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

by R.W. Stowe
Fusion UV Systems, Inc.*

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 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. 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 requirements 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 lab. 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 interaction, 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 radiometric 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 minimum exposure parameters that are required to sufficiently define the process:

- Irradiance—either peak or profile of radiant power arriving at a surface, measured in W/cm² or mW/cm²
- Spectral distribution—relative radiant power versus wavelength in nanometers (nm)
- Time (or "speed")—energy is the time-integral of irradiance, measured in J/cm² or mJ/cm²
- 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.
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In 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.

A larger and more complex object is 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. The study concentrates on some of the key features and shortcomings of radiometric 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 radiometric films in terms of transmission or reflection densitometry, and correlate them to instrument radiometry.

INTRODUCTION

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REPORTING

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UV EXPOSURE: IRRADIANCE, SPECTRAL DISTRIBUTION, AND ENERGY

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RADOMETRIC 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.
**Table 1—Comparison of Color Range to Radiometer Energy**

<table>
<thead>
<tr>
<th>UV Bulb</th>
<th>15 mJ/min</th>
<th>30 mJ/min</th>
<th>60 mJ/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>UV-23</td>
<td>23 mJ/cm²</td>
<td>46 mJ/cm²</td>
<td>92 mJ/cm²</td>
</tr>
<tr>
<td>UV-217</td>
<td>217 mJ/cm²</td>
<td>434 mJ/cm²</td>
<td>868 mJ/cm²</td>
</tr>
<tr>
<td>UV-258</td>
<td>258 mJ/cm²</td>
<td>516 mJ/cm²</td>
<td>1032 mJ/cm²</td>
</tr>
<tr>
<td>UV-264</td>
<td>264 mJ/cm²</td>
<td>528 mJ/cm²</td>
<td>1057 mJ/cm²</td>
</tr>
</tbody>
</table>

**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 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-channel and multiple-channel sensors are available. Since these record the “history” of a pass under a lamp, 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.

**Spectro-Radiometers**

These are a narrow-band instruments, essentially responding to spectral irradiance, and are highly wavelength-specific—some with resolution as fine as 0.001 nm. 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.

**Radiochromic Dosimeters**

are tags 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. Radiochromic 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 nip rollers, and the like, with damage. They can be inexpensive and easy to apply.

**Radiochromic Films**

Radiochromic films respond to exposure only. They cannot "report" irradiance or any information on the irradiance profile of exposure. There are essentially two configurations of radiochromic 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 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 Wesns.

**Potential Advantages**

Radiochromic 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 radiochromic 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 radiochromic 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 subjective or difficult to analyze. One example of this is illustrated in Figure 1 and Table 1.

**Example 1**

First are the UV Tec films. The manufacturer provides them in two ranges, 50-250 mJ/cm² and 200-600 mJ/cm². 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 mJ/min. The exposed color and the corresponding radiometer measures of UVΔ were 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 EI PWR Mobile® Solarimeter clearly shows the response to be in the UV range.

A second example of visually resolved film is Green Detex Labels. 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/cm² and 200-600 mJ/cm².

**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 exposed to determine the nature of their spectral responsivity, resolution, and dynamic range. The films were FWT-60-00 from Far West Technologies, Inc. and Green Detex Labels from SenSys, Ltd. Exposures were made with bulbs of three different spectral distributions and varying exposure levels. A set of cut-off filters from International Light, Inc. at successive wavelengths was used to explore the spectral responsivity of the films. An International Light portable UV spectrophotometer, model RPS 200, was used to analyze the spectral exposure with filters.

The blue transparent FWT samples were read with a transmission densitometer, FWT model FWT-91U.

**Figure 1**—Visual resolution versus radiometer measure of exposure.

**Figure 2**—Color range of Green Detex labels.
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<th>Radiometer Type</th>
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<tr>
<td>UVB</td>
<td>UVB 15</td>
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<td>UVA</td>
<td>UVA 6</td>
<td>UVA 6</td>
</tr>
<tr>
<td>UBV</td>
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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 not calculate energy. Because this is the only measurement that incorporates time of exposure, it tends to be commonly used.

"Blanking" 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. 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.

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Radiometric 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.

Radiometric 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 nip, rollers, and the like, without damage. They can be inexpensive and easy to apply.

Radiatomic Films

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Radiometric 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

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Fundamental problems with radiometric films include:

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

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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 densimeters).

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

First are the UV-Tec films. The manufacturer provides them in two ranges, 50-250 mJ/cm² and 200-600 mJ/cm². These have a pre-printed color chart and energy increments. The example in Figure 1 was exposed to an "H" (mercury) bulb in six successive "passes" at 30 mJ/min. The exposed color and the corresponding radiometer measures of UVAtm are shown.

