UV LED Curing Systems: Not Created Equally

By Chad Taggard, Sara Jennings

Introduction

The ultraviolet (UV) Light Emitting Diode (LED) curing market has enjoyed considerable growth over the past several years as both new and existing markets recognize the inherent advantage of UV LEDs over traditional mercury lamp systems, whether arc or microwave driven. Therefore, this paper will strive to move beyond previous discussions of UV LED vs. mercury lamp systems and instead focus on the potential differences in UV LED systems. Additionally, measurement methods that can be used to contrast and compare the differences in performance of the various UV LED based systems available will be discussed. The reader can then quantitatively determine the performance of a UV LED curing system and see that not all UV LED curing systems are created equally.

Quick Recap: UV LED Curing Advantages

Application after application across many market segments have moved to UV curing using photopolymer chemistry away from solvents containing VOCs (volatile organic compounds) and requiring large, power hungry furnaces. The advantages of UV curing versus solvent based curing are well documented. The distinct advantages of UV LED curing over UV curing using traditional mercury

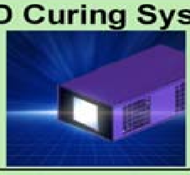
	LED Curing System 	Arc Lamps 
Lifetime	> 10,000 hours	500-2000 hours bulb life
Environmental	Mercury-free Ozone-free	Mercury waste Ozone generating
Input Power	Small (~half)	Large
Maintenance	Maintenance Free	Bulb replacement & cleaning
On/Off	Instant	Minutes
Heat	60 C	~350 C

Table 1: UV LED vs. Mercury Lamps

The environmental factors alone are considerable as people, companies, and governments recognize the inherent dangers in the building, handling, and disposing of a hazardous substance. Not to mention the operating dangers of machines that contains a hazardous substance and produces a second one, namely ozone. Studies have shown that in certain applications, replacing mercury lamp product with UV LED lamps can lead to 25 tons of CO_2 reduction (see *Environmental Benefits* in references). In addition, the true Total Cost of Ownership (TCO) when taking into account the cooling, venting, and maintaining of mercury based systems versus UV LED based systems shows a savings of 50-75% can be realized over the system's useful life. With the wide variety of inks, coatings, and adhesives having been formulated to take advantage of UV LED's unique benefits, there are no substantive reasons that UV LED curing systems will not replace mercury bas of "if", but of "when."

UV LED Lamps: Components and Comparisons
UV LED curing lamp systems consist of multiple sub-components which taken together can be used to define the system's overall performance. The key design sub-components are outlined in Examining these components in closer detail and their interactions and interdependencies will provide the reader with a better understanding of how UV LED curing lamps are not created equally.

	Component	Purpose
I	LED	Solid-state component that generates UV light
II	Array	Grouping of LEDs to maximize UV output to achieve desired curing rate.
III	Thermal Cooling	A properly designed thermal management system for the removal of heat generated by LED array to insure low operating temperature and long life.
IV	Optics	The shaping, molding, reflecting, and guiding of the UV LED light to insure maximum light reaches the media.

Table 2: UV LED Light Source Components.

I LEDs – The base building block
Let's start with the LED. As the base building block, this is the first choice a UV LED lamp supplier has to make. It is a critical choice that impacts the remainder of the systems architecture and design. A pictorial example of an LED's construction is shown in Figure 1: LED Construction. Simply put, an LED is a solidstate device that produces light when an electrical current is allowed to flow from the positive (anode) side of the circuit to the negative (cathode) side.

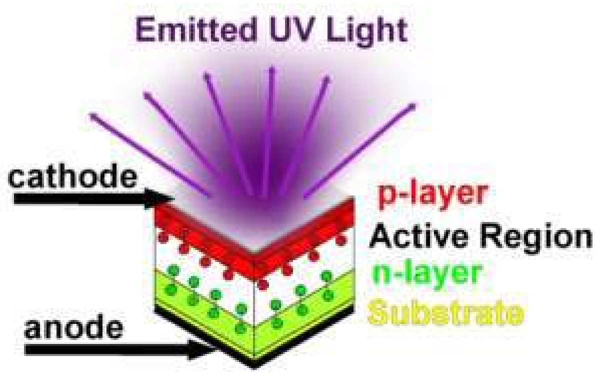


Figure 1: LED Construction

Not all LEDs are built the same nor do they exhibit the same characteristics. UV LED lamp suppliers have critical choices to make as to the quality, type, material and shape of LED for their systems. Key LED characteristics considered by each UV LED lamp supplier include wavelength and UV output.

