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Comparing Traditional UV Systems with UV-LED Systems for UV Curing

Editor's Note: *The following paper won the 2014 John Matteucci Technical Excellence Award for Web Coating at the Association of International Metallizers, Coaters and Laminators (AIMCAL) Web Coating & Handling Conference USA.*

Abstract

Enthusiasm and rapid development are two characterizations of the entry of UV-LED sources into UV-curing applications. In many cases, UV-LEDs are replacing the traditional mercury-based, medium-pressure lamps. We will explore some of the similarities and differences of these UV sources, concentrating on measurement. Whether applying medium-pressure mercury lamps or UV-LEDs, accurate UV measurements of spectral irradiance and exposure are essential to optimized design and production control of the UV-curing process.

The most important principle of effective radiometry is that the measurements must be *relevant to the process* or, in other words, must be related to the development of the physical properties of the final product. This also is true of the need for optical characterization (or specification) of UV lamps for the purpose of system design.

Key exposure parameters

The *optical thickness* of a curable film determines to what extent irradiance will affect, for example, depth of cure and adhesion. *Optical thickness* also can be described by the ratio of photon flux at the "top" of a film to the photon flux at the "bottom." The implications of "optical thickness" on adhesion are quite clear.

The *spectral absorbance* of the films will affect which wavelengths will more effectively penetrate and how the irradiance level will achieve depth of cure. Of course, the *action spectrum* of the photoinitiator blend will determine the wavelength *responsivity*. The key parameters are as follows:

- **Irradiance** – the profile of radiant power arriving at a surface, measured in W/cm² or mW/cm², in a specific wavelength band; (often, only the *peak* value is reported);
- **Time (or speed)** – the time in seconds of exposure; inverse of speed;
- **Spectral distribution** – relative radiant power versus wavelength, in nanometers (nm).

The *temperature* of the film (ink or coating) is important to the curing process. It is a consequence of radiant energy delivered from the UV source – including infrared – and the absorbance of the work surface. Some heat is beneficial to the reaction, but excessive heat can cause damage to temperature-sensitive media. A non-contacting optical thermometer is recommended for surface temperature measurement.

A useful measure is *exposure* – commonly, but incorrectly, called "dose." Exposure is the time-integral of the irradiance profile, so it is *not a separate variable* – it is the consequence of two independent variables – *irradiance profile and time* – expressed in J/cm² or mJ/cm² in a specific wavelength band. *Exposure* – or "dose" – can be useful only if spectral distribution and irradiance or time is known, as none of the key design variables can be derived from it.

Radiometric instruments and devices

Radiometers measure *irradiance* – usually in watts/cm² – at a point, but over a uniquely defined wavelength

