Radiometry and Methods of UV Monitoring

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Radiometry is a powerful analytical tool for UV curing and invaluable as a quality control (QC) tool for process monitoring. Radiometry provides the quantitative measurement of the key exposure parameters that have most significant effect on the performance of the end product. It is also essential to process design, in which UV exposure is optimized to produce essential physical properties and quantified to create process control specifications.

This chapter will focus on:
- the use of radiometry for process design, control and monitoring;
- key exposure factors to measure;
- types of radiometers and
- recommended methods of reporting data.

Process control

Process control maintains the process within the window of operating limits. The primary purpose of process monitoring is to know when something has changed before that change threatens the process. If the radiometric data collected doesn't relate to the process window and product performance, it doesn't mean much. For example, if the chemistry requires UV wavelengths in the 250nm region, measurement in the 365nm region may not be relevant. Also, if lamp design characteristics, such as irradiance profile or spectral radiance, have been determined in the design of the system, it is not necessary to repeatedly measure these for process control – unless they are expected to change. Proper measurements can be valuable to determine when replacement or maintenance is required as lamps age or become dirty.

Key exposure factors

There are four key factors (outside of the formulation itself) that affect the curing and the consequent performance of the UV-curable material. These factors are the UV exposure conditions, which are a consequence of the optical characteristics of the curing system. Simply stated, all of these are the exposure parameters that are necessary and sufficient to define the process:
- Irradiance. Either peak or profile, measured in W/cm² or mW/cm², in defined wavelength ranges.
- Wavelength. Distribution of radiant power vs. wavelength, in nanometers (nm). There are several ways of expressing this distribution, for example, in bands.
- Time (or "speed"). Exposure (energy) is the time-integral of irradiance; measured in J/cm² or mJ/cm²; time is a primary variable, while exposure is not a primary variable – it is a combination of two independent variables.
- Temperature. Temperature is a consequence of the specific absorbance of a surface and the radiant exposure, including IR, and the temperature of the substrate.

Quick summary

Once a UV-curing process is designed, optimized and quantified, monitoring in production may be limited to "surveillance" on only a few key parameters – those which, when out of predetermined limits, trigger corrective action. These critical parameters should be identified in the process design phase.

Relatively inexpensive, simple and rugged tools and methods can be used in production monitoring. These may be online monitors, dosimeter tabs (radiachromic films), single-band radiometers and the like. Ultimately, these measurements must be related to target properties of the inks, coatings, paints or adhesives being cured.

Selecting a method of measurement or a particular radiometer should be based on the specific process and the identification of the key variables that have the greatest effect on the process.

Irradiance is the proper term for the "intensity" of radiant power arriving at a surface. Irradiance data always must include identification of the wavelength range to which it applies.

Peak irradiance is the maximum irradiance of the focused UV exposure profile. The exposure profile is characteristic of the lamp design. Peak irradiance has a distinct effect on the speed and depth of cure.

Infrared (IR) energy is emitted primarily by the quartz envelope of the UV source. Because commercial UV radiometers do not measure IR irradiance, measurement of surface temperature is the usual method of determining the effect of IR. The heat may be a benefit or a nuisance, but it is an inseparable factor in the curing process. A non-contacting optical thermometer is recommended for surface temperature measurement.

Exposure is the time-integral of irradiance. UV exposure is the UV energy to which a surface is exposed as it travels past a lamp or a sequence of lamps. (It is sometimes loosely – but incorrectly – referred to as "dose.") Since energy is a function of irradiance and time, it is not always the most useful measure for process specification. However, data on energy can be useful in monitoring or control of a production UV process.

As illustrated in Figure 1, the area under the exposure profile (time-integral of irradiance) is proportional to energy. The physical design of a lamp determines its irradiance profile. The relationship of peak irradiance to energy and time is important to cure efficiency. One must always be aware that during production if the bulb is of a type that can sag out of the focused position or if the reflector is deformed, the irradiance profile of a lamp can change (deteriorate).

