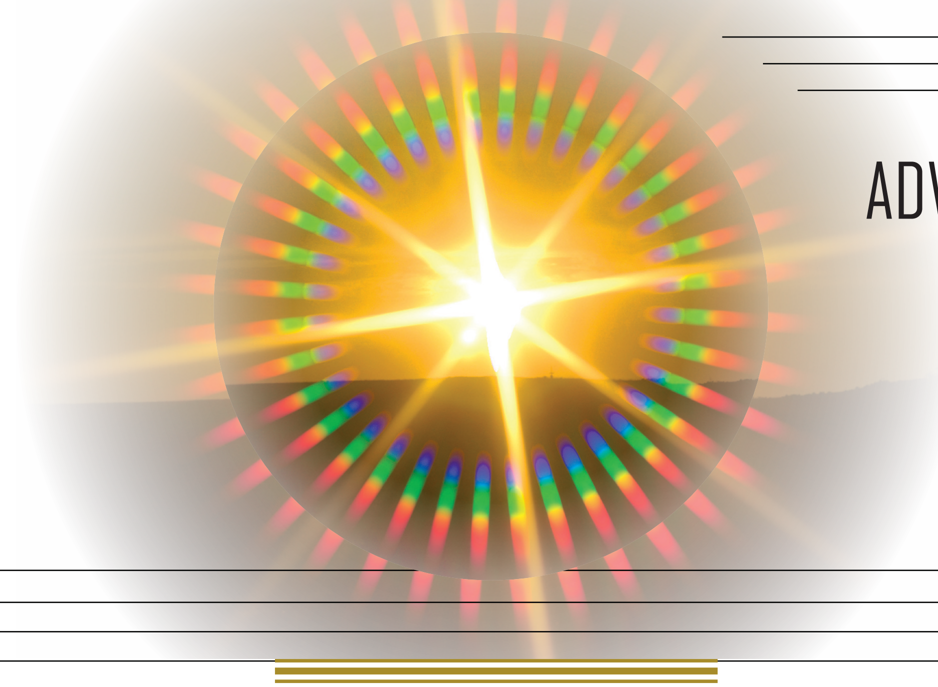

ADVANCED RADIACHROMIC RADIOMETRY FOR UV-CURING PROCESSES

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This study examines the use of instrument-resolved radiachromic radiometry to solve some of the difficulties presented by traditional radiometry in 3-D processing, roll-to-roll printing and coating, and ink-jet printing. Elements of responsivity, dynamic range, and adaptability of various types of films are discussed. Commercially available films and experimental films are studied. Methods of correlation to produce a numerical measure of UV exposure are presented. These methods can be applied easily to laboratory characterization of materials and to production quality control. The principal purpose is to explore the use of standard instruments to *quantify* the response of radiachromic films in terms of transmission or reflection densitometry. This allows correlation of their optical density to instrument radiometry for (1) process design optimization and/or (2) periodic measurements to verify lamp condition over time.

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:

- Films or tabs whose surface is coated with a photochromic coating. Most commercial films of this type exhibit a change of hue with exposure, changing their optical density in a specific color component. Typically, these are opaque tabs or labels that are applied to the surface of interest with a pressure-sensitive adhesive.
- Films whose composition includes a photochromic component. These films are initially nearly transparent, and change their transmission color or optical density with exposure.

An earlier paper discussed the features, advantages, and disadvantages of radiachromic films.[1]

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UV EXPOSURE

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, in a specific wavelength band;

Spectral distribution—relative radiant power versus wavelength, in nanometers (nm);

Time (or "speed")—*exposure* is the time-integral of irradiance, measured in J/cm^2 or mJ/cm^2 in a specific wavelength band; and

Infrared (IR) or heat—usually observed by the temperature rise of the substrate, °F or °C. (A noncontacting optical thermometer is recommended for surface temperature measurement.)