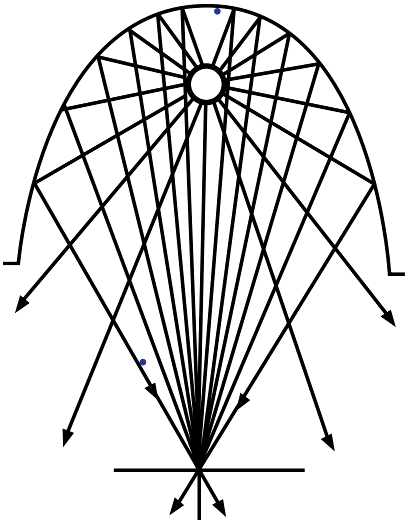

FIGURE 1. *Typical elliptical "focusing" reflector used with MP UV lamps*

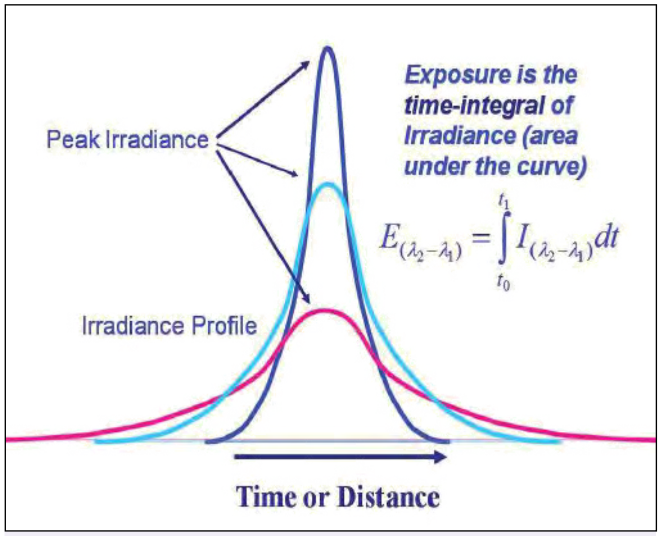

FIGURE 2. *Typical irradiance profiles of MP UV lamps*

band. The wavelength range to which they respond is defined by the spectral responsivity of their internal filters and detectors. Advanced instruments can "map" the irradiance profile and also calculate exposure.

Exposure meters measure accumulated energy at a surface – watt-seconds/cm² or joules/cm² – also over a uniquely defined wavelength band. Because this is the only measurement that incorporates *time*, reporting of exposure tends to be commonly used.

Spectroradiometers are very narrow-band instruments, essentially responding to spectral irradiance, and are highly wavelength-specific – some with resolution as fine as 0.50 nanometer. These instruments – actually miniature monochromators – can be valuable when there is a need to evaluate irradiance in a selected wavelength band to a high degree of detail.

Radiachromic dosimeters are tabs or films that attach to a test surface and respond to total time-integrated energy by changing color or by changing optical density. These can be evaluated with a densitometer and can be correlated to an exposure meter.

Medium-pressure mercury lamps

The most common arrangement of the medium-pressure (MP) UV lamp – either arc- or microwave-powered – is with the tubular lamp set in a semi-elliptical reflector. The typical reflector and irradiance pattern are shown in Figures 1 and 2. These lamps usually are classified in "watts per inch," which does little to describe their optical features.

Irradiance and irradiance profile

Although *peak irradiance* is a very important component of exposure and is easily measured, the *irradiance profile* is more important. This is because parts of the exposure-profile curve will have *different effects on cure and depth of cure*. Depending on the power and optics of the UV source, irradiance and peak irradiance may fall into any one of the following general categories:

- Very high: Over 10 W/cm²
- High: 1 W/cm² to 10 W/cm²
- Low: 100 mW/cm² to 1 W/cm²
- Very low: 1 to 100 mW/cm²

page 46 ▶

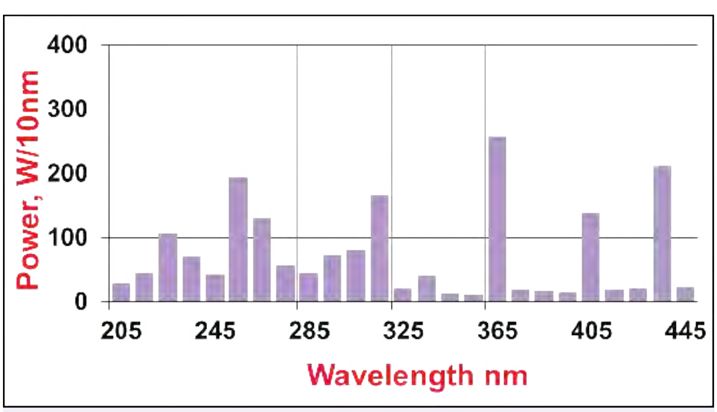

FIGURE 3. *Spectral distribution of MP mercury UV source (shown in 10 nm integration)*