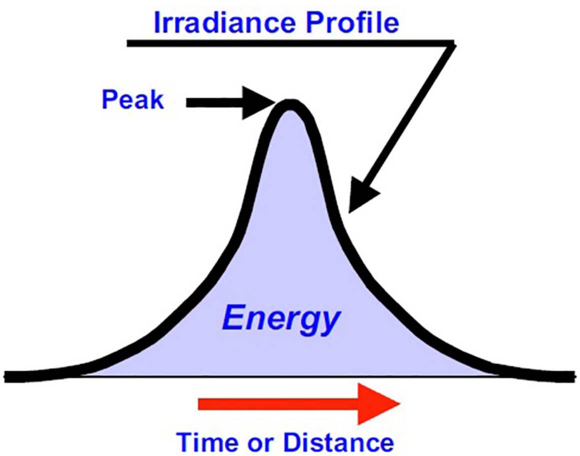

FIGURE 1. Illustration of irradiance profile, peak irradiance and energy

Radiometric instruments

In selecting radiometric instruments, the desire is to find one instrument that "does it all" and provides universally understood information. Unfortunately, no one method gets a perfect score.

Radiometers measure irradiance, (typically in mW/cm²) over a uniquely defined wavelength band. They report the instantaneous value at the location of their diffuser and sensor. Differences in detectors, filters, construction, and principles of operation result in the fact that different narrow-band radiometers give different results when measuring broadband sources (Figure 2). A radiometer from one manufacturer can report UV data significantly different from another instrument from a different manufacturer, although both may be properly calibrated and correct. This is because instruments have different responsivity, or wavelength sensitivity. Further, instruments differ in their spatial sensitivity (angle of view). Most radiometers 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.

Integrating radiometers have on-board clocks and data storage. They make irradiance measurements over a period of time at an internal clock rate. They will sum all of the consecutive irradiance samples and report total exposure (in mJ/cm²).

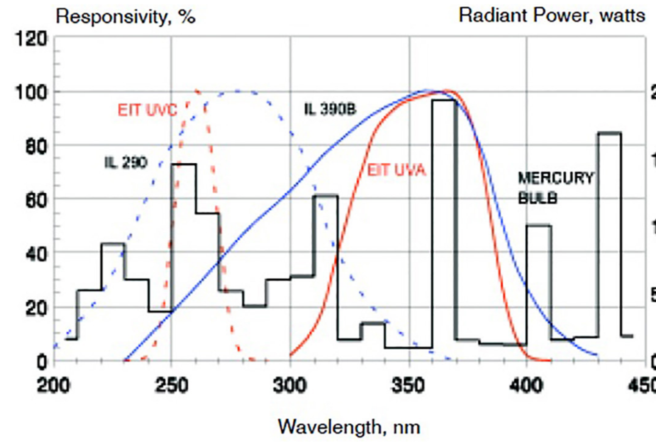

FIGURE 2. Selected examples of radiometer spectral response and mercury lamp emission

Mapping or profiling radiometers can record and display the complete irradiance profile of an exposure. This dramatic adaptation of sampling radiometers with on-board memory radiometers for UV processing literally presents a picture of irradiance vs. time in a dynamic exposure. After a test exposure, the instrument is connected to an external device – either a computer or a dedicated processor – to display the entire exposure profile. These instruments can also calculate peak irradiance and energy. Single-band and multiple-band instruments are available. Since these record the "history" of a pass under lamps, they can provide data on the irradiance profile of each lamp in rows of lamps. Relating the time scale to distance requires only the knowledge of the precise speed of the measurement. A profile of a two-row lamp system is shown in Figure 3. Some display software can isolate the profile and exposure of individual lamps in a multi-lamp exposure system.

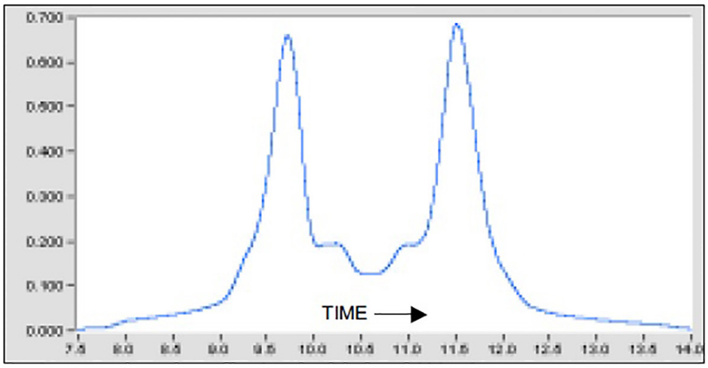

FIGURE 3. Irradiance profile of two lamps (rows) in sequence

Wavelength Band Designations: UVA, UVB and UVC

Although the UV portion of the electromagnetic spectrum is wider than the visible portion, the language of UV wavelength designations has no equivalent terms, such as "color." UV-curing technology uses actual wavelength, λ, in nm, as the language of description and differentiation and groups these into bands, or ranges. The UV ranges UVA, UVB and UVC are only loosely defined, having been modified slightly to represent dominant emission ranges in the emission of mercury (Hg) vapor plasmas.

