Aspects of Radiometry and UV Exposure Verification for UV Curing of Complex Surfaces and 3-D Objects

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Traditional UV radiometry typically uses instruments that are very adaptable to conveyors and discrete-part transport systems through curing systems. Special difficulties in making on-line radiometric measurements are encountered in multipoint 3-D systems and in web, or roll to-roll systems.

As larger and more complex objects are candidates for UV-curable coatings, the challenges of exposing curable surfaces to adequate UV energy become greater and 3-D processing presents some new and different problems for radiometry. For optimized lamp positioning and process verification, this could require irradiance and energy measurements at almost every point on the surface.

Web systems present a completely different problem for in-line radiometry. Although lamps can be monitored with static methods, it is difficult to measure the actual process exposure of a web surface. Electronic instruments will simply not pass through most web systems without risk to the instrument or the machine.

For both of these processes, alternative methods of radiometric verification of UV exposure and process radiometry are explored. This study concentrates on some of the key features and responses of radiachromic films with emphasis on their adaptability to complex surface (3-D) curing systems. The principle purpose is to explore the use of instruments to quantify the response of radiachromic films in terms of transmission or reflection densitometry, and correlate them to instrument radiometry.

INTRODUCTION

Three-dimensional processing presents some new and different problems for radiometry. Parts have complex surfaces, so the irradiance levels will vary by location. For optimized lamp positioning and process verification, this could require irradiance and energy measurements at almost every point on the surface. The motion can range from the straight-through linear travel of a paint line past a fixed set of lamps, to compound motion of chain-on edge

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conveyors, to combinations of part motion and limited lamp motion, and to totally robotically controlled motion of lamps themselves. The exposure (time-integration of the irradiance profile) at any point will result from the combined effects of part geometry, relative surface velocity, and lamp configuration.

While large-part 3-D processing, such as automotive body components, receives considerable attention, most industrial 3-D coating and curing is for smaller components, ranging from cell phone covers, to automotive lighting, to containers and furniture, where it becomes difficult to equip the surfaces with sufficient instrumentation for exposure verification and quality control.

STEPS IN THE DESIGN PROCESS

All UV processes should go through a logical sequence of development and specification. Three-dimensional processes add the complexity of configuration, but the essential steps are the same.

1. The coating, ink, or paint must be characterized in its response to UV exposure variables: irradiance, profile, wavelength, and temperature.[1] The determination of the maximum and minimum exposure required by the coating is accomplished with flat, linear processing—in the lab. Radiometry is used to *quantify* the exposure specifications required for a photo-curable material to develop its ideal properties on the substrate involved. The exposure conditions must be within the range achievable by a production system.

2. The mechanics of the line are identified—degrees of motion, surface velocities, lamp organization, total power, etc.—and lamps are positioned for maximum effectiveness.

3. Radiometry is used to *verify* the process design. Dry parts are instrumented with radiometers (or dosimeters) to verify that the exposure is within specified limits on all surfaces. The spectral exposure (wavelength distribution) must be the same as used in the development phase (step 1). It is often difficult to use the same instruments that were used in the laboratory. This raises serious issues of measurement consistency with different instruments.

4. Finally, radiometry is used to monitor the consistency of the process over time.

Steps 1, 3, and 4 all involve radiometry. 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. By thoroughly understanding the lamp-chemistry-application interactions, more precise and useful specifications can be determined for *what* to measure in the design of a process and for the establishment of meaningful limits that can be applied to process monitoring. In addition, data from radiometers must be communicated in a consistent and uniform way. This facilitates the duplication of the UV exposure conditions that produce the desired curing result, and is also important in the event that problem-solving communication between R&D, production, QC, or suppliers is necessary.

REPORTING

A wide variety of radiometric instruments is now available for measuring the radiant characteristics of industrial and laboratory UV lamps and curing systems. Relating these characteristics to the performance of a UV-cured product depends on how well the selected parameters match the critical factors of the cure process. Because of the significant differences in measurement equipment, the specific instrument(s) used to report data must be clearly identified in order to specify or reproduce the required cure (exposure) conditions.

