UV-LED Curing Systems: Not Created Equal

By Sara Jennings, Bonnie Larson and Chad Taggard

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 benefits of UV-LEDs. This paper will 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 available UV-LED based systems 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 equal.

UV-LED Curing Advantages

Application after application across many market segments have moved to UV curing using photopolymer chemistry and away from solvent-based formulations that contain volatile organic compounds (VOCs) and require large, power-hungry furnaces. The advantages of UV-curable formulation systems versus conventionally cured solvent-based formulation systems are well documented. The advantages of UV-LED curing over UV curing using traditional mercury lamps for specific applications have also been well documented in previous articles.

Most, though not all, UV-LED lamps are focused on the UV-A range and the ability to generate high-irradiance UV light with sufficient energy levels to cure most materials. However, due to its focused wavelength characteristics, the typical UV-LED lamp doesn't generate UV-B, UV-C or even infrared emissions that are sometimes useful for certain curing applications. With the wide variety of inks, coatings and adhesives having been formulated to take advantage of UV-LED curing, there are no substantive reasons that UV-LED curing systems will not continue to enjoy rapid growth in the marketplace.

Components and Comparisons

UV-LED curing lamp systems consist of multiple sub-components which taken together can be used to define

Table 1

UV-LED light source components

	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 ensure 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.

the system's overall performance. The key design subcomponents are outlined in Table 1.

UV-LED Light Source Components

Examining these components in closer detail along with their interactions and interdependencies will provide the reader with a better understanding of how UV-LED curing lamps are not created equal.

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 system's architecture and design. A pictorial example of an LED's construction is shown in Figure 1.

LED Construction

Simply put, an LED is a solid-state 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.

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 manufacture 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.

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 little impact as the photoinitiator that kicks off the reaction has a broad absorption range. For example, as you can see in Figure 3, three-fourths of the LED energy output (with a peak at 385 nm versus a peak at 395 nm) share the same wavelength band. Material testing

