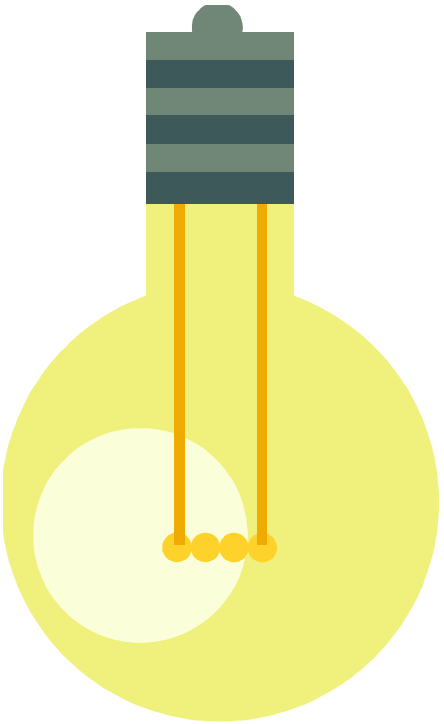


surface area = $4\pi r^2$





Light intensity decreases
With the square of the
Distance.



Wavelength

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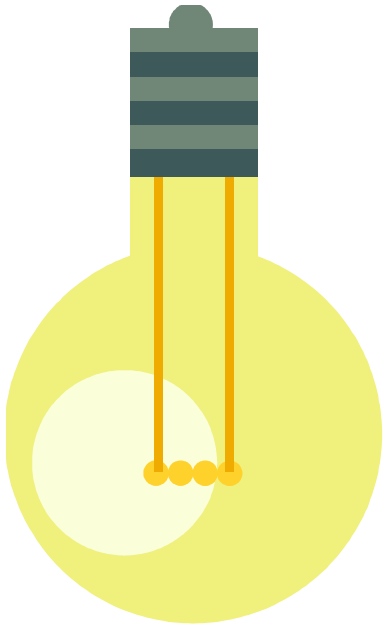
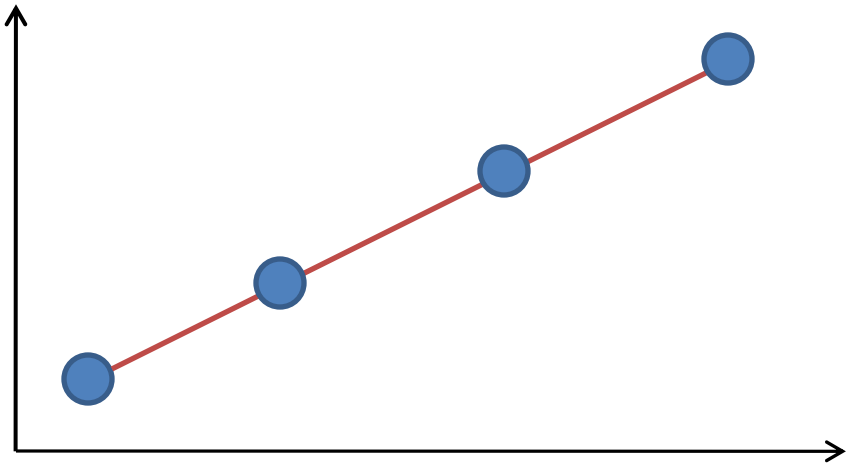



3DCure™
SENSOR: 00998



Energy Density ↔ Irradiance

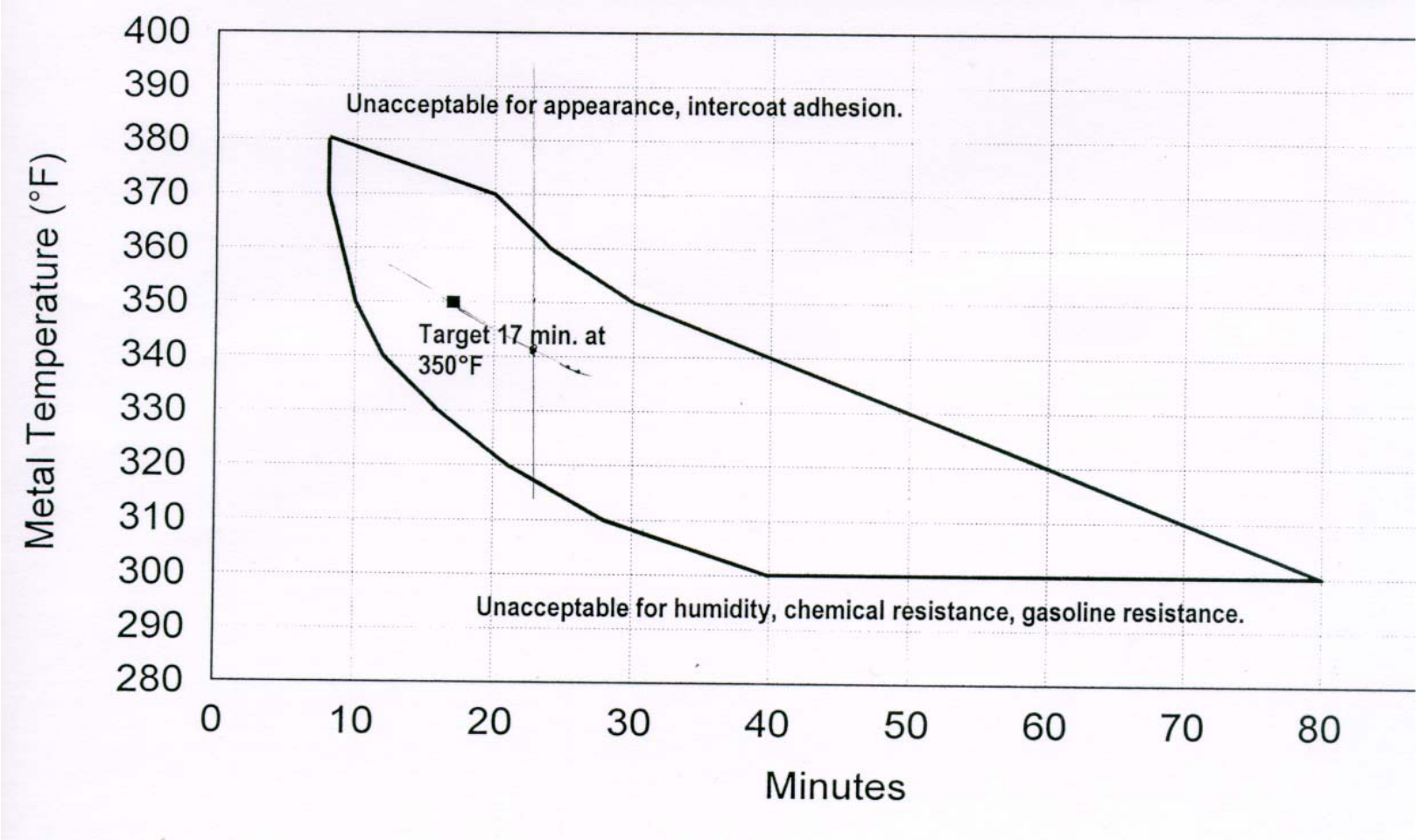
- Irradiance does not change with time.

- However both time and irradiance affect energy density

- Time can be the length of time a fixed object is exposed to a part, the time exposure of a moving part (e.g. a conveyorized part), or a moving lamp.

Powder Cure Requirements

Manufacturer's Recommended Specifications



Poor Specifications

- Nordson Gallium Lamp
- “5 Seconds under Mercury Lamp”
- “5 Seconds under a 600W/inch lamp”
- “5 Seconds under a Fusion H lamp”
- “Expose to Mercury Lamp at 10 fpm”

Not much better

- Mercury Lamp – 5 Joules
- Fusion D lamp – 3 Watts
- American Ultraviolet Hg Lamp – 3”

Getting Better

- Fusion V Lamp – 1200 mW/cm2 / 2100 mJ/cm2

Good Specification

- Nordson Iron Additive Lamp, UVA = 1100 mw/cm2, 2100 mJ/cm2

Proper Specification

- Fusion V lamp, 600W/in @ 100%

Band	Irradiance (mw/cm2)	Energy Density (mJ/cm2)
UVA	1100	2100
UVB	1500	2600
UVC	360	450

- Measured with EIT PowerPuck II @ 2.5” from lamp face.

A Reasonable UV Cure Specification:

1. The peak irradiance at relevant wavelengths
2. The energy density requirement at the same wavelengths
3. The instrument to be used for this measurement
4. The type of lamp (e.g. mercury, iron additive)

Relevant ?

1. Line speed
2. Distance from the lamp
3. Lamp manufacturer
4. Reflector type
5. Temperature
6. Material thickness

Sample Specification

- Coating thickness 1.0 to 1.5 mils
- Cured with a mercury lamp
- UV Readings EIT PowerPuck II

	Irradiance	Energy Density
UVA	2259 mw/cm^2	2908 mJ/cm^2
UVB	506 mw/cm^2	696 mJ/cm^2
UVC	57 mw/cm^2	75 mJ/cm^2
UVV	969 mw/cm^2	1275 mJ/cm^2

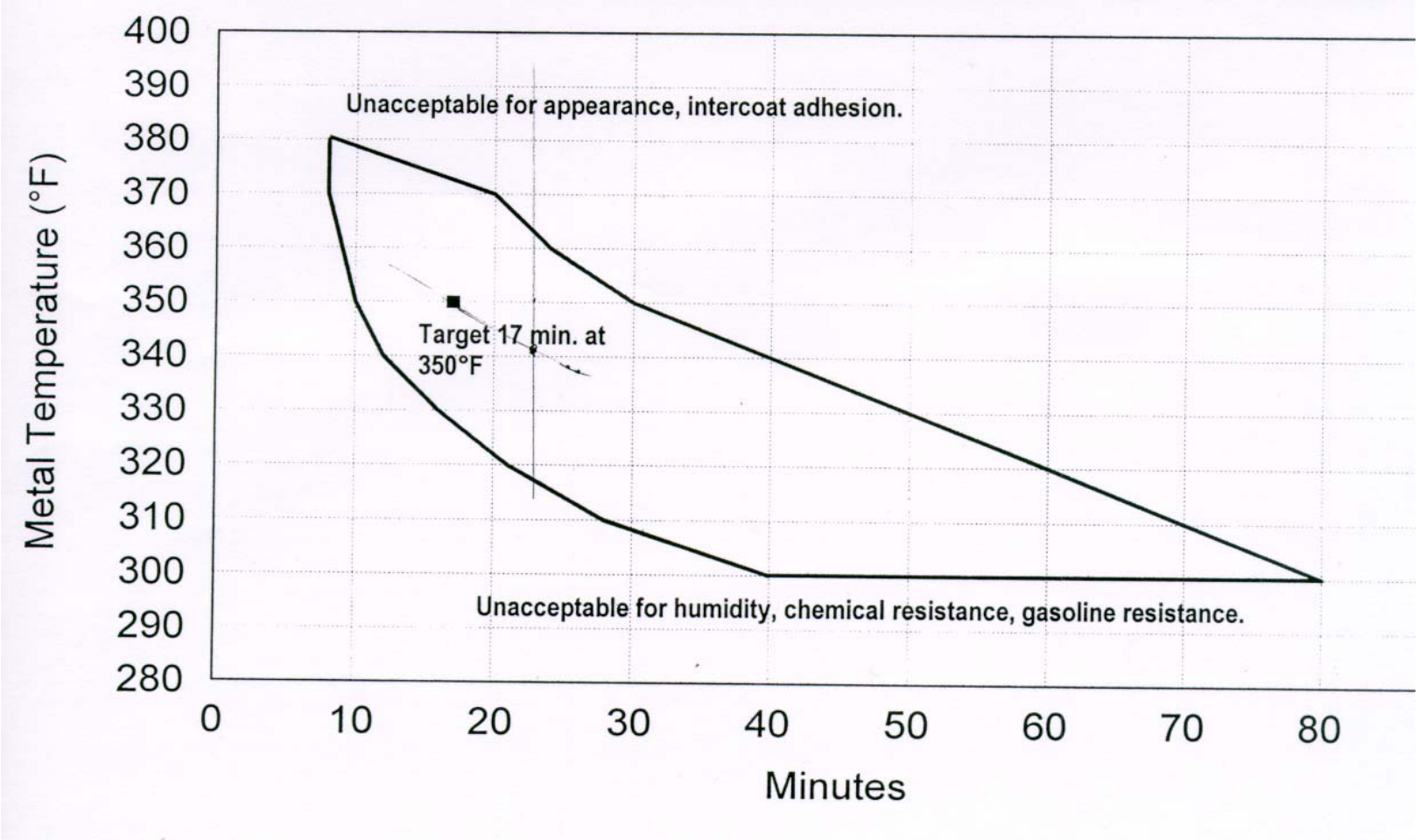
	J/CM2	W/CM2
UVA	2.908	2.259
UVB	0.696	0.506
UVC	0.075	0.057
UVV	1.275	0.969

RUN

Bulb Type & Focus Reminder

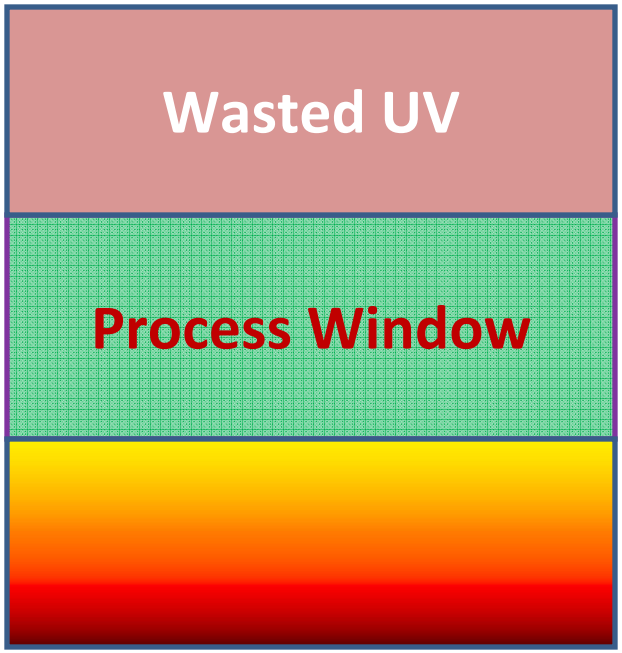
Powder Cure Requirements

Manufacturer's Recommended Specifications



Optimization

- Minimum irradiance
  - Lower lamp power
  - Increase distance
- Minimum energy density
  - Less time
  - Faster line speed
- Find point of failure?

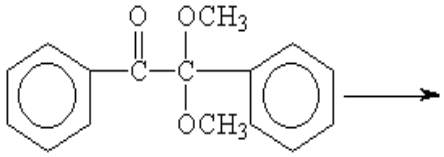


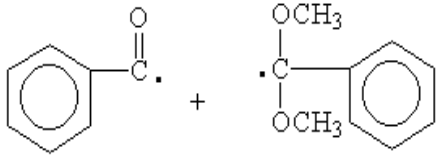

Jiffy Pop

Temperature

Time

Cleavage Type Initiator:

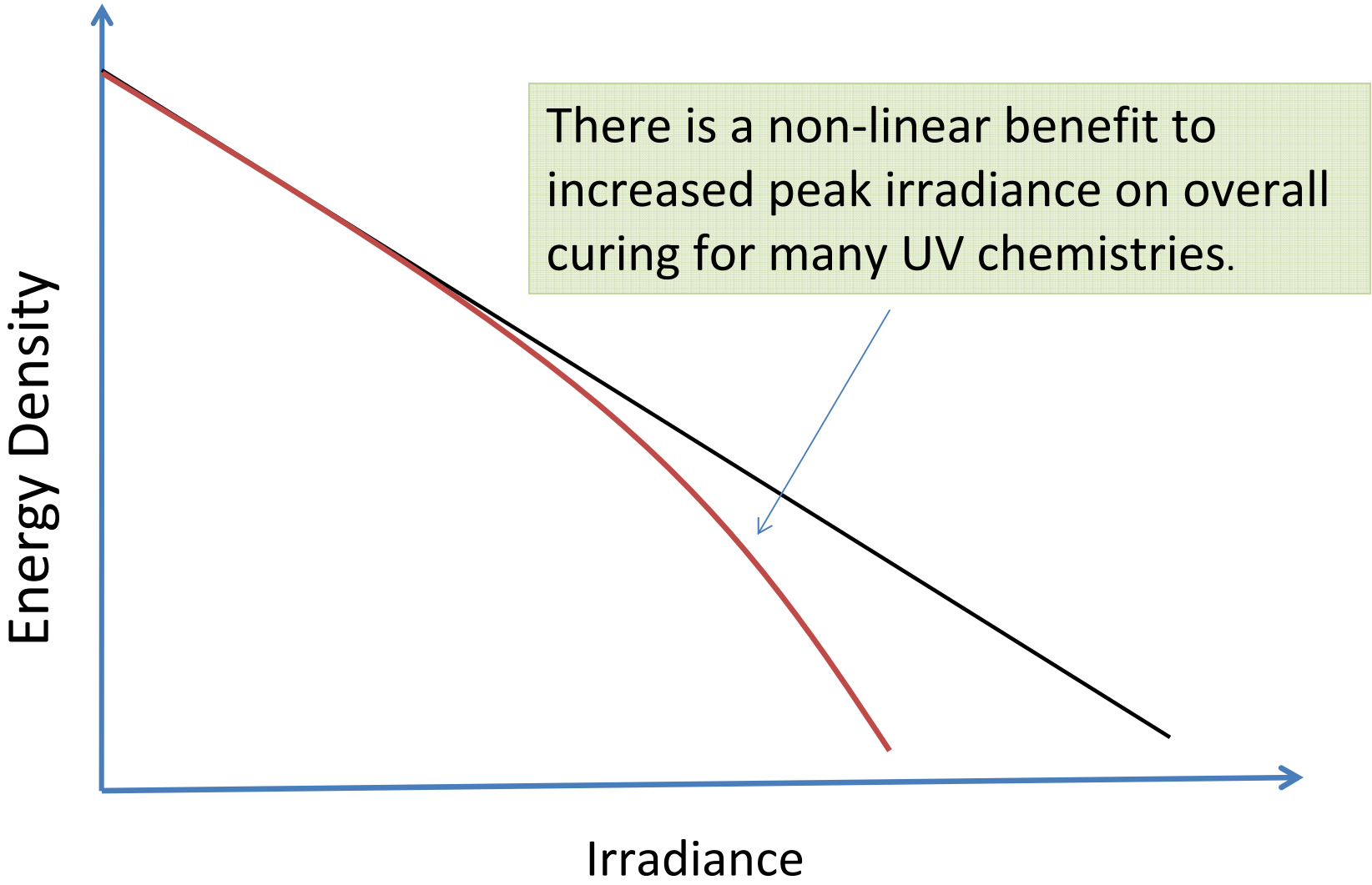




Wavelength

Energy

Time


There is a non-linear benefit to increased peak irradiance on overall curing for many UV chemistries.
Energy Density
Irradiance

High Peak Irradiance
Automotive Lighting Comparison

Low Peak Irradiance

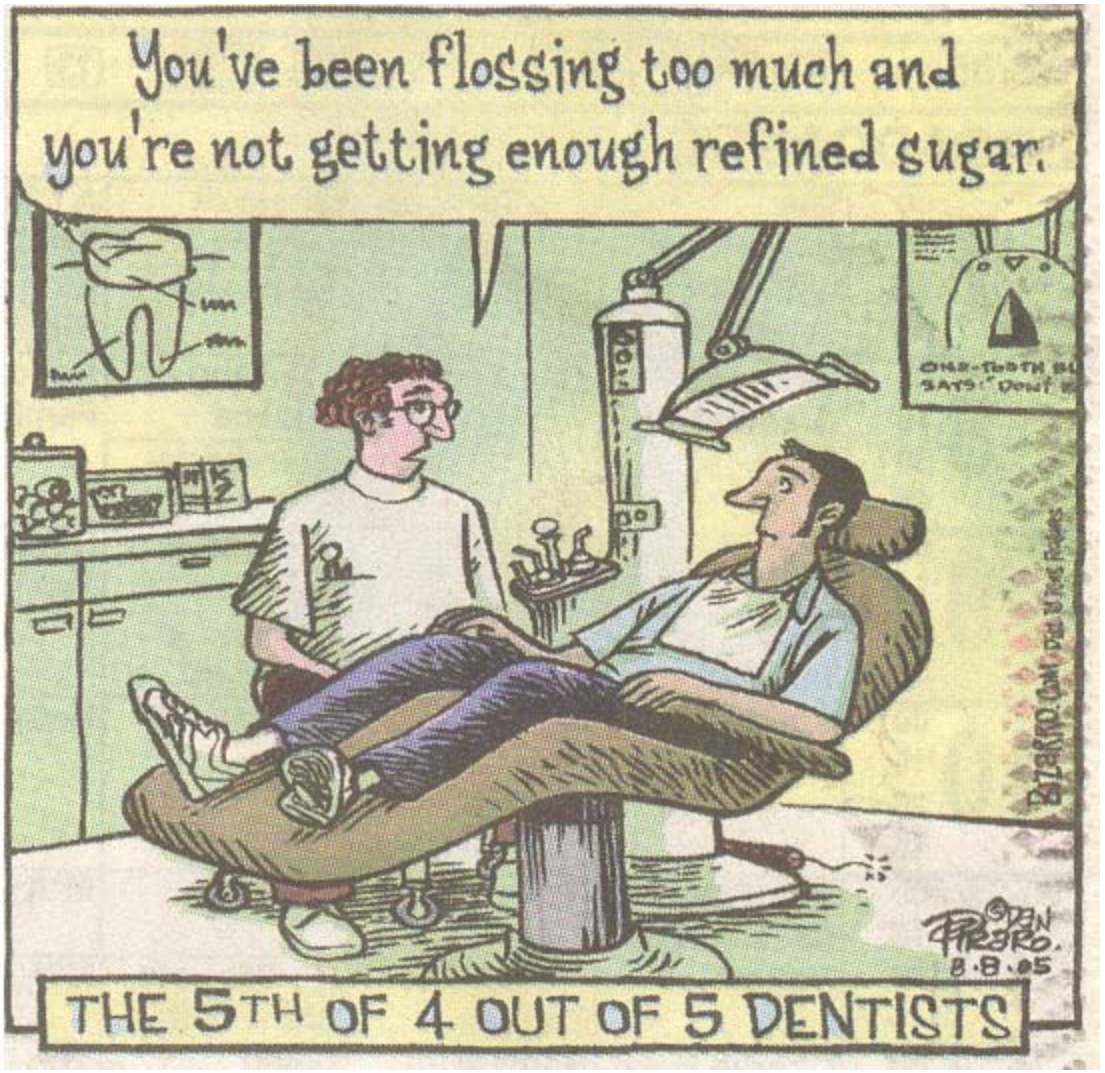
- 10 x 600 W/in lamps
- 6-8 total Joules UV

