UV Curing

UV Light as the Energy Source for Industrial Processing of Coatings, Inks, and Adhesives

by

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Ultraviolet Curing, the process of transforming a liquid into a solid by the action of light, is an energy-efficient and relatively low-temperature technology with many applications in coating, printing, adhesives, electronics, and communication products. UV Curing provides improved overall physical or chemical properties of polymeric materials and produce superior results in bonding, surface finish, and durability. It is used on virtually all substrates, plastics, paper, film and foil, wood, metal, glass, fibers and composites. Speed and controllability in a huge variety of applications are driving increasing worldwide markets for this proven technology.

A number of variables of a UV lamp system can be designed or selected to improve the efficiency of a UV curing process. While the desired properties of a cured material are essentially designed into the formulation, the development of the target properties of UV curable materials themselves depends on how well these lamp factors are designed and managed. Variables which can be controlled are: total UV power, UV spectral distribution, irradiance and irradiance *profile*, and infra-red energy. The ability to match all of these lamp characteristics to the optical and physical properties of a UV-curable material widens the range of tools available to the process designer, and yields more efficient and stable UV curing processes in production.

UV-cured materials have become widely used in an astounding variety of product applications. The parameters which define a successful cure are entirely dependent on the process involved. Cure, for example, is the object of the UV curing process, but it is not a clearly defined result. Cure is meaningful only as it relates to properties of the cured product. The properties of interest include such characteristics as hardness, scratch resistance, adhesion to a substrate, or simply surface tack. There seems to be a limitless list of properties to achieve, varying greatly from one application to another. In fact, each application has a unique set of properties which characterize it.

Benefits

UV Curing is highly desirable for processing, owing to benefits of productivity as well as advantages of being a "clean" technology. This process has a number of key attributes:

- **no solvents** -- cure is by polymerization rather than by evaporation, so VOC and HAP emissions are eliminated;
- **low temperature** -- heat is not required;
- **high speed** -- cure is nearly instantaneous;
- **energy-efficient** -- energy is invested only in the curing reaction, not in heating;
- **easily controlled** -- inks and coatings do not "dry," so do not set up in printing/coating equipment, or change viscosity;
- **quality finishes** -- superior resistance to scratch and chemicals.

Applications

UV processing offers major advantages over other finishing methods. Typical product lines involve coatings (on wood, metal, paper, and plastic), inks (for letterpress, lithographic, gravure, and screen printing), and adhesives (for film, foil, or paper substrates). The industries using these technologies are diverse and varied; they include automotive components, medical products, electronics, CDs and DVDs, 2-piece and 3-piece can printing, pipe and tube coating, furniture, fiber optics, flooring, packaging and containers.

Background: Solvent-based 'Drying' vs UV Curing

Solvent-based, thermally cured (or dried) inks or coatings are composed of a resinous binder, pigments and fillers, and diluent solvents. After application to the substrate, heat is applied, driving off the solvents and drying the coating film. The evaporated solvents are generally flammable and toxic, and become airborne pollutants. Solvent emissions can require the use of more energy and capital investment to be incinerated or "scrubbed" and recovered by distillation.

In contrast, the UV curing process achieves the transition from liquid to solid by means of chain-addition polymerization. This polymerization is triggered by the reaction of a low concentration of an ingredient called a *photoinitiator*. The photoinitiator absorbs and reacts to ultraviolet light. In UV-curable material, the resin binder is replaced by a formulation of liquid monomers and oligomers, which are induced to 'cross-link' by the reaction of the photoinitiator. To create an ink, pigments may be dispersed in the liquid formulation. The coating is completely reactive and the thickness that is laid down wet is essentially the same as the thickness after curing. In UV inks, the pigment does not enter into the cross-linking reaction, but are literally "locked in place" There's no mass transfer, no evaporation of solvents -- just 'wet' to 'dry' by exposure to a UV light source.

Technology: UV Curing

When photoinitiators are exposed to UV light, they react and begin the polymerization of the adjacent oligomers and monomers. Typically, the radiant energy produced by the UV lamp is focused by a reflector onto a (moving) work surface -- the coating or ink to be cured. The UV energy striking the surface causes the photoinitiator to trigger the polymerization reaction. The material is usually solidified ("dry") when it exits the UV cure zone. The time, and consequently the space, required for cure is significantly less than thermal drying methods. Because the process relies on UV light to initiate the cross-linking of molecules, it does not evaporate any solvents, nor significantly heat the substrate.