Wavelength:

The wavelength emitted from an LED is controlled using differing amounts of dopants such as aluminum, gallium or indium derivatives during the manufacturing of the LED. The general rule of thumb is that the shorter the wavelength, the lower the peak UV output available from the die, as shown in Figure 2.

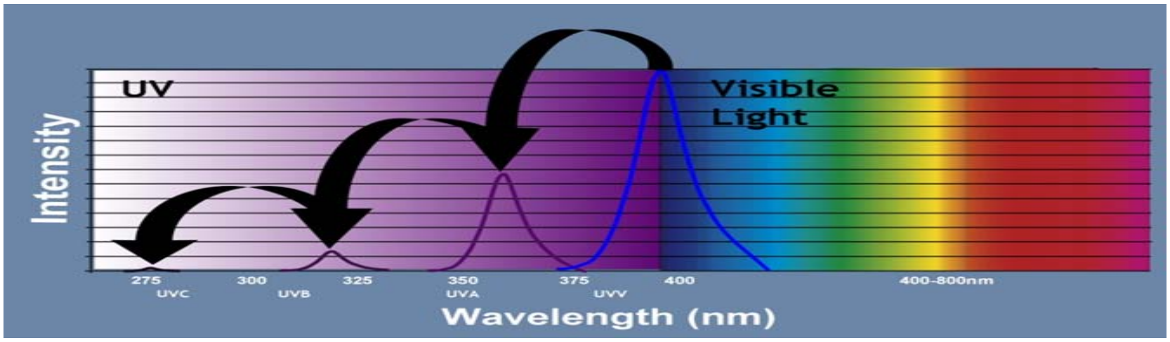


Figure 2: Wavelength Characteristics

The UV LED supplier must weigh the trade-offs between wavelength and the associated total energy with cure rate. Chemistry plays a significant role in this discussion. Some applications, due to their specific chemistry, require a given wavelength. However, for many applications a small shift in the peak wavelength will have no impact as the absorption of the UV by the photoinitiator which kicks-off the reaction has a broad absorption range. For example, as you can see in Figure 3, three-fourths of the energy outputs by a LED with a peak at 385nm versus a peak at 395nm share the same wavelength band. There have been materials tested to confirm that the difference in either cure rate or quality when using die with peak outputs centered at 385nm and 395nm had no discernable differences.