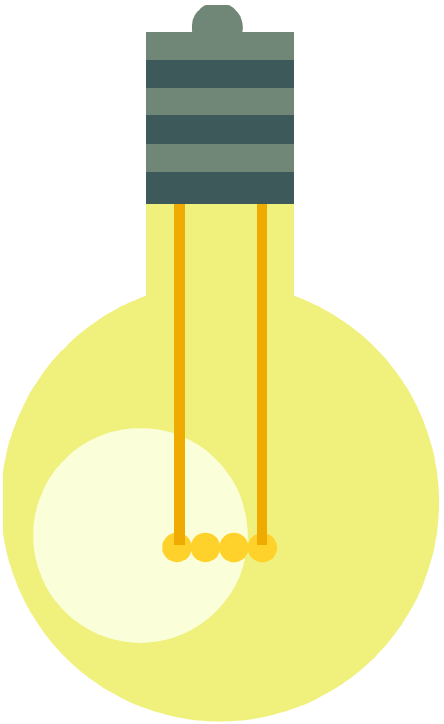
High Peak Irradiance

- 1 robot 600W lamp
- 2.5 total Joules UV

Coating: Red Spot UVT-200

Sources of Measurement Error



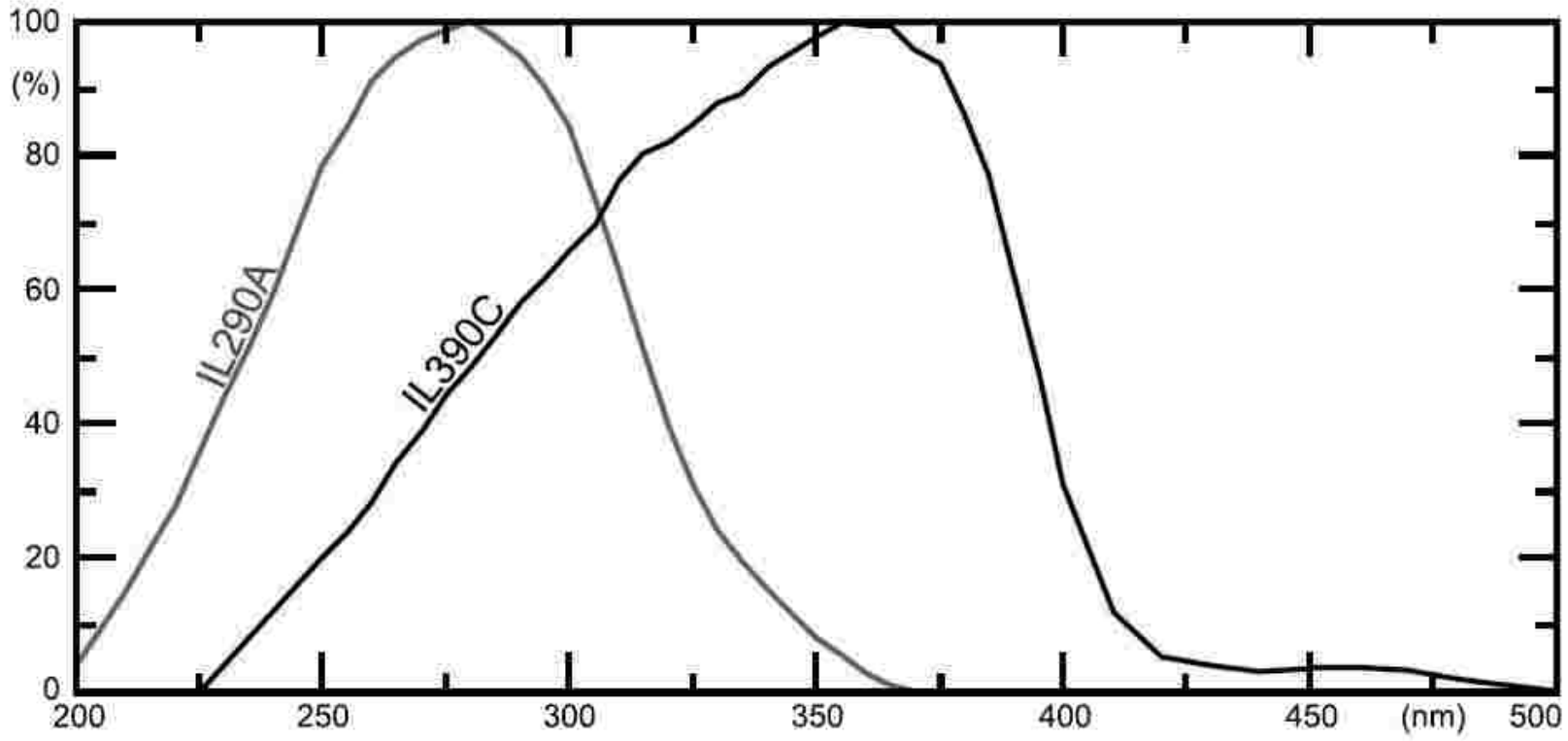


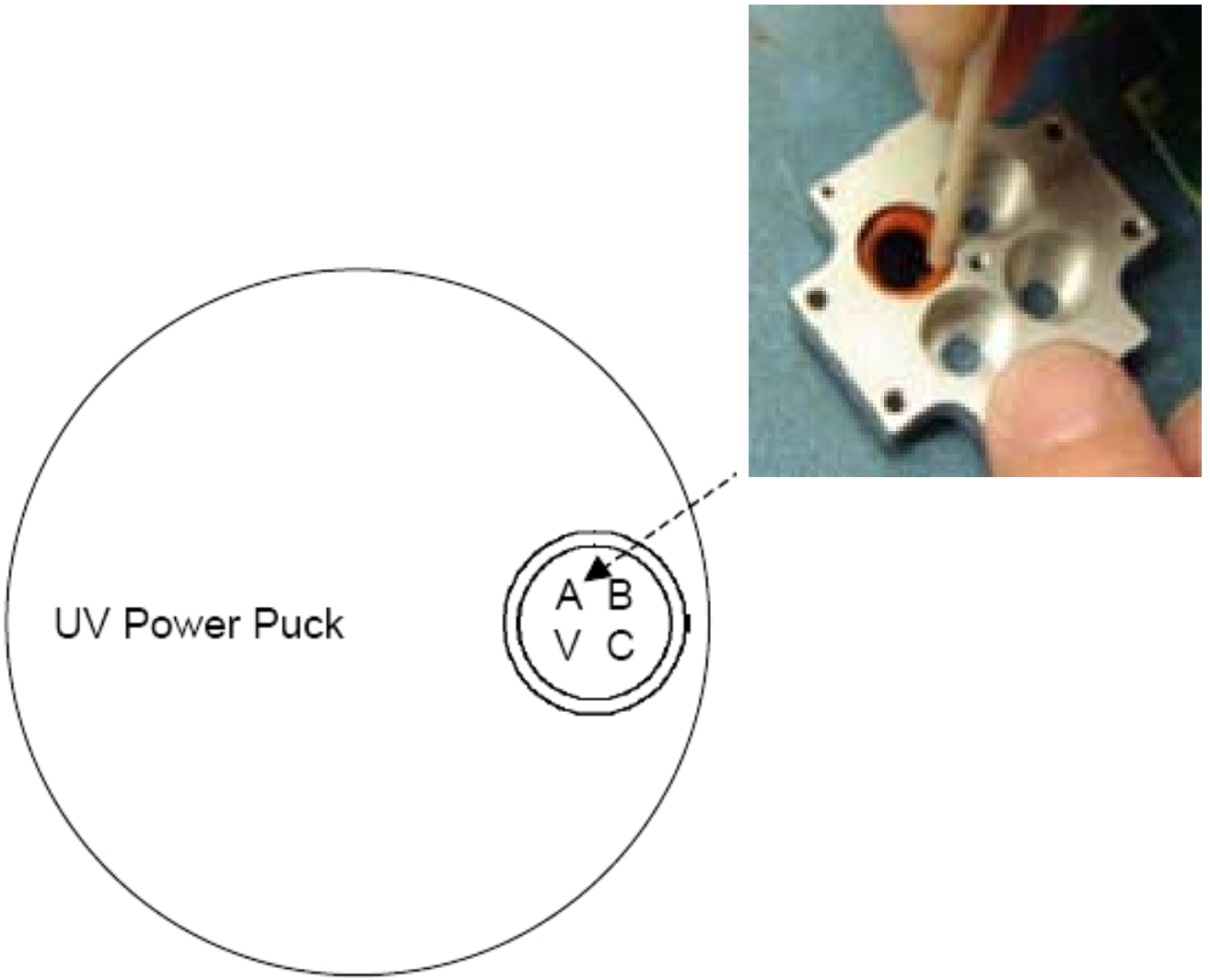
Wavelength

Peak Irradiance

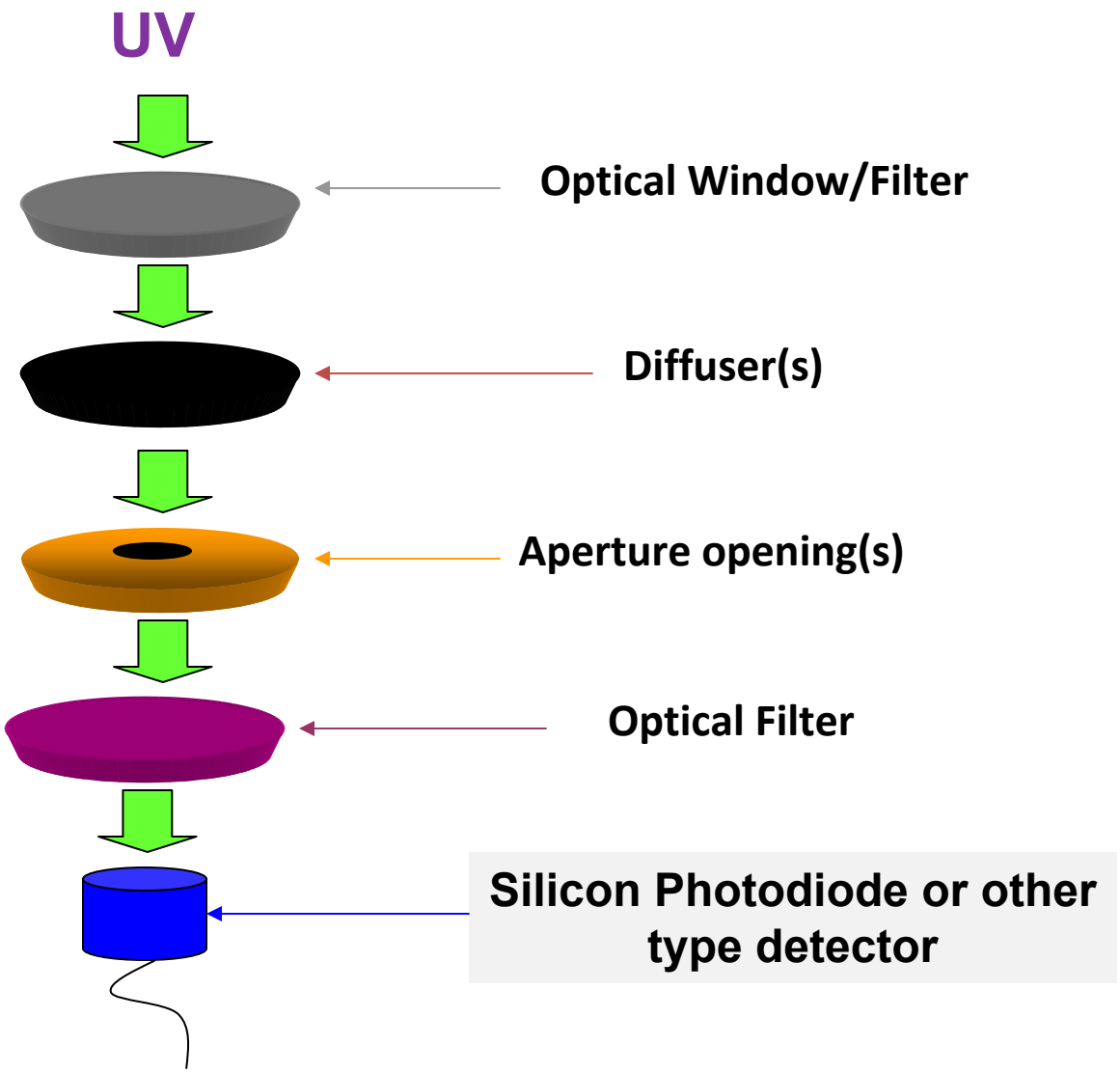
Energy Density

Single Broadband Instrument

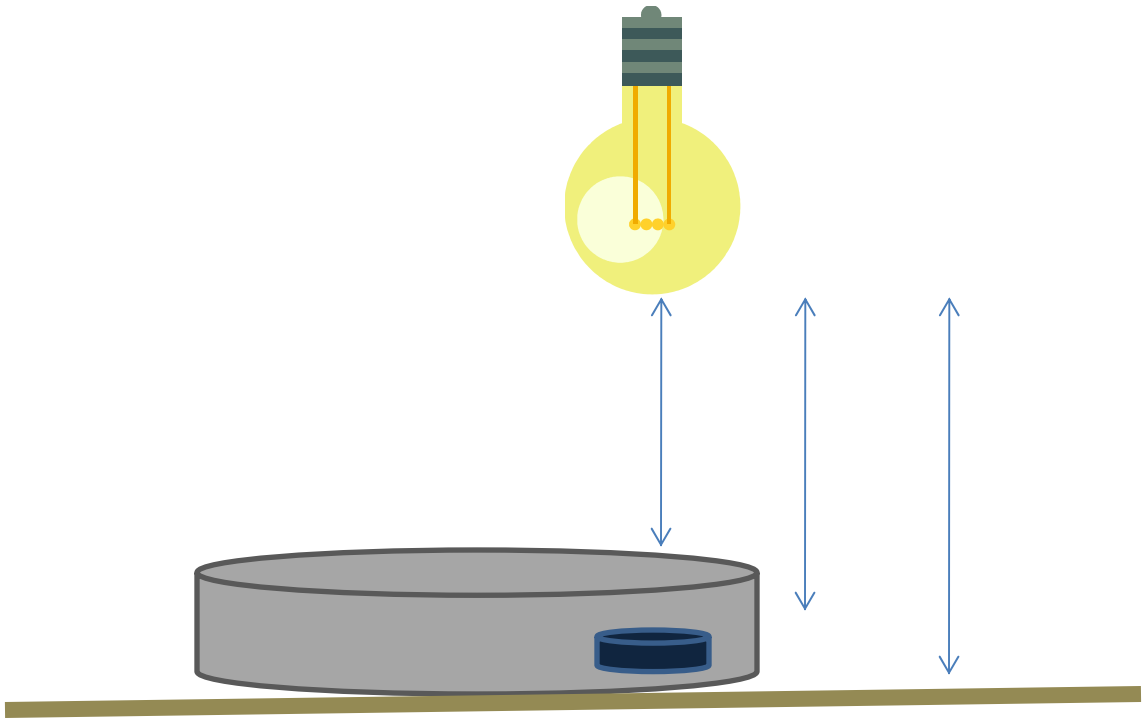



UV Power Puck
A B
V C

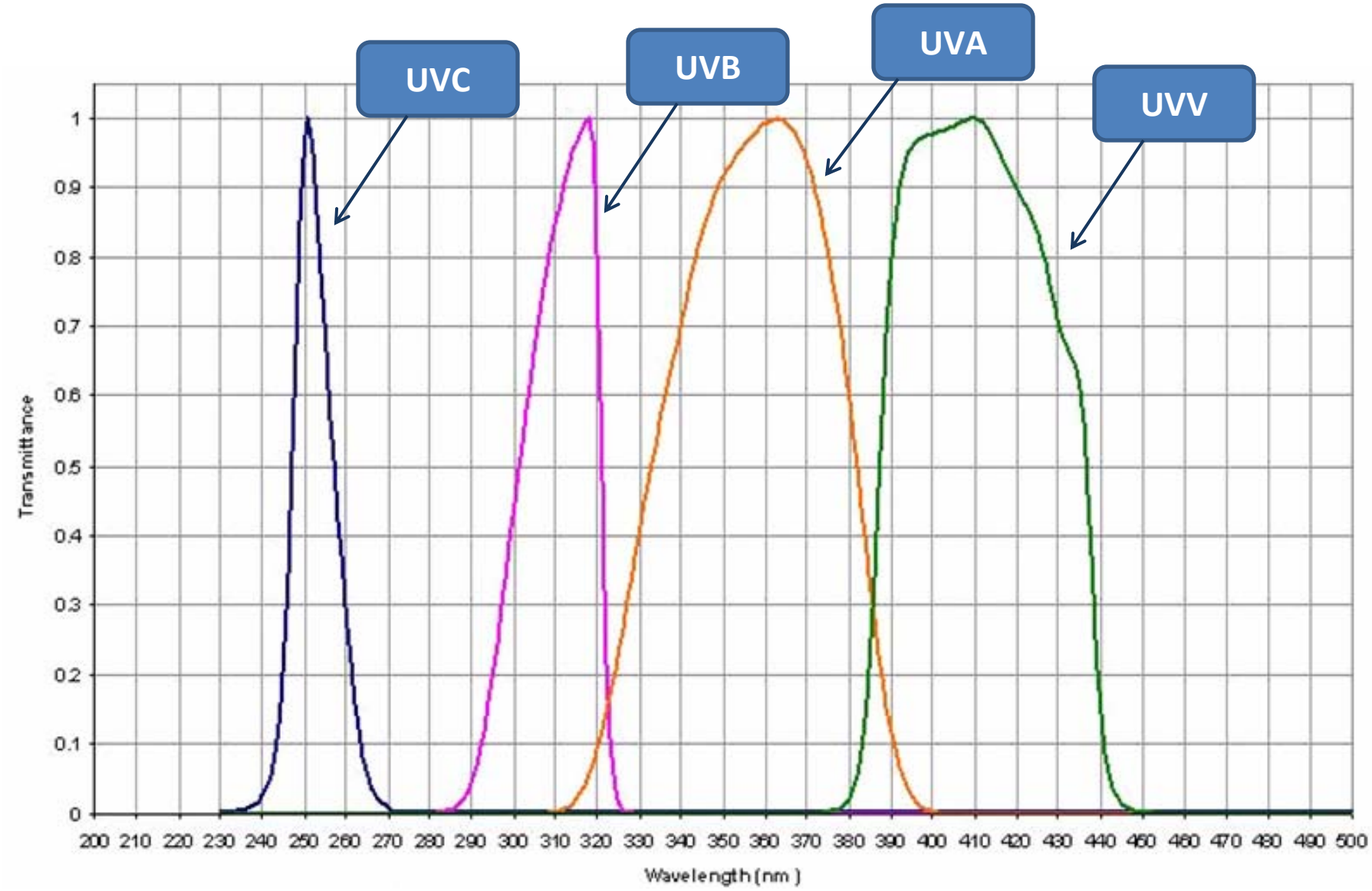
Optics Designs



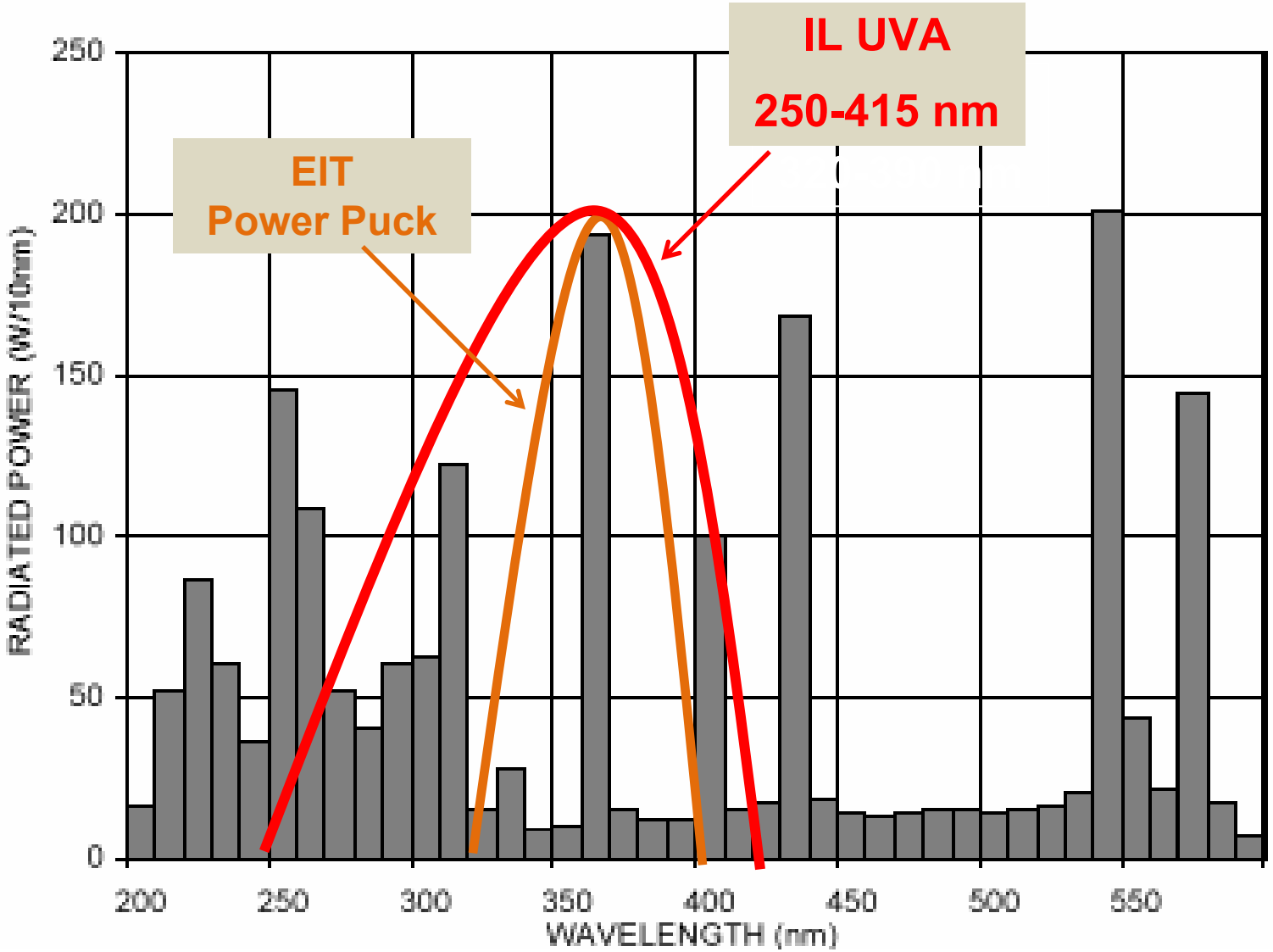
Note the location of the sensor versus the location of the part.



