

# SUCCESSFUL UV CURING & COMMUNICATION FOR PRESSURE SENSITIVE ADHESIVES (PSAs) *It's as simple as a Day at the Movies*

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## **Introduction**

Pressure sensitive adhesives are used in a wide range of applications from simple stickers and tapes to LCD screen protectors and RFID labels. While many of these products use conventional adhesives, a growing share of the market utilizes UV cured formulations. Along with environmental, health and safety benefits, UV formulations also enhance the temperature and chemical resistance properties of PSAs. A roll of finished film used for medical devices, electronic components, or packaging can be worth as much as \$30,000 and better process control can have a significant financial impact for applicators.

Imagine attending a movie filmed in a language that you do not understand. Without the help of subtitles, chances are that you would miss much of the story. If you do not understand the finer points of your UV process, it too is also in a language that you do not understand. Chances are you will also have trouble understanding the story which is establishing, maintaining and operating a profitable UV process.

Borrowing from movie titles and themes, this paper and corresponding presentation addresses key topics and themes for successful UV Curing and Communication of Pressure Sensitive Adhesives (PSAs). Each "movie review" will offer information, concepts and tips that can be utilized in the lab and the production floor. This paper also covers communication to make sure all stakeholder groups (lab, production, different manufacturing facilities, supply chain and customers) are communicating clearly and in the same technical (UV) language.

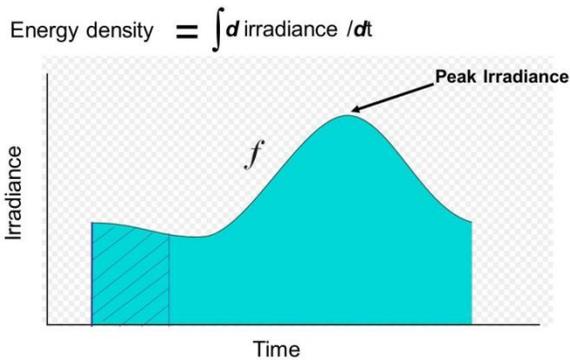
## **Prequel: 10,000 BC**

This Prequel section is included to make sure we are all communicating in the same language-the language of UV. Key terms and concepts that are important to successful UV Measurement include:

**Irradiance** is the radiant power arriving at a surface per unit area. With UV curing, the surface is most often the substrate or film and a square centimeter ( $\text{cm}^2$ ) is the unit area. Irradiance is expressed in units of watts or milliWatts per square centimeter ( $\text{W}/\text{cm}^2$  or  $\text{mW}/\text{cm}^2$ ). Irradiance better describes the concept of UV arriving at a two-dimensional substrate than the word intensity which is also sometimes used to describe radiant power. In Figure 1 below, the irradiance varies with time as the product moves under the UV source. Many radiometers report only the highest irradiance value (peak) while others can report the irradiance as a function of time (irradiance profile). How well your radiometer captures the "peak" value is a function of the radiometer sampling rate and line speed.

**Radiant Energy Density (Energy Density)** is the energy arriving at a surface per unit area ( $\text{cm}^2$ ) with joules or milliJoules per square centimeter ( $\text{J}/\text{cm}^2$  or  $\text{mJ}/\text{cm}^2$ ) used as the units. The radiant energy density is the time integration of the irradiance with one watt for one second equaling one joule. In an exposure where the irradiance value is constant over time (square profile exposure), the radiant energy density could be estimated from this relationship. Most exposures in UV curing have the product move into an intense UV area and then out as it exits the UV system. The profiles with moving exposures are

not ‘square profiles’. To determine the radiant energy density in a moving exposure, the radiometer calculates the ‘area’ under the irradiance curve. In UV curing, the term ‘dose’ has commonly been used to describe radiant energy density. Decide what term you will use in your facility. Radiant energy density is important for total and complete UV cure. In Figure 1, the Radiant Energy Density is the area under the curve in blue.



**Figure 1. Graphic representation of the peak Irradiance, irradiance profile and Energy Density under the curve. The section with diagonal lines represents the time between instrument sample points. Thousands of these individual sections are used to calculate the radiant energy density.**

**Wavelength** As the name implies UV or ultraviolet light is beyond the violet end of the visible spectrum that we can observe with our own eyes. Light is typically described by its wavelength expressed in nanometers (or nm, a billionth of a meter). Most agree that the UV spectrum ranges from around 200nm to about 400nm at the longer, visible end of the spectrum. By convention, the UV band has been further subdivided into a few large “bands” that are important to the properties of cured formulations (See Figure 2)

Band Name	Wavelength Range (nm)	Properties and Sources
UVC	200 - 280	Shortest wavelength, greatest effect on surface
UVB	280 - 320	Mid-range, penetrates
UVA	320 - 390	Longer range penetrates thicker adhesives, pigmented systems
UVV	395 - 445	Visible longest wavelength, LED sources popular

**Figure 2. The UV spectrum and UV band designations.**

**Other Variables** There are ‘other’ variables beyond the irradiance and radiant energy density values (Watts/cm<sup>2</sup>, Joules/cm<sup>2</sup>) that you may need to document, monitor and measure in your process and equipment. Consider tracking the following:

**Line Speed/Dwell Time:** The line speed/dwell time is important because it controls the amount of time that your product is exposed to UV. Faster speeds mean less exposure time to UV and slower speeds mean more exposure to UV. The relationship between line speed and the amount of UV (radiant energy density-Joules/cm<sup>2</sup>) reaching your substrate is inversely proportional. Doubling the line speed will cut in half the radiant energy density. Check and confirm your line speed.

**Hour Meter:** Many UV systems have an hour meter that allows you to track (with a little subtraction) the number of hours on the current bulb in the lamp housing. This number is worth tracking over time but keep in mind that the information it provides will only give you an estimate of bulb life. The hour meter does not indicate the number of UV system starts and stops, which can be hard on a bulb. The

hour meter does not indicate if the bulb has been running hot or cool or if there is contamination deposited on the bulb's surface.

**Amp Meter:** Many UV systems have an amp meter that allows you to track incoming electrical power. Keep an eye on the amp meter, especially if you are in an area prone to power fluctuations or if you find that you are close to the minimum amount of UV to cure your product.