UV EXPOSURE: IRRADIANCE, SPECTRAL DISTRIBUTION, AND ENERGY

There are four key factors of UV exposure that affect the curing and the consequent performance of the UV curable material. Simply stated, these are the minimum exposure parameters that are required to sufficiently define the process[2]:

- **Irradiance**—either peak or profile of radiant power arriving at a surface, measured in W/cm^2 or mW/cm^2
- **Spectral distribution**—relative radiant power versus wavelength in nanometers (nm)
- **Time** (or "speed")—energy is the time-integral of irradiance, measured in J/cm^2 or mJ/cm^2
- **Infrared** (IR) or heat—usually observed by the temperature rise of the substrate (°F or °C). (A non-contacting optical thermometer is recommended for surface temperature measurement.)

RADIOMETRIC INSTRUMENTS AND DEVICES

In selecting radiometric instruments, there is a variety of type choices. Usually, an important consideration is simply if the instrument or device is compatible with the process equipment. Another important determination is whether the instrument measures the proper exposure parameter.[3]

Table 1—Comparison of Color Range to Radiometer Energy[7]

"H" Bulb @15 m/min			"D" Bulb @ 15 m/min		
Energy, mJ/cm²		UV-Tec	Energy, mJ/cm²		UV-Tec
UVC	23		UVC	9	
UVB	217	200 mJ/cm² range	UVB	157	400 mJ/cm² range
UVA	258		UVA	436	
UVV	184		UVV	249	

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. A radiometer from one manufacturer can report significantly different UV data than another instrument from a different manufacturer. This is because instruments have different *responsivity*, or wavelength sensitivity. Also, instruments differ in their spatial sensitivity (angle of view), although most have diffusers to give them an approximate cosine response. As a practical matter, many users prefer to compare data from instruments only of the same type.

Dosimeters: measure accumulated energy at a surface (watt-seconds/cm² or joules/cm²), also over some uniquely defined wavelength band. There are electronic and chemical types. Many electronic integrating radiometers will also calculate energy. Because this is the only measurement that incorporates *time* of exposure, it tends to be commonly used.

"Mapping" Radiometers: some of the most dramatic adaptations of radiometers for UV processing are sampling radiometers with on board memory. After a test exposure, the instrument is connected to a 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.[4] 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.

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 of interest, but they do not measure time-integrated energy.[5,6]

Radiachromic Dosimeters: are tabs 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 typically respond to a wide range of UV wavelengths. They can be interpreted by visual comparison, or by instruments.

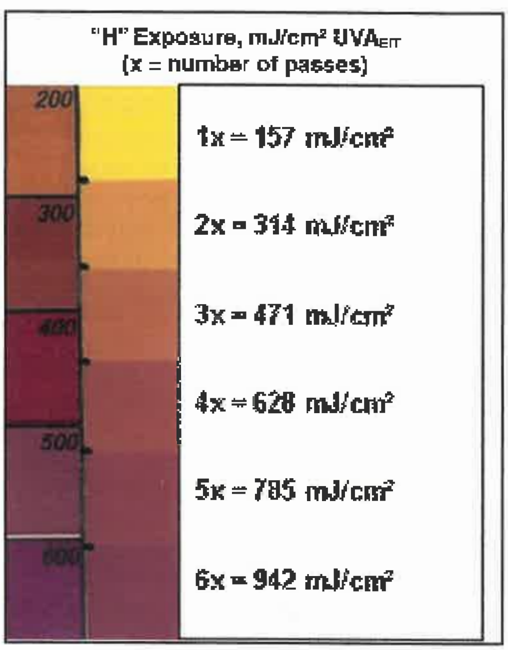
Radiachromic films or tabs can be very handy, especially for 3-D objects, as a number of them can be placed about the object to measure and compare the energy delivered to any part of the surface. For flat curing, tabs and strips have the obvious advantage that they can be attached to a flat web or sheet and can survive transit through nips, rollers, and the like, without damage. They can be inexpensive and easy to apply.

RADIACHROMIC FILMS

Radiachromic films respond to *exposure* only. They cannot "report" irradiance or any information on the irradiance profile of exposure. There are essentially two configurations of radiachromic films:

1. Films or tabs whose surface is coated with a photochromic coating. Most commercial films of this type exhibit a change of color with exposure. Typically, these

Figure 1—Visual resolution versus radiometer measure of exposure.



are opaque tabs or labels that are applied to the surface of interest with a pressure-sensitive adhesive.

2. Films whose composition includes a photochromic component. These films are initially nearly transparent, and change their transmission color or optical density with exposure. Although they appear to be a single color, they are similar to photographic films.