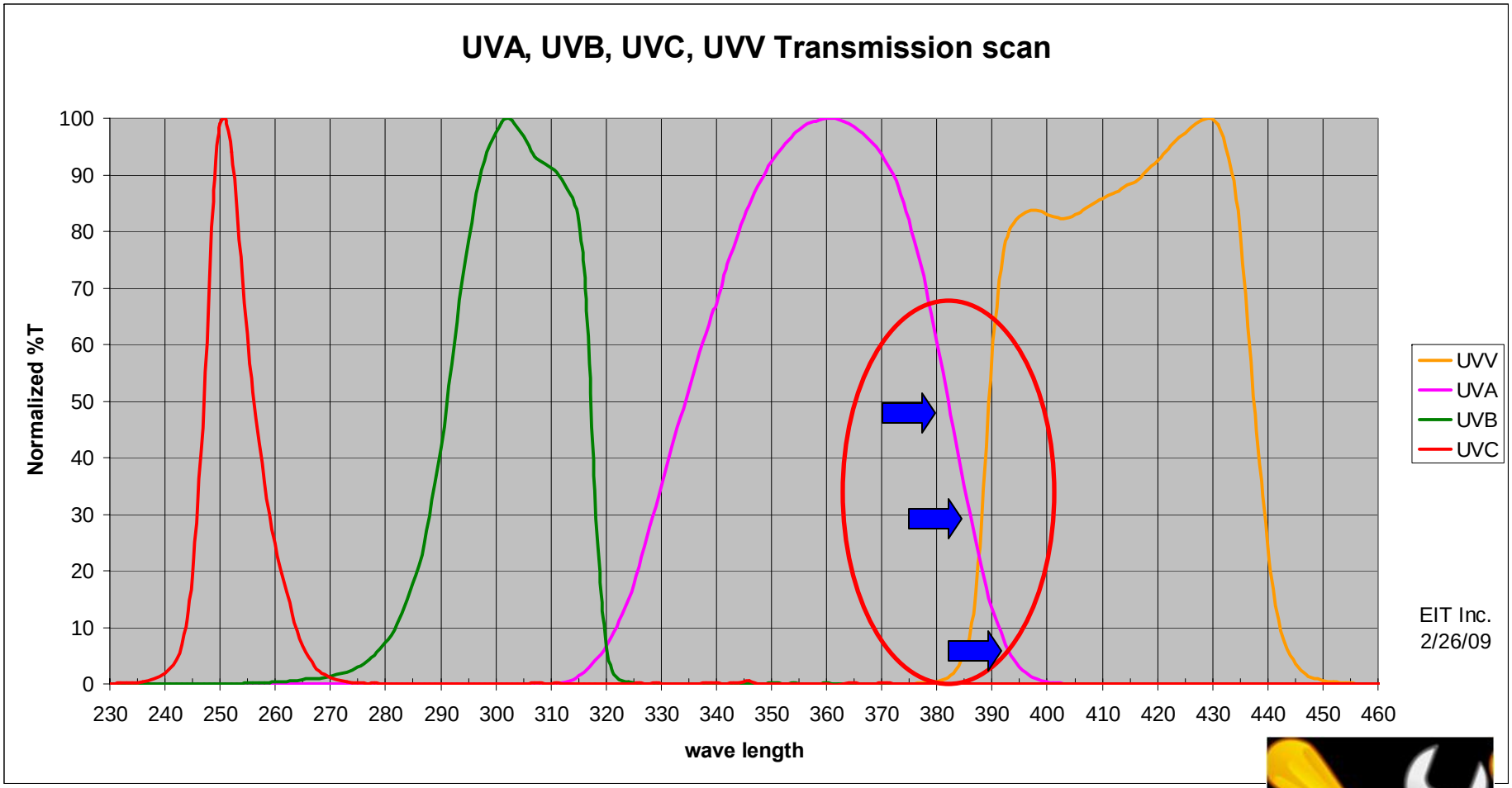
Multiple Band Instrument



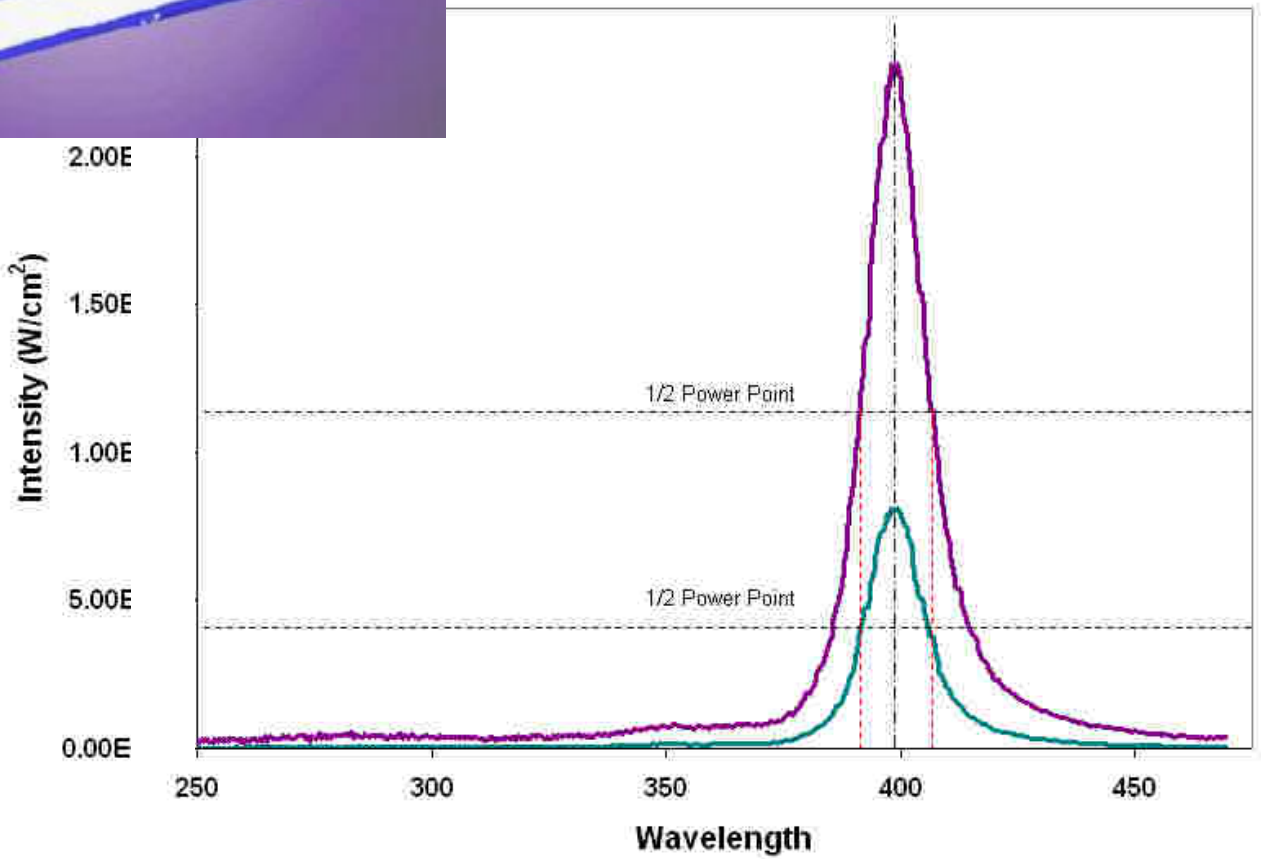
UVA-Spectral Bandwidth Comparisons



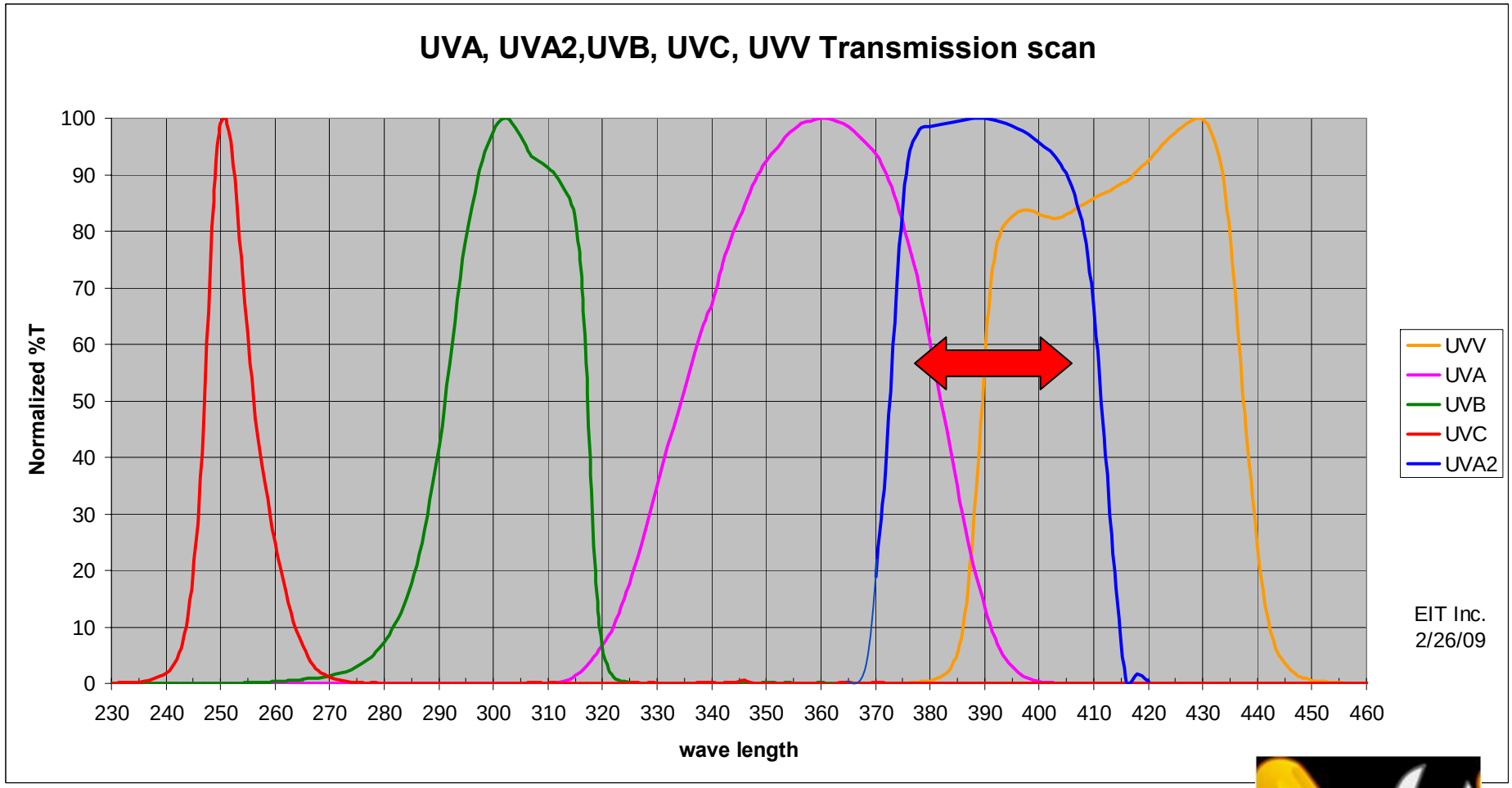
UV Bandwidths-UVA, UVB, UVC, UVV

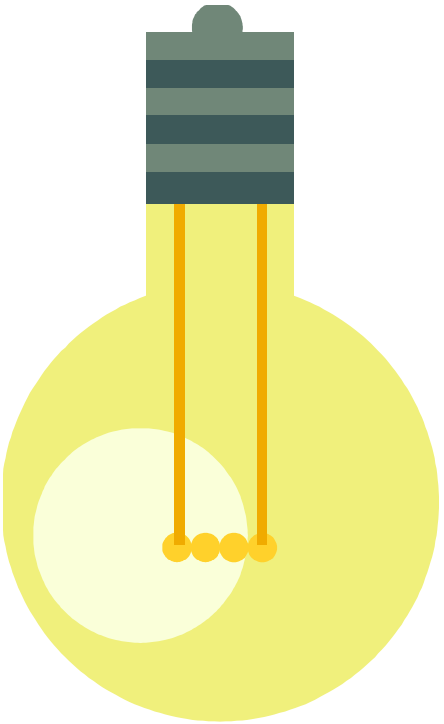


UV Lamp Output Data



UV Bandwidths - UVA2



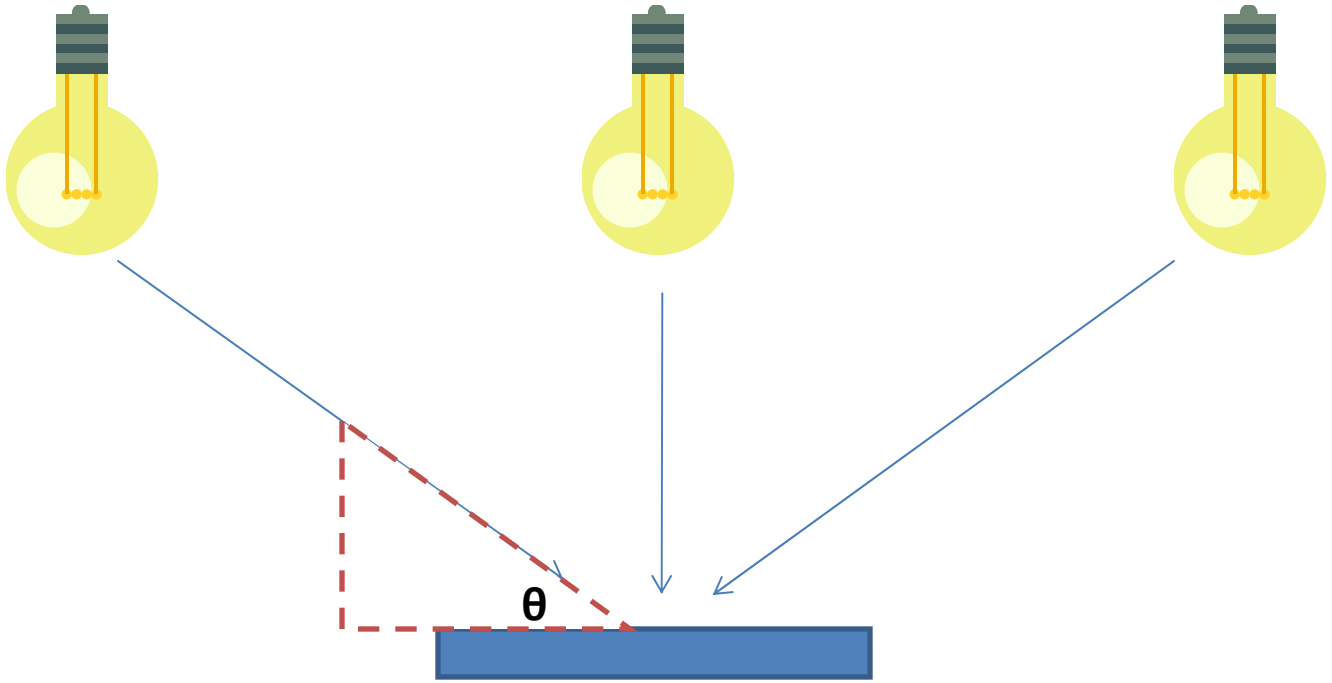


Wavelength

Peak Irradiance

Energy Density

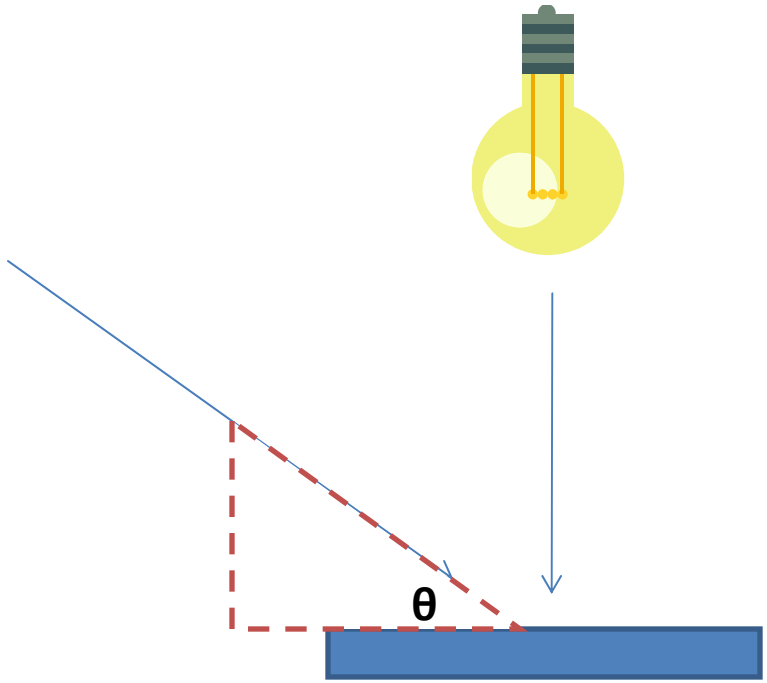
$$E_\theta = E \times \cos\theta$$



Cosine Error in Measurement

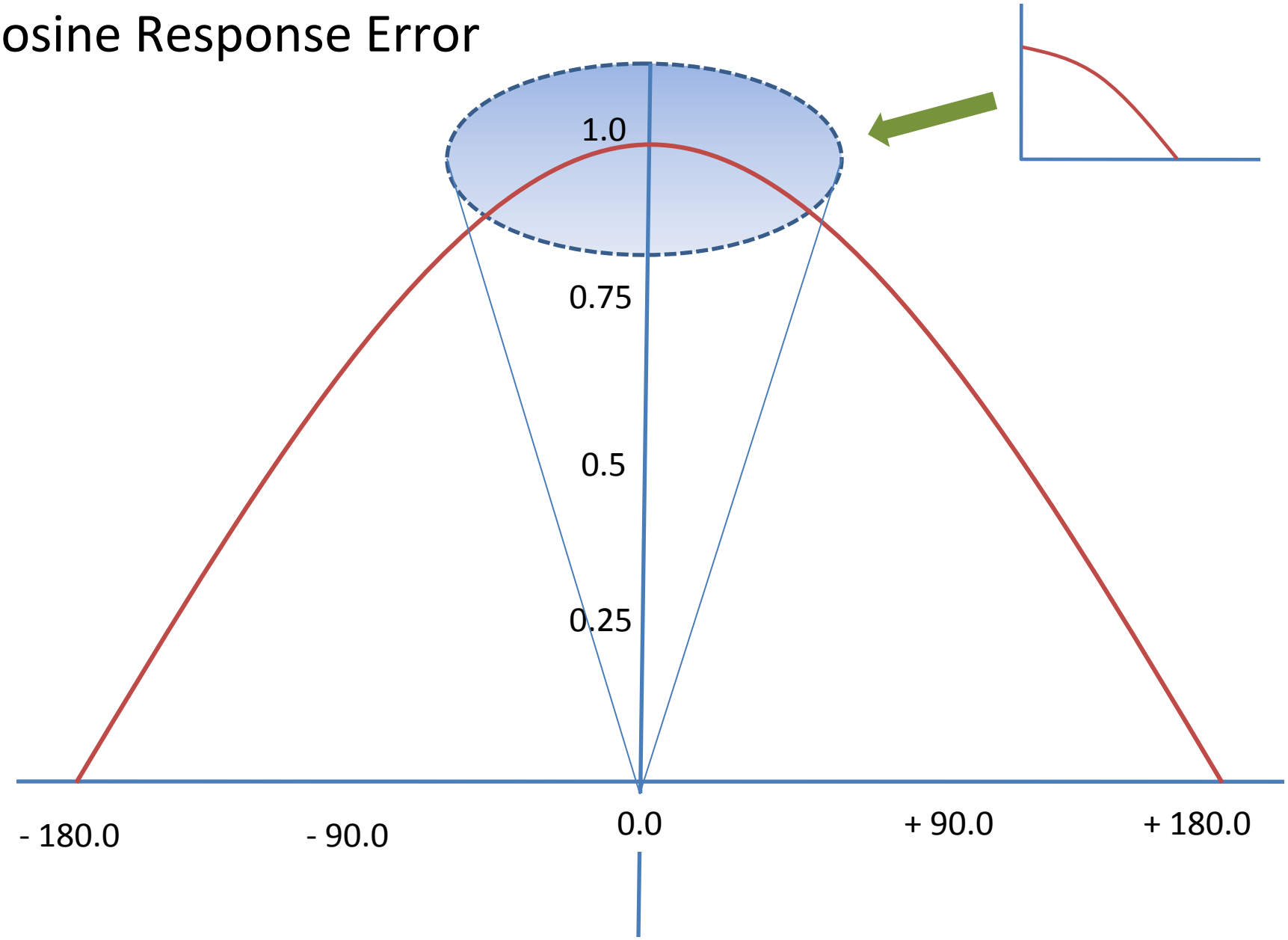
$$E_\theta = E \times \cos\theta$$

45° = .7 Watt **90° = 1.0 Watt**

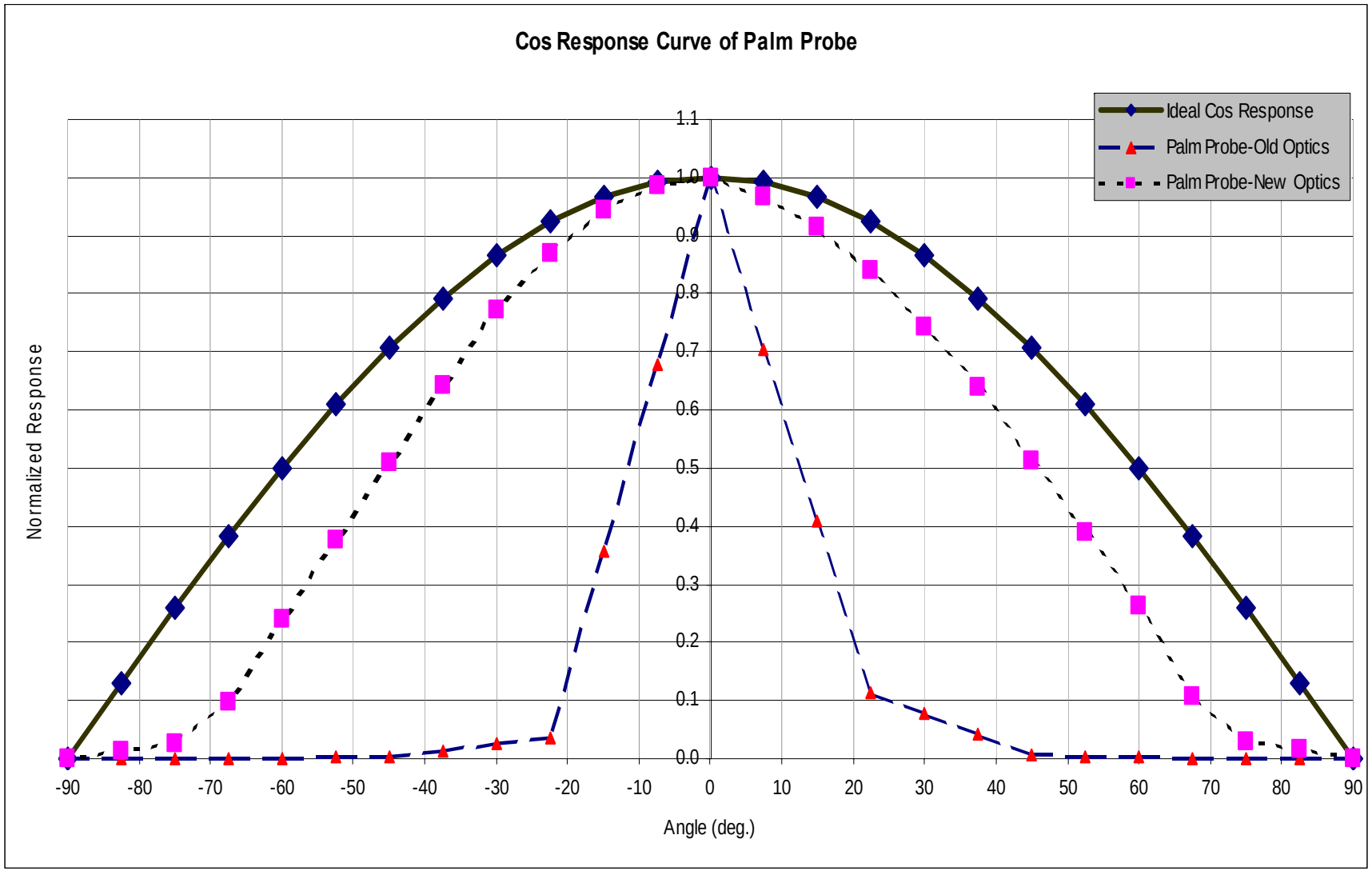


Cosine Error in Measurement

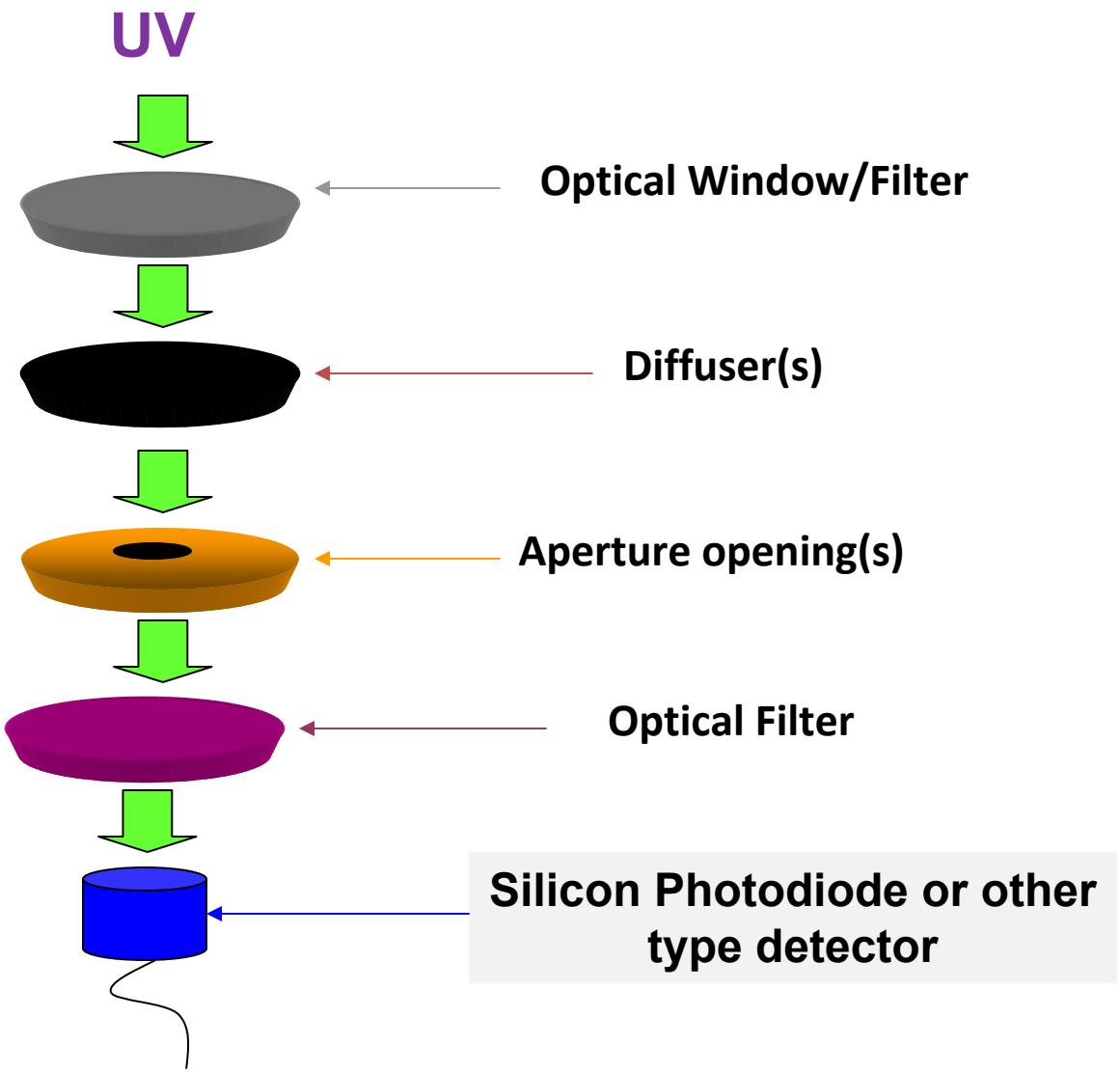
Cosine Response Error

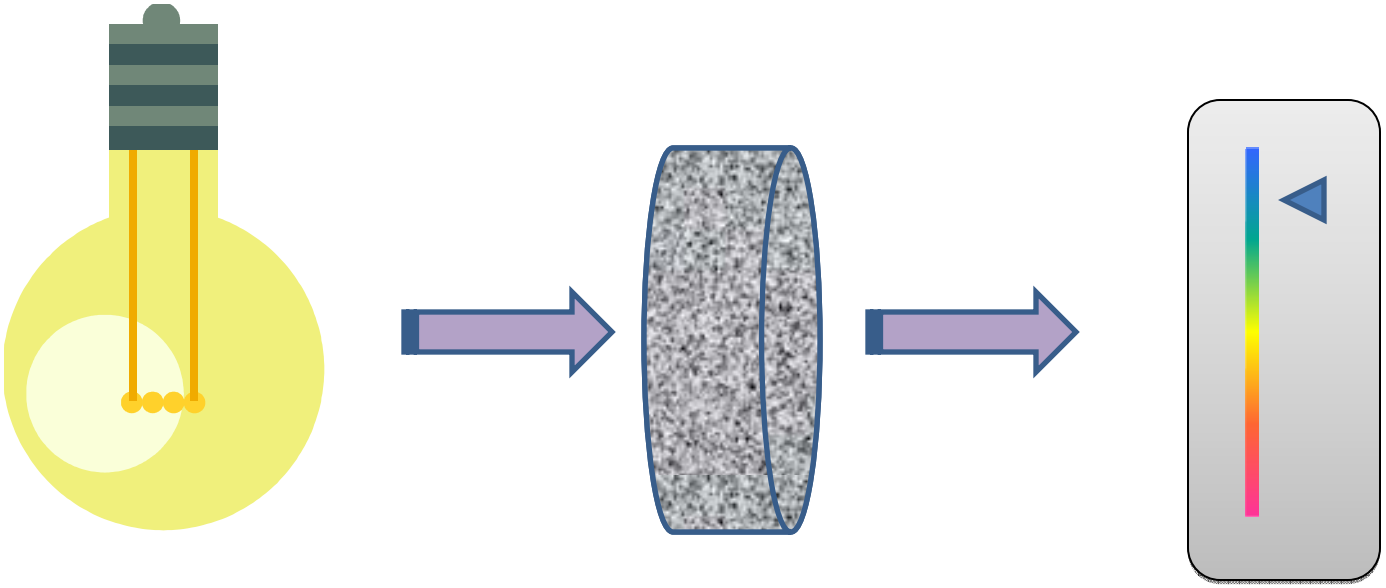


Spatial Response of Instruments Goal: Cosine Response



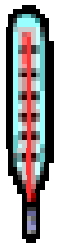
Optics Designs



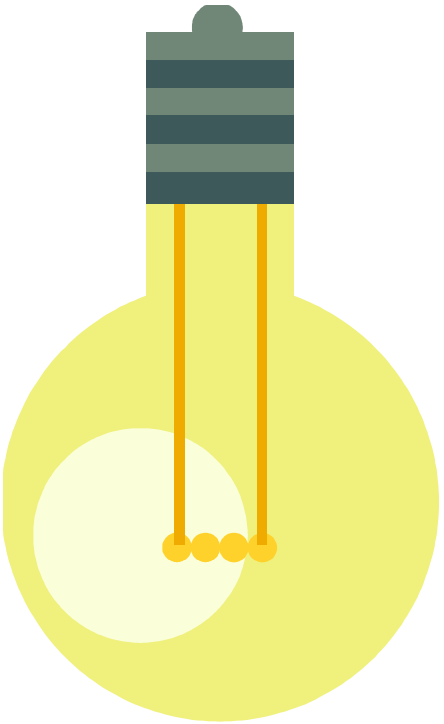


Solarization of Optics affects absolute measurement and requires maintenance

Radiometer Variations-Temperature



- Unknowingly introduce variations to readings based on the internal temperature of the unit
- As detector temperature raises, readings may drop
- Try to maintain consistent conditions and avoid rapid, repeated, long duration high intensity runs
- Typical detector variation: -0.2% per °C
- If it’s too hot to touch – it’s too hot to measure
- Internal temperature alarms (65 ° C)