**Reflectors/Quartz Plates:** The reflector is one of the workhorses in any UV system. It is estimated that 60-80% of the energy that reaches the substrate is reflected energy. In order to maximize the amount of UV reaching the cure surface, the reflector has to be properly maintained and kept clean. Dirty reflectors can reduce the irradiance value by over 50%. If you have quartz plates between your UV source and cure surface, these also need to be properly maintained. Be sure to use quartz plates that are equivalent to the original quartz if they need to be replaced.

RadTech International North America has produced a Glossary of Terms for UV Curing Process Design and Measurement. The glossary is posted on the RadTech website: <http://www.radtech.org/intro-to-uv-eb/uv-glossary> and it can help all users and suppliers communicate in a common language when it comes to UV measurement and process control.

UV curable PSAs have several key advantages compared to conventionally cured systems. These include:

- ✓ No solvents
- ✓ Lower application temperatures
- ✓ Improved chemical resistance
- ✓ Better shear at higher temperatures

And, while a number of UV curable PSA chemistries have been developed for various applications, many of the principles behind proper curing of UV PSAs applies broadly. The rest of this paper is therefore devoted to good practices of UV cure for PSAs generally.

**Now, let's go to the movies...**

## **1. The Cool Hand Luke: "We Have a Failure to Communicate"**

### **Internal/External Communication**

Communication can be internal (within your company even though there may be different facilities in different locations) or external (within your supply chain). It is important that all parties talking speak the same language.

### **Variation in Instrument Responses between Manufacturers**

Instruments that measure UV have different spectral bandwidths and spectral responses. It is often hard to directly compare instruments because of these differences. Some instruments are classified as narrow band while others are broadband instruments. R.W. Stowe of Heraeus Noblelight (formerly Fusion UV Systems) advocates adding identifying instrument information to numbers. Instead of just reporting 900 J/cm<sup>2</sup>, report 900 mJ/cm<sup>2</sup> (state the instrument name and response such as Brand X UVA) or 900 mJ/cm<sup>2</sup> (320-390 nm) to avoid any misunderstandings.

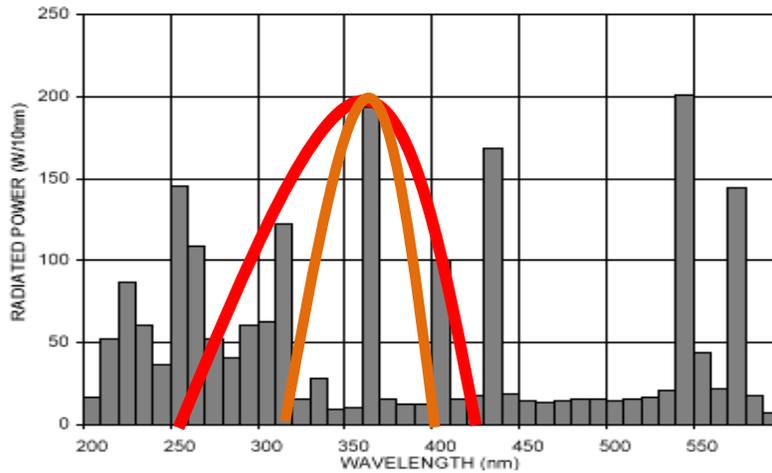


Figure 3. Comparing the response of two popular UVA radiometers.

Figure 3 illustrates the difference in the response of two different popular UVA bands from different manufacturers. You can see that one instrument has a narrow response and that one instrument has a wider broadband response. Both are sold as UVA instruments.

**Instrument Values**

When comparing readings, even within the same instrument family, make sure that the settings are the same. Many newer instruments have a faster sampling rate than older legacy instruments. Some radiometers have the ability to sample fast enough to see the cycling of 50/60 Hz AC driven power supplies. Products can report the RMS irradiance value (Smooth ON) or the instantaneous peak irradiance (Smooth OFF) value.

The readings shown in Figures 4A and 4B below are from the same lamp under the same conditions and show that the effect of smoothing can be substantial. In the measurement shown by the left panel (4A), with smoothing turned “ON”, the peak irradiance reported is 910 mW/cm<sup>2</sup>. Smoothing is turned “OFF” in the right panel (4B) and the peak irradiance is 1866 mW/cm<sup>2</sup>.

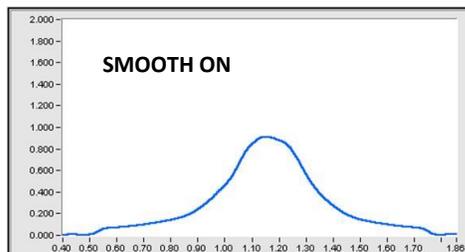


Figure 4A. Measurement with Smooth ON

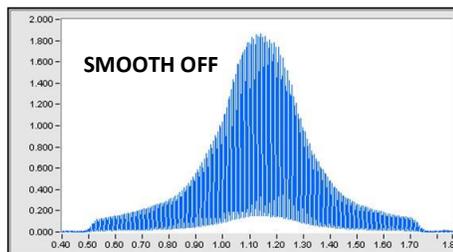


Figure 4B. Measurement with Smooth OFF

Technically both values are correct as long as the underlying assumptions are explained. You need to understand your radiometer and decide as a company and with your supply chain on what you will report. The best choice may depend on the instrument you use and a number of chemistry, equipment and process parameters. But once again, what is critical is to recognize the influence of *how* we measure, and how we *report* measurements, so they can be understood, interpreted and if needed repeated.

## Formulator Data Sheet Specifications

Formulator Data Sheets are generally a starting point for the amount of UV you will need to cure a particular adhesive. Work with the formulator of your choice to get more information and run tests so that you understand what is needed. There are some very good data sheets from formulators and also some data sheets that are so generic that you need to start at square one to figure out what is needed to cure a product.

## Measurement Strategies

In order to measure UV, an instrument or sensor has to be exposed to the UV in your system. Instruments and sensors can be passed through, inserted into or mounted permanently into the UV system. Instruments and sensors can provide either absolute or relative numbers. What strategy are you looking for to control your process?

**Absolute Instruments:** Instruments calibrated against a standard. For UV curing applications, absolute instruments most often report Watts/cm<sup>2</sup> or Joules/cm<sup>2</sup> for the spectral bandwidth(s) of the instrument. A radiometer can report the highest irradiance measured (peak irradiance) and/or a profile of the irradiance over time (irradiance profile). Absolute reading instruments allow comparison between different UV systems, different locations and between suppliers and customers; for example, a coating or adhesive formulator and user of the material.

