

Use of Modeling to Improve Formulation and Manufacturing Productivity

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Abstract

*Irradiance*¹ for *Dynamic exposure*² conditions produce *irradiance profiles*³ that can pose unique challenges for manufacturers dealing with free radical cured coatings. Figure 1.0 demonstrates irradiance profile variance for a *dynamic exposure* condition as a function of the type of reflector, lamp dimensions and direction of travel used.

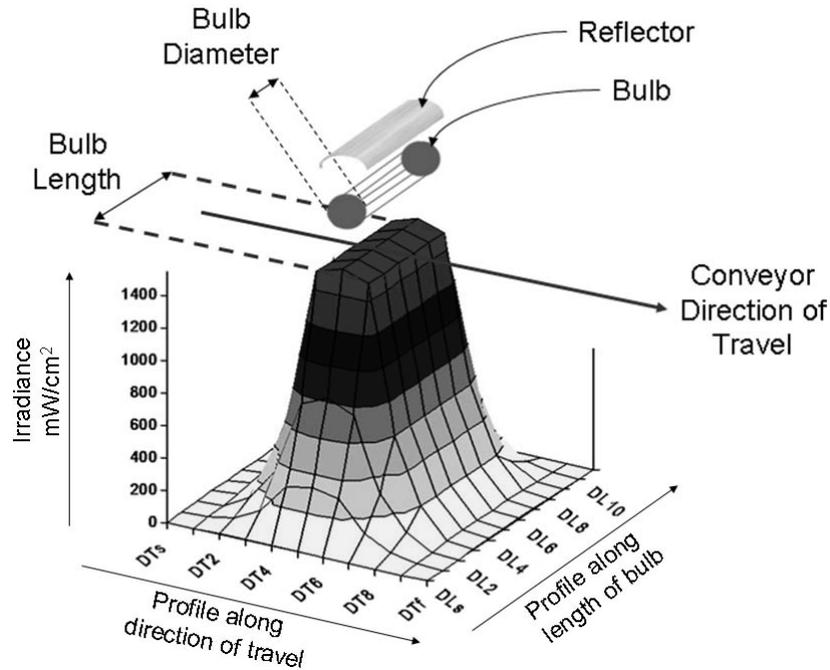


Figure 1.0 Dynamic Irradiance Profile

Variance in these irradiance profiles from the edges to the center of the lamp/reflector focus as well as the initiator package selected can affect the final coating ranging from insufficient surface or adhesive cure to obtaining inconsistent or unacceptable physical properties even from well developed formulations or exposure systems. The purpose of this paper is to outline use of modeling to develop and test solutions to better understand these effects and build more robust formulations and systems to achieve final product acceptance.

¹Irradiance is the radiant power arriving at a surface from all forward angles, per unit area, typically W/cm^2 or mW/cm^2 .

²Dynamic Exposure results when either the lamp or the exposed surface area is in motion such as a part traveling on a conveyor and passing under a UV Lamp.

³Irradiance profiles are a graphed measurement of the varying total irradiance at a surface point for various points in time through the field of illumination

Introduction

Radiation sensitive systems can be defined as a subset of the broad class of “Energy Density Response Systems” where response can be measured in many ways. The response of interest from application developers and manufacturers is typically associated with physical property change or simply obtaining a result from a formulation and exposure system “that works”. Obtaining a desired response varies with the interaction specifics of delivered energy density (**D**, typically expressed in mJ/cm²), the formulation used, and the production details for application curing. For formulator and manufacturer alike, defining and testing the variables associated with these interactions can be an overwhelming endeavor that limits complete practical analysis and understanding even with use of Design of Experiments (DOE). This paper will discuss concepts of energy density response and then describe how these concepts can be practically applied to real systems through the use of modeling in conjunction with lab experimentation.

In radiation sensitive systems, generally categorized as “radcure systems”, changes in response can be measured in relationship to delivered energy density, where energy density is the time integral of irradiance (**I**, typically expressed in mW/cm²). For a system delivering constant irradiance (static exposure) for a period of time *dt*:

$$\text{Energy density} = \mathbf{D} = \mathbf{I} * dt$$

The speed of the system would then be defined as the minimum required irradiance and time (energy density) to achieve a desired response or satisfactory rating for the critical property(s) of the intended application. Sometimes these properties are related to and measured as:

- Surface tack.
- Surface hardness.
- Cure to the base (is adhesion to the substrate adequate? Is it over cured as shown by brittle failure at the interface?).
- Resistance to rubbing with wipes saturated with methyl ethyl ketone (MEK) or acetone.
- Brittleness as measured by bending around varying diameter mandrels and noting the diameter at which fracture occurs.
- Film modulus, elongation to break, degree of elastic recovery.