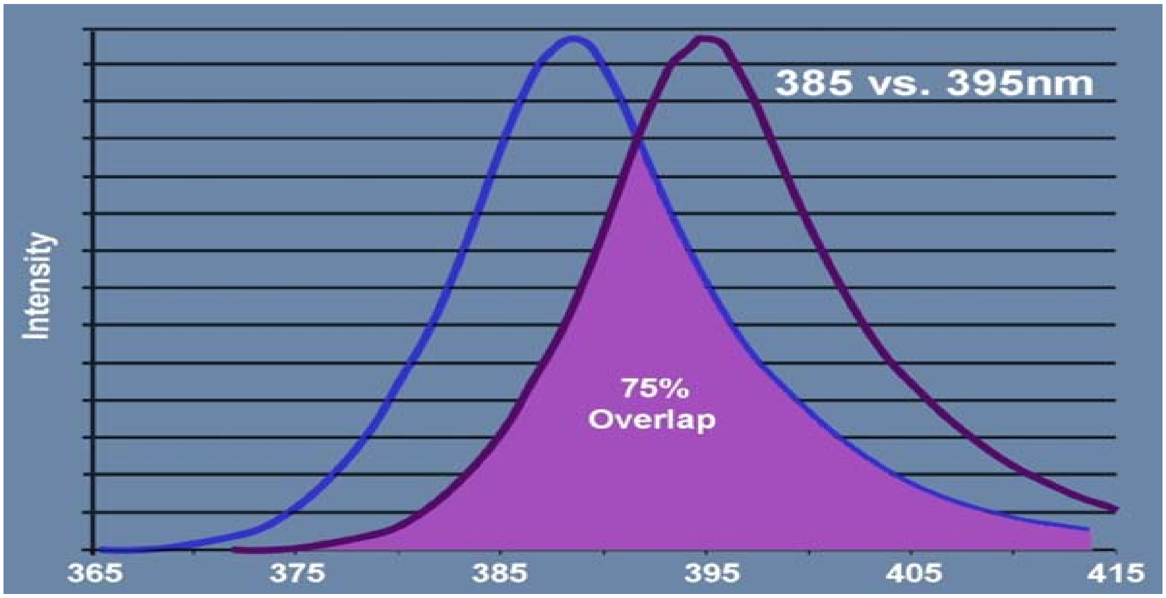


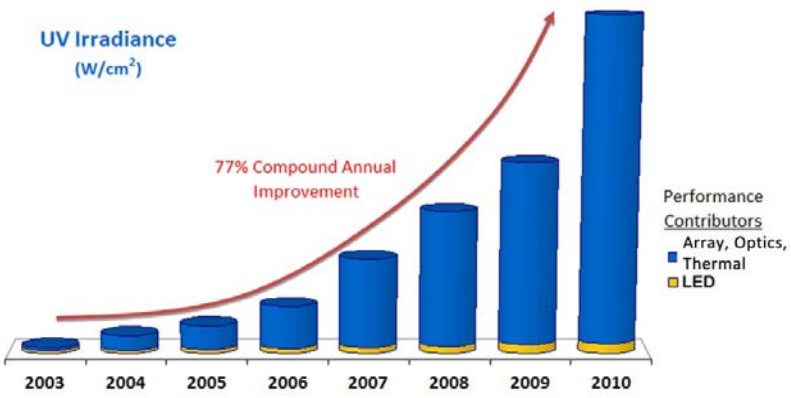
Figure 3: Wavelength Comparison

Therefore, UV suppliers will typically select the longer wavelength to achieve the highest UV output which allows for higher application throughput.

UV Output:

The output of a single UV LED is measured in milliwatts (mW) at a nominal input voltage and current. UV LED output has shown considerable improvement in recent years where specifications for LEDs from various vendors have improved from 2005 to 2011 with a compound annual growth of 5-10%. This improvement shows the LED vendors have and will continue to improve the output of UV LEDs, which only provides a better foundation for the UV LED curing lamps that utilize them.

While it would be tempting to jump to the conclusion that UV LEDs are the single biggest contributor to UV LED lamp performance, Figure 4 shows that UV LED curing system suppliers have more opportunity to differentiate themselves in the areas that go beyond the base LED. A close examination of the LED performance, while contributing, was not the major factor in improved peak irradiance over time.



The other three factors (arrays, cooling, and optics) significantly outweigh the increase in LED capability. This answers the question asked by UV LED naysayers, "If all LED suppliers are eating from the same bowl, then won't all the products essentially be the same?" Therefore, let's continue examining the other components that make up the system.

II Array – Grouping of LEDs

Arrays are the second area where suppliers can begin to differentiate their product offerings. How the LED's are combined, the number and type of LEDs chosen, the shape of the array, the method of electrically connecting the LEDs, and even the size of the LEDs all have significant impact on the performance of the system.

Most applications require UV LED curing systems that consist of more than one LED or LED array in order to achieve not only the desired throughput but to meet the demands for curing applications where the media can be 1-2m wide. Therefore, a key question is if the LED array can be uniformly scaled. UV LED curing lamps can have a continuous scalable array that provides for better uniformity or a discrete array package that can be scaled, but doesn't provide the same uniformity of output, see Figure 5: Typical LED Array.