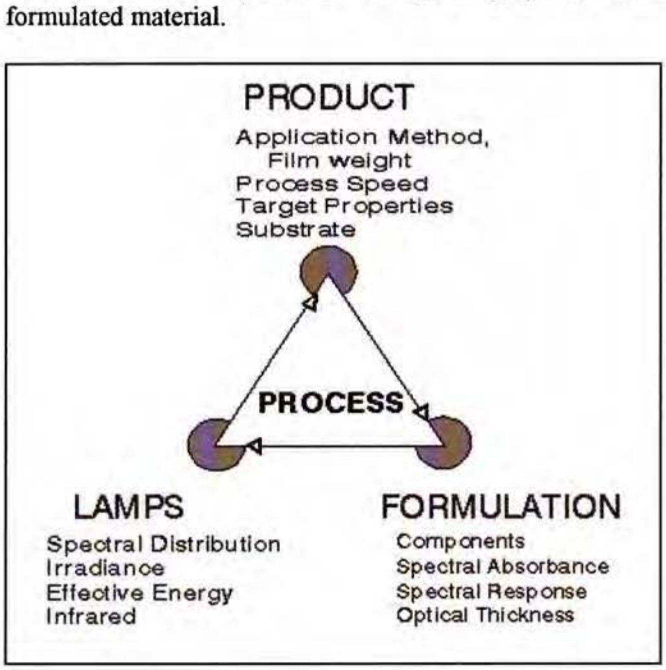
Key Components of a UV System

A UV Curing system consists of *three* component parts, all integrally related:

- **The end product** determines the requirements of the physical properties of the cured photochemistry. *Target properties*, such as opacity or hiding, film thickness, hardness or flexibility, chemical resistance, resistance to abrasion or scratching, and adhesion to the substrate are only a few which may represent the performance requirement of the application.

- **The photochemistry** is designed to achieve the *target properties* upon exposure to the appropriate UV energy. **Formulation** variables include a combination of monomers, oligomers, photoinitiators and functional additives, including pigments. The optical characteristics of the formulated material determine the most effective lamps to use.

- **The UV lamp system** has a number of variables such as power, wavelength, and focus, that will also have a significant effect on the target properties of the end product. The selection of these variables depends on the optical properties of the formulated material.



These three components -- application method, formulation, and cure exposure -- are coordinated to create a successful UV-cured system.

Categories of UV Curing

With a variety of materials and product handling methods involved in UV curing, the size of the part, the area of the surface, and the speed of the process will require curing systems designed to accommodate them. UV curing might be divided into several categories, distinguished by size of work surface and type of motion of the work piece.

Linear Curing

Linear processing is the most common arrangement for curing, and is characteristic of curing flat surfaces. The surface, which has been coated or decorated, is passed under or by UV lamps to expose the surface. Printing presses, roll-to-roll coaters, and conveyors are all variations on linear processing. Typically, a tubular lamp with a focusing reflector, or rows of tubular lamps extend across the surface, providing uniformity of UV exposure in that dimension, while the motion of the work surface provides uniformity of exposure along the direction of travel. Because the lamps can be arranged closely to the surface, very high intensity of UV can be achieved.

Flood (Area) Curing

The simplest method of UV exposure is to place an object or surface under a UV lamp and control the time during which it is exposed. This is often referred to as "static" curing. It is frequently used for laboratory exposure or for low-volume production curing. Flood exposure is regularly used in film transfer and printing plate making. Static flood curing is typically used in printed circuit manufacturing.

However, when the surface is complex, or curved, or even "3D," it becomes more difficult to cover the surface in a linear fashion with focused high intensity light. The illumination may be lower in intensity, as the energy is distributed over a larger area. By combining additional degrees of motion of the part, such as rotating *while* passing through the curing lamp region, a complex surface may be easily and adequately cured. Further, lamps of various configurations are be used, depending on type and degree of motion, size and complexity of the surface contours.

Spot Curing

Spot curing is characterized by a small, high intensity "spot" of UV light directed precisely at a work point. It is typically used for UV bonding of adhesives for medical product assembly and electronic assembly. The light is transmitted to the work area by means of a liquid light guide, with a projection lens at the tip. This enables the spot cure system to work in spaces and with small assemblies where a large lamp would be impractical.

