UV Measurements of Medium-Pressure Lamps and UV-LEDs for Process Design and Control

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Abstract

Accurate UV measurements of spectral irradiance and exposure are essential to optimized design and production control of the UV curing process. Methods of measurement as well as some sources of error are presented. Radiometers and exposure meters are discussed, along with several techniques of using them for process specification and troubleshooting for both medium-pressure and LED systems.

Introduction

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

Process design determines the exposure requirements of the chemistry to be cured -- such as irradiance profile, spectral distribution, power level, peak-to-energy ratio, temperature, and time (or speed). In addition to aiding in the optimization of the process, radiometric measurements are useful in quantifying the successful exposure parameters, so the process can be reliably duplicated. This is the important step of transferring the process form the lab to production design. The function of radiometry is to provide *quantitative* information about the critical requirements of the process and to establish the *limits* or "window" within which the process is successful.[1]

The Four Key Exposure Parameters

The *optical thickness* of a curable film determines to what extent irradiance will affect, for example, depth of cure and adhesion. 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*. Further, the temperature of the film -- typically the result of absorption of any radiant energy -- will affect the curing reaction.

The key exposure parameters are

- **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 <u>peak</u> 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);
- **temperature –** temperature rise of the substrate, °F or C. (A non-contacting optical thermometer is recommended for surface temperature measurement).

Another useful measure is **exposure**, commonly called "dose." Exposure is the time-integral of the irradiance profile, so is <u>not a separate variable</u> – it is the consequence of two independent variables -- irradiance profile and time -- expressed in J/cm² or mJ/cm² in a specific wavelength band.

$$E_{(\lambda_1 \rightarrow \lambda_2)} = {}_{t_0}\int^{t_1} I_{(\lambda_1 \rightarrow \lambda_2)} dt$$

Exposure (or “dose”) can be useful only when spectral distribution and irradiance or time is known – as none of the key variables can be derived from it.

We will examine the use of radiometry for the first three of the four variables, along with exposure in relation to medium-pressure mercury lamps and LEDs.

Radiometric Instruments and Devices

Radiometers measure *irradiance* (usually watts/cm²) at a point, but over a uniquely defined wavelength band. Differences in detectors, filters, construction, and principles of operation result in the fact that different narrow-band radiometers give different results when measuring broad-band sources. Many radiometers can electronically calculate *exposure* by summing a series of internally-timed irradiance measurements.

Exposure meters measure accumulated energy at a surface (watt-seconds/cm² or joules/cm²), over a uniquely defined wavelength band. There are electronic and chemical types. Because this is the only measurement that incorporates time and reports exposure, it 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 ½ nanometer. These instruments -- actually miniature monochromators -- can be valuable when there is a need to evaluate irradiance in a selected wavelength band.

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. Depending on the chemistry of the detector, it can change permanently or only temporarily. These photochromic detectors can respond to a range of UV wavelengths, depending on the chemical composition of their coatings.

Radiometry -- Medium Pressure Mercury Lamps

The most common arrangement of the medium pressure lamp, either arc or microwave-powered, is with the tubular lamp set in a semi-elliptical reflector. The typical reflector and irradiance pattern are illustrated in Figures 1& 2.

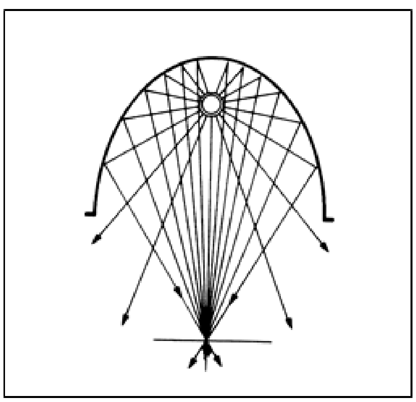

Figure 1 Typical Focused Elliptical Reflector

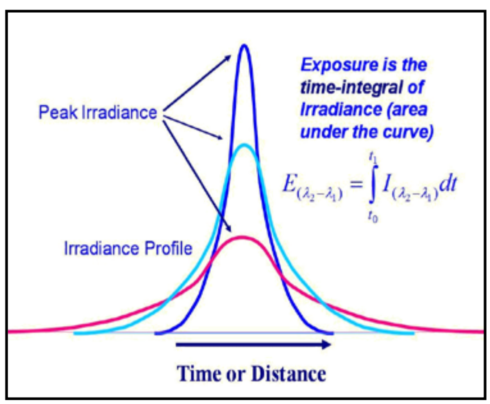

Figure 2 Typical Irradiance Profiles

Dynamic radiometers, designed to pass through the field of irradiance, can measure and report the peak of irradiance fairly easily – an electronic "sample-and-hold" type of circuit can report the maximum irradiance observed during a pass under a lamp (or lamps). Many can report the irradiance profile and the total integrated exposure. The wavelength range to which they respond is defined by the spectral responsivity[2] of their internal filters and detectors.