**Relative Instruments:** Relative instruments provide feedback to the user on the 'relative' intensity of UV reaching the sensor. A display, monitor or output signal is adjusted (often to 100%) when conditions are ideal (clean reflector, new bulb). The display will change as the relative intensity of the UV changes. Relative monitors are good for measuring UV on systems where the process window is small, where an absolute radiometer cannot be passed through or inserted into the system or where continuous feedback of the process is needed.

The definition of terms along with knowing how to measure and what instrument to use are an important (and necessary) and necessary first step in clear communication. We cannot communicate without a common language and set of rules. Most UV curing processes are characterized by the same three important variables: wavelength, irradiance, and energy density (or dose) although as we regularly see that other aspects such as what instrument was used, along with other potentially influential variables (such as temperature) should be recorded.

Info	Notes	Notes
Model PowerPuck2 Profiler Board Temperature 27 Battery Voltage 1.26546 Firmware Version 5 Serial Number 16772 Calibration Date 2012-05-29 Smoothing Profiler Date & Time 8/17/2012 3:46:11 PM	UV System Line: Lamp Number: Equipment: Lamp Type: Power Setting: Line Speed/Exposure Time: Reflector Poistion: Product: Product Notes: Maintenance Notes:	Formulator Product Name: Thickness: Application Method: Photoiniator: Photoiniator Concentration: Oligimer Type: Monomer Type: Additives: Trial Conditions:
UVA J/cm2 W/cm2 1.257 1.246 UVB 0.505 0.513 UVC 0.061 0.064 UVV 1.127 1.098		

**Figure 5. Data from your UV radiometer coupled with system, process, formulation and Quality/test data give you the details needed to produce a consistent product.**

We recommend that all PSA applicators discuss their application with the formulator and equipment suppliers to determine a comprehensive list of process parameters, the nominal values for each, the tolerance range for each, and the frequency with which they should be checked. This discussion should

result in the creation of a maintenance log and set of standard procedures for ensuring the appropriate level of quality control. Some parameters may be more forgiving and require checking only every shift or even every couple of days. Others may require more frequent checks or even constant monitoring. Some of the latest generation of UV profiling radiometers even provide the ability for the operator to record and store important information as part of the radiometer data file. This could include such information as the time and date of the measurement, the operator's name, and other details such as the adhesive thickness and other notes. (This electronic note taking ability is shown in Figure 5 above).

## 2. The Star Trek: "Scotty We Need More Power"

UV irradiance is important in your process because it provides the power or 'punch' to:

- Penetrate through opaque and pigmented coatings
- Give depth of cure and adhesion to the substrate

A higher irradiance value may allow you to run faster production speeds but it is more important to understand what your adhesive needs in order to properly cure.

**Lamp Power:** The numbers associated with lamp power are often confused with the amount of UV reaching the surface being cured. Lamp power is the electrical power applied to the UV system. Watts per inch (WPI) or Watts per centimeter (WPCM) are the units with values typically between 200-600 WPI or 80-240 WPCM. The numerical value is calculated by:

$$\frac{\text{Voltage} \times \text{Amperage (Watts)}}{\text{Arc length of the bulb (inch or cm)}}$$

The WPI/WPCM is electrical power applied to the system. It is not the effective amount of UV generated nor is it the effective amount of UV reaching the cure surface. Effective UV is the UV matched to your chemistry and process and delivered to the cure surface. The UV energy that reaches the cure surface is usually very small compared to the power applied to the system. A typical 300 WPI (120 WPCM) system may only have 0.5-4 watts per square centimeter ( $\text{W}/\text{cm}^2$ ) of effective UV reach the cure surface. The value can vary tremendously between different manufacturers and system types. Do not use the applied power as a measure of effective UV reaching the cure surface. Work with equipment suppliers and measure UV with a radiometer to compare different systems or power settings.

Running a product under the same UV source twice does not double the irradiance, it will double the number of Joules/ $\text{cm}^2$ . Multiple passes under the lamp does not increase watts.

Most UV applications are fairly forgiving about adding a little extra UV energy. It's hard to "over-cure" many inks or coatings unless the associated temperatures get too high, or some yellowing and discoloration become noticeable. This is not the case with UV curable PSAs however. Pressure sensitive adhesives often need to have the right balance of adhesive and cohesive forces and there can be a distinct tradeoff between UV energy density (dose) and these properties.

PSAs performance can be evaluated in terms of tack, peel adhesion (adhesion) and shear strength (cohesion). Tack is the ability of an adhesive to adhere quickly. Peel adhesion is the ability to resist removal by peeling and shear strength is the ability to hold in position when shearing forces are exerted. Generally, tack and peel adhesion are directly related to each other but are inversely related to shear strength.

As shown in Figure 6, beyond a certain energy, the tack properties of PSAs can be compromised. When the UV energy density increases, the holding power drastically increases because of increased polymerization and cross-linked networks in the adhesive, which lead to higher cohesive strength. Since the peel strength decreases with UV-dose, while the holding power increases, the proper performance of a UV-curable PSA could critically depend on establishing and maintaining the right UV cure process window. The temperature at which the adhesive layer fails is noted as the shear adhesion failure temperature (SAFT) and serves as a guide to the high-temperature performance of the adhesive.

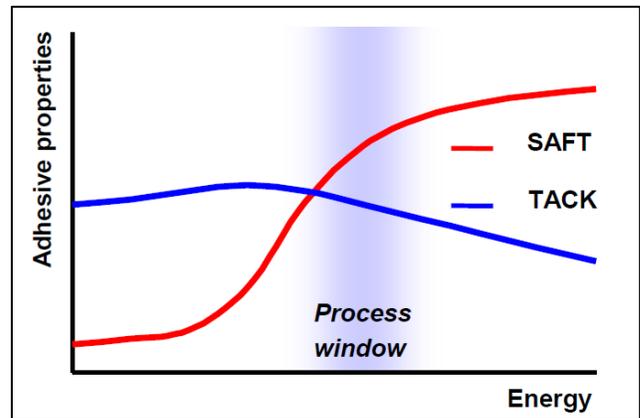


Figure 6. Source: UV Curable Pressure Sensitive Adhesives, (Petra Berger, Heraeus-Fusion UV Systems)

### UV LED Lamp Power –So Watt?

The above “more is better” discussion is important to the proper curing of UV PSAs. But even if proper cure is not at issue, the user should be aware that some skepticism and sophistication about the total output claims about UV light source output is healthy. For conventional sources, specifications of “Watts per Inch” do not provide much meaningful information when it comes to the UV cure process. This measurement refers to the maximum electrical input of electrical power to the system. A 400 watt per inch lamp that is 10 inches long consumes 4000 watts of electrical power. But this does not tell you how much UV is being generated, how much is reaching the cure surface and more importantly if the UV is of the right wavelength. Much of the energy of a UV mercury lamp is not useful UV energy, but rather heat, and visible light. A UV LED consumes much less power and may provide equivalent or even better curing if the match between the UV source and chemistry is optimized and sufficient.