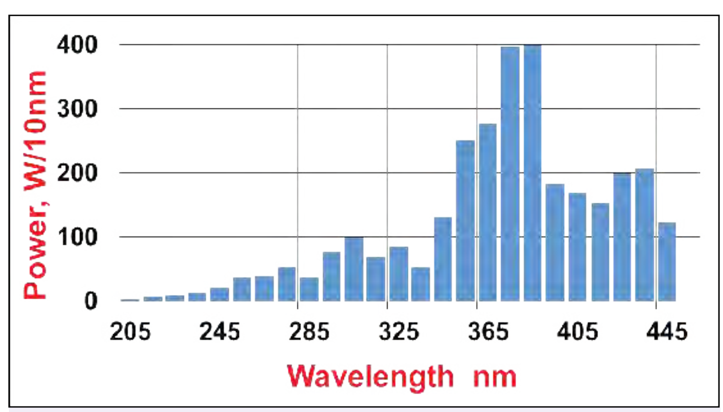

FIGURE 4. *Spectral distribution of MP mercury UV source with iron halide additive to enhance the UVA band ("D" bulb)*

◀ page 45

Figure 2 shows a comparison of different irradiance profiles, but all at approximately the same exposure – area under the curve. This is typical of a highly focused lamp, illustrated at positions progressively further from the work surface or radiometer.

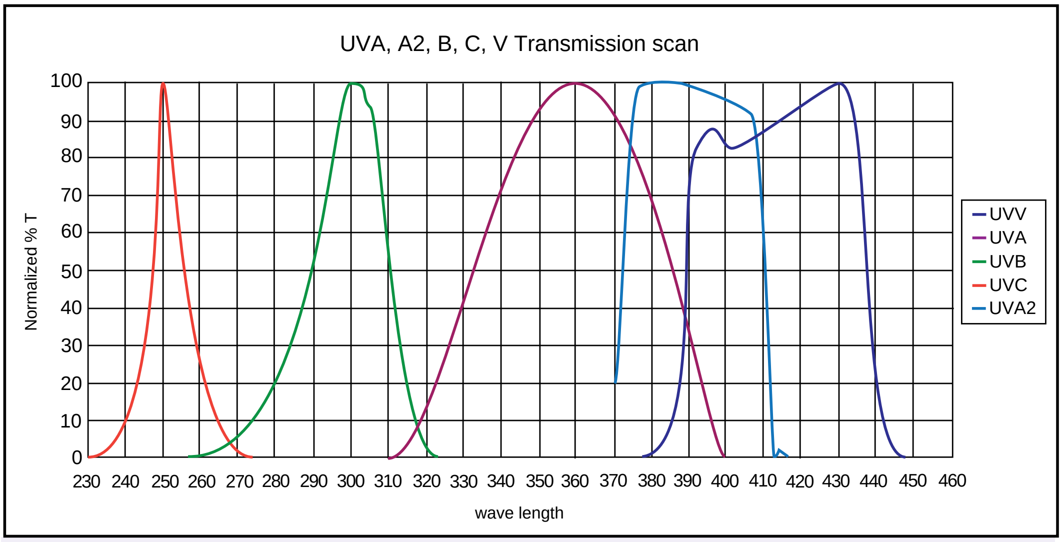

FIGURE 5. *Several measurement bands used for MP-UV lamps and UVA2 band for UV-LEDs (Courtesy of EIT)*

Spectral distribution

A benefit of the MP lamp is seen in its wide spectral distribution and its ability to alter the spectral output in different regions of the UV spectrum. This allows a range of photoinitiators to be selected with various action spectra to react to longer or shorter wavelengths, to achieve deeper cure by long wavelengths and surface cure by shorter wavelengths. The spectral distributions of two types of MP bulbs are shown in Figures 3 and 4.

Reporting exposure

Because *exposure* is directly proportional to time of exposure – or inversely proportional to speed – it can be calculated for any speed from data at a known speed. It does not have to be repeatedly measured at different speeds. To calculate exposure at any speed, simply multiply an error-free exposure measurement by its speed and divide by the desired speed.

MP lamp output

A comparatively high-powered MP lamp with an additive-type bulb may have an output peak irradiance of up to 10 watts/cm² and deliver an exposure of up to 2 J/cm² – in the UVA band at 20 fpm.

Radiometers

Several instruments are available for making irradiance and exposure measurements, and many of these instruments will provide both in spectrally divided and defined ranges – for example: UVC, UVB, UVA and UVV over the entire UV region.