Irradiance and Irradiance Profile

Although peak irradiance is a very important component of exposure, the irradiance ***profile*** is more important. This is because differing regions of the exposure curve will have *different effects on cure and depth of cure.* Irradiance and peak irradiance may fall into any one of these general categories:

VERY LOW:	1 to 100 mW/cm²
LOW:	100 mW/cm² to 1 W/cm²
HIGH:	1 W/cm² to 10 W/cm²
VERY HIGH:	Over 10 W/cm²

The illustration in Figure 2 shows a comparison of different irradiance curves, but all at approximately the same exposure. This is typical of a highly focused lamp, but at positions progressively farther from the work surface or radiometer.

Reporting Exposure

It's not necessary to repeatedly run a laboratory radiometer under a lamp at different speeds to evaluate exposure conditions for any given lamp and configuration. The recommended laboratory method for exposure measurement is to select a speed, $\mathbf{v}_o$, at which speed errors are a minimum, record several measurements, E_o, and speed -- then *calculate* energy, E_x , for any other speed, $\mathbf{v}_x$.

$$\text{Since} \quad E_x v_x = E_o v_o , \qquad \text{then} \quad E_x = E_o \cdot v_o / v_x$$

To calculate energy at any speed, simply multiply an error-free exposure measurement by its speed and divide by the desired speed.

How Important is Irradiance vs. Exposure?

A high "intensity" or peak of irradiance will have a beneficial effect on the depth of cure of many UV-curable materials. The effective irradiance, or photon flux rate at any depth within the film to be cured follows a definite relationship between irradiance at the surface and the spectral absorbance of the film (at any specific wavelength) according to the *Bouger-Lambert* law:[3]

$$I_{a\lambda} = \frac{I_{o\lambda}(1 - 10^{-A_\lambda})}{d}$$

I_o is the incident irradiance (flux rate) at wavelength λ, I_a is the flux rate at depth d, A_λ is absorbance at wavelength λ, and d is the depth from the surface or film thickness.

Optical Thickness can also 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.

Spectral Distribution

A benefit of the MP lamp is in its wide spectral distribution, and the ability to alter the spectral output in different regions of the UV spectrum. This allows selection from a range of photoinitiators with various action spectra to react to longer or shorter wavelength, affecting deeper cure by long wavelengths and surface cure by shorter wavelengths.

The spectral distributions of two types of MP lamps are shown in Figure 3.

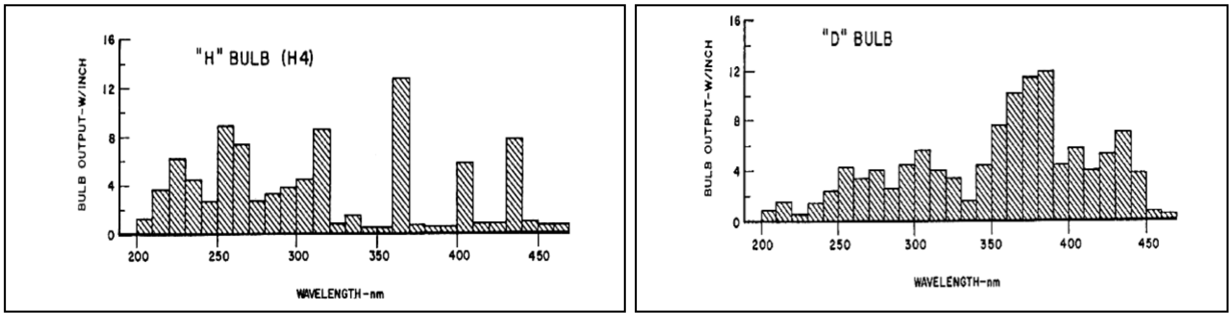

Figure 3 Spectral Distribution of MP Mercury "H" Lamp and Additive "D" Lamp (in W/10nm Integration

A radiometer from one manufacturer can report UV data differently from another instrument from a different manufacturer. 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. As a practical matter, many users prefer to compare data from instruments only of the same type.

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. Figure 4 shows the results of a study of several multi-band radiometers from various manufacturers and illustrates the fact that they may have different spectral ranges from another. ALL of these are accurate and calibrated – they simply cover different ranges.