Even among UV LED providers however, boastful claims of how many watts the LED produces should be evaluated carefully. The important criterion is the energy of the desired wavelength delivered to the material to be cured. This value should be obtained from the adhesive supplier, and the UV source should be selected which meets this specification.

### Bottom Line Questions:

- Is your UV source matched to your formulation?
- Does your source (arc, microwave, LED, pulsed) and process control allow you to consistently produce good quality products?

### **3. The Top Gun: “I Feel a Need for Speed (& Air)”**

Too often the temptation when production gets backed up is to turn up the line speed. As we have stressed, the energy density which is one of the critical measures of UV curing depends directly on time. Speeding up the production line does not change the irradiance of the cure process, since the peak intensity of a lamp is unaffected by the process speed. But a faster line speed directly affects the exposure time of the PSA to the light source, reducing the effective energy density. As we have seen, this directly affects the adhesive and cohesive properties of the PSA. When the UV energy decreases,

the holding power dramatically decreases because of reduced polymerization and cross-linked networks in the adhesive.

Just as planes need moving air for lift, UV curing systems need moving air for proper lamp cooling. In fact some UV systems have sensitive air pressure sensors to ensure that proper cooling is used to prevent the lamp from failing. Inadequate or poorly cooled sources may have shorter lamp life and have decreased and non-uniform output across the length of the UV lamp that can result in inconsistent and inadequate UV cure.

#### 4. The Color Purple: “What’s the Frequency”

**Spectral Output:** The spectral output of your UV system must be matched to your process and chemistry. There are many types of bulbs available. The type of bulb that you use will depend on your formulation, equipment, type of process and desired results.

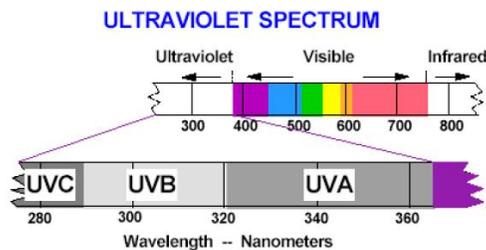


Figure 7. The UV spectrum and position of the UV bands.

The UV portion of the electromagnetic spectrum includes wavelengths from approximately 100 to 400 nanometers (nm). The spectral output of the UV system must be matched to the process and the chemistry. There are many types of bulbs available. The type of bulb used will depend on the formulation, equipment, type of process and desired results. Visible light uses with color names (red, orange, yellow, etc.) to identify spectral ranges. UV also has spectral ranges and these are identified by letters (A, B, C) as shown in Figure 7. It is not unusual to note slight variations in the spectral range descriptions depending on the paper or source.

- **UVA: 320-390 nm** The UVA bandwidth contains the long UV wavelengths. Mercury type UV bulbs contain a major band of UV energy at 365 nm. Most adhesives are formulated to respond to UVA. UVA provides adhesion of the adhesive to the substrate.
- **UVB: 280-320 nm** The UVB bandwidth assists with the curing of adhesive and provides toughness to the adhesive.
- **UVC: 200-280 nm** The UVC bandwidth contains the short UV wavelengths. The majority of UVC energy in this bandwidth is located in the 220-260 nm regions. UVC is important for surface cure and determining the texture, stain, chemical and scratch resistance of an adhesive.
- **UVV 395-450 nm** The UVV (UV-visible) bandwidth contains the ultra-long UV wavelengths. There is no precisely defined boundary between UV and Visible Light, and the boundary is considered between 400-450 nm. UVV is an important bandwidth because on a relative basis it has the ability to better penetrate through adhesives, especially those that contain titanium dioxide. Additive (mercury-gallium or mercury-iron) bulbs, which are rich in longer wavelengths, are often used for opaque adhesives where adhesion or depth of cure to the substrate is a problem. The additive bulbs must be matched to the formulation and UV system.

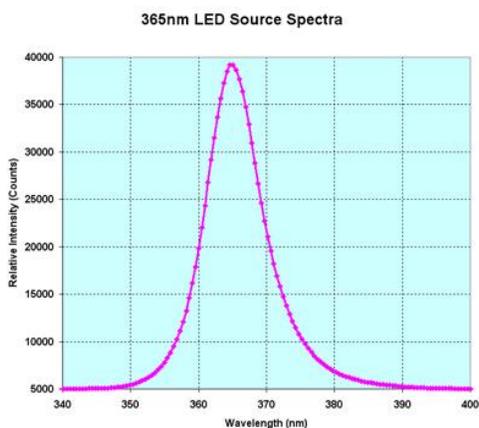
A radiometer that can measure irradiance and energy density in each of the UV bands that are important to your PSA process can help identify a number of cure related issues. For example, operators can install the wrong wavelength lamp when doing routine maintenance. Since different PSA formulations are more sensitive to some wavelengths than others, this could result in big problems with UV cure. And, this problem might go undetected if looking at the wrong wavelength, or if all UV measurements are aggregated. But by examining the spectral output of each band this problem is easy to detect and remedy.

Spectral shifts during natural aging are common particularly in “additive” (also called doped) lamps. These lamps contain additives such as iron or gallium which enhance the output at longer wavelengths. A broadband source or one that looks at only a portion of the spectrum might miss this spectral shift and cause potential cure problems related to achieving the proper match between the UV source and chemistry. A spectral shift can even be due to something as seemingly pedestrian as a dirty reflector where corrosion leads to the selective absorption of some wavelengths compared with others.