Several instruments are available for making irradiance and exposure measurements, and many of these instruments will provide the two in spectrally divided and defined ranges; for example, UVC, UVB, UVA, and UVV over the entire UV region.[3] These instruments are essential to material and process development, the optimization of the four key variables, and the determination of the "process window."[4]

REASONS FOR USING RADIACHROMIC FILMS

Physically, filter-detector radiometers can present difficulties in production design verification for several reasons: (1) not enough instruments to effectively collect multi-point data for complex surfaces, (2) rollers and nips of printing and coating machines make instrument measurements impossible, or (3) parts are simply too small to practically locate instruments. For large 3-D parts, on the other hand, there are multi-point filter-detector radiometers that can handle up to 32 locations simultaneously.[3]

Figure 1—Radiachromic sensors on complex part.

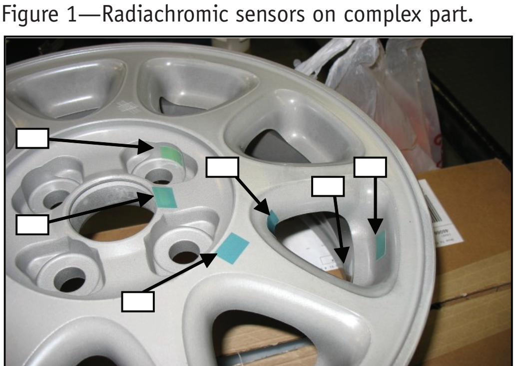


Figure 2—Ihara color densitometer.

There is a significant and growing list of applications and line configurations in which radiachromic films can be extremely valuable. Examples include cell phone and game box covers, automotive lighting, wheel and interior components, accessory items, rotational and nonrotational paint lines, cup and tube printing and coating, and container decorating, to name only a small fraction of the potential (see *Figure* 1).

CAUTIONS WITH RADIACHROMIC FILMS

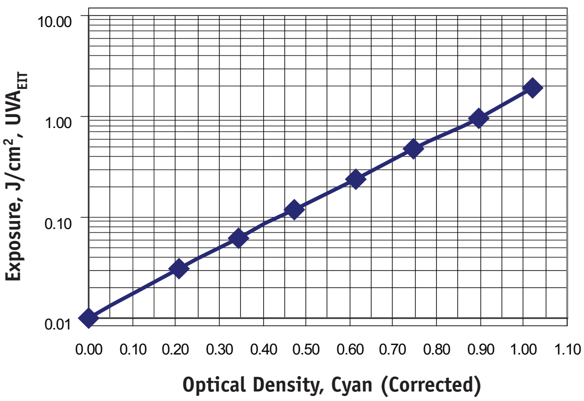
A number of commercial radiachromic films are designed for visual comparison with a color reference chart. These prove to be imprecise, owing to (1) subjective factors, (2) the absence of correlation with radiometry, and (3) their spectral responsivity being unknown. Some of these commercial films can be very expensive, partially defeating their purpose and benefit. Most films with a pressure-sensitive adhesive are not designed for a wide variety of substrates, such as wood, glass, plastic, or metal. Finally, many of these will fade or deepen with time, making archiving for later comparison difficult.

"READING" THE FILMS

A number of commercial films were considered for this study. Two films were selected for their dynamic range, stability, and cost. One is an opaque (reflective) film manufactured by Spectra Group Limited, Inc. (SGL) [5]; and the other is a transparent film manufactured by Far West Technology, Inc. (FWT). [6] The instruments used to read these films are an Ihara model R710 color reflection densitometer (*Figure* 2),[7] an Ihara model T500 black and white transmission densitometer, [7] and an FWT model FWT-91R radiachromic reader. The SGL films are initially yellow, turning shades of green as they are exposed. Because the color change is in the blue, the cyan band of the Ihara R710 was used to read the film. The FWT film changes its density in the blue range as it is exposed; the blue is relatively narrow, with a peak at 605 nm. To avoid color mismatch, the wider band black and white Ihara T500 was used to read the FWT-60 film.