Wavelength

Peak Irradiance

Energy Density

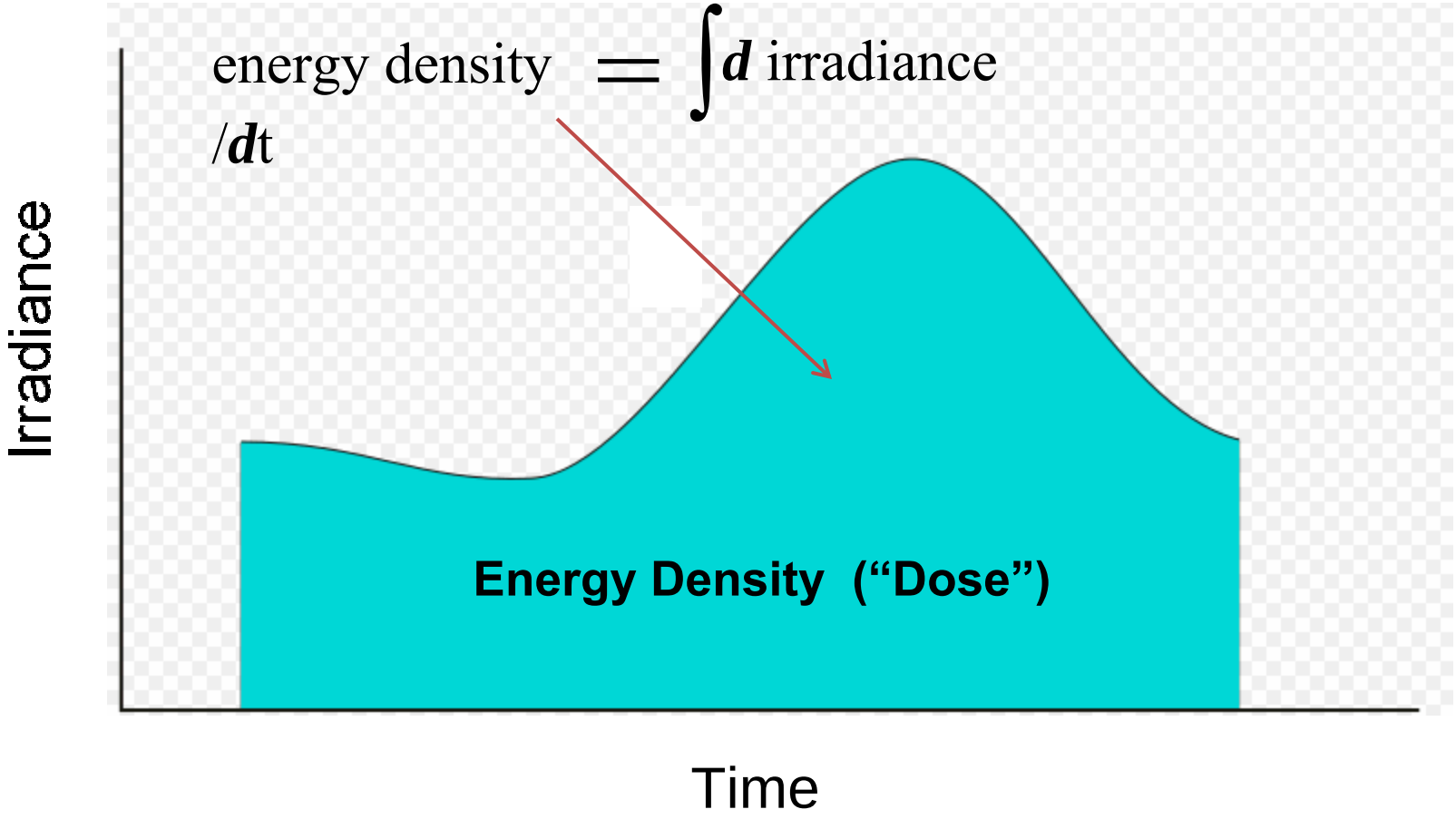
When is a Joule not a Joule?

- Bandwidths are not defined and vary from manufacturer to manufacturer
  - EIT UVA 320-390 nm, CWL 365 nm (narrow)
  - IL UVA 250-415 nm, CWL 365 nm (broad)

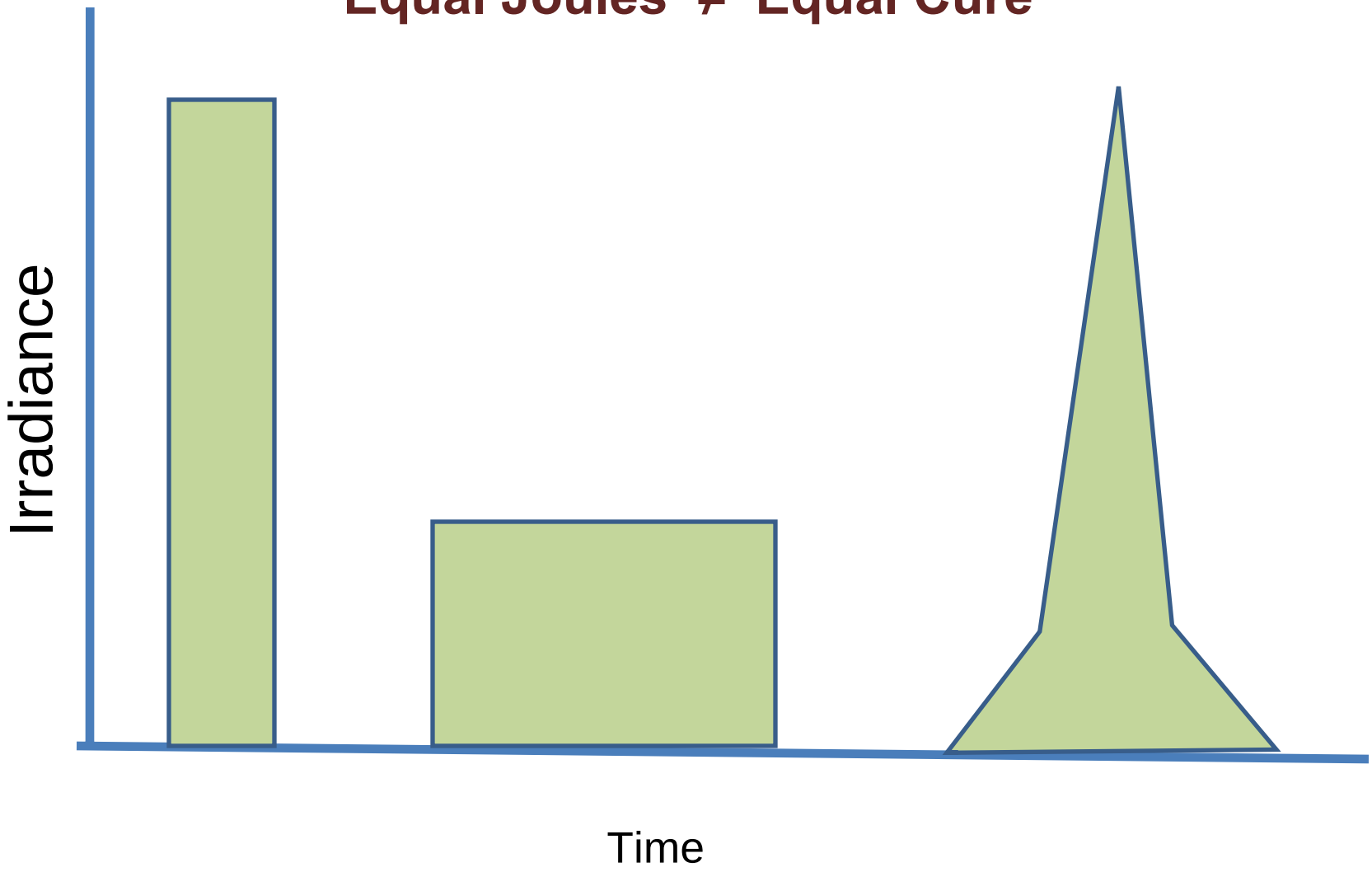
ANYthing that affects IRRADIANCE affects energy density.

Filters, cosine angle, solarization, etc.

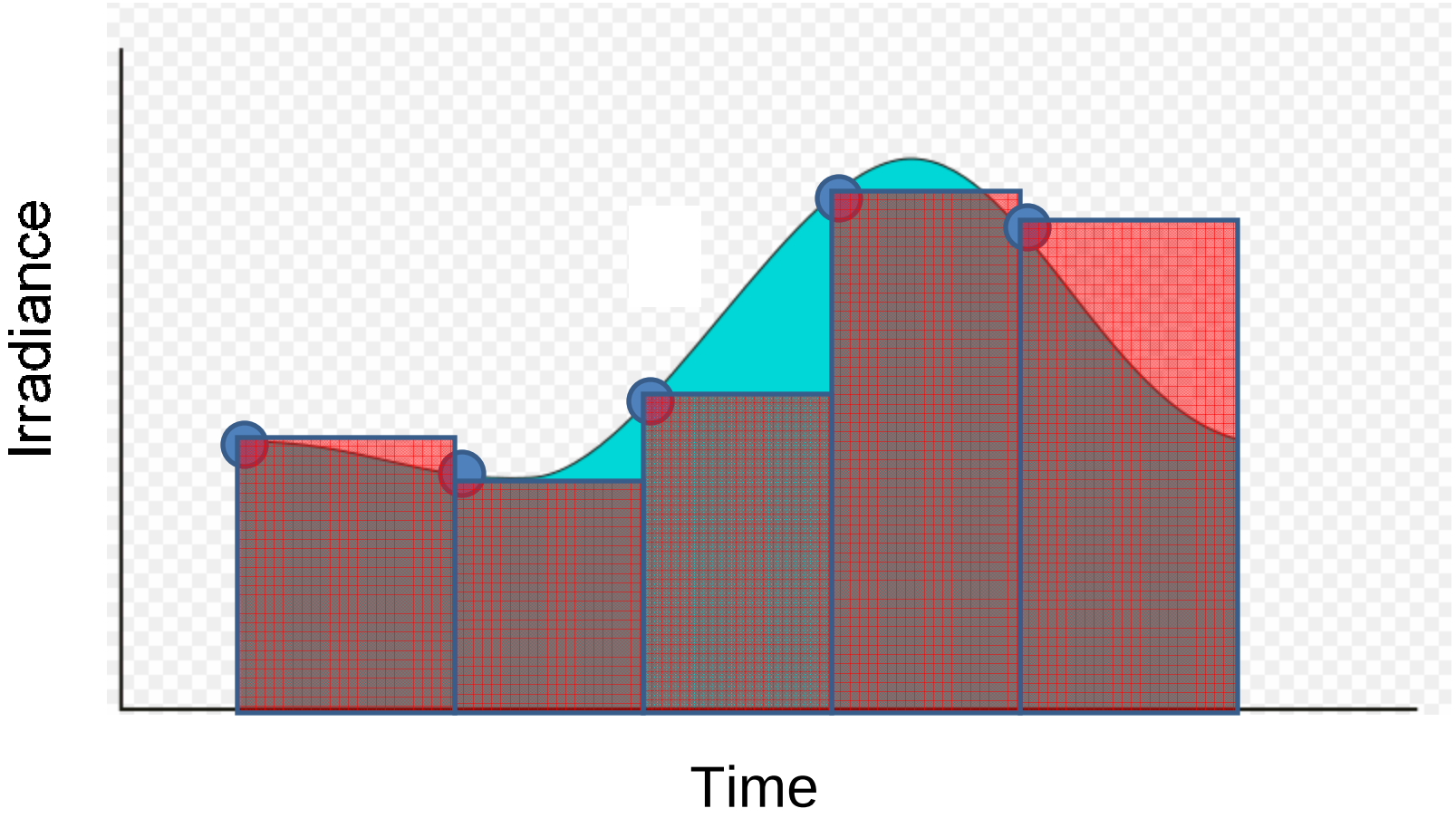
But there are some factors that do not affect irradiance and do affect energy density.

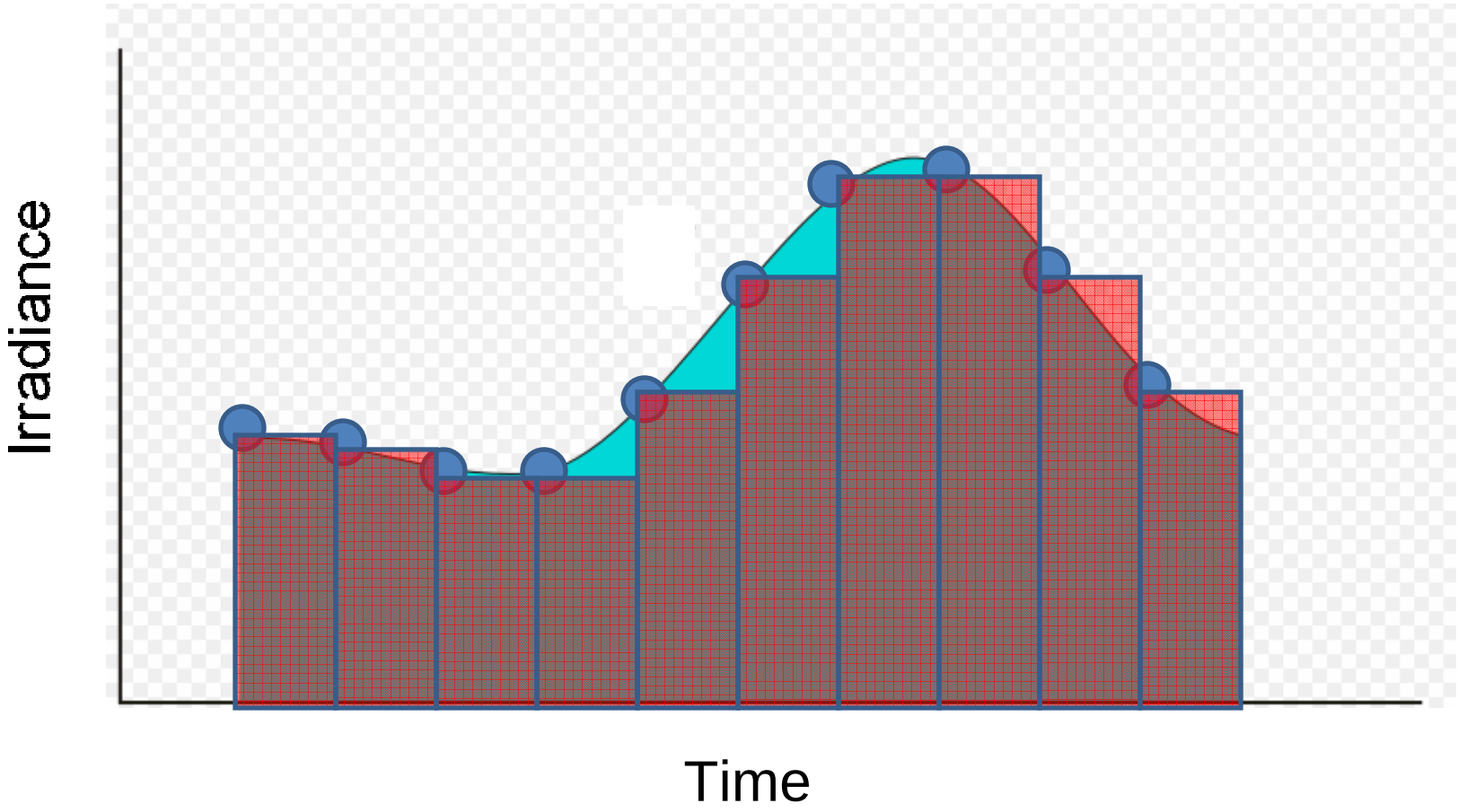

energy density
/dt
= ∫d irradiance
Irradiance
Energy Density ("Dose")
Time

Equal Joules ≠ Equal Cure



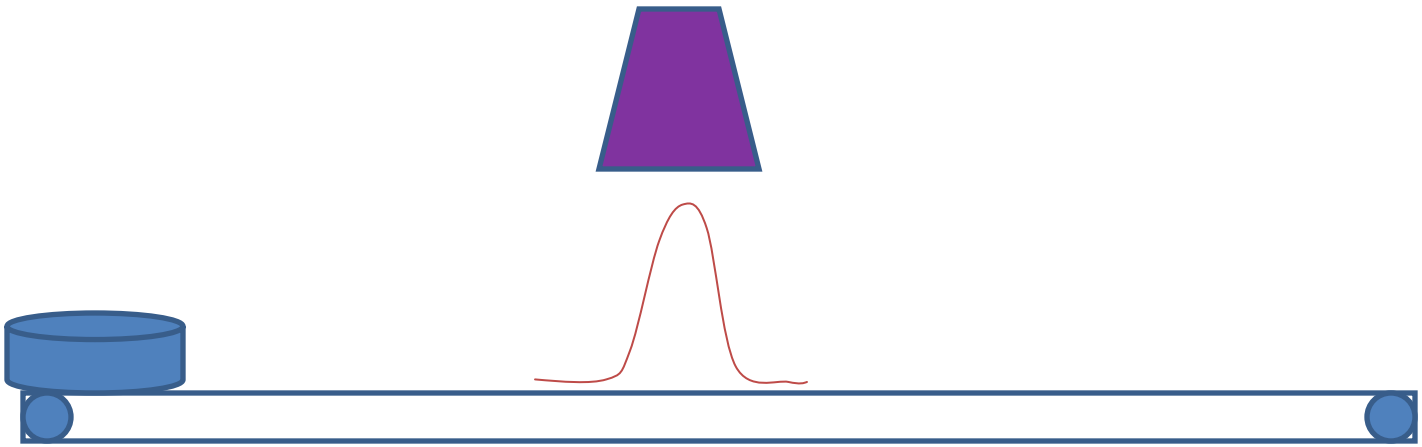
Low Sampling Rate = Less accurate for both Peak and Energy Density

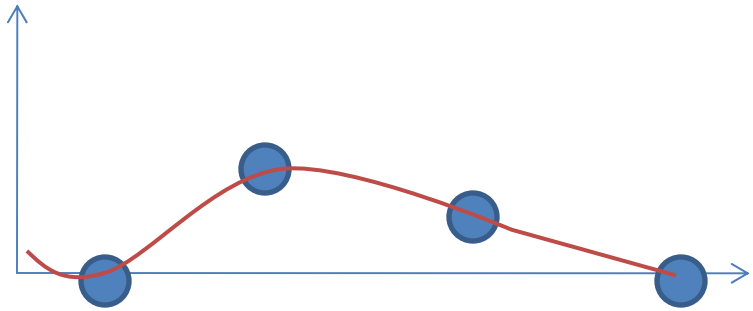



Irradiance
Time

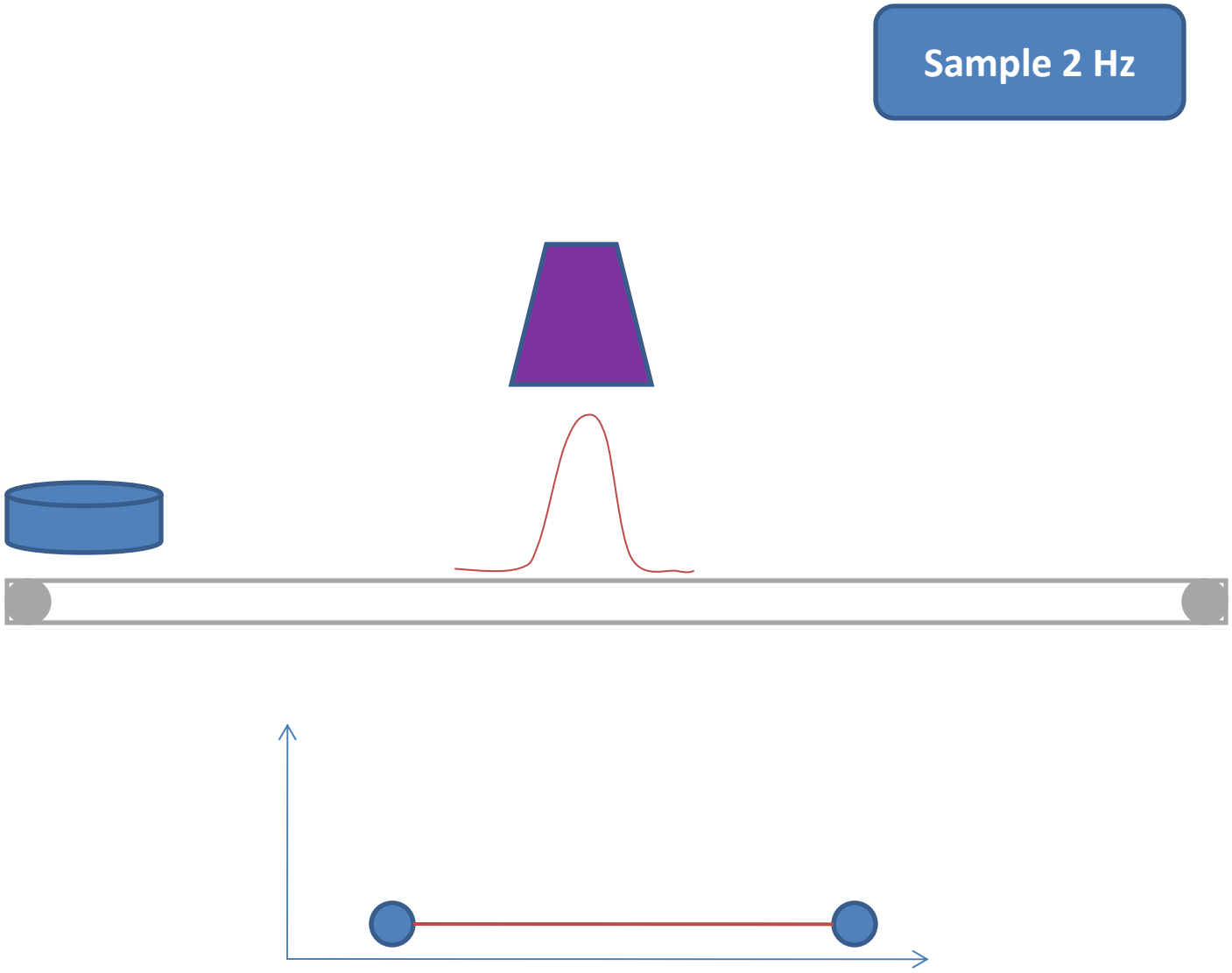
What works well at one line speed…

Sample 2 Hz



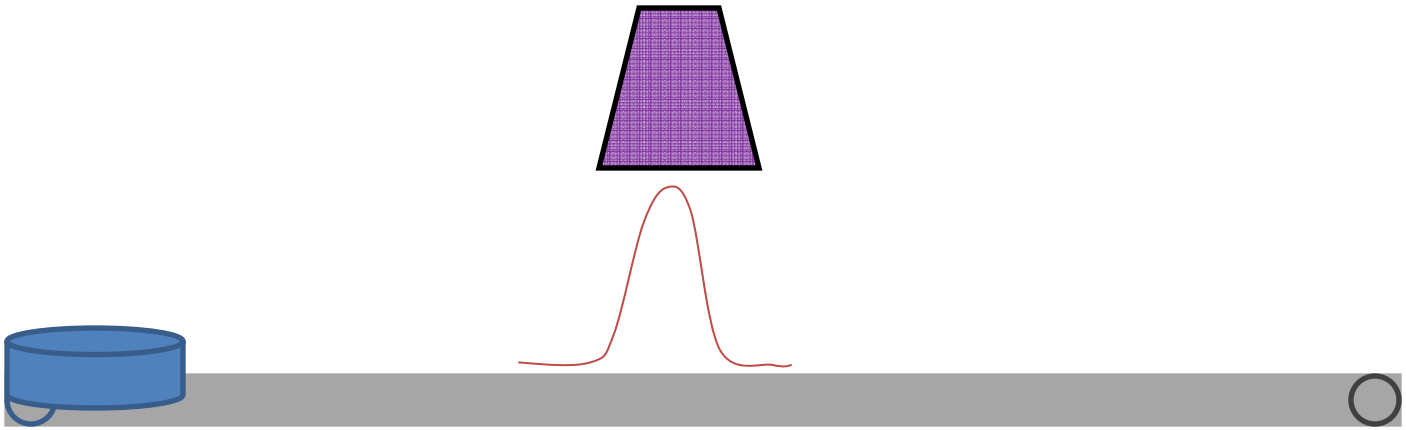


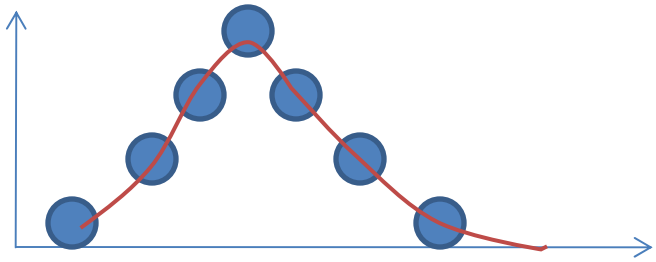
May not work well at another.