System manufacturers can tell you what types of bulbs your UV equipment can use. Bulb types are not always interchangeable. Have a system in place at your facility to make sure that you have the correct bulb for your process. Buy your UV bulbs on value (stability, consistency, effective useful UV output over time) instead of the lowest dollar cost per unit.

### **UV LED Sources**

A substantial innovation in UV curing is the commercial development of solid-state UV LED light sources. While conventional mercury lamps produce a broad spectrum of wavelengths spanning the entire UV spectrum, LEDs emit only a single wavelength of UV. Typically UV LEDs are engineered to emit a single peak of light somewhere in the 365nm to 405nm range (see figure 8)



**Figure 8. The narrow spectral output of a typical 365nm UV LED source.**

Commercial interest in LEDs for industrial curing is being driven by many of the same motives for selecting LED light sources as for other lighting applications. Compared to mercury lamps, LEDs use less energy, last much longer, have high output stability, emit less heat, and can be turned on and off instantaneously. The LEDs themselves are tiny, almost microscopic in size and are often referred to as “dies”. To be used commercially, many LED dies are frequently mounted in arrays so they can be used to cure larger surface areas. These arrays are often cooled using air or water cooling and may also incorporate optical reflectors or lenses to control the light output of the dies. Since the devices are small semiconductors, the

power supplies are low voltage and since the LED array can be energized instantly, no shutter mechanisms are needed. The precise control of LEDs makes them particularly attractive for PSA applications where a more stringent process window may be common.

While many feel that LEDs hold great promise for UV curing of PSAs, and many commercial installations already exist, LEDs also bring some challenges. First, the array sizes are usually smaller since the cost to make large LED arrays is still quite high. Second, most existing PSAs have been formulated to be cured with broad spectrum mercury lamps. Since LEDs have very narrow spectral output, and today they have very little UV output below 365 nm, the chemistry of existing PSAs may be

incompatible with these new LED sources. A number of formulators have begun reformulating for longer wavelength LEDs, but before installing an LED system, the applicator is strongly advised to test the curing of the PSA with any light source to assure proper cure performance.

Stay tuned for exciting developments in this area over the next few years.

### UVA2

Just as existing PSA chemistry had to be reformulated to be compatible with a new generation of UV LED light sources, so too, measurement equipment needed to be adapted to the change in spectral output of LED arrays.

As can be seen in the chart below, the conventional filters used for measuring irradiance in the UVA and UVV bands do not span all of the wavelengths commonly produced by UV LED manufacturers. Using an instrument designed for these bands can result in a misleading measurement. Radiometers incorporating a new band, the UVA2 band, spanning the 375nm-410nm range (see Figure 9) may be a more desirable approach to making measurements of LEDs with emissions in this spectral region.

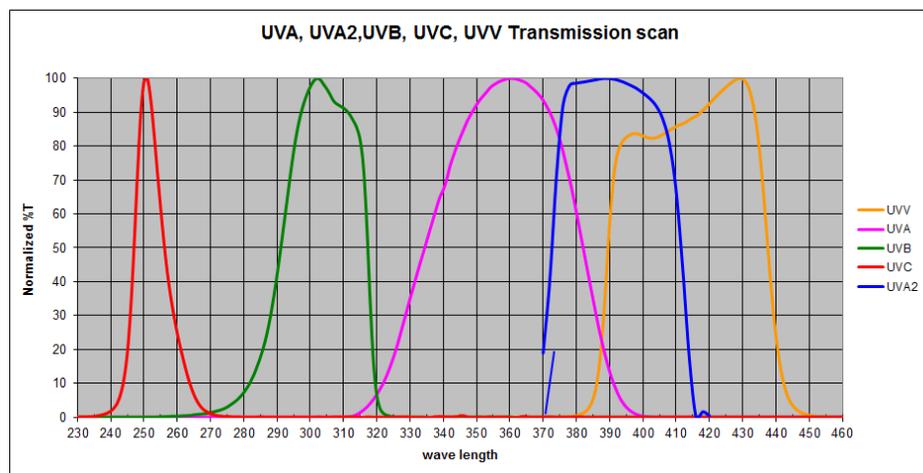


Figure 9. The response characteristics of UVC, UVB, UVA, UVA2 and UVV filters.

## 5. The Zorba: UV is all “Greek” to me

### Education

To be successful with UV, you need to understand the basic concepts about UV and your process. Documenting and maintaining your process is much easier than hoping that things work out. By reading this article, you are working to increase your knowledge about UV. Look to your suppliers, trade shows, conferences, web sites, trade organizations and webinars to further increase your UV and process knowledge.

### Emerging Technologies

The curing of adhesives with UV continues to evolve. New formulations and equipment make new applications with UV possible. One area of great interest is UV LED’s, that continue to evolve and can be used applications including digital printing. It is tempting to be lured by new technology, so the prudent user should always pay attention to changes in light source technology and evaluate them carefully to determine if they are right for a particular PSA process.

Other changes are more subtle but can also have important implications for both the process and for measurement equipment and technique. For example, choosing an instrument with the right dynamic range is critical to obtaining accurate measurements. If the test instrument is not sensitive enough to measure UV levels or conversely has too low a dynamic range the data may not be valid. Too much UV irradiance can overpower a sensor designed for lower output devices and cause clipping, or attenuation of the proper reading.

Another parameter worth paying attention to is whether the sampling rate of the measurement device is sufficient to capture the UV energy that the substrate is exposed to. Very fast line speeds mean that parts are exposed to the lamp for a much shorter period of time. Like the shutter on a movie camera, if the data recording speed (that is the sampling rate) is too slow, a large portion, perhaps even the peak intensity could be missed by the radiometer. You should discuss the line speed characteristics with the UV radiometer supplier so you can choose a device most appropriate for the production circumstances.

## **6. The Gang That Couldn't Shoot Straight**

If you search the internet for “Kimo’s rules”, one of the rules state: “Goals are deceptive-the unaimed arrow never misses.” Is your process window unaimed? Your UV progress towards a well-crafted and executed UV measurement program requires that you take time to decide what is needed. Establishing and documenting a process control window or target takes work. The best time to do it is when you are defining the process and working with your suppliers. The next best time is when the process is up and running. The worst time to document your process is when it is not working and curing is not taking place.

