Advanced Radiachromic Radiometry for UV Curing

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Abstract

An advanced study of 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. The most important conclusion is that, when carefully designed and used, radiachromic films can be a useful extension of – but not a substitute for – instrument radiometry.

Introduction

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 discusses the features, advantages, and disadvantages of radiachromic films.[1]

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/cm² or mW/cm², 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/cm² or mJ/cm² in a specific wavelength band, and
- **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).

Steps in the Design Process

All UV processes should go through a logical sequence of development and specification. 3D processes add to 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.[3] The determination of the maximum *and* minimum exposure required by the coating is accomplished with flat, linear processing – in the lab, where these variables can be altered independently. Radiometry is used to *quantify* these conditions and generate specifications

required for a photo-curable material to develop its ideal properties on the substrate involved. In addition to film weight, the laboratory exposure conditions must be within the same range achievable by a production system. This facilitates the specification and 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.

2. The mechanics of the line are identified – degrees of motion, surface velocities, part size and shape, fixturing, 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 radiance (wavelength distribution) must be the same as used in the development phase (step 1).

4. Finally, radiometry is used to monitor the *consistency* of the process exposure over time. When the lamp type, including its spectral distribution, and optical arrangement (distance, focus, etc.) are identified, and are not variable, it may be sufficient to verify the exposure.

In steps 3 and 4 it may be difficult or impossible to use the same instruments used in the lab in step 1. This raises the issue of correlation of different radiometric instruments or methods.

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.[4] These instruments are essential to material and process development, the optimization of the four key variables, and the determination of the "process window."

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 3D parts, on the other hand, there are multi-point filter-detector radiometers that can handle up to 32 locations simultaneously.[5]

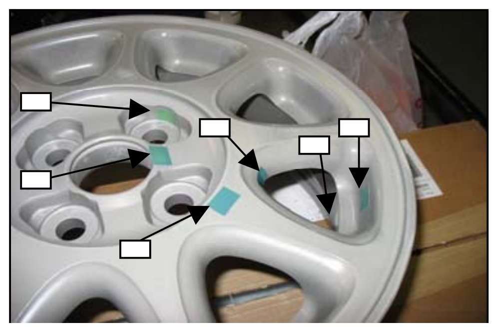

Figure 1. Radiachromic Sensors on Complex Part

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 non-rotational paint lines, cup and tube printing and coating, and container decorating, to name only a small fraction of the potential.

Cautions with Radiachromic Films

A number of commercial radiachromic films (discussed in the earlier paper) 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 is 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.

Radiachromic Films and Densitometry — Eliminating Subjective Errors

A number of commercial films were considered for this study, but three films were selected for their dynamic range, stability, and cost. One is an opaque (reflective) film manufactured by Spectra Group Limited, Inc.[5] (for which we will use the abbreviation "SGL"); one is a UV-Tec radiachromic strip, and the transparent film is manufactured by Far West Technology, Inc.[6] (for which we will use the abbreviation

"FWT"). The instruments used to read these films are an Ihara model R710 color reflection densitometer[(7)], an Ihara model T500 black & 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 UV-Tec film was read with all the color ranges of the Ihara R710 to determine the best choice. 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, so to avoid color mismatch, the wider band B&W Ihara T500 was used to read the FWT-60 film.

Reflection and transmission optical density are similar, but have slightly different definitions and expressions. Both represent the $\log_{10}$ of a ratio, so can be useful for comparisons.

Reflection "Optical Density," is based on reflection: $\boldsymbol{D} = \log_{10}\dfrac{100}{R}$ and $\boldsymbol{R}$ (% Reflection) = $100 \times \dfrac{1}{10^D}$

Transmission "Optical Density" is based on transmission: $\mathrm{OD} = \log_{10}\dfrac{I_0}{I}$

where $\boldsymbol{I_0}$ is the incident beam, and $\boldsymbol{I}$ is the transmitted beam.