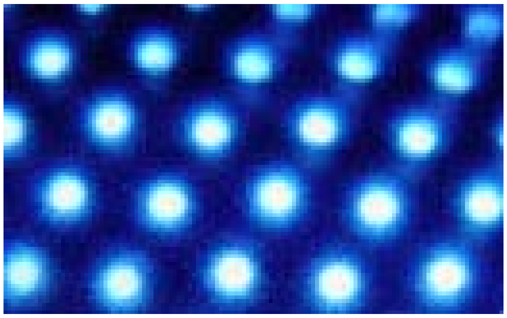


Figure 5: Typical LED Array

Some LED manufacturers only sell their LEDs pre-packaged into arrays or assemblies that they feel maximize the UV output. UV LED lamp system suppliers that purchase pre-packaged arrays have typically made a tradeoff between faster time-to-market and less differentiated lamps versus a slightly longer time-to-market and maximizing UV power. This is an area where UV LED lamp suppliers can differentiate themselves based on the suppliers' architecture and engineering capability where two suppliers can take the same batch of LEDs and achieve very different performance in the end product.

III Thermals – Keeping it Cool

The third component is cooling. As any reader knows after using a notebook PC on their lap for a length of time, the by-product of solid-state devices is heat. UV LEDs transfer about 15-25% of the received electrical energy into light. While this is significantly better energy efficiency than mercury lamps, the remaining 75-85% is transferred as heat; thus, the need to cool the LED arrays.

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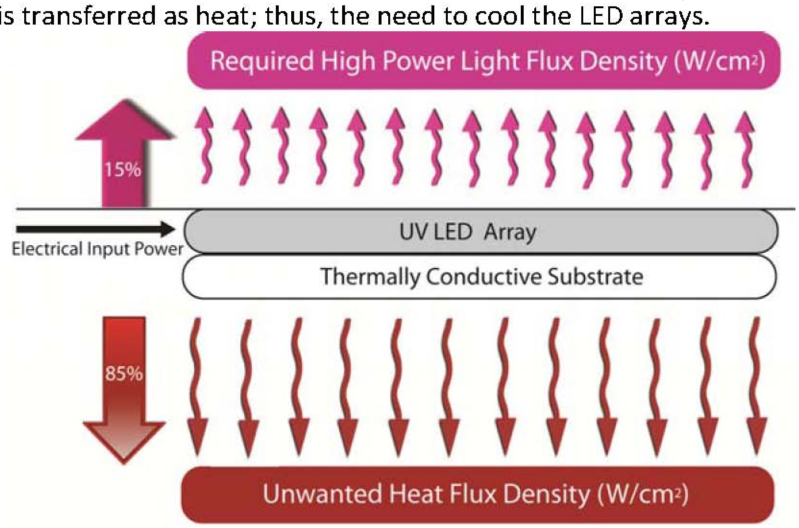


Figure 6: UV LED Energy Efficiency

Currently, UV LED arrays are cooled with either air or liquid, Table 3: Air vs. Liquid Cooled Light Sources compares the two most common methods used for cooling LED arrays.

AIR COOLED	LIQUID COOLED
Less expensive total UV light source solution	More expensive due to need for external cooling source
Lower irradiance levels as irradiance is directly proportional to ability to cool the LED array. Air is not as efficient at cooling.	Higher irradiance levels as water's thermal conductivity is higher than air's (0.6 vs 0.025 W/(m·K)), which means water can not only absorb more heat, but can do it faster than air.
For given irradiance, larger lamp size due to fan size	For given irradiance, UV source and cooling mechanism are separated allowing a smaller lamp sizes as no need for a fan

Table 3: Air vs. Liquid Cooled Light Sources

Important to note is that as the LEDs emit higher output power, the more heat is generated. Thus in the race to build ever higher irradiance products, the ability of suppliers to control and remove heat has become more crucial to building reliable systems. This is analogous to microprocessors where heat became a constraining factor due to increasing gigahertz performance by increasing the number of transistors while decreasing the trace width. Manufacturers eventually turned towards increasing the number of processing cores at lower clock speeds to stay within functioning thermal thresholds. UV LED lamps face a similar challenge. As the quality of LEDs improves and the irradiance increases, so does the need to remove the heat. OEMs and end-users do not want to spend more on the cooling of the lamps than the lamps themselves. Thus, the third area of differentiation is in the cooling technologies and capabilities that suppliers choose.

