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

Unacceptable for appearance, intercoat adhesion.

Target 17 min. at 350°F

Unacceptable for humidity, chemical resistance, gasoline resistance.
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
Terms / Units

Wavelength = Nanometers
(“light”)

Peak Irradiance = Watts / cm$^2$
(“intensity”) (“watts”)

Energy Density = Joules / cm$^2$
(“dose”) (“joules”)
Wavelength

Peak Irradiance

Energy Density
Example lamp output power 10 kW

Ultra-violet (100 - 400 nm)

Ultra-violet radiation:
- 25 - 30%
- 2.5 - 3.0 kW

Visible light (400 - 700 nm)

Visible light radiation:
- 5 - 10%
- 0.5 - 1.0 kW

Infra-red (700 - 1000 nm)

Infra-red radiation:
- 60 - 65%
- 6 - 6.5 kW
\[ \lambda = \text{Wavelength} \]

For UV Curing \(~ 200 \text{ nm} \) through \(~ 400 \text{ nm} \)
• **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
UV Relative Penetration

- UVC
- UVB
- UVA
- UVV

Film Thickness

Ink, coating, adhesive thickness

Substrate Surface
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.
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

[Graph showing temperature and time requirements for powder cure, indicating unacceptable conditions for appearance, intercoat adhesion, humidity, chemical resistance, and gasoline resistance.]
Poor Specifications

- Nordson Gallium Lamp
- “5 Seconds under Mercury Lamp”
- “5 Seconds under a 600W/inch lamp”
- “5 Seconds under a Fusion H lamp”
- “Exposure 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%

<table>
<thead>
<tr>
<th>Band</th>
<th>Irradiance (mw/cm²)</th>
<th>Energy Density (mJ/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UVA</td>
<td>1100</td>
<td>2100</td>
</tr>
<tr>
<td>UVB</td>
<td>1500</td>
<td>2600</td>
</tr>
<tr>
<td>UVC</td>
<td>360</td>
<td>450</td>
</tr>
</tbody>
</table>

- 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

<table>
<thead>
<tr>
<th></th>
<th>Irradiance</th>
<th>Energy Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>UVA</td>
<td>2259 mw/cm²</td>
<td>2908 mJ/cm²</td>
</tr>
<tr>
<td>UVB</td>
<td>506 mw/cm²</td>
<td>696 mJ/cm²</td>
</tr>
<tr>
<td>UVC</td>
<td>57 mw/cm²</td>
<td>75 mJ/cm²</td>
</tr>
<tr>
<td>UVV</td>
<td>969 mw/cm²</td>
<td>1275 mJ/cm²</td>
</tr>
</tbody>
</table>
Bulb Type & Focus Reminder
Powder Cure Requirements
Manufacturer’s Recommended Specifications

Unacceptable for appearance, intercoat adhesion.

Target 17 min. at 350°F

Unacceptable for humidity, chemical resistance, gasoline resistance.
Optimization

- Minimum irradiance
  - Lower lamp power
  - Increase distance

- Minimum energy density
  - Less time
  - Faster line speed

- Find point of failure?
Temperature
Time

Wavelength
Energy
Time

Cleavage Type Initiator:
There is a non-linear benefit to increased peak irradiance on overall curing for many UV chemistries.
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

You've been flossing too much and you're not getting enough refined sugar.

The 5th of 4 out of 5 dentists
Wavelength
Peak Irradiance
Energy Density
Single Broadband Instrument
UV Power Puck
Optics Designs

UV

Optical Window/Filter

Diffuser(s)

Aperture opening(s)

Optical Filter

Silicon Photodiode or other type detector
Note the location of the sensor versus the location of the part.
Multiple Band Instrument
UVA-Spectral Bandwidth Comparisons

- **EIT UVA**: 320-390 nm
- **IL UVA**: 250-415 nm

Diagram:
- EIT Power Puck
- IL UVA 250-415 nm
UV Lamp Output Data

Intensity (W/cm²)