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.***

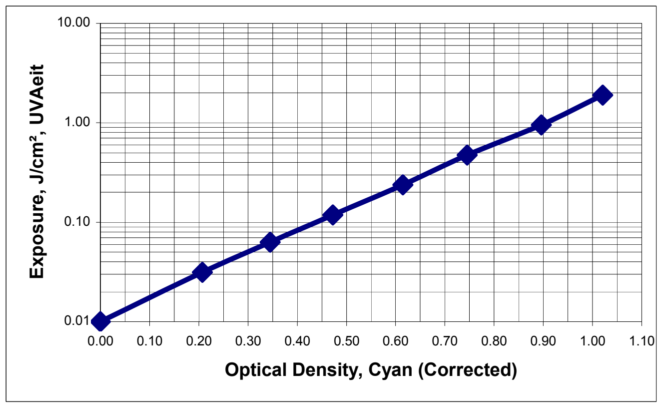

Figure 2 SGL Film[(5)] Exposure vs OD for "H" Bulb

In the example in Figure 2, the correlating radiometer was an EIT PowerPuck® or PowerMap®, and in the "UVA" range (referred to as "$\mathrm{UVA_{EIT}}$"). Thus, by reading the corrected OD of the film, a value of the $\mathrm{UVA_{EIT}}$ exposure can be imputed, so long as the exposure is from the same type of "H" 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" O.D.

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 3. "Ideal" linearity is a straight line.

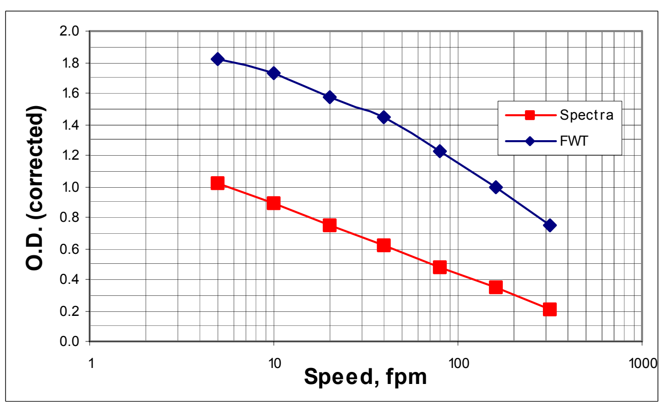

Figure 3. "Linearity" Plotted for SGL Film and FWT Film, "H" Bulb Exposure

Some films (not included here) do not have suitable linearity or dynamic range. Figure 4 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.

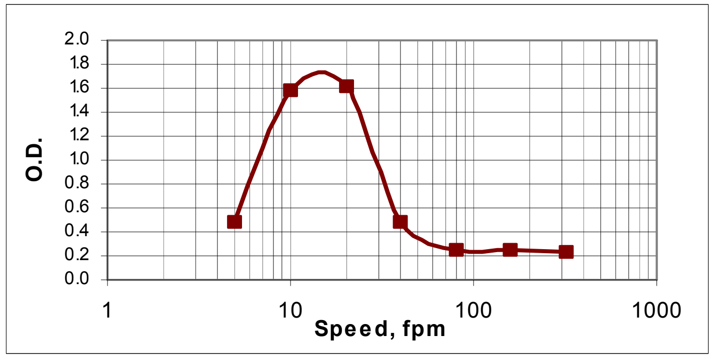

Figure 4 A non-linear Film

The Correlation Curves

The correlation curves of the two films of Figure 3, exposed by three types of lamp, are shown in Figures 5 and 6.