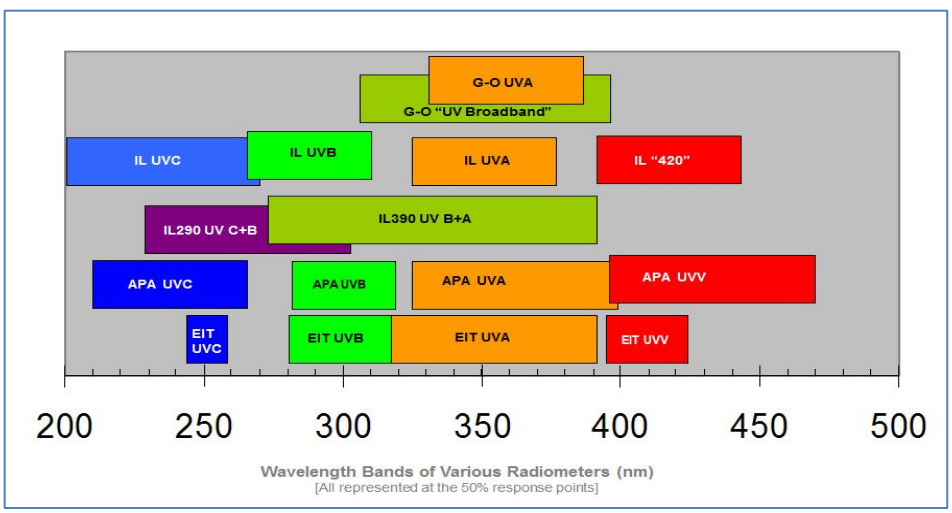

Figure 4 Spectral Response Bands of Several Commercial UV Radiometers

Radiachromic Films

Radiachromic films can be a useful extension of radiometry in situations where it is difficult or impossible to pass a bulky radiometer/exposure meter through the UV exposure zone.

The recommended method involves the correlation of radiachromic films when they change color or optical density with UV exposure to <u>any selected radiometer</u> of choice.. The method concentrates on the correlation of the quantitative value of exposure with the quantitative value of optical density.**[4]** (Using color charts or pre-printed exposure data is not recommended because the correlation is not specific to lamp type or radiometer, and may not be valid.)

For color-change reflective films,[5] a reflection color densitometer[6] is preferred. The resulting correlation curve is valid for only the specific exposure conditions, such as lamp spectrum, and radiometer model and its wavelength band. One of the simplest laboratory methods to generate the correlation is to place the radiachromic film ON the radiometer/exposure meter and expose both simultaneously. A typical set of correlations for MP lamps and the type of instrument used are illustrated in Figures 5 and 6.

Figure 5 Color Densitometer [6]

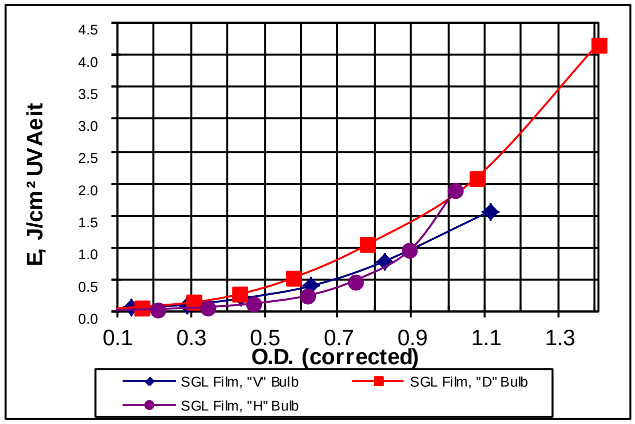

Figure 6. Correlation of SGL[5] Film to UVA_{EIT}[7] with "H" "D" and "V" MP bulbs

Radiometry – LEDs

For UV curing, UV-LEDs follow the same "rules" of exposure as MP lamps, but with characteristic differences. First, the spectral distribution is very limited. Individual chips ("dies") 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 is typically in the 395 nm group – others significantly lower farther from that. Almost monochromatic, each of these arrays may have a wavelength spread of approximately 10-20 nm, and irradiance in the "Very High" category (cf. page 3).

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 North America proposed that this band (first promoted commercially by EIT**[7]**) be designated “UVA_2” or simply “UVA2.” Figure 7 shows the relationship of UVA_2 to the other bands typically applied to MP lamps. Figure 8 illustrates the 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, compared to one responding to the UVA_2 band.