A radiometer from one manufacturer can report UV data differently from another. This is because instruments have different *responsivity*, or wavelength sensitivity. Further, instruments differ in their spatial sensitivity – angle of acceptance – although most have diffusers to give them a *cosine* response. All of these may be accurate and calibrated – they simply cover different ranges. This is the reason that data communication *always* must be accompanied by the identification of the radiometer used. As a practical matter, many users prefer to compare data from instruments only of the same type.

UV-LEDs for UV-curing applications

For UV curing, the use of UV-LEDs follows the same "rules" of exposure as MP lamps, but with characteristic differences. First, the spectral distribution is very limited. Individual chips ("die") for construction of LED arrays are nearly monochromatic, but are selected ("binned") based on three parameters: wavelength, power output and voltage. This permits the construction of arrays, each with different centerline wavelengths: typically 365 nm, 385 nm, 395 nm and 405 nm. The highest irradiance per watt typically is in the 395 nm group – others significantly lower further from that. Almost monochromatic, each of these arrays may have a wavelength spread of only 10-20 nm and irradiance in the "very high" category.

Owing to the fact that the radiant energy from today's UV-LEDs is entirely in the long wavelength UV – between UVA and UVV – they provide excellent depth of cure but potential difficulty in surface cure. This is remedied in the chemical formulation of LED-curable inks and coatings.

Wavelength – UV-LEDs

Generally, radiometers whose bands are suitable for MP-lamp measurements are not usable for UV-LED measurements. This has generated the need for filter-detector radiometers more suited for this range, which happens to lie between the traditional designations of UVA and UVV. For practical distinction from existing designations, the Measurements Group of RadTech International North America proposed that this band – first promoted commercially by EIT – be designated "UVA_2" or simply "UVA2."

Figure 5 shows the relationship of UVA_2 to the other bands that typically are applied to MP lamps. Figure 6 illustrates the

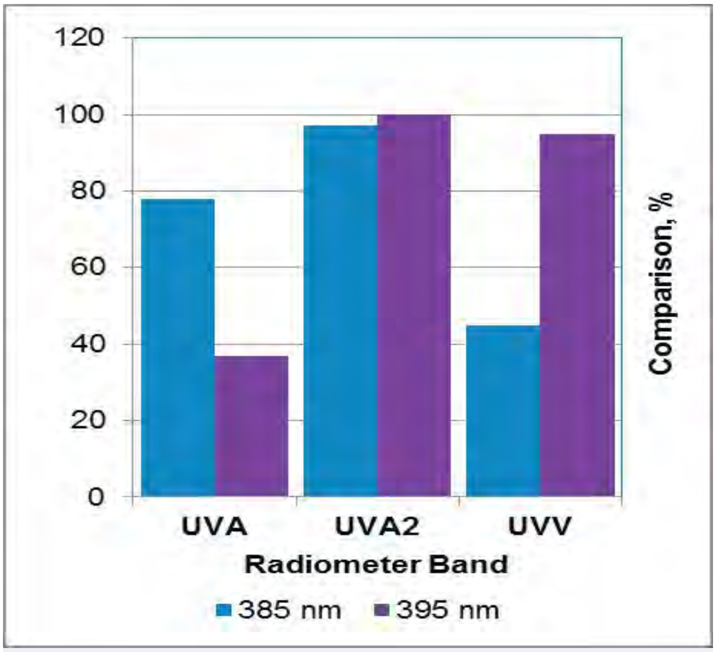

FIGURE 6. *Measurement error related to using the wrong (UVA or UVV) measurement band with 385 nm or 395 nm LEDs*

measurement and resulting error of measuring a 385-nm UV-LED and a 395-nm UV-LED with a radiometer designed for UVA and UVV wavelength bands, as compared to one responding to the UVA_2 band. An important lesson here: *Know the radiometer response band – don't use the wrong radiometer for measurement of LEDs.*

Irradiance vs. distance

For practical application of UV-LED lamps, the exposure pattern at the work surface is as important as it is for MP lamps. The UV-LED field of "illumination" – to borrow a term from visible lighting – is usually more flat and uniform owing to the construction of the multi-chip array that constitutes the lamp. Unlike MP lamps that typically "focus" the highest irradiance at a distance of a few inches in front of the lamp, irradiance of the UV-LED array is progressively lower from the lamp face (window) toward the work surface. Consequently, the most common applications of UV-LEDs today are in near-field and flat or nearly flat applications that can take advantage of the high irradiance near the lamp face.