FIGURE 2

Wavelength characteristics

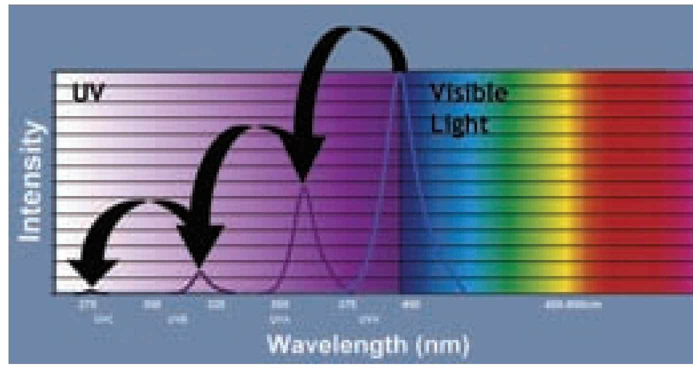


FIGURE 3

Wavelength comparison

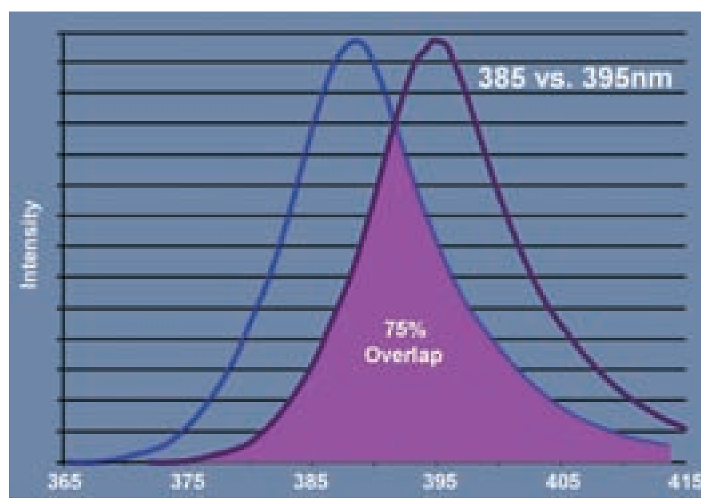


FIGURE 1

LED construction

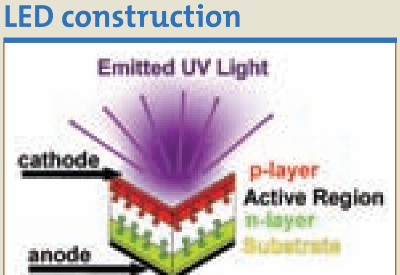
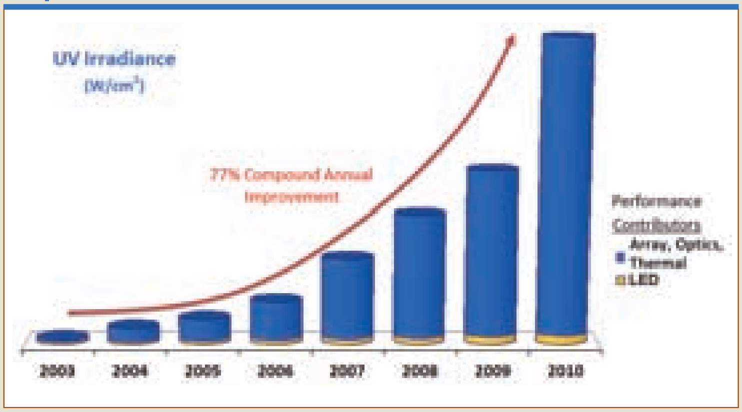


Figure 4

Contributing factors of peak irradiance improvement



confirms that the difference in either cure rate or quality when using die with peak outputs centered at 385 nm and 395 nm is negligible.

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

UV Output

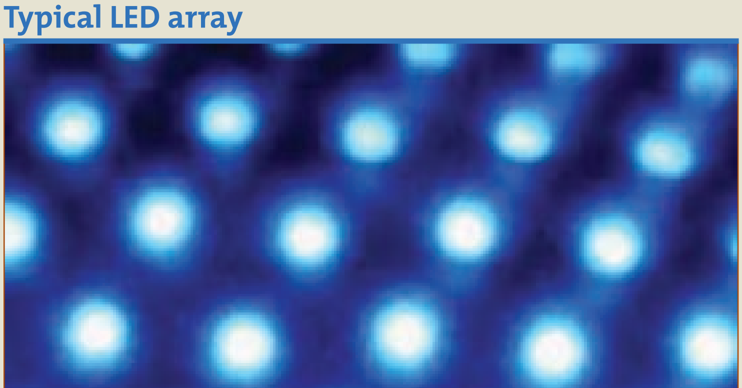
The output of a single UV-LED is measured in milliwatts (mW) at a nominal input voltage and current. UV-LED output has shown considerable improvement in recent years where specifications for LEDs from various vendors have improved from 2005 to 2011 with a compound annual growth of 5-10%. This improvement 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.

Figure 5

Typical LED array



II. Array—Grouping of LEDs

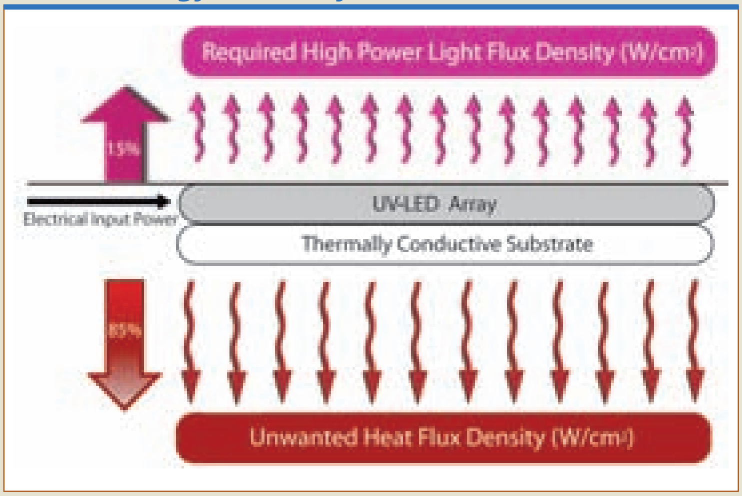
Arrays are the second area in which suppliers can begin to differentiate their product offerings. How the LEDs are combined; the number and type of LEDs chosen; the shape of the array; the method of electrically connecting the LEDs; and even the size of the LEDs all have significant impact on the performance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

This is an area where UV-LED lamp suppliers can differentiate themselves based on the LED suppliers’ architecture, modules and their own engineering capability where two suppliers can take the same batch of LEDs and achieve very different performance in the end product.