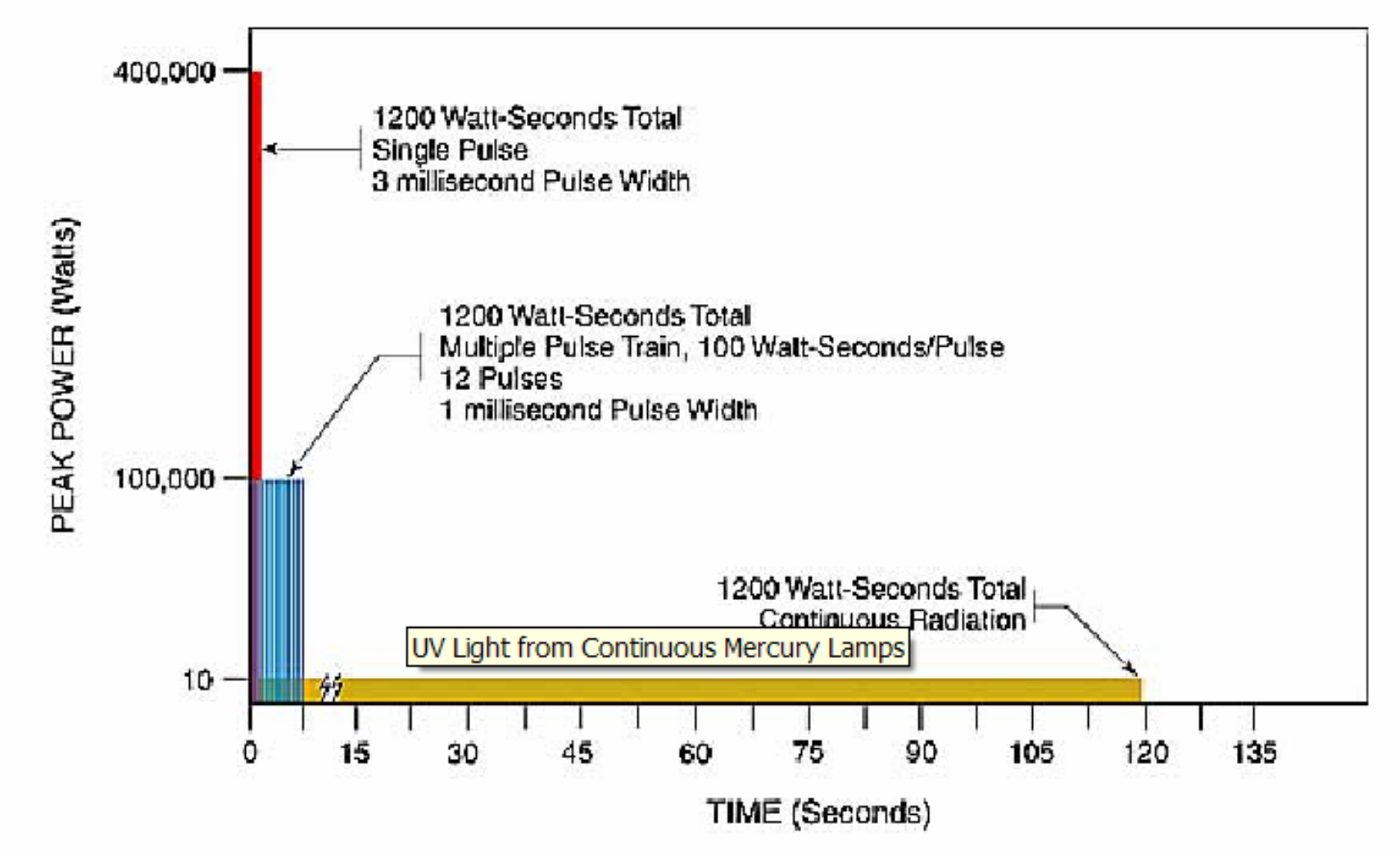
The sampling rate must be appropriate for the process. Typical rates can vary From 25 to 30,000 samples/second

Sample 6 Hz

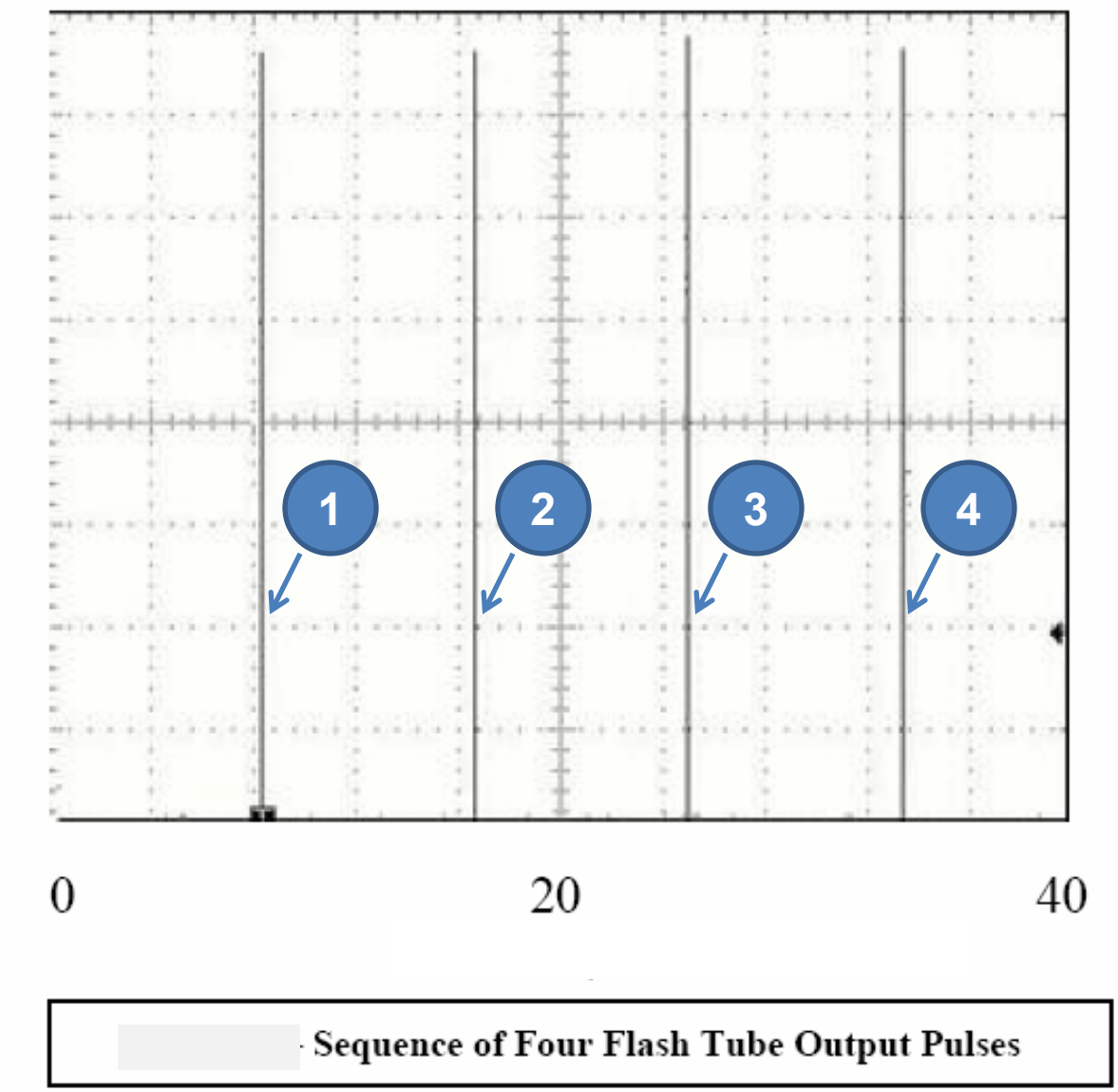




Pulsed Xenon Source



Pulsed Lamp Source - 4 Pulses

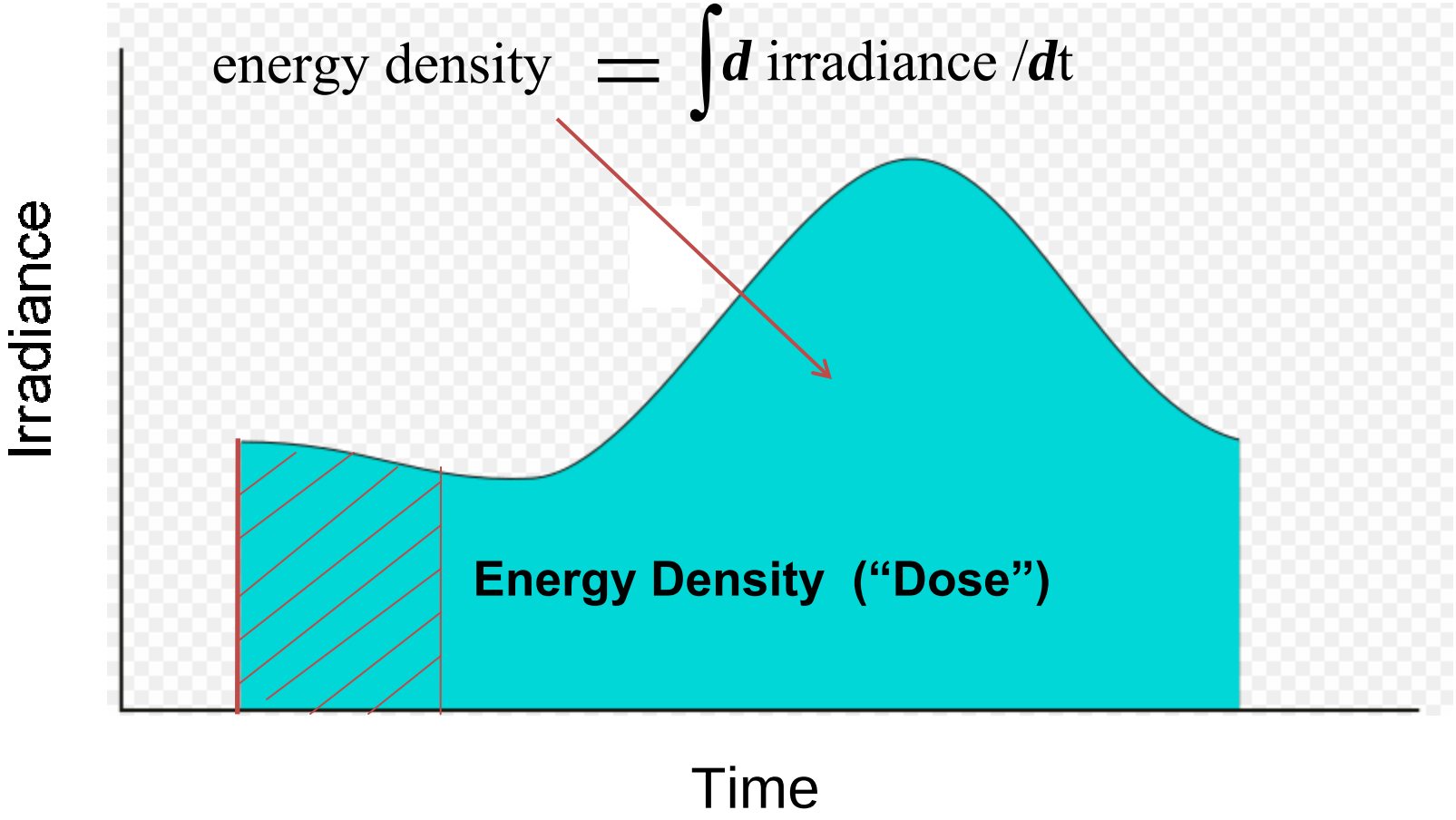


Sequence of Four Flash Tube Output Pulses

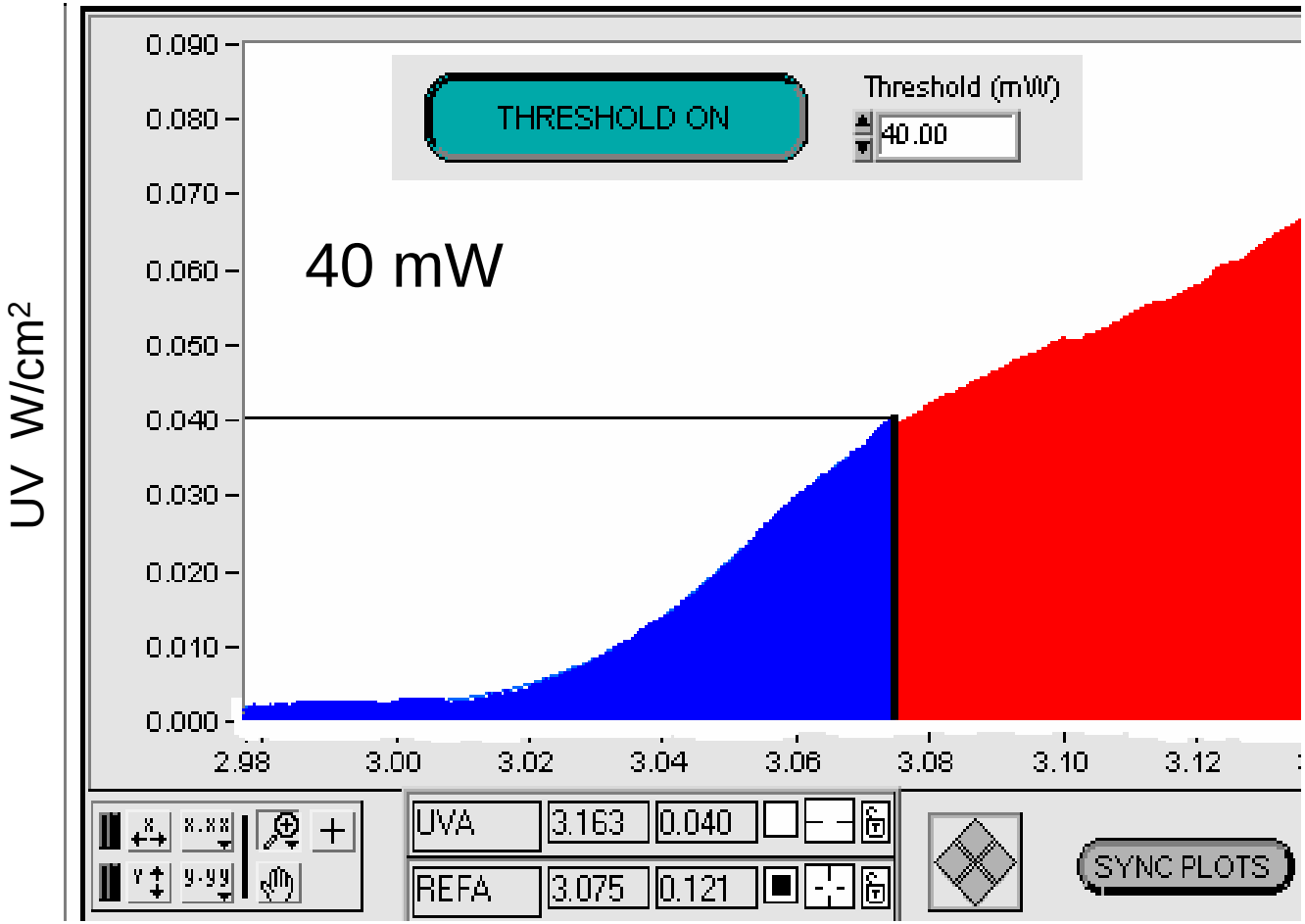
X-Axis
Milli
second
s

UV Power Puck® FLASH

- Modified electronics for pulsed sources
- Power Puck Flash-four UV Bandwidths
- Electronics designed for pulses between 100-120 times/second
- Provides energy density values
- User selectable parameters
- User changeable batteries


energy density = ∫d irradiance /dt
Irradiance
Energy Density ("Dose")
Time

Radiometer Variations-Threshold

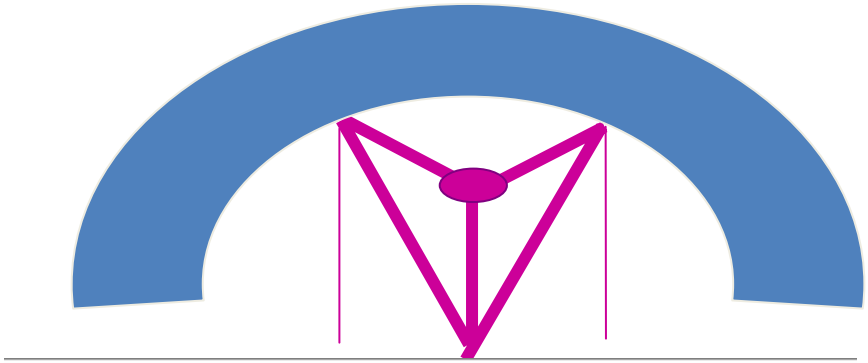


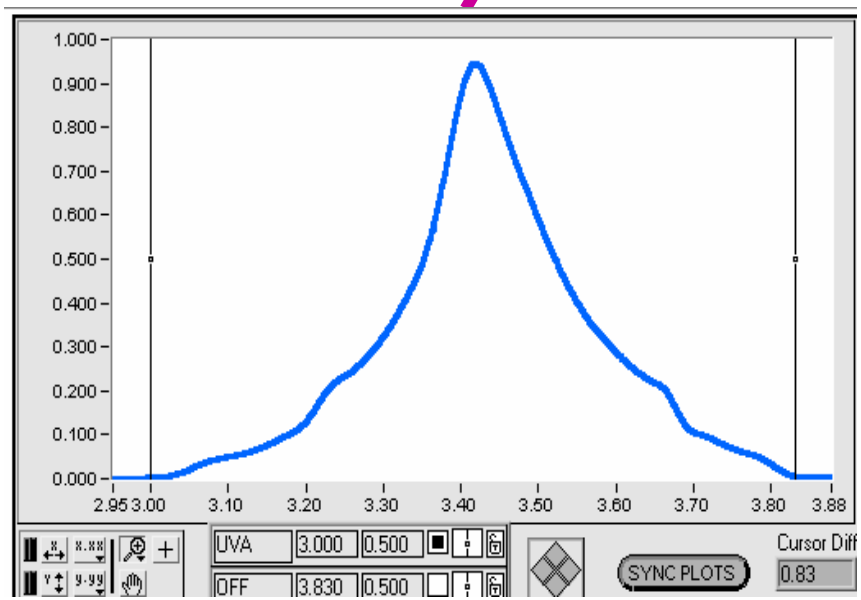
Radiometer Variations-Threshold

- Start threshold: Irradiance level which causes the unit to start measuring UV
  - Counts all UV past that point
  - Varies due to scale, electronic response, optics, design
- Data threshold: Software allows user to discard all readings below a set range
- Challenge: Long slow runs of low irradiance
  - Potential for wide variation in energy density-Joules

Some Practical Examples of UV Measurement Related Issues

Radiometer Variations - Sample Rate





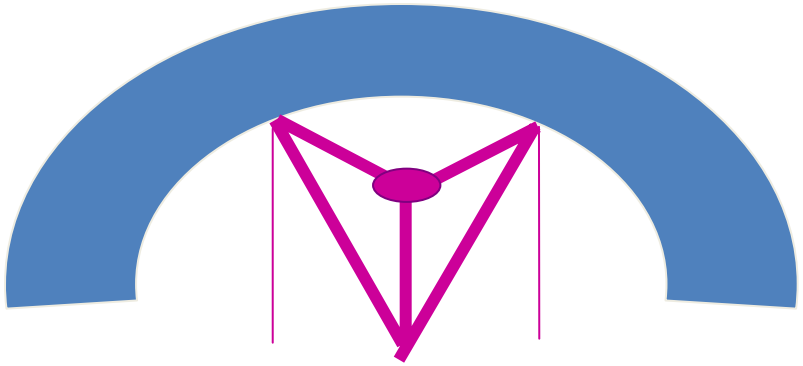
Speed: 33 fpm/10 mpm

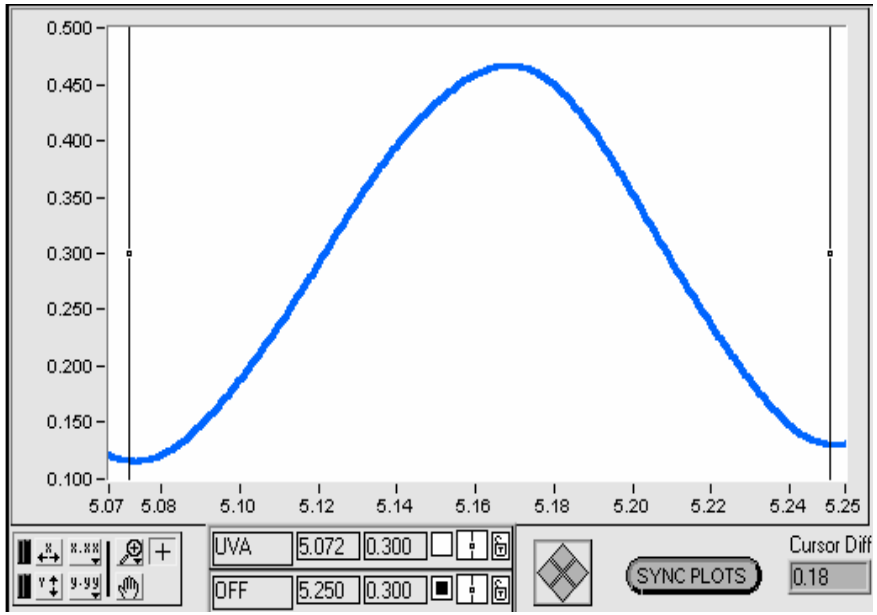
Total Time under UV reflector: 0.83 seconds

Time under Peak irradiance: 0.30 seconds

Inst. Sample Rate (#/sec)	Samples
25	20
40	33
128	106
256	212
1024	850
2048	1700

Radiometer Variations - Sample Rate





Speed: 240 fpm/74 mpm

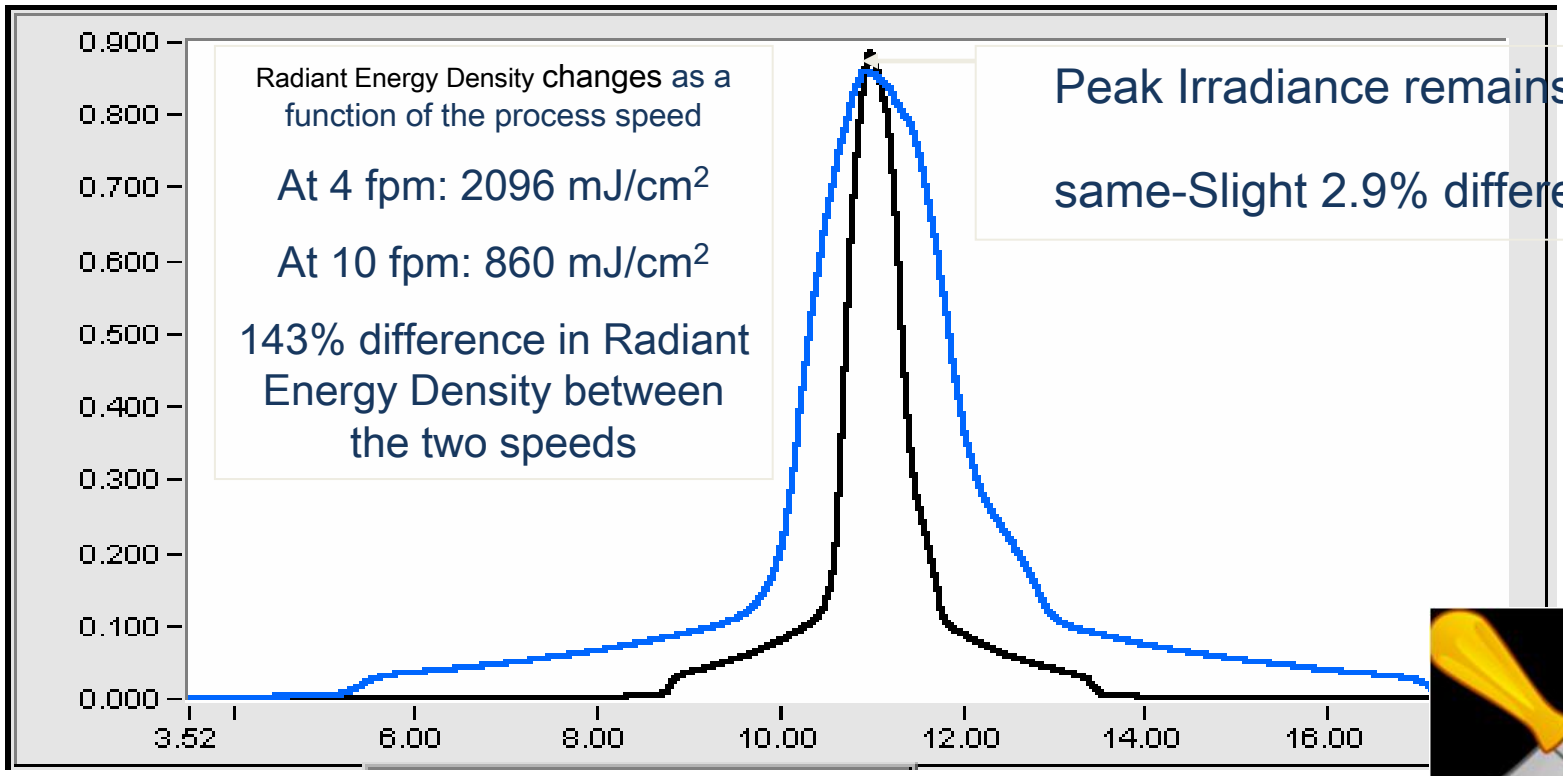
Total Time under UV reflector: 0.18 seconds

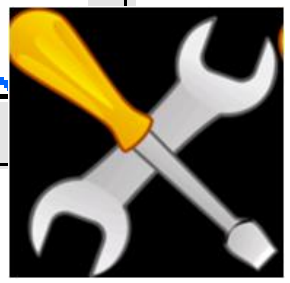
Time under Peak irradiance: 0.08 seconds