If you are trying to find minimum UV values, run tests in which you gradually increase the line speed until you produce an under cure situation. Document this failure point by recording the parameters - irradiance, radiant energy density, power applied to the system, line speed. We suggest building a cushion or caution zone of approximately 20% on your process window that allows for slight changes during a production run.

Job, Performance or Process Control Logs should be used to track each of your UV systems. It is a central place to keep performance information on the system that can be referred to if things stop working. It can be as simple as a clipboard and log generated with a word processing or spreadsheet program. Track the items (both measurable and non-measurable) that are important for your process.

When things stop working, examine your log.

- Was it a gradual change over time towards the identified caution area or was it a sudden change?
- Any changes to the process?
- Equipment?
- Suppliers?

When things stop curing:

- Confirm key equipment settings and measure the UV
- Perform UV system maintenance and clean the reflectors, rotate the bulbs if possible, check cooling and air flow on the housing
- Measure the UV again, looking for improvement and movement back within the process window
- Replace UV bulbs or adjust key equipment variables until you are back in your process window

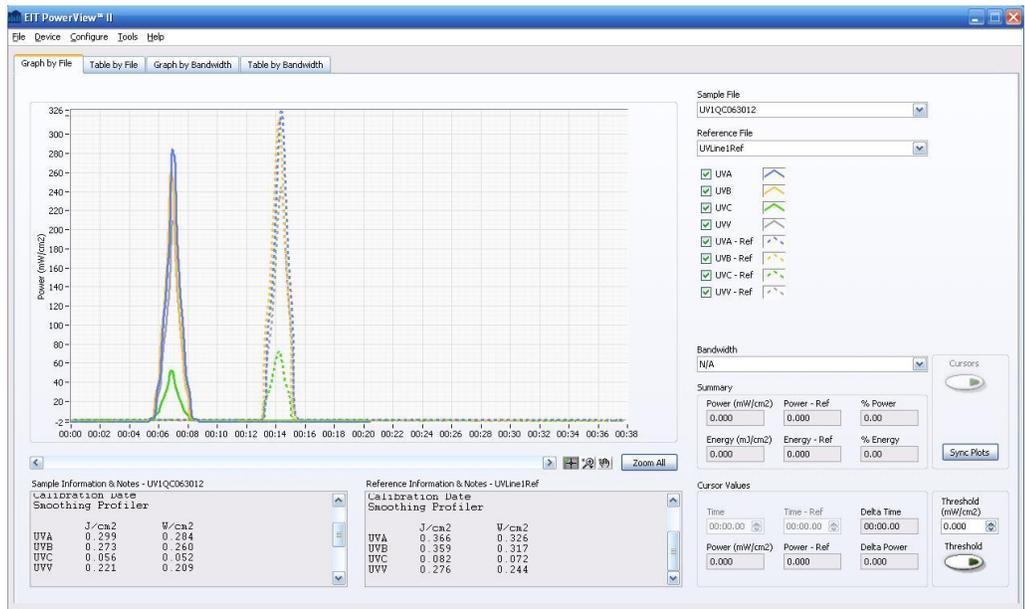
How often should you monitor and take UV readings? There is no easy answer and you will have to let the information that you collect and your process dictate the frequency of readings.

**Remember that:  
UV measurement can't help you unless you document and record the readings!**

### 7. The Profiler: When it is Good to be Profiled

The same revolution in hardware and software that gives us iPods and smartphones has reached the UV curing line. Today's radiometer is a turbo charged version of its predecessors. Not only can it record more data, more quickly and accurately, but the profiling radiometer provides the user with a simple, graphic, Windows driven interface to their UV curing process.

Data can be organized and presented either as a table or a graph (see examples in figures 10 and 11). Saved data can be used as a reference so that changes from one set of measurements to another can be quickly compared side-by-side and analyzed. Zooming in on problems with a few mouse clicks allows the operator to see even small changes such as the aging of a lamp, or the cleanliness of the reflectors. Rather than providing only the total energy density (dose) or a single number for the peak irradiance, graphical analysis provides a more complete picture by providing a complete profile of each separate light source on the curing system. And since the software allows the operator to examine measurements by UV wavelength band, changes such as spectral shifts in the output of a lamp due to aging or insufficient cooling can be pinpointed for repair.

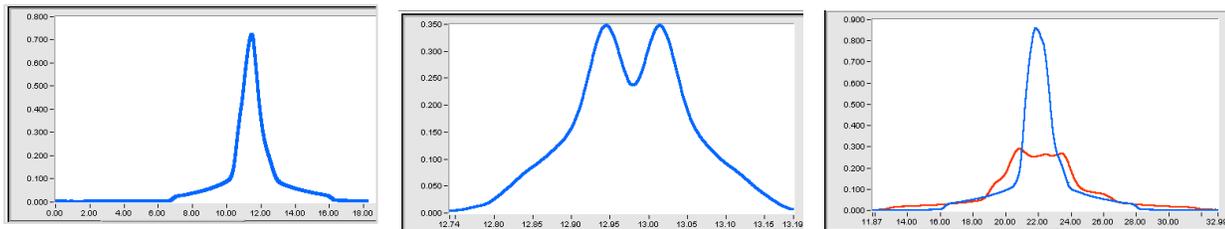


**Figure 10. Sample profiler software in graphical analysis mode. Comparing a current measurement (solid lines) with a previously saved file (dotted lines).**

Summary (by File)			
	Sample File	Reference File	Difference
UVA - Power (mW/cm2)	284.329	325.695	(41.367)
Power (%)	(12.70)	0	(12.70)
Energy (mJ/cm2)	269.049	373.638	(104.589)
Energy (%)	(27.99)	0	(27.99)
UVB - Power (mW/cm2)	259.686	317.299	(57.613)
Power (%)	(18.16)	0	(18.16)
Energy (mJ/cm2)	249.753	348.207	(98.455)
Energy (%)	(28.27)	0	(28.27)
UVC - Power (mW/cm2)	51.762	71.981	(20.220)
Power (%)	(28.09)	0	(28.09)
Energy (mJ/cm2)	52.497	81.237	(28.740)
Energy (%)	(35.38)	0	(35.38)
UVV - Power (mW/cm2)	209.280	244.436	(35.156)
Power (%)	(14.38)	0	(14.38)
Energy (mJ/cm2)	190.323	268.647	(78.324)
Energy (%)	(29.15)	0	(29.15)
Cursors	Off		
Time	00:00.00		
Time - Ref	00:00.00		