POTENTIAL ADVANTAGES

Radiachromic films have an immediate attractiveness, owing to:

- Comparatively low cost
- Easy application—no wiring, no mounting
- Cosine response
- Large number of test points can be exposed simultaneously

DISADVANTAGES

Fundamental problems with radiachromic films include:

- Dynamic range
- Resolution—type of reader/interpretation
- Spectral responsivity
- Adhesive or method of application
- Difficulty of reading/recording

VISUAL RESOLUTION—"EYEBALL" INTERPRETATION

A variety of radiachromic films that are read by visual observation of color change are available. Several of them rely on comparison to a printed color chart to make an estimation of the exposure. The visually resolved data is obviously affected by lighting, metamerism, and color perception.

Tabs or tapes that are interpreted by eye or by comparison to a printed color chart may be vulnerable to subjective error or difficulty of resolution, and consequently less accurate and less repeatable than films read by instruments (colorimeters or densitometers).

Two examples that illustrate the difficulty of visual resolution of color-change radiachromic films are illustrated in *Figure* 1 and *Table* 1.

First are the UV-Tec films.[7] The manufacturer provides them in two ranges, 50–250 mJ/cm^2 and 200–600 mJ/cm^2. These have a pre-printed color chart and energy interpretation. The example in *Figure* 1 was exposed to an "H" (mercury) bulb in six successive "passes" at 30 m/min.[8] The exposed color and the corresponding radiometer measures of UVA_{EIT} are shown. Reasons for the differences are not obvious, as neither the responsivity of the film nor the calibration basis are identified. When exposed to an "H" bulb (mercury) and a "D" bulb (iron halide additive), the correlation to an EIT PowerPuck®[9] (*Table* 1) clearly shows the response to be in the UVA range.

A second example of visually resolved film is Green Detex Labels.[10] The manufacturer's color interpretation is shown in *Figure* 2. These labels are designed primarily for use in printing applications. As illustrated, the manufacturer anticipates that they are used to assess the deterioration of arc lamps. They have a pressure-sensitive adhesive for application to webs or sheets. These labels are available in two ranges: 10–200 mJ/cm^2 and 200–600 mJ/cm^2.

INSTRUMENT RESOLUTION—METHOD AND DATA

This study utilizes optical density, measured by densitometers, to assess the response of the films. In this study, two types of films were explored to determine the nature of their spectral responsivity, resolution, and dynamic range. The films were FWT-60-00 from Far West Technologies, Inc.[11] and Green Detex Labels from Sessions, Ltd.[10] Exposures were made with bulbs of three different spectral distributions and varying exposure levels. A set of cut-off filters from International Light, Inc.,[5] at successive wavelengths was used to explore the spectral responsivity of the films. An International Light portable UV spectroradiometer, model RPS 200,[5] was used to analyze the spectral exposure with filters.

The blue transparent FWT samples were read with a transmission densitometer, FWT model FWT-91R.[11]

Figure 2—Color range of Green Detex labels.

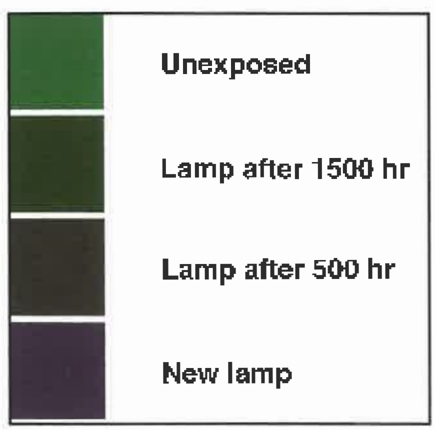


Figure 3—Unexposed FWT-60 film, OD .03 (left), and exposed film, OD 1.65 (right).

Transmission measurements were made at 510 nm. The range of measurement was from .03 OD for unexposed film to approximately 2.0 OD for fully exposed film.

The green opaque Sessions labels were read with a color reflection densitometer, Tobias Associates, Inc., model RCP.[12] The reflection measurements were made with a magenta filter, as this color showed the best sensitivity to changes in the film. The manufacturer's color chart (for visual comparison, see *Figure* 2) ranges from .33 OD to 1.42 OD (magenta), while the results herein ranged from .96 OD to 1.60 OD.

It should be noted that differences in batch lots and effects of storage age can affect the relative values of these films. It is not the object of this study to determine an absolute "calibration" of the films, but to explore methods of correlation and adaptability to radiometry.