Inst.Sample Rate (#/sec)	Samples
25	4
40	7
128	23
256	46
1024	184
2048	368

Dwell Time or Belt/Line Speed

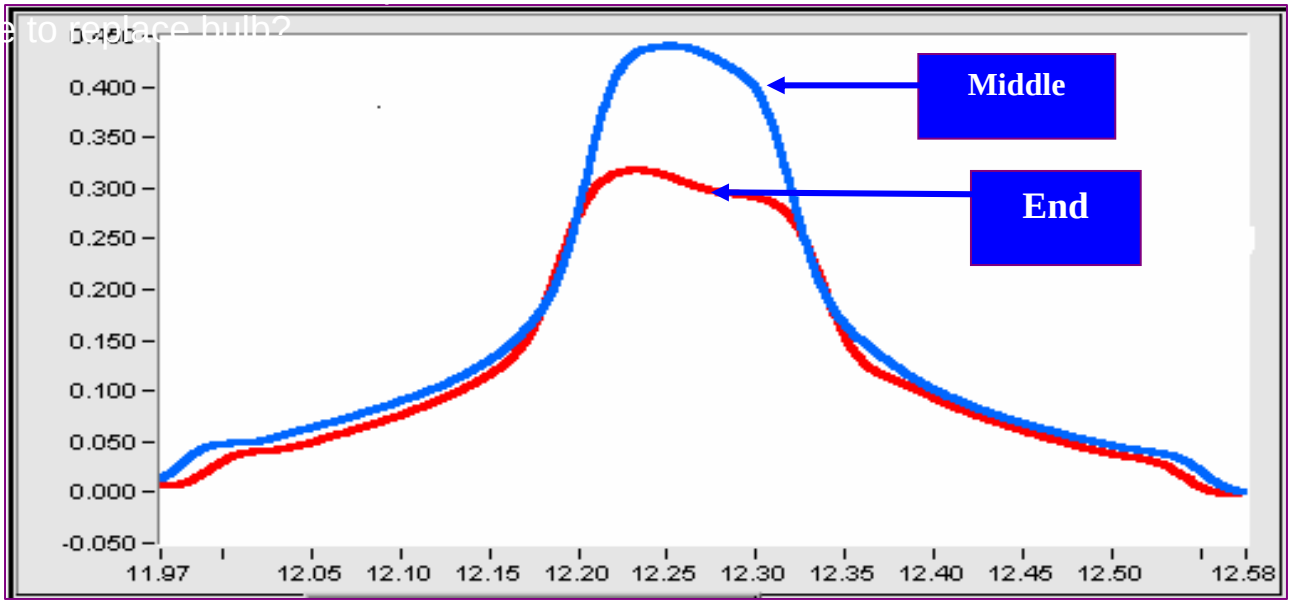
- Affects the amount of energy reaching the substrate
- Actual speeds may vary widely from settings on the speed controller and may not be linear (±25%)
- <u>Independently test and confirm dwell time or belt/line speed</u>



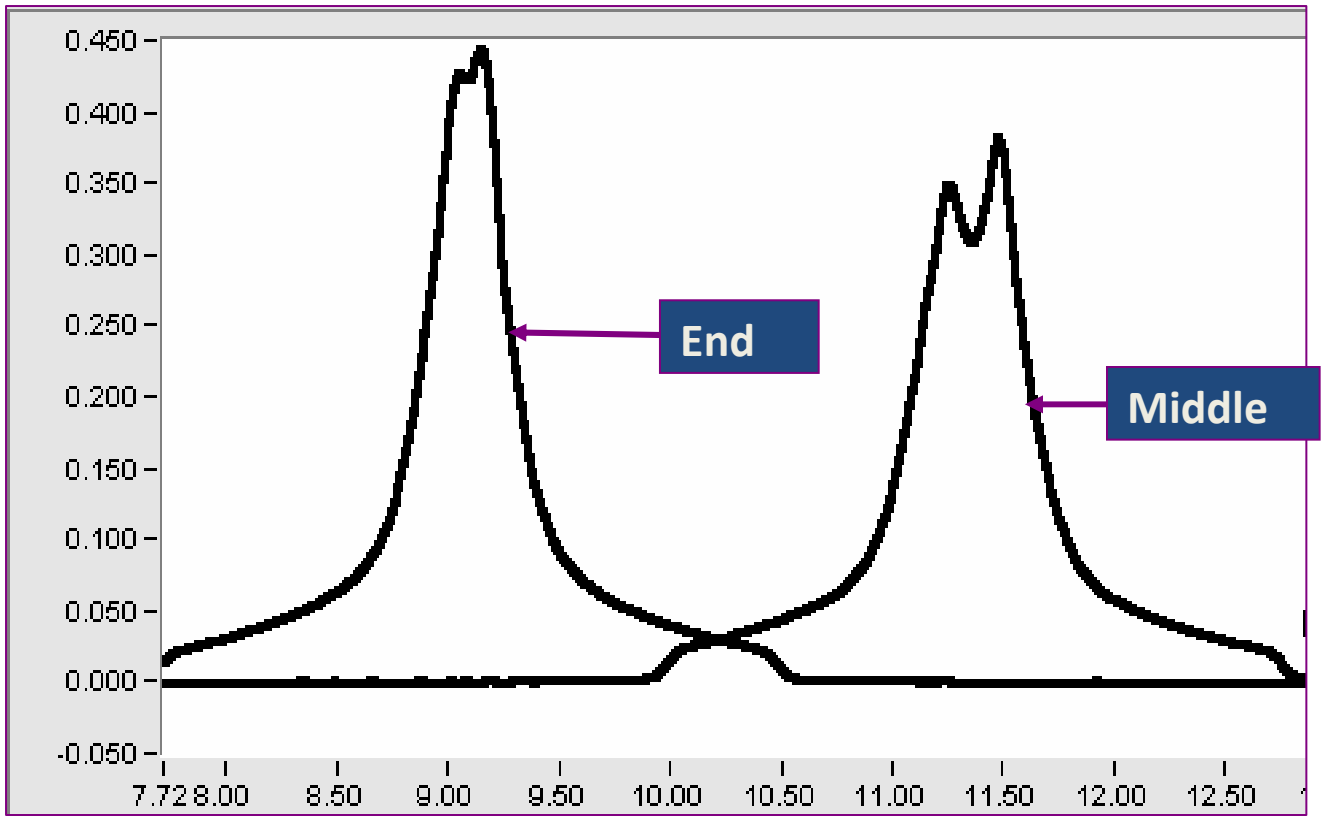


Effects of varying the process speed from 4 fpm (blue) to 10 (black) fpm


CLEAN NEW BULB
DIRTY OLD BULB

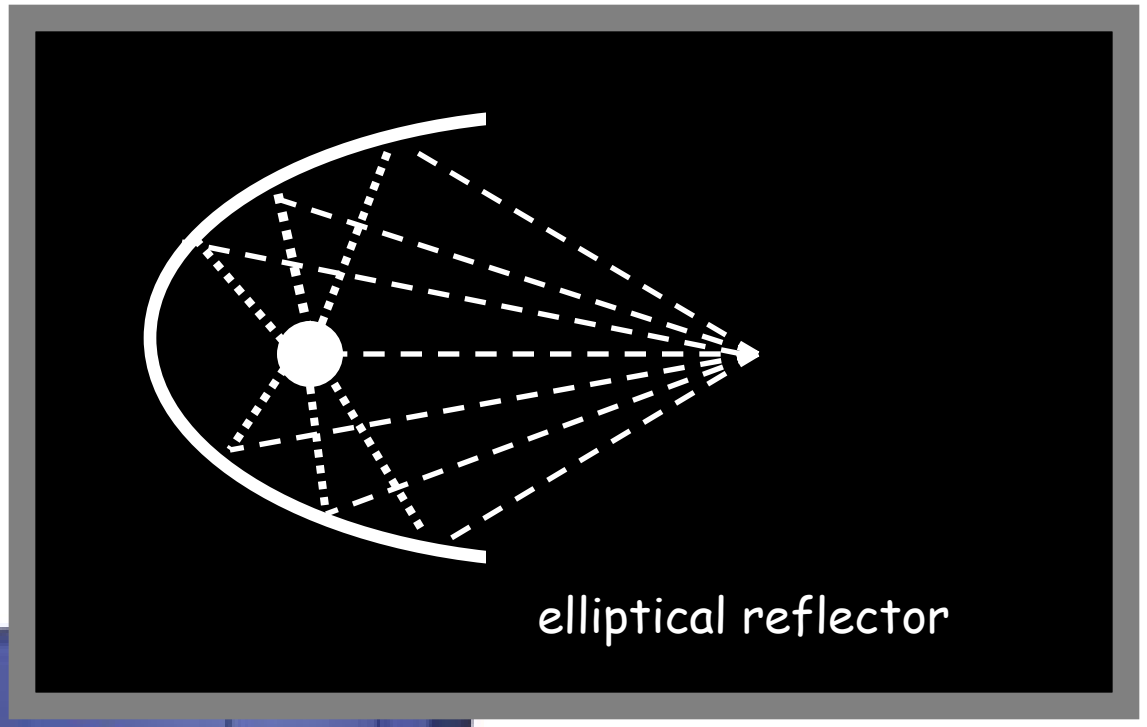

0.450
0.400
0.350
0.300
0.250
0.200
0.150
0.100
0.050
0.000
-0.050
11.97
12.05
12.10
12.15
12.20
12.25
12.30
12.35
12.40
12.45
12.50
12.58
Middle
End

Across the bulb-middle to end comparison (Inadequate Cooling/Air flow)

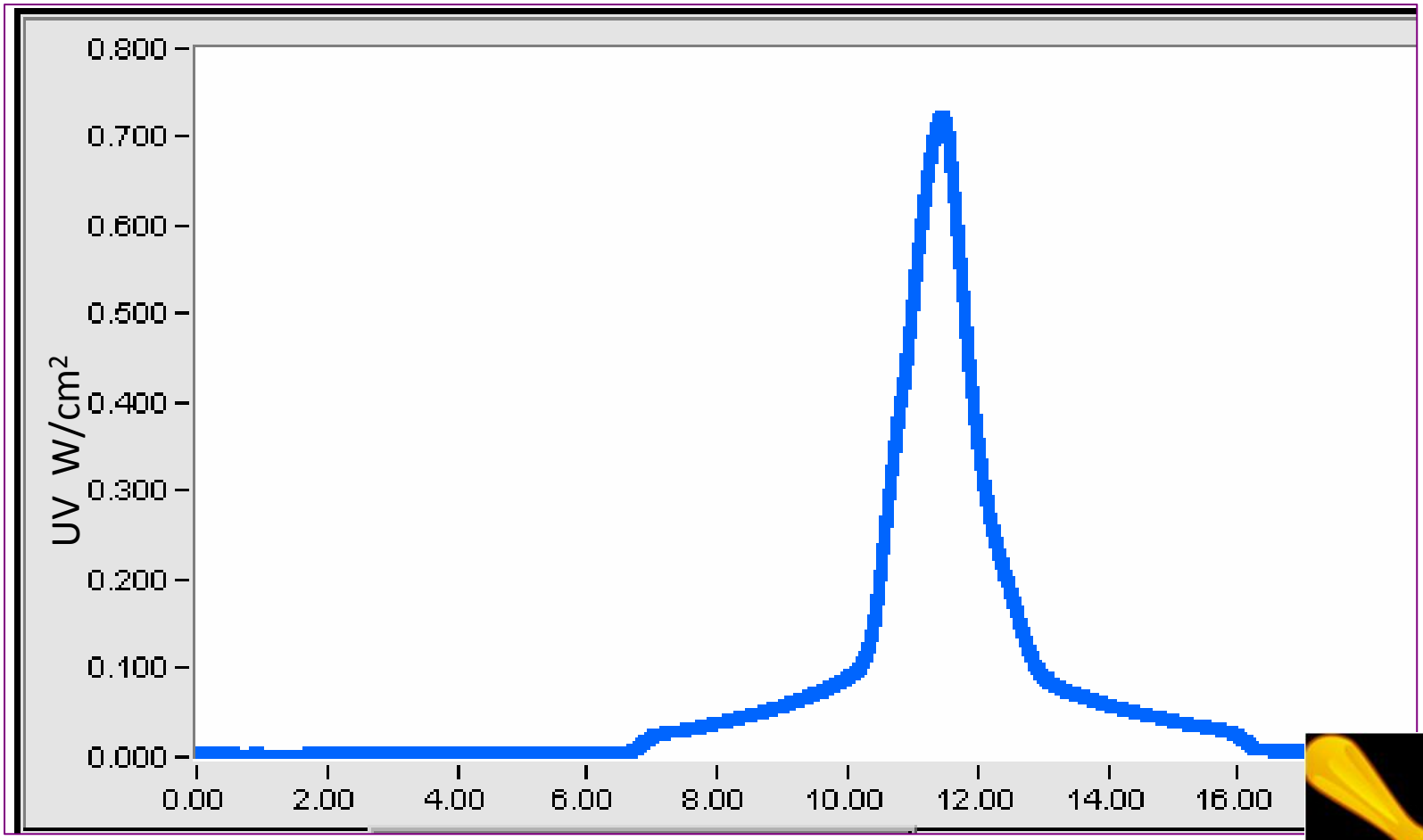


Sagging-15 % difference in irradiance levels middle to end

Data collected with EIT PowerMAP

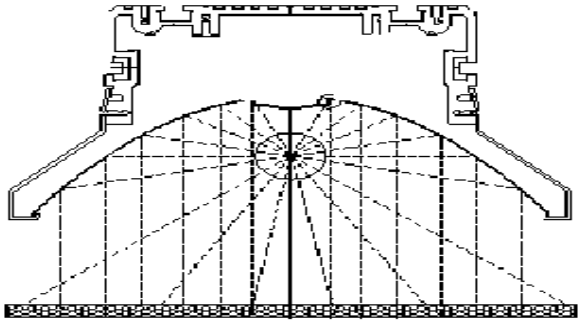

elliptical reflector

Focused lamp

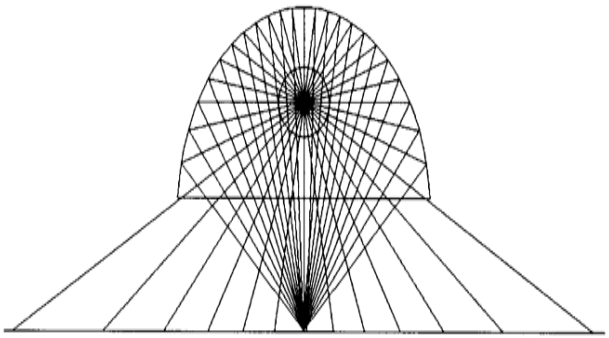


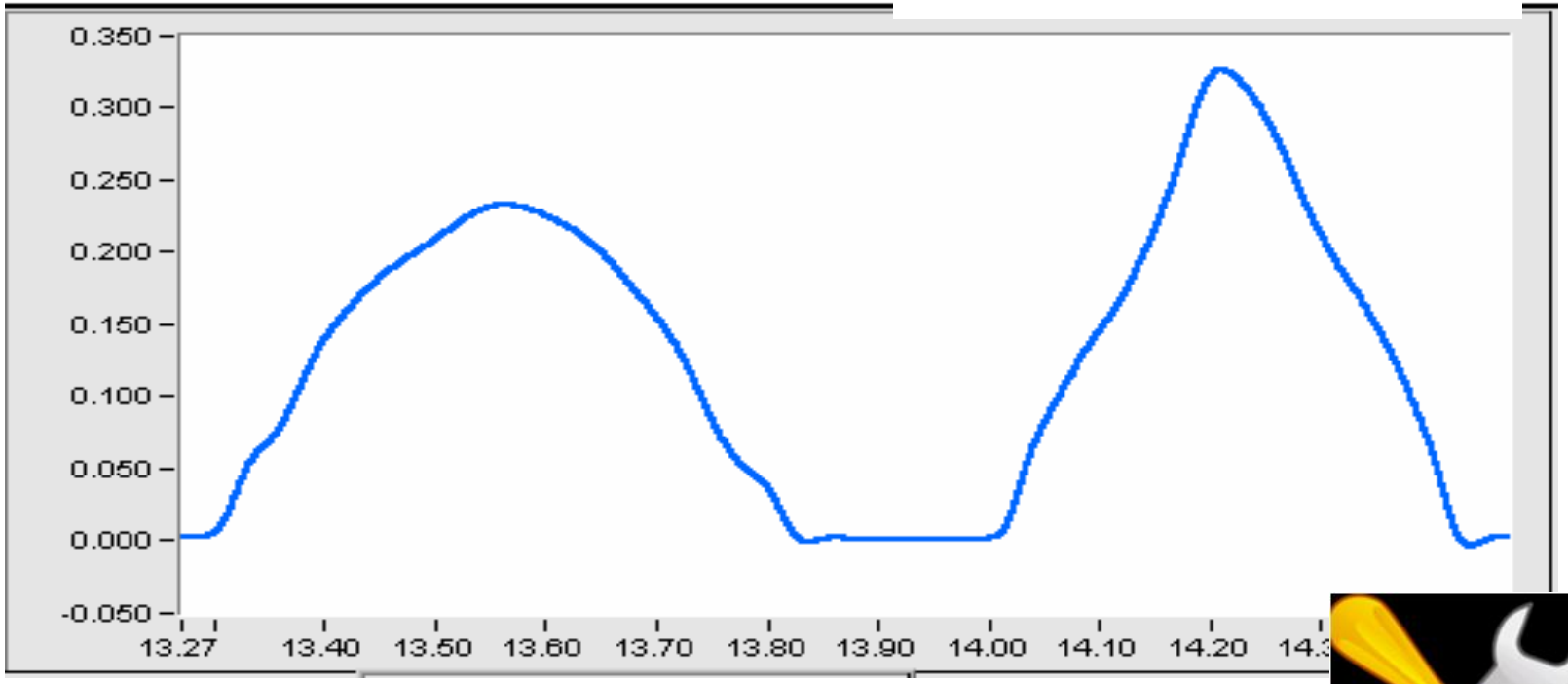
Time in seconds

Parabolic Reflector

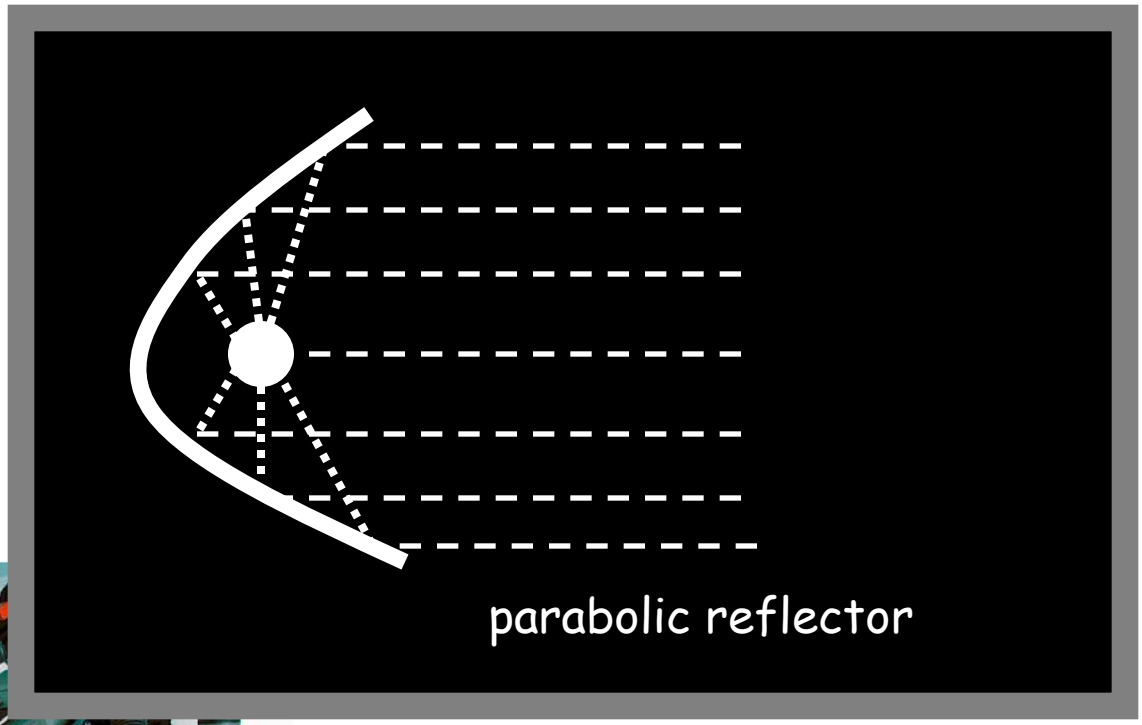


Elliptical Reflector

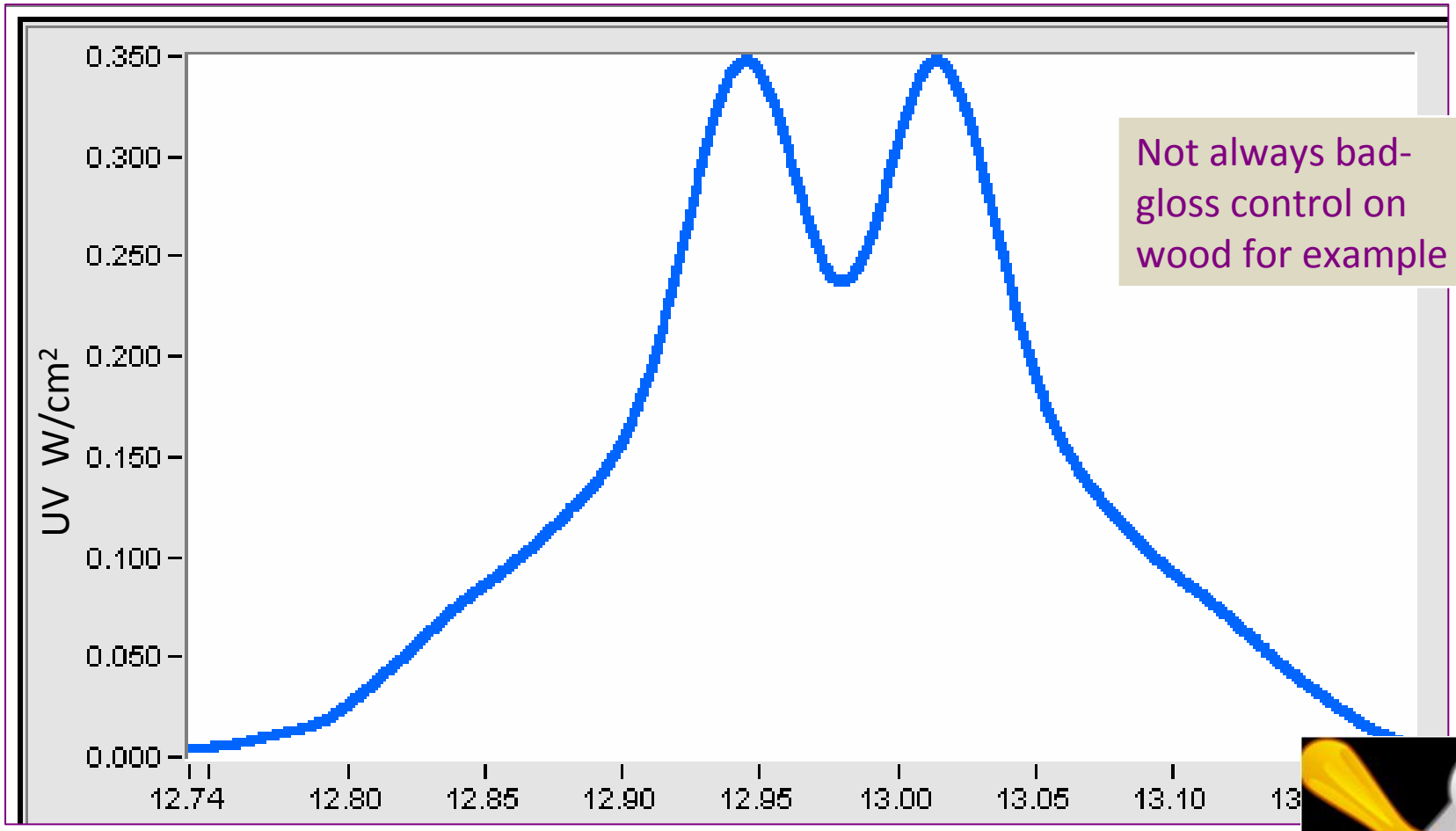




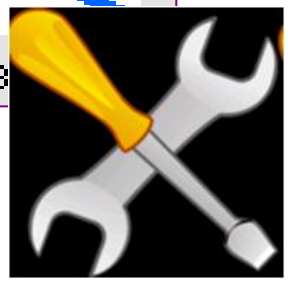
Parabolic vs. Elliptical reflectors


parabolic reflector

Parabolic Lamp



Not always bad- gloss control on wood for example

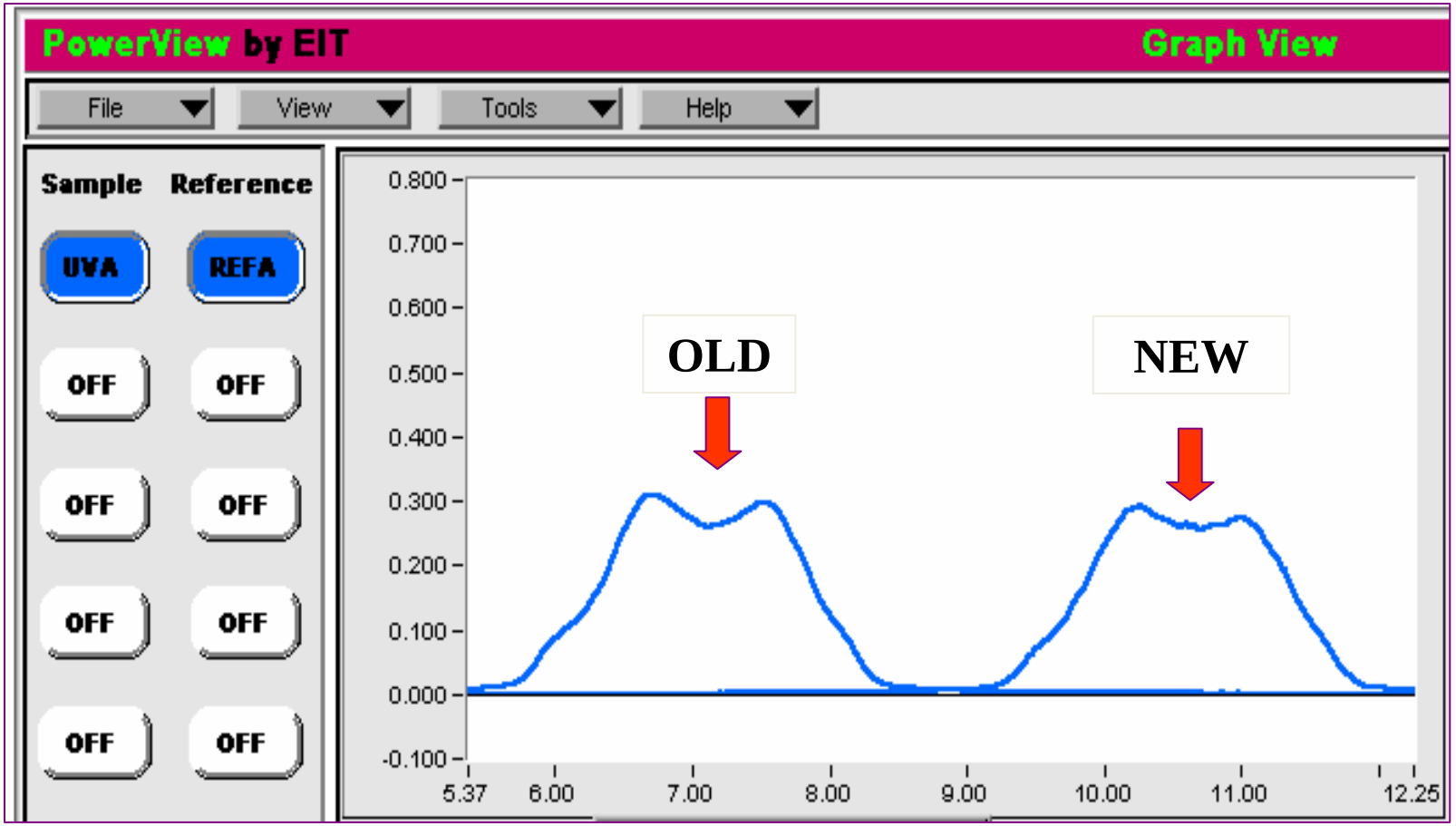


- Readings on a two lamp system
  - Energy Density: 953 mJ/cm^2 (UVA EIT 320-390)
  - Irradiance: 313 mW/cm^2 (UVA EIT 320-390)