Wavelength

1/2 Power Point

1/2 Power Point
UV Bandwidths - UVA2

UVA, UVA2, UVB, UVC, UVV Transmission scan

Normalized %T

EIT Inc.
2/26/09
Wavelength
Peak Irradiance
Energy Density
\[ E_\theta = E \times \cos \theta \]

Cosine Error in Measurement
\[ E_\theta = E \times \cos \theta \]

45° = 0.7 Watt

90° = 1.0 Watt

Cosine Error in Measurement
Cosine Response Error
Spatial Response of Instruments  Goal: Cosine Response
Optics Designs

UV

Optical Window/Filter

Diffuser(s)

Aperture opening(s)

Optical Filter

Silicon Photodiode or other type detector
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 \( = \int d \text{ irradiance} \)
Equal Joules ≠ Equal Cure

Irradiance

Time
Low Sampling Rate = Less accurate for both Peak and Energy Density
What works well at one line speed…
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.
Pulsed Xenon Source
Pulsed Lamp Source - 4 Pulses
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 = \int \frac{d \text{ irradiance}}{dt}
Radiometer Variations-Threshold

40 mW

UV W/cm²
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

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

Speed: 33 fpm/10 mpm
Radiometer Variations - Sample Rate

**Speed:** 240 fpm/74 mpm

Total Time under UV reflector: 0.18 seconds

Time under Peak irradiance: 0.08 seconds

<table>
<thead>
<tr>
<th>Inst. Sample Rate (#/sec)</th>
<th>Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>4</td>
</tr>
<tr>
<td>40</td>
<td>7</td>
</tr>
<tr>
<td>128</td>
<td>23</td>
</tr>
<tr>
<td>256</td>
<td>46</td>
</tr>
<tr>
<td>1024</td>
<td>184</td>
</tr>
<tr>
<td>2048</td>
<td>368</td>
</tr>
</tbody>
</table>
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%)
- Independently test and confirm dwell time or belt/line speed

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

- Peak Irradiance remains the same-Slight 2.9% difference

- Radiant Energy Density changes as a function of the process speed
  - At 4 fpm: 2096 mJ/cm²
  - At 10 fpm: 860 mJ/cm²
  - 143% difference in Radiant Energy Density between the two speeds
Sagging

• Middle reading lower on middle to end

• 15% difference in irradiance levels
• Rotate bulbs

Cooling issues?

Life After The UV Honeymoon

Aging

• Middle reading higher

• Arc bulb aging on ends

• 440 mW/cm² (middle) vs. 317 mW/cm² (end)

• Width of source to width of product?

• Time to replace bulb?
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

![Graph showing UV intensity over time in seconds]

- UV W/cm²
- Time in seconds
Parabolic vs. Elliptical reflectors

Parabolic Reflector

Elliptical Reflector

Parabolic vs. Elliptical reflectors
Parabolic Lamp

Not always bad-gloss control on wood for example
• Readings on a two lamp system
  – Energy Density: 953 mJ/cm² (UVA EIT 320-390)
  – Irradiance: 313 mW/cm² (UVA EIT 320-390)

• After: Readings on the same system
  – Energy Density: 1203 mJ/cm² (UVA EIT 320-390) + 26%
  – Irradiance: 449 mW/cm² (UVA EIT 320-390) + 43%

• Only one thing done Reflectors were cleaned

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/cm²  
**UVA** Irradiance: 309 to 290 mW/cm²
Change Now?

UVV Energy Density: 737 to 1331 mJ/cm²
UVV Irradiance: 397 to 734 mW/cm²
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/cm²
    • Production UV levels: 100’s to 1000’s mW/cm²
  – 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
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
3DCURE™ A Multi-Dimensional Measurement System For UV Curing Applications
3DCure Data Screen (Cure3D)

3D Cure Software (Above)
ActiveX Custom Control Example (Right)
Path Tuning for Uniform Peak Intensity

Peak Irradiance

Trial Number
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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UV Measurement For Formulators

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