Reflection and transmission optical density (OD) are similar, but have slightly different definitions and

Figure 3—SGL Film exposure vs. OD for "H".



expressions. Both represent the $\log_{10}$ of a ratio, so can be useful for comparisons.

$$\text{OD } (\textit{reflection}) = -\log_{10} I_r / I_i$$

$$\text{OD } (\textit{transmission}) = -\log_{10} I_t / I_i$$

where I_i is the incident beam, I_r is the reflected beam, and I_t is the transmitted beam.

For a reflective color-change film such as the SGL film, the color change (from yellow through green) is blue, making cyan the range choice. The FWT film exhibits a comparatively narrow hue, changing primarily its shade of blue as its transmission is reduced. To avoid "spectral mismatch," the broader black and white range was selected because it covers a range of hues.

BASE CORRELATION—THE OBJECTIVE

The fundamental correlation of exposure to optical density must be carried out with the same lamp or type of lamp as will be measured with the film. The correlation is the "calibrating" step, to create a chart or graph that can be interpreted in exposure units. It requires a relatively simple set of "ladders" to correlate OD with spectral exposure. If the source is complex, or consists of bulbs with additives, or the exposure consists of different types of bulbs, this same combination is used for each correlation. *The correlation is specific to the spectral exposure.*

In the example in *Figure* 3, the correlating radiometer was an EIT PowerPuck® or PowerMap®, and in the UVA range (referred to as "UVA_{EIT}"). Thus, by reading the corrected OD of the film, a value of the UVA_{EIT} exposure can be imputed, so long as the exposure is from the same type of medium-pressure mercury bulb and reflector. Because optical density is essentially a log function, the chart is effectively a log-log graph.

"Corrected" OD is simply the difference between the OD of the exposed film and its unexposed value. This applies to both types of films and either transmission or reflection OD measurements. This is also referred to as "relative" OD.

LINEARITY AND DYNAMIC RANGE—THE "QUICK CHECK"

As exposure is inversely proportional to speed, a quick check of film "linearity" (without correlation to a radiometer) can be plotted on a log scale, as in *Figure* 4. "Ideal" linearity is a straight line. Some films (not included here) do not have suitable linearity or dynamic range. *Figure* 5 shows a commercial film that begins to bleach out at higher exposure. This can be revealed by the initial "quick check" and a simple exposure ladder.

THE CORRELATION CURVES

The correlation curves of the two films of *Figure* 4, exposed by three lamp types, are shown in *Figures* 6 and 7.

Owing to the fact that the "D" bulb (an iron halide additive type) has significantly higher output in the

Figure 4—"Linearity" plotted for SGL Film and FWT Film: "H" bulb exposure.

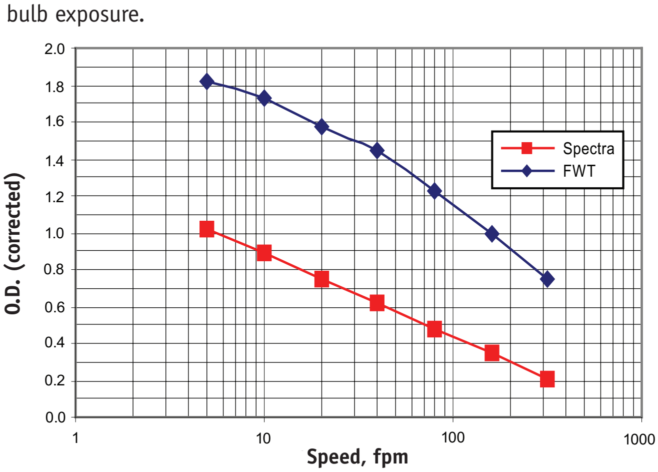
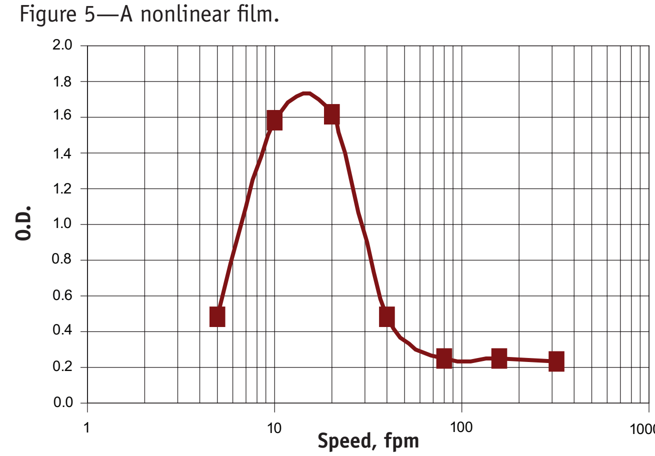