The FWT films were first studied in detail by L'Abbe and Diehl,[13] and a very detailed study of optical measurements on Green Detex was published by Lénédic et al.[14]

CORRELATION AND DYNAMIC RANGE

Figures 4 and 5 illustrate the two types of films whose optical density has been correlated specifically to an EIT PowerPuck radiometer.[3] These data are correlated to the UVA range of an EIT PowerPuck and plotted on a linear scale. The dynamic (exposure) range of these two examples is approximately one decade. At the upper exposures, the FWT-60 becomes difficult to differentiate, and the Green Detex begins to bleach, actually yielding lower optical density readings. The FWT-60 appears to provide good resolution at low exposures, while the Green Detex appears to be difficult to resolve below 100 mJ/cm^2 UVA with the method used.

The base response to different bulbs is shown in *Figure* 6. These are simply the OD measurements for exposure to interchangeable bulbs in the same lamp system, at the same focus and speed. This raises the question of *spectral responsivity*.

RUDIMENTARY METHOD OF DETERMINING SPECTRAL RESPONSIVITY

A series of six cutoff filters was placed between an "H" bulb and the film(s) to be exposed. The spectral distribution of the resulting exposure with three of the six filters used, and without, is illustrated in *Figures* 7a through 7d (not all the filters used are shown in *Figure* 7).

Both types of film were exposed to filtered UV using IL filters SCS 245, SCS 280, SCS 320, SCS 340, SCS 365, and SCS 395.[8] In *Figure* 8, the transmission OD of the FWT film and the reflection OD of the Green Detex are shown on the same scale.

RELATIVE RESPONSIVITY

The relative energy within the filtered ranges can be calculated from the spectral distribution. The response to those ranges is shown in *Figure* 9a, along with the fraction of total UV in each range. *Figure* 9b is the same

Figure 4—Correlation of FWT-60 film with "H" bulb exposure.

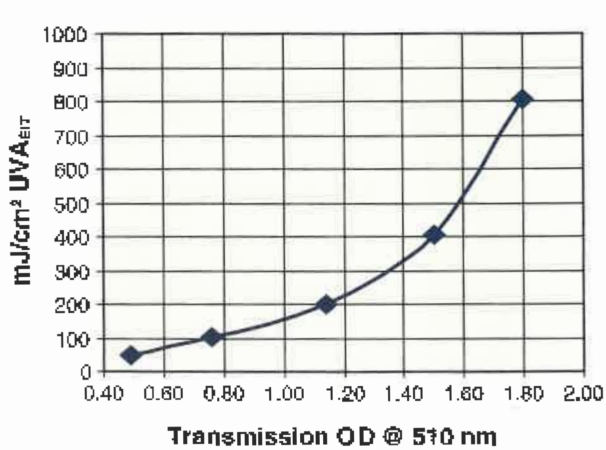


Figure 5—Correlation of Green Detex labels with "H" bulb exposure.

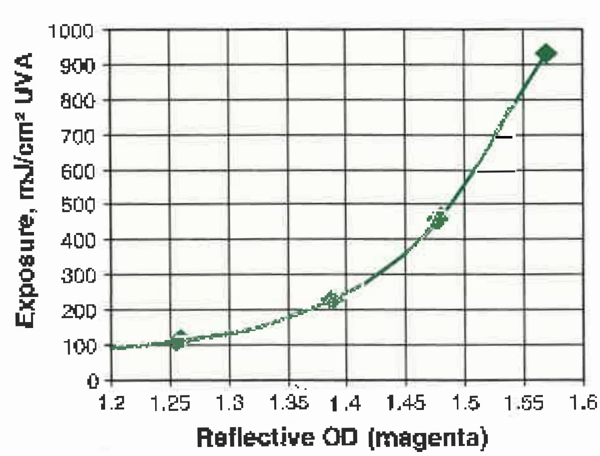
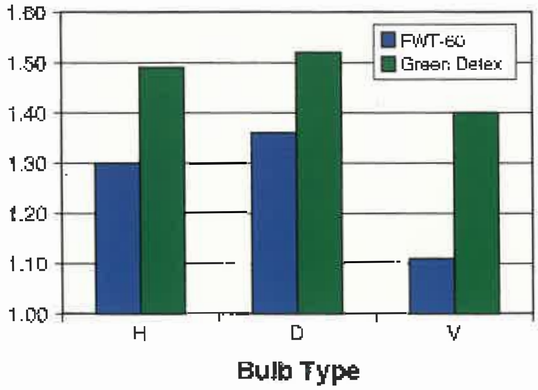


Figure 6—OD response to different bulbs.



data as *Figure* 9a, except that it shows the ratio of the response to the fraction of UV in each range.