Further, one must recognize that static exposure systems (application and lamp are stationary) which are primarily the province of imaging systems, often require the ability to clearly resolve fine detail. This is generally not significant in dynamic exposures such as protective coatings used for flooring or overcoats on printed material. Thus in imaging, overexposure (energy density beyond that required to give the sought after response) can be fatal while protective coatings can be quite tolerant of overexposure but may be totally intolerant of under exposure, particularly when it is delivered at ineffective irradiance levels. So, what are the factors of significance in understanding the interaction specifics of delivered energy density, the formulation, and the production details for an

application? Some say formulation, peak irradiance or energy density is most important but no one element tells the whole story.

Understanding and Defining System Response

The normal way of presenting the energy/response data is in the form of a plot of the measured response versus the log of the incident radiation exposure energy. This curve is referred to as the characteristic curve and has the general shape shown in Figure 1. With regard to this curve it is helpful to define a few terms associated with it that will be useful in understanding its application. These terms include:

- R = the measured response at any given exposure.
- R_{\max} = the maximum response that the system can detect.
- R_{\min} = the minimum response that the system can detect.
- D = the incident energy density exposing the system.
- $\Delta\text{Log}(D)$ = recording range, that is, the log of the exposure range over which information can be recorded and response can be discerned. It runs from the minimum detectable response to the point of maximum detectable response.
- γ = Contrast, or the slope of the response $\text{Log}(D)$ curve at any point. Usually expressed as an average that covers the nominally linear portion of the curve. When the plot is response versus exposure rather than log of exposure, the slope of the curve at 20% fraction reacted ($R/R_m = 0.2$) is converted to moles per liter-second and is reported as $R_p \max$.

Figure 1. Characteristic Curve

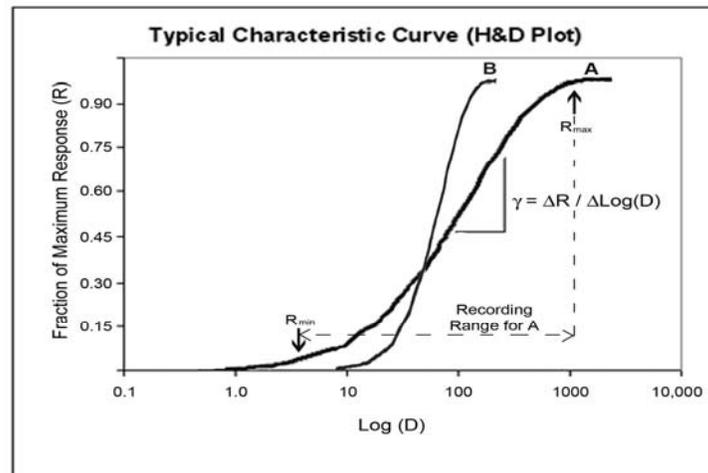


Figure 1 demonstrates two energy density-response curves for the same formulation and exposure system, viewed for two different responses. Curve A (in blue) has a minimum detectable response at lower energy than curve B (in red). That is, for the two responses, A is more sensitive than is B. Also, curve B is steeper than curve A (higher γ , or higher

contrast). Both maximize at $R_{\max} = 1$ (relative response). The two different responses could be physical properties manifested by the system in response to radiant energy, for example adhesion of the cured film to the substrate (Curve B) and tensile strength of the cured film (A).

Both of the physical properties represented by the two curves in Figure 1 derive from the overall conversion of the system as a function of input energy. However, most responsive systems do not “read out” in conversion units (exceptions are those that directly follow properties associated with molecular conversion, such as real-time infrared methods, like RT FTIR). “Read-out” is typically in units associated with physical properties such as optical density, solubility, or hardness.