Figure 5—A nonlinear film.



UVA range, much higher exposure is recorded by the films when correlated with the UVA range of the radiometer. It is not obvious why the several curves do not track (or parallel) each other. In addition to some nonlinearity in the films, nonlinearity in the radiometer itself may contribute. This also suggests that differences in spectral responsivity of the films will contribute to these differences under different lamps. Nevertheless, these are the correlation curves for each of these exposures. These curves also successfully demonstrate why a single color chart or single correlation is not appropriate for comparison of lamps.

SPECTRAL RESPONSIVITY

Spectral responsivity is the relative response to different wavelengths. The procedure used was to expose films to precisely the same exposure, but with a succession of cutoff filters[8] in front of the films. This allows the calculation of the incremental response versus the incremental stimulus. Two sequential cutoff filters allow analysis that would be similar to "pass band" filters. An illustration of a filter pair is shown in *Figure* 8.

The antilog of the incremental OD can be plotted against the incremental energy of filter pairs, and plotted at the wavelength where the filter pairs are centered. The object is to determine $\Delta\ \text{antilog}_{10}\ O_{\Delta\lambda} / \Delta E_{\Delta\lambda}$ which is the incremental increase in optical response (reflection or transmission in linear region), ΔO, when exposed to an increment of Energy, ΔE, in a specific wavelength band, Δλ. This will yield the relative spectral responsivity of the film, shown in *Figure* 9.

It becomes apparent from *Figure* 9 that these particular films are responding in the UVB range. However, so long as they are consistent, and there is no change or difference in the bulb emission spectrum, it should be possible to correlate the film with any selected band of a filter-detector radiometer, as in *Figures* 6 and 7. This,

Figure 6—Correlation of SGL Film with "H," "D," and "V" bulbs.

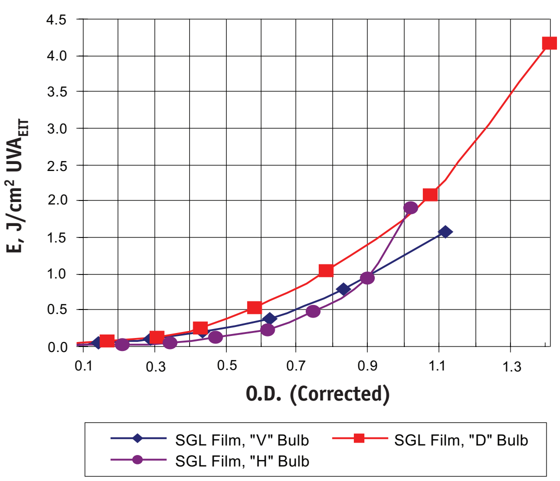


Figure 7—Correlation of FWT Film with "H," "D," and "V" bulbs.