OBSERVATIONS

Cosine Response

Radiachromic films appear to have a generally good cosine response. This is not particularly important in flat linear curing, where almost all of the radiant energy falls within a ±45° angle of incidence. However, in 3-D applications, cosine response can be important, owing to the fact that some critical surfaces may be oriented at very low angles to the UV source. *Figure* 10 shows the measured cosine response of several instruments and a radiachromic film.

Reflective Surfaces

An interesting difference between the types of film (transparent or opaque) is in their response on reflective and non-reflective surfaces. *Figure* 11 illustrates the effect of the underlying surface on the response of a "transparent" film. In some instances, this can emulate the effect of some UV reflection from a substrate and its effect of the curing of clear coatings, for example.

Size

There are several commercial films, in strip and tab form. When used in flat, linear exposure, size is not an issue. However, in order to be used on complex surfaces, it is desirable that they be small and flexible. For multiple and 3-D measurements, films approximately 1 cm square provided enough area to be read by instruments, and were small enough to be used in difficult areas of complex surfaces.

Adhesive

An important factor is the adhesive (or lack of adhesive) used. Green Detex is intended primarily for use on printing papers, and its adhesive works well on these applications. If it is to be used on complex ob-

Figure 7—Relative spectral exposure with SCS[3] series cutoff filters.

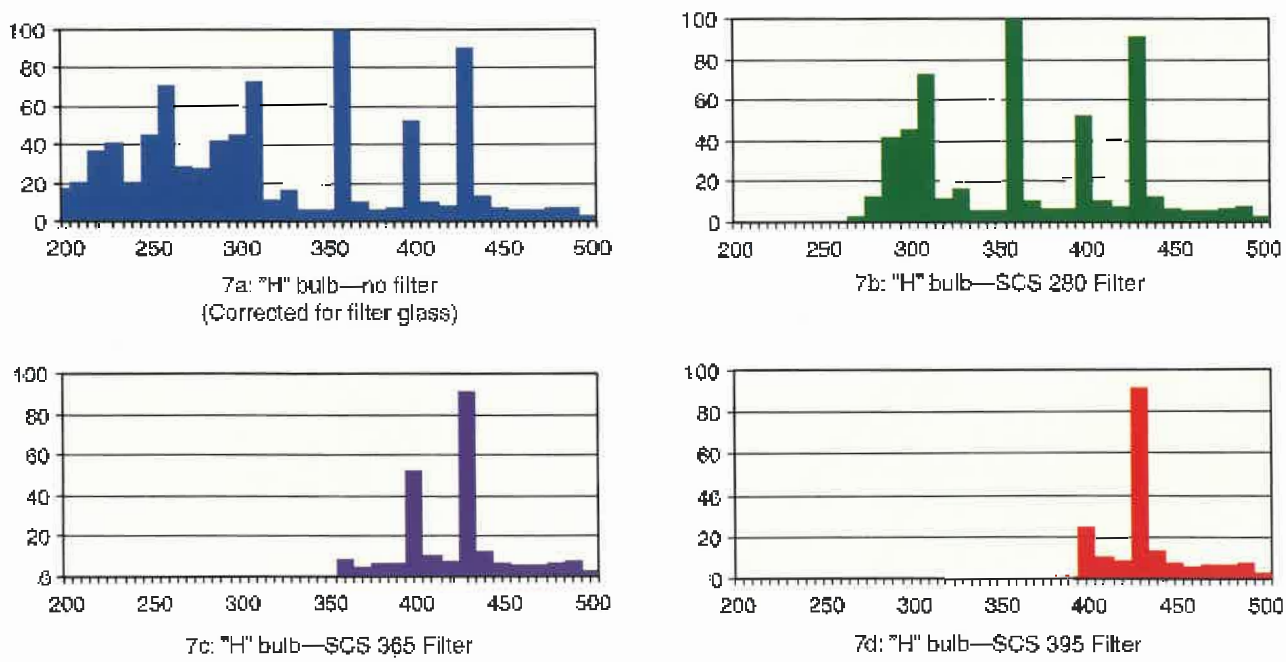


Figure 8—Spectral response to filtered exposure, "H" bulb, FWT-60 film, and Green Detex labels.