IV Optics – Guiding the Light

The final component and one of the most important differentiators is optics. The science / art of optically improving the LEDs to maximize their UV output is key to the lamp's final capability. Based on the end application the optical engineer has to decide what shape, form, and material best utilizes the LED's unique characteristics. Next they have to balance the fact the LEDs are a 'flood' type of light, unlike a focused mercury lamp where the light is captured by a reflector and directed to a specific point, focal length.

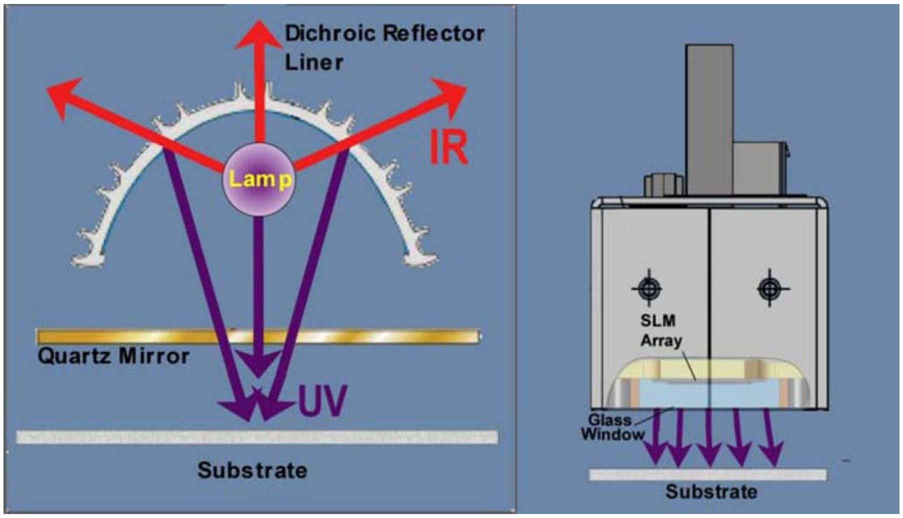


Figure 7: Traditional Mercury Lamp Optics vs. LED Optics

The optical engineer is challenged to use methods to ensure the maximum amount of light 'escapes' at the desired irradiance through the window/glass towards the material. LED Lamp suppliers have used various, confidential methods to maximize the UV LED light. A high level summary of optics typically used by UV LED suppliers with their pros and cons is shown in Table 4.

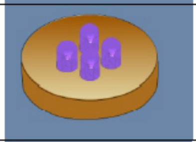
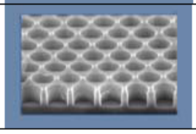
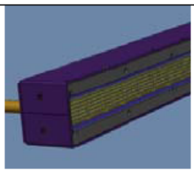
Optics	Pros	Cons	
Macro – LED array inside reflector optic	High peak irradiance over small area.	LED array cannot be scaled uniformly.	
Micro – Each packaged LED has an individual optic	Can be scaled uniformly.	LED to LED spacing and therefore maximum UV output limited by packaged LED size.	
Integrated Optic – Optic part of LED formation process	Increased optical efficiency.	Expensive and array is hard to scale uniformly.	
Directional Optic	Increased peak irradiance over narrow band.	Optics configuration limits number of LEDs that can be configured in system, limiting total available UV output.	
Scalable micro optic	SLM module can be scaled uniformly while maintaining high peak irradiance.	Light is not focused and diverges over distance.	

Table 4: UV LED Optical Options

While an end-user or OEM should not necessarily be concerned with how the optics are provided in the UV LED lamp, they should understand if the supplier has the ability to improve their design for their specific application needs. Too many times a supplier is chosen that cannot grow with the company into new application areas because the UV LED supplier either does not have the engineering talent or they purchase their LED Array's pre-packaged and are therefore limited to what their supplier can support.

Measuring the Differences between UV LED Curing Systems

Regardless of the LED, array, thermal and optics design employed, the end result that matters to endusers is that there material is cured. The two measurement parameter for this are: Peak Irradiance and Dose, as outline in Table 5. These two parameters work together and understanding their measurement method will allow OEMs and end-users to properly characterize the UV LED curing system.