- After: Readings on the same system
  - Energy Density: 1203 mJ/cm^2 (UVA EIT 320-390) + 26%
  - Irradiance: 449 mW/cm^2 (UVA EIT 320-390) + 43%
- Only one thing done <u>Reflectors were cleaned</u>

One little thing can have a big impact in the amount of UV reaching the cure surface

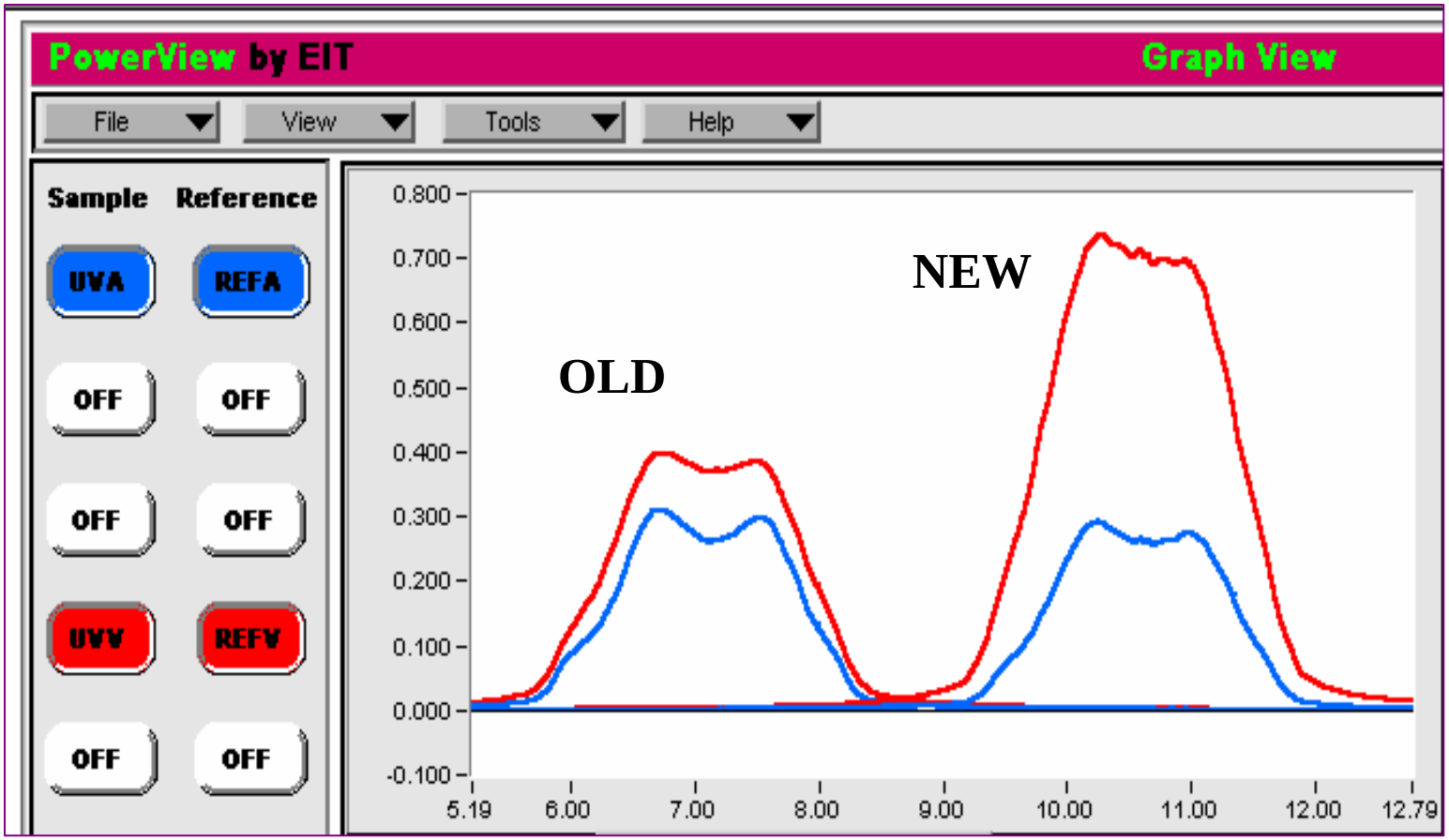
With 600 hours of run time would you change this bulb?



UVA Energy Density: 537 to 487 mJ/cm^2

UVA Irradiance: 309 to 290 mW/cm^2

Change Now?



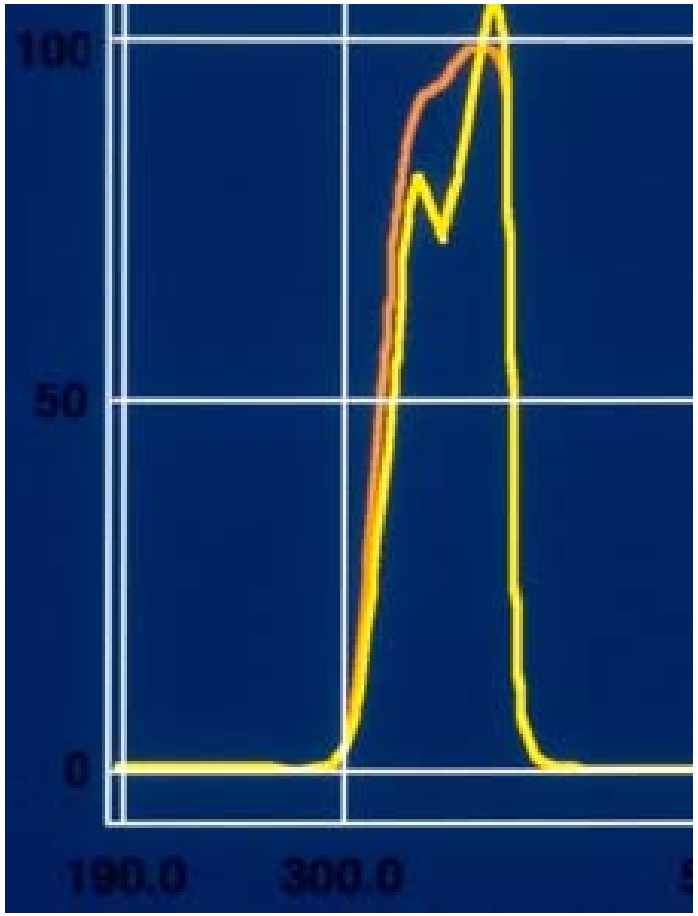
UVV Energy Density: 737 to 1331 mJ/cm^2

UVV Irradiance: 397 to 734 mW/cm^2

Radiometer Variations & Limitations

- Users expect the same accuracy as other instruments - current radiometer technology ± 10%
- Why can't radiometers do better than ± 10%?
- Optics
  - Filter and detector specifications
  - Spatial response
  - Design
    - Balance between optical stability (minimal solarization) and repeatable electronic signal level
- Electronics
  - Temperature sensitivity
  - Sample rates/Data Collection Speeds
  - Improvements in electronics since early EIT instruments
- Calibration Methodology
- User Induced Errors and Comparisons (Real vs. Perceived)
  - Comparison to other products within EIT family and from other manufacturers

Radiometer Variations-Optics/Filters



- Normal to expect small variations between filters
- Tradeoff is $ vs. performance
- EIT is careful to test each filter to avoid wide variations
- Select & test the optics for better performance and unit to unit comparisons

Why Calibrate?

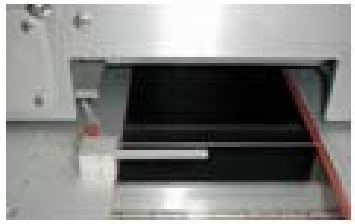
- Balance the amount of IR, Visible and UV the optics and detector “see” with the output signal from the detector
- Compensate for changes in the optics over time
  - Solarization
- Instruments used in harsh production & manufacturing environments
  - Irradiance levels:
    - Sunlight: +/- 20 mW/cm^2
    - Production UV levels: 100’s to 1000’s mW/cm^2
  - Physical damage to instrument
    - Drop, crush instrument, scratch optics
  - Optics/instrument coated with ?
- Electronics checkup
  - Physical and/or heat related damage

Instrument Selection

- Right Instrument/Product
  - Continuous, storage or mapping,
- Right Dynamic Range
  - Exposure vs. curing
  - But I get readings…..
- Right Application
  - Size, Flat or 3D, etc.
- Right Source
  - Traditional
  - Flash
  - LED
- Right Expectations

Radiometer Types

- Continuous Reading

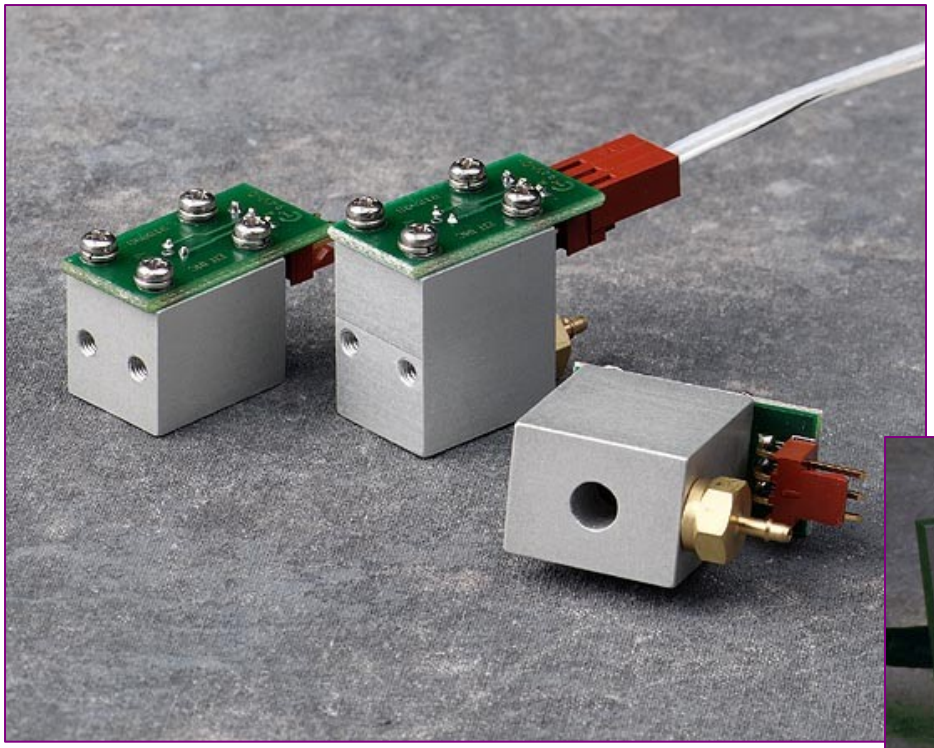


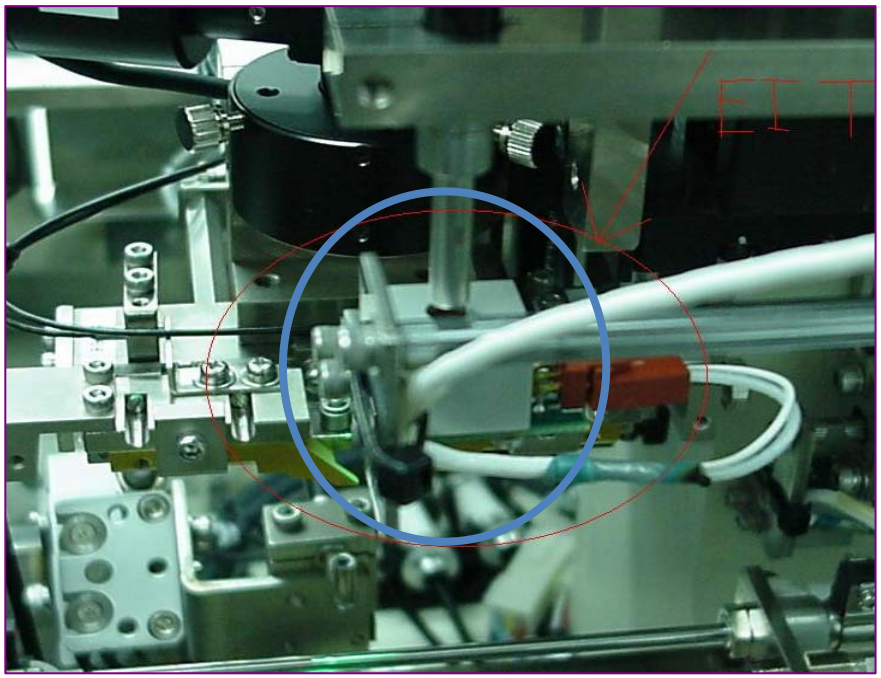
- Logging

- Profiling

- Multiple sensors - e.g. 3D Cure

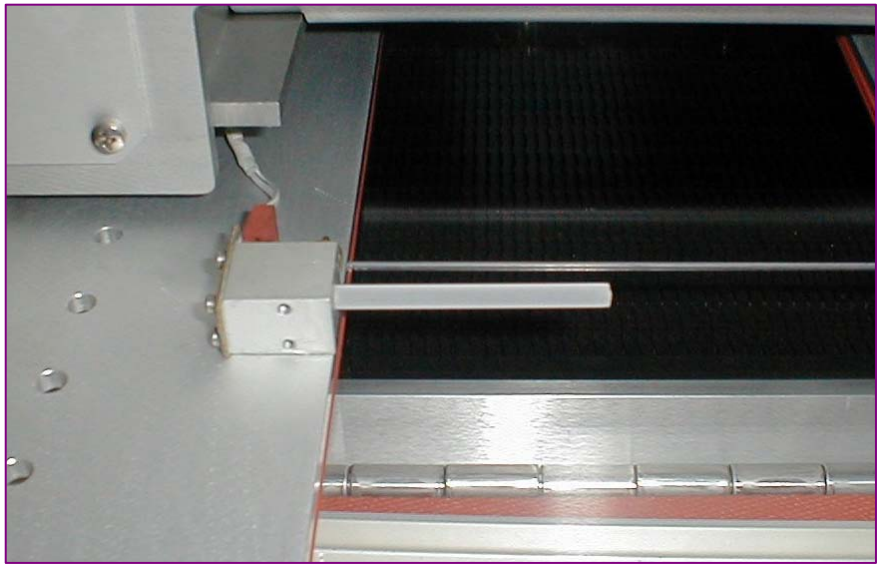
Relative Instrument Examples





Process Sensors

Examples of Compact Sensors used with either spotcure light guides (left) or quartz pick-up rod (below)

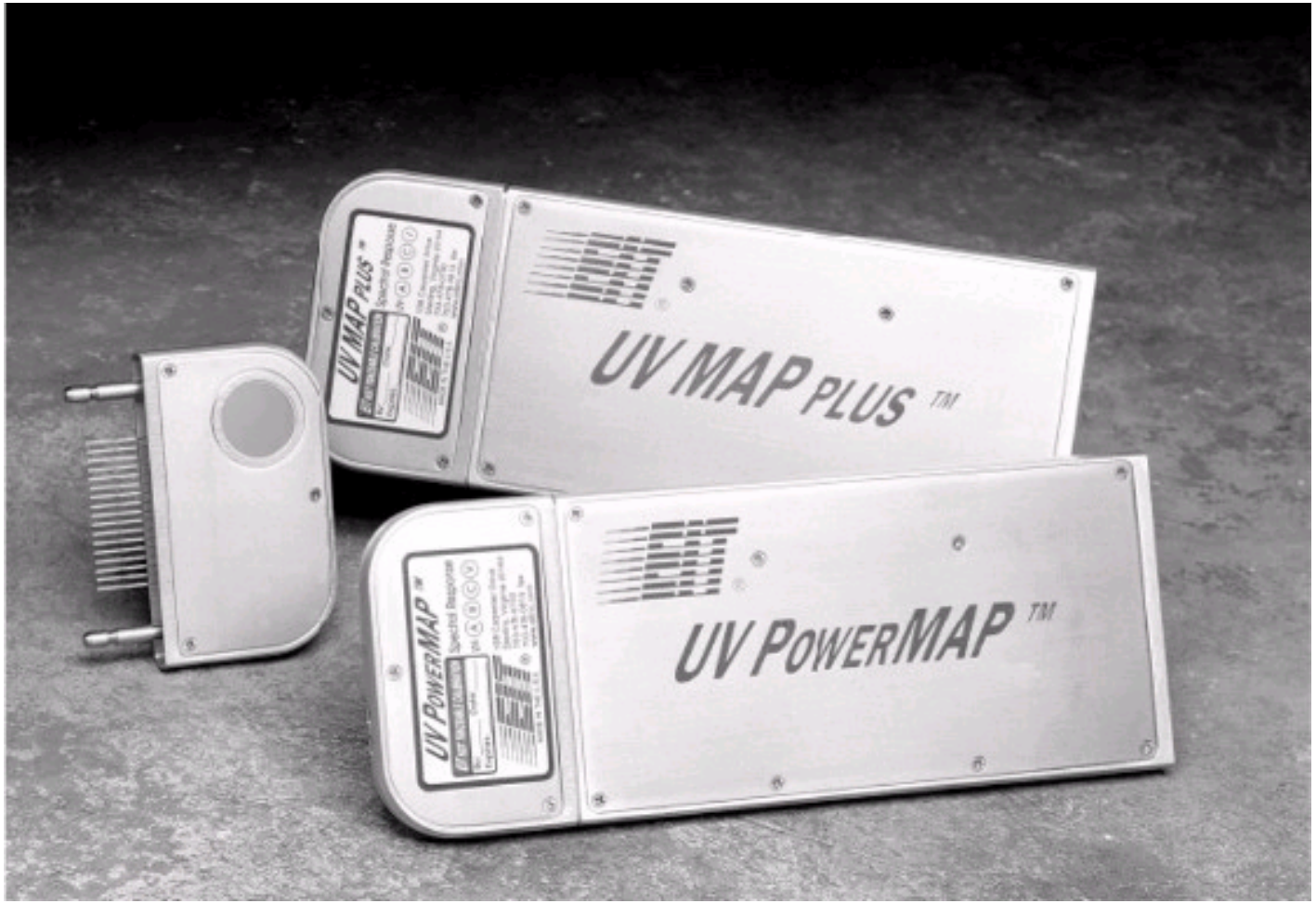


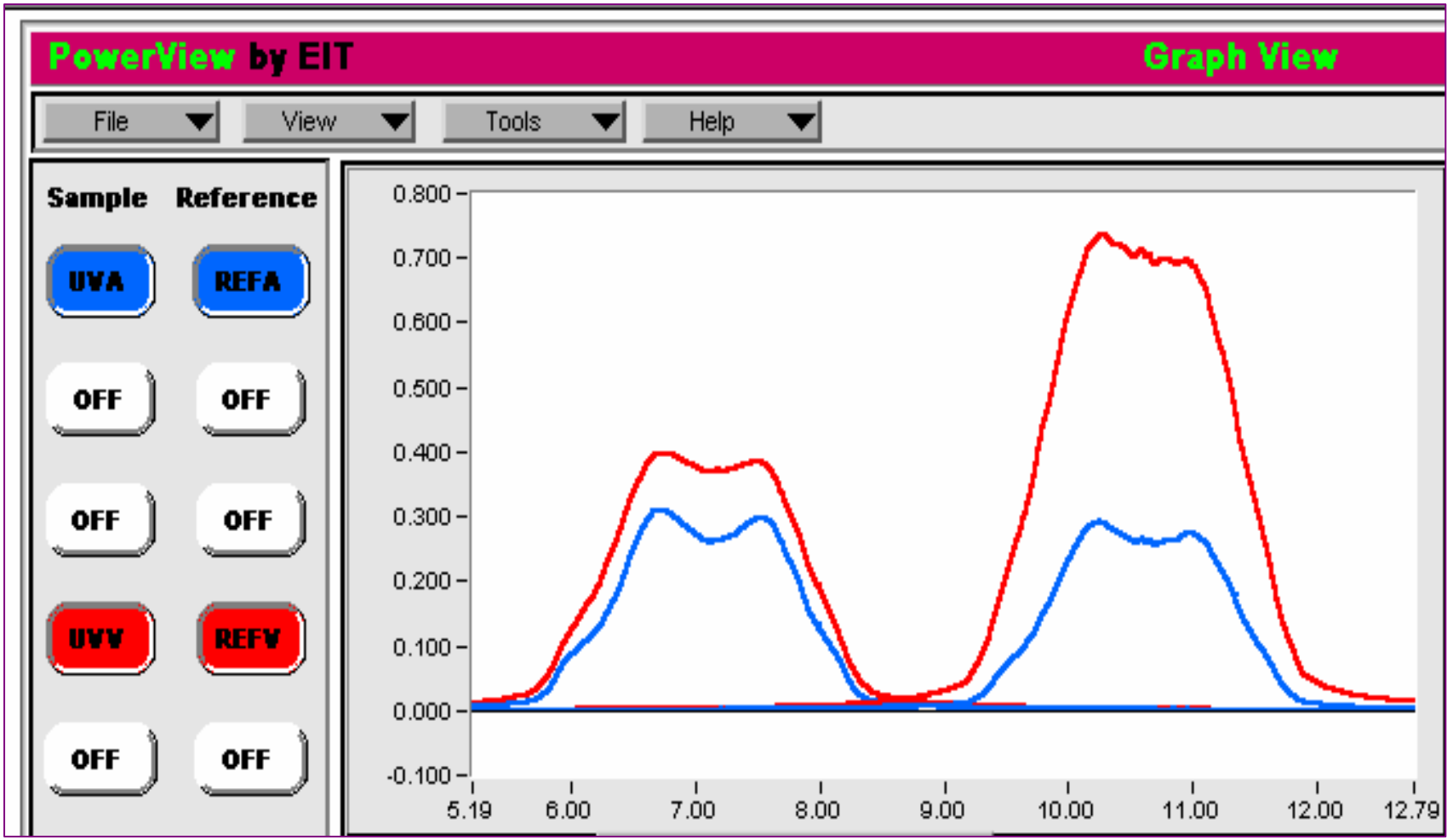
Modern Logging Radiometer

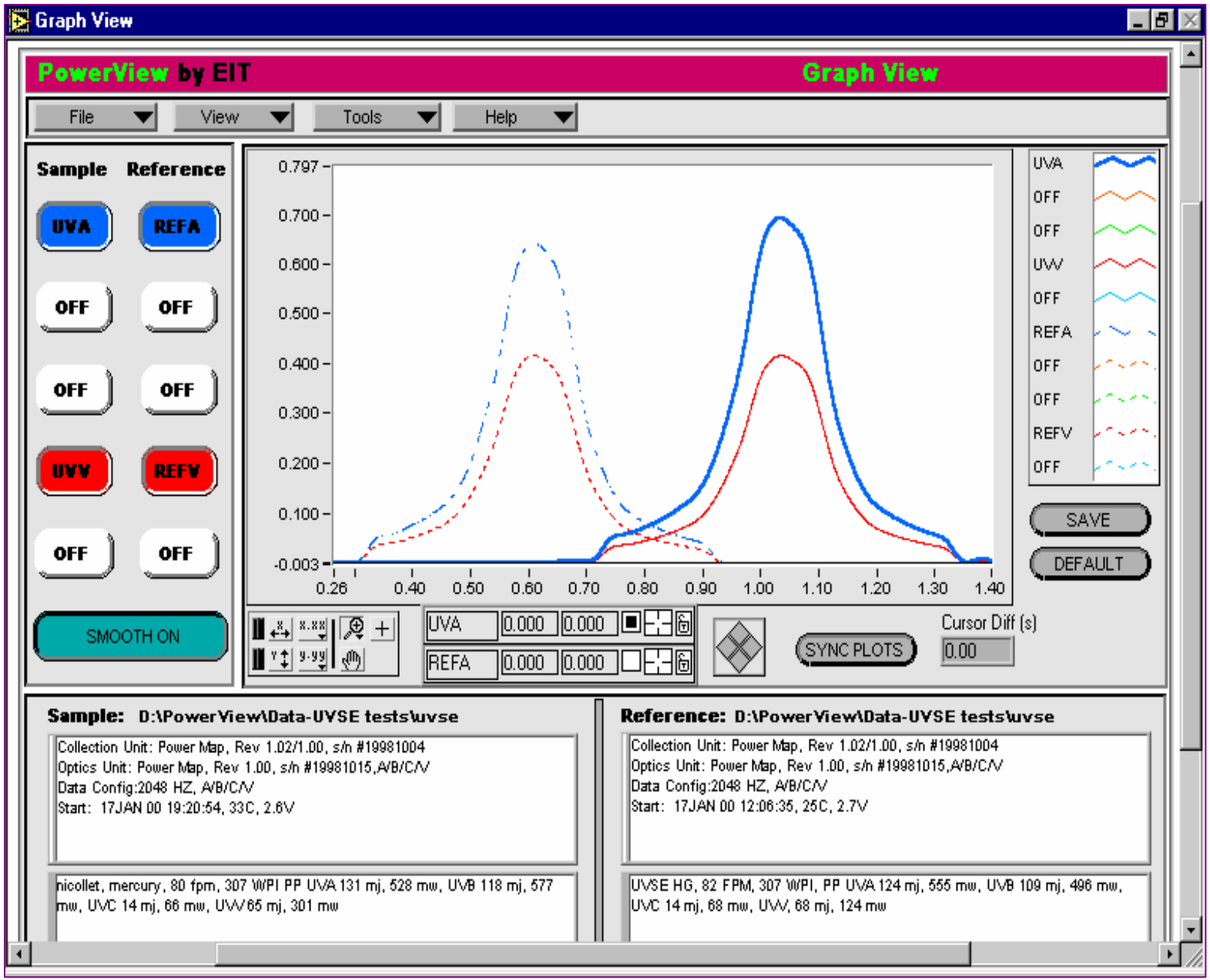
High Speed Loggers for Xenon Lamps

- Modified electronics for pulsed sources
- Electronics designed for pulses between 100-120 times/second
- Provides energy density values
- User adjustable parameters
- User changeable batteries