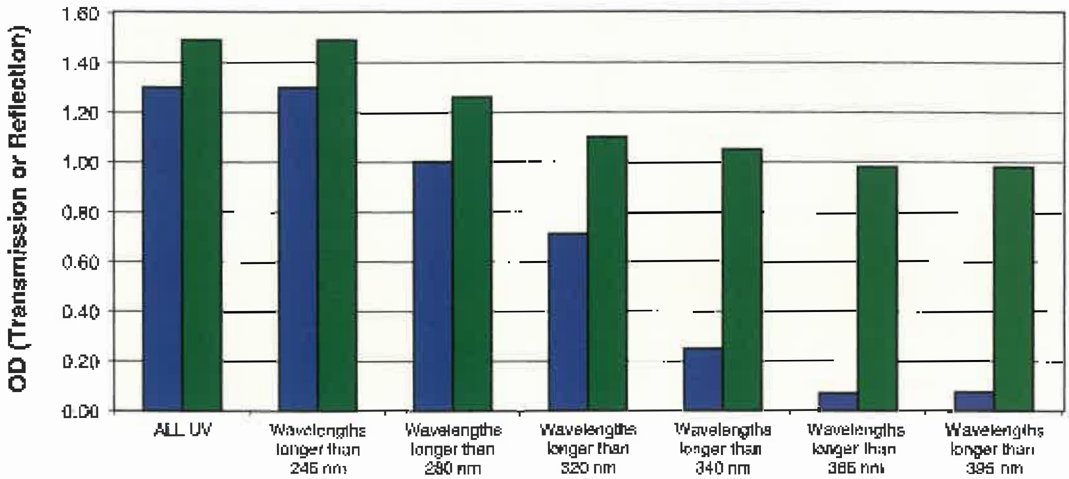


Figure 9a—Film response versus wavelength range.

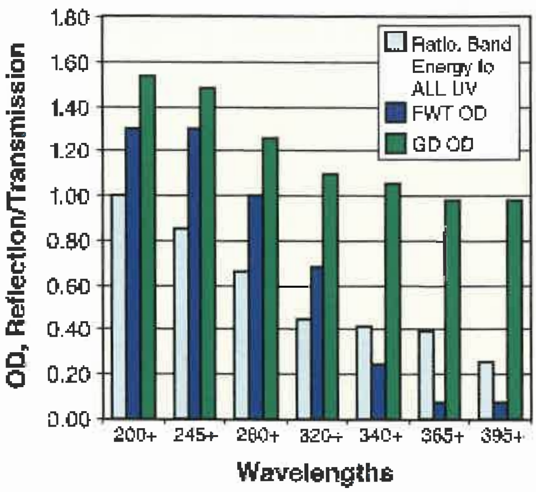


Figure 9b—Relative response to wavelength range.

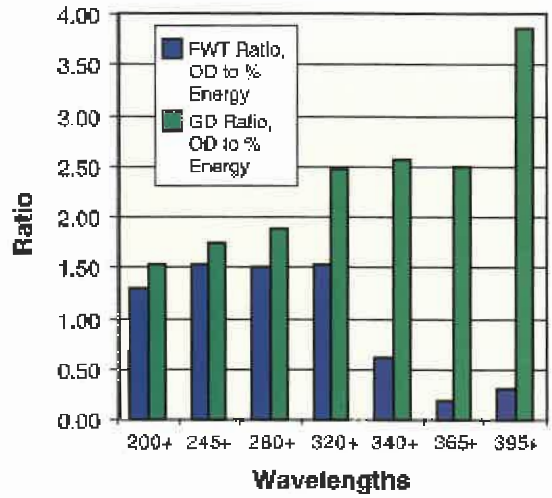


Figure 10—Cosine function and angular response of three commercial radiometers and FWT-60 radiachromic film.