	Peak Irradiance	**Dose**
Definition	radiant power per-unit-area	radiant power per area per unit time
Measurement	Watt per centimeter squared (W/cm_2)	$Joules/cm_2$ or $mJoules/cm_2$
Impacted by	Distance from material	Material speed Emitting window size

Table 5: Peak Irradiance vs. Dose

OEMs and end-users should consider two key questions when measuring UV LED Lamps output:
1. Where is the peak irradiance specification point of reference?
2. Over what area is the peak irradiance being delivered?
Table 6 below shows some of the typical measurement locations for measuring/specifying peak irradiance and the pros and cons of each approach:

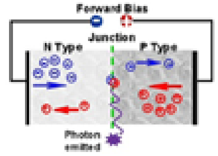
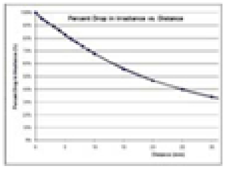
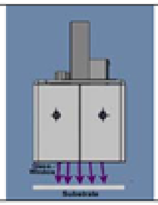
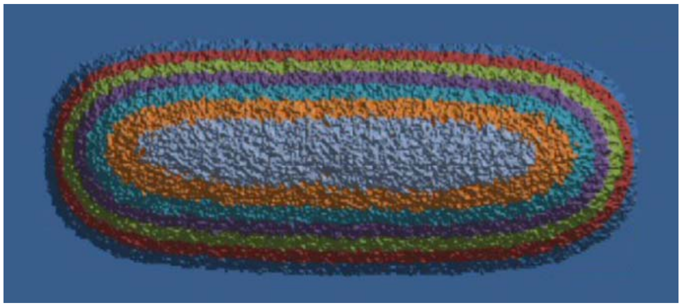
Usefulness	Location	Pros	Cons	Pic
Poor	At the LED	Gives some indication of the base LED, but this is only a small component of the performance of a UV LED Curing system.	Cannot be measured No practical application	Photon emitted at Junction 
Better	At the media	Most relevant to end user	Each customer's operating distance can be different and as noted above, the emitted UV light is divergent which means even through there is UV light, the measured peak changes with distance.	Irradiance vs. Distance 
Best	At the emitting window	Consistent metric regardless of application	Where on the glass should the irradiance be measured? In the middle? At the edges? The corners? Average across various locations?	

Table 6: UV LED Measurement Options

OEMs or end-users could be misled by a single number that was taken along a single axis. Knowing the location of the measurement and how that measurement metric changes over the UV emission area will give the best overall characterization of the UV LED Curing system.

Figure 8 is a thermal image which depicts a UV emission area. The white is the maximum UV irradiance and as the emission 'falls' off from the center the irradiance impacting the substrate decreases, which is shown as the series of concentric circles. Each color is a lower irradiance value.



The impact to the OEM or end-user is they may believe they have purchased a UV LED system that delivers 4 W/cm2 across the entire emission area when in fact only 2 W/cm2 are curing along the edges. Figure 9 shows a 3D model of a wide area source and a narrow emitting source that have the same Peak Irradiance, but delivery very different overall irradiance to the material, which is the topic of the next section, dose.

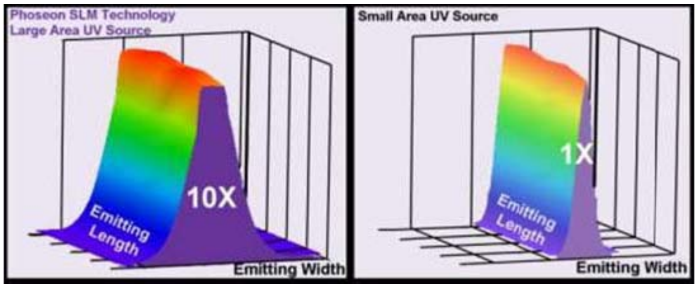


Figure 9: Uniformity along Emitting Width

Dose
Dose can be a very misunderstood concept and is also variously called density, energy density, or exposure. Dose is a function of exposure time, the faster the belt speed, the less dose is being delivered to the media even when the peak irradiance is the same as shown in Fig 10.
Conversely, even as the measured peak irradiance decreases with distance away from the media, if the media's exposure time remains the same, the measured dose remains the same. This decreased peak irradiance is due to the divergent nature of the LEDs. The light spreads out as the distance is increased, but the total amount of light delivered to the surface stays the same.