In practical system response, there is a minimum and a maximum detectable response in which continued energy density change above or below these limits is essentially indiscernible. As an example, where optical density is the response measured, 0.01 is a reasonable estimate of the minimum detectable response and 3.0 approximates the maximum beyond which the unaided human eye does not easily discern response change with exposure. Accepting these circumstances, the first discernible fraction of response is:

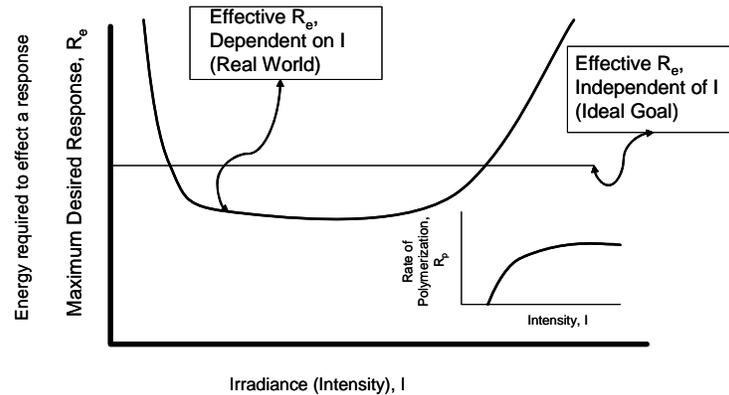
$$\text{First Discernible Fraction of Response} = 0.01/3.0 = 0.00333$$

Similar definitions can be developed for any physical property associated with a cured system and formulation. The concept of defining and understanding a minimum detectable fraction of response is important in that it enhances understanding for formulation and manufacturing optimization particularly through use of modeling in combination with targeted laboratory results. Essentially, in any formulation and system where the response measured is an observable property, the minimum detectable response and maximum detectable response can be defined in terms appropriate to that response or property. Therefore, successful application and process window optimization requires recognition that the rate and time of energy input is critically important to response. That is, matching a formulation, irradiance AND energy densities are all critically important to achieving a desired response.

Response Associated with Variable Irradiance

Now examining response as it varies with irradiance, the ideal system response would be independent of the level of irradiance. Practically however, no known energy-response systems behave in this ideal way. This is illustrated in Figure 2.

Figure 2. System Response as a Function of Irradiance Used in Exposure



The system response, R_e , that the user desires, is ideally independent of irradiance. In practical systems, R_e varies with irradiance as shown in the U-shaped curve in Figure 2. At very low irradiance, the energy required to effect the desired response becomes very high (possibly infinite – that is, no response will occur no matter how much energy is input perhaps as an example, due to inability to overcome oxygen.) At intermediate irradiance levels, the response may become relatively independent of input energy and its rate of input (flat region of the U-curve). Then, again, at very high irradiance, the energy required to effect response rises and it may become impossible again to obtain the desired response.

This seemingly bizarre behavior is due to a common property of all energy responsive systems. There is a competition between two processes: a first order, response developing process, and a second order, non-response developing process. Rather than describe this competition in general terms, we return to photopolymerization and radiation curing to illustrate this dilemma.

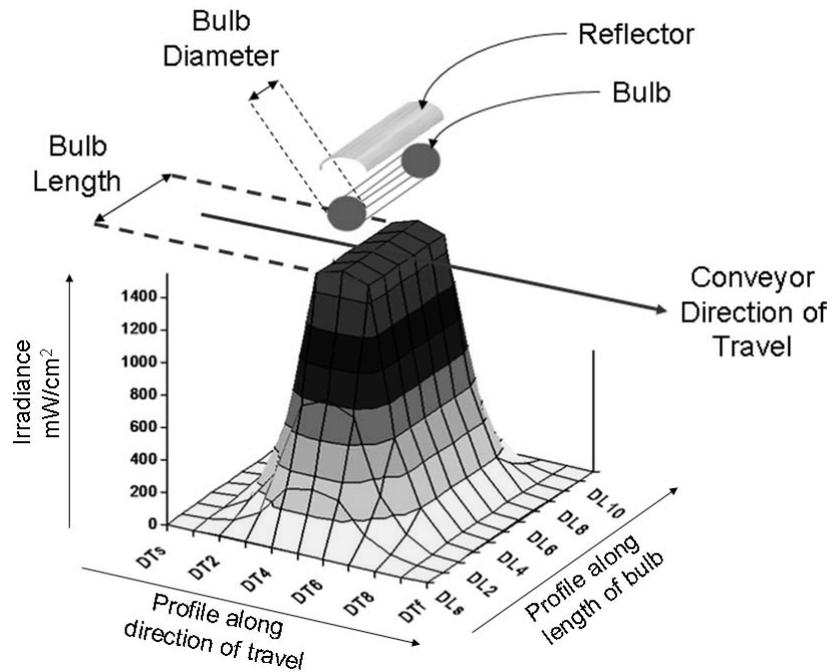
In Figure 2, the small insert to the lower right of the diagram shows the general progress of photopolymerizable systems (in the presence of air) as a function of irradiance applied. There is usually a power level at which the polymerization begins, and as irradiance is increased, the rate of the process (conversion versus time) increases. At higher irradiance levels, the rate of the conversion levels off (maximizes).

