

Spectroradiometry in UV Curing

By Lawrence E. Schmutz

Modern UV-curing technology has found its way into an enormous number of applications and involves a vast array of photoinitiators and direct-cure materials. A large variety of lamp systems are available to handle the many application/material combinations, making the task of matching the UV lamp to the application for consistent, high-quality results a tricky task indeed.

Once a system is chosen, curing parameters must be established and maintained to deliver coating properties that meet design spec every time. Under curing can disastrously affect product performance, with shortcomings in surface tack, gloss, hardness, strength and durability. Over-curing can damage the coated part, overheat the coating and product, and reduce production throughput by unnecessary

prolonging dwell time of the part in the UV-curing production step. Hence, optimal cure exposure is a critical factor to establish and maintain.

Wavelength and Intensity

For the most part, UV-cured materials do not respond in a general way to UV radiation, but have very selective responses to UV wavelength variation. Photoinitiators, for example, depend for their action on the breakup of chemical bonds, which releases free radicals into the bulk environment, resulting in a cascade of charge transfers ending in the polymerization of the coating material. The photon energy required to efficiently release the free radicals depends on the bond energy, and so specifies the UV wavelength needed to achieve a cure.

As an illustration, consider the UV-absorption spectra of two more-or-less randomly chosen photoinitiators in Figure 1. The spectrum of the benzyl material on the left shows a primary absorption peak at 320 nm, defining the most efficient cure wavelength. On the right is a benzophenone, which cures most efficiently at about 380 nm. Conversely, 380 nm radiation would be completely ineffective on the benzyl, and 320 nm radiation would have poor response on the benzophenone.

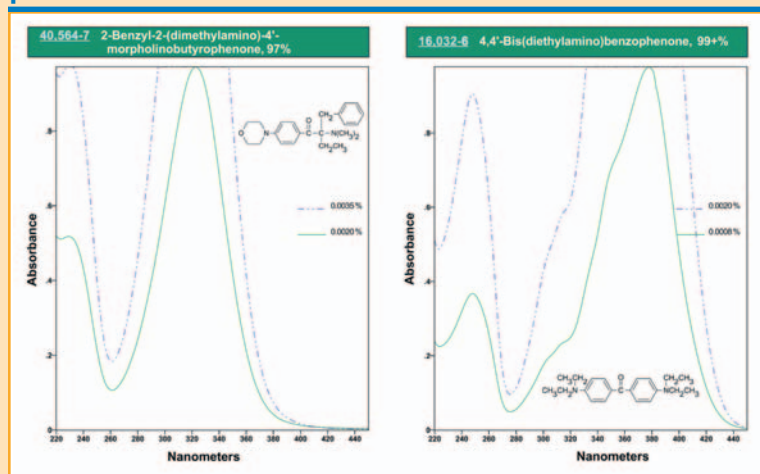
Clearly both the power and wavelength characteristics of the UV-curing lamp must be measured in order to establish an effective process.

Band-Filtered Radiometers

The first resort for UV measurement in this context is the band-

FIGURE 1

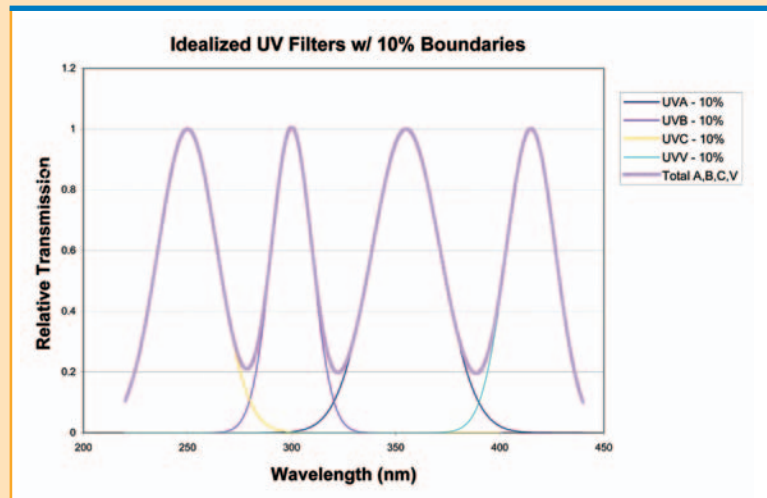
Absorption spectra for two common photoinitiator families



(Spectra reproduced by permission of Sigma-Aldrich Corporation)

FIGURE 2

'Generic' filter functions that fall to 10% of peak at the band boundaries



filtered UV radiometer: a self-contained measuring device which can be transported into the active area of a UV-curing system that records the intensity of UV irradiation, and in conveyorized systems, the total exposure of the device as it is carried through the system. A large number of radiometers are offered by many vendors, since this is such a crucial issue. The exposure (once referred to as the dose) is a measure of the UV energy deposited on the surface of the radiometer or the coated material. As the product of intensity and time, total exposure can be controlled by varying the UV intensity and exposure time. In conveyorized systems, the exposure time is changed by changing the belt speed.