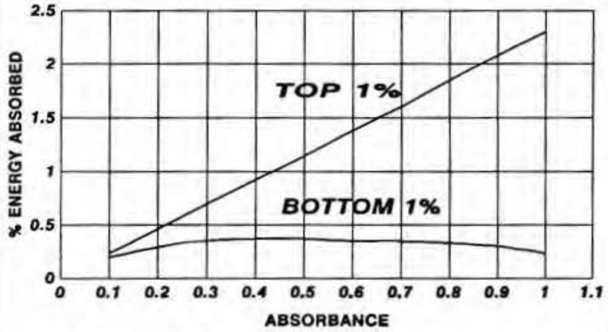
The Optical Character of Inks and Coatings

The curing process, in its simplest form, may be thought of as the interaction of a photon and a photoinitiator molecule. Rates of initiation are dependent on the rate of the photon-photoinitiator collisions. From an optical point of view, the efficiency of the process depends on the ease or difficulty of delivering photons to photoinitiators molecules.

All inks, coatings, or adhesives will absorb the UV arriving at the surface, but the radiant power available deeper within the film will depend on the absorption in the upper layers of the film. Only photons which are not absorbed or reflected in an upper layer of the film are available to lower layers. In addition, only those photons of wavelengths to which the photoinitiator is sensitive will be useful.

All of the ingredients of an ink or coating tend to block light, especially UV light. In fact, the reduction of light as it passes into an absorptive material will follow a very definite law, the Beer-Lambert law. Radiant power diminishes with depth and absorptivity. Immediately, we realize that the top and bottom of any UV curable material, ink or coating, are subjected to very different curing conditions. The top surface and the bottom represent the two extremes of these conditions.

We can examine this difference by plotting the result of the Beer-Lambert law for only the top 1% and the bottom 1% *for a film of any thickness*, as a function of its **absorbance** (a measure similar to optical density).



The Beer-Lambert Law Analyzed into Light Absorbed in Top 1% and Bottom 1% of Any Film Thickness, vs Absorbance

Much of the benefit of screenprint inks, for example, is in their ability to provide opacity, richness of color, and texture. In the ink world, screen inks represent some of the heaviest film thicknesses. This means that screen inks, with their high optical densities, present special problems in the interaction with UV curing lamps.

UV Exposure – Irradiance and Energy ["Dose"]

Irradiance is the radiant power arriving at a surface per unit area. It is measured in W/cm^2 or mW/cm^2. (It is sometimes loosely called "intensity," but unless it is clear that we mean "at the illuminated surface," it can be confused with other terms). *Peak Irradiance* is the highest value of the *irradiance profile* under a UV lamp -- usually at the focal point of the lamp. Irradiance depends on the radiant power from the bulb, *and* the bulb diameter, *and* the reflector focus *and* its reflectivity.

Energy ["dose"] is the term which applies to the time-integral of irradiance. It is measured in J/cm^2 or mJ/cm^2. ***Time*** is really the variable here, as energy is simply the product of time and irradiance. [Unfortunately, a measurement of energy alone does not allow the extraction of information about irradiance and *vice-versa*]. There are several radiometers available which measure both peak irradiance and energy ["dose"].

Effect of Irradiance and Energy on Cure

Comparing the cure speed of a black screen ink, 390 mesh, on polycarbonate for several lamp arrangements, we can demonstrate that irradiance, rather than energy ["dose"], can have a key effect on cure:

Comparison of Cure, Black Screen Ink

Lamp class:	300 watt/inch	300 watt/inch
Bulb Type:	mercury	mercury
Lamp Type:	electrodeless	electrode, arc
Bulb diameter:	9 mm	23 mm
Peak Irradiance:*	915 mW/cm^2	480 mW/cm^2
Energy* at cure speed:	435 mJ/cm^2	620 mJ/cm^2
Cure speed:	68 fpm	44 fpm

*measurements with EIT UVMAP®, UVA range

Here the smaller diameter bulb, with its higher peak of irradiance is more effective, and less energy is required, owing to the ability of higher *irradiance* to penetrate the ink.

We can also examine depth of cure as it is affected by irradiance versus energy. This time, without changing the lamp geometry, we can compare the depth of cure of a black screen ink as we make one or two passes under lamps of different peak power: The two "passes" under the lower power lamp, while increasing depth somewhat, didn't double it. We would expect a similar diminished return for a third pass; after all, the time that we expose the ink doesn't make up for "intensity."