Similar designations are used in various technologies involving UV. Typically, the generally accepted range designations are:

- UVC 200-280nm
- UVB 280-315nm
- UVA 315-400nm

A recently added term to the range of industrial UV radiometry is UVV. This represents wavelengths longer than 400nm (395-445nm) that actually extend into the visible range. It should not be confused with VUV, a designation for the very short wavelength UV range, from 100 to 200nm, and referred to as "Vacuum UV."

The spectral response of most UV radiometers is determined by the combined properties of their internal components – diffusers, filters and detectors. As illustrated in Figure 2, the characteristic wavelength response of a filter-detector type of radiometer is a "soft" curve, sloping off at the upper and lower wavelengths of its range. Defining this range in terms of upper and lower wavelengths is a matter of definition. It is traditional in optics to use the wavelengths at the 50% response points to describe the range, while some manufacturers use the 10% response points. The effect on the stated "spectral response" is quite clear.

Radiometers for UV-LEDs

Currently, UV-LED sources for UV curing are available in the 385-405nm range, and are nearly monochromatic. Because this range falls between the traditional UVA and UVV bands, UV radiometers with those bands may experience large errors owing to the reduced response in the vicinity of the band limits. Radiometers with wavelength response bands specifically designed for UV-LED measurements are available.

Calibration

It is useful to keep a history of radiometric records and to maintain proper calibration of the radiometer. Follow the manufacturer's recommendation for periodic calibration.

What you should know about your radiometer?

- Periodic calibration requirements
- Responsivity (wavelength range, $\lambda 2$-$\lambda 1$ and % response band limits)
- Sampling rate (samples per second)
- Threshold response (mW/cm^2)
- Temperature tolerance
- Dynamic range (saturation, mW/cm^2)
- Spatial response (cosine or other)
- Orientation preferred (position of sensor and radial symmetry)
- Does it report instantaneous or average peak?

> **Selecting a method of measurement or a particular radiometer should be based on the specific process and the identification of the key variables that have the greatest effect on the process.**

Some limitations and sources of error

Few commercial radiometers accurately respond in the 200-240nm range. This is primarily due to limitations in filter materials used with photodetectors and to internal scattering effects in spectroradiometers. Of the many types of instruments available, all have some characteristic that can result in errors in their readings depending on how they are used. Some of these errors can be related to sampling rate and speed of measurement, dynamic range (limit of watts/cm^2), non-cosine response or orientation while making a measurement. A more detailed discussion of these limitations can be found elsewhere.

Radiachromic films

Radiachromic dosimeters are tabs, strips or films that attach to a test surface and respond to total time-integrated energy – some by changing color and others by changing optical density. Depending on the chemistry of the detector, the change can be permanent or temporary. These photochromic detectors typically respond to a wide range of UV wavelengths. They can be very handy, especially for 3D objects, as a number of them can be placed about the surface of the object to measure and compare the energy delivered to any part of the surface. For graphic arts, these tabs and strips have the obvious advantage that they can be attached to a flat web or sheet and passed through the UV-curing system. They can survive transit through nips, rollers and the like without damage. They are inexpensive and easy to apply.

Laboratory measurements

Some preparation has to be done in order to correlate the results of these films with either radiometer measurements or physical properties, or both. This type of correlation must be done for each specific lamp configuration (number and type of bulbs, spectral distribution, etc.). Figure 4 illustrates a correlation of a commercial radiachromic film that has been correlated specifically to an EIT PowerPuck® radiometer Correction simply involves subtracting the unexposed O.D. Once done, the correlation can make quick work of multiple measurements.