Irradiance profile

A "mapping radiometer"– similar to those used with MP lamps – can determine the irradiance profile. However, as there usually is

page 48 ▶

◀ page 47

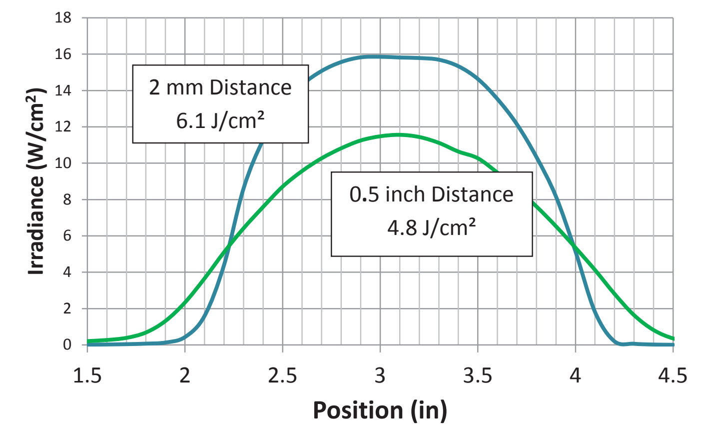

FIGURE 7. *Irradiance profiles of 16 W/cm2 385-nm LED at 2 mm and 0.50 in. from lamp face (UVA2 exposure at 20 fpm)*

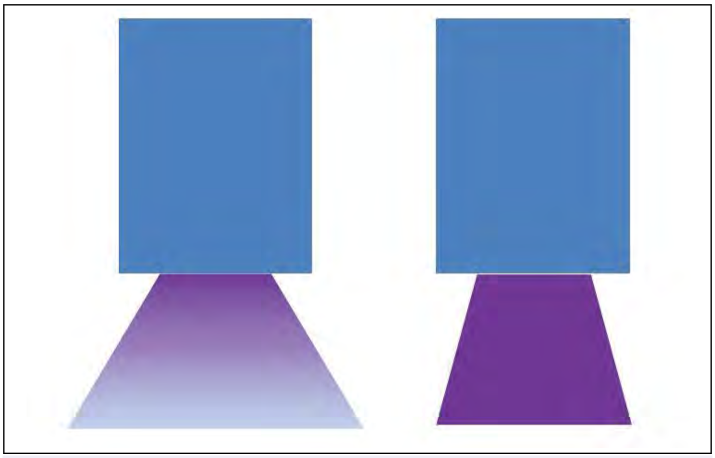

FIGURE 8. *Illustration of the effect and benefit of micro-optics*

very little distance between the LED and the work surface, it may be difficult to pass a common integrating radiometer or exposure meter under the lamp. Irradiance profiles can be determined using a small probe and plotting the profile from carefully spaced measurements. Figure 7 shows the irradiance profile of a comparatively high-power LED at two distances. Because LEDs are very stable, a one-time determination of profile may be sufficient and may be checked only periodically. Exposure at any speed can be calculated from this profile. Currently, no UV-LED manufacturers publish irradiance profiles.

Micro-optics and irradiance

The LED array – essentially a cluster of point-sources – exhibits a radiation pattern that can be described as a quasi-Lambertian source with radiant energy diminishing as a function of distance. Because the LED actually is an array of individual LEDs, irradiance measurements very close to the lamp's window can show some non-uniformity, which is reduced as measurements are made slightly further from the face.