Figure 6

UV-LED energy efficiency



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 byproduct of solid-state devices is heat. UV-LEDs transfer about 15-25% of the received electrical energy into light with the remaining 75-85% transferred as heat; thus, the need to cool the LED arrays. See Figure 6.

Currently, UV-LED arrays are cooled with either air or liquid. Table 2 lists a comparison of the two most common methods used for cooling LED arrays.

It is important to note that as the LEDs emit more light, they also generate more heat, which must be managed. Thus, in the race to build even 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 toward 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. Original equipment manufacturers (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 that 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. See Figure 7.

The optical engineer is challenged to use methods to ensure the maximum amount of light "escapes" at the desired irradiance through the

Table 2

Air versus liquid-cooled light sources

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 cannot 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 size as no need for a fan.

FIGURE 7

Traditional mercury lamp optics versus LED optics

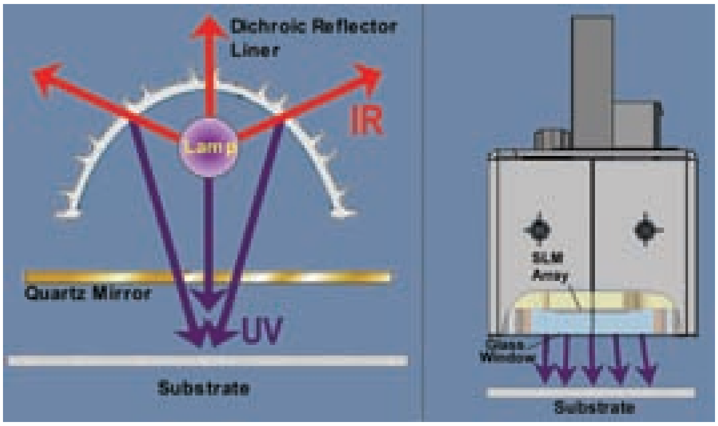
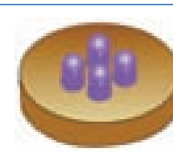
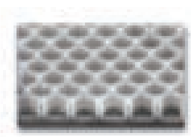
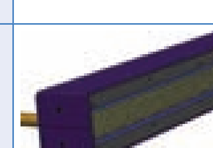


TABLE 3

UV-LED optical options

Optics	Pros	Cons	Example
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.	

window/glass toward 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 3.

As shown, this is a small subset of the myriad of choices an UV-LED supplier has to make concerning the light distribution generated by their chosen LEDs, whether individual diodes or previously assembled. Hence, it is the third major area for differentiation among UV-LED suppliers.

Measuring the Differences Between UV-LED Curing Systems

Regardless of the LED, array, thermal and optics design employed, the end result that matters to end-users

TABLE 4

Peak irradiance versus energy density

	Peak Irradiance	Energy Density
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

is that their material is properly cured. The two measurement parameters for this are peak irradiance and energy density (sometimes referred to as "dose"), and are outlined in Table 4. These two parameters work together and understanding their measurement method will allow OEMs and end-users to properly characterize the UV-LED curing system.

OEMs and end-users should consider two key questions when measuring UV-LED Lamp output:

1. Where is the peak irradiance specification point of reference?
2. Over what area is the peak irradiance being delivered?

Table 5 shows some of the typical measurement locations for measuring/specifying peak irradiance and the pros and cons of each approach.