Why is that? At low irradiance, free radicals produced by exposure of the photoinitiator are trapped by ambient oxygen before they can effectively grow polymer chains and become large enough to develop a physical property sufficiently. That is to say, a level of response required by the user for acceptable delivery to a customer cannot be achieved. In the “sweet spot” of the response-irradiance profile, good physical properties can be delivered. At excessively high irradiance however, so many free radicals are produced per unit time that they recombine (terminate) more often than they initiate new chain propagation. This dilemma is referred to as “low intensity reciprocity failure” at low irradiance levels and “high intensity reciprocity failure” at high irradiance levels. In photopolymerization, it occurs because of a dependence of the key propagation metric, kinetic chain length (KCL), on irradiance when combined with a particular formulation.

Line Speed Exposure Challenges

Why is KCL, the number of monomer functional units converted to polymer per radical generated important? It is important because KCL dependence on irradiance, and thus of the conversion of monomers and oligomers to a final polymerized product, is critical to the dynamic or line exposure so commonly used in web-based photocuring processes. Consider that a dynamic exposure system produces *irradiance profiles* that pose unique challenges as demonstrated in Figure 3.0 which depicts a three dimensional irradiance profile as a function of the type of reflector, lamp dimensions, focus, direction and speed of travel as well as position on the conveyor.

Figure 3.0 Dynamic Exposure Irradiance Profile



Consider that a formulation exposed to a profile as depicted in Figure 3.0, may experience different peak irradiance values leading up to the point of “complete” conversion both as a result of traveling into the exposure area and or location on the conveyor. As a result, “true” peak irradiance values will vary and in turn so will the “true” energy density and system KCL.

So, how does KCL and conversion of a formulation vary with irradiance at constant energy density? Figure 4 shows the variation in KCL and conversion (as a percent of the theoretical limit) for a formulation in which the amount of initiator is varied as shown below:

	<u>5 gram PI</u>	<u>2.5 gram PI</u>
<i>Initiator</i>	weight (gms)	weight (gms)
Benzophenone	3.0	1.5
1-Hydroxycyclohexyl phenyl ketone	2.0	1.0
<i>Monomer</i>		
Tripropylene Glycol Diacrylate	20.0	20.0
Trimethylolpropane Triacrylate (TMPTA)	10.0	10.0
Ethocylated (3) TMPTA	25.0	25.0
<i>Oligomer</i>		
Aliphatic Urethane Diacrylate	40.0	40.0

The formulations are coated at 20 microns thickness and exposed to a medium pressure mercury arc lamp in air, at variable intensities using PrecisionCure™ modeling software. KCL and conversion values were tabulated and plotted at a constant energy density delivered of 100 mJ/cm².