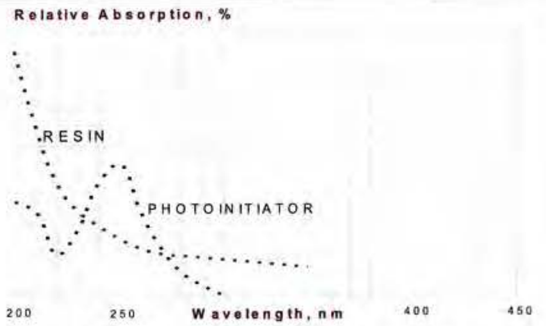
Comparison of Depth of Cure, Black Screen Ink

Lamp, Bulb Type	Passes	Peak, mW/cm^2	Depth of Cure, mils
300 w/in, D	1	3200	1.0
300 w/in, D	2	3200	1.5
600 w/in, D	1	6400	2.0

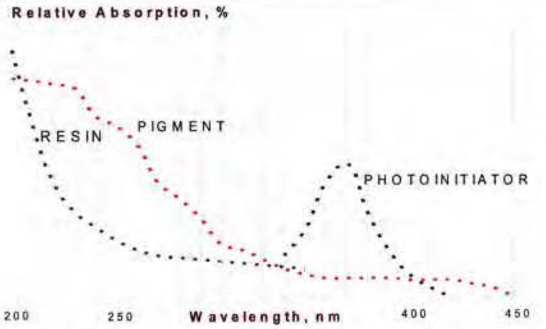
*measurements with EIT UVMAP®, UV-A range

Significance of Spectral Absorbance

A clear screenprint varnish, consisting of only monomers, oligomers (resin -- no pigment) and a photoinitiator, will readily absorb the very short UV short wavelengths at the top surface of the coating. Slightly longer wavelengths will be able to reach the photoinitiator. The characteristic absorption curve of light energy by the photoinitiator reveals its spectral response, but as it absorbs energy, it blocks that same light from photoinitiator molecules deeper within the material. Adhesion failures can occur. While increasing the concentration of photoinitiator may seem to improve cure at the surface, that will worsen the deeper cure.



Spectral Absorption of "Varnish" Resin and Photoinitiator only



Spectral Absorption of an Ink Resin, Pigment, and Photoinitiator

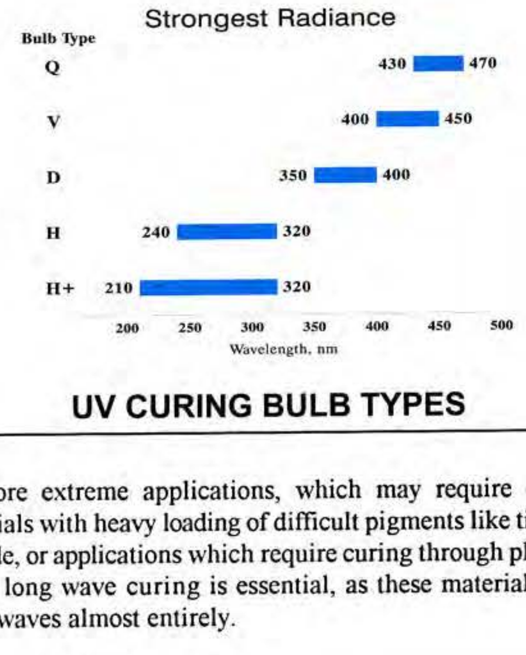
Pigments have their own characteristic UV absorption curves. A blue pigment is illustrated above. The graphs shows the typical spectral absorption for a photoinitiator, a pigment, and prepolymer. It is readily apparent that short UV wavelengths (200-300 nm) will be absorbed at the surface and not be available at all to lower depths. It also illustrates that a photoinitiator which may be appropriate for a clear coating or for a thin film, may not be at all a correct selection for use in an ink.

Astute ink formulators are keenly aware of these principles -- various basic colors of ink will have different concentrations or selections of photoinitiators to compensate for the optical effects of pigment absorption. Color matching is accomplished by color blends within a series of inks. A good color match system will also achieve the blending of the photoactive ingredients at the same time the pigments are blended. The result will be that all of the colors in the series will respond similarly to selected UV light.