A second example of visually resolved film is Green Dextex Labels. 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/cm² and 200-600 mJ/cm².

**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 exposed to determine the nature of their spectral responsivity, resolution, and dynamic range. The films were FWT-60-00 from Fox West Technologies, Inc. and Green Dextex Labels from Sessions, Ltd. Exposure was made with bulbs of three different spectral distributions and varying exposure levels. A set of cut-off filters from International Light, Inc. at successive wavelengths was used to explore the spectral responsivity of the films. An International Light portable UV spectroradiometer, model RPS 200, was used to analyze the spectral exposure with filters.

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

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**Figure 1**—Visual resolution versus radiometer measure of exposure.

**Figure 2**—Color range of Green Dextex labels.
Transmission measurements were made at 510 nm. The range of measurement was from 0.3 OD for unexposed film to approximately 2.0 OD for fully exposed film. The green opaque sessions were labeled with a color reflection densitometer, Tobias Associates, Inc. model RC 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 .9 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 PWT films were first studied in detail by L'Abbé and Oehl, and a very detailed study of optical measurements on Green Detex was published by Lenev et al.14

**Figure 4 and 5 illustrate the two types of films whose optical density has been correlated specifically to an EIT PowerPack radiometer.** These data are correlated to the UVA range of an EIT PowerPack and plotted on a linear scale. The dynamic (exposure) range of these two examples is approximately one decade. At the upper exposures, the PWT-60 becomes difficult to differentiate, and the Green Detex begins to bleach, actually yielding lower optical density readings. The PWT-60 appears to provide good resolution at low exposures, while the Green Detex appears to be difficult to resolve below 100 ml/cm² UVA with the method used.

The data as Figure 4a, except that it shows the ratio of the response to the fraction of UV in each range.

**OBSERVATIONS**

Cosine Response

Radiographic 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 radiographic 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 on visual contrast of clear coatings, for example.

**Size**

These 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-
Transmission measurements were made at 510 nm. The range of measurement was from 0.3 OD for unexposed film to approximately 2.0 OD for fully exposed film.

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CORRELATION AND DYNAMIC RANGE

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The results 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 special 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 and 7b (not all the filters used are shown in Figure 7).

Both types of film were exposed to filtered UV using H filters SCS 245, SCS 280, SCS 320, SCS 340, SCS 365, and SCS 395. 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 these ranges is shown in Figure 9a, along with the fraction of total UV in each range. Figure 9b is the same data as Figure 9a, except that it shows the ratio of the response to the fraction of UV in each range.

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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 on the curing of clear coatings, for example.

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These are several commercial films, in 4×6 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 provide enough area to be read by instruments, and were small enough to be used in difficult areas of complex surfaces.

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CONCLUSIONS

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

Radiometric films can be interpreted with relatively simple instruments—either transmission densitometers or reflection densitometers. 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 responsibility of the correlating radiometer, and a knowledge of the responsibility of the radiometric films are necessary.

A drawback to radiometric 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 radiometric films are rarely wavelength-specific. In fact, very little spectral responsivity data is available. Some preparation has been 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. Radiometric 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, radiometric coatings and films could become a far more useful process control tool.

References

(4) JET (UV-Ink) and PowerLight, PT Instruments, Sterling, VA (www.jet.com).
(5) International Light, Newburyport, MA (www.intl-light.com).
(6) Solargraph Instruments, Solargraf Ltd., Cranley, UK (www.solargraph.com).
(7) UV Tec, Technische GmbH, Waldemar 24, 17449 Zempin, Germany.
(9) JET Instruments, Sterling, VA (www.jet.com).
(10) Sensitons of York, Huntington Road, York YO31 7HS, U.K.
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 densitometers. 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 measured. An understanding of the wavelengths important to the process, the reponsivity 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 been done to 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.

References

(4) ETI (Europe) and Powerlight: ET Instruments, Sterling, VA (www.eti.com).
(5) International Light, Newburyport, MA (www.i-light.com).
(6) Solariel Instruments, Solariel Ltd., Corbydon, UK (www.solariel.com).
(7) UV Tec Matt Tech GmbH, Waldem 24, 17459 Zempin, Germany.
(9) ETI Instruments, Sterling, VA (www.eti.com).
(10) Sessions of York, Huntington Road, York, WV 29315, U.K.
(11) Far West Technology Inc., Goleta, CA (www.fwt.com).
(12) Tohno Associates Inc., Byfield, MA.