Figure 4 KCL and Conversion Plots

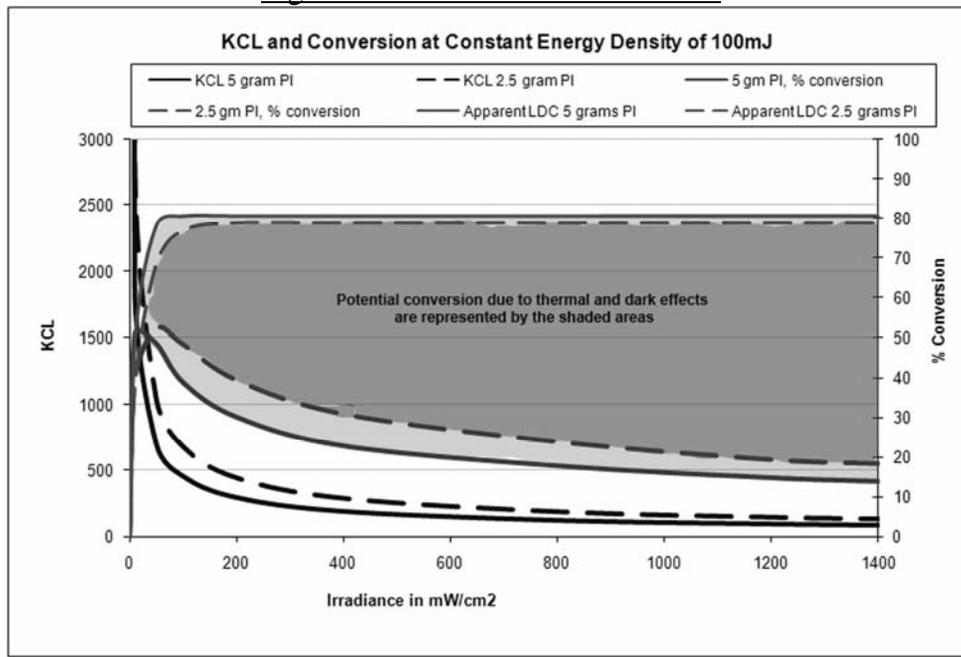


Figure 4 shows that KCL decreases exponentially as irradiance increases (energy density held constant) and real time conversion increases to a maximum value and then turns over and decreases as high intensity reciprocity occurs. When the photoinitiator level is cut 50%, KCL and conversion (for constant energy density) increase slightly. Recall, that this constant energy density conversion is the instantaneous response of this system to the delivered energy density. The actually observed conversion of the system such as that measured by infrared spectroscopy at the end of the run however, will show a continuation of polymerization toward a limiting degree of conversion (LDCa, represented by the green lines in Figure 4). This continuation of polymerization and the

impact of thermal effects that occur above the instantaneous response (red lines on Figure 4) are often referred to as dark time polymerization. This behavior and relational interaction between irradiance, formulation and duration of exposure has important consequences for dynamic exposure.

Traveling Along the Web

Exposure of a photosensitive coating on a moving web presents challenges to modeling. If the system is monitored with a Power Puck or other integrating measurement device, the user is presented with a detailed view of the change of irradiance with exposure time (or distance traveled along the web). The profile in Figure 3 shows that because a reflector (elliptical or parabolic) is not a perfect focusing or collimating device, and because it is out of contact with the moving web, light at low intensity “leaks” out of the high intensity exposure region. This low intensity “foot” region occurs on both entry into the high intensity region and exiting from it. But the behavior of the polymerizable film to the incident low intensity light sections (feet) and high intensity focus (and or collimatic) regions are very different and can produce surprising results.

As the film moves into the first low intensity foot, photoinitiator creates radicals which are either trapped by ambient oxygen, or initiate propagating chains (which can be terminated by oxygen before they attain a gel point). Depending on the irradiance in the foot, oxygen may or may not be overcome before the high intensity region is entered, and it is possible that at some level of foot irradiance the formulation could run short of photoinitiator before it enters the high intensity region. At this low level of irradiance, KCL is high, but rates of initiation are low.

As the moving web continues and begins to enter the high intensity region of the focused light source, irradiance and rate of initiator consumption increase dramatically and the KCL falls rapidly while the temperature of the film surface climbs.

When the moving film exits the high intensity region and experiences the low intensity foot for a second time, the irradiance decreases causing a rise in KCL again and may promote continued strong propagation even if photoinitiator is exhausted.

It is also clear to those with long experience in this field that physical properties of the final product will depend critically on where in the irradiance profile the major polymerization processes occurs. It is likewise clear that the behavior of the film depends critically on this prior history. At what point has photoinitiator run out if in fact this occurs? Are thermal effects and high concentration of free radicals at high irradiance levels going to produce dark polymerization or has its LDCa already been achieved at some point during one of the three regions of exposure. How has this impacted the resulting KCL? Fortunately, today’s formulators, manufacturers and product designers have access to powerful modeling techniques such as that represented by PrecisionCure to support “seeing” what occurs and optimizing use of radcure solutions with greater speed and ease.