**Figure 11. Sample profiler software in table analysis mode. Comparing readings from a current measurement (Sample File) with a previously saved file (Reference File).**

With experience, a profile of the irradiance allows the user to interpret changes in UV sources from arc lamps to microwave lamps to LED arrays. For example, the first profile below (Figure 12A) is for a lamp in proper focus, while the second profile (Figure 12B) shows the characteristic footprint of an unfocused lamp. The third profiler plot (Figure 12C) shows the effect of a small change in the distance from the lamp to the part. (X-Axis = time, Y-Axis = UV irradiance)



**Figure 12A, 12B and 12C. The profiler allows for easy identification of a wide range of UV cure problems. Here we see a focused lamp (12A left), unfocused lamp (12B center) and lamp that has been moved (12C).**

While all of the tables and graphs can be exported in popular formats to make reporting and sharing of data easier, the profiling radiometer can even export raw data in Excel format so that it can be analyzed by even more sophisticated graphical or numerical analysis packages.

### 8. Sense and Sensibility

As with most things in life, users of UV need to understand the requirements for safely working around a UV source. This includes leaving manufacturers safety guards in place and using eye and skin protection as required. Care should also be exercised before working on your equipment to make sure the electrical power has been tagged and locked off so that it cannot be accidentally turned back on while someone is working on the equipment.

Expectations of UV measurement instruments often exceed their actual performance. Users expect overall performance to be within a small fraction of a percent. Errors introduced with collection techniques can also lead to perceived problems with the instrument. It is important to understand and use your instrument properly and also use data collection techniques consistent with the instrument and instrument design. Work with the manufacturer of the instrument.

Why do readings differ between instruments? What are some of the things to keep in mind when making and comparing readings from different UV measurement instruments?

- **Data Collection Speeds:** For repeatable, reliable results, a UV instrument needs to collect an adequate number of samples. Newer radiometers sample much faster than previous radiometers. If you see fluctuations in the irradiance values, try collecting your data at either a slower speed or increase the sampling rate on the instrument if this is possible.
- **Temperature:** Long slow repetitive measurements with an instrument on high power UV sources can cause the readings to vary slightly. A good common sense rule is that if the instrument is too hot to touch, it is probably too hot to take an accurate measurement.
- **Calibration Sources:** Calibrating an instrument to one type of spectral source (mercury) and then using it under a second source (mercury-additive bulb) can lead to small differences in the readings. If you will consistently use the radiometer under a specific lamp source, ask the manufacturer to calibrate the instrument under that type of source.
- **Instrument Ranges:** What kind of results would you expect to get weighing a baby on a scale designed to weigh trucks? Probably not too good because the truck scale has a dynamic range set up for large objects. Make sure the dynamic range of your UV instrument matches the irradiance levels of your system. Too often, people try to measure very small amounts of UV with an instrument designed to measure high power sources. The instrument may register a reading but it may be out of the ideal range that it was designed for.
- **Spatial Response:** The spatial response of an instrument describes how the instrument handles light coming from different angles and is measured by the optics in the unit. Most instruments try to approximate a cosine response in their optics.
- **Electronics:** Differences in the electronics between instruments can cause one instrument to reach threshold and start counting UV while another instrument needs a higher irradiance value to reach threshold and count.

### **Maintenance of UV Cure and Measurement Equipment:**

Maintaining a proper cure for your PSA chemistry requires proper maintenance of your curing system. Anything that can affect how much UV light reaches the part, and for how long the part is exposed can adversely affect UV cure.

Lamps. The curing lamp itself is the most common source of variation in the cure process. The output of UV lamps, particularly arc or electrode lamps diminishes over time. For arc lamps this is a natural process which should be monitored regularly so that the lamp can be replaced when its output reaches a predetermined threshold related to the process

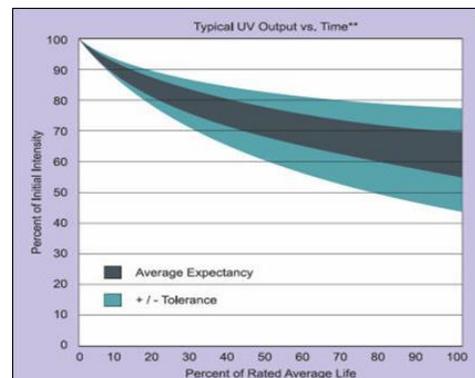


Figure 13. The output of a typical arc lamp falls off continuously over time.

window. Figure 13 shows the typical fall in UV output with age of the lamp.

Lamps do not also age uniformly across the span of the bulb. For longer length lamps readings should be made at intervals close to the edges and the center of the bulb. Figure 14 compares two sets of profiling radiometer measurements one at the edge and the other at the center of one meter lamp to reveal a difference of over 25% in measured output.

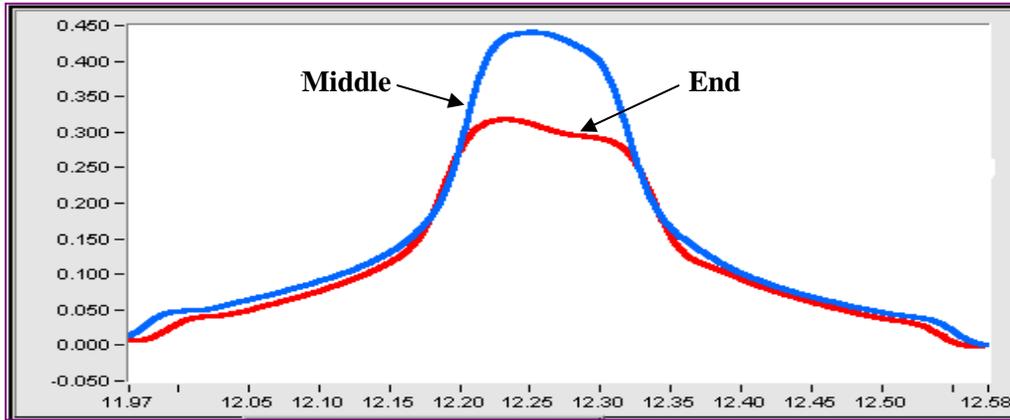


Figure 14. The output of a typical arc lamp with darkening at the ends results in non-uniform exposure. The middle of the same bulb reads 440 mW/cm<sup>2</sup> while the end of the bulb reads 317 mW/cm<sup>2</sup>

In fact, aging of UV lamps may not be uniform across different wavelengths. So while taking a measurement using one wavelength band may not so much difference between a lamp and a reference source, the picture may be quite different when measured using a different bandwidth. Such a situation is shown in Figure 15. The blue trace shows UVA on an old bulb with only 600 hours (left) and compares it to the UVA output of a new bulb on the right. If measuring only UVA, the output of an old and new lamp (blue) is similar. There appears to be little cause for concern since the UVA in the old bulb appears to be operating close to the UVA in the new bulb. The red trace is UVV. There is a substantial UVV difference between the old bulb and new bulb when also looking at the UVV wavelength band.