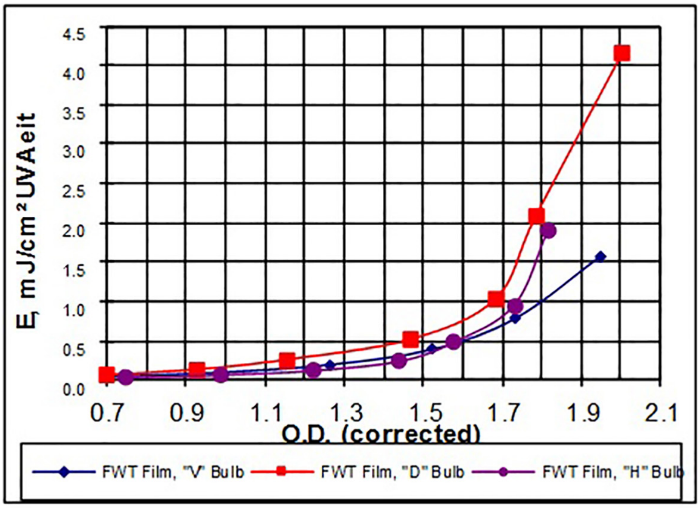

FIGURE 4. Correlation of radiachromic film with various medium-pressure bulbs

This approach can be very effective for use in process monitoring or in evaluation of configurations in process design. Radiachromic films can be helpful in the design of a system in the specific task of physical arrangement of lamps in, for example, surface curing of 3D objects.

Limitations
A drawback to radiachromic films is that they generally respond to and record accumulated energy only. In a multiple lamp system, they cannot distinguish the individual exposures of successive lamps. Commercial radiachromic films are not wavelength-specific. In fact, very little spectral responsivity data is available. Radiachromic chemistries tend to respond to UV wavelengths, typically from 200 up to 300 or 35 nm. Radiachromic detectors respond to a usually unidentified range of UV, and they are rarely calibrated for responsivity in any particular wavelength band. Practically, they require correlation to a radiometer.

Laboratory radiometer and radiachromic measurements
Passing a radiometer under a lamp or set of lamps in the laboratory is a practical way of determining the irradiance and exposure of a sample. By varying irradiance (focus and/or power) and exposure (typically controlled by speed), coatings and inks are generally exposed to a cure ladder in order to determine the exposure minimum and maximum required to achieve the desired cured properties. A radiometer is used to quantify the exposures used in this cure ladder.

Exposure at different speeds
It's not necessary to repeatedly run a laboratory radiometer under a lamp at different speeds to evaluate exposure conditions. The irradiance peak and profile DO NOT CHANGE with speed. Because exposure is strictly inversely proportional to speed, exposure at any speed can be calculated from the exposure at any other speed (see below). This is a useful point, because it allows radiometric measurements to be made in speed ranges where measurement error is a minimum. Measurement errors can be larger at low speeds, and high speeds may not be achieved easily. Sample rate errors can be introduced at higher speed, depending on the instrument, and speed errors can be introduced at very low speeds.

The recommended method for determining the range of exposure at various speeds is to select a speed, v_o, at which errors are a minimum, record several exposure measurements, E_o, and speed – then calculate energy, E_x, for any other speed, v_x.

$$\mathbf{E_x = E_o \cdot v_o / v_x}$$

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

Fixed location "online" monitors
Fixed location or "online" monitoring of the production equipment is not actually process monitoring but can be useful to avoid problems and anticipate required maintenance. Situated in a fixed location, online monitors view the lamp and possibly the reflector, recording any change that may occur. The purpose for these fixed detectors is simply comparison over time to determine, for example, when to change a bulb or service a reflector.

The disadvantage of online monitors is that they do not "see" what the ink or coating on the substrate sees, and therefore do not actually measure the process. The advantage is that they can be simple, continuous and automatic. Often, online detector electronics are designed to display relative lamp output in percent only.

Recommended practice for reporting data
A recommended practice is to accompany any reported measurement with an appropriate reference: either an indication of the manufacturer's wavelength range for that measurement or, at least, the identification of the instrument used. All radiometer manufacturers provide information on the wavelength band response of their instruments, and

instrument-to-instrument agreement within the same model is generally good. It is essential that this reference be included in the test description, and on the axis labels of charts and graphs. Reporting this reference information is critical to data interpretation and should include at least one of the following:

(a) manufacturer's designated band;
(b) wavelength-defined band (note 10% or 50%) or
(c) identifying the specific instrument used.

When exposure data are reported, it should include the speed at which the measurement was made. This permits the correlation of energy to other speeds.

Conclusion

Once a process is designed and optimized, monitoring in production may be limited to "surveillance" on only a few key parameters – those which, when out of predetermined limits, trigger corrective action. These critical parameters can be identified using process design. Relatively inexpensive, simple and rugged tools and methods can be used in production monitoring. These may be on-line monitors, dosimeter tabs, single band radiometers and the like. Ultimately, these measurements must be related to target properties of the inks and coatings being cured. Selecting a method of measurement or a particular radiometer should be based on the specific process and the identification of the key variables that have the greatest effect on the process. ■