This is an important point. So said another way, for a given media speed, altering the height of the UV LED light source from the media does not change the total amount of light (dose) delivered to the surface, but rather the peak irradiance decreases.

To show this graphically, see Figure 10. The blue curve is with a peak irradiance of 8 W/cm2 while the red curve is at shows a peak irradiance of 5 W/cm2. The key is the area under the curve is the equal. The peak irradiance is lower but the overall dose remains the same.

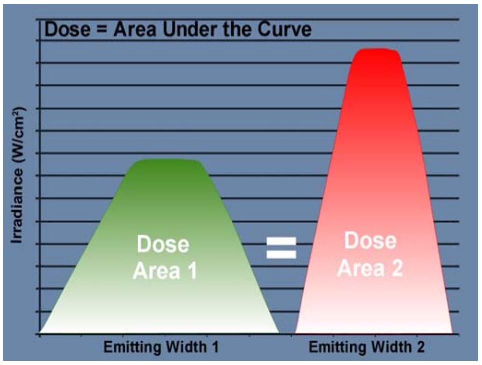


Figure 10: Dosage vs. Height (same speed)

The quickest way for an OEM to improve the speed of their machines is to either 1) utilize UV LED lamps with higher Peak Irradiance or 2) utilize UV LED lamps with larger arrays. Either of these will deliver more total dose to the curing surface, and allow faster cure speeds

Measuring Irradiance and Dose

Lastly, what device should be used to measure UV LED lamps? There are several manufacturers that provide products to measure irradiance. Most of these were converted from mercury lamp measurement devices and have not fully comprehended the unique LED characteristics. The sensors used in radiometers have been characterized and calibrated to work with the output profiles of mercury lamps. Since UV LEDs have a very different output profile, the sensor calibration for a given wavelength band is the most important characteristic. A radiometer that crops or doesn't count all of the UV emission based on a normal LED wavelength tolerance can lead to measurement errors and should therefore not be used to set irradiance and dose specifications.

The spectral characteristics of UV LED lamps are significantly different than traditional systems and UV meters are just coming onto the market that will accurately measure UV LED lamps.
Even then, radiometers need to be calibrated for specific LED characteristics of the lamp manufacturers. A 'generic' UV LED radiometer that can be used between different UV LED lamps does not currently exist. For process control, it is important for OEMs and end-users to utilize a UV LED radiometer that is calibrated to the UV LED lamp provider's specifications. Otherwise, false readings and/or improper conclusions are the likely results.

As shown, measuring irradiance and dose is not a simple task. The authors believe the industry, including UV LED lamp manufacturers, measurement device manufacturers, OEMs, and end-users should align around a single industry standard that can be used to consistently, accurately, and succinctly report irradiance and dosage measurements.

Result: UV LED Lamps are not created equally

UV LED lamps are not created equally. Suppliers of UV LED lamps have significant architectural and implementation decisions that significantly impact their product's performance. The end result will be a UV LED curing system with optimized LEDs, Arrays, Optics, and Cooling for a specific application. Knowing how to characterize the performance allows the user to identify the best overall system to meet their specific needs. OEMs and end-users would be wise to learn these differences and ensure their chosen suppliers are capable of not only meeting their needs today, but have the technical ability to design, manufacture, and support their needs in the future.

This article has attempted to build on previous work by highlighting the myriad of architectural and design tradeoffs UV LED lamp makers have at their disposal. More importantly, OEM and end-users considering the inevitable transition from legacy mercury tubes to solid-state UV LED technology must understand that not all UV LED lamp systems are created equally. It is vitally important they consider the needs of their application as well as the capabilities of their supplier. Lastly, the authors believe the UV LED industry must band together to create industry standards and capabilities the simplify OEM's transition to a bright UV LED future.

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