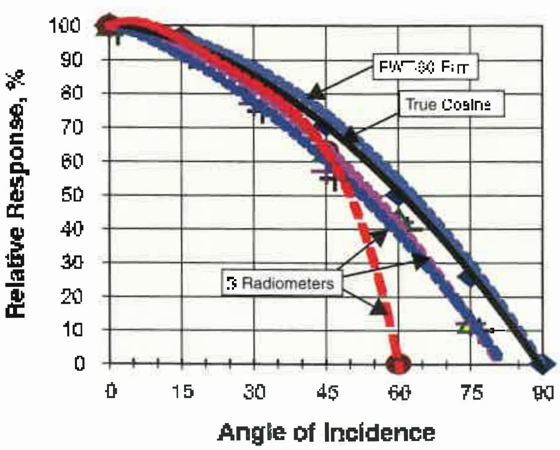
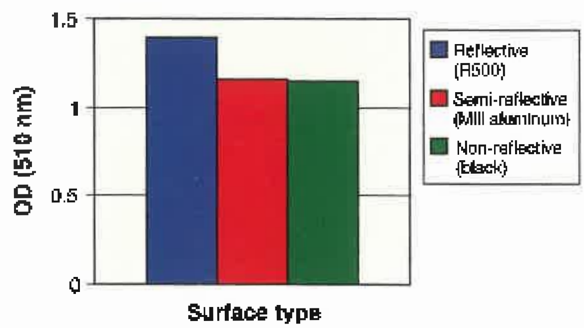


Figure 11—FWT-60 film on reflective and non-reflective surfaces.



jects, in the case of 3-D objects, its adhesive is too aggressive for plastics and glass, but is difficult, if not insufficient, on coarse surfaces, such as wood.

The FWT films have no adhesive at all— this makes them adaptable to a variety of surfaces—but it also complicates their use. Attachment with various pressure-sensitive adhesives was tried in the experiments with them, including self-adhesive ring binder reinforcements, commercial label stock, and 3M #810 tape. All of these were satisfactory, suggesting that systems with different adhesives for different substrates would be desirable.

CONCLUSIONS

The most important conclusion is that radiachromic films can be a useful *extension* of instrument radiometry. They can be applied in situations and geometries that are difficult for radiometers.

Radiachromic films can be interpreted with relatively simple instruments—either transmission densitometers or reflection densitomers. This requires only a simple correlation (see *Figures* 1 and 2) with the appropriate radiometer of choice, through exposure to the specific UV lamps set to be used in the process. Such a correlation is valid *only* for the specific type and spectral distribution of lamps to be monitored. An understanding of the wavelengths important to the process, the responsivity of the correlating radiometer, and a knowledge of the responsivity of the radiachromic films are necessary.

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 rarely wavelength-specific. In fact, very little spectral responsivity data is available. 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 exposure (type of bulb and spectral distribution). Once done, the correlation can make quick work of multiple measurements.

This suggests that these 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 for surface curing of 3-D objects for example. With more development in the area of responsivity and spectral calibration, radiachromic coatings and films could become a far more useful process control tool. CT

References

(1) Stowe, R.W., "Effects of UV Exposure Conditions on Speed, Depth of Cure and Adhesion," *Proc. RadTech North America*, 2002.
(2) Stowe, R.W., "Practical Aspects of Irradiance and Energy Density in UV Curing," *Proc. RadTech North America*, 2000.
(3) Stowe, R.W., "Radiometric Methods for UV Process Design and Process Monitoring," *Proc. RadTech Europe*, 2001.
(4) EIT UviMap® and PowerMap®, EIT Instruments, Sterling, VA (www.eitinc.com).
(5) International Light, Newburyport, MA (www.intl light.com).
(6) Solatell Instruments, Solatell Ltd., Croydon, UK (www.solatell.com).
(7) UV-Tec Meßtechnik GmbH, Waldstr.24, 17459 Zempin, Germany.
(8) Burger, Petra, "Fusion UV Systems Internal Lab Report 12/99-3," Fusion UV Systems GmbH, Martinsried, Germany, December, 1999.
(9) EIT Instruments, Sterling, VA (www.eitinc.com).
(10) Sessions of York, Huntington Road, York YO31 9HS, U.K.
(11) Far West Technology, Inc., Goleta, CA (www.fwt.com).
(12) Tobias Associates, Inc., Ivyland, PA.
(13) L'Abbe, P. and Diehl, D., "Measuring UV Cure: A Simple Method for Difficult Applications," Proc. FSCT Annual Meeting Program, Federation of Societies for Coatings Technology, Dallas, TX, 1999.
(14) Bénédic, M.H., Rousseau, S., Jorissen, L., Michetti, G., Ciza, C., Descroix, M., and Rich, D.C., "A Proposed Method for Evaluation of UV Exposure Rates in Energy Curing Liquid Inks," *American Ink Maker*, April 2000.