Carefully formulated inks are also designed for different application thickness, or film weight. The design of a screen ink for CD printing, which may call for a 6-8 micron laydown, is different from a labeling ink, which may require as much as 15 microns.

Selecting Bulb Type - Spectral Distribution

A variety of bulbs with different spectral outputs in the UV range is available. These are generally mercury-based medium pressure bulbs, which can have additives in them to alter their spectral distribution. Higher absorptivity materials, such as adhesives and screen inks benefit from the longer wavelengths, and are often formulated for longer wave cure. The longer wave bulbs emit sufficient short wave energy to assist with surface cure.



UV CURING BULB TYPES

In more extreme applications, which may require cure of materials with heavy loading of difficult pigments like titanium dioxide, or applications which require curing through plastic or glass, long wave curing is essential, as these materials block short waves almost entirely.

Heat and Infrared Energy

Infrared energy is emitted primarily by the quartz envelope of the source (UV bulb). This energy will be collected and focused with the UV energy on the work surface, depending on the IR reflectivity and efficiency of the reflector. IR energy can be evaluated in energy or irradiance units, but usually the temperature effect it produces is of prime interest. The heat that it produces may be a benefit or a nuisance, depending on the heat sensitivity of the substrate material.

The temperature of the surface is affected primarily by the absorption of IR energy, while the warm cooling air and the cure exotherm have a lesser effect on temperature. Depending entirely on the application, this heat can be beneficial or detrimental. Flow-out and wetting can be improved with heat; molecular mobility, hence cure speed, may be improved. Excessive temperature may cause volatilization of low molecular weight materials, "blooming" of plasticizers, migration of surfactants, and damage or deterioration of the substrate.

There are a number of techniques and schemes to manage temperature and IR associated with UV lamps. These can be grouped into methods for reducing emission, transmission and controlling heat removal. Absorption of IR energy is dictated primarily by the materials themselves -- the ink, coating and substrate -- but speed has a significant effect on the IR energy absorbed by the work surface.

> **Emission**: the surface area (diameter) of the bulb is the principal contributor - smaller bulbs emit less IR.
>
> **Transmission**: dichroic reflectors, hot mirrors, and water-filled filters are used in various lamps.
>
> **Heat removal**: air cooling of the work surface, temperature-controlled support surfaces such as air-cooled rollers or water-cooled cylinders, and water-jacketed housings are all designed to remove heat and reduce secondary radiation from hot surfaces.
>
> **Speed**: the relationship of temperature-versus-speed illustrates one of the simplest and most fundamental aspects of heat in a UV system: the faster the process moves, the less IR is absorbed, and consequently the lower the surface temperature.

Cost Considerations

The use of UV Curing as a decorating, finishing, or bonding technology presents a number of economic benefits over alternative methods. An economic benefit analysis for any one application may be substantially different from another. While they will vary with each application, cost savings may accrue from such factors as higher "mileage" yield from 100% solids inks and coatings, reduced setup time, reduced waste and scrap, better utilization of space, reduction of work-in-process, increased productivity, energy savings, increased yield, reduction or elimination of VOC processing, and improved product quality and performance.

Conclusion

The successful UV curing process is the practical result of a process design which takes into account a large number of factors, many of which are unique to each specific application. Careful analysis of the factors contributing to properties of interest can provide opportunities to improve the process.

Optical characteristics of lamp systems and their interaction with the optical properties of curable materials are an integral part of performance. Many analyses of cure results omit these characteristics, and in concentrating on a chemical outcome, tend to neglect the physics and optics.

Most UV curable films are "optically thick", thus much more radiant energy is absorbed near the surface of the material, and absorbance varies wildly with wavelength. Spectral absorbance is a critical factor in achieving an effective process. Lamp characteristics, such as spectral distribution, peak irradiance, and infrared energy can be used effectively, along with formulation strategies, to design successful UV systems.

Where are we?

UV curing is a proven process, used in a large variety of industries. It has displaced or replaced coating and decorating methods using conventional solvent-based systems because of reduced pollution, lower cost, higher product quality, higher production speed, and lower space consumption. Many of these have become possible because of the development of new commercially available UV-curable chemistry systems -- inks, coatings, and adhesives. Improvements in chemistries for existing and proven applications result in processes that are faster with improved physical properties.

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