The effective energy is only that which falls within the sensitivity of the coating material. In an attempt to restrict the UV measurement to the appropriate wavelengths radiometers are equipped with optical filters that allow only chosen wavelength bands to reach the UV detector in the instrument. Different filters are used with different materials. Historically, the

band definitions generally arose through biological considerations (e.g., tanning rays, burning rays, germicidal radiation, etc.) and have no particular relationship to the physics of UV curing. Three are in common use, UVA, UVB and UVC. Some manufacturers of equipment also refer to UVV. Unfortunately, the definitions of

these bands are not universally accepted. UVC, the "germicidal" band is variously defined as starting anywhere from 100 to 250 nm, and ending at 260 to 280 nm. The U.S. definition of UVB is 280 to 320 nm, while the common European usage is 280 to 315 nm. In the U.S., UVA is defined to be 320 to 390 nm, and in Europe 315 to 390. (However, according to DIN 5031 part 7, it is 315 to 400 nm.) UVV is declared to be 395 to 445 nm. In this paper, the common U.S. industrial definitions will be chosen:

UVA: 320-390 nm

UVB: 280-320 nm

UVC: 220-280 nm

UVV: 390-445 nm

The theoretical definition of these bands includes *all* the power within the band boundaries, *equally* weighted. Practical optical filters cannot come close to this sharp definition, and tend to be smooth and bell-shaped, peaking at the band center, and tapering to the edges. But what filter transmission should define the edges? Most commercial radiometers pick a number around 10% of peak to

FIGURE 3

'Generic' filter functions that fall to 50% of peak at the band boundaries

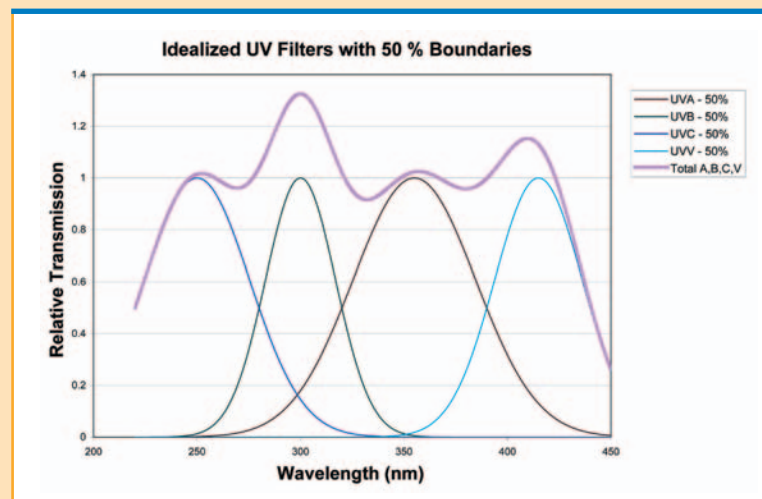
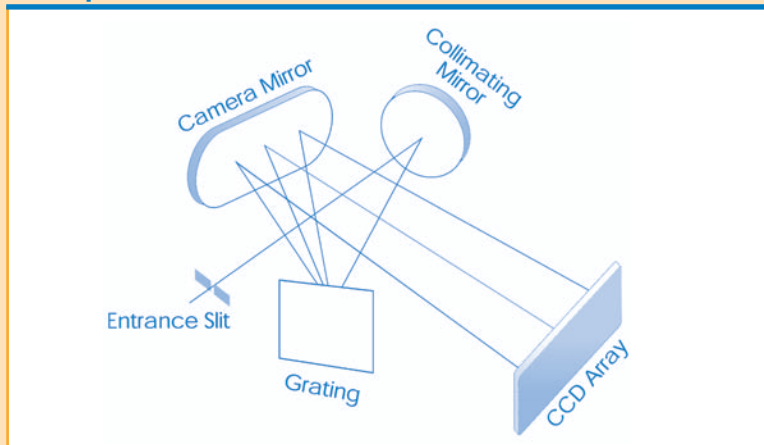