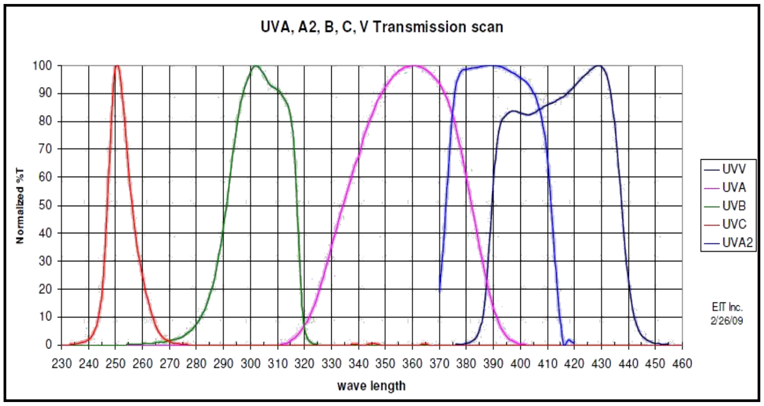

Figure 7 UV Band Illustration (Courtesy of EIT[7])

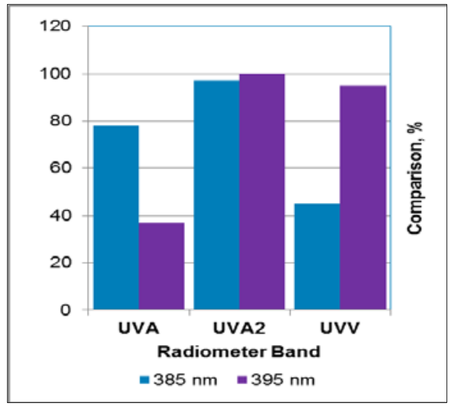

Figure 8 385 nm & 395 nm UV-LED Measured in Different Bands

Radiometer Spectral response

The radiometer response curves in Figure 9 were extracted from the manufacturer’s information. The vertical markers (red) overlay the various centerline wavelengths of typical LED lamps and are illustrated on the chart at 365, nm, 385 nm, 395 nm, and 405 nm.

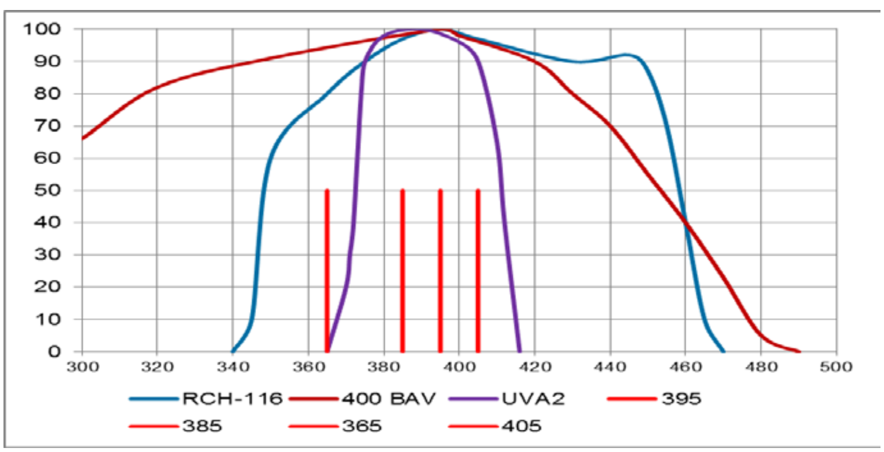

Figure 9 Three Commercial Radiometer Response Curves in the UV-LED Range

“Correction Factors” and Calibration Wavelengths

Some radiometers have a wavelength selection feature – this “corrects” the displayed reading for the usually small difference between the response curve and 100%. The purpose of this “correction” can be seen in Figure 9 where the centerline wavelengths fall to one side or the other of the 100% relative response point. Normally, these corrections are very small when the centerline wavelength is near the peak response, and have little effect on the absolute accuracy.

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 that are 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 reduction at any distance from the lamp face, as illustrated in Figure 10, this is the greatest source of confusion of lamp "specifications."

The important "dimensions" relate to the first three key process variables:

(1) the static peak irradiance at the center of the lamp face, at the working distance,
(2) the face dimensions of the window, width and length in mm, and
(3) the centerline wavelength(s) of the array.

For the purposes of this paper, the descriptions and abbreviations we will use are more specific:

(a) peak irradiance at full power at 10 mm (*or a specified distance*) from the lamp face
(b) width of the lamp face in the direction parallel to the travel of instrument or work surface;, and
(c) the centerline wavelength.

Thus, a description of a specific lamp would be, for example, "15W/cm²|44mm|395nm."