TABLE 5

UV-LED measurement options

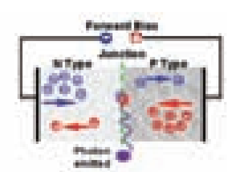
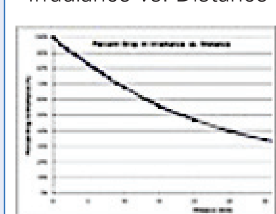
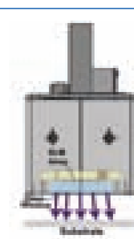
Usefulness	Location	Pros	Cons	Example
Poor	At the LED	Gives some indication of the base LED, but this is only a small component of the performance of a UV-LED curing system.	Cannot be measured. No practical application.	Photon emitted at Junction 
Better	At the media	Most relevant to end-user.	Each customer's operating distance can be different and, as noted above, the emitted UV light is divergent which means even though 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?	

Figure 8

Irradiance profile

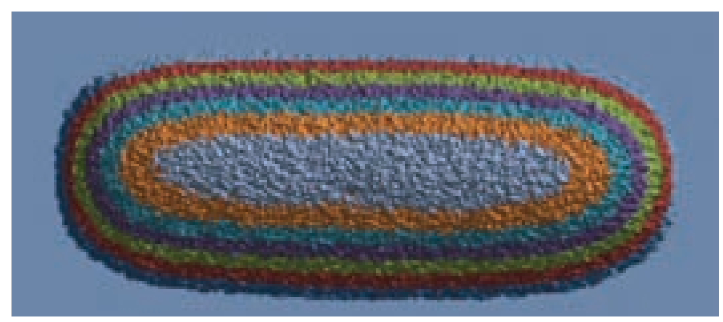
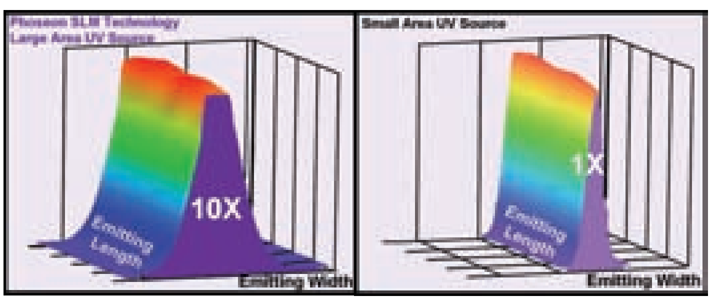


Figure 9

Uniformity along emitting width



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 center 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/cm^2 across the entire emission area when, in fact, only 2 W/cm^2 is delivered at 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 that deliver very different total energy to the material, which is the topic of the next section, energy density.

Energy Density

Energy density can be a very misunderstood concept and is also variously called density, dose or exposure. Energy density is the time integral of irradiance; thus, the higher the peak irradiance and/or the longer the exposure time, the higher the energy density. Consequently, even with the same lamp unit operating at the same peak irradiance and same distance, media exposed at different belt speeds do not receive the same energy density.

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.

Figure 10

Energy density versus height (same speed)

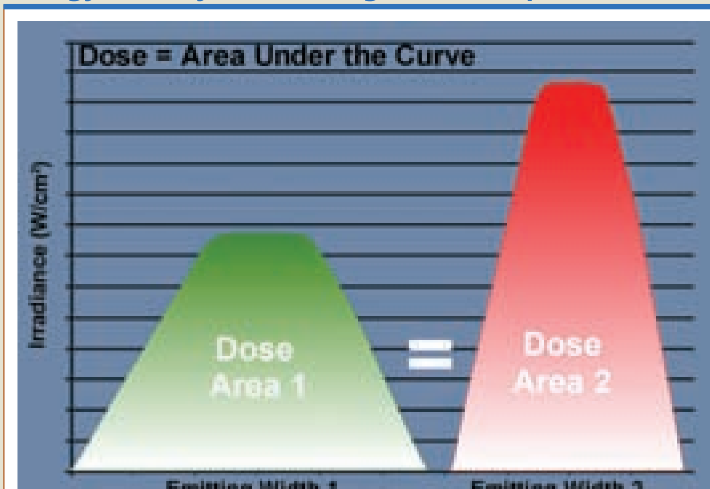
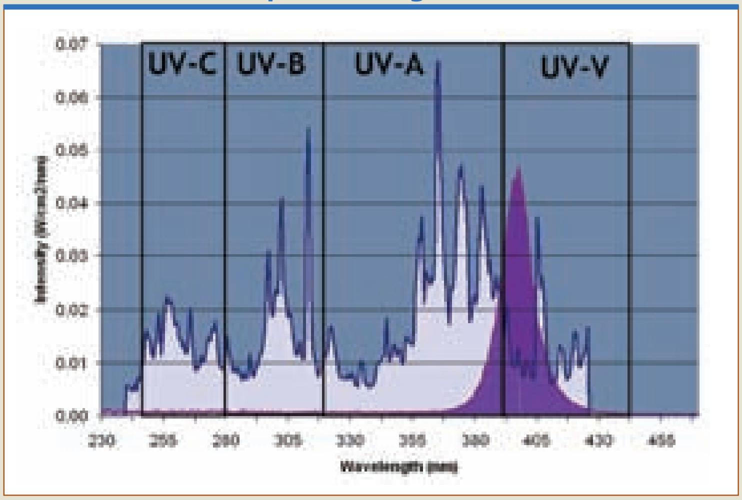