FIGURE 4

Optical layout of a typical compact CCD spectroradiometer



define the filter boundary. We can model generic band filters by a Gaussian function:

$$t(\lambda) = e^{-((\lambda_c - \lambda)/w)^2}$$

Where t is the filter optical transmission, λ is the wavelength, λ_c is the band center wavelength, and w is the bandwidth. A set of filter functions, which drop to 10% at their edges is shown in Figure 2.

The advantage of sharp filter functions like this is that very little crosstalk occurs in which radiation from outside the band definition is included in the band measurement. The disadvantage is that the contributions

from different wavelengths are very unevenly weighted. It seems intuitive to expect that if you add up the measurements from UVA to V you should get all the radiation in the range 220-445 nm. In Figure 2, the sum of all four-filter functions is shown, and there are clearly big “holes” in the measurement of total UV power.

Alternatively, the filter boundaries could be defined to be the 50% transmission points, as shown in Figure 3. Here the total power is much more evenly weighted. Sadly though, a great deal of out-of-band power is included in each separate band measurement.

The Spectroradiometer

Some kind of ground truth is clearly needed. This is provided by the spectroradiometer. As its name implies, the spectroradiometer measures the irradiance at every wavelength, not just within some roughly defined band. Compact instruments of this type are now available to the UV-curing industry, and all operate generally according to the principles illustrated in Figure 4. Light is brought to the instrument from the region to be measured using an optical receptor capable of withstanding the high incident powers in a curing system and an armored optical fiber (Figure 5). The output of the fiber is coupled to the entrance slit of the spectroradiometer at the bottom left of the diagram. The

FIGURE 5

High power optical receptor



FIGURE 6

Spectrum of Hg lamp showing relationship of UVA filter to major lines

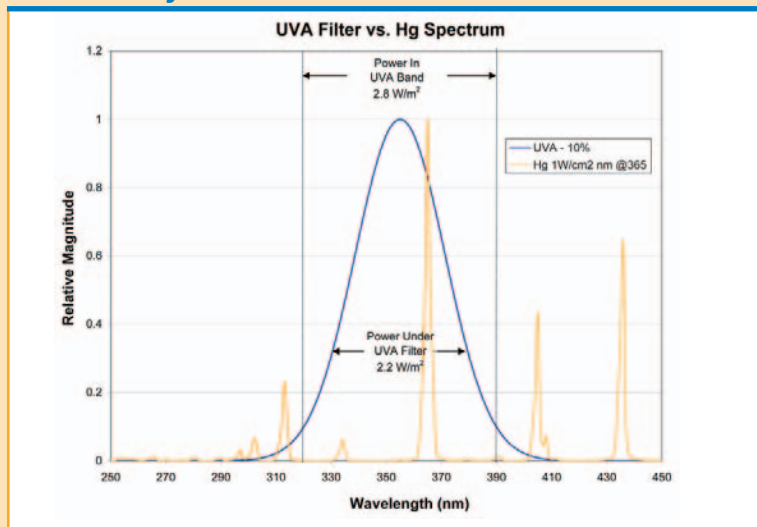
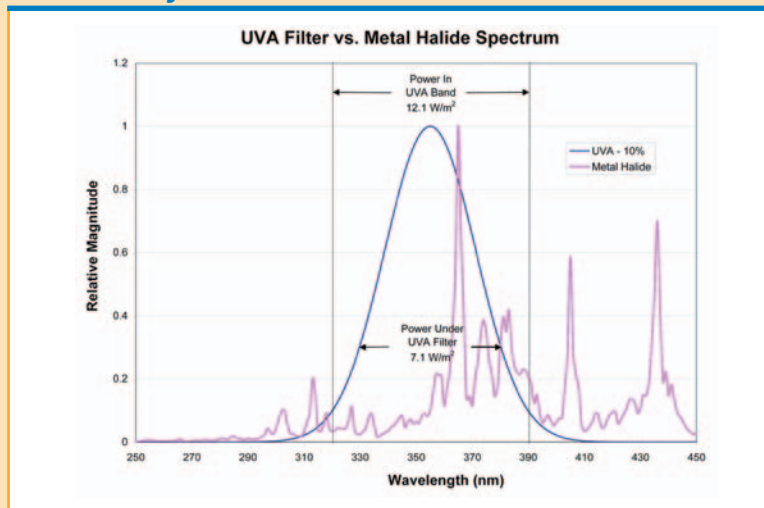


FIGURE 7

Spectrum of MH lamp showing relationship of UVA filter to major lines



light spreads and strikes a collimating mirror, which makes the rays parallel and directs them toward an optical grating. The grating disperses different wavelengths of light at different angles.