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 applications that can take best advantage of the high irradiance near the lamp face.

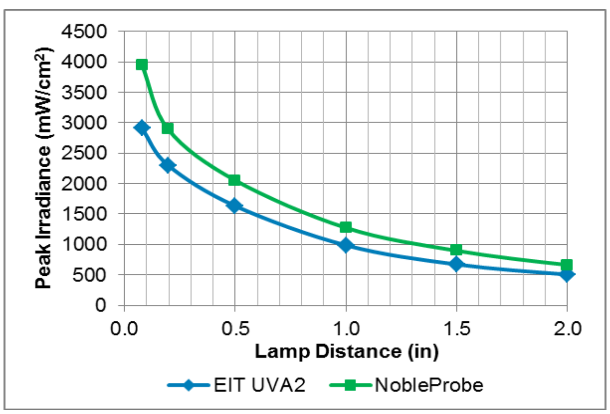

Figure 10 Irradiance vs. Distance from 4W/cm²|13mm|385nm lamp, Different Radiometers

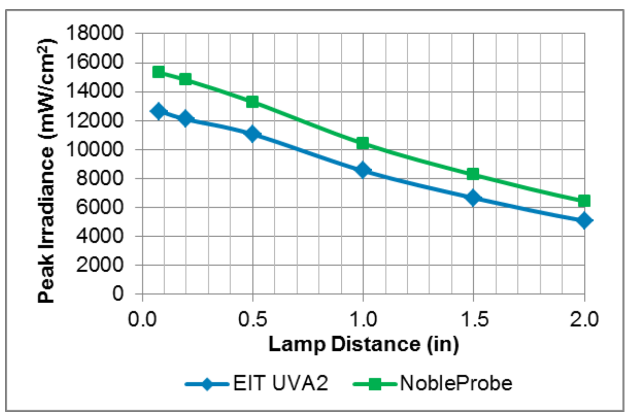

Figure 11 Irradiance vs. Distance from 15W/cm²|44mm|385nm lamp, Different Radiometers

Figures 10 and 11 show the irradiance measurements vs. distance from two different sizes of lamps with two different radiometers. These measurements are taken at the center of the field of irradiance. The UV-LED lamp in Figure 10 is an air-cooled 4W/cm²|13mm|395nm lamp. The lamp in Figure 11 is a water-cooled 15W/cm²|44mm|395 nm lamp. The data was collected with a NobleProbe[8] and a UVA2 radiometer, modified by the manufacturer [7] to have a dynamic range of 30W/cm². The curves illustrate not only the peak irradiance comparison, but the fact that the "drop-off" rate as a function of distance will be different, owing to the difference in the face area of the lamps. (The suggestion that the radiant energy falls off as the inverse square of distance is simply incorrect.)

Measuring "Distance"

The lamp configuration raises some problems for traditional radiometry and dosimetry. The radiometers that are popular for use in MP measurements, have some thickness to them – from approximately ¼ inch to ½ inch – raising the question of where and how they can be used for measurement of lamp output. (In MP radiometry, this answer is simple – the radiometer is placed ON the surface of interest for consistent measurements and "distance" is noted from the lamp face to the surface on which the radiometer is placed.)   For UV-LEDs it is becoming a usual practice to note the distance from the lamp face (window) to the radiometer top surface, where the diffuser is located.

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. Large-scale optics (lenses or reflectors) to "focus" this energy are impractical, owing to the fact virtually all rays are diverging from the surface. Individual "micro-lenses" in the forward region of each LED can re direct much of the energy into the forward direction. This decreases the area of exposure and increases the irradiance.   Figure 12 illustrates the function of micro-optics and Figure 13 shows the benefit of micro-optics in irradiance and irradiance at distance from the lamp face.

Figure 12   Illustration of the Effect and Benefit of Micro-Optics

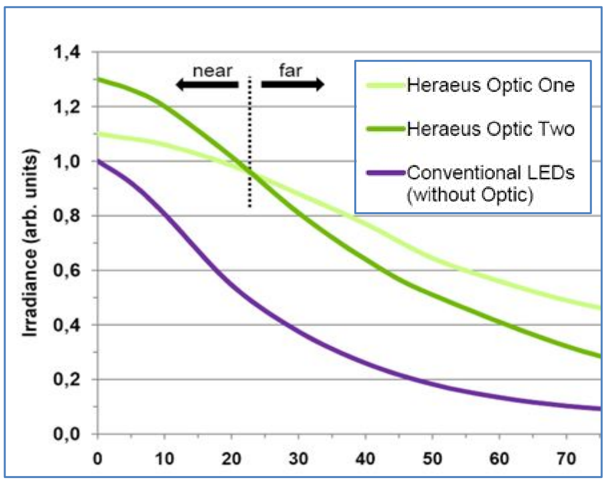

Figure 13   Near-Field and Far-Field Effects of Micro-Optics

Irradiance with Different Radiometers

Measuring peak irradiance in the near-field using several different radiometers can yield varied results, shown in Figure 14. In this example, the LED lamps are (1) a water-cooled