Profiling Radiometer




PowerView by EIT
Graph View
File
View
Tools
Help
Sample
Reference
UVA
REFA
OFF
OFF
OFF
OFF
UVV
REFV
OFF
OFF
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
-0.100
5.19
6.00
7.00
8.00
9.00
10.00
11.00
12.00
12.79


Graph View
PowerView by EIT
Graph View
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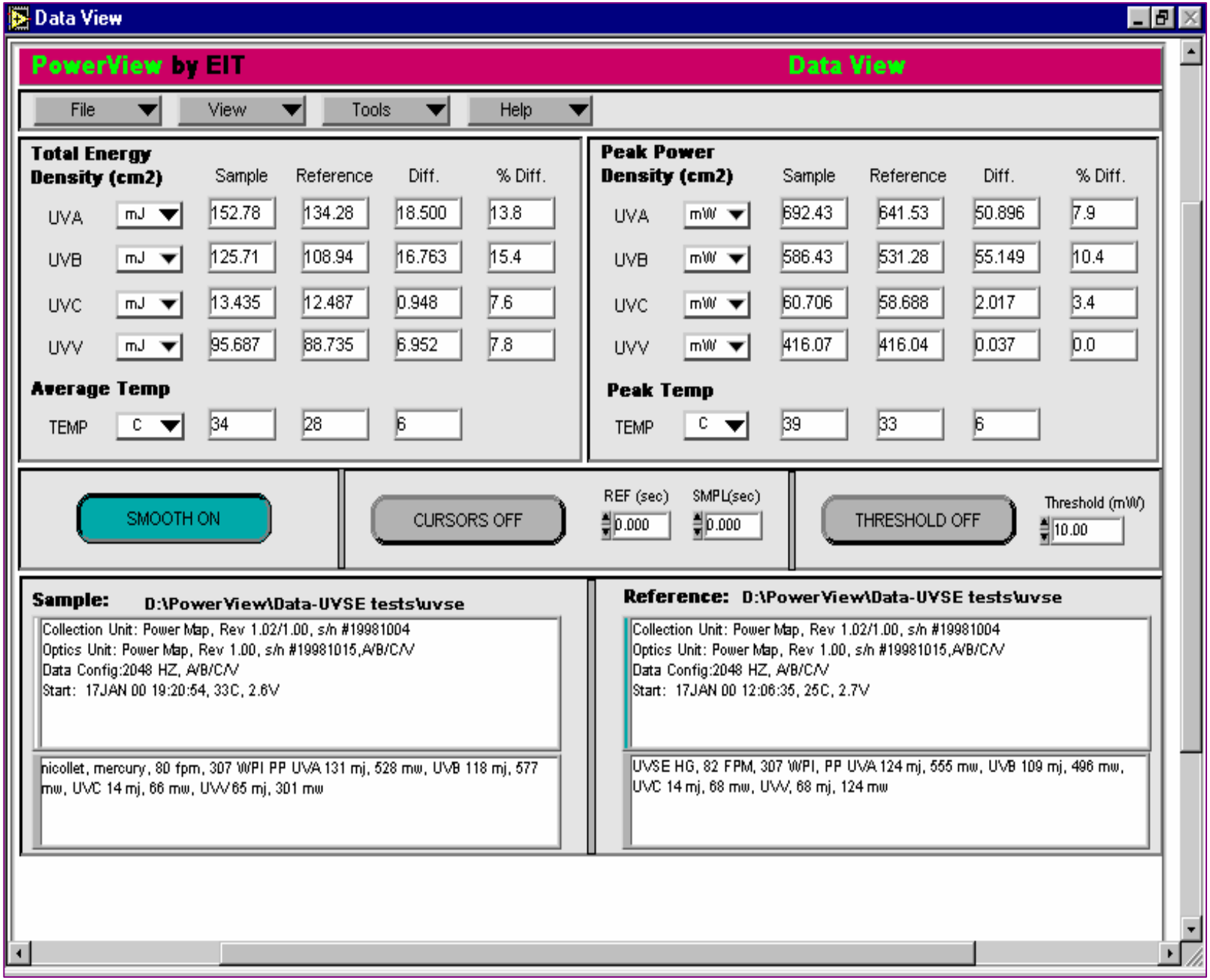
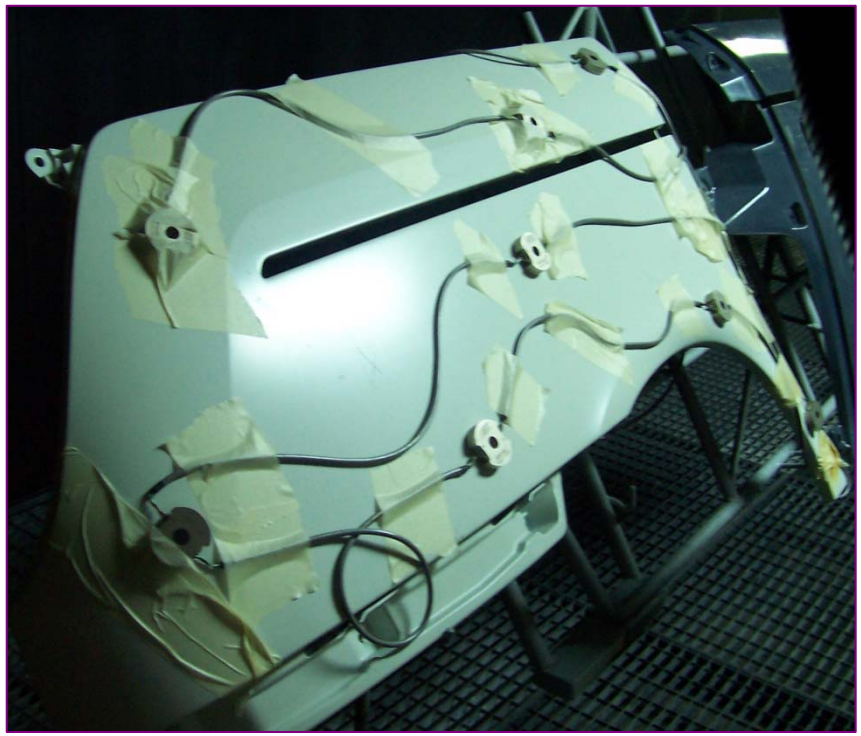
View
Tools
Help
Sample
Reference
UVA
REFA
OFF
OFF
OFF
OFF
UVV
REFV
OFF
OFF
SMOOTH ON
0.797
0.700
0.600
0.500
0.400
0.300
0.200
0.100
-0.003
0.26
0.40
0.50
0.60
0.70
0.80
0.90
1.00
1.10
1.20
1.30
1.40
UVA
OFF
OFF
UVV
OFF
REFA
OFF
OFF
REFV
OFF
SAVE
DEFAULT
UVA
0.000
0.000
REFA
0.000
0.000
SYNC PLOTS
Cursor Diff (s)
0.00
Sample: D:\PowerView\Data-UVSE tests\uvse
Collection Unit: Power Map, Rev 1.02/1.00, s/n #19981004
Optics Unit: Power Map, Rev 1.00, s/n #19981015,A/B/C/V
Data Config:2048 HZ, A/B/C/V
Start: 17JAN 00 19:20:54, 33C, 2.6V
nicollet, mercury, 80 fpm, 307 WPI PP UVA 131 mj, 528 mw, UVB 118 mj, 577 mw, UVC 14 mj, 66 mw, UVV 65 mj, 301 mw
Reference: D:\PowerView\Data-UVSE tests\uvse
Collection Unit: Power Map, Rev 1.02/1.00, s/n #19981004
Optics Unit: Power Map, Rev 1.00, s/n #19981015,A/B/C/V
Data Config:2048 HZ, A/B/C/V
Start: 17JAN 00 12:06:35, 25C, 2.7V
UVSE HG, 82 FPM, 307 WPI, PP UVA 124 mj, 555 mw, UVB 109 mj, 496 mw, UVC 14 mj, 68 mw, UVV, 68 mj, 124 mw

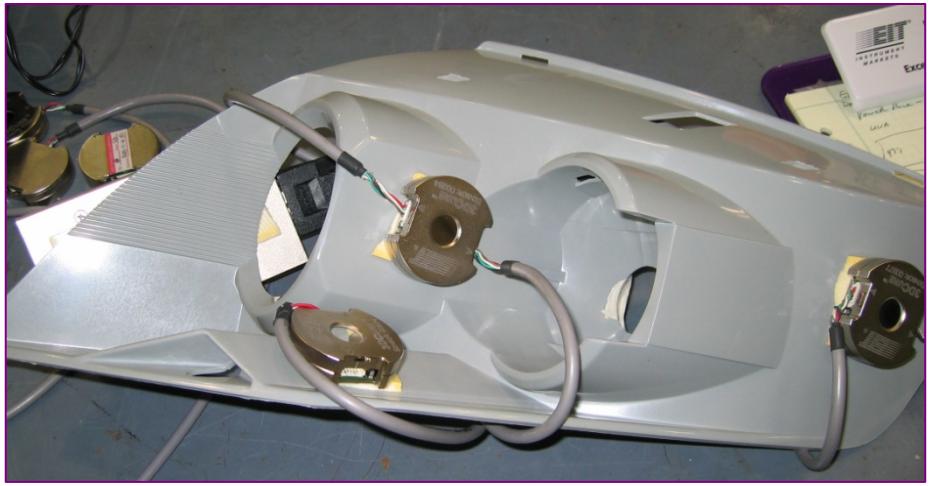

Data View
PowerView by EIT
Data View
File
View
Tools
Help
Total Energy Density (cm2)
Sample
Reference
Diff.
% Diff.
UVA mJ 152.78 134.28 18.500 13.8
UVB mJ 125.71 108.94 16.763 15.4
UVC mJ 13.435 12.487 0.948 7.6
UVV mJ 95.687 88.735 6.952 7.8
Average Temp
TEMP C 34 28 6
Peak Power Density (cm2)
Sample
Reference
Diff.
% Diff.
UVA mW 692.43 641.53 50.896 7.9
UVB mW 586.43 531.28 55.149 10.4
UVC mW 60.706 58.688 2.017 3.4
UVV mW 416.07 416.04 0.037 0.0
Peak Temp
TEMP C 39 33 6
SMOOTH ON
CURSORS OFF
REF (sec)
SMPL(sec)
0.000
0.000
THRESHOLD OFF
Threshold (mW)
10.00
Sample: D:\PowerView\Data-UVSE tests\uvse
Collection Unit: Power Map, Rev 1.02/1.00, s/n #19981004
Optics Unit: Power Map, Rev 1.00, s/n #19981015,A/B/C/V
Data Config:2048 HZ, A/B/C/V
Start: 17JAN 00 19:20:54, 33C, 2.6V
nicollet, mercury, 80 fpm, 307 WPI PP UVA 131 mj, 528 mw, UVB 118 mj, 577 mw, UVC 14 mj, 66 mw, UVV 65 mj, 301 mw
Reference: D:\PowerView\Data-UVSE tests\uvse
Collection Unit: Power Map, Rev 1.02/1.00, s/n #19981004
Optics Unit: Power Map, Rev 1.00, s/n #19981015,A/B/C/V
Data Config:2048 HZ, A/B/C/V
Start: 17JAN 00 12:06:35, 25C, 2.7V
UVSE HG, 82 FPM, 307 WPI, PP UVA 124 mj, 555 mw, UVB 109 mj, 496 mw, UVC 14 mj, 68 mw, UVV, 68 mj, 124 mw

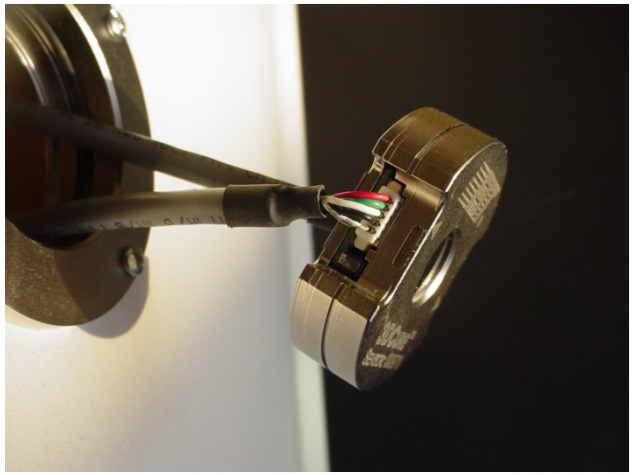
3DCURE™ A Multi-Dimensional

Measurement System For UV Curing Applications

3DCure System Examples

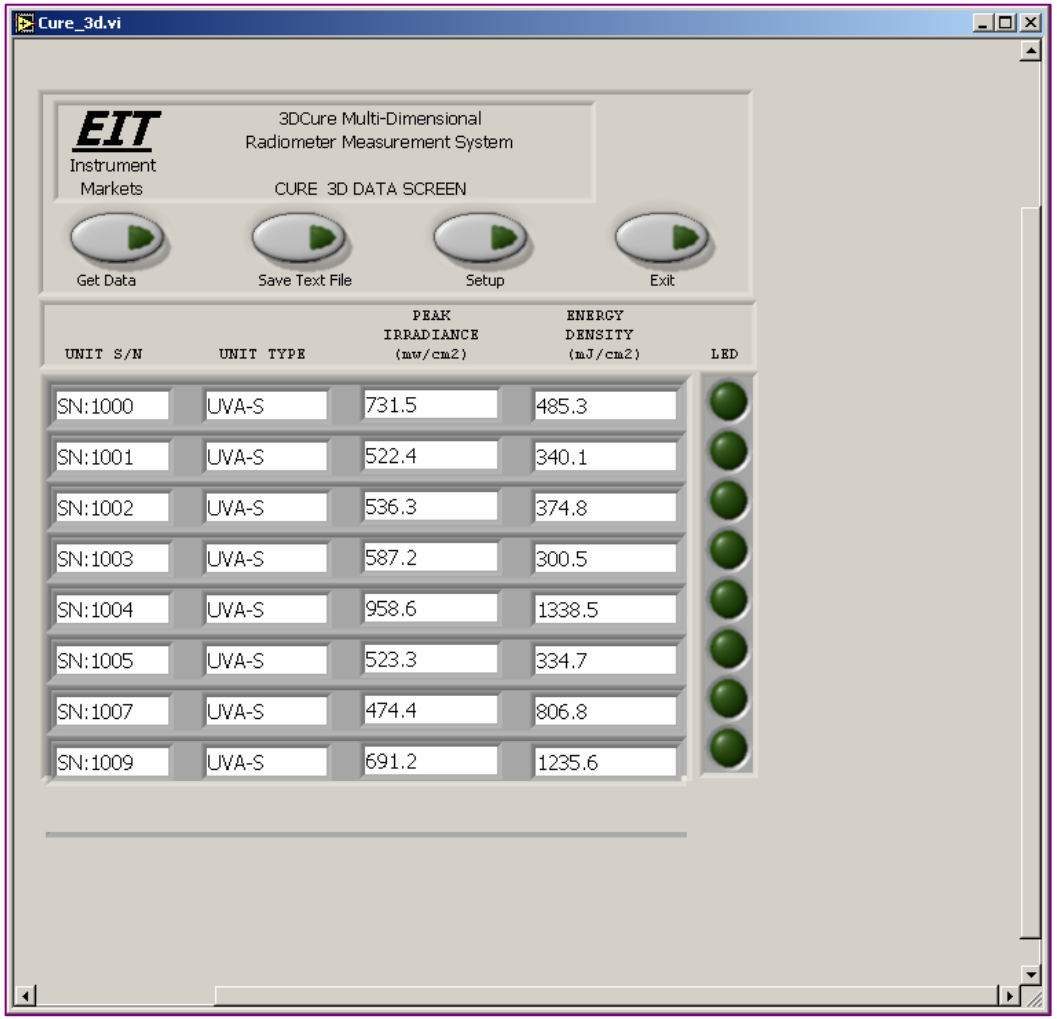


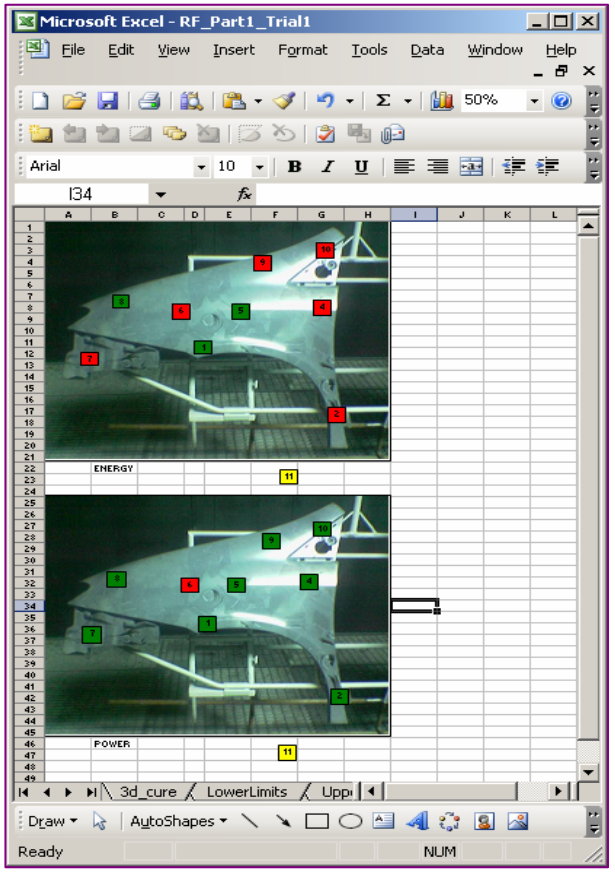


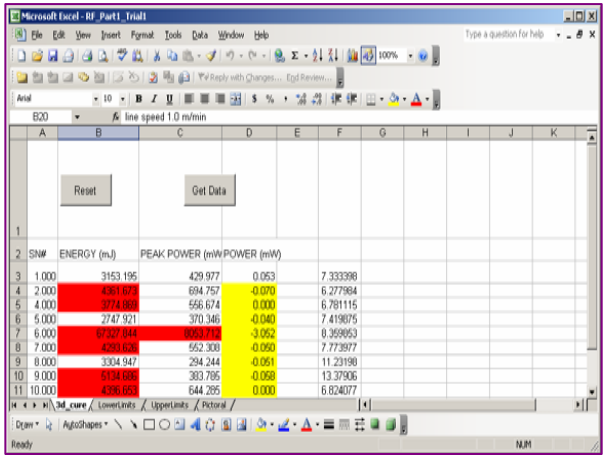


974
972
978
Sensor on end.
977
980
976
Sensor on end.
970
975

3DCure Data Screen (Cure3D)



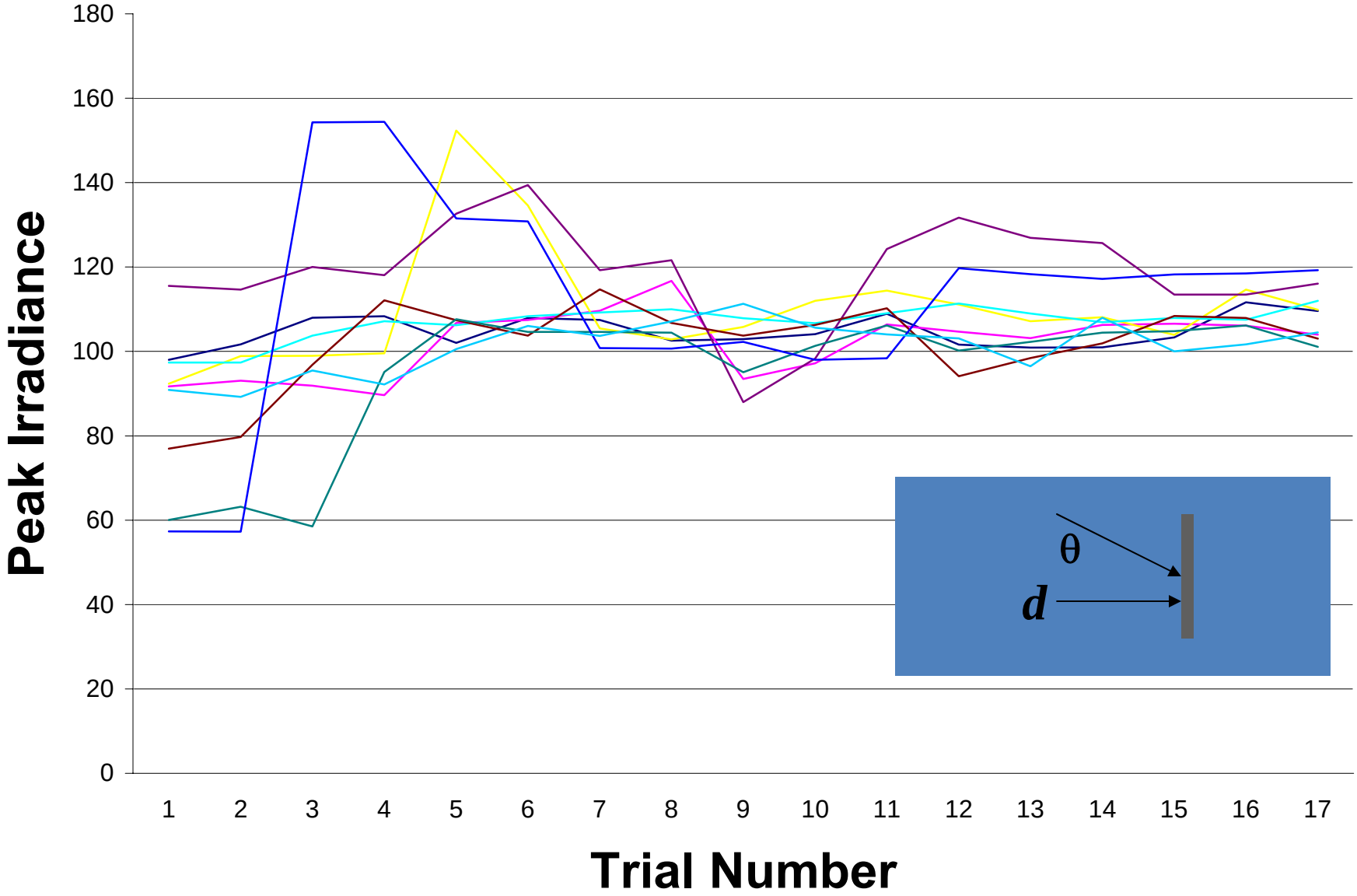




3D Cure Software (Above)

ActiveX Custom Control Example (Right)

Path Tuning for Uniform Peak Intensity



Summary

- A good specification contains information about lamp type, irradiance and energy density (dose) measurements on a specified and appropriate instrument.
- Wavelength is affected by optics, and band-pass filtering
- Irradiance is affected by source intensity, distance (inverse square), temperature and reflector optics (e.g. solarization)
- Energy Density is affected by irradiance as well as sampling rate, and threshold.

Summary

- Edge effects, sagging, poor cooling, reflector design and condition, focus, etc. effect results.
- Calibrate! Instrument variation of +/- 10% is a practical, and unavoidable condition but time and solarization affect accuracy.
- Instrument selection depends on dynamic range, sampling rate, sensitivity, cost, size, etc. as well as many practical issues – the lab should replicate what happens in the field. A common instrument eases comparison.

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Thank You !

UV Measurement For Formulators

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