The dispersed beam is imaged by a camera mirror onto a linear CCD array, where each wavelength to be measured falls on a different pixel. The CCD output is digitized and sent to a

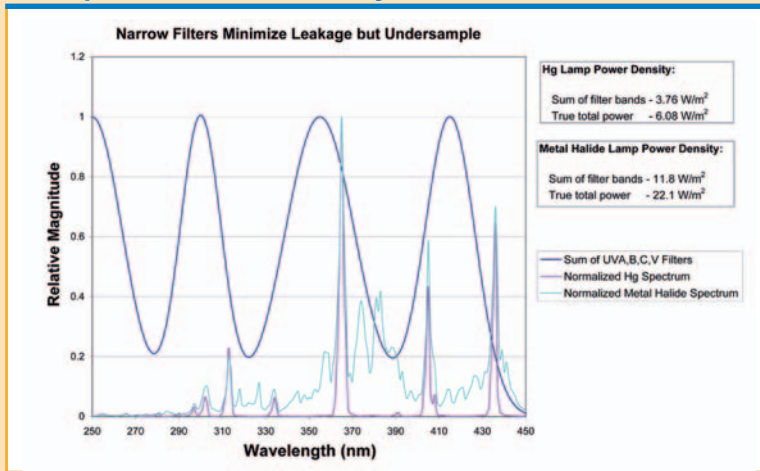
computer, whose software provides calibration and display features that result in a plot of irradiance (in units like W/m^2) vs. wavelength (in nm).

Data taken in this way can be captured and simply manipulated in such things as an Excel® spreadsheet. Figure 6 is a spectrum of a standard Hg (mercury) lamp, with its intensity normalized to 1 at the peak of the 365 nm spectral line. Superposed is the envelope of the generic UVA filter. Integrating the power under the filter curve would give a measurement of $2.2 \text{ W}/\text{m}^2$, which is what a typical radiometer would report. The “perfect” measurement is achieved by summing all the power between 320 and 390 nm, which yields an answer of $2.8 \text{ W}/\text{m}^2$. Not great agreement but probably useful.

In Figure 7, however, the same filter function is applied to the commonly used MH (metal halide) lamp. Now the discrepancy is large; $7.1 \text{ W}/\text{m}^2$ using

FIGURE 8

Total power transmitted by sum of all narrow filters



the filter and 12.1 W/m² using the spectroradiometer data.

A summary of the problems encountered using sharp filters is presented in Figure 8, which shows what a user would get by adding up the outputs of four radiometers in the four bands, compared with the spectroradiometer result. The filtered radiometers are, on the average, off by a factor of about 2.

If the wide filter functions were used instead, the output shown in

Figure 9 would result. Now the total outputs are in good agreement, but each individual band has gotten so wide that it is of little use in separating the wavelength regions.

Real Application

If we refer back to Figure 1, we can see what use all this is. For the benzophenone on the right, we have a fortunate overlap between the generic UVA filter function, the photoinitiator

absorption spectrum, and the 365 nm Hg line. In this case the spectroradiometer could be used to make a one-time correction to the radiometer reading, and thereafter the radiometer would work fine in controlling the process exposure.

With the benzyl the story is different. The 320 nm absorption peak falls right in the “hole” between UVA and UVB. There is the weaker 313 nm Hg line to effect the cure, but measuring it is the problem with a simple radiometer. Going to the wide filter version will bring in leakage from the powerful 365 nm line, ruining the accuracy of the radiometer.

Here the only recourse is to use the spectroradiometer directly, and use the benzyl absorption function with the data output to compute an *effective* irradiance, from which things like exposure time can be determined.

Conclusion

The relationship between what radiometers measure, what lamps provide, and what coatings need is not simple. The spectroradiometer can be a powerful, and, in some cases, essential tool in the quest for the optimum application of UV technology. ▶

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FIGURE 9

Total power transmitted by sum of all wide filters