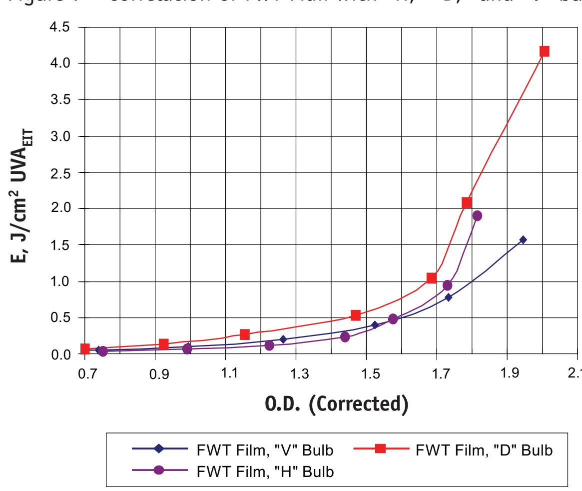


Figure 8—Differential between cutoff filters.

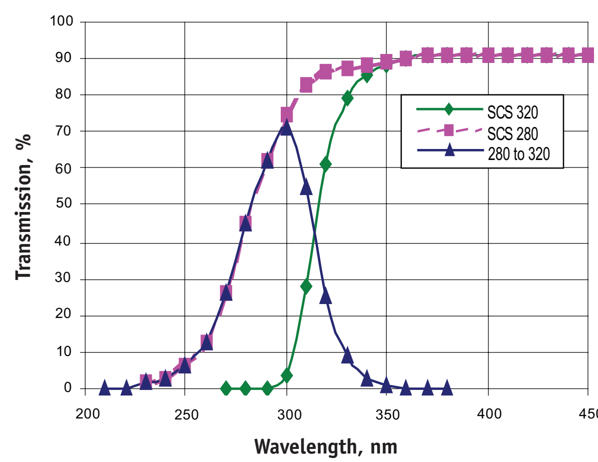
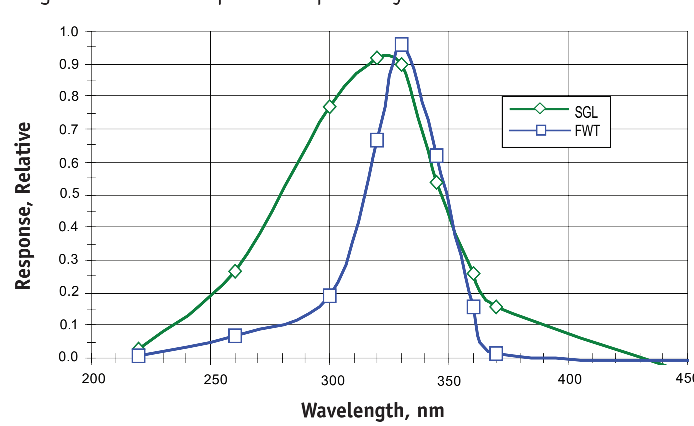


Figure 9—Relative spectral responsivity of two films.



of course, assumes that the spectral distribution of the lamp is reasonably stable, and the ratio of energy in the radiachromic response band is constant with respect to the radiometer band of interest for correlation.

OBSERVATIONS AND CONCLUSION

Several radiachromic films have been demonstrated to have a wide dynamic exposure range, good linearity, nearly perfect cosine response, are economical, and can be read with comparatively inexpensive instruments. Effective use of these films is enhanced through resolving their optical density change with an appropriate color densitometer. The selection of a densitometer depends on the color change or opacity change of the film. Reflection color densitometers are usually limited to yellow, magenta, cyan, and black, and the selected range is the one that best approximates the change of color—not the original, or base color of the film.

The dynamic range and linearity of a radiachromic film is easily determined. With a logical selection of densitometer type and range, correlation of film OD to exposure, measured with a radiometer-of-choice, can be achieved with simultaneous exposure. A graphical correlation allows exposure (mJ/cm²) to be read directly from the graph. Consequently, radiachromic films, resolved with an appropriate densitometer, can be an effective extension of, but not a substitute for, instrument radiometry in the UV range. CT

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