FIGURE 11

LED versus arc lamp wavelength



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 delivered to the surface, but rather the peak irradiance decreases.

To show this graphically, see Figure 10. The red curve has a peak irradiance of 8 W/cm^2 while the green curve shows a peak irradiance of 5 W/cm^2. The key is that the area under the curve is equal. The peak irradiance is lower but the overall energy density remains the same.

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 energy density to the curing surface, and allow faster cure speeds.

Measuring Irradiance and Energy Density

Lastly, what device should be used to measure UV-LED lamp output? 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 (Figure 11). 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 energy density 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 energy density measurements.

Result: UV-LED Lamps Aren't Created Equal

UV-LED lamps are not created equal. 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

Different types of UV-LED lamps.

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 trade-offs UV-LED lamp makers have at their disposal. More importantly, OEM and end-users considering the transition from mercury tubes to solid-state UV-LED technology must understand that (1) UV-LED isn't for every application and (2) not all UV-LED lamp systems are created equal. 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 that simplify OEM's transition to a bright UV-LED future.

—Sara Jennings, Bonnie Larson and Chad Taggard are part of the marketing team at Phoseon Technology in Portland, Ore.

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RadTech News

RadTech Europe Held Successful Metal Coatings Seminar

RadTech Europe held a successful two-day curing event "2nd RTE Metal Coatings Seminar" Jan. 26-27 in Belgium with 85 attendees, 20 of whom were end-users. The event was organized in collaboration with OCAS N.V. and field experts from coating suppliers, manufacturers and end-users. Attendees learned about the state-of-the-art chemicals, formulations and equipment for metal, can and coil coatings. A number of interesting case studies underlined current possibilities.

The first day dealt with various general aspects of raw materials, formulations and equipment for implementing UV/EB—all highlighted in a joint presentation by BASF, Sartomer and Cytec. This was followed up with a presentation about OCAS; and a guided laboratory tour around the OCAS facilities. In the evening, a networking dinner took place in the city of Ghent.

The second day was dedicated to industrial applications for metal coatings with an emphasis on economic use, environmental caring, processing and energy savings. The day started with an overview of current and upcoming relevant legislation, together with the impact of these on metal coating applications by Adrie Winkelaar. Presentations by IST METZ GmbH, AkzoNobel, Fusion UV and PCT gave attendees further insight into the drivers and challenges for the technology; available equipment; and specific possibilities and applications for EB technology.

RadTech Europe and its metal coatings working group, in particular, were proud to present a number of case studies from Crown Cork, Thyssen Krupp, Daimler, Venjakob and OCAS. These demonstrated that UV and EB metal coating not only sounds good in theory but companies are already developing various successful applications using the technology.

Overall, the seminar was highly rated by attendees for having both a well-balanced program and excellent networking possibilities. Companies interested in purchasing the proceedings of the seminar should contact the Secretariat of RadTech Europe at *mail@radtech-europe.com.*