15W/cm²|44mm|395nm lamp (cf. Figure 10) and (2) a water-cooled 15W/cm²|44|mm|385nm lamp; the radiometers are UViCure Plus®II [7], NobleProbe® [8], and ILT 400 [9].

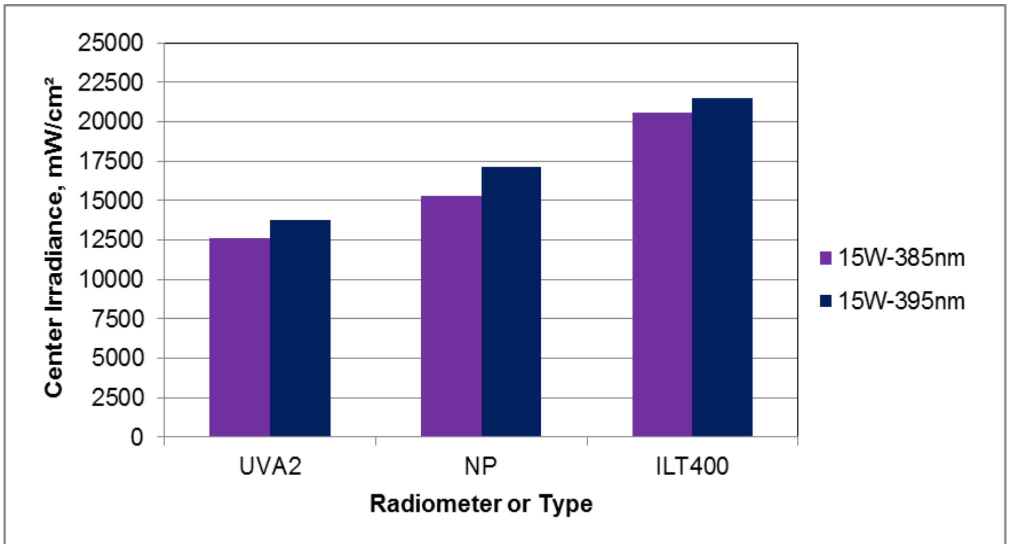

Figure 14 Irradiance of 385 nm and 395 nm UV-LED Lamps as measured by Different Radiometers (all at 1" distance)

Irradiance Profile Using a Radiometer?

Irradiance probes tend to be flat and comparatively thin compared to dosimeters. They usually do not contain the electronic means to measure and calculate the dynamic exposure, and are 'tethered' to an instrument for readout. With comparatively small apertures and diffusers, they can be calibrated with confidence.

If we want to base process design data on a calibrated probe rather than a dynamic exposure meter, the method is a bit tedious, but accurate. By making a simple succession of irradiance measurements at precisely spaced distances along the path of interest, an accurate map of the irradiance profile results.

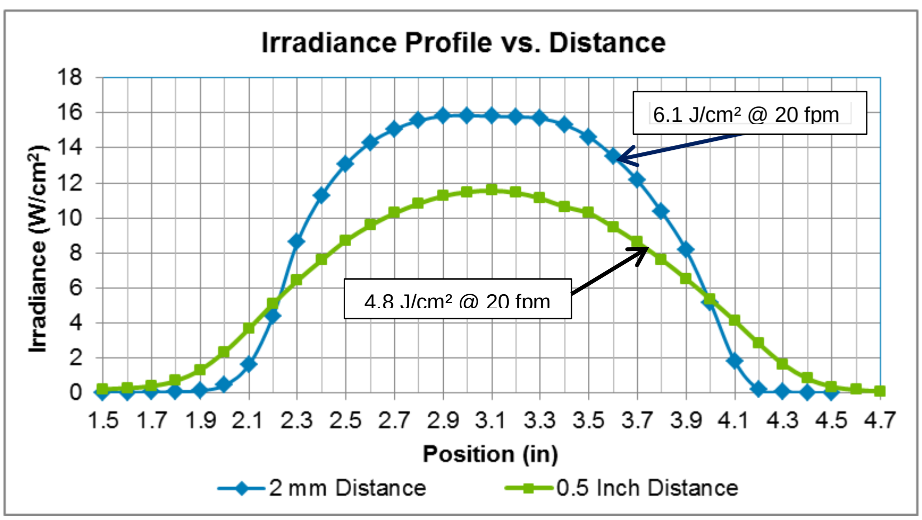

Figure 15 Series of Static Irradiance Measurements Made with NobleProbe® [8] of 15W/cm²1|44mm|385nm UV Lamp made at 0.1 inch intervals, at 2mm Distance and 0.5 inch Distance