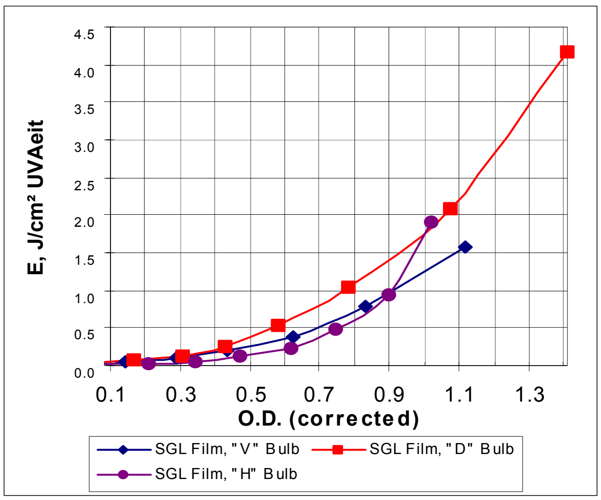

Figure 5. Correlation of SGL Film[5] with “H,” “D,” and “V” Bulbs

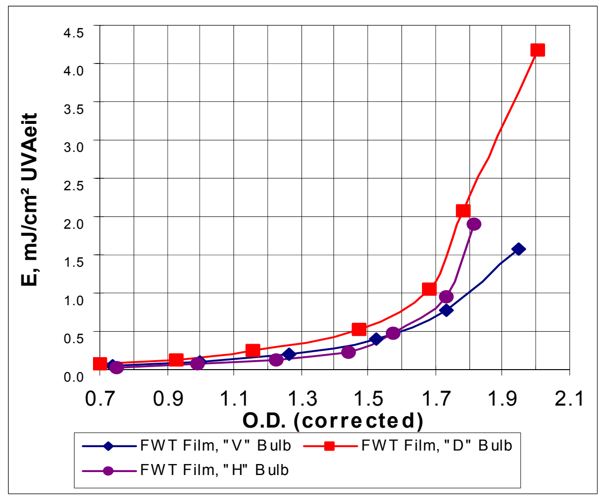

Figure 6. Correlation of FWT Film[6] with “H,” “D,” and “V” Bulbs

Owing to the fact that the “D” bulb (an iron halide additive type) has significantly higher output in the 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 non-linearity in the films, non-linearity 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.

Example: A Sensitive Film

An example of a commercial film that has excellent response, but over a narrower dynamic range is UVTec Control Strips.[8] These are available in two ranges, 10-200 mJ/cm² and 200-600 mJ/cm². The higher range strips were used to demonstrate the application of the proposed correlation method with an “H” bulb and the UVA_{EIT} exposure range. The “quick check” of range and linearity in Figure 7 reveals that resolution is possible in the cyan, magenta, or black ranges of the reflection color densitometer, and that the film has approximately one decade of dynamic range. The “flat” curve of the yellow hue shows that the yellow content of the reflection does not change, so would not be a good indicator. Figure 8 shows the corresponding correlation curves. Any of the three filter choices could be used, but the best resolution is obtained with the magenta scale.

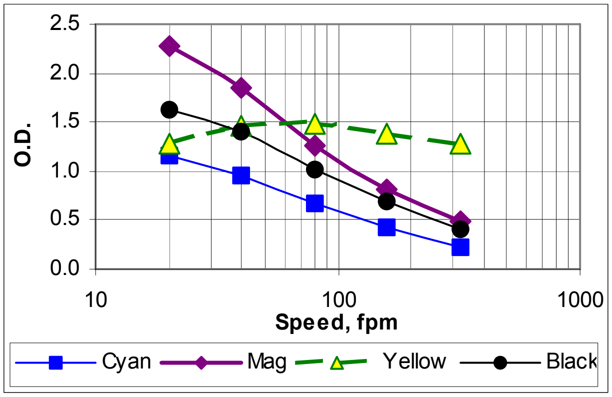

Figure 7. "Quick Check" of Linearity and Dynamic Range, UVTec Film

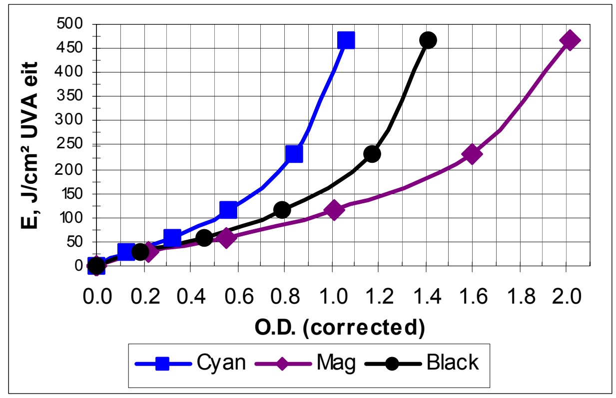

Figure 8. Correlation with Exposure, UVTec Film

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. An "H" (mercury) bulb was chosen, even though it has a complex spectral distribution, it has a reasonably broad emission over the 200-450 nm region.

Two sequential cutoff filters allow analysis that would be similar to "pass band" filters. An illustration of a filter pair is shown in Figure 9. The filter sets are shown in Figure 10, overlaid on the spectral emission of an "H" bulb.