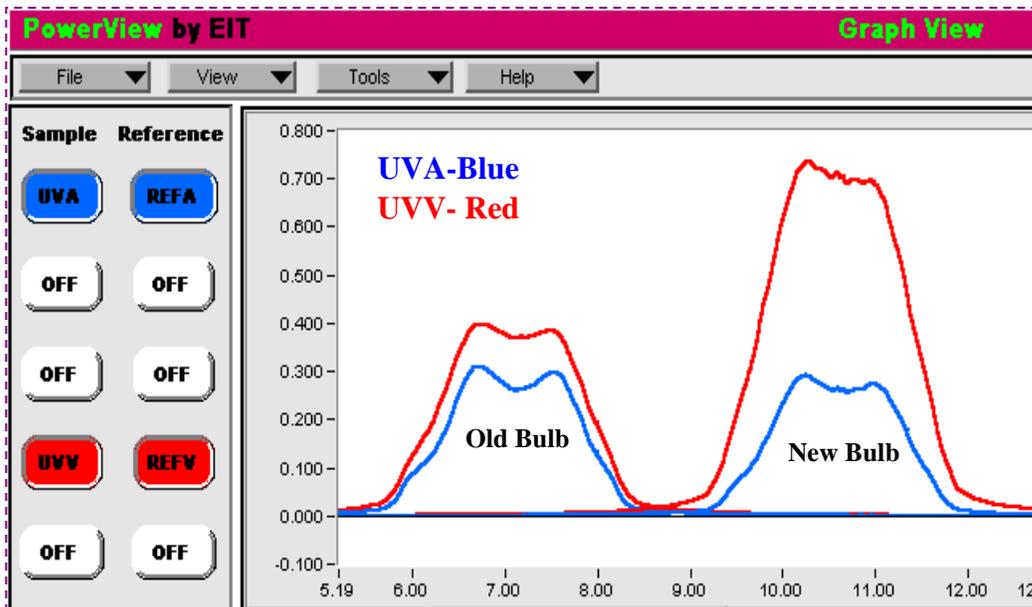


Figure 15. A multichannel profiler helps identify problems that affect one UV band differently than another.

The UV curing process depends on irradiance, on energy density, and on wavelength, and that good measurement practice dictates that we try to pay attention to all three parameters to avoid UV curing failures.

Some failures are part of a natural process and due to the chemistry and physics involved. Other failures come about due to human operator error and neglect. For example, failure to properly maintain a system can result in poor performance due to the corrosion, warping, and misalignment of UV reflectors. This diminishes UV output and can lead to complete failure of the lamp. Inattention to proper cooling can not only lead to premature lamp failure, but also to reabsorption of UV by the lamp, and to improper mixing of additive materials in the bulb. This produces unwanted changes in the spectral output of the lamp. Even with proper maintenance lamps are often cleaned, and then improperly repositioned so that the distance to the part changes over time. Good housekeeping habits should include properly measuring and maintaining proper lamp position a problem that can be particularly vexing on lines where different part styles may require changing lamp position regularly. See Figure 16 for an extreme example.



**Figure 16. Neglecting to clean reflectors causes corrosion and contamination. This reduced UV output and may affect some wavelengths more than others.**

UV measurement equipment also ages and requires maintenance. Radiometers are often exposed to powerful UV radiation and operated under continuously in tough industrial environments. Over time natural aging occurs, such as the darkening or “solarization” of the optical window on the radiometer. This changes the accuracy of measurements over time. These optics can also become scratched, or contaminated.

If the optics on your radiometer look dirty, the first reaction is often to clean them with whatever shop rag is handy and with whatever solvent is nearby. But the cloth you use to wipe it clean may contain optical brighteners or have coarse fibers that just make the problem worse. The wrong solvent can also react with wipes and swabs, dissolving materials such as fibers and glue and transferring these contaminants to the optical surface. Check with the manufacturer of your instrument to find out their recommended procedure. A lint free, nonabrasive cloth that does not contain any detergents or additives is a good starting point. That will help to avoid these common pitfalls, and enhance the accuracy and reliability of your device.



**Figure 17. Damage to the optical window on a UV radiometer such as this scratch, can result in improper measurements.**

Radiometers, like any test instrument require regular calibration and repair to keep them operating properly and so that the measurements can reliably be tied to known measurement standards. It is both risky and a waste of valuable time to use a measurement instrument which is not properly maintained and calibrated.

## **Conclusions**

The topic of UV measurement and process control is broad and surprisingly complex.

Proper UV measurement involves measuring several parameters such as irradiance and energy density which are inter-related, and which vary by wavelength. As a result there is often a misunderstanding of UV measurement. We often see even the most knowledgeable suppliers fail to sufficiently specify the right UV curing parameters. We also rarely find users who know the upper and lower limits of their UV cure process window.

This is particularly alarming in considering curing for UV cure PSAs, where the tolerances can be tighter, and there is a danger in applying too much UV.

While we have attempted to illuminate some of the most important aspects of UV cure, the three general key points to remember from this article are:

1. Understand your UV equipment and process and operate in the 'zone' where your process will allow you to optimize production, reduce waste and save your company time and money.
2. Measure and track both the UV conditions (irradiance and energy density) as well as the 'other' variables in your process
3. Work and communicate with all suppliers

Unlike many other UV cure applications, PSAs can be sensitive to over-curing. Too much irradiance, or too much cure exposure time can cause a loss of important properties. Therefore with UV curable PSAs it's more important than usual to establish, monitor and maintain a proper UV cure process window.