If the increments of position are precise, the effective exposure can be calculated for any proposed speed.

$$\text{Since} \quad E = \int_0^t i\,dt \quad \text{then} \quad E = \frac{1}{v}\sum_0^n i\,\Delta d$$

In the examples of Figure 15, the lamp is 15W/cm²1|44mm|385nm and the probe is a NobleProbe® [8]. The horizontal position increments are 0.1 inch. (The units of area are watt/cm²-inch, so to convert to exposure, multiply by sec/inch for any selected velocity.) The total exposure for this lamp, at 20 fpm at 2mm distance is 6.1 J/cm², and at a distance of 0.5 inch is 4.8 J/cm².

Calculating Exposure at Any Speed

Exposure vs. speed, plotted on a log-log scale is a straight line, making calculation of exposure easy from a single reference measurement. Reference measurements can be made at speeds where error is minimal, and exposure can be calculated for speeds at which measurement is impractical.

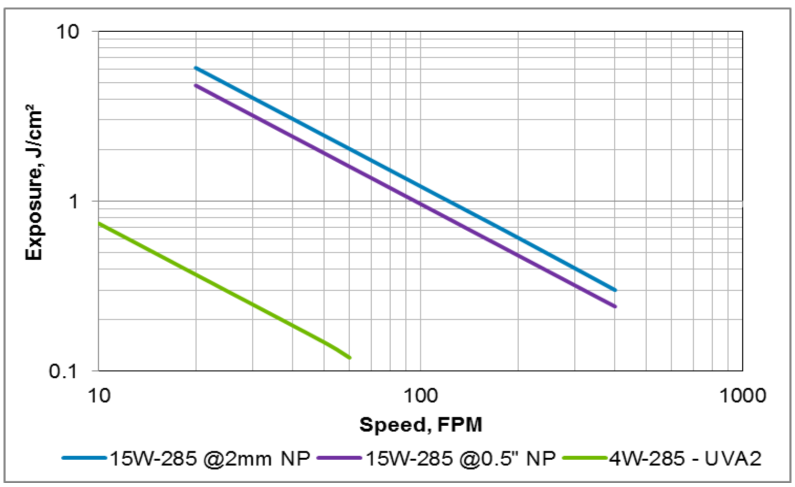

Figure 16 Plotting Exposure by log-log for Any Unknown Speed from a Reference Measurement for a Lamp, Distance and Radiometer

Radiachromic Film Dosimeters for UV-LEDs

The method of radiachromic dosimetry for UV-LEDs is the same as for MP lamps (see page 5). As discussed earlier, the film is exposed to specific conditions and correlated with a exposure meter that is exposed to the identical conditions. The potential advantage of film dosimetry is that the film can be placed on the work surface and the lamp does not have to be repositioned to make a measurement. This can be important to UV-LED measurement, as the lamp is typically placed very near the surface.

Laboratory correlation of the radiachromic film and the exposure meter of choice does require repositioning the lamp and running a set of incremental speed exposures, illustrated in Figures 17a, b, and c. The films show a very repeatable response to UV exposure.