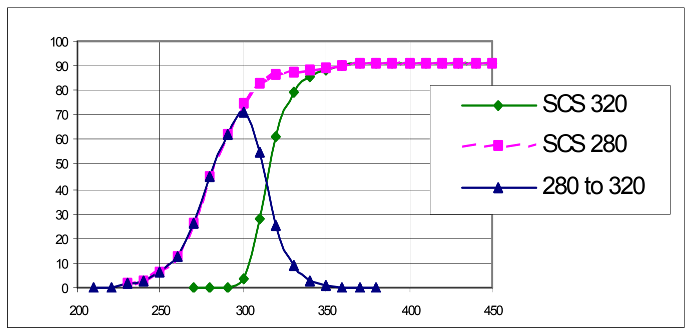

Figure 9. Differential Between Cutoff Filters

By integrating the spectral emission of the "H" bulb in 10-nm bands, each centered on the data points of the transmission curves, a calculation table can be created of the energy delivered and filtered in each 10-nm band. The antilog of the incremental O.D. 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

$$\Delta\ \mathrm{antilog}_{10}\, O_{\Delta\lambda} / \Delta E_{\Delta\lambda}$$

Which is 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 11.

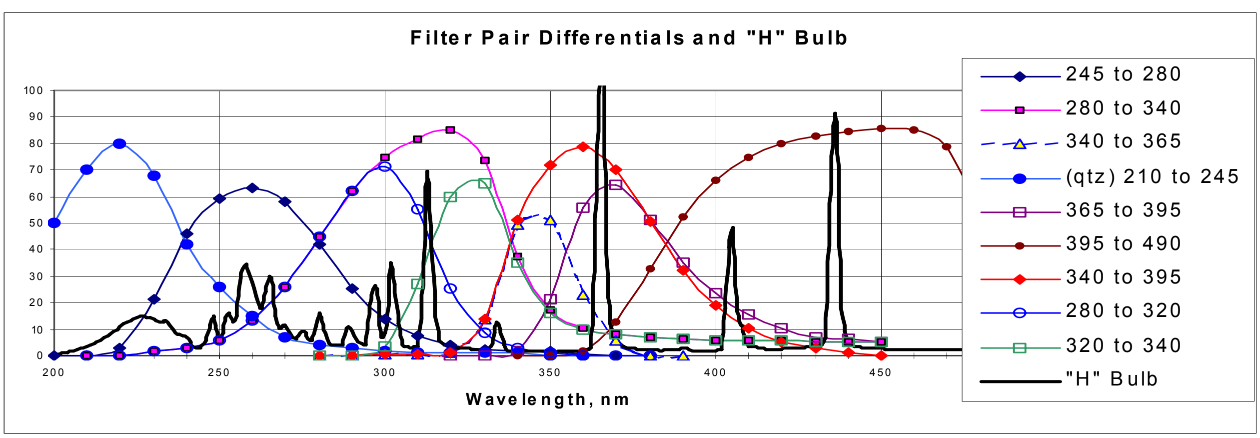

Figure 10. Transmission Differentials of Selected Cutoff Filters and Spectral Output of "H" Bulb.

It becomes apparent from Figure 11 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 5 and 6. This, 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.

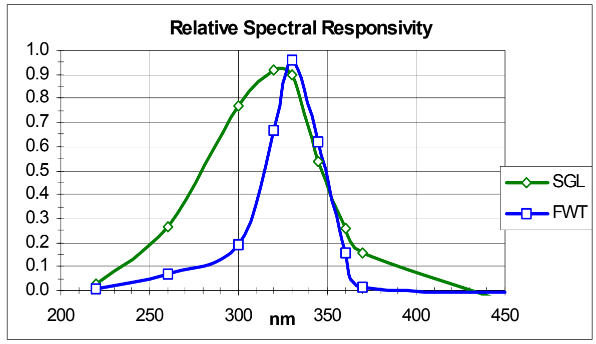

Figure 11. Relative Spectral Responsivity of Two Films

Observations and Conclusion

Several radiachromic films have been demonstrated to have a wide dynamic exposure range, good linearity, and 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. For a reflective color-change film such as the Spectra Group film, the color change (from yellow through green) is blue, making cyan the range choice. The Far West film exhibits a comparatively narrow hue, changing primarily its shade of blue, as its transmission is reduced. To avoid “spectral mismatch,” the broader black & white range was selected because it covers a range of hues.

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.

References

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