Large-scale optics – lenses or reflectors – to "focus" this energy are impractical, owing to the fact that virtually all rays are diverging from multiple points. Individual "micro-lenses" in the forward region of each LED can redirect much of the energy into the forward direction. This decreases the area of exposure and increases irradiance. Figure 8 illustrates the function of micro-optics, and Figure 9 shows the benefit of micro-optics in irradiance at distances from the lamp face.

Describing and specifying UV-LED lamps

The ways in which UV-LED lamps are described varies from manufacturer to manufacturer. UV-LEDs – comparatively new to UV curing – have not yet developed a consistency of description relating to the features important to process design. The importance of the length or width is that – depending on the orientation of the lamp to the process travel – it will have a controlling effect on the exposure in a dynamic process. Because of differing patterns of irradiance, array densities, distance from the lamp face, lack of instrument identification and the ways they are presented by manufacturers, there can be some confusion of lamp "specifications."

Important optical-design information to know about a UV-LED system includes the following:

1. The principal wavelength of the array; occasionally the wavelength spread – at the 50% point from the center wavelength – will be disclosed.
2. The static peak irradiance at the center of the lamp face at a distance, preferably at the working distance; this is the most common characterization of UV-LEDs – typically expressed in watts, although the units are actually watts/cm². This distance must be part of the irradiance specification.
3. The dimensions of the irradiance profile – ideally, the length and width of the exposure field at the 50% irradiance points, as these determine the length (and time) of dynamic exposure and the width of exposure along the length of the lamp. Most often, only the mechanical dimensions of the transmitting window are provided.

Conclusion

For UV-curing applications, the key exposure variables for characterizing the output of UV-LEDs and MP mercury-based lamps are the same. These parameters can be used for system designs, as well as for the characterization of UV systems. The ability to determine the optimum exposure for UV-LED-curable material and the ability to characterize the output of any selected UV-LED source can shorten the trial-and-error that may otherwise be required and can simplify the process of lamp selection. Wavelength, irradiance and time and temperature are the important variables of the UV-curing process. The fact that exposure over a range of speed can be calculated for a given lamp type and configuration can be helpful for system design. ◆

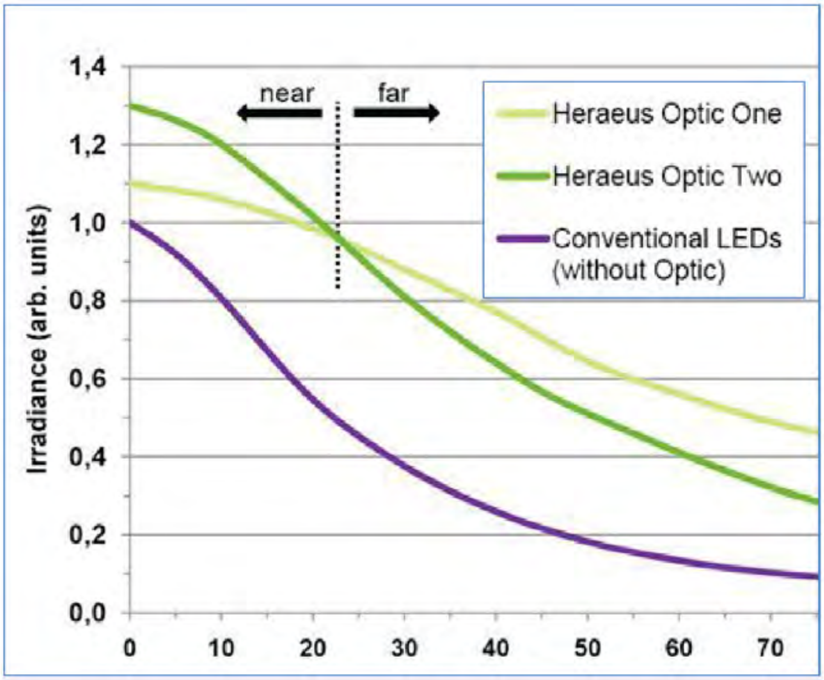

FIGURE 9. *Near-field and far-field effects of micro-optics*

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