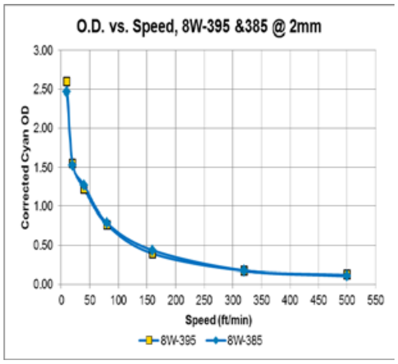

Figure 17a O.D. Response to high-power, 395 and 385 nm Exposure

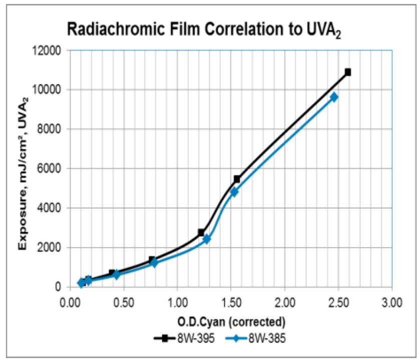

Figure 17b Correlation to UVA2 Radiometer, 395 and 385 nm

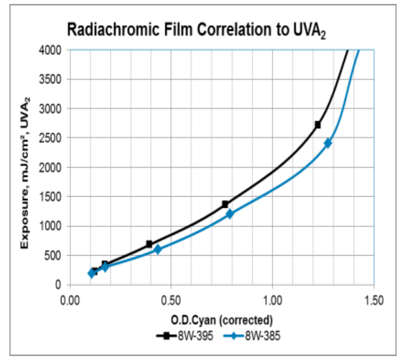

Figure 17c Correlation to UVA2 in the lower exposure range

Figures 17b and c show the correlation of a UVA_2 exposure meter,[7] (specially calibrated in the UVA_2 band to have a range of 30 W/cm²). The film is a commercial SGL film.[10] The lamps are both water-cooled, 15W/cm²|44mm|385nm and 395nm lamps.

Two radiachromic films were used in these experiments. The difference is in the expected spectral response of the photochromic coating. One commercially available and one experimental films were manufactured by Spectra Group Limited, Inc.[10] Factors affecting the responsivity of the films relate to the photochromic chemistry and the concentration of the chromaphores in the coating.

Experimental Radiachromic Films for UV-LEDs

The experimental film for LEDs was designed to have higher sensitivity, potentially making it more useful for low exposure LED applications and to be more sensitive specifically in the 365-405nm range. The films in Figure 18 were exposed to a medium-power, air-cooled

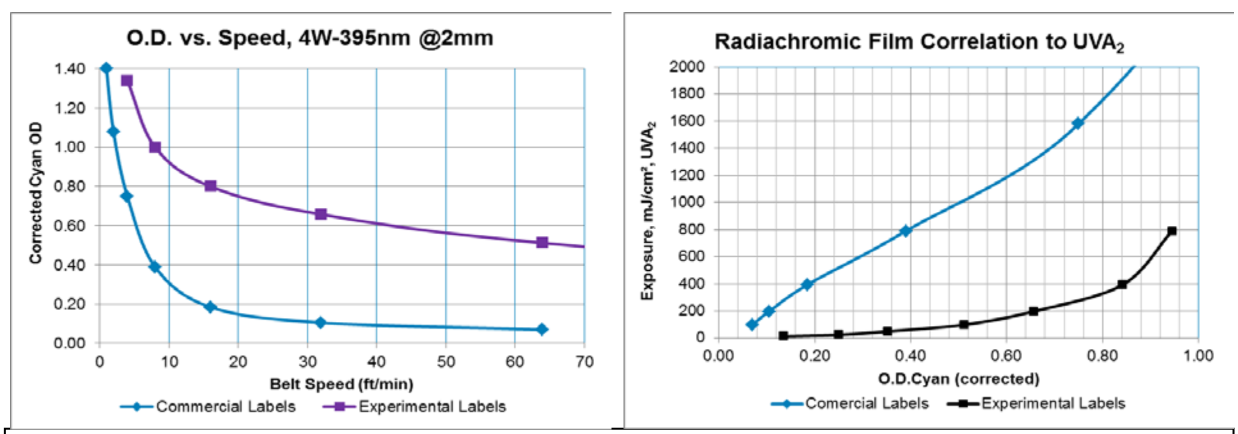

Figure 18 Exposure and Correlation of Experimental Film for low-power or high speed Application with LEDs

lamp, 4W/cm²|13mm|395nm lamp and compared to the standard commercial film under the same exposure. Again, the correlation is to a UVA_2 integrating radiometer. The films show some characteristic wavelength sensitivity, but this should not be a problem, assuming that the center wavelength of the lamp under test is identified.

Conclusions

For UV curing application, 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 design of systems as well as for the characterization of UV sources. The ability to determine the optimum exposure for a 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 simplify the process of lamp selection. 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.

UV curing technology does not yet use a consistent set of descriptors for UV-LED sources, relying on product names, and catalog numbers. In this paper, a compact set of descriptors are suggested for UV-LEDS that generally relate to information useful for process design and lamp selection. They are:

(1) the irradiance level in the lamp center, including
  (a) the distance to the sensor and
  (b) identification of the sensor, and
(2) at least one window dimension – along the path of travel,
(3) the centerline wavelength, in nm.

Owing to the difficulty of using instrument-type radiometers and exposure meters in UV-LED production equipment, the methods described here of using radiachromic films can answer the question of feasibility of on-line "transfer radiometry."

Acknowledgements:

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